Neighborhood Greenness and 2-Year Changes in Body Mass Index of Children and Youth

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Background: Available studies of the built environment and the BMI of children and youth suggest a contemporaneous association with neighborhood greenness in neighborhoods with high population density. The current study tests whether greenness and residential density are independently associated with 2-year changes in the BMI of children and youth.

Methods: The sample included children and youth aged 3–16 years who lived at the same address for 24 consecutive months and received well-child care from a Marion County IN clinic network within the years 1996–2002 (n=3831). Multiple linear regression was used to examine associations among age- and gender-specific BMI z-scores in Year 2, residential density, and a satellite-derived measure of greenness, controlling for baseline BMI z-scores and other covariates. Logistic regression was used to model associations between an indicator of BMI z-score increase from baseline to Time 2 and the above-mentioned predictors.

Results: Higher greenness was significantly associated with lower BMI z-scores at Time 2 regardless of residential density characteristics. Higher residential density was not associated with Time 2 BMI z-scores in models regardless of greenness. Higher greenness was also associated with lower odds of children's and youth's increasing their BMI z-scores over 2 years (OR=0.87; 95% CI=0.79, 0.97).

Conclusions: Greenness may present a target for environmental approaches to preventing child obesity. Children and youth living in greener neighborhoods had lower BMI z-scores at Time 2, presumably due to increased physical activity or time spent outdoors. Conceptualizations of walkability from adult studies, based solely on residential density, may not be relevant to children and youth in urban environments.
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Background

Over the last 3 decades, obesity (i.e., BMI ≥95th percentile of national growth standards) doubled among children aged 2–5 years and adolescents aged 12–19 years; it tripled among children aged 6–11 years.[1] In 2003–2004, 17% of children and youth were obese, and 34% were overweight (i.e., between BMI ≥85th and <95th percentile of national standards).[2]

Childhood obesity is associated with health problems including type 2 diabetes, asthma, hypertension, sleep apnea, and emotional distress.[3–6] Obese children and youth are likely to be obese as adults[7,8]; experience morbidity from cardiovascular disease, high blood pressure, and stroke[4,9]; and incur higher healthcare costs.[10,11] Together these problems highlight an urgent need for new preventive strategies.[1]

The built environment is emerging as important for obesity prevention; however, most studies are adult-centric and cross-sectional. Among adults, the within-neighborhood availability of supermarkets is positively associated with the consumption of fruits and vegetables[12] and inversely associated with obesity.[13] In other studies, street connectivity, land-use mix, and residential density are associated with moderate physical activity,[14] while urban sprawl is related to obesity[15] and inversely related to walking.[16]

Among children and youth, physical activity is positively associated in most[17–19] but not all[20] studies with time spent outdoors and with proximity to recreational facilities and parks.[17,21–23] In one study,[23] land-use mix, residential density, and recreational amenities were not associated with adolescent girls' BMI. In a longitudinal study,[15] urban sprawl was not associated with adoles-

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cent BMI in the longitudinal context, but the contemporaneous relationship was significant.

Given the importance of parks and time spent outdoors, neighborhood greenness could be associated with the BMI of children and youth as an indicator of access to spaces that promote physical activity. In one cross-sectional study,[24] higher greenness was associated with lower child and youth BMI, but only in areas with high population density. Greenness is inversely correlated with residential density[25] that is, in turn, associated with physical activity and BMI in observational studies of adults.[14,26] Greenness and residential density are modifiable attributes of the built environment; however, it remains unknown whether each has independent effects on the BMI of children and youth.

Understanding the independent and relative influences of residential density and greenness on the BMI of children and youth is an essential first step toward targeted preventive intervention. If density is distinct and more influential than greenness, then urban development that encourages highly connected street networks, mixed commercial and residential land use, and concentrated housing would be warranted. If greenness is more important, then the creation or preservation of open green spaces would be indicated instead of high-density development. If both variables are significantly associated with the BMI of children and youth, then urban-development schemes that encourage density while preserving greenness would be required.

Consistent with calls for multidisciplinary research examining salutary environmental exposures,[27] the current study was designed to test (1) whether greenness and residential density were independently associated with 2-year changes in the BMI of children and youth, and (2) whether the associations were modified by race/ethnicity, gender, age, or SES.

