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Associations between green space, air pollution and birthweight in Sydney Metropolitan Area, Australia

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ABSTRACT

Growing number of evidence have reported that exposure to air pollution was associated with unfavourable birth outcomes while increased exposure to green spaces was associated with better birth outcomes. However, the effect of interactions between air pollution and green spaces on pregnancy outcomes remain unclear. Using the data on all the live births recorded in Sydney between 2016 January and 2017 December, we built up multilevel linear and logistic regression models with random intercepts for statistical area level 2 (SA2) to examine the association between residential levels of air pollution (NO2, PM2.5, SO2 and O3) and pregnancy outcomes including birthweight, low birthweight, and preterm birth. This was followed by assessment of potential effect modification by green space quantity by fitting 2-way interaction term between each air pollutants and green space quantity separately. Furthermore, building on the 2-way interaction term, we explored 3-way interactions by adding area level socio-economic status and population density. Higher levels of PM2.5, NO2 and SO2 were statistically significantly associated with decrease in birthweights (p < 0.05) in the adjusted models. We observed statistically significantly association between the lower risks of preterm birth and higher levels of NO2 in the adjusted models (p < 0.05). However, none of the other air pollutants were statistically significantly associated with the odds of low birthweight and preterm birth. In the adjusted models, green space quantity was statistically significantly association with reduced odds of preterm birth (p < 0.05). The results for birthweights were in the same direction (p < 0.05) however, some of these associations did not remain statistically significant after adjusting the models for air pollution. In general, no associations were found for low birthweight. Statistically significant 2-way interactions between green space quantity and NO2, PM2.5 and SO2 levels indicated that association between moderate levels of NO2, PM2.5 and birthweight weakened in the greener areas (>20 %) especially in the affluent and densely populated areas while the effect of SO2 did not differ consistently across green space levels with benefit of exposure to the greenest areas (>40 %) was evident, yet not statistically significant. Our findings suggest that increasing green spaces in cities may help supporting a healthy start in life by decreasing harms of moderate levels of air pollution. Replication in different contexts and consideration of potentially contrasting results with different types of green space is warranted.

1. Introduction

Birthweight is an important predictor of neonatal health as well as long-term health. Low birthweight was associated with neonatal mortality (Wilcox and Russell, 1983). It is also found to be linked with childhood and adulthood health (Barker et al., 1993). Growing evidence have shown that air pollution has adverse effects on human health (Brunekreef and Holgate, 2002). However, pregnant women appear to be more susceptible to air pollution than the non-pregnant women due to physiological changes subject to pregnancy such as increased breath
rate (LoMauro and Aliverti, 2015) and oxygen consumption (Heidenmann and McClure, 2003). In epidemiological studies, exposure to higher levels of air pollution is increasingly recognized as a risk factor for adverse birth outcomes such as preterm birth, low birthweight (Klepac et al., 2018). Exposure to air pollution is hypothesized to affect birthweight through several biological mechanisms. These include maternal susceptibility to infection, causing oxidative stress, pulmonary and placental inflammation, affecting blood coagulation, endothelial function and hemodynamic responses which may cause alteration of trans placental oxygen and nutrient transport (Kannan et al., 2006). The biological mechanisms through which individual air pollutants including SO2, NO2, PM2.5 and O3 influence birth outcomes have been also previously reported (Shah et al., 2011). Furthermore, air pollution can influence time spent outside and level of physical activity which would have plausible health effects (Evans and Jacobs, 1981).

On the other hand, exposure to residential green space has been linked to favourable pregnancy outcomes such as reduced risks of preterm birth (Casey et al., 2016; Hystad et al., 2014; Laurent et al., 2013a), and increased birthweight (Akaraci et al., 2020). The health benefits of green spaces may arise from mitigation of noise pollution and heat, reduction of stress and promotion of physical activity, social connections and sleep (Markeychvych et al., 2017). Furthermore, green spaces have been associated with lower levels of air pollution in different geographies (Paolletti et al., 2011; Nowak et al., 2006; Nowak, 2002; Selmi et al., 2016). This can be explained by several reasons including vegetation’s capacity to improve air circulation (Zapancic et al., 2015), reduce ambient temperature (Zapancic et al., 2015) and remove air pollution mainly via dry deposition of airborne particles (Nowak, 2002), uptake of gaseous pollutants through the leaf stomata or plant surface (Nowak, 2002). However, this depends, to some extent, on greenspace types as each type might influence abovementioned pathways at different levels of potency. For example, it may be hypothesised that association between air pollution and birth weight might be comparatively weaker in areas with more tree canopy, based upon evidence that trees are more effective in filtering air pollution than grass due to the larger leaf area (Agay-Shay et al., 2018). Also, greening may increase pollution concentration in some settings i.e., street canyons wherein poor air circulation would delay dispersion of pollutants (Kumar et al., 2019).

