



OPEN Exploring the role of green space in mitigating childhood opportunity across the U.S

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Green space exposure enhances children's well-being and has the potential to mitigate the impact of neighborhood deprivation. However, racial and ethnic disparities in green space availability persist, limiting the potential for equitable access and benefits for children. The Child Opportunity Index (COI) 3.0 was used to measure neighborhood opportunity, while tree canopy coverage and the normalized difference vegetation index were used to assess green space exposure. Tukey's test and correlation analysis were employed to evaluate the relationship between green space, children's neighborhood opportunities, and race or ethnicity across the U.S. at the census-tract level. Census tracts with lower COI scores have significantly less green space than those with higher COI scores, and a significantly higher proportion of Hispanic children live in neighborhoods with limited green space exposure ($p < 0.05$). The percentage of Hispanic children in a neighborhood shows significant negative associations with all green space measures, with a stronger negative association in high-deprivation neighborhoods compared to low-deprivation neighborhoods (-0.2 versus -0.5 , $p < 0.05$). Communities of color disproportionately experience both neighborhood deprivation and limited access to green space, and green space does not currently mitigate the impact of growing up in a deprived neighborhood.

Keywords Children, Well-being, Green space, Race, Ethnicity, Neighborhood deprivation

Child development and growth

Bronfenbrenner's bioecological systems theory emphasizes the importance of interactions across five individual and environmental "systems" that are critical for child development and growth^{1–4}. A nested hierarchical system, the child's immediate environment, designated the microsystem, refers to the immediate home environment and interactions with parents and siblings^{1–4}. However, the microsystem is nested within a meso-system (e.g., interactions that include parent-teacher, peer groups, etc.), exosystem (e.g., parent workplaces, public transportation services, local organizations), macrosystem (e.g., cultural norms, health care systems), and a chronosystem (e.g., historical events, educational policies)^{1–4}. Many of these systems are shaped by the broader neighborhood environments in which children live. For example, the strength of a child's meso-system may depend on the property values in a neighborhood to generate adequate taxes to support a school district. Moreover, historical policies such as redlining may influence neighborhood conditions, including high temperatures and limited shade due to limited green space availability that may curtail outdoor physical activity⁵. Consequently, examinations of environmental influences on children's health and well-being should be framed using a child development perspective.

The Child Opportunity Index, which is normed for children in the US, provides a robust tool to examine neighborhood influences on child health due to the inclusion of specific domains that are aligned with bioecological systems theory^{6,7}. The educational domain, for example, aligns with the microsystem and mesosystem by capturing the connection between adult education attainment and early childhood education participation⁷. Moreover, the exosystem and macrosystem are represented in the health and social and economic domains where proximity to health care systems, housing vacancy rate, unemployment rate, and proximity to toxic waste sites represent environmental factors that determine whether parents have the resources to take care

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of their children (e.g., low unemployment rate, low housing vacancy rate) to reduce adverse health outcomes (e.g., developmental delays). Notwithstanding, we examine the role of green space in attenuating the impact of other socio-environmental factors on child health.

Green space and child health and well-being

Socio-environmental and economic factors in the United States have been shown to impact child health outcomes. Factors such as access to (a) safe housing and safe neighborhoods, (b) high-quality education, and (c) affordable health care options, among others, have all been shown to impact the well-being of children⁶. Due to historical and contemporaneous reasons, such as redlining (designating areas with high numbers of Blacks as unsatisfactory for development) and zoning rules and racial covenants (e.g., prohibiting the sale of homes in certain neighborhoods to Blacks)^{8–11}, these socio-economic factors are distributed in a manner that disadvantages minoritized groups^{6,12–16}. Minoritized youth are more likely to live in racially and residentially segregated neighborhoods with inadequate assets for children, including highly segregated schools with limited resources. Moreover, neighborhoods characterized by limited support for health-promoting environments or behaviors (e.g., recreational spaces, access to health care facilities, poor air quality), where higher concentrations of minoritized youth reside, are also more likely to result in poorer health outcomes for children^{17–19}. Consequently, minoritized youth tend to live in neighborhoods where poverty and poor health outcomes are prevalent, with constrained opportunities for social and financial mobility^{20,21}.

The presence of neighborhood green space is associated with many positive impacts on the health and well-being of children; thus, recent scholarship is increasingly considering green space as a potential mitigation strategy to alleviate the negative health outcomes associated with neighborhood socio-economic disparities^{22–24}. According to the World Health Organization²⁵, green space is considered “land covered by vegetation” to include trees, shrubs, parks, and gardens. Green space is thought to be particularly important for attenuating patterns of health driven by socio-economic factors due to “equigenic” factors, namely that access to green space confers more substantial health benefits to socially disadvantaged groups²⁴. Access to green space has been associated with better mental health outcomes, including cognitive development, inattention, and increased levels of physical activity and sleep among children. Conversely, neighborhood deprivation is often associated with limited access to green space, which may contribute to disparities in children's physical and mental health^{26–32}. However, there is limited evidence for other outcomes such as asthma, and BMI as a measure of obesity^{30,33}. Notwithstanding, given the associated benefits of neighborhood green space with improved air quality, levels of physical activity, and social cohesion, exploring the potential for mitigating the racial and socio-economic patterning of opportunities for children remains important³⁴.

Previous research has shown that childhood opportunity is associated with racial and ethnic composition⁶, but there is limited research exploring the relationship between childhood opportunity, race or ethnicity, and green space. The existing research examining the relationship between race or ethnicity and green space is limited and focuses primarily on adult populations^{35–40}. Moreover, studies that examine neighborhood opportunity and green space often use socioeconomic status as a proxy, relying primarily on indicators such as household income, educational attainment, employment rates, and household amenities^{35–37,40}.

In this paper, we examine the associations between the validated national Child Opportunity Index 3.0, green space, and racial and ethnic composition across the U.S. We explore whether green space availability is also linked to neighborhood opportunity and racial/ethnic composition at the U.S. census tract level to determine whether green space mitigates the disparities in access to neighborhood opportunity between racial and ethnic groups. We hypothesize that patterns of green space inequality may align with patterns of racial/ethnic segregation at the neighborhood level across levels of neighborhood opportunity, limiting the ability of green space to mitigate the impact of neighborhood deprivation.

Methods

Study design

We conducted a cross-sectional analysis of the association between green space, child opportunity, and race or ethnicity at the census tract level across the US. The analysis aimed to explore how green space availability (as measured by NDVI and tree canopy) is associated with neighborhood opportunity and racial/ethnic composition at the U.S. census tract level. The analysis is separated into three parts. First, we examined the association between green space and child opportunity, accounting for education, health, environmental, and socioeconomic dimensions of opportunity. Second, we investigated the association between green space and the demographic makeup at the census tract level, defined as the racial and ethnic makeup of children in each census tract. Third, we analyzed the association between race or ethnicity and green space exposure within different levels of childhood opportunity. An overview of the study design can be found in Fig. 1.