Methods

Sample

Data for this retrospective cohort study were derived from electronic medical records for a primary care clinic network in Indianapolis IN. Children and youth aged 3–16 years were included if they were Marion County residents and received routine well-child care from the network during 1996–2002; they were excluded if they had medical documentation of risk factors that might systematically bias BMI measurements (e.g., pregnancy, congenital heart disease, cystic fibrosis, cerebral palsy, congenital anomalies).

Each young person's address was geocoded using ArcGIS 9.0 automated address-matching procedures, supplemented by manual matching (match rate=92%, N=57,559). None of the demographic characteristics of individuals with and without successful address matches differed significantly.

To analyze BMI change over time, the sample was restricted to children and youth who maintained the same address for at least 24 months and had same-day clinical measurements of height and weight recorded 2 years apart (n=3901). This smaller subgroup with stable addresses and biennial well-child visits was slightly older (9.16 years vs 8.76 years, $p<0.01$); had a higher percentage of male children and youth (51% vs 50%, $p<0.01$); and a higher percentage classified as obese (23% vs 21%, $p=0.04$). Of these individuals, 59 were excluded because their homes were <1 kilometer from the county boundary, and data were not available to compute environmental measures extending beyond county borders (n=3842).

Dependent Variable

The dependent variable was the child's gender- and age-specific BMI z-score (i.e., the number of SD units that the child's BMI deviates from the mean reference value for age and gender) relative to U.S. growth reference charts for 2000,[28] and measured at Time 2 (i.e., the second of the biennium appointments beginning in 1996–2000 for which anthropometric measures were most recently available). The child's BMI z-score at the beginning of the biennium (Time 1) was included as a covariate in all models.

The young person's BMI was based on height and weight measured by clinic staff using scales and stadiometers.[29] Recommended algorithms were applied to identify implausible values,[30] with 11 observations excluded (n=3831).

Rather than absolute BMI, BMI z-scores were measured to permit valid estimates in a sample pooled by gender and age and because the heights and weights of the study subjects were expected to increase as part of normal development.[28] Compared to categorical dependent variables (e.g., obese, overweight, normal weight), continuous BMI z-score measurements have the advantage of capturing subtle changes in weight status across the distribution as well as more dramatic shifts from one weight category to the next.

To further assess 2-year changes in BMI z-scores, a dichotomous dependent variable was developed to categorize BMI z-scores as increasing between Time 1 and Time 2 versus remaining the same or declining (ref: declining).

Measures of Urban Form

Greenness was measured using the normalized difference vegetation index (NDVI), derived by converting pixel values in satellite images encompassing 30x30-meter areas to continuous measurements that can range from –1 (usually water) to +1 (dense, healthy green vegetation).[31] NDVI calculations are based on the principle that healthy green plants absorb radiation in the visible region of the spectrum and reflect radiation in the near-infrared region.

For this analysis, the NDVI was scaled by a factor of 10, so that a 1-unit increase in this variable (i.e., 0.01) corresponded to land-use changes that were reasonable in urban settings (e.g., from parking lots or industrial sites with little vegetation to school yards with moderate greenness, or from vacant land/right-of-ways to parks with lush vegetation).

Due to the timing of cloud cover and data collection, satellite-derived NDVI data were not available for Marion County every year (1996–2000) in the same month. Therefore, a summer measurement (June 6, 2000) was chosen that corresponds to high green biomass in residential environments. The current analysis assumed no change in the mean

NDVI in the same season by year, a reasonable assumption given that the correlation coefficients for available summer NDVI measures during the study period ranged from 0.97 to 0.99.

Mean NDVI was calculated within a 1-kilometer straight-line circular (hereafter, radial) and a road-based network (hereafter, network) buffer surrounding each child's residence. The buffer size represents the distance a subject can travel in all directions around his or her residence within a given period of time. In the absence of empirical findings for ideal buffer size in child studies, 1 kilometer was chosen based on environmental correlates of adult walking.[14] Network buffers vary in size, based on the level of street connectivity within the area and are proposed to represent more accurately than radial buffers the areas that adults can access around their homes.[14] This proposition has not been tested among children and youth. Defining access according to travel constrained to roads or sidewalks may be less relevant to children and youth because their physical activity differs from that of adults by type and motivation (e.g., play versus utilitarian transit). Consequently, all models were tested with both buffer specifications. Results of greater magnitude and significance with network versus radial buffers[14,32] would underscore the importance of street networks to children and youth.

