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Remy Landon Date

Urban Greenness and Birth Outcomes in Atlanta, Georgia

By

Remy Landon
Master of Public Health

Environmental Health

Michael Kramer, PhD
Committee Chair

Dana Boyd Barr, PhD
Committee Member

Julie Clennon, PhD
Committee Member

Paige Tolbert, PhD
Committee Member

Urban Greenness and Birth Outcomes in Atlanta, Georgia

By

Remy Landon

B.S.
Emory University
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Thesis Committee Chair: Michael Kramer, PhD

An abstract of
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Abstract

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Introduction: Increased greenness has been shown to decrease stress, improve social functioning, increase physical activity, decrease air pollution, and moderate ambient temperature. These effects have all, in turn, been associated with improved birth outcomes. Previous studies have found a generally protective effect of greenness on adverse birth outcomes in other locations, but have not evaluated the association in the Southeastern United States. I investigated the association between greenness and low birth weight-preterm birth (LPTB) in the novel setting of Atlanta, Georgia, a city unique for its racially and economically diverse population and high average greenness.

Methods: Data was obtained from a population-based vital records system for all live births in the 10-county Metropolitan Atlanta Region from 2005-2007 (n=164,748). Average greenness was calculated in a 250m buffer around the maternal residence using the Normalized Difference Vegetation Index (NDVI), derived from a Landsat 5 Thematic Mapper satellite image (30x30m resolution). Logistic regression was used to evaluate the association between average residential NDVI and LPTB, controlling for individual and neighborhood-level covariates.

Results: Significant effect modification by race was observed between White and Black women ($p=0.0082$). Among Black women, a significant quadratic relationship was observed between residential greenness and LPTB, with the highest risk of LPTB in the areas of highest greenness [NDVI OR: 1.07 (1.03, 1.12); $NDVI^2$ OR: 1.31 (1.03, 1.66) per 1-IQR increase]. However, among White women, there was no significant association between residential greenness and LPTB [NDVI OR: 1.00 (0.94, 1.05); $NDVI^2$ OR: 1.12 (0.81, 1.55) per 1-IQR increase]. Results were robust to changes in birth outcome, NDVI buffer size, and scale of neighborhood deprivation, as well as adjustment for additional covariates.

Discussion: The greenness-birth outcome association is not consistent across locations and can vary as a result of changing demographic and geographic factors. The null association among White women may be due to Atlanta's high average greenness, while the association among Black women is more complex and warrants further investigation.

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I. INTRODUCTION

The Urban Environment and Health

Urbanization is increasing throughout the United States and across the globe. As of the 2010 Census, 80.7% of the U. S. population lived in an urban area, up from 79.0% in 2000. There has been particularly rapid growth in major urban centers, with the percentage of U.S. residents living in an urban area of 50,000 people or more rising from 68.3% in 2000 to 71.2% in 2010 (U. S. Census Bureau, 2010b). Globally, the percentage of the world population living in an urban area has steadily increased from 30% in 1950 to 54% in 2014 (United Nations, 2014). As more people move to urban areas, understanding the influence of the urban environment on public health will become increasingly important.

In general, living in an urban area is associated with improved health. From 2005-2009, the life expectancy of people in the United States living in metropolitan areas was a full 2 years longer than the life expectancy of people living in nonmetropolitan areas (78.8 years compared to 76.8 years) (Singh & Siahpush, 2014b). Living in an urban area is associated with a lower rate of all-cause mortality and mortality due to a number of specific factors including suicide, cardiovascular diseases, heart disease, stroke, COPD, diabetes, Alzheimer's disease, and pregnancy-related causes (Singh & Siahpush, 2014a). Urban environments also show a protective effect against mortality due to many types of cancer (Singh & Siahpush, 2014a). This urban-rural disparity is likely a result of a combination of multiple factors, including increased access to health care, particularly specialists, lower rates of smoking, and lower rates of obesity in urban areas (Aboagye et al., 2014; Chan et al., 2006; Eberhardt & Pamuk, 2004).

However, urban environments are also associated with negative health effects. Air pollution is generally higher in urban environments, leading to increased rates of asthma (Timm et al., 2015). Cities are also generally warmer than rural areas because of the urban heat island effect, which increases heat stress and heat-related mortality among urban residents (Clarke, 1972; Figuerola & Mazzeo, 1998). Cities also tend to have less green space, which can have a wide range of health consequences (James et al., 2015).

As urban populations grow, city planners and government officials need to be equipped with the best information on how to mitigate the negative health effects of urbanization. Understanding the effect of green space is of particular importance because of the wide range of potential health benefits, from physical health to mental health (James et al., 2015). Given the rapidly growing urban population, understanding the nature of the effect of greenness on health is of significant public health importance. Equipped with the right information, city planners and government officials can design cities that will not only protect, but advance, the health of America's growing urban population.

Mental Health Benefits of Increased Greenness

Much of the early research on green space and health focused on the psychological benefits of increased contact with nature. According to a recent review, increased greenness is associated with reduced psychiatric morbidity, psychological distress, depression, clinical anxiety, and mood disorder in adults (James et al., 2015). The underlying mechanisms for the beneficial effect of greenness on mental health can largely be divided into two categories: the ability of greenness to reduce stress and the ability of greenness to improve social functioning.

Greenness and Stress

Frederick Law Olmsted, widely considered the founder of American landscape architecture, began to extol the stress-reduction capabilities of public parks as early as the mid-nineteenth century (Larice & Macdonald, 2013). According to Olmsted, green space had the power to counteract many of the "special evils" of living in cities and provide the "ability to maintain a temperate, good-natured, and healthy state of mind" (Olmsted, 1870). This philosophy influenced his designs of Central Park in New York City, the Druid Hills area of Atlanta, and various other parks in Brooklyn, Boston, and more (Hartle, 2008; Larice & Macdonald, 2013). However, it wasn't until the mid-twentieth century that rigorous psychological studies and theories began to emerge that supported Olmsted's philosophy.

In 1983, Roger Ulrich proposed a psychoevolutionary theory to explain the mechanisms behind the restorative capacity of nature on stress. From a psychological point of view, he argued that natural settings are less complex and thus easier to process, eliciting less arousal and quicker recovery from stressful encounters (Ulrich, 1983; Ulrich et al., 1991). From an evolutionary point of view, he argued that humans have an inherent preference for environments that would have benefited survival during the time of our ancestors, such as those containing vegetation and water (Ulrich, 1983; Ulrich et al., 1991). The psychoevolutionary theory combines these perspectives to postulate that nature scenes produce unconsciously triggered positive emotional states which then affect cognitive functioning, and can thus affect behavior (Ulrich, 1983).

Rachel and Stephen Kaplan (1989) expanded on the psychological aspect of Ulrich's theory, arguing that humans have a strong inherent preference for, and fascination with, natural scenes. This preference and fascination allows for increased attention-holding capacity in natural environments, without the mental fatigue required to maintain attention in more complex urban environments. The ability to stay focused with ease is integral to the restorative properties of green spaces, and forms the basis of the Attention Restoration Theory (R. Kaplan & Kaplan, 1989; S. Kaplan, 1995).

Many studies have since provided empirical evidence to support these theories by showing that higher levels of surrounding greenness reduce stress, both through perceived stress and biological measurements. The perceptions of stress among residents of nine cities in Sweden was significantly associated with the number of visits to a park, the time spent at a park, and the distance to a park (Grahn & Stigsdotter, 2003). Although these results may have been confounded by physical activity, the protective effect of greenness on stress persists even without physical contact with green space. Simply viewing a natural scene instead of an urban one has been shown to reduce stress in multiple studies (Ulrich et al., 1991). Exposure to nature sounds produces a similar stress-reduction effect to viewing a natural scene (Alvarsson et al., 2010). Cortisol measures, often used as a biomarker for stress, have also been shown to be associated with the level of surrounding greenness (Roe et al., 2013; Thompson et al., 2012). In Thompson et al. (2012) the association between cortisol slope and green space was significant even while controlling for physical activity. Roe et al. (2013) built off the findings of Thompson by showing that this association was also modified by gender, with women showing higher levels of stress in areas of lower greenness and steeper declines in stress with increased greenness. In addition to cortisol measures, contact with green space has also been shown to decrease diastolic blood pressure, pulse rate, and heart rate (Laumann et al., 2003; J. Lee et al., 2009).

Greenness and social functioning

Building upon the work on greenness and stress, Frances Kuo conducted a series of studies on the effect of greenness on social cohesion in two public housing developments in Chicago (Kuo, 2003). In these communities, all the buildings were generally the same design and layout, but with varying degrees of surrounding greenness. Residents were randomly assigned to units and had no control over the maintenance of the vegetation (Kuo, 2003). Despite previous preconceptions that trees would reduce visibility and therefore cause residents to feel unsafe, Kuo found that residents strongly preferred areas with trees over those without, both in a photosimulation study (Kuo, Bacaicoa, et al., 1998) and three studies observing the everyday activities of residents (Coley et al., 1997; Kuo, Sullivan, et al., 1998; Sullivan et al., 2004). Areas of greenness encouraged significantly more social interaction, including adult-adult interaction, child-child interaction, and adult-child interaction (Coley et al., 1997; Faber Taylor et al., 1998; Sullivan et al., 2004). As a result of increased time spent outside, residents in more green buildings reported stronger social ties and a stronger feeling of belonging (Kuo, Sullivan, et al., 1998). Greener areas were also correlated with higher perceptions of safety (Kuo, Sullivan, et al., 1998) and fewer crimes reported to the police (Kuo & Sullivan, 2001).

In addition to increased social interactions, Kuo found increased effectiveness in coping with poverty among residents with more greenness. Residents living in units with a green view as opposed to a barren view assessed themselves to be more effective in managing major life issues (Kuo, 2001). Further analyses revealed that these women procrastinated less in dealing with major issues, felt these issues were less difficult to deal with, and reported them to be less severe and more short-lived (Kuo, 2001). This relationship between greenness and improved functioning was also observed in young children, although results were only significant for girls, not boys. Young girls living in units with a green view performed better on tests of self-discipline than their barren-view counterparts (Faber Taylor et al., 2002). These findings suggest that young girls living in areas with higher levels of surrounding greenness are better able to deal with social stressors and therefore are more likely to lead more effective, self-disciplined lives (Faber Taylor et al., 2002). These findings support Kaplan's Attention Restoration Theory (S. Kaplan, 1995). Together, the improved social cohesion and improved effectiveness in dealing with major life problems help individuals not only become more productive members of society, but also build stronger communities.

The findings of Frances Kuo and colleagues on the positive effect of greenness on social functioning have since been supported by multiple other studies in the literature. One study found that residents with less residential greenness were more likely to experience feelings of loneliness and more likely to perceive a shortage of social support in their lives (Maas et al., 2009). In another study, women with higher residential greenness reported higher neighborhood satisfaction and higher neighborhood social capital, which were in turn associated with improved self-rated health (Orban et al., 2017). In fact, throughout the literature, stress reduction and social cohesion often emerge as particularly important variables in the association between green space and health, often showing stronger associations than other variables, including physical activity (Dadvand et al., 2016; Groenewegen et al., 2012).

Physical Health Benefits of Increased Greenness

Following the extensive research described above on the effects of greenness on mental health, researchers began to explore the effects of greenness on physical health. One of the first studies on the physical health benefits of green space was conducted by Roger Ulrich as a follow up to his studies on stress reduction. Ulrich observed that cholecystectomy patients with a view of trees outside of their hospital room window recovered quicker and required less analgesic than patients with a view of a brick wall (Ulrich, 1984). Tree-view patients also had more positive comments in the nurses' evaluations and had lower scores for minor postsurgical complications, although these associations were not statistically significant (Ulrich, 1984). These results were replicated in a 2003 study on bronchoscopy patients which found significantly better pain control among patients who viewed a nature scene mural and listened to nature sounds (Diette et al., 2003). These studies indicate that the restorative and stress-reduction capabilities of greenness are not limited to just mental health outcomes, but can have physical benefits as well.

However, green space can also directly impact physical health through mechanisms completely separated from psychological effects. The three main pathways through which greenness has been shown to improve physical health are increased physical activity, reduced air pollution, and a more moderate ambient temperature (James et al., 2015).

Greenness and Physical Activity

One of the main hypotheses behind the beneficial health effects of green space is that with increased availability of green space, physical activity will increase (Bedimo-Rung et al., 2005). This hypothesis has received plenty of support in the literature (Almanza et al., 2012; Giles-Corti et al., 2005; Gomez et al., 2010; Mytton et al., 2012; E. A. Richardson et al., 2013;

Sugiyama et al., 2010). In one study in England, individuals living closer to a formal park were significantly more likely to visit green space at least once a week and significantly more likely to achieve the government physical activity guidelines, even after controlling for a variety of individual and neighborhood-level factors (Coombes et al., 2010). However, there is also considerable evidence that the association between green space and physical activity is mediated by the accessibility, quality, safety, and size of the green space (Branas et al., 2011; Evenson et al., 2006; Giles-Corti et al., 2005; A. C. Lee & Maheswaran, 2011). For example, one study found that recreational walking is associated with the attractiveness of nearby green spaces, but not the number of green spaces in the neighborhood (Sugiyama et al., 2010).

