Longitudinal Association between Greenspace and Type 2 Diabetes: Evidence from MESA

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Abstract

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This study aimed to evaluate the longitudinal association between the abundance of nearby greenspace in urban and suburban environments and incident type 2 diabetes mellitus (T2DM). Data was used from the Multi-Ethnic Study of Atherosclerosis (MESA). Normal Difference Vegetation Index (NDVI) was used as a proxy for greenspace. Exposure categories used NDVI median values from two time-periods (annual and high-vegetation season) and three buffer radii (500m, 1km, and 2.5km). Incident T2DM cases were identified from fasting glucose levels and medication review. Using Cox proportional hazards regression, we estimated hazard ratios (HRs) of incident T2DM associated with greenspace, adjusting for covariates including demographics, family history of T2DM, socioeconomic status, and neighborhood factors. The skewed distribution of NDVI values prompted the exclusion of participants from Forsyth County, NC. There were 659 incident T2DM cases (11.2%). For 1km exposure categories excluding NC participants, HRs for incidence T2DM were 0.95 (0.74 – 1.21), 0.78 (0.55 – 1.07), and 0.82 (0.55 – 1.24) for high-vegetation season median and 0.93 (0.72 –

1.20), 0.79 (0.58 – 1.07), and 0.72 (0.50 – 1.06) for annual median for increasing quartile of greenspace exposure compared to the lowest quartile. Overall, the results of this study were null, but showed a protective effect in point estimates with increasing greenspace exposure. The null results could be because there is no association between greenspace and T2DM or could be due to study limitations including insufficient statistical power, NDVI measurement error, or the validity of NDVI as a proxy for greenspace. More research is needed to give a better estimate of the effect of greenspace on T2DM.

Background:

Type 2 diabetes mellitus (T2DM) is a growing health concern worldwide, with the global prevalence of diabetes increasing from 4.7% to 8.5% from 1980 to 2014 (1). The CDC estimated that in 2015, 12% of the US population was living with diabetes, representing over 30 million Americans, but only about 75% of those cases had been diagnosed (2). Among 45-64-year olds, the 2015 incidence in the US was estimated at 10.9 new diagnosed cases per 1,000 individuals (2). Obesity and being overweight, genetic factors, and stress are known risk factors for T2DM (3,4). Behavioral and lifestyle factors such as improved diet and increased exercise are associated with decreased risk for diabetes.

Local policy makers and urban planners view parks, recreation areas, green belts, community gardens, and other urban greenspaces as promoting healthy choices and improving health outcomes. In prior studies, greenspace has been associated with decreased stress (5–7), improved mental health (7,8), reduced cardiovascular morbidity (9), and improved pregnancy outcomes (10). Some of the pathways urban greenspace have been hypothesized to improve health outcomes is by reducing exposure to harmful environmental factors and, at the individual level, increasing availability and accessibility to healthy choices (11). Greenspace has been shown to reduce air pollution (12), the heat island effect (13), and noise pollution (14). Meta-analyses have found that both noise and air pollution may be risk factors for the development of T2DM (15,16), suggesting these environmental factors may be possible pathways for an association between greenspace and T2DM in addition to other pathways including lifestyle choices like exercise.

Several recent studies have explored the association between T2DM and greenspace using primarily cross-sectional study designs (17–21). All but one of these studies (20) found an inverse association between greenspace and diabetes. However, none of these studies have focused on a US population, with previous studies located in Europe, Australia, and Canada. Furthermore, few of these studies have focused on urban greenspaces, but rather included more rural populations as well (17–19). Prior studies in the Multi-Ethnic Study of Atherosclerosis (MESA) cohort have demonstrated associations between neighborhood-level factors, including physical activity and food access, and incident T2DM, but did not include greenspace among these factors (22).

The aim of this study was to evaluate the longitudinal association between the abundance of nearby greenspace in urban and suburban environments and incident T2DM.

