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The association between tree planting and birth outcomes

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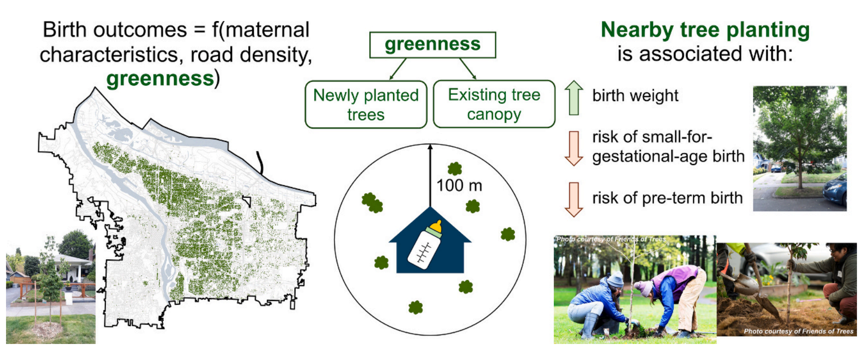
HIGHLIGHTS

- We examined the relationship between tree planting and birth outcomes.
- Number of trees planted around maternal address was associated with higher birth weight.
- Results are likely not due to healthier people choosing to in areas with more trees.
- Tree planting may be a cost-effective way of improving birth outcomes.

GRAPHICAL ABSTRACT



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ABSTRACT

Multiple studies have found that exposure to greenspace during pregnancy is associated with increased birth-weight (Hu et al., 2021) and a reduced probability of a small-for-gestational-age birth. However, because exposure to greenspace is associated with demographic correlates of health, studies may suffer from residual confounding. In addition, results may be influenced by the self-selection of healthier women into greener neighborhoods. We address these limitations by using the number of trees planted around maternal address as a novel exposure metric. Compared to existing tree cover, new tree planting is less prone to residual confounding or self-selection bias. We found that each tree planted within 100 m of maternal address within the last 10 years was associated with a 2.3 g (95 % CI: 1.5–3.0) increase in birth weight. In addition, we found that 1-SD increase in tree planting was associated with a 4.3 % (95 % CI: 0.3 to 8.2 %) reduced risk of a small-for-gestational-age birth and a 4.9 % (95 % CI: 0.3 to 9.3 %) reduced risk of a preterm birth. All models controlled for mother's race/ethnicity, education, major road density, and existing tree canopy. Our finding that both newly-planted and established trees are associated with improved birth outcomes strengthens the evidence that trees may be an effective public-health intervention.

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1. Introduction

The relationship between exposure to the natural environment and birth outcomes is perhaps the most studied health outcome in the green-health literature. Since the first studies in the early 2010s (Dadvand et al., 2012; Donovan et al., 2011), over 30 papers have found an association between greenness around maternal address and improved birth outcomes (Hu et al., 2021). The most commonly studied birth outcome is birth weight (Dadvand et al., 2012; Hystad et al., 2014), although a smaller number of studies have shown an inverse association between greenness and the probability of a small-for-gestational-age birth (Donovan et al., 2011; Glazer et al., 2018) or the probability of a pre-term birth (Abelt and McLafferty, 2017; Agay-Shay et al., 2019). This interest in the relationship between greenness and birth outcomes is consistent with the direction of the broader public-health literature, which has increasingly focused on the relationship between neighborhood characteristics and poor birth outcomes, because persistent racial and social-class differences in birth outcomes cannot be adequately explained by individual-level characteristics (Rossen and Schoendorf, 2014).

Unfortunately, there are major challenges to quantifying the causal effect of greenness on birth outcomes. In particular, the association between the natural environment and birth outcomes is prone to residual confounding, which can occur when a variable is missing from a model and is correlated with both the model's outcome and the variable of interest (Groenwold et al., 2013). In birth-outcome studies several important variables—including race, education, and income—can be correlated with both the birth outcome and the green exposure metric. White people tend to live in greener neighborhoods (Jesdale et al., 2013) and have healthier babies (Swamy et al., 2012), for example. If any of these confounders are missing from the model, then the estimated association between greenness and birth outcomes may be biased. In addition to issues with residual confounding, (Jesdale et al., 2013; Victora et al., 2020; Morisaki et al., 2017; Pollock et al., 2021) observed associations between greenness and birth outcomes may be due to self-selection of healthy women into greener neighborhoods rather than a true causal effect (Oakes, 2004).