Child Opportunity Index (COI) 3.0

We used the Child Opportunity Index (COI) 3.0 to conduct our analysis. The COI is a composite index measuring children's neighborhood opportunities for healthy development⁷. The index aims to evaluate indicators of childhood opportunity for every census tract (neighborhood) in the United States. Specifically, the COI score comprises 44 indicators across three domains (education, health and environment, and social and economic) and 14 subdomains⁷ (Table S2). The COI is published for the years 2012 to 2021, with each year's index calculation based on data from the preceding five years⁷. The Child Opportunity Scores range from 1 (lowest) to 100 (highest), ranking all neighborhoods nationally based on overall COI z-scores and dividing them into 100 rank-ordered groups by youth population⁴¹. Based on these COI scores from 1 to 100, neighborhoods are ranked into one of five COI levels ('very low', 'low', 'moderate', 'high', and 'very high'), each containing exactly 20% of the child population⁴¹.

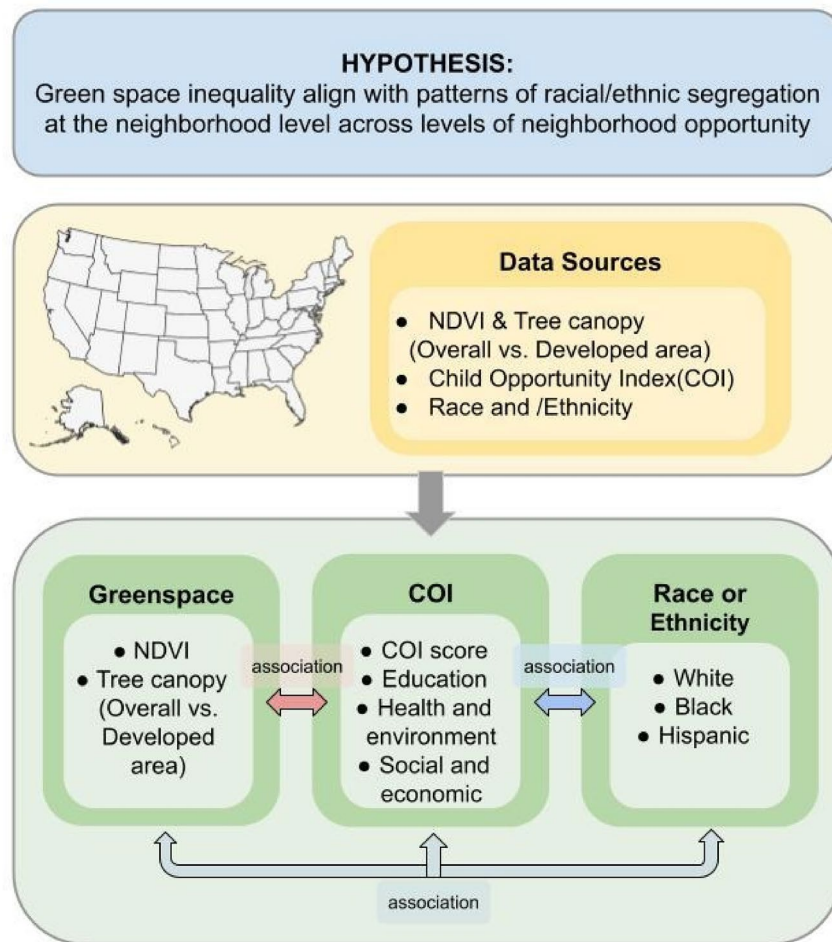


Fig. 1. Overview of the study design.

In our study, we analyzed the 2021 COI data, using both the overall and COI levels for the three domains. The COI data excluded census tracts (1549, 0.2%) that were entirely covered by water, had missing data for more than 50% of the COI indicators, or had no children (ages 0–17) recorded in the 2010 or 2020 censuses⁷.

Green space

Two measures of green space were utilized for this study: overall vegetation, as measured by the Normalized Difference Vegetation Index (NDVI)⁴², and tree canopy cover⁴³.

Normalized difference vegetation index (NDVI)

The NDVI is the most widely used vegetation index and has been applied in various studies to assess the vigor of vegetation on the land surface, using satellite imagery^{42,44–46}. As seen in Eq. 1, the NDVI is calculated using a ratio of the red and near-infrared(NIR) light bands reflected by vegetation. Healthy vegetation absorbs most of the red light and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more red light and less near-infrared light. NDVI values close to 1 correspond to complete coverage of live vegetation, values close to 0 correspond to bare soil, and values close to –1 correspond to water, ice, or snow^{42,46}. The satellite imagery bands (i.e., red and near-infrared bands) are obtained from the USGS Landsat 8 satellite (Landsat 8 Collection 2 Tier 1 calibrated top-of-atmosphere (TOA) reflectance) at a 30 m spatial resolution^{47,48}. To minimize the potential distortion of the NDVI value due to cloud cover, we calculated the maximum NDVI values for each raster pixel from January 1 to December 31, 2021, using Google Earth Engine^{46,49}. Next, we calculated the average NDVI for each census tract in the U.S. by computing the mean of all maximum NDVI pixel values within the census tract polygon. We classified the NDVI values into three categories: low (less than 0.2), moderate (0.2–0.5), and high (more than 0.5), which are defined as barren land, sparse vegetation, and dense vegetation by the U.S. Geological Service^{44,50}.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

Tree canopy cover (TCC)

The tree canopy cover (TCC) is a measurement that encompasses the layer of tree leaves, needles, branches, and stems that provide coverage of the ground when viewed from an aerial perspective⁴³. The U.S. Forest Service (USFS) uses forest inventory and analysis plots, combined with spectral and topographic data, to create random forest models and develop annual tree canopy cover maps⁵¹. We obtained 2021 tree canopy cover data from the USFS Tree Canopy Cover Datasets⁵² in ArcGIS Pro. It represents the tree canopy cover percentage value in each pixel, ranging from 0 to 100, with a pixel size of 30 m spatial resolution. We calculated the average tree canopy cover percentage for each census tract in the United States by computing the mean of all pixel values within the tract polygon. To compare the tree canopy cover among census tracts, we applied two thresholds: the median tree canopy value and the 30% tree canopy cover threshold proposed by Browning et al.⁵³ Tree canopy cover was thus categorized into two groups for each threshold: below the median and above the median, and less than 30% canopy cover and more than 30% canopy cover.