If green space does increase physical activity, at least in certain situations, then the increased physical activity will in turn lead to improved health outcomes. In one study, increased greenness was associated with both increased physical activity and decreased cardiovascular disease (E. A. Richardson et al., 2013). Another study found that increased tree cover was associated with improved general health, reduced overweight/ obesity rates, and reduced rates of type 2 diabetes (Ulmer et al., 2016). Given the wide range of health benefits associated with increased physical activity (Booth et al., 2011; Janssen & Leblanc, 2010), the potential for improved public health with increased greenness is significant.

Greenness and Air Pollution

Increased urban tree cover also reduces air pollution, which decreases associated respiratory health problems (Escobedo & Nowak, 2009; Nowak et al., 2006; Yang et al., 2005). Trees remove gaseous pollutants primarily through uptake via leaf stomata. Particle pollutants are removed primarily through intercepting particles and retaining them on the plant surface, which are then usually washed off by rain or deposited on the ground with falling leaves (Nowak et al., 2006). Nowak et al. (2006) estimated that all urban trees in the United States remove about

711,000 metric tons of pollutants (O_3, PM_{10}, NO_2, SO_2, CO) from the air each year. For reference, that would cost about $3.8 billion to clean up using man-made technologies (Nowak et al., 2006).

Given this significant impact of trees on air pollution, planting more trees has been proposed as a mechanism to clean up urban air quality and improve health (Nowak et al., 2006). Air pollution has been linked to a multitude of adverse health effects including asthma, chronic obstructive pulmonary disease, and cardiovascular disease (Brunekreef & Holgate, 2002). The International Agency for Research on Cancer has also classified outdoor air pollution as carcinogenic to humans for its association with lung cancer, and to a lesser extent, bladder cancer (Loomis et al., 2013).

Greenness and Temperature

Finally, greenness can improve health through moderation of the ambient temperature. Cities are often subject to the heat island effect, causing increased temperatures and increased risk of heat-related illnesses (Clarke, 1972; Figuerola & Mazzeo, 1998). Vegetation helps to reduce the heat island effect by casting shade over windows, walls, and roofs that would otherwise reflect solar heat waves back into the atmosphere (Dimoudi & Nikolopoulou, 2003). Vegetation also cools the air through evapotranspiration, the process of releasing excess moisture from the plant leaves into the air (Dimoudi & Nikolopoulou, 2003). One study found that, during days of higher than average temperatures in July, individuals who visited green spaces more frequently and for longer periods of time reported greater perceived well-being, indicating a higher capacity to handle heat stress (Lafortezza et al., 2009). In the current environment of growing urbanization and accelerating climate change, increased urban tree canopy cover has the ability to significantly improve public health.

Greenness and Birth Outcomes

Many of the above hypotheses positing effects of greenness on general health can also be applied to adverse birth outcomes, mainly preterm birth and low birth weight. Preterm birth is defined as a delivery that occurs before 37 weeks gestation. About 60-70% of preterm births occur during weeks 34-36, however infants born at earlier gestational ages are at a much greater risk for mortality or morbidity (Goldenberg et al., 2008; Institute of Medicine, 2007). A newborn is considered low birth weight if he or she weighs less than 2500 grams at delivery, and very low birth weight if less than 1500 grams (Valero de Bernabé et al., 2004). Preterm birth is the leading cause of infant mortality in the United States (Callaghan et al., 2006; Institute of Medicine, 2007). Infants born preterm or at low birth weight are also at greater risk for a wide range of health complications, including cerebral palsy, intellectual and/or developmental disabilities, sensory impairments, severe respiratory distress, and more (McCormick, 1985; Saigal & Doyle, 2008). In addition to the consequences for the child, the increased morbidity and mortality associated with preterm birth and low birth weight present a significant economic burden on the infant's family, the healthcare system, and society (Petrou, 2003). Significant economic and racial disparities in the prevalence of preterm birth and low birth weight often place this economic burden disproportionately upon those who are least prepared to handle it (Parker et al., 1994). Black women consistently have higher rates of preterm birth and low birth weight, although the exact mechanisms behind this association are the subject of continued research (Institute of Medicine, 2007; Parker et al., 1994). Many of the hypotheses and current evidence attempting to explain the underlying causes of preterm birth and low birth weight, and the racial and economic disparities of each, fit closely with the hypothesized mechanisms behind the beneficial effects of green space on health. This indicates a potential link between increased greenness and reduced adverse birth outcomes.

Hypothesized Mechanisms of the Association Between Greenness and Birth Outcomes

The first main hypothesis behind the health benefits of greenness is the ability of natural environments to reduce stress. Increased stress has been shown to be a risk factor for both preterm birth and low birth weight (McDonald et al., 2014; Rondo et al., 2003; Staneva et al., 2015). Arline Geronimus (1992) proposed that the accumulation of stress over a lifetime begins to break down physical health, a theory she termed the “weathering hypothesis.” This hypothesis arose as a mechanism to explain the lower risk of adverse birth outcomes among Black teenagers compared to their older counterparts, an opposite pattern than observed in most races. The weathering hypothesis states that, specifically for Black women, socioeconomic disadvantage, racism, and other stressors begin to accumulate over time leading to decreased general health and therefore a higher risk of adverse pregnancy outcomes (Geronimus, 1992). In support of this theory, Hux et al. (2014) used NHANES data to show that the allostatic load of women who gave birth to a term-born or healthy weight infant was significantly lower than the allostatic load of women who gave birth preterm or to a low birth weight baby. Frances Kuo showed that greenness can allow women to cope more effectively with major life problems (Kuo, 2001) and that greenness can reduce crime rates (Kuo & Sullivan, 2001), both of which could help reduce chronic stress and potentially decrease allostatic load. This could, in turn, lead to fewer adverse birth outcomes. Decreased allostatic load associated with increased greenness can also keep the body healthier and less vulnerable to environmental exposures, which may affect pregnancy (Morello-Frosch & Shenassa, 2006).

In addition to decreased stress, greenness also improves social functioning, which has been associated with improved pregnancy outcomes. Morenoff (2003) found that social exchange/ voluntarism, as well as crime rates, was significantly associated with birth weight, even when controlling for individual-level variables and other neighborhood structural characteristics. Furthermore, Morenoff also found that the association between increased social exchange/ voluntarism and increased birth weight is not limited to just the immediate neighborhood, but actually becomes stronger when surrounding neighborhoods are included, indicating that increased social functioning in a broadly-defined geographic region can have meaningful impacts on birth weight. Other studies have confirmed this association: perceived levels of neighborhood social cohesion were positively associated with increased birth weight in White women (Buka et al., 2003), and increased social capital and decreased income inequality was associated with lower rates of teen pregnancy (Crosby & Holtgrave, 2006; Gold et al., 2002). Social support may also act as a buffer between stress and preterm birth (Hetherington et al., 2015) and can help improve other pregnancy outcomes such as antenatal hospital admission and cesarean birth (Hodnett et al., 2010).

Physical activity is associated with increased green space and with improved general pregnancy health, but with limited evidence that increased physical activity decreases rates of preterm birth and low birth weight. One meta-analysis found a slightly reduced risk of having a large newborn (birth weight greater than 4,000g or greater than the 90th percentile for gestational age and sex) with increased physical activity during pregnancy (Wiebe et al., 2015). Another study found a slightly reduced risk of preterm delivery for women who exercised three to five times a week in week 17 or week 30 (Owe et al., 2012). However, other reviews have found no association between physical activity and birth weight (Harrison et al., 2016). Beyond just birth outcomes, increased physical activity during pregnancy has been shown to improve cardiovascular function, limit pregnancy weight gain, reduce muscle cramps, and attenuate gestational diabetes mellitus and gestational hypertension (Melzer et al., 2010). Physical activity is clearly important for general health, but this evidence indicates that the other four hypotheses may be stronger explanations for the effect of green space on birth outcomes.

Air pollution, on the other hand, is significantly associated with both green space and birth outcomes. Pregnant women in Barcelona with higher residential surrounding greenness had significantly reduced air pollution levels, both inside and outside of their home (Dadvand, de Nazelle, Triguero-Mas, et al., 2012). Lower air pollution levels have been associated with reduced rates of preterm birth (Darrow et al., 2009; Leem et al., 2006; Nieuwenhuijsen et al., 2013) and birth weight (Shmool et al., 2015).

Finally, the beneficial effect of green space on temperature reduction in urban environments can also lead to improved birth outcomes. In both a warm climate (California) and a more moderate climate (Belgium), heat extremes were significantly associated with increased risk of preterm birth (Basu et al., 2010; Cox et al., 2016). Similarly, risk of stillbirth was found to increase both in California and Quebec, Canada with elevated ambient temperature (Auger et al., 2016; Basu et al., 2016).

Previous Studies on Greenness and Birth Outcomes

Increased levels of surrounding greenness have been shown to decrease stress, improve social functioning, increase physical activity, decrease air pollution, and create a more moderate ambient temperature. All five of these effects, in turn, are associated with improved birth outcomes, providing strong theoretical support for the effect of surrounding greenness on birth outcomes.

Thirteen previous studies have attempted to quantify this association between greenness and birth outcomes (Table 1). Ten of the thirteen studies used the Normalized Difference Vegetation Index (NDVI), an index of greenness derived from the different light reflectance patterns of vegetation versus non-vegetation (1-6, 9-10, 12-13). The NDVI calculation uses the near-infrared and red bands of a satellite image to derive a value between -1 and 1 for each pixel, with areas of low greenness nearing -1 and more intense greenness nearing 1. Of the ten studies that used NDVI, all but two derived the NDVI measures from a Landsat satellite image with a 30m resolution, meaning each pixel in the satellite image covers an area of 30x30m on the ground. The remaining two studies used an image from MODIS (Moderate Resolution Imaging Spectroradiometer), which has a 250m resolution (2, 3). Comparatively, these two studies had weaker results than the other studies, possibly because of the coarser resolution of the base image.

This is especially pertinent in Cusak et al. (3) where they only tested associations in a 250m buffer around the maternal residence, the same size as the pixel, and found that almost all the significant results were attenuated after adjusting for confounders.

The most common, and most significant, outcome of interest was birth weight. Eleven of the thirteen studies included some measure of birth weight as one of the outcomes of interest (1-6, 8-10, 12-13). All eleven studies tested either birth weight or term birth weight as a continuous variable, and nine out of the eleven found a significant relationship between increased greenness and increased birth weight (1, 3-6, 8, 10, 12-13). Three of the eleven tested additional categorical measures of birth weight, including low birth weight (<2500 grams), term low birth weight (<2500 grams and >37 weeks gestation), and very low birth weight (<1500 grams) (1,8-9). Agay-Shay et al. (1) and Ebisu et al. (8) both found a significantly decreased risk of low birth weight with increased surrounding greenness, but Grazuleviciene et al. (9) only observed a significant effect with term low birth weight.

Associations with other birth outcomes were less consistent. Six studies tested preterm birth, and four found significant associations (2, 9, 10, 12). However, Grazuleviciene et al. (9) only found an association between preterm birth and proximity to nearest green space, not NDVI, and Hystad et al. (10) and Casey et al. (2) both failed to observe an association between increased greenness and very preterm birth. Six studies also tested small for gestational age, with only three finding significant results (2, 7, 8). Four studies tested gestational age as a continuous variable (ranging from days to weeks), but none found any significant associations with greenness (1, 4, 5, 9). A few studies tested additional outcomes, including 5 min Apgar score, head circumference, infant mortality, and preeclampsia (2, 5, 11, 12). Of these four, only head circumference and infant mortality were related to increased greenness. Overall, associations between green space and birth weight appear to be strong, but more research is needed to fully understand the relationship between greenness and other birth outcomes.

Contributions of the Present Study

This study aims to build upon the work of the previous thirteen studies by investigating the relationship of greenness and birth outcomes in the novel setting of the Southeastern United States. Of the thirteen studies, only five were conducted in the United States, and none in the Southeast. Atlanta is meaningfully different than the other study sites for two reasons: it has a larger proportion of Black women and it has a higher level of average greenness, especially for a large urban area. Understanding the intricacies of the relationship between greenness and birth outcomes in the context of Atlanta, and generally the broader Southeast region, would help inform local city planners and government officials on how best to design urban areas that promote public health.

Within the United States, the Black population is highly concentrated in the Southeast (Rastogi et al., 2011). Of the five previous studies in the United States, the highest percentage of Black women reported in any study population was only 11.2% (Ebisu et al., 2016), while the total population in the 10-county Metro Atlanta region is 37% Black (U. S. Census Bureau, 2010a). Black women are at a significantly higher risk for adverse birth outcomes than either White or Hispanic women, with nearly 2 times rate of low birth weight births, 1.5 times the rate of preterm births, and about 2.5 times the rate of very low birth weight births and very preterm births (Martin et al., 2017). Dadavand et al. (2014) observed effect modification by race, but only analyzed White British women and women of Pakistani origin, with no data on how the association may change for Black women. Therefore, this study will attempt to assess whether the greenness-birth outcome association is consistent across racial groups in Atlanta, with special emphasis on the Black population. Since Black women bear the highest burden of disease in the United States, understanding how the greenness-birth outcome association manifests itself in Black women is of great public health importance.