Residential density was calculated as the number of housing units per acre devoted to residential land use within the child's census block-group of residence.[14]

Covariates

All models controlled for racial/ethnic group (ref: non-Hispanic white, non-Hispanic black, Hispanic, other); gender (ref: female, male); a race/ethnicity X gender interaction; age at baseline (ref: 3–5 years, 6–10 years, 11–13 years, and 14–16 years); and health insurance status (private/other, ref: Medicaid) as a proxy for individual SES.[33] Models were tested with the addition of (1) linear, quadratic, and cubic terms in baseline BMI z-scores to test nonlinear relationships and (2) Time-1 clinical weight classification categories (i.e., ref=normal weight, overweight, obese). Results did not differ substantively; therefore, findings are presented with control for linear BMI z-scores at Time 1.

To address confounding by neighborhood SES, all models included census block-group median family income measured continuously and log-transformed to correct skewness.

Statistical Analysis

The analysis was conducted in 2007–2008. Using GeoDa software, Moran's I was computed to test for spatial autocorrelation in the dependent variable (i.e., the possibility that individuals with similar weight status living close to one another would lead to biased estimates).[34] Remaining analysis was conducted with Stata version 10.0.

The study variables were summarized with descriptive statistics. ANOVA, adjusted as needed for multiple comparisons, was used to test for differences in mean NDVI and residential density by each study variable. Multiple linear regression was used to model BMI z-scores at Time 2, controlling for BMI z-scores at Time 1, the urban-form variables, and covariates. SEs were adjusted for clustering of observations within census block-groups using the Huber–White estimate of variance; p-values ≤ 0.05 were considered significant.

Residential density and the NDVI were included in the multiple regression models—first separately, then together. The fully adjusted models were repeated with the NDVI in radial and network buffers. The effect modification of associations among the NDVI and BMI z-scores by age (categorized as above); race/ethnicity (non-Hispanic black versus the other groups combined); gender; and SES (Medicaid versus private/other insurance) was assessed for each, using modified F-tests of the joint significance of the interaction terms.

Finally, logistic regression was used to model the dichotomous measures of 2-year BMI z-score increase as a function of greenness, residential density, and all covariates.

Results

Most children and youth in the sample were non-Hispanic black (58%); aged 6–10 years (35%); and Medicaid enrollees (83%; Table 1). The average block-group median family income was lower than in the county as a whole ($36,917/year vs $49,387/year). At Time 1, 23% of the children and youth were obese, 17% were overweight, and the average BMI z-score was 0.68 SDs above the national reference. Over the study period, the average BMI z-score increased by 0.08 SDs.

The mean NDVI was higher among non-Hispanic black children and youth and those with normal weight, private/other insurance, high block-group family income, and index year of BMI measurement in 2000. As expected, the mean NDVI was lower for children and youth in neighborhoods with residential density above the 50th percentile, and mean residential density was lower among children and youth with higher SES (Table 1).

There was no evidence of spatial auto-correlation in the Time-2 BMI z-scores (univariate Moran's I with fourth-order, nearest-neighbor spatial weights=0.05, SD=0.01, p=0.58)[34]; therefore, analysis proceeded without spatial regression models. Results are reported for linear NDVI measurements and pooled models because quadratic and cubic NDVI specifications were not significant, and F-tests indicated no effect modification by age, race/ethnicity, or gender.