Although the independent associations between air pollution, greenness and birthweight have been the subject of relatively large body of research, few studies investigated the interaction between air pollution, green spaces and birthweight (Hystad et al., 2014; Laurent et al., 2013a; Sun et al., 2020a, 2020b; Laurent et al., 2019; Asta et al., 2019; Choe et al., 2018; Cusack et al., 2017a, 2017b, 2018; Agay-Shay et al., 2014; Markeychvych et al., 2014; Glazer et al., 2018; Fong et al., 2018; Dadvand et al., 2012a; Ebisu et al., 2016; Liao et al., 2019; Vilcins et al., 2020; Dzhambov et al., 2019). This is a crucial gap in knowledge because this type of study is needed to assess the mitigation potential of green space of harms wrought by air pollution on birthweight. Furthermore, except for one recent study (Vilcins et al., 2020), all the studies were conducted in the northern hemisphere. However, the association between green space and air pollution are likely to be contingent on context due to the meteorological and environmental characteristics that is likely to differ across diverse geographies, in turn might cause different health impacts. Thus, further studies from other regions which would investigate direct as well as interaction effects of air pollution and green space on birthweight are still warranted. In addition, previous studies mostly used Normalized Difference Vegetation Index (NDVI), satellite based indicator of green biomass density which shows spatial and temporal variability (Weier and Herring, 2000), as an indicator of exposure to greenness. Studies evaluating green space percentage which has ability to inform urban planners and policy makers were less common. In this study, we use a variable representing green space percentage as an exposure metric.

Given the abovementioned gaps in the literature, the aim of the current study was to expand our understanding of complex relationship between green space, air pollution and birthweight by evaluating the direct as well as interaction effects of green space and air pollution on birthweight using a registry-based birth cohort of live births during 2016 January and 2017 December, in Sydney Metropolitan Area, Australia. The current study builds directly on our recent study that reported higher green space quantities were associated with higher birthweights within the same context (Akaraci et al., 2021). The aims of the previous study were: (i) to assess the association between green space quantity within SA2 corresponding to mother’s residential address and the birthweight; (ii) to examine potential effect modification by mother’s country of birth as well as area socio-economic level in this association. In the current study, we aimed to understand complex relationship between air pollution, green space quantity and birth outcomes. First, we examined the association between multiple air pollution variables and birth outcomes including birthweight, low birthweight, and preterm birth. Next, we explored the role of green space quantity as a potential effect modifier of the association between air pollution and birth outcomes across areas with varying level of socioeconomic level and population density.

In the current study, we hypothesised that (a) mothers living in neighbourhoods having higher levels of air pollution would have newborns with lower birthweights on average, and (b) associations would be weaker among newborns to mothers in greener neighbourhoods.

2. Method

2.1. Study population

Data on all births occurring from 01 January 2016–31 December 2017 in Sydney were obtained from the NSW Perinatal Data Collection (PDC). The PDC contains all live births and still births reported in public and private hospitals if they are at least 20 weeks gestation and at least 400 g at birth. The data covers information of sociodemographic characteristics (e.g., age, country of birth of the mothers, address of residence at time of deliever), medical condition (e.g., chronic hypertension, gestational diabetes), delivery (e.g., type of delivery, plurality of birth) and infant (gestational age, baby’s sex). We excluded participants who resided outside of the study area at the time of birth (n = 4916) and those with missing data on residential address, residential green space quantity, air pollution, birthweight and gestational age, multiple births (n = 5548), babies with gestational age less than 20-week (n = 21), post term births (gestational age>=42) (n = 1950), those who born with less than 400 g (n = 442) or had excessive birthweights (>4500 g) (n = 2288). Furthermore, other known causes of pregnancy complications including chronic maternal hypertension, pregnancy-induced hypertension – non-proteinuric, pregnancy-induced hypertension – proteinuric, and gestational diabetes (n = 10,030) were excluded.