Second, Atlanta is a major metropolitan center with substantial tree cover, even in very urban areas. According to an analysis by Georgia Tech, 47.9% of metropolitan Atlanta is covered by urban tree canopy, making it the city with the highest percentage of urban tree canopy cover in the United States, compared to other cities that have conducted an Urban Tree Canopy Assessment (Giarrusso & Smith, 2014). The previous studies on greenness and birth outcomes have been conducted in locations that represent a wide range of greenness, from Southern California to rural Pennsylvania, but Atlanta represents an area of high urban greenness which has yet to be fully explored. This may affect the relationship between greenness and birth outcomes as the abundance of greenness in Atlanta may make it a "non-discriminatory predictor of health," as was hypothesized by previous studies in New Zealand (E. Richardson et al., 2010; Witten et al., 2008).

Both the demographic and geographic factors of Atlanta make it meaningfully different that the other locations previously studied, which may impact the association between greenness and birth outcomes. Therefore, this study aims to analyze and quantify the relationship between greenness and birth outcomes in the Atlanta metropolitan region. Based on the literature, I hypothesize that an increase in the average Normalized Difference Vegetation Index (NDVI) surrounding the maternal residence is associated with a decrease in adverse birth outcomes.

II. METHODS

Birth Cohort

Birth outcome data was obtained from a population-based vital records system administered by the Georgia Department of Public Health (DPH). This dataset contains information on all live births in the state of Georgia from 1994 to 2012. In addition to extensive information on infant health and maternal/ paternal demographics, this dataset also contains high quality geocodes for the maternal residence at birth.

However, like any database of birth certificate information, there are some limitations on the reliability and validity of the data. A systematic review found that insurance, birth weight, and delivery method are generally reliable measures from birth certificates, however tobacco and alcohol use, obstetric procedures, and delivery events are less so (Northam & Knapp, 2006). Tobacco and alcohol use, maternal risk factors, and pregnancy complications were also assessed to be generally invalid measures (Northam & Knapp, 2006).

For this analysis, the population was limited to women residing in the 10-county metropolitan Atlanta region who gave birth between 2005 and 2007. There are a variety of ways to define the Metro Atlanta region, but the 10-county definition used here represents the area managed by the Atlanta Regional Commission, one of twelve regional commissions in Georgia (Atlanta Regional Commission, 2016a). The counties include Cherokee, Clayton, Cobb, DeKalb, Douglas, Fayette, Fulton, Gwinnett, Henry and Rockdale. This area includes the urban center of Atlanta along with the surrounding suburbs in order to provide adequate variation in greenness exposure, while still maintaining the consistency of a generally urban area. The study period 2005-2007 was chosen to align with the availability of quality satellite data.

The maternal residence for each birth was geocoded by the Office of Health Information and Policy at the Georgia Department of Public Health. A majority of the points were geocoded at the street-level, but when a street-level match was not available, a match was made at the block or tract level. The DPH provided information on the quality of the geocode for 2005, however this variable was unavailable for 2006-2007. For 2005 data, 78.8% were matched at the street-level, 15.3% at the block-level, and 0.7% at the tract-level. 5.2% had a geocode quality worse than tract-level, and were thus excluded from analysis. Although the lack of information on geocode quality for 2006 to 2007 could introduce some exposure misclassification, it is likely to be non-differential misclassification and thus would bias towards the null. Furthermore, a previous study using data from the same birth registry showed that the median location error was less than 100 meters and that there was no evidence for systematic bias in the angle or direction of the location error (Strickland et al., 2007).

The original study sample consisted of a total of 195,971 births across the 10 counties and 3-year period. 3,274 births (1.67% of total; 5.20% of 2005) were excluded based on geocode quality, as discussed above. An additional 820 births (0.42%) were excluded due to unrealistic point locations: 781 because the geocoded point was located in a county other than the county of residence reported on the birth certificate and 39 because the point was located in a lake or other body of water. 815 out of these 820 births were from 2006 or 2007, indicating that these points were likely low-quality geocodes that would have been excluded if the geocode quality variable had been available for 2006-2007. 6,641 non-singleton births (3.4%) and 5,821 births to mothers under age 18 (3.0%) were also excluded. Finally, observations missing any of the main variables of interest were excluded, including 10,225 births (5.2%) missing maternal education, 619 (0.32%) missing maternal tobacco use, 10 (0.005%) missing the neighborhood deprivation index, 30 (0.015%) missing marital status, and 17 (0.009%) missing plurality. The final study sample analyzed contained 168,748 births (86.1% of original population).

The main outcome of interest analyzed was low birth weight-preterm birth (LPTB), representing infants that were born before 37 weeks gestation and weighing less than 2500 grams. This combined outcome was chosen in order to analyze a more homogenous and high-risk group than that of just preterm birth or low birth weight alone. Birth weight and gestational age were both provided by the DPH as continuous variables, so a binary LPTB variable was created based on the standard medical definitions (<2500g for low birth weight and <37 weeks gestation for preterm birth). Binary variables were also created for low birth weight (<2500g), very low birth weight (<1500g), and preterm birth (<37 weeks gestation). These additional outcomes were used for sensitivity analyses.

Residential Greenness

Residential greenness was calculated using the Normalized Difference Vegetation Index (NDVI). This index is derived from the different light reflectance patterns of vegetated areas versus non-vegetated areas. Chlorophyll in the leaves of plants absorbs a high percentage of red light, while the cell structure of the leaves reflects a high percentage of near infrared light. The more vegetation there is in an area, the more red light will be absorbed and the more near infrared light will be reflected. Non-vegetated areas will not absorb as much red light nor reflect as much near infrared light as vegetation does (Weier & Herring, 2000). The Landsat 5 satellite detects red light reflected from the earth's surface at 0.63-0.69 µm (Band 3) and near infrared light at 0.76-0.90 µm (Band 4) (Jensen, 2007). Using these two measurements, NDVI is calculated as follows:

$$NDVI = \frac{(Band\ 4 - Band\ 3)}{(Band\ 4 + Band\ 3)}$$

The resulting NDVI value can range from -1 to 1. A highly vegetated area will reflect a high amount of near infrared light and a low amount of visible light, producing an NDVI value close to 1. Sparsely vegetated areas, such as urban centers, will have an NDVI value close to 0 and areas of high reflectance of visible light, such as water, will have an NDVI value close to -1 (Weier & Herring, 2000).

The NDVI values used in this study were derived from a Landsat 5 Thematic Mapper satellite image downloaded from the United States Geological Survey. To cover the entire study area, two images (Path 19, Rows 36 and 37) were downloaded and mosaicked together. Both images were taken on 3 July 2006 at 30m resolution. This date was chosen based on the availability of cloud-free images at peak vegetation time (June-August). NDVI values were assumed to be consistent over time, as demonstrated by Dadavand et al. (2012) and Hystad et al. (2014). Image processing, including calculating the raw NDVI values, was done using ERDAS Imagine (Hexagon Geospatial, Norcross, Georgia). Average NDVI values were then calculated within circular buffers of 100, 250, 500, and 1,000 meters around each maternal residence by using the focal statistics tool in ArcMap 10.4.1 (ESRI, Redlands, California).

Large bodies of water were excluded from the underlying satellite image because water's high reflectance of visible light, and resulting low NDVI value, would negatively skew the average NDVI value of any woman living near a lake, even if she lived in an otherwise heavily vegetated area. Water is not hypothesized to have a negative effect on birth outcomes, and therefore could contribute to exposure misclassification if not adjusted for. In order to exclude large areas of water, a polygon shapefile of all water bodies in Georgia was obtained from the Atlanta Regional Commission (Atlanta Regional Commission, 2016b). Bodies of water from this shapefile were excluded from the satellite image if they met three criteria. First, the polygon area exceeded 9,000 m^2 (10 pixels) and therefore represented an area large enough to potentially skew a woman's average greenness measure. Second, the average NDVI value within the polygon was less than 0.1, and therefore represented an area of high reflectance of visible light. Third, the average Tasseled Cap value for the wetness feature was greater than 15. A Tasseled Cap is a transformation technique that converts the raster data into three main bands which can be directly associated with physical scene characteristics (brightness, greenness, and wetness) (Crist & Cicone, 1984; Kauth & Thomas, 1976). This third qualification for exclusion helped ensure that the polygon represented an area not only of high visible light reflectance, but also significant moisture. 402 bodies of water met all three of the above criteria and were thus excluded from the underlying NDVI raster. These areas were then classified as "No Data" and ignored during calculations of the average NDVI around each maternal residence.

Individual and Neighborhood-level covariates

Individual covariates were provided by the Georgia Department of Public Health. Variables included: maternal race (White, Black, Asian, American Indian/ Alaska Native, Native Hawaiian/ Pacific Islander, Multiracial), maternal education (less than 9^{th} grade, 9^{th} through 11^{th} grade, high school diploma or GED, some college or higher), maternal age (18-19, 20-24, 25-29, 30-34, 35-39, over 40), maternal tobacco use during pregnancy (yes/no), marital status (married/ unmarried), and previous live birth (yes/no). Given the high proportion of Hispanics racially classified as White in Atlanta (93.01%) and the lack of disparities in birth outcomes among Hispanics and Whites, the racial categories in this analysis were pooled across ethnicities.

Three neighborhood-level covariates were also included based on the census tract of the maternal residence: neighborhood deprivation index, personal crime index, and rural-urban commuting area code. The neighborhood deprivation index (NDI) represents average income/poverty, education, employment, housing, and occupation of each census tract (Messer et al., 2006). For analysis, the standardized NDI was used, where negative values represent less deprivation than the Georgia average and positive values represent more deprivation than the Georgia average. The personal crime index is a standardized index modelled using FBI crime data collected annually from about 16,000 law enforcement jurisdictions across the country. This index represents murder, rape, robbery, and assault, however each of these crimes are weighted equally in the calculation (Applied Geographic Solutions, 2013). Rural-urban commuting area (RUCA) codes represent the urbanicity of the census tract based on the percentage of traffic flow to an urbanized area. There are a total of 10 RUCA code levels, but only two were present in the study area: metropolitan area core (primary flow within an urbanized area) and metropolitan area high commuting (primary flow 30% or more to an urbanized area) (U. S. Department of Agriculture, 2010). Based on available NDI and crime data, the 2010 census tract boundaries were used for all three neighborhood-level covariates.

Statistical Analyses

Logistic regression was used to evaluate the association between greenness and birth outcomes. The main analysis focused on LPTB and average NDVI within 250m of the maternal residence. The 250m scale provided a small enough radius to only capture greenness immediately around the residence, while still allowing for variation between pixels at 30m resolution. Models were originally fit using quintiles of NDVI, but upon observation of a quadratic relationship between greenness and LPTB, a switch was made to continuous NDVI and $NDVI^2$. In order to reduce collinearity between NDVI and $NDVI^2$, the continuous NDVI term was centered by subtracting the mean from each individual value. This centered NDVI term was then squared to produce a new $NDVI^2$ term (Appendix A).

Sensitivity analyses were also conducted to explore how the greenness-birth outcome association observed in the main analysis changed across various factors. First, analyses were conducted using additional scales of NDVI (100m, 500m, and 1,000m), additional birth outcomes (preterm birth, low birth weight birth, and very low birth weight birth), and additional scales of neighborhood deprivation (500m, 1,000m, 4,000m). Second, a sensitivity analysis was conducted to assess the effect of pooling racial categories across ethnicities. Third, the final model from the main analysis was compared to models adjusting for additional individual or neighborhood covariates. Covariates tested include distance to nearest major hospital (Atlanta Regional Commission, 2017), food access (U. S. Department of Agriculture, 2017), number of prenatal care visits (GA DPH), and Black population per census tract (U. S. Census Bureau, 2010c).

III. RESULTS

Descriptive analyses

Full demographic characteristics of the study population stratified by NDVI quintiles are presented in Table 2. The mean NDVI value within 250m of the maternal residence is 0.358. The lowest NDVI quintile has the highest proportion of LPTB babies, however, the association between LPTB and NDVI does not appear to be linear and is not significant. As greenness increases, the proportion of White women increases while the proportion of every other race declines. NDVI is significantly associated race, as well as all other individual and neighborhood-level covariates.

Figure 1 depicts the spatial distribution of raw NDVI values across the study area, while Figure 2 depicts the mean NDVI within a 250m radius, classified by the NDVI quintiles presented in Table 2. Both maps show generally high coverage of greenness across the Metro Atlanta region, with areas of low greenness surrounding Downtown Atlanta and the airport, as well as along major highway routes. Figure 3 illustrates the spatial distribution of the standardized neighborhood deprivation index. Generally, the southern area of Atlanta tends to be more highly deprived than the northern region.

Demographic characteristics stratified by birth outcome are presented in Table 3. Across the entire cohort, 8,141 babies were born preterm and at low birth weight (4.82%). The risk of LPTB among Black women is more than double that of White women (6.7% compared to 3.1%). Mean NDVI values are slightly lower among LPTB babies at 100m and 250m, but generally are almost exactly the same across birth outcomes. With the exception of RUCA code, LPTB is significantly associated with all covariates.

Main Analyses

Various logistic models of the association between NDVI and LPTB are summarized in Table 4. All odds ratios are presented per one interquartile range (1-IQR) increase in residential greenness (0.105 for NDVI and 0.075 for $NDVI^2$ at 250m). The unadjusted odds ratio for a 1-IQR increase in NDVI is 0.99 (0.96, 1.02), indicating a non-significant relationship between LPTB and residential greenness. The addition of individual and neighborhood-level covariates to the model produces slightly increased odds ratios for NDVI compared to the unadjusted model, but there is very little change in the association across different combinations of covariates.