Developed area NDVI and TCC

To further analyze green space in children's neighborhoods, we focused specifically on green space in developed areas. We adopted the 'developed' area concept from the National Land Cover Database 2021⁵⁴, which provides nationwide data on land cover and land cover changes, offering spatial reference and descriptive information about land surface characteristics categorized into thematic land classes^{55–58}. The database provides eight thematic land classes: water, developed, barren, forest, shrubland, herbaceous, planted/cultivated, and wetland⁵¹. Specifically, "developed" areas are defined by the percentage of impervious surfaces (surfaces that water cannot infiltrate, such as roads, transportation infrastructure, or building rooftops) to quantify and map the extent of developed land use⁵⁹. Developed areas were then categorized based on the percentage of impervious surfaces as follows: open space (impervious surfaces less than 20%), low density (impervious surfaces range from 20 to 49%), medium density (impervious surfaces range from 50 to 79%), and high intensity (impervious surfaces above 80%)⁶⁰.

Historically, impervious surface classifications have been utilized to assess the health of green space⁶¹ and, in combination with green space indicators, to analyze environmental factors influencing children's health outcomes, such as early childhood development or childhood obesity^{62,63}. Focusing specifically on developed land allows us to account for green space that children are more likely to access and utilize, as opposed to forest, wetland, or planted green spaces that may be more difficult to access and may provide fewer opportunities for children to engage in the green space. Thus, we calculated the mean NDVI and tree canopy cover percentage only in census tracts defined as developed using the Google Earth Engine.

Race or ethnicity

We obtained data on the racial and ethnic makeup of the youth population at the census tract level from the American Community Survey (ACS). The ACS is an annual nationwide survey that provides communities with reliable data on social, economic, housing, and demographic trends, collecting approximately 3.5 million samples each year⁶⁴. We used estimates for the youth population (defined as 0–17 by the ACS) from the 2017 to 2021 ACS 5-Year Data⁶⁵. We collected data for the following estimates at the census tract level: White alone, not Hispanic or Latino; Black or African American alone; and Hispanic or Latino.

Statistical analysis

For the COI and green space analysis, we used Tukey's test to compare the COI score with NDVI and tree canopy cover across U.S. census tracts and developed areas of census tracts with TukeyHSD function in RStudio. The test evaluated differences in mean NDVI and tree canopy cover among COI levels (very low, low, moderate, high, and very high) for both the overall COI score and the three COI domains. We also used the paired t-test to compare the difference between overall green space and developed area green space within the COI level. For race or ethnicity and green space analysis, we used Tukey's test to compare green space exposure categories—NDVI (low, moderate, high) and tree canopy (below vs. above median, below/above 30%)—with the racial/ethnic makeup of a census tract. Tukey's test was calculated for both overall census tracts and the developed areas. Next, we analyzed COI scores, green space, and the race or ethnic makeup of a census tract. We calculated Pearson correlation coefficients to assess the relationship between green space exposure (NDVI and tree canopy cover) and the percentage of youth identifying as specific racial/ethnic groups within COI levels. Correlations were performed separately for overall green space and green space in developed areas. In the above statistical analyses, we used the *TukeyHSD*, *t.test*, and *cor.test* functions in RStudio.

Sensitivity analysis

In the primary analysis, the NDVI was calculated using data from 2021 to examine the associations among green space, COI score, and race or ethnicity. Since COI 3.0 is constructed using data mostly collected from 2017 to 2021, we conducted a sensitivity analysis employing the average NDVI from 2017 to 2021 to reassess these associations.

Moreover, the NatureScore^{®57}, which measures green vegetation, bodies of water, and human-made structures such as buildings and roads, is an indicator for the Health and Environment Domain of the COI. Specifically, the Nature Score[®] is one of the 13 indicators measured for the health and environment domain. Thus, we performed a correlation analysis between NDVI and the Health and Environment domain of the COI to assess collinearity.

Results

COI and green space

Comparing green space and child neighborhood opportunity, patterns of green space inequality generally align with neighborhood deprivation. As the COI level increases from ‘very low’ to ‘very high’, the mean values of the NDVI and tree canopy cover also increase, both in developed areas and the United States overall (Table 1, Figure S1).

On average, vegetation is moderate (i.e., NDVI 0.2–0.5) in neighborhoods with very low COI scores, while vegetation is generally high (i.e., NDVI greater than 0.5) in neighborhoods with higher COI scores. Tree canopy is also limited, with average values less than 26% across the US, under the recommended 30% threshold⁵³. Moreover, the mean availability of tree canopy covers a spectrum, from 17.9% in census tracts with ‘very low’ COI scores to 26.0% in census tracts with ‘very high’ COI scores. These differences are statistically significant: green space measures are significantly lower at the ‘very low’ COI level, while they are significantly higher at the ‘very high’ COI level (Fig. 2). These trends remain generally consistent across the overall COI measure as well as the education, social, and economic domains, with green space increasing alongside greater opportunity. This indicates that green space is significantly associated with various components of neighborhood opportunity. There are a few exceptions, including that tree canopy coverage was higher in “low” and “very low” opportunity census tracts compared to “moderate” opportunity census tracts, and NDVI was lower in “very high” social and economic opportunity census tracts compared to “low”, “moderate”, and “high” opportunity census tracts.

Race or ethnicity and green space

Next, we compare the youth demographic makeup of census tracts with available green space. Figure 3 illustrates that the spatial distribution of the youth population in the U.S. by race or ethnicity varies considerably between neighborhoods and across geographic regions. The Hispanic and Latino youth population is clustered in the southwestern U.S., while the Black and African American youth population is clustered in southern states.

Thus, we compare measures of green space to the racial/ethnic makeup of a census tract, specifically, the percentage of the population under the age of 17 that identifies as Hispanic, White (non-Hispanic), or Black/African American (Table 2 and Figure S2). The significant difference among green space groups is shown in Fig. 3. Overall, we see broadly that neighborhoods with a higher proportion of children who identify as racial/ethnic minorities have less green space.

Comparing NDVI scores in the developed portions of the census tract, we see disparities in green space exposure between Hispanic and non-Hispanic children (Table 2 and Fig. 4). On average, 46% of children living in census tracts with low NDVI are Hispanic compared to 14% of children in census tracts with high

