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Original Contribution

The Association Between Urban Tree Cover and Gun Assault: A Case-Control and Case-Crossover Study

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Green space and vegetation may play a protective role against urban violence. We investigated whether being near urban tree cover during outdoor activities was related to being assaulted with a gun. We conducted geographic information systems–assisted interviews with boys and men aged 10–24 years in Philadelphia, Pennsylvania, including 135 patients who had been shot with a firearm and 274 community controls, during 2008–2011. Each subject reported a step-by-step mapped account of where and with whom they traveled over a full day from waking until being assaulted or going to bed. Geocoded path points were overlaid on mapped layers representing tree locations and place-specific characteristics. Conditional logistic regressions were used to compare case subjects versus controls (case-control) and case subjects at the time of injury versus times earlier that day (case-crossover). When comparing cases at the time of assault to controls matched at the same time of day, being under tree cover was inversely associated with gunshot assault (odds ratio (OR) = 0.70, 95% confidence interval (CI): 0.55, 0.88), especially in low-income areas (OR = 0.69, 95% CI: 0.54, 0.87). Case-crossover models confirmed this inverse association overall (OR = 0.55, 95% CI: 0.34, 0.89) and in low-income areas (OR = 0.54, 95% CI: 0.33, 0.88). Urban greening and tree cover may hold promise as proactive strategies to decrease urban violence.

firearm violence; green space exposure; gun assault; urban tree canopy

Abbreviations: CI, confidence interval; OR, odds ratio.

Gun violence is a pervasive public health problem that undermines the physical, mental, and social health of individuals and communities globally (1, 2). In the United States, gun homicide is the second leading cause of death among youth aged 10–24 years, African-American men are disproportionately affected, and this violence is predominantly an urban phenomenon (3–6). In 2014, approximately 11,500 gun homicides occurred, and over 110,000 people were injured by firearms (3). Firearm injuries result in over $48 billion in medical and work-loss costs annually (4).

Preventing violent crime is imperative to promoting the health of individuals and communities. Many youth-violence prevention efforts have focused on changing the knowledge, attitudes, and behaviors of individuals (7–10). Another set of programs target people involved in a violent incident, such as hospital-based case management programs or juvenile justice system programs (10). While important for reducing the burden of violent crime, these programs often require tremendous effort on the part of targeted individuals and may have limited population impact and sustainability (11, 12).

It is prudent, therefore, to expand the scope of public health interventions for violence prevention beyond individuals and into the physical environment in which individuals are situated (13, 14). Research now suggests that aspects of neighborhood physical environments, such as urban green space and trees, may in fact influence rates of violent crime (15, 16).

This study evaluated whether there is an association between where gunshot assaults occur and where trees are located in an urban environment. While previous studies have examined associations between crime occurrence and environmental features, to our knowledge, this is the first study of its type to focus on adolescents and young adults (aged 10–24 years).

We analyzed data from the Space-Time Adolescent Risk Study (STARS), completed in Philadelphia, Pennsylvania, in 2012, that involved an in-depth investigation into the nature and locations of hundreds of individuals' daily activities and the likelihood of being assaulted. The parent study investigated whether spending time around alcohol outlets, recreation centers, vacant lots, and other environmental features was related to assault risk (17). We capitalized upon these novel and rich data by investigating the hypothesis that tree cover is associated with occurrence of assault. To enhance rigor, we used both case-control and case-crossover study designs.

METHODS

Study population

The Space-Time Adolescent Risk Study recruited 135 case subjects in Philadelphia, Pennsylvania, during 2008–2011 from emergency departments of local adult and pediatric hospitals. Case subjects had sustained a wound in a gunshot assault. Following a matched case-control design, the study recruited 274 controls randomly drawn using random-digit dialing to residential telephones from the area encompassing neighborhoods where case subjects resided. Controls were recruited on a continual basis with the goal of ensuring enough age variability to allow for stratified case-control analysis. Both case and control subjects were aged 10–24 years, and control-subject recruitment was stratified to ensure adequate sample size by age group. Details of the study design, data collection, and analytic methods have been reported previously (17).

An in-person interview with each subject addressed demographic factors, health, school performance, relationships with friends and family, risk-taking behaviors, and perspectives about the area where they lived and included standardized instruments (18, eTable 1, listing the questions). Activities included, for example, waking, eating, traveling (and mode), hanging out with friends, playing sports, and watching television.