2.2. Study Location

Our study was conducted in the Sydney metropolitan area. It is located on the east coast of Australia and is one of the most developed cities in the country. Sydney is one of the fastest growing cities in the world and the most populated metropolitan area in Australia with over 5 million residents (ABS,2017). Of this, 1,773,49 were overseas born (Statistics, 2017). Overseas migration has been major contributor to population growth in Sydney, with the highest proportion of overseas born residents (44.8 %) (ABS, NSW State and Regional Indicators, 2016), compared with the general Australian population (29.8 %) (ABS, 2020). The rapid population growth in Sydney will likely affect distribution of green spaces and use of these places. Moreover, Sydney has a distinct geographical characteristic with a basin bordered by the Pacific Ocean in the east which stretches to the south, west and north by elevated terrain which delays dispersion process of air pollution. Sydney is vasty urbanised area with less than 380 ha of open space which...
corresponds to 14% land area (Greening Sydney Plan: 2012) and has a temperate climate with warm summers and mild winters with a weak to moderate air stream, resulting in calm weather which increases air pollution (Dean and Green, 2018). Therefore, although level of air pollution in Sydney are relatively low compared to the major cities in many industrialised countries, it occasionally exceeds the national health standards and is associated with unfavourable birth outcomes e.g., lower birth weights (Dean and Green, 2018; Mannes et al., 2005). These physical and social characteristics of Sydney make abundance and structure of urban green spaces a critical factor in promoting health benefits.

Residential address of the mothers was available at Statistical Areas Level 2 (SA2). SA2s are geographical zones designed by the ABS to approximate communities of about 10,000 residents on average (range 3000 to 25,000). Our sample covered approximately 200 SA2s. The mean population of the SA2s of study participants was approximately 21,000 (standard deviation ~ 5600).

2.3. Outcome data

The outcome of interest for this analysis was term birthweight (completed 37–41 weeks gestation) which is the weight of the newborns that is measured immediately after the birth by a clinician, low birthweight (birthweight lower than 2500 g), term low birthweight (birthweight lower than 2500 g and completed 37–41 weeks gestation) and preterm birth (live birth before week 37).

2.4. Exposure data

2.4.1. Green space

Data of green space percentage within each SA2 of the mother’s residential address at the time of birth was derived from “parkland” mesh block in the ABS land-use classification for 2011. This data was acquired as it was the most recent data available as well as it was the nearest date to the date of the birth data (2016–2017). The parkland mesh block data was already used in earlier studies (Feng and Astell-Burt, 2018, 2017; Sanders et al., 2015). Mesh blocks are the smallest geographic unit in geographical area in the classification of ABS. Parkland mesh block contains areas which are classified as nature reserves; other minimal use protected or conserved areas and any public open space and sporting arena or facility whether enclosed or open to the public, including racecourses, golf courses and stadiums. Agricultural lands and private gardens are not included in the parkland mesh-blocks. This is an important distinction as it minimises potential issues related to inclusion of areas within the green space metric which are not usually open to the public access.

2.4.2. Air pollution

NO2, PM2.5, SO2 and O3, commonly used markers of ambient air pollution in previous studies, were the main air pollutants of interest in this analysis. The data was obtained from The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and contained daily means for NO2, SO2, O3 and PM2.5 which were available for each SA2 in the Sydney metropolitan area from July 2010 to June 2011. Air pollution data were developed by CSIRO using a chemical transport model in raster format with a grid spacing of 0.01 degrees to 0.03 degrees. Air pollution values were assigned to each birthweight record using the following methodology. A nearest-neighbour function in ArcGIS Pro was used to assign the centroid of each Mesh Block to the nearest raster cell and associated air pollution value. Mesh Blocks are the smallest set of geographical boundaries developed by the Australian Bureau of Statistics, typically ranging from 30 to 60 households each. Mesh Blocks can be aggregated to fit fully within the geographic boundaries available in the birthweight data (the SA2). Area-weighted air pollution values were calculated for each SA2 from the Mesh Blocks located within and their associated air pollution values, weighted by the geographical area of each Mesh Block (km²). This process was done for all air pollutants (NO2, SO2, O3 and PM2.5) for separate rasters representing all days in the period July 2010 to June 2011 inclusive. In the final step, monthly averages were used to estimate exposure to each air pollutant during gestation by calculating the average of each pollutant over 1st trimester, 2nd trimester, 3rd trimester and entire pregnancy for term births (9 months) for every mother based on the conception month of the mother.