	Overall NDVI, mean (SD)	Developed area NDVI, mean (SD)	Overall tree canopy, mean (SD)	Developed area tree canopy, mean (SD)
COI Level				
Very Low	0.49(0.18)	0.46(0.15) *	17.87(19.53)	15.68(11.17) *
Low	0.55(0.18)	0.51(0.15) *	22.73(20.88)	18.12(11.67) *
Moderate	0.56(0.18)	0.51(0.14) *	20.81(18.92)	17.85(11.26) *
High	0.55(0.17)	0.52(0.13) *	21.52(17.80)	19.86(11.75) *
Very High	0.54(0.16)	0.53(0.14) *	25.99(18.54)	24.60(13.56) *
Education Domain Level				
Very Low	0.48(0.17)	0.45(0.15) *	16.31(17.68)	15.07(10.84) *
Low	0.55(0.18)	0.51(0.15) *	22.37(20.86)	18.10(11.61) *
Moderate	0.57(0.18)	0.53(0.14) *	22.41(19.95)	18.75(11.68) *
High	0.55(0.17)	0.52(0.14) *	22.05(18.60)	20.01(12.07) *
Very High	0.54(0.16)	0.53(0.14) *	25.49(19.36)	24.11(13.31) *
Health and Environment Domain Level				
Very Low	0.53(0.18)	0.50(0.15) *	21.78(22.07)	17.96(12.99) *
Low	0.52(0.18)	0.49(0.16) *	20.24(20.27)	16.90(11.76) *
Moderate	0.53(0.18)	0.50(0.15) *	19.35(18.06)	17.18(10.86) *
High	0.55(0.17)	0.51(0.13) *	20.63(16.94)	19.10(10.97) *
Very High	0.55(0.16)	0.53(0.13) *	25.95(18.14)	24.10(12.79) *
Social and Economic Domain Level				
Very Low	0.49(0.18)	0.47(0.15) *	18.18(19.44)	15.90(10.96) *
Low	0.55(0.18)	0.51(0.15) *	22.72(20.70)	18.02(11.51) *
Moderate	0.55(0.18)	0.52(0.14) *	21.03(19.02)	17.99(11.35) *
High	0.55(0.16)	0.52(0.14) *	21.82(18.12)	20.02(11.98) *
Very High	0.53(0.16)	0.52(0.14) *	24.98(18.72)	24.07(13.81) *

Table 1. Green space exposure and Child Opportunity Index (COI) 3.0 levels across the United States. * Shows statistically significant difference between overall and developed green space (paired t-test, $p < 0.05$), SD: Standard deviation.

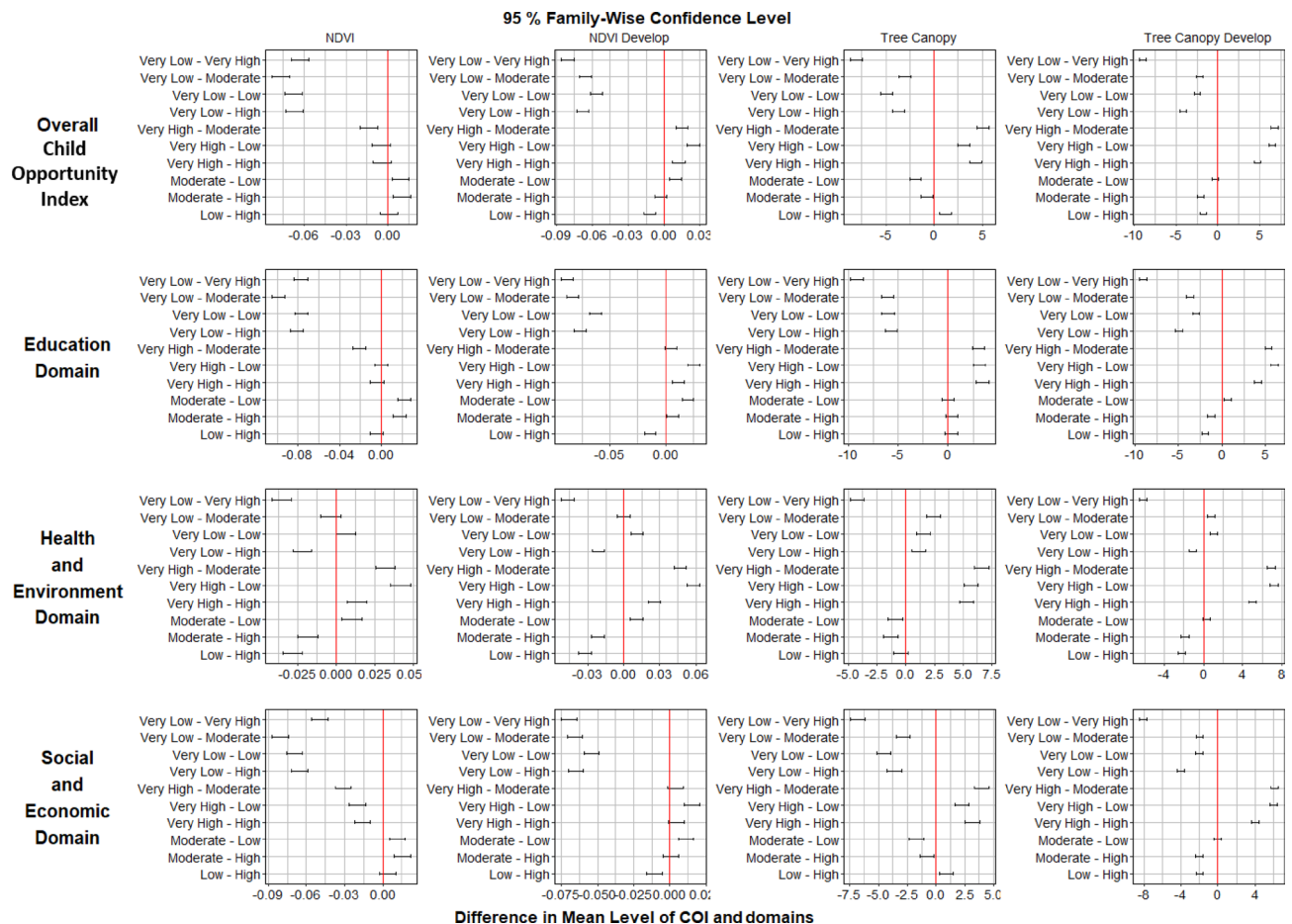


Fig. 2. Tukey's test of the Child Opportunity Index (COI) 3.0 and domains compared to green space exposures in the United States.

NDVI ($p < 0.05$). This disparity only increases when looking at developed areas; on average, 50% of children living in census tracts with low NDVI in developed areas are Hispanic compared to 13% of children in census tracts with high NDVI in developed areas ($p < 0.05$). All comparisons of the proportion of Hispanic children living in a census tract and NDVI were significant ($p < 0.05$). As the NDVI of a given census tract increases, the average proportion of Hispanic children living in that census tract decreases. In contrast, a significantly higher proportion of White children live in census tracts with increased green space availability as measured by NDVI. All comparisons of the proportion of White children living in a census tract and NDVI were significant ($p < 0.05$). These results indicate that a significantly higher proportion of White children and fewer Hispanic children live in census tracts with increased exposure to green space.