All covariates in Model 3 were significant, and therefore this model was chosen as the main model for further analyses. This choice was also confirmed by a similar model selection process conducted using NDVI as a categorical variable (Appendix B). The adjusted odds ratios from Model 3 were 1.03 (1.00, 1.07) for NDVI and 1.17 (0.97, 1.41) for $NDVI^2$, indicating a small, but statistically significant, increase in odds of LPTB among women living in greener areas.

There was no significant interaction by race observed when all six racial groups were included (p-value=0.0667). However, there was significant interaction observed between White and Black women alone, who together make up 92.58% of the study population (p-value=0.0082). Table 5 presents the unadjusted and adjusted odds ratios for NDVI and $NDVI^2$ for the full cohort, White and Black women, White women only, and Black women only. In the adjusted model for White women only, NDVI and $NDVI^2$ are both not significantly associated with LPTB [NDVI OR: 1.00 (0.94, 1.05); $NDVI^2$ OR: 1.12 (0.81, 1.55)]. However, among Black women, both NDVI and $NDVI^2$ are significantly associated with LPTB [NDVI OR: 1.07 (1.03, 1.12); $NDVI^2$ OR: 1.31 (1.03, 1.66)]. As was observed in the full models, higher greenness is associated with slightly higher odds of LPTB among Black women.

Figure 4 provides a visual comparison of the different associations between greenness and LPTB among White and Black women in Atlanta. The risk of LPTB among White women remains relatively consistent across all greenness values. However, in Black women, the association between NDVI and LPTB forms a quadratic relationship, with slightly increased risk at the lowest levels of greenness, decreased risk in areas of low-to-moderate greenness, and then considerably increased risk in the areas of highest greenness. Overall, Black women consistently have a higher risk for giving birth to a LPTB infant than White women do, but this disparity is particularly wide in the areas of very high greenness.

Sensitivity analyses

Sensitivity analyses were conducted using preterm birth, low birth weight, and very low birth weight (Appendix C). Results with each additional birth outcome were generally consistent with the findings of LPTB. NDVI was significantly associated with all birth outcomes among Black women, and no birth outcomes among White women. However, the $NDVI^2$ term was only significant among Black women in the model with LPTB, not with any of the additional birth outcomes.

A second set of sensitivity analyses were conducted using additional scales of NDVI measurements, keeping the outcome of LPTB consistent (Appendix D). Similar to the sensitivity analyses of birth outcomes, the results using additional scales of NDVI did not meaningfully differ from those of the main analysis. Among White women, NDVI was not significant at any scale, while among Black women, NDVI was significant at every scale. Of the three additional analyses, $NDVI^2$ was only significant at 500m for White women and 1,000m for Black women. Although the significance of the association did not change across scales, Appendices E and F show a stronger quadratic relationship when using NDVI at a larger scale compared to a smaller scale for both White and Black women. This leads to a slightly higher risk of LPTB in the areas of extremely low or extremely high greenness when using NDVI at a larger scale.

The third sensitivity analysis examined various scales of the neighborhood deprivation index (NDI), paired with similar scales of NDVI (Appendix G). The main analysis used NDI at the tract level and NDVI at 250m, creating mismatched spatial scales of deprivation and greenness. However, the additional NDI and NDVI pairings using the same spatial scale did not produce meaningfully different results from the main analysis, indicating that there is not confounding by spatial scale. NDVI was significant across all scales for Black women and no scales for White women.

A fourth sensitivity analysis examined results using pooled and un-pooled ethnicities. This analysis confirmed that the Hispanic, non-Hispanic White, and pooled White groups all produced similar results (Appendices H and I).

Finally, a sensitivity analysis was conducted using additional individual and neighborhood covariates (Appendix J). Neither the addition of distance to nearest hospital nor Black population per census tract produced meaningfully different results. Two measures of food access were also tested, but both produced similar results to the main analysis. Adjusting for prenatal care also failed to produce meaningfully different results, although this variable had a considerable number of missing observations so the full population was not included in the regression analysis.

IV. DISCUSSION

For the full cohort, greenness was significantly associated with low birth weight-preterm birth, but not in the hypothesized direction. Surprisingly, as residential greenness increased, the odds of LPTB also increased. However, this association differed between White and Black women. Among White women, there was no significant association between NDVI and LPTB. Among Black women, there was a significant quadratic relationship between NDVI and LPTB, with the highest risk at the highest levels of greenness and moderately increased risk at the lowest levels of greenness.

Although most previous studies did find some protective association between greenness and birth outcomes, the finding of a null association between greenness and LPTB among White women in Atlanta is not uncommon. The previous studies tested multiple outcomes with multiple scales of NDVI and often only found significant associations among a few exposure-outcome pairings. However, the finding of increased risk of LPTB among Black women in areas of increased greenness is unexpected given the previous literature. This indicates that the effect of greenness on birth outcomes might not necessarily be consistent across all locations, and could be influenced by shifting demographic and geographic factors.

One possible explanation for the null association observed among White women in this study is the fact that Atlanta is generally more green than other study areas. Among the eight other studies that estimated greenness exposure using NDVI at a 30m spatial resolution, all but one had lower average NDVI values than those observed in the Metro Atlanta region. Only Grazuleviciene et al. (2015), which was located in Lithuania, reported higher mean NDVI values than Metro Atlanta (0.55 compared to 0.36 at a 500m radius). However, this study only found a significant association between term low birth weight and NDVI at 500m, despite having tested six outcomes (low birth weight, term low birth weight, preterm birth, small for gestational age, birth weight as a continuous variable, and gestational age as a continuous variable) at three different scales of NDVI. My null findings among White women in Atlanta are therefore generally consistent with the findings of Grazuleviciene et al. for similar birth outcomes.

The high average greenness in Atlanta may be causing a null association among White women for two reasons. First, there may be a threshold effect, where additional greenness past a certain level may no longer be protective against adverse birth outcomes. Even if some women in Atlanta have substantially more vegetation around their homes than others, all women may be above the "threshold" of greenness necessary to confer at least some of the hypothesized benefits. Second, the high levels of greenness spread throughout Atlanta may cause a lack of variation in exposure to greenness when women's movement throughout the city is accounted for. Humans are inherently mobile and are not limited to the residential location through which greenness exposure was assigned, a concept termed by Stephen Matthews as "spatial polygamy" (2011). The vast majority of women will likely be exposed to high levels of greenness as they travel throughout Atlanta, even if there is not necessarily high greenness surrounding their home. This could make greenness a "non-discriminatory predictor of health" since most women will have at least some exposure to greenness (Witten et al., 2008).

Among Black women, however, the greenness-birth outcome association is more complex, with perhaps more heterogeneous risk factors for low birth weight-preterm births. To the best of my knowledge, this is the first study to observe significant interaction by race among White and Black women, and the first to observe a significant quadratic relationship between greenness and birth outcomes among Black women. Based on the strong theoretical benefits of greenness and the results of the previous studies, the increased risk of LPTB associated with increased greenness is likely due to uncontrolled confounding, not a harmful effect of the greenness itself.

One potential explanation may be isolation and lack of access to healthcare or other services among Black women living in very green areas, removed from urban centers. It is traditionally hypothesized that more green areas outside of the city are generally wealthier suburbs. However, in a decentralized, sprawling city such as Atlanta with high levels of greenness and inadequate public transportation, this may not be the case. There is potentially a substantial population of Black women living in lower SES neighborhoods located outside of a main city center, without readily available transportation. Although these women may be exposed to high levels of greenness, the lack of access to healthcare and other basic services would likely outweigh any theoretical benefits of greenness. The sensitivity analysis of additional covariates (Appendix J) explored this hypothesis further. However, when distance to nearest major hospital, food access, or number of prenatal care visits were added to the analysis, the results were largely unchanged. It is important to note that these are very rough approximations of access to health-related services and do not take into account any measure of accessible transportation.

Given the fact that LPTB risk among Black women increases with increasing greenness while risk among White women remains consistently null, racial disparities in birth outcomes are actually highest in the greenest areas. Since the greenest areas also generally have the largest White population, this indicates that the Black women living in the areas of highest greenness are more likely to be living in White-dominated neighborhoods than Black women living in areas of low greenness. Over time, Black women in areas of higher greenness may consequently experience increased discrimination, and resulting chronic stress, which can negatively affect birth outcomes (Geronimus, 1992; Hux et al., 2014). The addition of a covariate representing the Black population percentage in each census tract did not meaningfully change the results (Appendix J), however this measurement may not fully account for experiences of discrimination.

There are also a number of limitations of my study which may have contributed to the differences in results from previous studies. First, I assigned greenness exposure values based on maternal residence, which does not account for the movement of a woman throughout her daily life or the possibility that she spends significantly more time in a different location, such as her place of work. Additionally, many women move while pregnant so the maternal residence recorded on the birth certificate may not be the location she spent all, or even most, of her pregnancy. Previous studies have shown that women of lower socioeconomic status are generally more likely to move during pregnancy, although the distance moved is often short. However, for such a small-scale exposure as greenness, this mobility may have contributed to some differential exposure misclassification (Bell & Belanger, 2012; Fell et al., 2004).

There were also a number of variables that were not controlled for in the models that could have influenced the results. First, information on each woman's insurance coverage (Medicaid/ non-Medicaid) was missing for 2005-2006. Had this been available, it would have helped to better control for socio-economic status. Air pollution was also not controlled for in this analysis, as it was in many of the previous studies. However, air pollution levels theoretically would decline in areas of more greenness and therefore would not explain the increased risk observed in highly green areas among Black women. Finally, blue space was removed from the underlying satellite image, but blue space might confer additional health benefits not captured by green space alone and thus not accounted for in this study (Völker & Kistemann, 2011).

V. CONCLUSION

The relationship between greenness and birth outcomes is complex and likely varies across changing geographic and demographic factors. In the Metro Atlanta region, I observed a null association between greenness and low birth weight-preterm birth among White women, but a significant quadratic relationship among Black women. The underlying causes behind the elevated risk for Black women in highly green areas requires further investigation. These results do not match the protective effect of greenness on birth outcomes observed in multiple previous studies conducted in other locations. Further research into the effect of greenness on birth outcomes in areas of high baseline greenness is needed in order to fully understand this relationship. This will allow for more tailored urban planning efforts to best promote public health in the context of each city's unique environmental and social characteristics.

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Table 1: Summary of previous literature on the association between greenness and birth outcomes

Authors	Title	Year	Setting	Exposure Variable	Birth Outcomes	Main Result
1. Agay-Shay et al.	Green spaces and adverse pregnancy outcomes.	2014	Tel Aviv, Israel	NDVI and proximity to major green space	BW, GA (weeks), LBW, VLBW, PTB, VPTB	Significantly increased birth weight and decreased risk of LBW associated with NDVI within 250m.
2. Casey et al.	Greenness and Birth Outcomes in a Range of Pennsylvania Communities	2016	Pennsylvania	NDVI[a]	TBW, SGA, PTB, low 5 min Apgar score	Significantly lower odds of SGA and PTB associated with NDVI within 250 and 1250m.
3. Cusak et al.	Associations between residential greenness and birth outcomes across Texas	2017	Texas	NDVI[a]	TBW, PTB, SGA	Significantly increased birth weight associated with NDVI, but results were substantially attenuated after adjustments
4. Dadavand et al.	Green space, health inequality and pregnancy	2012	Barcelona, Spain	NDVI and proximity to major green space	BW, GA (days)	Significantly increased birth weight associated with NDVI and proximity to park, but only among lowest education group
5. Dadavand et al.	Surrounding greenness and pregnancy outcomes in four Spanish birth cohorts	2012	Two distinct regions of Spain	NDVI	BW, GA (days), head circumference	Significantly increased birth weight and increased head circumference associated with NDVI
6. Dadavand et al.	Inequality, green spaces, and pregnant women: Roles of ethnicity and individual and neighbourhood socioeconomic status	2014	Bradford, UK	NDVI and proximity to major green space	BW	Significantly increased birth weight associated with NDVI at 100, 250, and 500m. Effect modification observed for race, education, and neighborhood SES.
7. Donovan et al.	Urban trees and the risk of poor birth outcomes	2011	Portland, Oregon	Tree canopy layer of classified aerial imagery	PTB, SGA	Significantly decreased risk of SGA with increased tree canopy cover within 50m.
8. Ebisu et al.	Association between greenness, urbanicity, and birth weight	2016	Connecticut	National Land Cover Database	BW, LBW, SGA	Significantly increased birth weight and decreased risk of LBW associated with increased green space. Decreased risk of LBW and SGA also associated with increased urban open space.
9. Grazuleviciene et al.	Surrounding greenness, proximity to city parks and pregnancy outcomes in Kaunas cohort study.	2015	Kaunas, Lithuania	NDVI and proximity to major green space	GA (weeks), PTB, BW, LBW, TLBW, and SGA	Significantly decreased risk of TLBW associated with NDVI at 500m. Significantly decreased risk of PTB associated with decreased distance to major green space.