To address these two issues, we take advantage of a natural experiment: the planting of 50,000 trees by an environmental nonprofit, Friends of Trees, in Portland, Oregon (the availability of this unique dataset is why we conducted the study in Portland). Rather than relying on measures of total greenness, as all extant birth-outcome studies do (Hu et al., 2021), we used the number of newly-planted trees around maternal address as our primary exposure metric. This longitudinal approach improves causal inference in several ways. First, the number of trees planted by Friends of Trees is not associated with existing tree canopy or demographic correlates of birthweight. This is because Friends of Trees plant in two main ways: they have a large scale tree-planting program that focuses on economically disadvantaged neighborhoods that are less green, but they also provide trees to individuals who request them, and these requests tend to come from residents of greener, more affluent neighborhoods. We don't know exactly how many trees were planted in these two ways. However, we do know that, over time, Friends of Trees focused more heavily on large-scale plantings in disadvantaged neighborhoods, such that between 2009 and 2019, 73 % of the trees they planted met one or more of Portland's equity criteria: low canopy, low income, or above average percentage community of color. (Vasef, 2025). A consequence of planting trees in these two ways is that the total number of trees planted by Friends of Trees is independent of both existing tree canopy as well as important demographic correlates of birth outcomes such as maternal race and education (Supplementary Table 1). In addition, newly-planted trees are less likely to induce people to move into a neighborhood compared to well-established components of a neighborhood's green infrastructure such as mature trees and parks. Finally, the use of newly-planted trees as an exposure metric helps to confirm the temporal order of the association between greenness and birth-outcomes.

In addition to improving causal inference, using the number of newly planted trees as an exposure metric allows our results to be more easily translated into a specific public-health intervention. In contrast, when studies find that higher greenness around maternal address is associated with improved birth outcomes, then applying the results is more difficult, because greenness could be increased by a wide range of interventions. Planting trees would increase greenness in most cases but so would converting impervious surface to grass or planting fast-growing agricultural crops.

Formally, we hypothesize that exposure to newly planted trees is associated with improved birth outcomes (higher birthweight, lower probability of a pre-term or small-for-gestational-age birth). The mechanisms linking trees and improved birth outcomes likely include, but are not limited to, stress reduction, improvements in air quality, increased physical activity, and more social connections (Hystad et al., 2014).

1.1. Literature review

Most extant green birth-outcome studies measure women's exposure to the natural environment during pregnancy in buffers around maternal address (Dadvand et al., 2012; Hystad et al., 2014) with some studies also using metrics describing distance to the nearest park or open space (Abelt and McLafferty, 2017; Donovan et al., 2011). The most common metric for assessing maternal exposure to greenness is the normalized difference vegetation index (NDVI), which is a greenness index bounded by -1 and $+1$ that measures photosynthetic activity (Ghaderpour et al., 2023; Rouse et al., 1974; Jiang et al., 2006). The reliance on NDVI as an exposure metric is understandable, as Landsat imagery, the imagery most commonly used to calculate NDVI, is freely available across the entire globe every 16 days from 1972 to the present (Roy et al., 2016).

A smaller number of studies use exposure metrics derived from land-cover data (Nichani et al., 2017) or light detection and ranging (LiDAR) data (Donovan et al., 2019). Several studies also use proximity to parks as a primary exposure metric or to complement exposure metrics describing greenness around maternal address (Cusack et al., 2017; Yin, 2019). Proximity to parks has been expressed as Euclidean distance to parks (Grazuleviciene et al., 2015), area of parks around maternal address (Nichani et al., 2017), or whether a park is less than a threshold distance from maternal address (Agay-Shay et al., 2014).

More recent research has made incremental improvements to exposure metrics based on NDVI. For example, early studies calculated NDVI using 30 m-resolution Landsat imagery (Dadvand et al., 2012; Laurent et al., 2013), whereas more recent studies have used NDVI derived from 5 m-resolution (Su et al., 2019) or 3 m-resolution data (Donovan et al., 2022a). A handful of studies (Xiao et al., 2021; Zhang et al., 2022) have also made use of the Enhanced Vegetation Index (EVI), which unlike NDVI includes atmospheric correction and ground reflectance adjustments (Rokni and Musa, 2019). Finally, a few studies have accounted for seasonal changes in greenness, so exposure metrics are specific to a mother's gestational period (Agay-Shay et al., 2019; Sun et al., 2020). However, these improvements do not address the fundamental problems of residual confounding or self-selection.

The rest of the paper is organized as follows: methods (study area and study population, outcome assessment, exposure assessment, covariates, and statistical analysis), results, discussion (including a discussion of study limitations), and conclusions.

2. Methods

2.1. Study area and study population

Our study population is all singleton live births that occurred between January 1, 2015, and December 31, 2020, where maternal address was in Portland, Oregon and the child survived at least 12 months after birth ($n = 36,564$). We identified children who had died within 12 months of birth by linking to death certificates ($n = 174$).

Portland is the largest city in Oregon (area 34,558 ha) with a population of 652,503 according to the 2020 decennial Census (US Census, 2024); 72.1 % of the population is white; 52.5 % of the population over the age of 25 has a bachelor's degree or higher; median household income (2018–2022) is $85,876 (2022 dollars) (US Census, 2024).