Similar patterns emerge when tree canopy coverage is compared in census tracts. On average, 62% of children living in census tracts with tree canopy above the median are White, while only 40% of children living in census tracts below the median tree canopy are White ($p < 0.05$). Hispanic children also disproportionately live in census tracts that do not meet tree canopy guidelines. On average, Hispanic children make up 32% of census tracts with tree canopies below the median compared to 13% of census tracts with tree canopies above the median ($p < 0.05$). Similar results were observed when comparing census tracts with tree canopy coverage above and below the recommended threshold of 30%: a higher proportion of Hispanic children live in census tracts with tree canopy coverage below the recommended threshold, and a higher proportion of White children live in census tracts with tree canopy coverage above the recommended threshold. These relationships hold for both the tree canopy in the entire census tract and only in developed areas.

In contrast, there are smaller differences in green space exposure among Black and African American children. On average, more Black and African American children live in high NDVI census tracts compared to low NDVI census tracts (14% versus 9%, $p < 0.05$). However, the difference in the proportion of Black and African American children between moderate and high NDVI census tracts is not statistically significant. Considering tree canopy coverage, there are also significant differences in the average proportion of Black and African American children living in census tracts below the median tree canopy, although the difference in proportion is limited—the average percent of children who are Black and African American in census tracts above the median tree canopy is 14.9% compared to 13.5% in census tracts that are below the median tree canopy ($p < 0.05$).

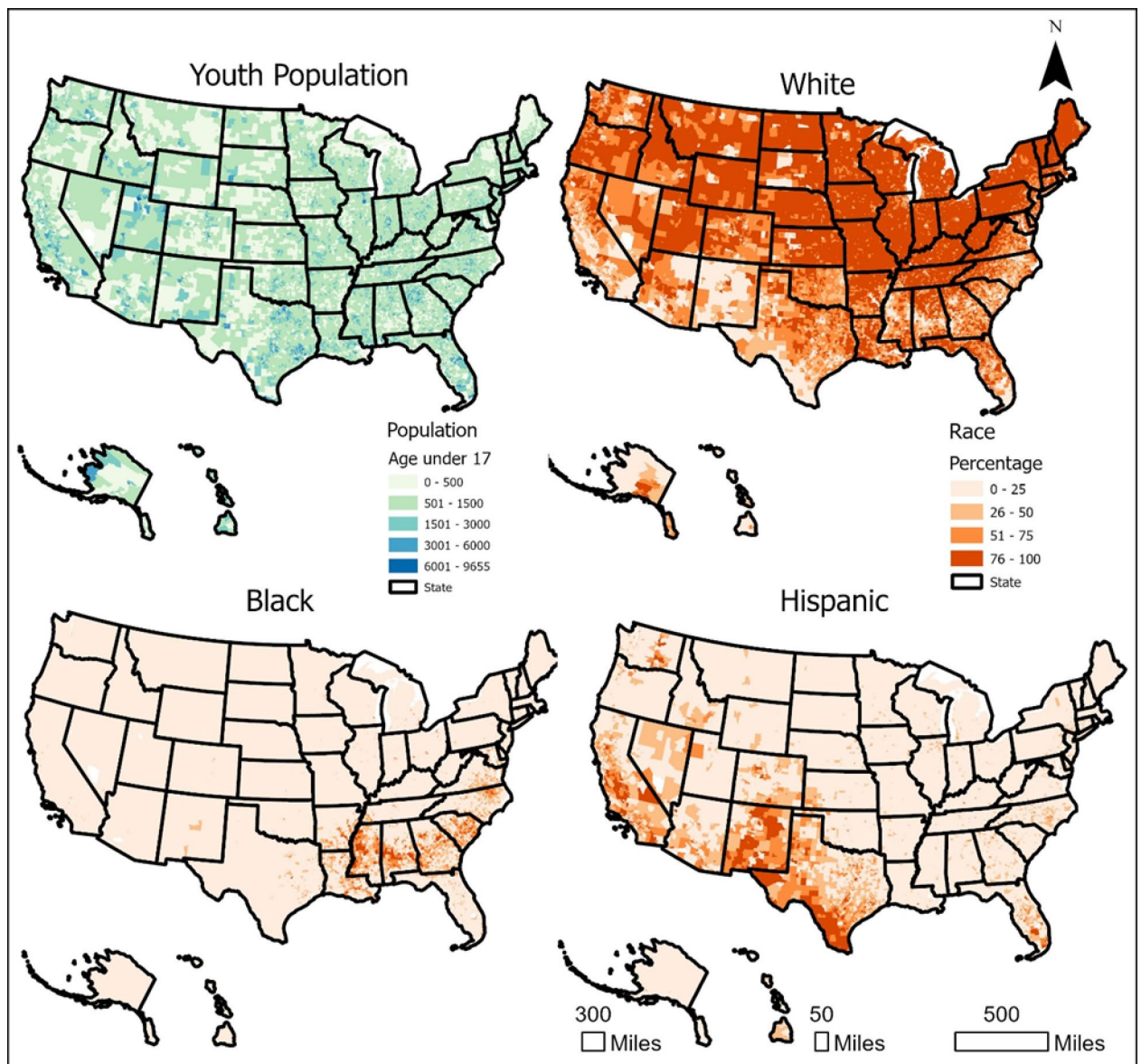


Fig. 3. Spatial distribution of youth population and race or ethnicity percentage at the US census tract level.

COI, race or ethnicity, and green space

Finally, we assess the strength of the relationship between measures of green space and the youth racial/ethnic makeup of census tracts within COI levels to ascertain if green space potentially modifies the relationship (Tables 3 and 4). Across COI levels, there are consistent statistically significant correlations between green space exposure and the racial/ethnic makeup of a census tract. Considering NDVI for all COI levels, the correlation coefficient for the percentage of White children is 0.51 ($p < 0.001$), indicating a moderate positive correlation, while the correlation coefficient for the percentage of Hispanic children is -0.48 ($p < 0.001$), indicating a moderate negative correlation. Generally, there are moderate to strong positive correlations between green space exposure and the proportion of White children in a census tract and moderate to strong negative correlations between green space exposure and the proportion of Hispanic children in a census tract. This indicates that Hispanic children disproportionately live in census tracts with limited green space exposure, and White children live in census tracts with increased green space exposure. In contrast, there are limited associations between the proportion of Black and African American children in a census tract and green space exposure. Across all COI levels, the corresponding correlation coefficients for the relationship between race or ethnicity and green space are between -0.1 and 0.25 , indicating weak correlations. These findings mirror those found in Table 2.