As expected, the NDVI and residential density were inversely correlated (r=−0.48); however, the intracorrelation coefficient was low enough to model the variables together and avoid problems with multicollinearity.[35] A 0.01-unit increase in the NDVI was associated with lower Time-2 BMI z-scores (β=−0.06 SD, 95% CI=−0.09, −0.02; Table 2, Model 1). Residential density was not significantly associated with Time-2 BMI z-scores when modeled without the NDVI (Table 2, Model 2). In contrast, a higher NDVI was associated with lower Time-2 BMI z-scores (β=−0.07 SD, 95% CI=−0.11, −0.03), and residential density was marginally associated with lower Time-2 BMI z-scores when

Table 1. Characteristics of the study sample[a] (n=3831)

Variable	% or M (SD)	NDVI M (SD)	p-value	Residential density[b] M (SD)	p-value
Gender					
Female	49	0.09 (0.08)	0.83	6.7 (4.2)	0.83
Male	51	0.09 (0.08)	—	6.8 (3.5)	—
Race/ethnicity					
Non-Hispanic white	36	0.07 (0.09)	—	6.5 (3.6)	—
Non-Hispanic black	58	0.11(0.07)	<0.01	6.8 (4.1)	0.15
Other	2	0.12 (0.07)	<0.01	6.0 (2.6)	<0.01
Hispanic	4	0.06 (0.08)	0.03	7.9 (3.1)	<0.01
Age (years)					
3–5	24	0.09 (0.08)	—	6.9 (4.8)	—
6–10	37	0.09 (0.08)	1.00	6.7 (3.3)	1.00
11–13	22	0.09 (0.08)	1.00	6.7 (3.8)	1.00
14–16	17	0.09 (0.09)	1.00	6.8 (4.0)	1.00
Health insurance type					
Medicaid	83	0.09 (0.07)	—	7.1 (3.6)	—
Private/other	17	0.14 (0.09)	<0.01	5.3 (5.8)	<0.01
Tract median family income	$36,906 ($15,272)	—	—	—	—
Low (<25th percentile)	25	0.06 (0.07)	<0.01	8.7 (5.5)	<0.01
Middle(≥25th–≤75th percentile)	50	0.08 (0.07)	<0.01	7.0 (2.7)	<0.01
High (>75th percentile)	25	0.14 (0.08)	—	4.2 (2.2)	—
Index year					
1996	346	0.09 (0.09)	1.00	6.9 (3.3)	1.00
1997	576	0.11 (0.09)	<0.01	6.5 (5.0)	1.00
1998	692	0.10 (0.08)	0.02	6.8 (5.1)	1.00
1999	960	0.09 (0.08)	1.00	6.8 (3.4)	1.00
2000	1268	0.09 (0.08)	—	6.7 (2.9)	—
Residential density[b]	6.49 (3.90)	—	—	—	—
High (>50th percentile)	50	0.05 (0.07)	<0.01	—	—
Low (≤50th percentile)	50	0.13 (0.07)	—	—	—
Baseline BMI z-score	0.70 (1.28)	—	—	—	—
Normal weight	2305	0.10 (0.08)	—	6.7 (4.0)	—
Overweight (≥85th–<95th percentile of national standards)	653	0.09 (0.08)	0.19	6.9 (4.6)	0.34
Obese (≥95th percentile of national standards)	884	0.09 (0.08)	0.03	6.8 (2.8)	1.00
Time 2 BMI z-score	0.81 (0.76)	—	—	—	—

[a]Children and youth receiving well-child care in a Marion County IN Pediatric Clinic Network with same address for at least 24 months
[b]Housing units per acre residential land
NDVI, normalized difference vegetation index

greenness and density were modeled together (Table 2, Model 3).

In all models, children and youth with higher Time-1 BMI z-scores had higher Time-2 BMI z-scores. Non-Hispanic black children and youth had higher Time-2 BMI z-scores in both models that included NDVI (Table 2, Models 1 and 3).

Relationships between NDVI and Time-2 BMI z-scores were significantly modified by insurance status (F-test, p<0.01), with results of greater magnitude for children and youth with private/other insurance (β=−0.13 SD, 95% CI=−0.21, −0.04, p=<0.01) versus Medicaid (β=−0.06 SD, 95% CI=−0.10, −0.01, p=0.01; not shown in tables).

Associations between the NDVI and Time-2 BMI z-scores were similar with radial (Table 2, Model 3) and network buffers (β=−0.07 SD, 95% CI=−0.11, −0.03; not shown in tables), and the model fits were identical (adjusted r^2 =0.53). In both models, the estimates for residential density were of similar direction, magnitude, and significance.

In the logistic regression model, higher greenness was associated with lower odds of increasing BMI z-scores (OR=0.87; 95% CI=0.79, 0.97; not shown in tables).