10. Hystad et al.	Residential greenness and birth outcomes: evaluating the influence of spatially correlated built-environment factors.	2014	Vancouver, Canada	NDVI[b]	VPTB, MPTB, TBW, SGA	Significantly increased TBW and decreased risk of MPTB associated with increased NDVI.
11. Kihal-Talantikite et al.	Green space, social inequalities and neonatal mortality in France	2013	Lyon, France	Green space index	Infant mortality	Most likely cluster of infant mortality was no longer significant after adjustment for greenness and deprevation indices, indicating these factors explain the excess infant mortality
12. Laurent et al.	Green spaces and pregnancy outcomes in Southern California.	2013	Southern California	NDVI	TBW, PTB, preeclampsia	NDVI was positively associated with TBW at 50 and 100m, and PTB at 150m.
13. Markevych et al.	Surrounding greenness and birth weight: results from the GINIplus and LISAplus birth cohorts in Munich	2014	Munich, Germany	NDVI	BW	Significantly increased birth weight associated with NDVI at 500m.

[a] *Used MODIS satellite (250m resolution) instead of Landsat satellite (30m resolution)*

[b] *Average NDVI taken around residential postal code centroid, not residence*

Birth outcome abbreviations: BW = birth weight (grams); TBW = term birth weight (grams); LBW = low birth weight (<2500 grams); TLBW = term low birth weight (<2500 grams); VLBW = very low birth weight (<1500 grams); PTB = preterm birth (<37 weeks), VPTB = very preterm birth (<32 weeks); GA = gestational age; SGA = small for gestational age (weight below 10th percentile for gestational age)

Table 2: Characteristics of the study population included for analysis, according to NDVI quintiles at 250m [n (%)]

Variable	Entire cohort	NDVI Q1 (0.004 - 0.29)	NDVI Q2 (0.29-0.34)	NDVI Q3 (0.34-0.38)	NDVI Q4 (0.38-0.42)	NDVI Q5 (0.42-0.61)	Test of association
Study population (n)	168,748	33,749	33,751	33,749	33,749	33,750	
NDVI at various radii							
100m [median (IQR)]	0.34 (0.12)	0.23 (0.08)	0.30 (0.06)	0.34 (0.06)	0.39 (0.05)	0.44 (0.05)	
250m [median (IQR)]	0.36 (0.11)	0.25 (0.06)	0.32 (0.02)	0.36 (0.02)	0.40 (0.02)	0.44 (0.03)	
500m [median (IQR)]	0.37 (0.09)	0.28 (0.07)	0.33 (0.05)	0.37 (0.04)	0.40 (0.04)	0.43 (0.04)	
1,000m [median (IQR)]	0.37 (0.08)	0.31 (0.08)	0.35 (0.06)	0.37 (0.05)	0.39 (0.05)	0.42 (0.05)	
Birth outcome							
Low birth weight-preterm birth							
Yes	8,141 (4.82)	1,702 (5.04)	1587 (4.70)	1,631 (4.83)	1,581 (4.68)	1,640 (4.86)	0.1884
No	160,607 (95.18)	32,047 (94.96)	32164 (95.30)	32,118 (95.17)	32,168 (95.32)	32,110 (95.14)	
Individual covariates							
Race							
White	93,345 (55.32)	17,023 (50.44)	17,601 (52.15)	18,201 (53.93)	19,547 (57.92)	20,973 (62.14)	<0.0001
Black	62,879 (37.26)	13,548 (40.14)	13,104 (38.83)	12,879 (38.16)	12,010 (35.59)	11,338 (33.59)	
Asian	9979 (5.91)	2586 (7.66)	2535 (7.51)	2136 (6.33)	1725 (5.11)	997 (2.95)	
American Indian/ Alaska Native	368 (0.22)	97 (0.29)	77 (0.23)	71 (0.21)	69 (0.20)	54 (0.16)	
Native Hawaiian/ Pacific Islander	87 (0.05)	27 (0.08)	22 (0.07)	13 (0.04)	17 (0.05)	8 (0.02)	
Multiracial	2,090 (1.24)	468 (1.39)	412 (1.22)	449 (1.33)	381 (1.13)	380 (1.13)	
Maternal education							
Less than 9th grade	13,174 (7.81)	3,935 (11.66)	3,153 (9.34)	2,448 (7.25)	2,159 (6.40)	1,479 (4.38)	<0.0001
9th through 11th grade	19,923 (11.81)	4,595 (13.62)	4,072 (12.06)	4,032 (11.95)	3,642 (10.79)	3,582 (10.61)	
High school diploma or GED	48,611 (28.81)	10,252 (30.38)	9,969 (29.54)	9,671 (28.66)	9,519 (28.21)	9,200 (27.26)	
Some college or higher	87,040 (51.58)	14,967 (44.35)	16,557 (49.06)	17,598 (52.14)	18,429 (54.61)	19,489 (57.75)	
Maternal age							
18-19	10,670 (6.32)	2,197 (6.51)	2,016 (5.97)	2,096 (6.21)	2,137 (6.33)	2,224 (6.59)	<0.0001
20-24	39,345 (23.32)	9,014 (26.71)	8,124 (24.07)	7,653 (22.68)	7,386 (21.89)	7,168 (21.24)	
25-29	46,937 (27.81)	10,519 (31.17)	9,860 (29.21)	9,436 (27.96)	8,776 (26.00)	8,346 (24.73)	
30-34	43,865 (25.99)	7,895 (23.39)	8,742 (25.90)	8,886 (26.33)	9,194 (27.24)	9,148 (27.11)	
35-39	23,044 (13.66)	3,508 (10.39)	4,158 (12.32)	4,664 (13.82)	5,139 (15.23)	5,575 (16.52)	
Over 40	4,887 (2.90)	616 (1.83)	851 (2.52)	1,014 (3.00)	1,117 (3.31)	1,289 (3.82)	
Maternal smoking							
Yes	5,451 (3.23)	808 (2.39)	908 (2.69)	953 (2.82)	1,234 (3.66)	1,548 (4.59)	<0.0001
No	163,297 (96.77)	32,941 (97.61)	32,843 (97.31)	32,796 (97.18)	32,515 (96.34)	32,202 (95.41)	
Marital status							
Married	102,666 (60.84)	18,578 (55.05)	20,049 (59.40)	20,826 (61.71)	21,402 (63.42)	21,811 (64.63)	<0.0001
Unmarried	66,082 (39.16)	15,171 (44.95)	13,702 (40.60)	12,923 (38.29)	12,347 (36.58)	11,939 (35.37)	
Previous live birth							
Yes	102,981 (61.03)	20,056 (59.43)	20,726 (61.41)	20,823 (61.70)	20,835 (61.74)	20,541 (60.86)	<0.0001
No	65,767 (38.97)	13,693 (40.57)	13,025 (38.59)	12,926 (38.30)	12,914 (38.26)	13,209 (39.14)	
Neighborhood covariates							
Neighborhood deprivation index [mean ± SD]	-0.31 ±0.90	-0.07 ±0.94	-0.24 ±0.86	-0.33 ±0.86	-0.41 ±0.87	-0.48 ±0.89	<0.0001
Personal crime index [mean ± SD]	113.48 ±160.05	123.22 ±178.03	91.77 ±132.25	102.42 ±142.26	109.57 ±145.93	140.44 ±189.53	<0.0001
RUCA code							
Metro area core	167,546 (99.29)	33,741 (99.98)	33,724 (99.92)	33,688 (99.82)	33,507 (99.28)	32,886 (97.44)	<0.0001
Metro area high commuting	1,202 (0.71)	8 (0.02)	27 (0.08)	61 (0.18)	242 (0.72)	864 (2.56)	

Figure 1: Distribution of raw NDVI in the 10-county Metro Atlanta region

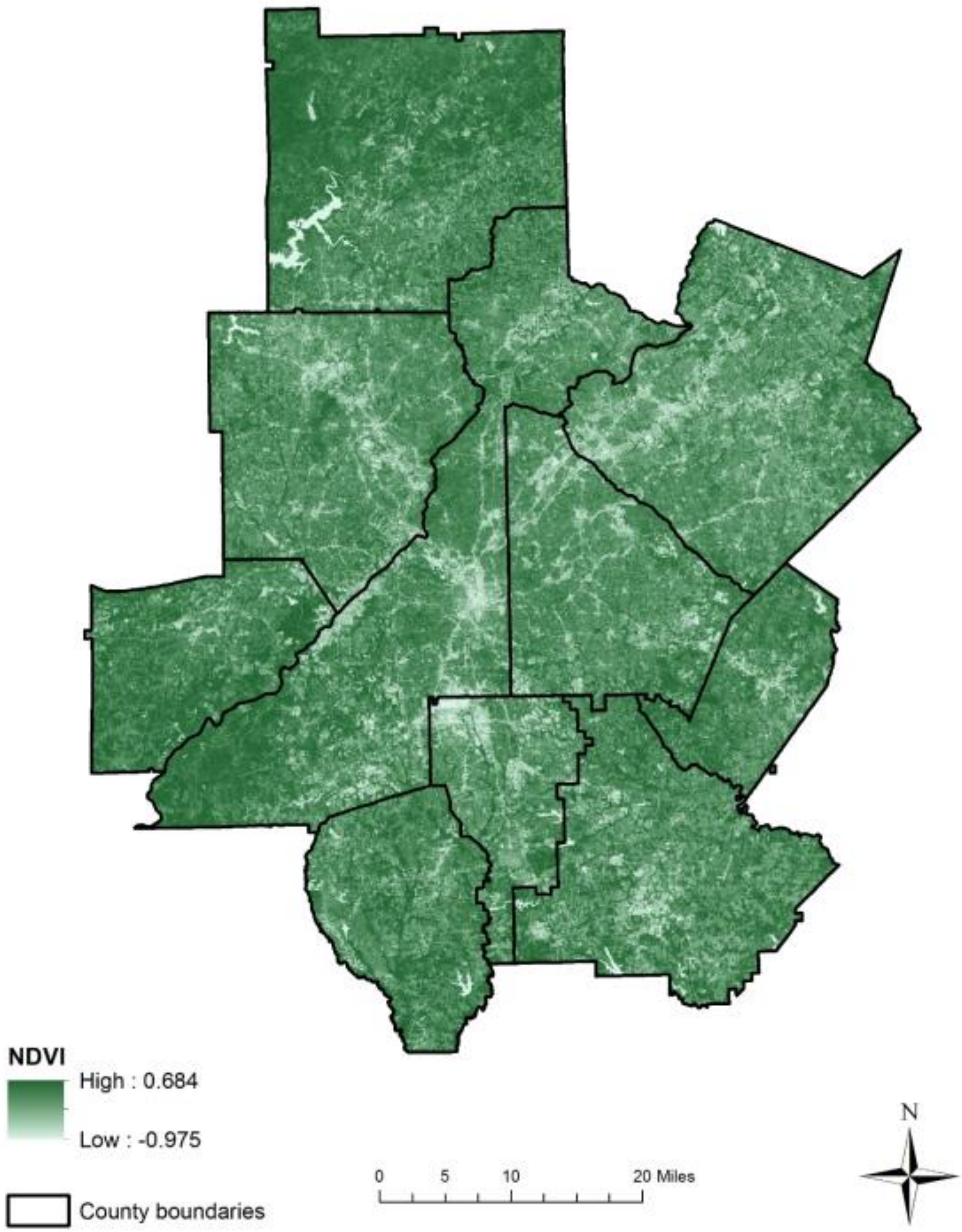


Figure 2: Distribution of mean NDVI within 250 meters, classified by quintiles of residential greenness in the study population

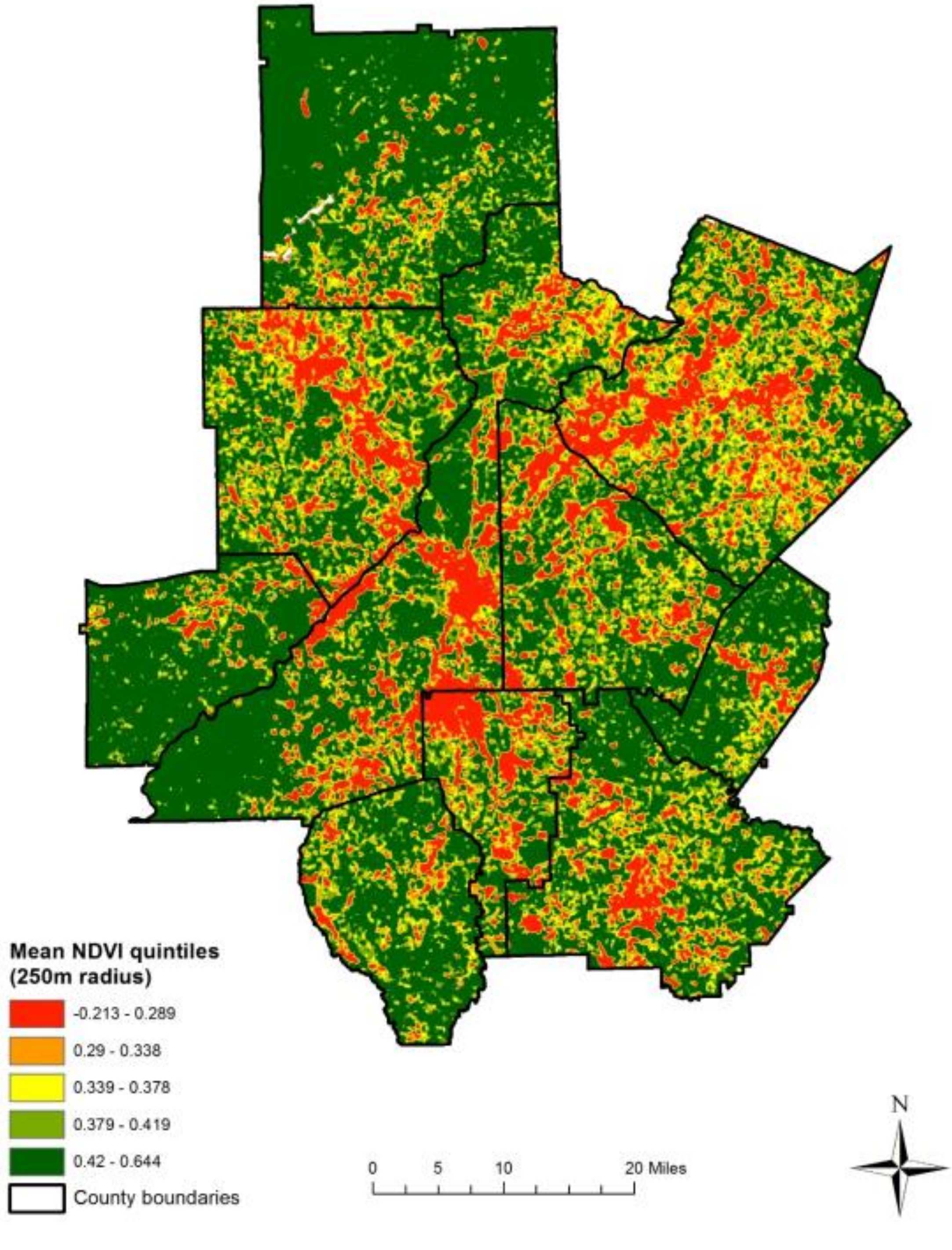


Figure 3: Distribution of neighborhood deprivation index (standard deviation from Georgia mean)