2.2. Outcome assessment

Our primary outcome is birthweight continuously expressed in grams. We also created a binary indicator variable denoting a small-for-gestational-age (SGA) birth, if a child's birthweight was below the 10th percentile based on gestational age and gender (Fenton and Kim, 2013). In addition, we created binary indicator variables denoting a pre-term or a very pre-term birth, if a child's gestational age was <37 or 33 weeks respectively.

Birth records were obtained from the Oregon Health Authority's Center for Public Health Practice and Health Statistics. Drexel University IRB determined that this research did not require continuing review (protocol #: 2305009935).

2.3. Exposure assessment

Our primary exposure metric was the number of trees planted around maternal address in the 10 years before a child was born in buffer sizes ranging from 50 m to 500 m in radius, which is the range of buffer sizes used by the majority of extant green birth-outcome studies (Hu et al., 2021). Tree planting data were obtained from Friends of Trees, which is a Portland-based non-profit. Between 1990 and 2020, they planted 49,246 trees in Portland; 87.5 % of these trees were planted in parking strips (the strip of grass between the sidewalk and the road), and the remaining 12.5 % were planted in private yards. We used a geocoder (Metro Data Resource Center, 2022) to assign coordinates to each tree. Only 119 trees could not be assigned coordinates. To account for existing tree cover we measured tree canopy in 50 m to 500 m-radius buffers around maternal address using LiDAR data that was flown in 2014 (Metro Data Resource Center, 2014). The resultant tree canopy layer had a resolution of 0.9 m.

We chose to use the number of trees planted in the 10 years before a child was born as our exposure metric to limit overlap between the tree-planting variable and existing tree canopy, which was measured in 2014. To check if our results were sensitive to this 10-year cutoff, we also calculated the number of trees planted around maternal address five years and 15 years before a child was born.

Fig. 1 shows the spatial distribution of newly planted trees and existing tree cover in Portland, Oregon.

2.4. Covariates

We included covariates in our statistical models that past research had found to be associated with either birth weight or gestational age: maternal age, race/ethnicity, education, body mass index (BMI, weight in kilograms divided by height in meters squared), gravidity (first birth versus all other), existing tree canopy, and major road density. We did not have access all relevant demographic covariates. In particular, we did not have access to data on household income, which is a concern, because some studies have found that income is associated with both birthweight (Bramsved et al., 2018) and residential greenness (Jesdale et al., 2013).

To account for maternal exposure to traffic-related air pollution, we measured the density of primary and secondary roads around maternal address in buffers of 50 m to 500 m in radius (these two classes of road include freeways, U.S. or state highways, and major arterial roads). We included road density as a covariate for two reasons. First, research has shown that proximity to major roads is associated with lower birth weight (Wang et al., 2020), and as tree canopy may be lower in areas of high road density, road density may be a confounder of the relationship between tree planting and birth outcomes. Second, we hypothesize that trees may attenuate the negative effect of roads on birth weight by absorbing air pollution (Grote et al., 2016) or buffering noise (Fang and Ling, 2003).

2.5. Statistical analysis

We estimated a linear model of the association between birthweight and tree planting. We used a backwards stepwise model-selection process beginning with all independent variables that previous studies had shown to be associated with birthweight. For groups of related variables—those describing maternal education, for example—we included the variable that had the lowest *p*-value when individually regressed against birthweight. Independent variables were dropped from the model using progressively lower p-value thresholds finishing with a threshold of $p < 0.05$. Dropped variables were systematically reintroduced into the model and retained, if variables of interest changed by >10 % (Rothman et al., 2008).

To test for multicollinearity, we calculated variance inflation factors (VIF) for all independent variables and dropped any variable with VIF > 5. Residual plots were used to investigate both heteroskedasticity and to ensure that covariates and model residuals were independent. The normality of model residuals was assessed using a Q-Q plot.

We hypothesized that tree planting may attenuate the negative association between exposure to traffic-related air pollution and birth outcomes. To test this proposition, we included an interaction between tree planting and major-road density around maternal address. To ensure that new tree planting is not simply a proxy for existing tree canopy, we also included an interaction term between roads and existing tree canopy.

Past research has found that the association between exposure to the natural environment and birth outcomes may differ across demographic strata (Dadvand et al., 2014). Therefore, we estimated two additional linear birthweight models: one stratified by race (white mother versus non-white mother) and the other stratified by education (mother had some college education versus mother had no college education). To test whether the relationship between trees and birthweight was significantly different between model strata, we included interaction terms between the two tree variables (new tree planting and existing tree canopy) and a binary stratification variable denoting either race or education.

To estimate the association between new tree plantings and the probability of SGA and preterm birth we estimated logit models. As with the linear model, we used specification tests to determine if model assumptions were met. For scaling, and to make the results of the logit models easier to interpret, we standardized both tree variables by subtracting the mean and dividing by the standard deviation.

3. Results

The analytical sample ($n = 36,197$) has 367 fewer observations than the full sample because of covariates with missing values (maternal BMI accounted for 345 of the observations with missing values). Most mothers in the sample are white and have at least some college education (Table 1). Compared to national averages (Centers for Disease Control and Prevention, 2016–2022), mothers in Portland are older (US mean: 29.51 years old), their babies are heavier (US mean: 3242 g), and their babies have higher gestational ages (US mean: 38.33 weeks).