Discussion

In a sample of predominantly African-American, economically disadvantaged children and youth, a significant inverse association was apparent between neighborhood greenness and BMI z-scores at Time 2, controlling for the child's BMI z-score at baseline and other important covariates. It also was found that children and youth in greener settings were less likely to increase their BMI z-scores over 2 years compared to

Table 2. Linear regression of neighborhood greenness and residential density on BMI z-scores[a,b] (n=3831)

	Model 1 NDVI		Model 2 residential density		Model 3 NDVI+residential density	
	β (95% CI)	***p*-value**	**β (95% CI)**	***p*-value**	**β (95% CI)**	***p*-value**
Gender (ref: female)						
Male	−0.01 (−0.09, 0.09)	0.98	−0.01 (−0.09, 0.08)	0.94	0.01 (−0.08, 0.09)	0.98
Race/ethnicity (ref: non-Hispanic white)						
Non-Hispanic black	0.08 (0.01, 0.16)	0.04	0.05 (−0.02, 0.12)	0.20	0.09 (0.01, 0.16)	0.03
Hispanic	0.15 (−0.08, 0.37)	0.20	0.15 (−0.07, 0.38)	0.18	0.15 (−0.07, 0.38)	0.18
Other	0.22 (−0.05, 0.49)	0.11	0.20 (−0.07, 0.47)	0.15	0.22 (−0.05, 0.49)	0.11
Age (years) (ref: 3–5)						
6–10	0.03 (−0.05, 0.11)	0.48	0.03 (−0.05, 0.11)	0.49	0.03 (−0.05, 0.11)	0.48
11–13	0.05 (−0.02, 13)	0.13	0.06 (−0.02, 13)	0.17	0.06 (−0.02, 13)	0.17
14–16	0.03 (−0.05, 0.11)	0.46	0.03 (−0.05, 0.11)	0.45	0.03 (−0.05, 0.11)	0.45
Health insurance type (ref: Medicaid)						
Private/other	0.01 (−0.07, 0.09)	0.87	−0.02 (−0.10, 0.06)	0.58	0.01 (−0.07, 0.09)	0.86
Tract median family income (log)	0.02 (−0.01, 0.05)	0.30	−0.01 (−0.03, 0.03)	0.86	0.01 (−0.02, 0.04)	0.44
Baseline BMI z-score	0.76 (0.69, 0.76)	<0.01	0.73 (0.69, 0.76)	<0.01	0.73 (0.69, 0.76)	<0.01
NDVI	−0.06 (−0.09, −0.02)	<0.01	—	—	−0.07 (−0.11, −0.03)	<0.01
Residential density	—	—	−0.01 (−0.01, 0.01)	0.99	−0.01 (−0.01, 0.01)	0.06

[a]Models also controlled for index year and race X gender interaction
[b]SEs adjusted for neighborhood-level clustering
NDVI, normalized difference vegetation index

their counterparts in less-green neighborhoods. These findings add to prior cross-sectional studies demonstrating associations between greenness and weight[24] and are distinguished by modeling density and greenness together and by longitudinal measures of BMI.

These findings demonstrate that the effect of greenness on weight status is independent of residential density. In contrast, density modeled without greenness had no effect on BMI z-scores, while marginally protective effects of higher density were apparent only when greenness was controlled. Assuming that the inverse relationships between density and BMI in the adult literature are driven by enhanced walkability—as defined by street characteristics, commercial–residential land-use mix, and population density—the current results suggest that such conceptualizations may have less relevance to children and youth in urban environments unless greenness is taken into account. Even then, the magnitude of the association with residential density was small.

Associations between greenness and BMI z-scores were significant and similar when NDVI was measured within radial versus network buffers. There was no evidence that network buffers better depict than radial buffers regions of access and exposure in this sample of children and youth. In contrast to prior cross-sectional work demonstrating differences in NDVI–BMI relationships by population density,[24] no effect modification of associations was found between neighborhood NDVI and BMI z-scores by density, perhaps due to different specification of the dependent variable or areal units used to measure density.