Also during a key component of the interview, subjects were asked to trace their activity paths via geographic information system on a laptop computer to learn details of the timing and location of the subjects' activities from the time they awoke in the morning until they were assaulted (cases) or went to bed (controls). Cases referred to the day of the assault; controls were asked to refer to a recent day (within 3 days of the interview) designated at random. Data were processed to create a record of the minute-to-minute location ("path points") and activities of each subject over their reporting period of up to 24 hours. There were 94,733 gunshot case-subject path points and 249,966 control path points. Most path points (188,331) occurred within the city of Philadelphia. Some (4,634) path points fell within Montgomery County, Pennsylvania, to the west and northwest of Philadelphia. A small number of path points (823) were located in Delaware County, Pennsylvania, to the southwest of Philadelphia. Maps of these path points are shown in Figure 1.

Green exposure measures

We determined whether tree cover was present or absent at each path point using available urban tree canopy data sets. Urban tree canopy data were developed in 2008 at a 0.5-m resolution from a land-cover data set using high-resolution aerial imagery and light detection and ranging (LiDAR) data from the US Department of Agriculture Forest Service's tree canopy assessment for Philadelphia (19, 20). We approximated presence of tree cover for each path point as being within 15.25 m of tree canopy (typical width of a residential street in the study area). We used a buffer method to assign presence or absence of this tree cover.

We used the Montgomery County land-cover assessment to assign tree cover to path points that fell within Montgomery County. No urban tree canopy or comparable land-cover data were available in Delaware County and therefore we excluded these path points, leaving a total of 343,876 path points in the study. In addition, we generated and assigned a dichotomous variable representing leaf season (April through September) to all path points.

Statistical analyses

We compared cases with controls along a variety of individual and environmental characteristics in addition to percentage of their day spent outdoors and spent outdoors under tree cover using interquartile range (25th to 75th percentiles), mean, and median value calculations. Regression analyses included only the path points for participants' time spent outdoors and not driving. We tested for differences in characteristics (means) using the Wilcoxon rank-sum method.

We conducted regression analyses to test whether the presence of tree cover (within 15.25 m) during daily activities was associated with the occurrence of gun assault. First, we constructed conditional logistic regression models using a matched case-control design to examine whether the environments surrounding case subjects, at the moment they were assaulted, differed from the environments surrounding control subjects at the same time of day (see Web Figure 1, available at https://academic.oup.com/aje/). Tree cover was the exposure of interest. This was accomplished by stratifying all case-control models by time of day using 7 phases (6:00–8:59 AM, 9:00–11:59 AM, 12:00–2:59 PM, 3:00–5:59 PM, 6:00–8:59 PM, 9:00–11:59 PM, and 12:00–5:59 AM) and comparing each case subjects' environmental exposures near the time they were assaulted to control subjects' exposures at that same time of day.

Second, we constructed conditional logistic regression models using a case-crossover design to examine whether the environment where each case subject was located at the time of assault differed from the environment where the case subject traveled and spent time earlier that day, with tree cover being the exposure of interest (see Web Figure 1). We compared environmental features at the point of injury to environmental features at all other points during a case-subject's activities, excluding 50 minutes prior to the point of injury.

For both case-control and case-crossover models, the first 3 "base" regression models controlled only for tree cover and leaf season. We ran the base regression models on all participants, and we then stratified the participants by age group.

We then ran regression models that adjusted fully for the demographic variables described earlier, in addition to leaf season. Each adjusting model included 6 index sociodemographic covariates derived from a factor analysis (21, eTable 3). The