To assess the relationship between new tree planting, existing tree canopy, and key maternal demographics, we calculated the correlation coefficients between the number of new trees planted within 100 m of maternal address, existing tree canopy, road density, maternal race and maternal education (Supplementary Table 1). Notably, new tree planting and existing tree canopy within 100 m of maternal address

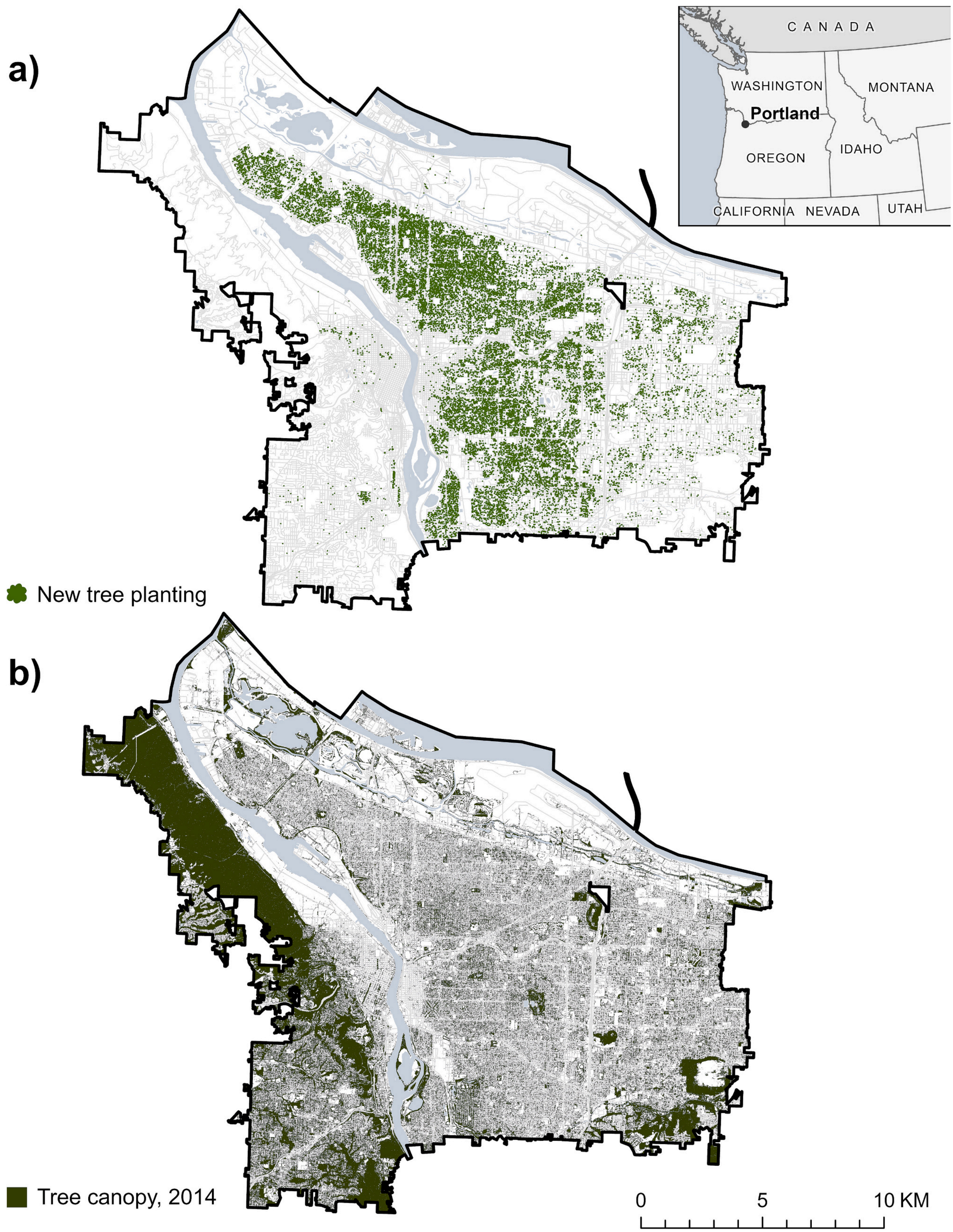

Fig. 1. Shows the spatial distribution of (a) newly planted trees and (b) existing tree cover canopy (in 2014) within the city limits of Portland, OR.

Table 1
Descriptive statistics for singleton births in Portland, Oregon (January 1, 2015, to December 31, 2022; n = 36,564; all children lived at least 12 months after birth). Data sources: Tree canopy (Metro Data Resource Center, 2014), Roads (U. S. Department of Commerce, 2023).