2.5. Covariates

Model covariates included gestational age (weeks), infant sex (male, female), mother’s age (< 19 years, 20–34 years, > 35 years), population density, mother’s country of birth (born overseas, born in Australia), season of birth (spring (September-­November), summer (December-­February), autumn (March-May), winter (June-August), number of antenatal care (0–7, ≥ 8) gestation at the time of first antenatal care visit (at first trimester ( gestational age of < <12 weeks) (Møller et al., 2017), at later stages), number of previous pregnancies(0, 1–3, > 4), smoking during pregnancy (did not smoke at all, smoked during first half of the pregnancy, smoked second half of the pregnancy, smoked throughout entire pregnancy), area level socioeconomic status (SES) (affluent, average, deprived), Socio-Economic Index for Areas (SEIFA) ‘Index of Relative Socio-Economic Advantage/Disadvantage (IRSD) (Statistics, 2011) Socio-Economic Index for Areas (SEIFA) ‘Index of Relative Socio-Economic Advantage/Disadvantage (IRSD) (Dadvand et al., 2012a) was used to measure area level socio-economic status which is a composite variable based on income, education, employment, occupation and housing circumstance. The areas with higher scores have a large number of families who have advantaged circumstances such as high income, high education level, skilled occupations and fewer number of disadvantaged people.

2.6. Statistical analysis

We examined correlations between: (1) green space quantity and NO2, PM2.5, SO2 and O3 exposures dur the entire pregnancy period (Table S1), and (2) air pollution levels during the entire pregnancy and each trimester (S2-S5) using Spearman’s rank correlation. There was a strong correlation between air pollution levels during the entire pregnancy and trimesters. The strongest association was observed between birthweight and air pollution during the entire pregnancy period. Therefore, all other analyses in this study were conducted using air pollution exposure during entire pregnancy. Air pollution variables were categorized into area-specific tertiles and green space variable was categorized into 3 levels (0%–20%, 20%–40%, >40 %) to interpret ‘low’, ‘medium’ and ‘high’ values and to capture the pattern of exposure-response relationships while maintaining a sufficient number of observations in each category.

We developed multilevel linear and logistics regression models to assess associations between air pollution metrics and continuous birthweight, odds of low birthweight and preterm birth, respectively by adding different groups of covariates. The following incremental adjustment for all analyses was undertaken to capture confounding effects of individual and area-level characteristics: Model 1 is unadjusted model. In the next step, the model 1 is adjusted for gestational age, infant sex, mother’s age, year of birth (Model 2); mother’s country of birth was added (Model 3); number of antenatal care visits, gestation at the time of first antenatal care visit, number of previous pregnancies, smoking during pregnancy were added (Model 4). Additionally, area level SES and population density were taken into account (Model 5).

Finally, green space quantity was added in the model (Model 6). Akaike’s Information Criteria (AIC) and Bayesian Information Criteria (BIC) were used to choose the best model that fits the data better. Adjusted regression coefficients (β) and odds ratios (OR) along with 95% credible intervals (CIs) were reported.

Furthermore, we explored effect modification by green space
quantity in the statistically significant associations ($P < 0.05$) between air pollution variables and birth outcomes by fitting 2-way interaction terms between air pollution and green space variables in the fully adjusted model (model 6), one at a time for each pollutant. This step was followed by exploring 3-way interactions between: (1) air pollution, green space and area level socio-economic status and, (2) air pollution, green space and area level population density. Statistically significant evidence of effect modification was determined using Wald test. Predicted means were extracted from fully adjusted models to demonstrate results from the two and three-way interactions. All analysis were conducted using STATA version 14 (StataCorp LP, College Station, TX, USA).

3. Results

3.1. Descriptive analysis

Our final sample included 87,978 births of which 79,430 was full-term births. The population characteristics are summarized in Table 1. Mean birthweight and gestational age (in weeks) of the babies were, 3377 and 39, respectively. Larger portion of the mothers aged between 20 and 34 (%70), were born overseas (%52) and lived in areas with less than 20 % green space (95 %). Correlations between green space quantity and pollutant levels during 1st, 2nd and 3rd trimester and entire pregnancy were presented in table S1-S5. We observed moderate (0.3 $\leq$ Spearman’s rank correlation $< 0.5$) to strong (Spearman’s rank correlation $> 0.5$) correlation between air pollutant values across entire pregnancy and trimesters. Green space quantity was negatively correlated with NO2, PM2.5 and SO2 (Table S1). Negative correlation was most pronounced with NO2 ($\rho = -0.33$), followed by PM2.5 ($\rho = -0.30$) and SO2 ($\rho = -0.19$). There was a weak positive correlation between green space quantity and O3 ($\rho = 0.23$). The averaged values of air pollutants by green space quantity are presented in Table 2. We obtained the lowest value for AIC and BIC for the model accounted for all covariates (model 6), indicating that it fit the data better than other models (Table S6-S7).

4. Main analysis

4.1. Air pollution and birth outcomes

In the unadjusted models (model 1), we observed statistically significant (p-value <0.05) negative associations between exposure to air pollutants and birthweight (Table 3), meaning that babies of mothers who lived in areas with higher levels of NO2, PM.25 and SO2 had lower birthweights. After adjusting the models for different sets of covariates, the associations were slightly attenuated, though remained statistically significant. We did not find statistically significant association between O3 and birthweight in both unadjusted and fully adjusted model (model 6).