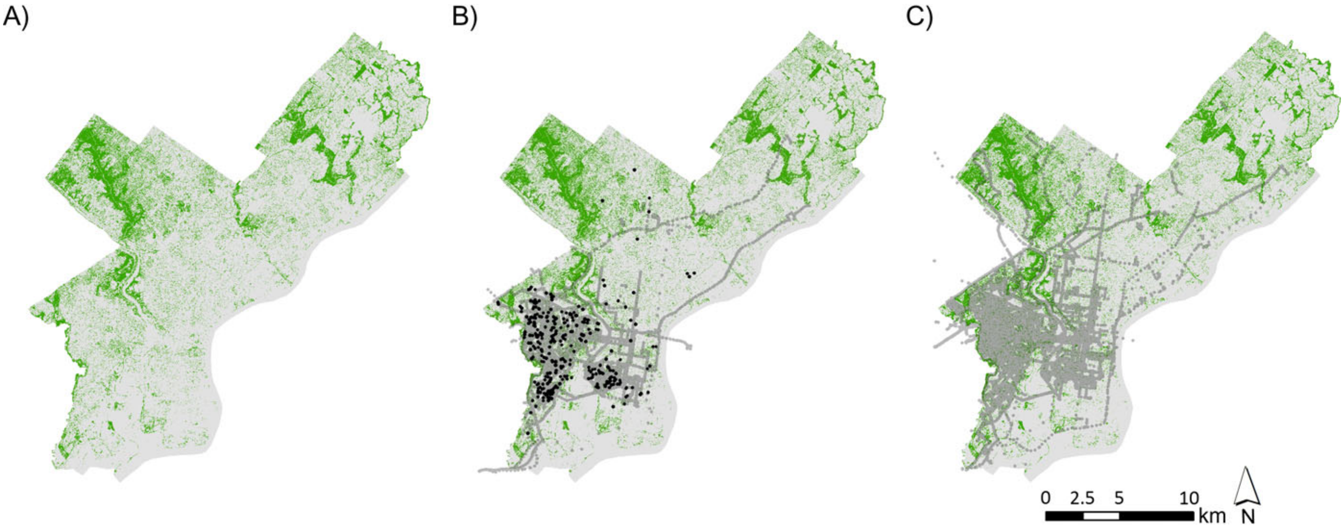

Figure 1. Tree cover and 1-minute path points for gunshot case subjects and controls, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011. A) Tree cover only. B) Tree cover with 1-minute path points and gunshot locations for gunshot case subjects. C) Tree cover and 1-minute path points for control subjects. Green shading represents tree cover. Dark grey points represent 1-minute path points. Black points represent gunshot locations.

6 factors corresponded to connectedness among neighbors, income, presence of nearby alcohol outlets and drunkenness and disorderly conduct, vacant lots and vandalism and violence, fire stations and police stations, and race and ethnicity at the location of each path point. Income for a given area (block group) was measured as a factor variable (composite score) built, using principal components analysis, from 3 US Census variables: median household income, per capita income, and unemployment. We also included 4 covariates about environmental features at each path point that were based on answers to the Public Health Management Corporation's Southeastern Pennsylvania Household Health Survey (22) regarding prevalence of household gun ownership, proportion of the population aged 15–24 years old, prevalence of recreation centers, and school truancy. We converted data from these answers to a standardized value (mean of 0, standard deviation of 1) in the form of a z score. Thus each factor and variable used as a covariate represents the relative prevalence of that environmental characteristic that was present at a given location a subject traveled through or spent time in. Where appropriate, we included a weekday-weekend covariate.

We also used these factors and variables to stratify the analyses to test theory-related questions about the association between gun assault and presence versus absence of green leaves and vegetation, weekday versus weekend routines, and location in high-income versus low-income areas. Regression estimates are presented as odds ratios. For case-control models, odds ratios represent the odds of exposure (to tree cover) at the time of assault among cases divided by the odds of exposure (to tree cover) at that same time among controls. For case-crossover models, the odds ratios represent the odds of exposure to tree cover at the time of assault divided by the odds of exposure to tree cover experienced among case subjects earlier in their day. The odds ratios are our estimates of whether environmental features (tree cover in particular) were associated with the occurrence of assault. Analyses were performed using Stata, version 13.1 (StataCorp LP, College Station, Texas).

RESULTS

Study participants were all male and almost all African American (Table 1). Gunshot case subjects lived in areas with lower academic achievement and more vacant property compared to control participants.

Two-thirds (64%) of the gunshot case subjects were located under tree cover at the time they were shot. Table 2 shows 25th percentile, mean, median, and 75th percentile values of the percentage of daily time spent outdoors and percentage of outdoor time spent under tree cover according to subject group. The median amount of time (percentage of total) gunshot case subjects spent outdoors was 46%. The median percentage of outdoor time (percentage of total) gunshot case subjects spent under tree cover was 78%.

The case-control logistic regression base models (Table 3), stratified by age and not controlling for demographics, found that being under tree cover was inversely associated with being assaulted (odds ratio (OR) = 0.72; 95% confidence interval (CI): 0.58, 0.89). Stratifying by age group suggested that tree cover was inversely associated with gunshot assault only among individuals under the age of 18 years (OR = 0.51, 95% CI: 0.29, 0.89). Case-crossover base models showed an even stronger inverse association, most notably for subjects under the age of 18 years (OR = 0.32, 95% CI: 0.12, 0.84).