Interestingly, non-Hispanic black children and youth had significantly higher BMI z-scores at Time 2 only when greenness was controlled. This finding suggests that the advantageous BMI z-scores in Table 2, Model 2, similar to those of non-Hispanic white children and youth, may have been conferred, at least in part, by greener neighborhood environs.

The magnitude and significance of the NDVI estimates reported here are clinically meaningful and biologically plausible. Holding height constant and comparing to a national reference group,[28] a BMI z-score lower at Time 2 by 0.05 SDs equates to lower weight of approximately 1.6 kg for girls aged 4 years (2 kg for boys) and 5.1 kg for girls aged 16 years (5.9 kg for boys).

This study's findings align with previous research linking exposure to green landscapes with health improvements. Among adults, greenness is associated with less stress and lower BMI,[36] improved self-reported health,[37] and shorter post-operative recovery periods.[38] Among children and youth, the positive health effects of green landscapes include improved cognitive functioning[39] and reduced attention deficit hyperactivity disorder symptoms.[40]

Physical activity is one obvious pathway through which urban vegetation might influence the BMI of children and youth. Unlike adults, children and youth in urban environments may be active in a wider variety of open spaces (e.g., yards, parks, vacant lots) and less likely to constrain activity to streets and sidewalks. Consistent with other work,[17–19,21,22,24] this study posited that greenness might indicate proximity to parks, playfields, or other open spaces that promote either physical activity or increased time spent outdoors in active play. The findings are consistent with these claims and supported by prior literature. For instance, in inner-city neighborhoods, outdoor spaces with trees are used with higher frequency than treeless outdoor spaces, and the more trees, the more simultaneous users.[41,42] Children and youth are twice as likely to be supervised by adults in green urban spaces compared to barren but otherwise similar spaces.[43] Tree shade and scenery are associated with reports of increased walking.[44]

Green landscaping might also influence indirectly the physical activity of children and youth as an indicator of territorial personalization, implying that inhabitants actively care about their homes.[45] In one study, greener apartment-building surroundings were associated with reports of fewer crimes.[46] It is reasonable to conjecture that territorial personalization could be associated with increased community surveillance that deters crime and thereby increases parents' willingness to encourage outdoor physical activity as well as perceptions of safety by children and youth.

Finally, if improved mental health or self-esteem influence health behavior, greenness could indirectly influence the BMI of children and youth by providing access to places for mental and sensory stimulation, privacy, or opportunities for creative play.[40,47,48] Future research is required to test these potential pathways and mechanisms with direct measures of child behavior in prospective studies, ideally those designed to take advantage of natural experiments in which green space in urban settings is radically increased or decreased.

The results are subject to limitations. The study region, geographic scale, and sample limit generalizability. As an observational study, results may reflect selection bias if families exhibiting healthier behaviors related to diet or physical activity also choose to live in greener neighborhoods. Omitted variables, including more-robust measures of SES and neighborhood attributes such as crime and the presence of resources and amenities, may also influence the findings. Additionally, physical activity is not available in medical records, precluding the examination of the full sequence of environmental factors influencing behavior and, ultimately, weight status. The temporal mismatch between the clinical and greenness measures limits the ability to assess the impact of changing greenness exposure. Residential density in the study region may have had insufficient variability to measure its effects. Future research is warranted within or across settings with wider-ranging measures of density.

The results may reflect unmeasured confounding by SES. In Denver, the NDVI was associated with census tract–level socioeconomic advantage.[49] In Denmark, access to green areas was associated with lower self-reported stress and obesity; however, the number of trips to green areas did not predict either outcome, raising the question of whether it is greenness per se that matters to health, or other associated factors.[36] In this study, most subjects were Medicaid enrollees, presumably from economically disadvantaged families. Notably, these estimates were of similar direction and significance in high- and low-SES strata; only the magnitude of the estimate differed. It is unlikely that the general findings were due solely to unmeasured confounding by SES.

Conclusion

Greenness is inversely associated with the BMI z-scores of children and youth at 2 years, controlling for baseline BMI z-score and important covariates. The effect appears to be independent of residential density; robust by buffer type; and of similar direction, magnitude, and significance by gender, age, and race/ethnicity. These findings support the exploration of the promotion and preservation of greenspace within neighborhoods as a means of addressing childhood obesity.

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