In the model 6, compared with mothers lived in the areas with the lowest air pollution levels, babies of those who lived in highest tertile of NO2, PM2.5 and SO2 had lower birthweights by 37 g (95 %CI: −46.60, −26.90), 35 g (95 %CI: −43.70, −25.40) and 12 g (95 %CI: −20.40, −3.50) respectively (Table 3).

Lying in the areas with moderate levels of NO2 was associated with a 15 % lower risk of preterm birth compared to those lived in the SA2s with low level NO2 (OR = 0.85, 95 % CI: 0.75-0.90) (Table S8). However, there was no statistically significant association between the other air pollutants and the preterm birth. Similarly, none of the indicators of air pollution was statistically significantly associated with the low birthweight (Table S8).

4.2. Green space quantity and birth outcomes

Living in greener areas was associated with statistically significant increase in birth weight in the adjusted models (Table S9). Compared with those who lived in the least green areas, babies born to mothers who lived in areas with 20–40 % and more than 40 % green space was heavier by 15 g (95 %CI: 8.70, 20.60) and 17 g (95 %CI: 4.30, 30.20), respectively. Positive association between green space quantity and term birthweight were observed across the models after further adjustment of NO2, PM2.5, SO2 and O3 however, only some of these associations remained statistically significant. Similarly, greener areas were statistically significant with reduced odds of preterm delivery (Table S10). Results for the odds of low birthweight and term low birthweight were in the same direction, however none of these associations were statistically significant (Table S10).
and moderate levels of PM2.5 and birthweight in greener areas was less significant. As it was the case for NO2, negative association between low high level PM2.5 and birthweight across areas with varying level green space (Table 4). Furthermore, exposure to high level of SO2 was associated with reduction in birthweight was observed in areas of which over 40 % was covered with greenspaces, though was not statistically significant. The weakest association between moderate levels of SO2 and reduced birthweight was observed in areas of which over 40 % was covered with greenspaces, though was not statistically significant (Table 4). Furthermore, exposure to high level of SO2 was associated with increase in birthweight by 52 g in the greenest areas which was also not statistically significant. Three-way interaction revealed that the weaker association between SO2 and birthweight in greener areas was more pronounced in the affluent and densely populated areas (Fig. 4).

### 5. Discussion

The current study examined the associations between multiple air pollution measures and birth outcomes with a further investigation of effect modification by greenspace quantity across areas with varying levels of socioeconomic levels and population density. We found a mixture of results contingent upon the type of air pollution assessed. First, areas with more green space coverage tended to have lower levels of PM2.5, NO2 and SO2, with opposite trend was observed for O3. Second, as expected, higher levels of PM2.5, NO2 and SO2 were associated with lower birthweight, associations for low birth term and pre-term did not reach significance level. In fully adjusted models, O3 levels within SA2s were not statistically significantly associated with any of the birth outcomes. Third, negative association between lower and moderate levels of NO2, PM2.5 and SO2 appeared to be weaker in areas with > 20 % green space. This trend was more apparent in the affluent and densely populated areas.

Our findings have shown that greener areas generally had lower concentrations of PM2.5, NO2 and SO2 which was in line with the literature as vegetation can biologically filter some air pollutants via dry deposition onto their surfaces and might help cooling ambient temperature which leads to lower levels of pollution (Vilcins et al., 2020). Deposition level of vegetation varies according to the size of the particles, with fine particles such as PM 2.5 can be deposited more efficiently (Kumar et al., 2019). Higher quantity of O3 in greener areas could be explained with the absence of nitric oxide emissions which reduce ozone via atmospheric reactions (Markey et al., 2017).

Our results supports previous studies which showed that ambient NO2, PM2.5 and SO2 was associated with lower birthweights (Mannes et al., 2005). Contrary to our hypothesis, we observed that babies of mothers who lived in areas with the highest level of O3 (3rd quartile) was heavier than those living in areas with least O3 (1st quartile) in fully adjusted models, though these results were not statistically significant. However, these findings were not consistent with the findings of some studies which demonstrated association between O3 and decrease in birthweight (Laurent et al., 2013b; Geer et al., 2012). Our unexpected results could be the consequence of relatively low ozone levels (mean value: 30 ppm) in the study area. Moreover, areas with high levels of O3 had lower levels of NO2, PM2.5 and SO2 and larger quantity of green spaces, meaning that the benefit of latter factors might have mitigated the adverse effect of O3. Our previous study in the study area reported...
statistically significant association between green space quantity and birthweight (Akaraci et al., 2021). In the current study, living in areas with moderate quantity of green space compared with the least green areas was associated with increase in birthweight. The strength of the association reduced yet remained significant after accounting for PM2.5, SO2 and O3. In contrary, living in the greenest versus least green areas did not render statistically significant differences on the birthweight. No statistically significant association was observed when the model was adjusted for NO2.