Regression models adjusted for sociodemographic factors and leaf season (Table 3) also found an inverse association between tree cover and assault. Being under tree cover was inversely associated with assault especially for time spent in

Table 1. Characteristics of Case and Control Subjects, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011

Characteristic	Gunshot Cases (*n* = 123)		Controls (*n* = 274)	
	Median	%	Median	%
Individual				
Age, years	19		18	
Male, %		100		100
Race/ethnicity, %				
African American		97		99
White		1		3
Other		2		0
Environment of residence location				
Median annual household income, $	24,000		26,000	
No. of unemployed persons aged ≥16 years[a]	82		74	
No. with some college[a]	217		246	
No. of African Americans[a]	951		966	
No. of Hispanic persons[a]	16		15	
No. of vacant properties[b]	587		425	

[a] Per 1,000 population.
[b] Per square mile.

low-income areas according to both case-control models (OR = 0.69, 95% CI: 0.54, 0.87) and case-crossover models (OR = 0.54, 95% CI: 0.33, 0.88).

When comparing case subjects to control subjects, the presence of tree cover during leaf season was inversely associated with gunshot assault (OR = 0.65, 95% CI: 0.50, 0.84). The presence of trees without leaves was not associated with assault in the case-control analysis, but was inversely associated with assault in the case-crossover analysis (OR = 0.39, 95% CI: 0.17, 0.87).

Regression analyses stratified by weekday (Table 4) versus weekend (Table 5) showed that the inverse association between presence of trees and assault was more evident on weekdays than on weekends. Base models found this to be true more so for individuals under the age of 18 years. On weekdays, full-adjustment models found tree cover to be inversely associated with assault especially in low-income areas for both case-control (OR = 0.65, 95% CI: 0.48, 0.87) and case-crossover analyses (OR = 0.47, 95% CI: 0.26, 0.83) and during leaf-off season for both case-control (OR = 0.49, 95% CI: 0.26, 0.93) and case-crossover (OR = 0.35, 95% CI: 0.13, 0.94) analyses. On weekends, case-crossover models showed an inverse association during leaf-off season (OR = 0.07, 95% CI: 0.01, 0.60).

DISCUSSION

While an increasing number of studies support an inverse association between green space and violent crime, to our knowledge, there has yet to be a study investigating whether the location of greenery relates to gun assaults among adolescents

Table 2. Descriptive Statistics of Time Spent Outdoors and Time Spent Outdoors Under Tree Cover Among Case and Controls, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011

Characteristic and Study Cohort	25th Percentile	Mean	Median	75th Percentile
Average percentage of daily time spent outdoors				
Gunshot cases	26	50	46	76
Controls	28	50	49	71
Average percentage of daily time spent outdoors under tree cover				
Gunshot cases	48	68	78	91
Controls	53	69	73	92

Table 3. Logistic Regression Odds Ratios Estimating the Association Between Tree Cover and Gunshot Assault, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011

Model	Case-Control			Case-Crossover		
	OR	95% CI	*P* Value	OR	95% CI	*P* Value
Base model[a]	0.72	0.58, 0.89	0.002	0.55	0.34, 0.87	0.011
Age <18 years	0.51	0.29, 0.89	0.017	0.32	0.12, 0.84	0.021
Age ≥18 years	0.73	0.50, 1.07	0.106	0.64	0.37, 1.11	0.112
Full-adjustment model[b]	0.70	0.55, 0.88	0.002	0.55	0.34, 0.89	0.015
Low-income areas	0.69	0.54, 0.87	0.002	0.54	0.33, 0.88	0.014
Leaf season, yes	0.65	0.50, 0.84	0.001	0.70	0.37, 1.31	0.265
Leaf season, no	0.74	0.44, 1.24	0.254	0.39	0.17, 0.87	0.021

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] Base model adjusted for tree cover and leaf season.
[b] Full-adjustment model stratified by either low- or high-income area or leaf season and adjusted for sociodemographic factors or environmental variables, including connectedness among neighbors, income, presence of nearby alcohol outlets and drunkenness and disorderly conduct, vacant lots and vandalism and violence, fire stations and police stations, race and ethnicity, prevalence of household gun ownership, proportion of the population aged 15–24 years, prevalence of recreation centers, and school truancy. Full-adjustment model in high-income areas did not converge due to limited sample size.

and young adults. This study, working with novel data on essentially the step-by-step activities and whereabouts of a large sample of urban youth and young adults, found compelling evidence of an inverse association between tree cover and gun assault.