Comparing this relationship within different COI levels, the largest correlation coefficients are found in census tracts with lower COI scores. Considering the relationship between NDVI and race or ethnicity within low-opportunity census tracts, there is a strong positive relationship between the percentage of children who are White and NDVI (correlation coefficient 0.62, $p < 0.001$), and a moderate negative relationship between the percentage of children who are Hispanic and NDVI (correlation coefficient -0.57 , $p < 0.001$). In contrast,

	Average percentage of children who are White (non-Hispanic) (SD)	Average percentage of children who are Black/African American (SD)	Average percentage of children who are Hispanic (SD)
NDVI in total census tract			
Low	26.72 (27.73)	8.85 (15.50)	45.62 (32.39)
Moderate	35.19 (29.24)	14.84 (15.50)	34.45 (29.22)
High	61.32 (29.40)	14.16 (23.07)	13.78 (17.86)
NDVI in developed land of census tract			
Low	22.58 (24.70)	8.69 (14.71)	50.28 (31.90)
Moderate	35.35 (28.97)	14.70 (24.09)	35.03 (29.13)
High	62.71 (28.92)	14.34 (23.20)	12.51 (16.23)
Tree canopy in total census tract (median value:15.77%)			
Below median	40.11 (31.57)	13.54 (23.32)	31.87 (29.34)
Above median	61.59 (28.91)	14.87 (23.24)	12.58 (15.91)
Tree canopy in developed land of census tract (median value:16.52%)			
Below median	41.41 (31.94)	12.93 (22.69)	31.82 (29.45)
Above median	60.66 (19.21)	15.66 (23.90)	12.74 (16.023)
Tree canopy in total census tract			
Below 30%	44.67 (31.87)	14.36 (23.74)	27.21 (27.61)
Above 30%	65.58 (27.60)	13.85 (22.18)	10.37 (13.50)
Tree canopy in developed land of census tract			
Below 30%	47.53 (32.15)	14.58 (23.66)	25.12 (26.91)
Above 30%	65.89 (27.18)	13.08 (21.91)	10.23 (13.11)

Table 2. The youth racial/ethnic makeup of a census tract stratified by green space in the United States. SD: Standard deviation. Racial/Ethnic makeup is defined as the percentage of the youth population in a given census tract that identifies as a particular race or ethnicity.

looking at this same relationship between NDVI and race or ethnicity within very-high-opportunity census tracts, there is a moderate positive correlation between the percentage of children who are White and NDVI (correlation coefficient 0.36, $p < 0.001$) and a weak positive correlation between the percentage of children who are Hispanic and NDVI (correlation coefficient -0.28 , $p < 0.001$). This indicates there is a stronger correlation between ethnicity and NDVI in low-opportunity census tracts compared to high-opportunity census tracts.

The same trend is observed using tree canopy as a measure of green space availability. For the relationship between tree canopy and percent White children, there are moderate positive associations within very-low and low-opportunity census tracts, but weak positive associations within high and very-high census tracts (correlation coefficients 0.49, 0.46, 0.25, and 0.30, respectively, all $p < 0.001$). For the relationship between tree canopy and percent Hispanic children, there are moderate negative associations within very-low and low-opportunity census tracts, but weak negative associations within high and very-high census tracts (correlation coefficients -0.49 , -0.46 , 0.27, and 0.24, respectively, all $p < 0.001$). Again, there is a stronger correlation between ethnicity and green space (tree canopy) in low-opportunity census tracts compared to high-opportunity census tracts. This indicates that green space does not mitigate the impact of living in a low-opportunity neighborhood for Hispanic children; rather, green space is often not accessible to these children.

Sensitivity analysis

The sensitivity analysis comparing NDVI measurements indicates that the NDVI patterns in 2021 are consistent with the mean NDVI from 2017 to 2021. The Pearson correlation coefficients between the 2021 NDVI and mean NDVI from 2017 to 2021 in overall census tracts and developed land of census tracts are both 0.99 (Table S1). Figures S3 and S4 (2017–2021 NDVI) show similar significant differences in mean green space across levels of the COI and domains with racial or ethnic groups, as seen in Figs. 2 and 4 (2021 NDVI). This analysis assesses the sensitivity of inferences regarding the significant differences in mean green space across levels of the COI and racial or ethnic groups. Given that the analysis focuses on the 2021 COI, we rely on the 2021 NDVI for the interpretation of the results.

For our second sensitivity analysis, we compared NDVI, tree canopy, and the COI, which includes the NatureScore®, a machine learning-based metric that quantifies the amount and quality of nearby natural elements at any address by integrating satellite, GIS, pollution, imagery data, park data and features, and tree canopies (The NatureScore® is a component of the Health and Environment Domain, and thus, overall COI score). We see there are only weak to moderate correlations (Fig. 5). Given these results, we are using green space measures (e.g., NDVI) independently in our analysis, as the low correlation with the COI domains suggests green space measures capture distinct environmental characteristics that are not already represented within the COI.