These findings could be indicating that green space and birthweight association might be confounded by exposure to air pollution. Nonsignificant associations for the greenest areas and NO2 models could be explained with few/no areas containing both high levels of NO2 and green space.

Similar results were found in previous study which reported that statistical significance of association between NDVI within 100 m around mother’s residential address and birthweight disappeared after model adjustment for NOx, O3 and CO (Laurent et al., 2013a). We observed protective associations between ambient air pollutants and preterm births with most associations were non-significant. These results supported the findings from another study conducted in Sydney (Jalaludin et al., 2007).

Furthermore, we observed statistically significant interaction between green space quantity and NO2, indicating that the mean birthweight difference between 1st tertile and 2nd tertile of NO2 was highest in the areas with the least green space availability. Similar trend was observed for PM2.5 exposure. This result indicates that increase in existing green space structure might be modifying the effect of low to moderate level of air pollution on birthweight, although may not influence the association when pollution level is high. On the other hand, there was no statistically significant interaction between SO2 and green space quantity on birthweight. This could be due to complex relationship between vegetation and air pollutants which is likely to vary by climate, vegetation type, size, density and use, however our green space metric was not informative about these factors.

Previous studies (Hystad et al., 2014; Laurent et al., 2013a; Sun et al., 2020a, 2020b; Laurent et al., 2019; Asta et al., 2019; Choe et al., 2018; Cusack et al., 2017a, 2017b; 2018; Agay-Shay et al., 2014; Markeycvch et al., 2014; Glazer et al., 2018; Fong et al., 2018; Dadvand et al., 2012a; Ebisu et al., 2016; Liao et al., 2019; Vîlcins et al., 2020) examined the effect of inter-relationship between air pollution and green space on birth outcomes, mostly either by evaluating the potential role of exposure to air pollution as a mediator or effect modifier between green space and birth outcomes, while few studies considered green space as effect modifier (Sun et al., 2020a; Asta et al., 2019) of association between air pollution and birth outcomes. Most studies aimed to test the role of air pollution as effect modifier of the relationship between green space and birth outcomes, adjusted air pollution as a model covariate. Results were mixed. Majority of these studies (Hystad et al., 2014; Cusack et al., 2017a, 2017b, 2018; Agay-Shay et al., 2014; Fong et al., 2018; Ebisu et al., 2016; Vîlcins et al., 2020) did not observe remarkable change in the green space and birth outcome association when the air pollution was added in the model which could be indicating that green space has an independent effect on birth outcomes. However, in a study conducted in Spain, association between NDVI and birthweight was weakened after inclusion of NO2 (Dadvand et al., 2012b). Study from Munich observed minor increase in magnitude of association after adjusting NO2 and PM2.5 (Markeycvch et al., 2014). However, this method has limitations as it can only test direct effects of air pollution and green space on birth outcomes without taking potential interaction effect into consideration.

Relatively few studies tested possible effect of interaction between air pollution and green space quantity on birth outcomes (Sun et al., 2020a, 2020b; Laurent et al., 2019; Asta et al., 2019; Dzhambov et al., 2019). Living closer to green space was associated with weaker associations between ambient PM2.5 and the odds of preterm births (Asta et al., 2019). Another study (Sun et al., 2020b) observed stronger association between ambient air pollution risk and odds of preterm birth in less green neighbourhoods. In contrary, study from California did not identify interaction effect between air pollution and NDVI on the risk of low birthweight (Laurent et al., 2019). Another study (Zhou et al., 2021) examined effect modification by air pollution of the association between greenspace and lung health found similar results which indicated that higher quantities of greenspace was associated with improved lung health in areas with low to moderate levels of air pollution but not in high air pollution areas. These results were parallel with our findings.