	Mean	SD	Min.	Max.
Birth weight (g)	3377	534	440	7001
Probability SGA = 1 (*n* = 2879)	0.079			
Gestational age (weeks)	38.99	1.74	23	44
Probability gestational age < 37 (*n* = 2248)	0.062			
Probability gestational age < 33 (*n* = 350)	0.010			
Tree canopy [2014] within 100 m (%)	25.08	11.32	0.00	96.36
Trees planted within 100 m in last 10 years	5.53	7.26	0	53.00
NDVI within 100 m (median of maximum values)	0.579	0.104	0.068	0.938
Primary and secondary roads within 100 m (m)	15.36	54.74	0.00	646.06
Mother's age (year)	31.40	5.66	13	55
Mother white (%) (n = 28,8110)	78.8			
Mother African American (%) (*n* = 3016)	8.3			
Mother Asian (%) (*n* = 3363)	9.2			
First birth (%) (n = 17,536)	48.0			
Mother at least some college (%) (*n* = 27,350)	74.8			
Mother BMI	25.64	6.16	13.98	69.72

were uncorrelated ($r = -0.15$). New tree planting was also uncorrelated with maternal race ($r = 0.11$) and maternal education ($r = 0.17$). This suggests that the number of new trees planted is not merely a proxy for existing tree canopy, and new tree planting is also not correlated with important demographic correlates of birth outcomes, which reduces the probability that the association between the number of trees planted and birthweight suffers from residual confounding.

Independent of existing tree cover, tree planting around maternal address is significantly associated with higher birthweight (Table 2). Specifically, each tree planted within 100 m of maternal address and within 10 years of a child's birth was associated with a 2.3 g (95 % CI: 1.5–3.0) increase in birthweight. We found that a model using the number of trees planted in 100 m-radius buffers around maternal address had higher explanatory power than models using buffers of 50 m, 200 m, or 500 m in radius, although the difference in explanatory power was modest. Therefore, we used 100 m-radius buffers in all subsequent models.

Existing tree cover was also positively associated with birthweight, which is consistent with the broader green birth-outcome literature (Hu et al., 2021), and it is also consistent with several studies that specifically used tree cover as an exposure metric (Abelt and McLafferty, 2017) including a study conducted in Portland (Donovan et al., 2011).

To gain more insight into the association between tree planting and birthweight, we re-estimated our model of birthweight using a series of indicator variables to denote the number of trees planted around maternal address (Fig. 2). The association between tree planting and birthweight is not significant until at least four trees are planted and plateaus at about 10 trees, which corresponds to an increase in birthweight of approximately 50 g. A 50 g increase in birthweight may have only modest clinical relevance at the individual level, but if birthweight were increased by 50 g for every baby in our sample, then the number of SGA births would decline by 642 from 2879 to 2237, and SGA births are associated with significant increases in perinatal morbidity and mortality (Grisaru-Granovsky et al., 2012), as well as worse developmental markers later in life such as lower academic performance (Hollo et al., 2002) and reduced lifetime earnings (Strauss, 2000).

The direction of the association between birthweight, sex, maternal race, maternal education, primigravida, and maternal BMI are consistent with past research (Heaman et al., 2013; Pollock et al., 2021; Yu et al., 2013). In addition, the negative association between road density and birthweight is consistent with several previous studies (Wang et al., 2020). The positive coefficient on the interaction between road density and existing tree canopy suggests that trees may attenuate the negative effect of traffic-related air pollution on birthweight. In contrast to existing tree canopy, new tree planting did not modify the association between road density and birthweight. Finally, the year indicator

Table 2
The association between birthweight and the number of new trees planted within 100 m of maternal address within 10 years of a child's birth in Portland, Oregon controlling for existing tree canopy, birth year, maternal race, primigravida, maternal education, maternal BMI, and road density. Singleton live births from January 1, 2015, to December 31, 2020, where the child survived at least 12 months after birth (n = 36,197; $R^2 = 0.0464$).

Variable	Coefficient	p-value	95 % CI	
BIRTH YEAR [2015 omitted]				
2016	−12.4	0.170	−30.1	5.3
2017	−26.3	0.004	−44.4	−8.3
2018	−13.9	0.135	−32.2	4.3
2019	−38.4	<0.001	−56.8	−19.9
2020	−37.9	<0.001	−56.6	−19.1
Male	112.2	<0.001	101.5	123.0
RACE				
White	32.6	0.030	3.2	62.0
African American	−123.5	<0.001	−157.4	−89.5
Asian	−111.3	<0.001	−145.1	−77.4
First birth	−103.0	<0.001	−113.9	−92.0
Mother at least some college	109.7	<0.001	96.4	123.1
BMI	5.96	<0.001	5.06	6.86
Tree canopy [2014] within 100 m (%)	0.626	0.017	0.114	1.138
Trees planted within 100 m in last 10 years	2.25	<0.001	1.48	3.02
Primary and secondary roads within 100 m (m)	−0.289	0.007	−0.499	−0.079
Tree canopy*Length of roads	0.0104	0.025	0.0013	0.0195