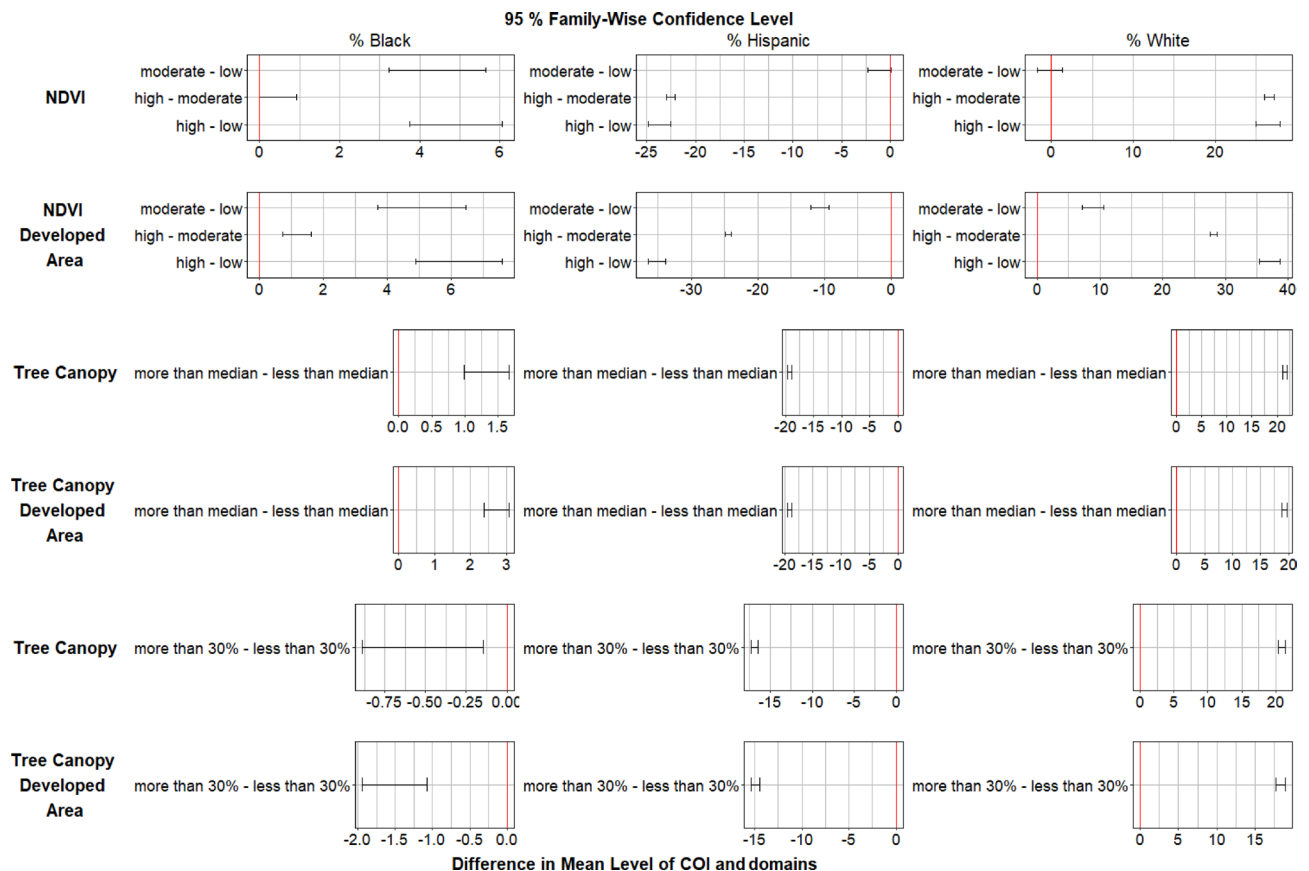


Fig. 4. Tukey's test of green space exposure classification with the racial/ethnic makeup of US census tract.

	COI					
	Levels					Overall census tract
	Very low	Low	Moderate	High	Very high	
NDVI in total census tract						
NDVI v. % Black/ African American	0.187***	−0.093***	−0.130***	−0.030***	0.023***	−0.036***
NDVI v. % White (non-Hispanic)	0.477***	0.618***	0.585***	0.472***	0.363***	0.510***
NDVI v. % Hispanic	−0.550***	−0.571***	−0.507***	−0.407***	−0.282***	−0.484***
NDVI in developed land						
NDVI v. % Black/ African American	0.248***	−0.048***	−0.091***	−0.013	0.007	−0.012**
NDVI v. % White (non-Hispanic)	0.457**	0.600***	0.572***	0.482***	0.416***	0.519***
NDVI v. % Hispanic	−0.594***	−0.599***	−0.532***	−0.434***	−0.304***	−0.525***

Table 3. Correlation between race or ethnicity and green space exposure within levels of the Child Opportunity Index (COI) 3.0 in the United States. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Discussion

These analyses demonstrate that census tracts with limited opportunities for children also have limited green space exposure. This relationship is consistently observed in the overall COI score, as well as within the *education, health and environment, and social and economic* domains, indicating that structural disparities in opportunity across dimensions are closely tied to unequal environmental resource availability. This pattern aligns with other children-related indices, such as analyses of social mobility, which indicate that groups with lower social mobility also tend to have lower levels of greenness⁶⁶. However, there were some exceptions identified. Average tree canopy in “low” and “very low” opportunity tracts was higher than in “moderate” tracts, possibly due to rural landscapes with greater forest or agricultural cover but limited access to essential services. Moreover, NDVI values were lower in census tracts classified as having “very high” levels of social and economic opportunity, which may be attributed to the concentration of high-opportunity areas within dense urban environments, where existing infrastructure limits green space. Nevertheless, it remains the case that children

	COI					
	Levels					Overall census tract
	Very low	Low	Moderate	High	Very high	
Tree canopy in total census tract						
Tree canopy v. % Black/ African American	0.129***	−0.023**	0.024**	0.083***	0.030***	0.003
Tree canopy v. % White (non-Hispanic)	0.491***	0.462***	0.317***	0.252***	0.298***	0.377***
Tree canopy v. % Hispanic	−0.490***	−0.461***	−0.340***	−0.270***	−0.238***	−0.394***
Tree canopy in developed land						
Tree canopy v. % Black/ African American	0.256***	0.071***	0.090***	0.109***	0.017	0.030***
Tree canopy v. % White (non-Hispanic)	0.391***	0.369***	0.240***	0.210***	0.311***	0.345***
Tree canopy v. % Hispanic	−0.526***	−0.448***	−0.317***	−0.253***	−0.254***	−0.404***

Table 4. Correlation between race or ethnicity and tree canopy exposure within levels of the Child Opportunity Index (COI) 3.0 in the United States. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

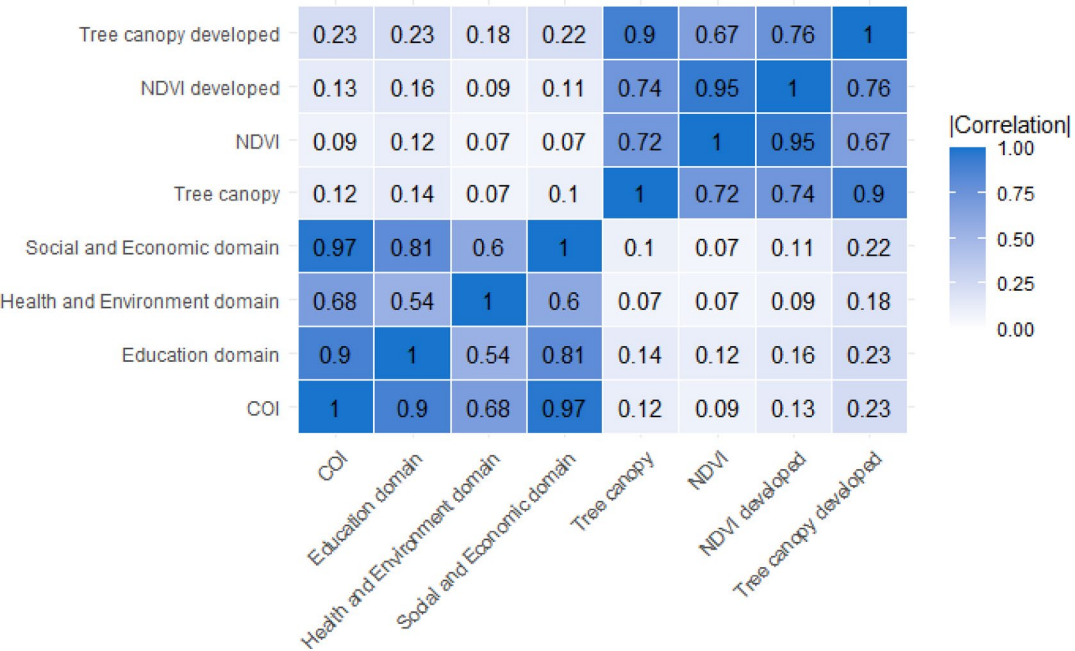


Fig. 5. Sensitivity analysis of green space measures and Childhood Opportunity Index (COI) 3.0 in the United States.

residing in socioeconomically deprived communities generally have reduced exposure to green space, yielding compounding negative exposures that can be detrimental to children’s health.