Our findings indicated that the effect modification of the association between air pollution and birth outcomes by green space quantity was greater in affluent and densely populated areas. A possible explanation for this trend might be that mechanisms through which green space elicits health benefits may vary across the settings with different socioeconomic status and population densities. For instance, a number of studies have reported positive association between densely populated

### Table 3

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*Denotes significance (p-value<0.05)

Model 1 Unadjusted model

Model 2 Adjusted for gestational age, infant sex, mother’s age, year of birth

Model 3 + number of antenatal care visits, gestation at the time of first antenatal care visit, number of previous pregnancies, smoking during pregnancy

Model 5 + area level SES, area level population density

Model 6 + green space quantity
areas and higher levels of physical activity (Brownson et al., 2009; Nagel et al., 2008). This may be due to the fact that populated areas generally have more facilities which can provide more opportunities for participation in physical activity. Another possible explanation for spatial variation in effect of green space might be that although some form of green space is present around the residential area, they may not be accessed or used (Nordbø et al., 2019). It has been reported that green spaces in deprived neighbourhood have lower quality compared to affluent areas (Vaughan et al., 2013; Sister et al., 2010; Hoffmann et al., 2017; Rigolon, 2016). Therefore, they may be visited less frequently (Fongar et al., 2019; Flowers et al., 2016) or visiting such places may not elicit the benefit of good quality green space (Nguyen et al., 2021). In contrast, residents of affluent areas are more likely to access to good quality green spaces which was associated with better health outcomes (Vaughan et al., 2013; Sister et al., 2010; Hoffmann et al., 2017; Rigolon, 2016). Furthermore, particular type of green spaces may be more preferable by pregnant women. For instance, given physical limitations posed by pregnancy and sunny climate of Sydney, small parks with well-maintained resting areas, which are adequately shaded would plausibly be more preferred by pregnant women compared with green spaces without such features. Similarly, safety feature of greenspaces likely to play an important role to influence frequency and duration of visits of pregnant women. Some studies have posited that green spaces in areas with lower income levels presented more safety concerns (Rigolon, 2016; Wolch et al., 2014). However, it is not possible to draw a clear conclusion as we were unable to assess type or quality of green space and frequency or duration of use of green space by study participants. Furthermore, affluent areas of Sydney Metropolitan Area are typically located along the coast. These areas are also where population is concentrated (ABS, 2022). Although little is known about the effect of blue spaces on pregnancy outcomes (Akaraci et al., 2020), recent

Table 4
Adjusted regression coefficients (95% confidence interval) for increase in average of air pollution levels in SA2 level maternal residential address stratified by green space quantity.

<table>
<thead>
<tr>
<th></th>
<th>Least Green Space (0 %-20 %)</th>
<th>Average Green Space (20 %-40 %)</th>
<th>Maximum Green Space (&gt;40 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO2 exposure during pregnancy (relative to 1st Tertile) 2nd</td>
<td>-36.10 (-50.50, -21.40)</td>
<td>-4.7 (-38.70, 29.40)</td>
<td>-21.10 (-38.70, 27.60)</td>
</tr>
<tr>
<td>Tertile</td>
<td>-21.70*</td>
<td>-6.70*</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>-35.30 (-50.40, -40.10)</td>
<td>-55.90 (-24.30)</td>
<td></td>
</tr>
<tr>
<td>Tertile</td>
<td>-21.10*</td>
<td>-24.30*</td>
<td></td>
</tr>
<tr>
<td>PM 2.5 exposure during pregnancy (relative to 1st Tertile) 2nd</td>
<td>-40.70 (-53.90, -19.10)</td>
<td>-28.90 (-64.00, 6.20)</td>
<td>-19.10 (-32.50, 13.10)</td>
</tr>
<tr>
<td>Tertile</td>
<td>-27.50*</td>
<td>-5.70*</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>-35.20 (-48.00, -37.30)</td>
<td>-52.30 (-34.40, 52.10)</td>
<td></td>
</tr>
<tr>
<td>Tertile</td>
<td>-22.30*</td>
<td>-22.40*</td>
<td></td>
</tr>
<tr>
<td>SO2 exposure during pregnancy (relative to 1st Tertile) 2nd</td>
<td>-13.90 (-23.60, -23.40)</td>
<td>-9.70 (-54.70, 35.30)</td>
<td>-4.30 (-10.30, -10.30)</td>
</tr>
<tr>
<td>Tertile</td>
<td>-4.30*</td>
<td>-10.30*</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>-7.80 (-18.60, -17.30)</td>
<td>-31.70 (52.10 (-6.50, 110.60)</td>
<td></td>
</tr>
<tr>
<td>Tertile</td>
<td>3.01</td>
<td>-2.90*</td>
<td></td>
</tr>
</tbody>
</table>

* There was no area containing > 40 % green space that had high levels (3rd tertile) of NO2. Therefore, regression result for this cell could not be calculated.