Regression models adjusting for sociodemographic factors and leaf season showed that the prevalence of tree cover at the time of assault among cases was lower than the prevalence among control observations, and hence that tree cover was inversely associated with the likelihood of being assaulted, especially for young individuals and in low-income areas of an urban environment. Future work with experimental study designs is needed to gain insight into whether this association may be causal.

The case-control results may, to some extent, be biased due to uncontrolled differences between the cases and controls. The models using the case-crossover design do not include this bias, and in fact controlled for behaviors like risk-taking that we would not have been able to measure accurately, and they confirm the results that show inverse associations. Moreover, the case-crossover analysis accomplished a test of whether a change in exposure status preceded the abrupt onset of assault, which compared with the case-control analysis provided a

Table 4. Conditional Logistic Regression Odds Ratios Estimating the Association Between Tree Cover and Gunshot Assault on Weekdays, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011

Model Parameter	Case-Control			Case-Crossover		
	OR	95% CI	*P* Value	OR	95% CI	*P* Value
Base model[a]	0.67	0.50, 0.90	0.009	0.54	0.31, 0.94	0.030
Age <18 years	0.45	0.25, 0.79	0.005	0.22	0.07, 0.67	0.008
Age ≥18 years	0.71	0.43, 1.16	0.173	0.73	0.38, 1.40	0.340
Full-adjustment model[b]	0.67	0.50, 0.91	0.010	0.47	0.26, 0.82	0.008
Low-income areas	0.65	0.48, 0.87	0.004	0.47	0.26, 0.83	0.010
Leaf season, yes	0.72	0.48, 1.09	0.121	0.53	0.26, 1.09	0.084
Leaf season, no	0.49	0.26, 0.93	0.029	0.35	0.13, 0.94	0.037

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] Base model adjusted for tree cover and leaf season.
[b] Full-adjustment model stratified by either low- or high-income areas or leaf season, and adjusted for sociodemographic factors or environmental variables, including connectedness among neighbors, income, presence of nearby alcohol outlets and drunkenness and disorderly conduct, vacant lots and vandalism and violence, fire stations and police stations, race and ethnicity, prevalence of household gun ownership, proportion of the population aged 15–24 years, prevalence of recreation centers, and school truancy. Full-adjustment model in high-income areas would not converge due to limited sample size.

Table 5. Conditional Logistic Regression Odds Ratios Estimating the Association Between Tree Cover and Gunshot Assault on Weekends, Space-Time Adolescent Risk Study, Philadelphia, Pennsylvania, 2008–2011

Model Parameter	Case-Control			Case-Crossover		
	OR	95% CI	*P* Value	OR	95% CI	*P* Value
Base model[a]	0.76	0.48, 1.23	0.266	0.53	0.21, 1.34	0.179
Age <18 years	0.74	0.16, 3.48	0.705	0.93	0.13, 6.37	0.937
Age ≥18 years	0.81	0.54, 1.21	0.301	0.44	0.15, 1.26	0.127
Full-adjustment model[b]	0.81	0.42, 1.56	0.524	0.80	0.28, 2.31	0.679
Low-income areas	0.81	0.41, 1.59	0.541	0.80	0.28, 2.31	0.679
Leaf season, yes	0.57	0.22, 1.50	0.255	1.77	0.37, 8.43	0.474
Leaf season, no	0.78	0.06, 10.00	0.847	0.07	0.01, 0.60	0.018

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] Base model adjusted for tree cover and leaf season.
[b] Full-adjustment model stratified by either low/high income areas or leaf season, and adjusted for sociodemographic factors or environmental variables including connectedness among neighbors, income, presence of nearby alcohol outlets and drunkenness and disorderly conduct, vacant lots and vandalism and violence, fire stations and police stations, race and ethnicity, prevalence of household gun ownership, proportion of the population aged 15–24 years, prevalence of recreation centers, and school truancy. Full-adjustment model in high-income areas would not converge due to limited sample size.

more rigorous test of whether locations of tree cover and locations of assault were associated.

Measures of exposure to green space are often area-based, where green space and/or human presence are aggregated to administrative boundary levels (e.g., percentage of green space related to population or health statistics by census boundary or municipality), which can pose challenges to testing causal hypotheses and generalizability (23). The present study uses a more dynamic space-time measure of exposure to green features within participants' routine activity spaces.

There was no consensus in study models about the association between tree exposure and gun assault when stratifying by leaf season. Note that deciduous trees lose their leaves in general in October and then regrow leaves in April. Also, results from models stratified by weekday versus weekend showed that the inverse association between tree cover and gun assault was stronger on weekdays than on weekends. It could be fruitful to pursue qualitative research into whether and why leaf season or week period may modify the association between tree cover and assault that we have found here.