Considering the relationship between green space exposure and children’s race and ethnicity, census tracts with more green space and tree canopy are disproportionately White, while census tracts with less green space and tree canopy are disproportionately Hispanic, Black, and African American. This is consistent with the literature, whereby minority communities often have reduced exposure to green space and experience less green space exposure^{13,36,67}. Moreover, there is a stronger correlation between green space and ethnicity in lower-opportunity neighborhoods. In high-deprivation areas, there are even more Hispanic children with disproportionately less exposure to green space, while census tracts with more opportunity generally experience less of a disparity in green space exposure.

In contrast, this analysis observed smaller differences in green space availability, neighborhood deprivation, and race for Black and African American children. These relationships were significant, but smaller than the disparities generally seen in the literature^{13,36,67}. This is likely because we define race as the proportion of children in a census tract who identify as a given race, but there is a limited range in the proportion of children who identify as Black and African American at the census tract level. In 66% of census tracts, the proportion of children who identify as Black/African American is less than 10%, while in 81% of census tracts, the proportion of children who identify as Black/African American is less than 25%⁶⁵. This limited the ability of our statistical tests and models to differentiate between health opportunity outcomes based on racial makeup in a census tract.

Overall, we see that both green space and neighborhood opportunity are inequitably distributed across the U.S.: children of color disproportionately face dual exposure to limited neighborhood opportunity and green space availability. Thus, this paper does not provide evidence that increased green space availability currently mitigates the impact of growing up in a deprived neighborhood for minoritized children in the U.S. Despite the potential “equigenic” effects of green space^{24,68}, whereby minoritized children may receive more health benefits, the current lack of green space availability in deprived neighborhoods and in communities of color prevents those benefits from being equitably realized. The impact of neighborhood deprivation is compounded by an associated lack of green space availability, thereby reinforcing existing health and opportunity disparities. Historical structural violence, such as redlining, as well as contemporary factors, such as discriminatory zoning rules, contribute to a system whereby socio-economic resources are distributed in a way that disadvantages minoritized groups, and environmental injustice remains prevalent. As a result, without intervention, health inequities may persist and continue to disproportionately affect marginalized children.

The study has several limitations to consider. First, the COI's Health and Environment domain includes the NatureScore®, which includes green space as one of the components³¹. Although our sensitivity analysis revealed only a limited correlation, this remains an important limitation. Second, this analysis focuses on three main racial and ethnic groups: White, Hispanic, and Black/African American. Thus, we did not consider the associations between neighborhood opportunity and green space for other racial/ethnic groups, which may be differentially affected. Third, there are other confounding variables we could consider in the analysis, such as income and poverty level. However, these variables are already included in the COI domain indicators; therefore, we did not include them in the study to avoid collinearity. Moreover, there are potential endogeneity concerns regarding the relationship between green space and neighborhood opportunity. In future work examining causal relationships, we will address these concerns along with other potential confounding factors. Fourth, this analysis uses NDVI and tree canopy measures for the entire census tract, which is not always representative of actualized green space exposure, as the green space captured by NDVI or tree canopy may be inaccessible. Additionally, the census tract may not be the appropriate spatial unit to capture the neighborhood environment of children, or the most relevant for policy initiatives that may be implemented at the city level, for example. Fifth, other aspects of the characteristics of green space, in addition to availability, were not included in our study, such as quality or type—another important metric for determining the association between green space and child development and well-being. Lastly, green space changes throughout the year, so using only maximum green space measures without considering seasonal variation may overlook how seasonal effects influence the relationship between green space and COI, thereby limiting children's ability to benefit from the health and well-being advantages.

Notwithstanding, the study also has several strengths. The analysis utilizes nationwide data, allowing the results to be generalizable across the U.S. Second, green space measures were separated into total green space and developed green space, allowing the consideration of green space exposure patterns for children living in both rural and developed environments. Third, this is one of the first studies to consider the relationship between green space, neighborhood deprivation, and green space exposure in children. Moreover, the use of the Child Opportunity Index 3.0 allows us to consider opportunity and deprivation factors beyond socioeconomic status, including proximity to resources such as the density of healthy food retailers and non-profit organizations³². Finally, this study directly considers whether green space mitigates the impact of neighborhood deprivation in communities of color.

Conclusion

These findings contribute to our understanding of the associations between green space exposure, neighborhood deprivation, and race and ethnicity in youth populations at the census tract level across the U.S., offering insights into potential disparities in environmental availability and community resources. Hispanic children were more likely to live in low-opportunity census tracts and have reduced exposure to green space. Moreover, the strength of the relationship between green space and race or ethnicity increased as neighborhood deprivation increased, indicating a clear health disparity whereby Hispanic children are negatively impacted by a range of interconnected neighborhood-level factors that compound each other. While previous research has shown that increased green space can mitigate the impact of neighborhood deprivation for disadvantaged communities^{10,33,34}, this analysis highlights that this is not currently occurring in the U.S.; Hispanic children disproportionately face both neighborhood deprivation and limited green space availability. Thus, interventions are necessary to increase green space exposure, neighborhood opportunity, or both to reduce the burden of health disparities among children. These interventions may be most effective at the community level to adequately address health equity concerns and consider how limited community resources may impact green space usage.

Data availability

All data used for this analysis is publicly available. The Child Opportunity Index 3.0 dataset is publicly available and can be found on the Diversity Data Kids Website: https://data.diversitydatakids.org/dataset/coi30-2010-tracts-child-opportunity-index-3-0-database-2010-census-tracts?_external True Green space was calculated using the USGS Landsat 8 satellite at a 30 m spatial resolution: <https://www.usgs.gov/landsat-missions/landsat-8> Tree canopy cover data is available from the United States Forest Service Tree Canopy Cover Dataset: <https://data-ufs.hub.arcgis.com/datasets/78592dac7150449d944c8fc838df221a/about> The United States Geological Survey publishes the National Land Cover Database, used to determine developed/non-developed land: <https://www.usgs.gov/centers/eros/science/national-land-cover-database#data> Race or Ethnicity information for the population on group 0–17 in the US for 2017–201 is available from the American Community Survey: <https://www.census.gov/newsroom/press-kits/2022/acs-5-year.html>.

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Author contributions

JY, BU, SD, and DGT contributed to conceptualization. JY and BU contributed to data curation. JY and BU contributed to the formal analysis. JY, BU, SD, and DGT contributed to the methodology. DGT contributed to project administration. DGT contributed to supervision. JY, BU, and DGT contributed to writing—original draft. JY, BU, and DGT contributed to writing—reviewing & editing.

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Competing interests

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Additional information

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