Fig. 1. Effect measure modification by green space quantity of the association between birthweight and: (1) average NO2 exposure during pregnancy; (2) average PM2.5 exposure during pregnancy; (3) average SO2 exposure during pregnancy.
evidence has shown that living closer to the blue spaces are associated with better health outcomes (White et al., 2020). In these areas, blue space and green space may have synergetic effect. However, this could not be assessed in the present study due to unavailability of blue space data.

There are several strengths of this study. Given the importance of contextual factors in affecting the relationship between health and environmental exposures, presenting novel evidence on the role of green space in modifying impact of air pollution on birth outcomes from Sydney, Australia may help addressing an existing gap with respect to the generalization of the evidence. Moreover, we measured direct and interaction effect of air pollution and green space on birthweight using large sample size which ensured the statistical power. Also, we had information on multiple air pollutants which allowed us to compare the effect of various air pollutants. Similarly, we used green space percentage as exposure indicator which could be used in urban planning regulations. Furthermore, we could adjust our models for relevant person (e.g., maternal smoking, country of birth) and area-level confounders (e.g., population density, socio-economic level).

Our study also had some limitations. First, the information on mother’s residential history prior to birth, address, and status of or any other information regarding daily activity pattern of mothers were not available. Therefore, we used mother’s residential address at the SA2 level at the time of birth for exposure assessment, assuming that moving in a new place is an effortful activity, it is plausible that pregnant women would be less likely to prefer moving in a new place during pregnancy. Expectedly, most of the women would move to new place before or at the very beginning of pregnancy or they would prefer moving somewhere closer where she would have similar environment. However, some studies (Fell et al., 2004; Miller et al., 2010; Canfield et al., 2006) posited that the rate of mobility during pregnancy varied around 11 %–30 % which is prevalent enough to introduce exposure misclassification.

It should be also acknowledged that a degree of exposure misclassification will remain also due to the boundaries of SA2s which are not developed based on the resident’s perceptions and it is possible that some participants might be using another green space which is located outside of their SA2s. However, obtaining this data for the large sample of this study was not feasible. Furthermore, our green space measure does not contain information on the quality of green spaces such as landscape character, maintenance, and safety which hinders deeper

Fig. 2. Effect measure modification by green space quantity of the association between birthweight and average NO2 exposure during pregnancy; (2.1) area level SES and (2.2) population density.
understanding on the role of quality of green spaces in influencing birth outcomes.

Another limitation is the time difference between the measurement of air pollution and birthweight, which was due to the absence of more recent chemical transport model data for air pollution. Although more recent air pollution data is available from NSW Government, it is based upon only 19 monitoring stations across Australia’s largest city of > 5 million residents and so lacks sensitivity to local context (including road traffic, temperature, wind speed and direction) that the CSIRO’s chemical transport model addresses. Our study assumes consistency in spatiotemporal variations in air pollution measured between (2010–2011) and for the period in which birthweight records were analysed (2016–2017), which is supported by the absence of major bushfire events in the Sydney metropolitan area. Also, there has not been remarkable changes in annual levels of air pollutants during this time period (Government, 2017).

The implications of the study are that protecting and restoring green space may help mitigate harms of certain air pollutants on birthweight. A further limitation is the focus on discrete green spaces, since prior work indicates certain types of green space may have greater potency for this mitigation effect (Kumar et al., 2019). For example, the current green space measure does not distinguish discrete green spaces consisting mainly open grass (e.g., sports ovals) from those composed mainly of trees (e.g., woodlands). Furthermore, trees along streets are also not included, but may play an important role in filtering air quality, promoting outdoor recreation and psychological restoration. These points may explain the role of green space type as a potential complicating factor in the associations. It is plausible that two discrete green spaces of similar size comprised mainly of trees (e.g., woodlands) and grass (e.g., sports ovals) may have potential to modify associations between air pollution and birthweight with different levels of potency. Accordingly, consideration of different types of green space including but not isolated to parklands could help to extend the field of enquiry in a way that is useful to urban planners.

6. Conclusion

Our study found that ambient air pollution was associated with decrease in birthweight, with weaker associations for exposure to low to moderate levels of NO2 and PM2.5 observed in areas with over 20% greenspace coverage especially in the affluent and densely populated areas. These findings support the idea of urban greening as a potential air pollution mitigation intervention strategy for improving birthweight. Further investigations on the inter-relationship between air pollution,
green space types and birthweight is warranted.

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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.

Data Availability

The authors do not have permission to share data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127726.

References


Fig. 4. Effect measure modification by green space quantity of the association between birthweight and average SO2 exposure during pregnancy across strata of (4.1) area-level SES and (4.2) population density.