Methods:

This study was conducted using data from the Multi-Ethnic Study of Atherosclerosis (MESA) and its ancillary studies the MESA Air Pollution Study (MESA Air) and MESA Neighborhoods Study. The MESA study was a prospective cohort study aimed to study subclinical cardiovascular disease. It consisted of 6 exams including baseline exam and recruited non-institutionalized adults who were cardiovascular disease-free at baseline, aged 45-84 years, who self-identified as white, black, Hispanic, or Chinese from 6 study sites: New York, NY, Baltimore, MD, Forsyth County, NC, Chicago, IL, St. Paul, MN, and Los Angeles, CA. The MESA Air study aimed to study the association between air pollution and cardiovascular health. It collected

extensive data on key air pollutants in MESA Air communities and combined this data with meteorological and geographical data to develop air pollution exposure models of these communities. The MESA Neighborhoods study was designed to capture data on neighborhood factors such as crime, social cohesion, and built environment in MESA communities to better study neighborhood effects within the main MESA study. For this study, data from exams 1-5 of the main MESA study were used for outcome and covariate data. MESA Air data were used for the exposure variables and MESA neighborhood data were use for neighborhood-level covariates.

Outcome:

T2DM status was determined at each follow-up exam for study participants using both fasting glucose levels and medication review. Using 2003 criteria from the American Diabetes Association (23), incident cases were defined as having a fasting glucose level of at least 126 mg/dL or use of insulin or oral antihyperglycemics. While this study considered all incident cases as T2DM, these cases may include some patients who developed Latent Autoimmune Diabetes in Adults (LADA) rather than T2DM, and additional clinical information to distinguish between these diseases was unavailable. Since incident LADA is less common among adults 50+ (24), it is expected that most of the incidence cases were T2DM cases. Because of the uncertainty of the exact time of diabetes incidence, the date of incidence for T2DM cases was assigned to midway between the last T2DM-free exam and the exam with an indication of T2DM.

Exposure:

Normal Difference Vegetation Index (NDVI) data from the MESA Air study were used as a proxy for the abundance of nearby greenspace in this study. NDVI is a measure of greenness based on satellite imagery of surface reflectance that is often used in greenspace studies (25,26). NDVI measures greenness by measuring the ratio of red and infrared reflected light, which changes for vegetative surfaces. Photosynthetic activity absorbs red light while reflecting infrared light. Less active or dying plant matter absorbs less red light, and non-vegetated areas reflect more light across the light spectrum. NDVI is often presented as a ratio ranging from -1 to 1 with values of 0 to 1 representing greenness measures, but researchers from the University of Maryland converted NDVI data from NASA to the 0 to 255 pixel brightness scale that was used for this study (27). On this scale, areas with dense vegetation have values around 200 and values lower than 50 are considered non-vegetative surfaces (i.e. roads and buildings). For this study, satellite imagery from 2006 was used to calculate NDVI measures.

Since this study is limited to more urban locations, the NDVI greenness measure can be used as proxy for greenspace as it is not likely to capture large amounts greenness from non-public access greenspace (e.g. large backyards, agricultural land, golf courses) and more accurately reflects greenspace available to the general public. This study used six different NDVI exposure categories (500m annual median, 500m high-vegetation season median, 1km annual median, 1km high-vegetation season median, 2.5km annual median, and 2.5km high-vegetation season median) from three buffer radii (500m, 1km, 2.5km) and two time periods (median NDVI measure of the

entire year and the median of the 'high-vegetation' season, defined as April 1st to September 30th). The different time periods were used because NDVI measurement can change dramatically across seasons. Participants' residence at time of baseline exam was used as the center for each buffer area. Exposure measurements were calculated as the average of NDVI values for each pixel within the buffer radius. Based on prior research (17,21), 1km was expected to have the strongest association among these radii and was considered the *a priori* exposure metric of interest; 500m and 2500m radii exposure categories were used in sensitivity analyses.

For each NDVI exposure category, participants were classified by quartile, as in prior greenspace research (18,19). Because of the skewed distribution of NDVI quartiles by study site, the relationship between NDVI and T2DM was modeled using a continuous NDVI variable in addition to NDVI quartile comparison.