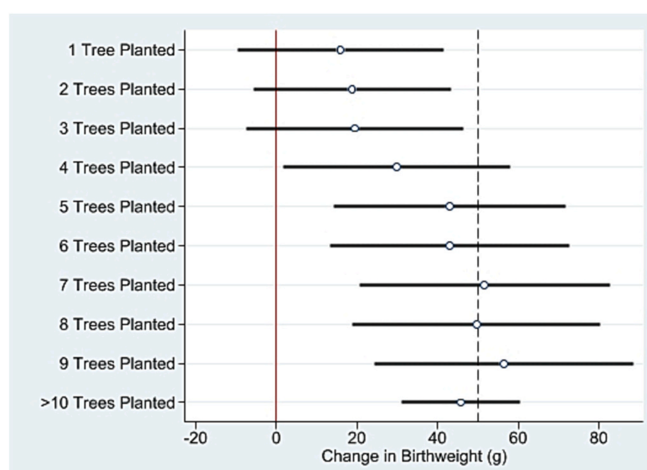

Fig. 2. The association between the number of trees planted (expressed as indicator variables (omitted reference variable denotes zero trees planted)) in 100 m-radius buffers around maternal address in the 10 years before a child was born in Portland, Oregon controlling for birth year, maternal race, primigravida, maternal education, maternal BMI, and road density. Singleton live births from January 1, 2015, to December 31, 2020, where the child survived at least 12 months after birth ($n = 36{,}197$; $R^2 = 0.0463$). The dashed line at X = 50 denotes the approximate plateau of the association between tree planting and increased birthweight.

variables show that birthweight trended down across the study period. In our stratified models, we found that the magnitude of the association between the number of trees planted and birthweight is greater for white women ($p = 0.045$), but there was no difference in the association between existing tree canopy and birthweight by race ($p = 0.512$) (Supplementary table 2[a]). We also found that the magnitude of the association between the number of trees planted and birthweight is greater for women with some college education ($p < 0.001$), but there was no difference in the association between existing tree canopy and birthweight by education ($p = 0.105$) (Supplementary table 2[b]). Our stratified analyses suggest that white women with at least some college education derive greater benefit from new tree planting than non-white women who lack any college education.

The results we have presented are based on the number of trees planted within 10 years of a child's birth. When we re-estimated models using either the number of trees planted 5 or 15 years before a child's birth, the association between tree planting and birthweight remained statistically significant, positive, and of a similar magnitude to our 10-year model (Supplementary Tables 3[a] and 3[b]). This suggests that results are not simply an artifact of our choice of a 10-year cutoff.

Table 3 shows the association between the probability of an SGA birth and tree planting. Results are broadly consistent with the linear model of birthweight, although we did not find a significant association between road density and the probability of an SGA birth. A 1-SD increase in the number of trees planted was associated with a 4.3 % (95 % CI: 0.3 to 8.2 %) decrease in the probability of an SGA birth.

Table 4 shows the association between the probability of a preterm birth and tree planting. There are a several differences between the SGA and preterm models. Consistent with the broader birth-outcome literature, race was not a risk factor for preterm birth (Manuck, 2017). Maternal age is a risk factor for preterm birth but is not associated with the probability of an SGA birth. Conversely, maternal race is not significant in the preterm model but is significant in the SGA model. Finally, higher BMI is a risk factor for preterm birth but is protective of an SGA birth. A 1-SD increase in the number of trees planted was associated with a 4.9 % (95 % CI: 0.3 to 9.3 %) decrease in the probability of a preterm birth.

Table 3
The association between the probability of an SGA birth and the number of new trees planted within 100 m of maternal address within 10 years of a child's birth in Portland, Oregon controlling for existing tree canopy, birth year, maternal race, primigravida, maternal education, maternal BMI, and road density. Singleton live births from January 1, 2015, to December 31, 2020, where the child survived at least 12 months after birth (n = 36,197; Pseudo $R^2 = 0.0235$).

Variable	Odds Ratio	P-value	95 % CI	
BIRTH YEAR [2015 omitted]				
2016	0.974	0.687	0.858	1.106
2017	0.999	0.989	0.878	1.137
2018	0.929	0.273	0.813	1.060
2019	1.009	0.892	0.885	1.151
2020	1.020	0.772	0.893	1.165
Male	1.077	0.059	0.997	1.164
RACE				
White	0.875	0.219	0.707	1.083
African American	1.581	<0.001	1.251	1.998
Asian	1.370	0.008	1.084	1.732
First birth	1.840	<0.001	1.698	1.995
Mother at least some college	0.762	<0.001	0.695	0.835
BMI	0.971	<0.001	0.964	0.978
Tree canopy [2014] within 100 m (standardized)	0.961	0.057	0.923	1.001
Trees planted within 100 m in last 10 years (standardized)	0.957	0.034	0.918	0.997

Table 4
The association between the probability of preterm birth (<37 weeks gestational age) and the number of new trees planted within 100 m of maternal address within 10 years of a child's birth in Portland, Oregon controlling for existing tree canopy, birth year, maternal race, primigravida, maternal education, maternal BMI, and road density. Singleton live births from January 1, 2015, to December 31, 2020, where the child survived at least 12 months after birth (n = 36,197; Pseudo $R^2 = 0.0139$).