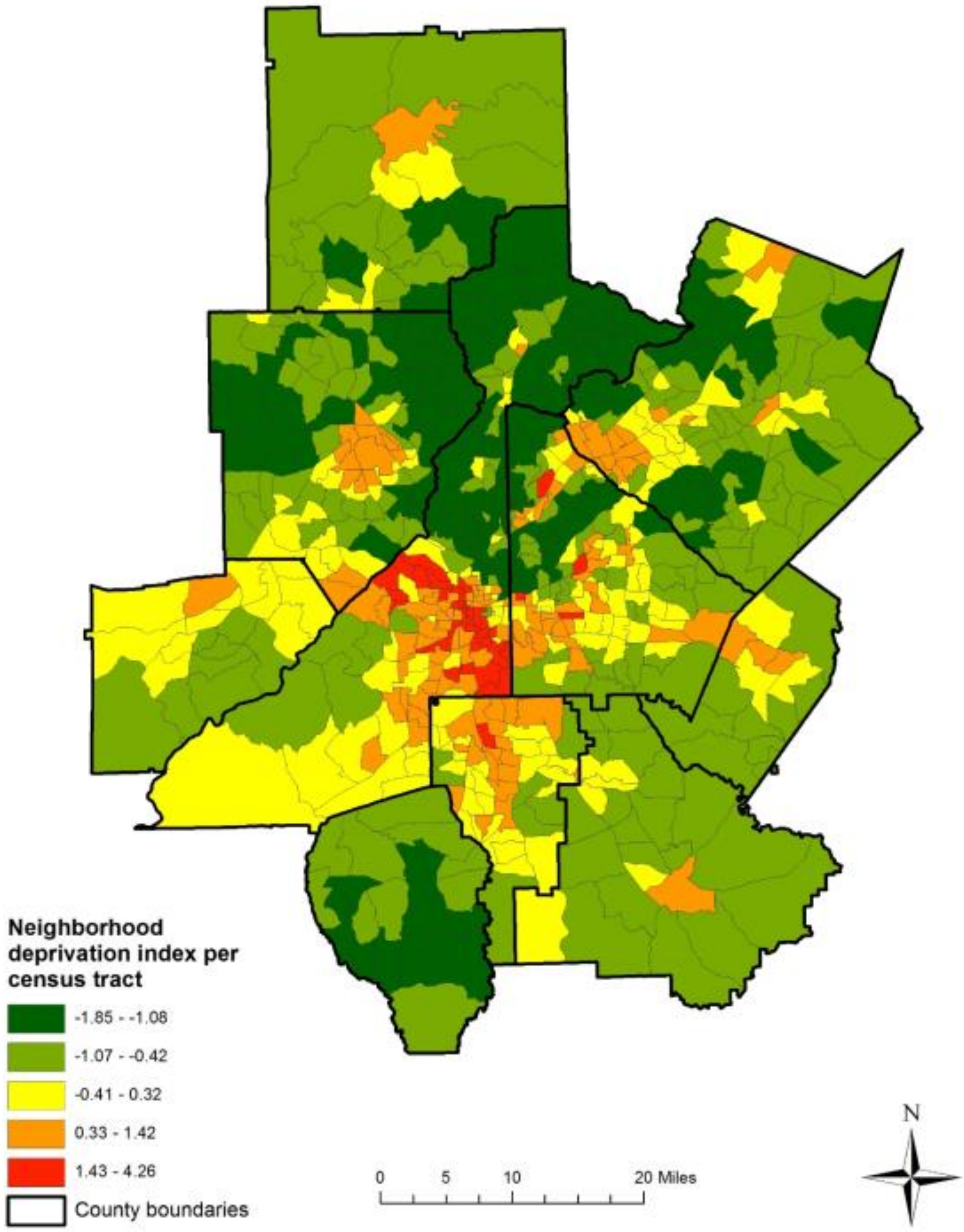


Table 3: Characteristics of the study population included for analysis, by low birth weight-preterm birth status [n (%) or mean ± SD]

Variable		Entire cohort	LPTB	Not LPTB	Test of association
Study population (n)		168,748	8,141 (4.82)	160,607 (95.18)	
NDVI at various radii					
100m		0.34 ±0.09	0.34 ±0.09	0.34 ±0.09	0.2543
250m		0.35 ±0.08	0.35 ±0.08	0.35 ±0.08	0.1828
500m		0.36 ±0.07	0.36 ±0.07	0.36 ±0.07	0.8929
1,000m		0.36 ±0.06	0.36 ±0.06	0.36 ±0.06	0.7838
Individual covariates					
Race					
	White	93,345 (55.31)	2,849 (35.00)	90,496 (56.35)	<0.0001
	Black	62,879 (37.26)	4,802 (58.99)	58,077 (36.16)	
	Asian	9,979 (5.91)	368 (4.52)	9,611 (5.98)	
	American Indian/ Alaska Native	368 (0.22)	19 (0.23)	349 (0.22)	
	Native Hawaiian/ Pacific Islander	87 (0.05)	3 (0.04)	84 (0.05)	
	Multiracial	2,090 (1.24)	100 (1.23)	1,990 (1.24)	
Maternal education					
	Less than 9th grade	13,174 (7.81)	461 (5.66)	12,713 (7.92)	<0.0001
	9th through 11th grade	19,923 (11.81)	1,108 (13.61)	18,815 (11.71)	
	High school diploma or GED	48,611 (28.81)	2,691 (33.05)	45,920 (28.59)	
	Some college or higher	87,040 (51.58)	3,881 (47.67)	83,159 (51.78)	
Maternal age					
	18-19	10,670 (6.32)	648 (7.96)	10,022 (6.24)	<0.0001
	20-24	39,345 (23.32)	2,046 (25.13)	37,299 (23.22)	
	25-29	46,937 (27.81)	2,081 (25.56)	44,856 (27.93)	
	30-34	43,865 (25.99)	1,914 (23.51)	41,951 (26.12)	
	35-39	23,044 (13.66)	1,138 (13.98)	21,906 (13.64)	
	Over 40	4,887 (2.90)	314 (3.86)	4,573 (2.85)	
Maternal smoking					
	Yes	5,451 (3.23)	478 (5.87)	4,973 (3.10)	<0.0001
	No	163,297 (96.77)	7,663 (94.13)	155,634 (96.90)	
Marital status					
	Married	102,666 (60.84)	3,910 (48.03)	98,756 (61.49)	<0.0001
	Unmarried	66,082 (39.16)	4,231 (51.97)	61,851 (38.51)	
Previous live birth					
	Yes	102,981 (61.03)	4,535 (55.71)	98,446 (61.30)	<0.0001
	No	65,767 (38.97)	3,606 (44.29)	62,161 (38.70)	
Neighborhood covariates					
Neighborhood deprivation index		-0.31 ±0.90	-0.09 ±0.95	-0.32 ±0.89	<0.0001
Personal crime index		113.48 ±160.05	132.95 ±176.15	112.49 ±159.12	<0.0001
RUCA code					
	Metro area core	167,546 (99.29)	8,089 (99.36)	159,457 (99.28)	0.4185
	Metro area high commuting	1,202 (0.71)	52 (0.64)	1,150 (0.72)	

Table 4: Model selection using continuous NDVI (centered)

Variable	Model 0: Unadjusted effects			Model 1: Race and education			Model 2: All individual covariates			Model 3: All individual covariates plus NDI			Model 4: All individual covariates plus NDI and			Model 5: All covariates		
	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI
NDVI at 250m[a]																		
NDVI	0.99	0.96	1.02	1.04	1.00	1.07	1.03	0.99	1.06	1.03	1.00	1.07	1.03	0.99	1.07	1.03	0.99	1.06
$NDVI^2$	1.20	0.99	1.45	1.26	1.05	1.52	1.20	0.99	1.45	1.17	0.97	1.41	1.15	0.95	1.40	1.14	0.94	1.38
Race																		
White	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Black	2.63	2.51	2.75	2.64	2.51	2.77	2.58	2.45	2.72	2.45	2.32	2.59	2.45	2.32	2.59	2.46	2.32	2.59
Asian	1.22	1.09	1.36	1.26	1.13	1.41	1.30	1.17	1.46	1.29	1.16	1.45	1.29	1.16	1.45	1.30	1.16	1.45
American Indian/ Alaska Native	1.73	1.09	2.75	1.72	1.08	2.74	1.75	1.10	2.78	1.72	1.08	2.74	1.73	1.08	2.75	1.73	1.09	2.75
Native Hawaiian/ Pacific Islander	1.13	0.36	3.59	1.14	0.36	3.60	1.18	0.37	3.74	1.14	0.36	3.60	1.14	0.36	3.60	1.14	0.36	3.60
Multiracial	1.60	1.30	1.96	1.63	1.33	2.00	1.61	1.31	1.97	1.58	1.29	1.94	1.58	1.29	1.94	1.58	1.29	1.95
Maternal education																		
Less than 9th grade	0.78	0.70	0.86	1.12	1.01	1.24	1.21	1.09	1.34	1.13	1.01	1.25	1.13	1.01	1.26	1.13	1.02	1.26
9th through 11th grade	1.26	1.18	1.35	1.28	1.19	1.37	1.28	1.18	1.38	1.20	1.11	1.30	1.20	1.11	1.30	1.20	1.11	1.30
High school diploma or GED	1.26	1.19	1.32	1.12	1.06	1.18	1.13	1.07	1.19	1.09	1.03	1.16	1.10	1.04	1.16	1.10	1.04	1.16
Some college or higher	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Maternal age																		
18-19	1.39	1.27	1.53				0.89	0.80	0.98	0.89	0.81	0.98	0.89	0.81	0.98	0.89	0.81	0.98
20-24	1.18	1.11	1.26				0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00
25-29	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
30-34	0.98	0.92	1.05				1.16	1.09	1.24	1.18	1.10	1.25	1.18	1.10	1.25	1.18	1.10	1.25
35-39	1.12	1.04	1.21				1.38	1.28	1.49	1.40	1.30	1.51	1.40	1.30	1.51	1.40	1.30	1.51
Over 40	1.48	1.31	1.67				1.70	1.50	1.93	1.73	1.53	1.96	1.73	1.52	1.96	1.73	1.52	1.96
Maternal smoking																		
Yes	1.95	1.77	2.15				1.99	1.80	2.20	1.98	1.79	2.19	1.98	1.79	2.19	1.98	1.79	2.19
No	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Marital status																		
Married	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Unmarried	1.73	1.65	1.81				1.29	1.23	1.37	1.26	1.19	1.33	1.26	1.19	1.33	1.26	1.19	1.33
Previous live birth																		
Yes	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
No	1.26	1.20	1.32				1.41	1.34	1.48	1.43	1.36	1.50	1.43	1.36	1.50	1.43	1.36	1.50
NDI																		
	1.29	1.26	1.32							1.10	1.07	1.13	1.09	1.06	1.13	1.09	1.06	1.13
Personal crime index																		
	1.00	1.00	1.00										1.00	1.00	1.00	1.00	1.00	1.00
RUCA code																		
Metro area core	Ref	Ref	Ref													Ref	Ref	Ref
Metro area high commuting	0.89	0.68	1.18													1.23	0.92	1.63

[a] *ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for $NDVI^2$)*

Table 5: Odds ratios (95% confidence interval)[a] for the effect of greenness on LPTB, stratified by race