More generally, though, we understand already that there are multiple pathways by which green space may alter the environmental context in which opportunities for violence exist. Increased green space may increase social interactions between neighbors, and such interactions may be important to the development of collective efficacy, or the sharing of mutual trust and willingness to intervene for the common good (24, 25). Collective efficacy is associated with decreased fear and violence (26), and the informal surveillance, or "eyes on the street," that develops as a result of more residents participating in and observing day-to-day activities in a neighborhood may help deter violence (27).

Mental health is related to exposure to nature or green space (or lack thereof), which can have implications for crime or violence. Mental fatigue and stress associated with living in low-income urban communities may lead to inattention, decreased control over impulses, and irritability, all precursors to aggressive and violent behavior (28–30). Neighborhood characteristics influence residents' sense of safety and well-being, and can be linked to symptoms of depression (31).

On the other hand, people living in urban settings with more green space report less psychological aggression and violent behavior, a relationship explained through differences in attention restoration (28). Further, access to green views is associated with improved overall mental health (32), and it has been found to mitigate stress, mental fatigue, anxiety, and depression (33–36), especially in urban environments (34, 37–41). Spending time in a vegetated setting has been shown to be effective therapy for stress-related mental health issues (42). In a blighted urban environment, there were lower levels of self-reported high stress around newly-greened vacant lots (43). In addition, a small randomized trial found that participants had lower ambulatory heart rate (a measure of stress), when they walked in view of "clean and greened" vacant lots versus in view of untreated vacant lots (44).

Temperature moderation is another way in which urban green space might influence violence. Densely developed urban areas experience a heat island effect, which can increase discomfort for residents. There are established relationships between temperature and violent crimes as well as "aggressive" crimes such as domestic violence and nonaggravated assaults, using localized data accounting for temporal variation (45–48). The relationship could be stronger for violent than for nonviolent crimes (47). Multiple possible mechanisms exist; for example, field studies have demonstrated that with increased heat comes increased aggression (49). An increased vegetation or tree canopy in areas of dense development could mitigate this effect (50).

This study has limitations. Information bias from poor recall or untruthful responding is a threat to the validity. However, there is evidence that these issues are not present at a level that is problematic (17). With the key exposure in this analysis being subjects' proximity to tree cover, it is important to consider the accuracy of these data. Consider that the primary aim of the parent study was to investigate whether spending time around alcohol outlets and other environmental features related to assault risk. Yet interviewers made no mention of these to the subjects during the mapping exercise used to collect these data, nor did they mention our interest in tree cover; thus, we have no reason to expect response bias on this exposure. The tree cover data were measured in one year but were used to classify subjects reporting activities for that year and several years later. Perhaps, then, some misclassification bias occurred. We expect this would be nondifferential by case status and that if anything results would be biased toward the null.

The participation rate was 57% among both cases and controls, so nonparticipation bias should also be considered. Controls were recruited only from homes with a landline telephone, whereas cases were recruited regardless of their telephone status. A concern is that income and telephone type may be related. We do not know how many of the case subjects did not have a landline telephone; however, we did report more direct evidence that cases and controls did not differ regarding income levels where they resided. This provides assurance that the controls did not differ systematically from the base population. For cases, we enrolled only patients who survived an assault. We know of no literature or clinical evidence suggesting that a disparity exists systematically between urban violence assault victims who live versus die, and we therefore judge this threat to validity as minimal.

Our findings relate to a growing body of studies that find an association between urban green space and violence. In another study set in Philadelphia, a higher prevalence of green exposure was associated with lower levels of violent crime (51). A quasiexperimental study found that gun violence was significantly less common around vacant land that had been cleaned and greened compared with proximity to untouched vacant land (43). In Chicago, a natural experiment conducted at a public housing development found that more vegetation was associated with a decrease in violent crime (28).

Existing efforts or plans to expand green space by municipalities are often expected to provide conditions that will lead to improvements in general quality of life or physical health, such as increased physical activity or improved air quality (52). Our findings provide further evidence that the potential for violence reduction could be considered an added benefit. Local and state policy makers, including law enforcement officials, urban planners, and elected officials interested in expanding their violence prevention efforts could consider adding a component of urban greening to existing initiatives. While urban greening targeted to high crime areas would be experimental at the current time, it would provide opportunity for meaningful collaboration for design and evaluation between public health researchers, community, and local government.

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