Variable	Odds Ratio	P-value	95 % CI	
BIRTH YEAR [2015 omitted]				
2016	1.141	0.080	0.984	1.322
2017	1.206	0.013	1.039	1.398
2018	1.093	0.255	0.938	1.274
2019	1.218	0.010	1.048	1.416
2020	1.235	0.006	1.061	1.438
Male	1.180	<0.001	1.081	1.287
Mother's age	1.017	<0.001	1.008	1.025
RACE				
White	0.880	0.233	0.712	1.086
African American	1.095	0.459	0.861	1.391
Asian	0.908	0.450	0.706	1.167
First birth	1.206	<0.001	1.099	1.322
Mother at least some college	0.617	<0.001	0.555	0.687
BMI	1.026	<0.001	1.019	1.032
Tree canopy [2014] within 100 m (standardized)	0.946	0.022	0.902	0.992
Trees planted within 100 m in last 10 years (standardized)	0.951	0.036	0.907	0.997

4. Discussion

We found that tree planting around maternal address was associated with increased birthweight as well as a reduced probability of an SGA or preterm birth. Our results are consistent with the broader green birth-outcome literature (Hu et al., 2021). However, extant studies all use exposure metrics that measure total greenness—such as NDVI, area of parks, or total tree canopy—and these measures of total greenness are subject to residual confounding and self-selection bias (Jesdale et al., 2013; Wu et al., 2021). In contrast, the trees planted by Friends of Trees are not correlated with existing tree cover, maternal race, and maternal education level. In addition, because newly-planted trees are relatively small, they are less likely to influence neighborhood selection when compared to established parts of a city's green infrastructure such as mature trees or parks. Therefore, our tree-planting findings strengthen the evidence that exposure to the natural environment during pregnancy improves birth outcomes.

Our findings support tree planting, which is a specific public-health intervention that can be implemented in most neighborhoods at modest cost. In addition, tree planting is associated with a wide range of co-benefits from reduced energy consumption (Akbari et al., 1997) to lower crime (Kondo et al., 2017). In contrast, the finding that NDVI is associated with improved birth outcomes is more difficult to implement, because NDVI can be increased in a myriad of ways, and some NDVI-increasing interventions may have little effect on birth outcomes. Finally, studies showing that proximity to parks or open space is associated with improved birth outcomes may be difficult to implement, as it's impractical to add parks in many, if not most, urban settings.

We found that trees within 100 m of maternal address are most strongly associated with improved birth outcomes suggesting that mechanisms that operate over short distances—such as psychological restoration—may be important mediators of the relationship between trees and birth outcomes (Turner-Skoff and Cavender, 2019). In particular, the pioneering work of the environmental psychologists Rachel and Stephen Kaplan showed that interacting with the natural environment encourages soft fascination that is psychologically restorative, whereas focusing on the built environment requires hard fascination that is psychologically draining (Kaplan and Talbot, 1988;

Kaplan, 1987). In addition, we found that existing tree cover attenuates the negative association between road density and birthweight, but new tree planting did not. This may be because the likely mechanisms through which trees attenuate the effect of road density on birthweight are a reduction in air pollution (Nowak et al., 2006) and noise (Fang and Ling, 2003), and large trees with greater leaf area are better able to do both than small newly-planted trees.

There are several possible explanations for the downward trend in birthweight across the study period. First, the racial composition of births changed. Specifically, in 2015, 80.5 % of mothers in Portland were white. This declined to 77.3 % by 2020. This may have contributed to lower mean birthweights, because white women in on average had heavier babies (mean = 3409 g; SD = 529 g) compared to non-white women (mean = 3259 g; SD = 537 g). It's also possible that climate change contributed to the downward trend in birthweight, as exposure to high temperatures during pregnancy is associated with lower birthweight (Lawrence et al., 2021). The study period included the first year of the COVID-19 pandemic. However, COVID-19 is unlikely to have contributed to the observed decline in birthweight, because multiple studies have shown that birthweights increased during the pandemic (Yao et al., 2023). Finally, in September 2020, dense smoke from wildfires caused the air quality index in Portland to exceed the hazardous threshold (>300) for multiple days (Oregon Department of Environmental Quality, 2021), and studies have shown that exposure to air pollution is associated with lower birthweights (Bekkar et al., 2020).

We found that tree planting had diminishing returns. Specifically, planting six trees within 100 m of maternal address was associated with an increase in birthweight of approximately 50 g, but planting more than six trees did not yield any additional increments in birthweight. Although these specific results are unique to Portland, it's likely that tree planting in other cities would also exhibit diminishing returns and maximum thresholds. Determining what these thresholds are in different cities is a highly policy-relevant goal for future research.