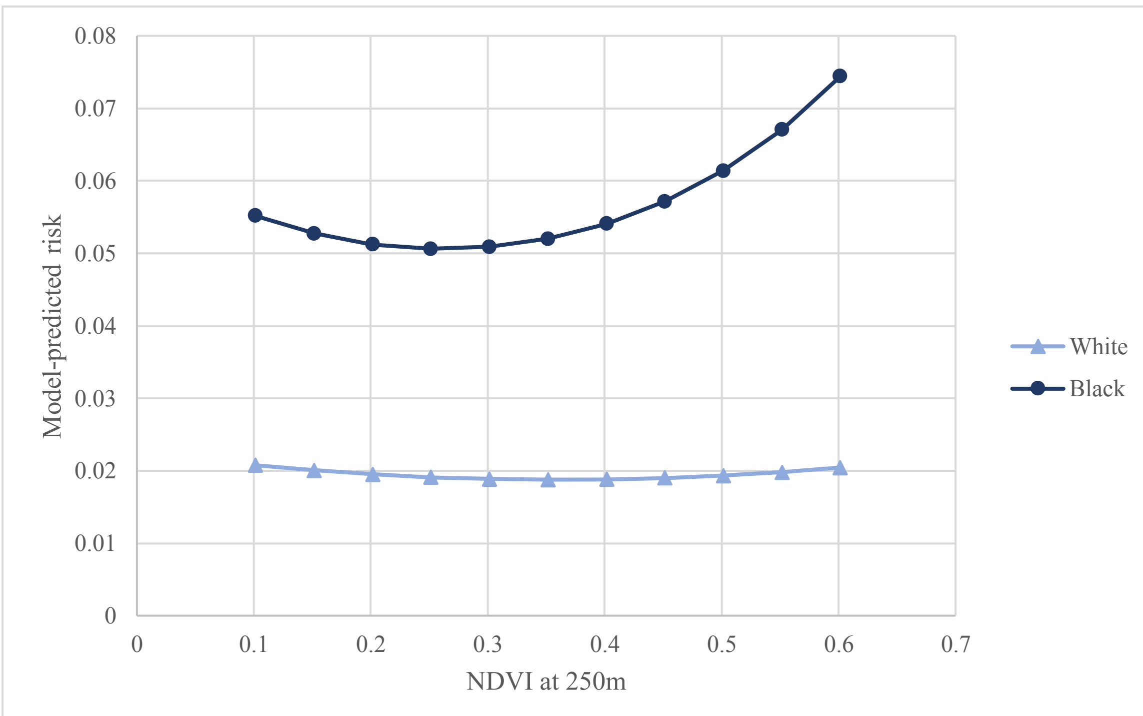
	Full population	White and Black	White	Black
Unadjusted				
NDVI	0.99 (0.96, 1.02)	0.98 (0.95, 1.01)	0.96 (0.91, 1.02)	**1.08 (1.03, 1.12)***
$NDVI^2$	1.20 (0.99, 1.45)	**1.22 (1.01, 1.48)***	1.22 (0.88, 1.68)	**1.39 (1.10, 1.77)***
Adjusted[b]				
NDVI	**1.03 (1.00, 1.07)***	**1.03 (1.00, 1.07)***	1.00 (0.94, 1.05)	**1.07 (1.03, 1.12)***
$NDVI^2$	1.17 (0.97, 1.41)	1.21 (0.99, 1.47)	1.12 (0.81, 1.55)	**1.31 (1.03, 1.66)***

** Significant at alpha=0.05*

[a] ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for $NDVI^2$)

[b] Adjusted models include: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index

Figure 4: Association of LPTB and NDVI among White and Black women in Atlanta



**Model adjusted for maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index*

Appendix A: Comparing raw NDVI data to centered NDVI data

Variable	Raw NDVI			Raw NDVI and $NDVI^2$			Centered NDVI			Centered NDVI and $NDVI^2$		
	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI
NDVI at 250m[a]												
NDVI	1.02	0.99	1.06	0.89	0.74	1.06						
$NDVI^2$				1.17	0.97	1.41						
NDVI at 250m centered[a]												
NDVI							1.02	0.99	1.06	1.03	1.00	1.07
$NDVI^2$										1.17	0.97	1.41
Race												
White	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Black	2.45	2.32	2.59	2.45	2.32	2.59	2.45	2.32	2.59	2.45	2.32	2.59
Asian	1.29	1.15	1.44	1.29	1.16	1.45	1.29	1.15	1.44	1.29	1.16	1.45
American Indian/ Alaska Native	1.72	1.08	2.74	1.72	1.08	2.74	1.72	1.08	2.74	1.72	1.08	2.74
Native Hawaiian/ Pacific Islander	1.13	0.36	3.59	1.14	0.36	3.60	1.13	0.36	3.59	1.14	0.36	3.60
Multiracial	1.58	1.29	1.94	1.58	1.29	1.94	1.58	1.29	1.94	1.58	1.29	1.94
Maternal education												
Less than 9th grade	1.12	1.01	1.25	1.13	1.01	1.25	1.12	1.01	1.25	1.13	1.01	1.25
9th through 11th grade	1.20	1.11	1.30	1.20	1.11	1.30	1.20	1.11	1.30	1.20	1.11	1.30
High school diploma or GED	1.09	1.03	1.16	1.09	1.03	1.16	1.09	1.03	1.16	1.09	1.03	1.16
Some college or higher	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Maternal age												
18-19	0.89	0.81	0.98	0.89	0.81	0.98	0.89	0.81	0.98	0.89	0.81	0.98
20-24	0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00
25-29	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
30-34	1.18	1.10	1.25	1.18	1.10	1.25	1.18	1.10	1.25	1.18	1.10	1.25
35-39	1.40	1.30	1.51	1.40	1.30	1.51	1.40	1.30	1.51	1.40	1.30	1.51
Over 40	1.73	1.53	1.96	1.73	1.53	1.96	1.73	1.53	1.96	1.73	1.53	1.96
Maternal smoking												
Yes	1.99	1.80	2.20	1.98	1.79	2.19	1.99	1.80	2.20	1.98	1.79	2.19
No	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Marital status												
Married	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Unmarried	1.26	1.19	1.33	1.26	1.19	1.33	1.26	1.19	1.33	1.26	1.19	1.33
Previous live birth												
Yes	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
No	1.43	1.36	1.50	1.43	1.36	1.50	1.43	1.36	1.50	1.43	1.36	1.50
NDI												
	1.10	1.07	1.13	1.10	1.07	1.13	1.10	1.07	1.13	1.10	1.07	1.13

[a] *ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for $NDVI^2$)*

Appendix B: Model selection using NDVI quintiles

Variable	Model 0: Unadjusted effects			Model 1: Race and education			Model 2: All individual covariates			Model 3: All individual covariates plus NDI			Model 4: All individual covariates plus NDI and personal crime index			Model 5: All covariates		
	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI	OR	Lower CI	Upper CI
NDVI at 250m																		
Q1	1.04	0.97	1.12	0.95	0.89	1.02	0.97	0.91	1.04	0.95	0.89	1.03	0.96	0.89	1.03	0.96	0.89	1.03
Q2	0.97	0.90	1.04	0.90	0.84	0.97	0.92	0.86	0.99	0.91	0.85	0.98	0.92	0.85	0.99	0.92	0.86	0.99
Q3	0.99	0.93	1.07	0.94	0.87	1.01	0.96	0.89	1.03	0.95	0.89	1.02	0.96	0.89	1.03	0.96	0.89	1.03
Q4	0.96	0.90	1.03	0.94	0.87	1.01	0.95	0.88	1.02	0.95	0.88	1.02	0.95	0.88	1.02	0.95	0.89	1.02
Q5	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Race																		
White	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Black	2.63	2.51	2.75	2.64	2.51	2.77	2.58	2.45	2.72	2.45	2.32	2.59	2.45	2.32	2.59	2.46	2.32	2.59
Asian	1.22	1.09	1.36	1.27	1.13	1.41	1.30	1.17	1.46	1.29	1.16	1.45	1.29	1.16	1.45	1.30	1.16	1.45
American Indian/ Alaska Native	1.73	1.09	2.75	1.72	1.08	2.73	1.74	1.10	2.77	1.72	1.08	2.74	1.72	1.08	2.74	1.73	1.09	2.75
Native Hawaiian/ Pacific Islander	1.13	0.36	3.59	1.14	0.36	3.59	1.18	0.37	3.73	1.14	0.36	3.60	1.14	0.36	3.60	1.14	0.36	3.60
Multiracial	1.60	1.30	1.96	1.63	1.33	2.00	1.61	1.31	1.97	1.58	1.29	1.94	1.58	1.29	1.94	1.58	1.29	1.94
Maternal education																		
Less than 9th grade	0.78	0.70	0.86	1.12	1.01	1.24	1.21	1.09	1.34	1.13	1.01	1.25	1.13	1.01	1.26	1.13	1.01	1.26
9th through 11th grade	1.26	1.18	1.35	1.28	1.19	1.37	1.28	1.18	1.38	1.20	1.11	1.30	1.20	1.11	1.30	1.20	1.11	1.30
High school diploma or GED	1.26	1.19	1.32	1.12	1.06	1.18	1.13	1.07	1.19	1.09	1.03	1.16	1.10	1.04	1.16	1.10	1.04	1.16
Some college or higher	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Maternal age																		
18-19	1.39	1.27	1.53				0.89	0.80	0.98	0.89	0.81	0.98	0.89	0.81	0.98	0.89	0.81	0.98
20-24	1.18	1.11	1.26				0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00	0.94	0.88	1.00
25-29	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
30-34	0.98	0.92	1.05				1.17	1.09	1.24	1.18	1.10	1.26	1.18	1.10	1.25	1.18	1.10	1.26
35-39	1.12	1.04	1.21				1.38	1.28	1.49	1.40	1.30	1.51	1.40	1.30	1.51	1.40	1.30	1.51
Over 40	1.48	1.31	1.67				1.70	1.50	1.93	1.73	1.53	1.96	1.73	1.53	1.96	1.73	1.53	1.96
Maternal smoking																		
Yes	1.95	1.77	2.15				2.00	1.80	2.21	1.98	1.79	2.19	1.98	1.79	2.19	1.98	1.79	2.19
No	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Marital status																		
Married	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Unmarried	1.73	1.65	1.81				1.29	1.23	1.37	1.26	1.19	1.33	1.26	1.19	1.33	1.26	1.19	1.33
Previous live birth																		
Yes	Ref	Ref	Ref				Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
No	1.26	1.20	1.32				1.41	1.34	1.48	1.43	1.36	1.50	1.43	1.36	1.50	1.43	1.36	1.50
NDI																		
	1.29	1.26	1.32							1.10	1.07	1.13	1.09	1.06	1.13	1.09	1.06	1.13
Personal crime index																		
	1.00	1.00	1.00										1.00	1.00	1.00	1.00	1.00	1.00
RUCA code																		
Metro area core	Ref	Ref	Ref													Ref	Ref	Ref
Metro area high commuting	0.89	0.68	1.18													1.24	0.93	1.64

Appendix C: Sensitivity analysis of additional birth outcomes [OR (95% confidence interval)][a]

	NDVI	$NDVI^2$
All women		
LPTB	**1.03 (1.00, 1.07)***	1.17 (0.97, 1.41)
PTB	1.02 (0.99, 1.04)	1.11 (0.97, 1.26)
LBW	**1.04 (1.01, 1.07)***	1.09 (0.93, 1.28)
VLBW	1.02 (0.96, 1.09)	1.09 (0.78, 1.54)
White women		
LPTB	1.00 (0.94, 1.05)	1.12 (0.81, 1.55)
PTB	0.99 (0.96, 1.03)	1.10 (0.90, 1.34)
LBW	1.02 (0.98, 1.07)	1.05 (0.80, 1.38)
VLBW	0.97 (0.86, 1.09)	0.81 (0.40, 1.62)
Black women		
LPTB	**1.07 (1.03, 1.12)***	**1.31 (1.03, 1.66)***
PTB	**1.04 (1.01, 1.07)***	1.16 (0.96, 1.39)
LBW	**1.06 (1.02, 1.10)***	1.21 (0.99, 1.49)
VLBW	**1.08 (1.00, 1.16)***	1.39 (0.93, 2.08)

**Significant at alpha=0.05*

[a] ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for $NDVI^2$)

Models adjusted for: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index

Appendix D: Sensitivity analysis of additional NDVI scales [OR (95% confidence interval)] [a]