Our stratified analyses showed that college-educated white women derive greater benefit from new tree planting than women of color without any college education. This result is not surprising, given that white women are more likely to work from home (Gould and Shierholz, 2020) and to receive paid parental leave (Goodman et al., 2021), so they may have greater exposure to trees around their homes during pregnancy. However, if this were the only mechanism at play, then we would expect that college-educated white women would also derive more benefit from existing tree cover, and we did not find that. One possible explanation for this finding is that women who participate in the Friends of Trees tree-planting program gain more social connections than women who do not. The specifics of the tree-planting program support this interpretation of the results. Friends of Trees canvasses residents of a neighborhood asking them if they would like to plant a tree in the parking strip outside their homes. Residents who agree gather on a specific day and help each other plant trees throughout the neighborhood. They also help water and maintain the trees as they grow. The dual purposes of this approach are to increase tree cover and to build social connections within a neighborhood. Research on the Friends of Trees program found that residents in neighborhoods with lower rates of education are less likely to participate in the program (Donovan and Mills, 2014). Therefore, if college-educated white women are more likely to participate, they may benefit in two ways. First, it is more likely that a tree is planted directly outside their homes rather than elsewhere within the 100 m-radius buffers around maternal address. Second, if they participate in the program, they may benefit from the social connections that are made both on the planting day and while jointly maintaining the trees as they grow. This would be consistent with research showing that people living in greener neighborhoods have more social connections and better health (de Vries et al., 2013; Liu et al., 2020).

This finding suggests that the way a neighborhood is greened may influence subsequent health benefits. For example, if Friends of Trees had simply planted trees without the involvement or consent of residents, then the trees may have had a lesser impact on neighborhood social cohesion and ultimately maternal health. Therefore, any organization that is planning a large-scale greening program may wish to involve residents in all phases of that effort. Specifically, residents could be first asked whether they want a street tree planted outside their home at all. If they do, they could be consulted on the how many trees are to be planted, the species, and the timing of planting. To help residents make informed decisions, they could be provided with the watering and maintenance requirements of different species. Doing so may maximize public-health benefits in two ways. First, community involvement may improve the impact of greening on social cohesion. Second, robust community involvement may improve the survival rate of the trees (or other plantings).

4.1. Limitations

This is an observational study that cannot prove a causal relationship between trees and birth outcomes. In addition, our tree-planting metric included trees planted by Friends of Trees but not those planted by other organizations or individuals. If these missing trees are correlated with the trees planted by Friends of Trees, the coefficient estimates may be biased. Data on these missing trees are imperfect, but the trees planted by Friends of Trees constitute the majority of street trees planted in Portland during the study period (Donovan et al., 2022b). Our tree metrics also didn't account for trees species, which is a limitation, because exposure to diverse trees and plants may influence the human microbiota (Hanski et al., 2012). Furthermore, we did not have access to some variables that may be confounders of the relationship between trees and birth outcomes. Not having access to data on household income is of particular concern, although the inclusion of race, age, and education in our models may attenuate any confounding (future research may wish to use neighborhood-level data on income, if data on household income are not available). However, we were able to adjust our models for birthweight, sex, maternal race, maternal education, primigravida, maternal BMI, road density, and existing tree cover and estimates for these factors are consistent with past research. Finally, our tree-planting metric included some trees planted in 2014 or earlier, and these trees would have been captured by our 2014 measure of total canopy cover. However, we don't believe that double counting is a major issue for two reasons. First, any double-counted trees would have been small, so they would have contributed little to total tree canopy cover. Second, the number of newly planted trees is only weakly (and negatively) correlated with existing tree cover (Supplementary Table 1). Finally, using LiDAR from a single year (2014) to measure tree canopy at baseline across a six-year study period will introduce some measurement error, which may contribute to inefficiency and bias in coefficients of interest.

Given these limitations, it would be useful if future research used a randomized controlled study design to definitively determine whether trees, and other components of the natural environment, are causally associated with improved birth outcomes.

5. Conclusions

Multiple studies have found an association between exposure to the natural environment during pregnancy and improved birth outcomes. However, the policy impact of these studies is limited by possible residual confounding and the self-selection of healthier women into greener neighborhoods. In addition, the use of NDVI as an exposure metric makes it difficult to translate results into practical interventions. Our finding that newly-planted trees are associated with improved birth outcomes complements and strengthens the extant literature and suggests that tree planting could be used as an effective public-health intervention to improve birth outcomes.

CRediT authorship contribution statement

Geoffrey H. Donovan: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Jeffrey P. Prestemon:** Writing – review & editing, Investigation, Formal analysis. **Abigail R. Kaminski:** Writing – review & editing, Formal analysis. **Yvonne L. Michael:** Writing – review & editing, Writing – original draft.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179229.

Data availability

The data that has been used is confidential.

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