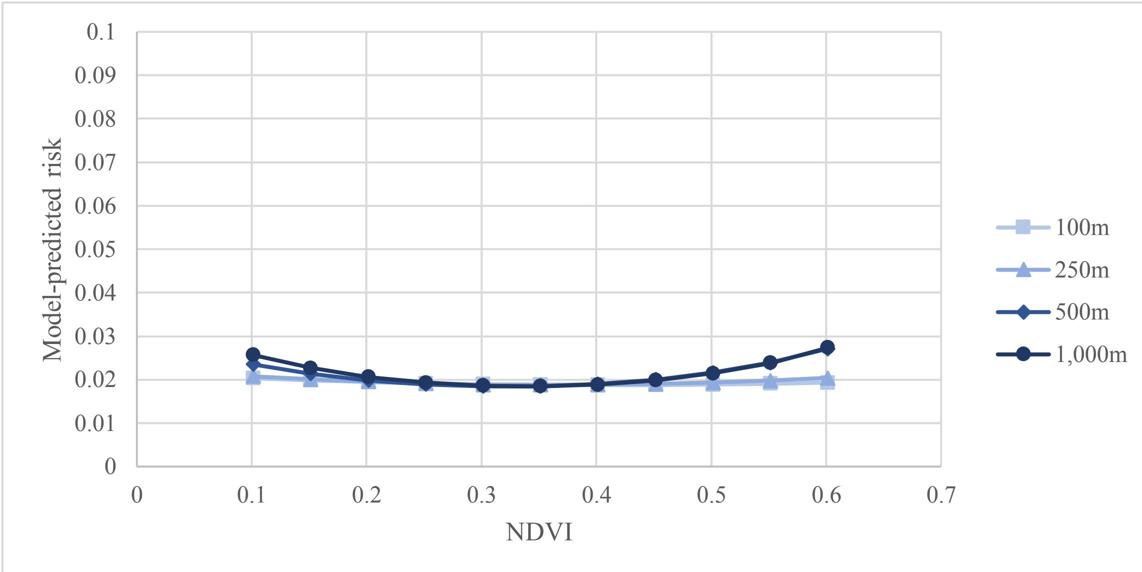
	NDVI	$NDVI^2$
All women		
100m	1.03 (0.99, 1.06)	1.09 (0.91, 1.30)
250m	**1.03 (1.00, 1.07)***	1.17 (0.97, 1.41)
500m	**1.05 (1.02, 1.08)***	**1.24 (1.02, 1.50)***
1,000m	**1.05 (1.02, 1.08)***	**1.36 (1.12, 1.65)***
White women		
100m	0.99 (0.93, 1.04)	1.07 (0.80, 1.45)
250m	1.00 (0.94, 1.05)	1.12 (0.81, 1.55)
500m	1.03 (0.97, 1.08)	**1.40 (1.01, 1.93)***
1,000m	1.01 (0.96, 1.07)	1.41 (0.99, 2.01)
Black women		
100m	**1.07 (1.03, 1.12)***	1.19 (0.95, 1.50)
250m	**1.07 (1.03, 1.12)***	**1.31 (1.03, 1.66)***
500m	**1.07 (1.03, 1.12)***	1.27 (0.99, 1.62)
1,000m	**1.08 (1.03, 1.12)***	**1.46 (1.14, 1.86)***

**Significant at alpha=0.05*

[a] *ORs and 95% CIs reported per 1-IQR increase (100m: 0.123 for NDVI and 0.084 for $NDVI^2$; 250m: 0.105 for NDVI and 0.075 for $NDVI^2$; 500m: 0.090 for NDVI and 0.065 for $NDVI^2$; 1,000m: 0.080 for NDVI and 0.058 for $NDVI^2$)*

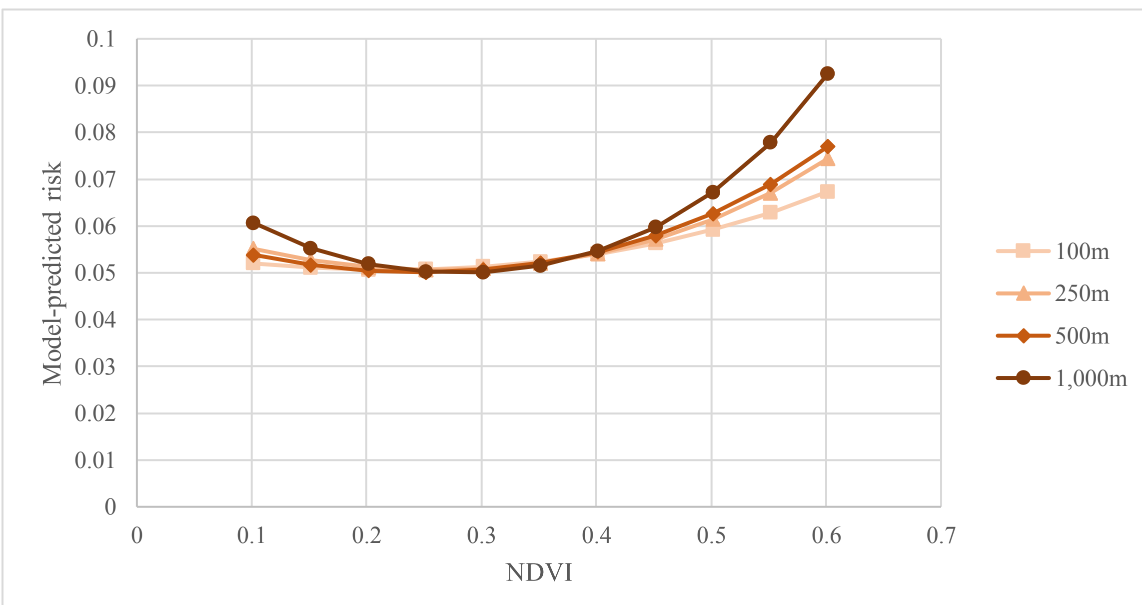
Models adjusted for: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index

Appendix E: Association of LPTB and NDVI among White women at various scales of NDVI



**Models adjusted for maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index*

Appendix F: Association of LPTB and NDVI among Black women at various scales of NDVI



**Models adjusted for maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index*

Appendix G: Sensitivity analysis with additional scales of neighborhood deprivation [OR (95% confidence interval)] [a]

	NDVI	$NDVI^2$
All women		
Tract NDI & NDVI at 250m	**1.03 (1.00, 1.07)***	1.17 (0.97, 1.41)
Tract NDI & NDVI at 500m	**1.05 (1.02, 1.08)***	**1.24 (1.02, 1.50)***
NDI at 500m & NDVI at 500m	**1.05 (1.02, 1.08)***	**1.21 (1.00, 1.47)***
Tract NDI & NDVI at 1,000m	**1.05 (1.02, 1.08)***	**1.36 (1.12, 1.65)***
NDI at 1,000m & NDVI at 1,000m	**1.06 (1.02, 1.09)***	**1.44 (1.18, 1.75)***
NDI at 4,000m & NDVI at 1,000m	**1.04 (1.01, 1.08)***	**1.40 (1.15, 1.70)***
White women		
Tract NDI & NDVI at 250m	1.00 (0.94, 1.05)	1.12 (0.81, 1.55)
Tract NDI & NDVI at 500m	1.03 (0.97, 1.08)	**1.40 (1.01, 1.93)***
NDI at 500m & NDVI at 500m	1.02 (0.97, 1.08)	1.38 (0.99, 1.91)
Tract NDI & NDVI at 1,000m	1.01 (0.96, 1.07)	1.41 (0.99, 2.01)
NDI at 1,000m & NDVI at 1,000m	1.02 (0.96, 1.07)	**1.48 (1.04, 2.10)***
NDI at 4,000m & NDVI at 1,000m	1.01 (0.96, 1.06)	**1.46 (1.03, 2.07)***
Black women		
Tract NDI & NDVI at 250m	**1.07 (1.03, 1.12)***	**1.31 (1.03, 1.66)***
Tract NDI & NDVI at 500m	**1.07 (1.03, 1.12)***	1.27 (0.99, 1.62)
NDI at 500m & NDVI at 500m	**1.07 (1.03, 1.12)***	1.23 (0.96, 1.57)
Tract NDI & NDVI at 1,000m	**1.08 (1.03, 1.12)***	**1.46 (1.14, 1.86)***
NDI at 1,000m & NDVI at 1,000m	**1.08 (1.04, 1.13)***	**1.53 (1.20, 1.96)***
NDI at 4,000m & NDVI at 1,000m	**1.07 (1.02, 1.11)***	**1.48 (1.15, 1.89)***

**Significant at alpha=0.05*

[a] *ORs and 95% CIs reported per 1-IQR increase (250m: 0.105 for NDVI and 0.075 for $NDVI^2$; 500m: 0.090 for NDVI and 0.065 for $NDVI^2$; 1,000m: 0.080 for NDVI and 0.058 for $NDVI^2$)*

Models adjusted for: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index

Appendix H: Sensitivity analysis of ethnicity pooling [OR (95% confidence interval)] [a]

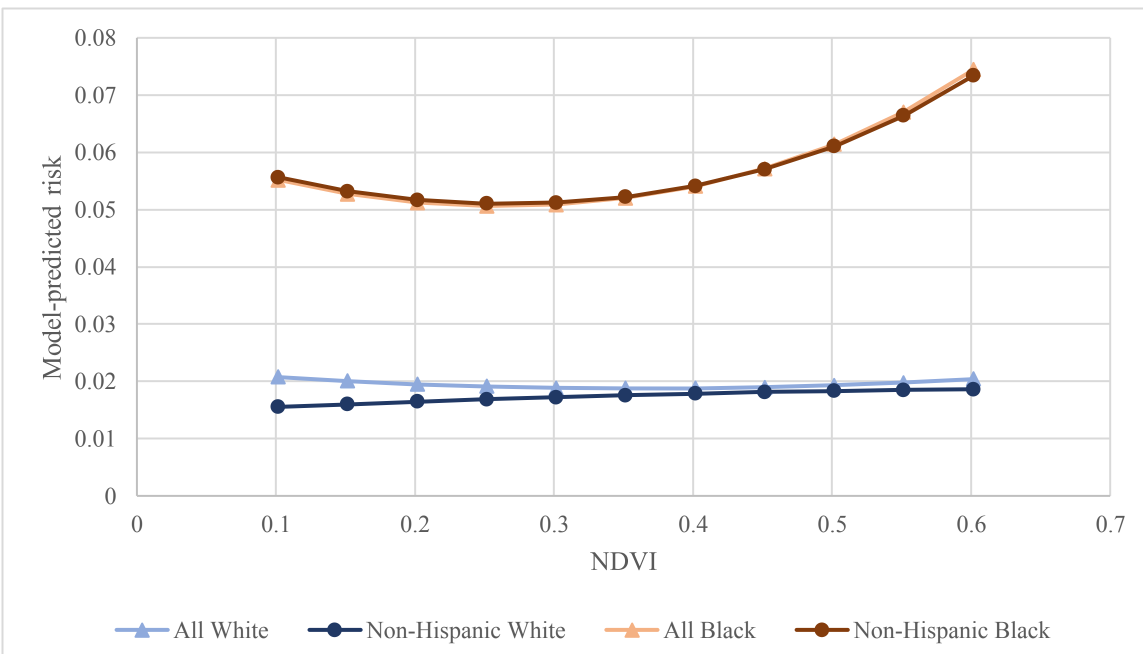
	NDVI	NDVI²
White	1.00 (0.94, 1.05)	1.12 (0.81, 1.55)
Non-Hispanic White	1.04 (0.97, 1.12)	0.96 (0.62, 1.50)
Black	**1.07 (1.03, 1.12)***	**1.31 (1.03, 1.66)***
Non-Hispanic Black	**1.06 (1.02, 1.11)***	**1.29 (1.02, 1.65)***
Hispanic	0.97 (0.88, 1.07)	1.24 (0.72, 2.14)

**Significant at alpha=0.05*

[a] ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for NDVI²)

Models adjusted for: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index

Appendix I: Association of LPTB and NDVI among White and Black women with pooled and un-pooled ethnicities



**Models adjusted for maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index*

Appendix J: Sensitivity analysis of additional covariates [OR (95% confidence interval)] [a]

	NDVI	$NDVI^2$
Main analysis[b]		
All women	**1.03 (1.00, 1.07)***	1.17 (0.97, 1.41)
White women	1.00 (0.94, 1.05)	1.12 (0.81, 1.55)
Black women	**1.07 (1.03, 1.12)***	**1.31 (1.03, 1.66)***
Main analysis + distance to nearest major hospital		
All women	1.03 (0.99, 1.07)	1.18 (0.98, 1.42)
White women	0.99 (0.94, 1.05)	1.13 (0.82, 1.57)
Black women	**1.07 (1.02, 1.12)***	**1.31 (1.03, 1.66)***
Main analysis + food access		
All women: flag for food desert[c]	**1.03 (1.00, 1.07)***	1.17 (0.97, 1.42)
White women: flag for food desert[c]	1.00 (0.95, 1.06)	1.13 (0.81, 1.56)
Black women: flag for food desert[c]	**1.07 (1.02, 1.12)***	**1.30 (1.02, 1.66)***
White women: White low food access[d]	1.00 (0.94, 1.06)	1.13 (0.81, 1.56)
Black women: Black low food access[d]	**1.06 (1.01, 1.11)***	**1.30 (1.02, 1.66)***
Main analysis + number of prenatal care vists		
All women	**1.04 (1.01, 1.08)***	1.06 (0.87, 1.30)
White women	1.01 (0.95, 1.07)	1.02 (0.72, 1.45)
Black women	**1.07 (1.02, 1.12)***	1.19 (0.92, 1.55)
Main analysis + Black population per census tract (%)		
Black women	**1.06 (1.01, 1.11)***	**1.30 (1.03, 1.66)***

**Significant at alpha=0.05*

[a] *ORs and 95% CIs reported per 1-IQR increase (0.105 for NDVI and 0.075 for* $NDVI^2$*)*

[b] *Main analysis adjusted for: maternal race, maternal education, maternal age, maternal smoking status, marital status, previous live birth, and neighborhood deprivation index*

[c] *Food desert defined as a low income and low access census tract measured at 1 mile for urban areas and 10 miles for rural areas*

[d] *Percent of tract population that are White/Black and living further than 1/2 mile from a supermarket*