Covariates:

Time-invariant covariates included in this study were sex, race/ethnicity, education level, family history of T2DM, study site, wealth index, and neighborhood social cohesion, safety, and walkability survey scores. Race/ethnicity categories were white, black, Hispanic, and Chinese. Education level was categorized as less than or equal to high school degree/GED, some college with no degree, and greater than or equal to college degree. Family history of T2DM was coded dichotomously from responses to a family medical history questionnaire answered at exam 2. The wealth index was calculated using data on self-reported ownership of house, land, car, and investments. The wealth index was categorized as low, moderate, and high with low

defined as no assets reported, moderate as 1 or 2 assets reported, and high as 3 or 4 assets reported.

Social cohesion, safety, and walkability scores were weighted averages by census tract based on survey responses from MESA participants and a random sample of people living in the same census tracts as MESA participants, as in prior MESA research (28). Social cohesion was measured with a four-item scale including items about willingness to help neighbors, getting along with neighbors, neighborhood trust, and sharing values with neighbors. Safety was measured using a two-item scale about feeling safe in one's neighborhood and violence in the neighborhood. Walkability was measured using a four-item scale about ease of walking to places in the neighborhood, seeing others walking or exercising, and pleasantness of walking in the neighborhood. Each survey item response ranged from 1 (strongly agree) to 5 (strongly disagree). Questions were reverse coded so that higher values were associated with more desirable/favorable outcomes. Census tract-level scores for participants were calculated using an empirical Bayes estimate (29) and weighted to account for respondents' gender, age, study site, and whether in MESA or community sample. For participants in census tracts with few responses, estimates included respondents from nearby census tracts.

Time-varying covariates included age, chronic stress, alcohol consumption, income, smoking status, and neighborhood deprivation index (NDI). Chronic stress was determined from questionnaires given at exams 1 and 3 similarly to prior MESA research using the Chronic Burden scale (30). Participants were categorized as chronically stressed if they responded that they had had 6+ months of relationship-, job-

, or financial-related strain/difficulties for themselves or 6+ months of medical-related problems for themselves or someone close to them. As in prior MESA research (22) alcohol consumption was categorized as heavy, moderate, and not current drinker at exams 1-4. Heavy alcohol use was defined as more than 14 drinks per week or more than 4 drinks in one day in last 30 days for males and more than 7 drinks per week or more than 3 drinks in one day in last 30 days for females. Moderate alcohol use was defined as reported alcohol consumption under heavy-use thresholds. Participant income was calculated from total annual household income divided by number of household members and categorized as <$12,000, $12,000 - $24,999, $25,000 - $39,999, $40,000 - $74,999 and $75,000+ from data available from exams 1, 2, and 3. Smoking status was categorized as current, former, and never using data available from exams 1-4. A neighborhood deprivation index (NDI) was developed from U.S. Census and American Community Survey data (31–33). Higher index values indicate greater neighborhood deprivation (i.e. lower neighborhood socioeconomic status (SES)) (34). For all time-varying covariates, data were carried forward if missing from future follow-up exams.

Statistical Approach:

Descriptive statistics examined the distribution of NDVI quartile by study site. Cox proportional hazards regression models were used to estimate the individual-level hazard ratio (HR) of T2DM risk for each NDVI exposure category. Participants were considered at risk until an indication of T2DM at a follow-up visit, last follow-up visit, or administrative censoring at exam 5, whichever occurred first. Despite internal censoring

of these data, Cox proportional hazards regression was used to better account for the time-varying confounders in these analyses rather than using more complex approaches needed to account for time-varying confounders with interval-censored models.

Potential confounders were determined *a priori* using a causal diagram (Figure 1) and were added in stages to the model. Model 1 adjusted for sex, race/ethnicity, age, and study site. Model 2 adjusted for education level, income, smoking status, alcohol consumption, and family history of diabetes as well as the covariates in Model 1. Model 3 adjusted for chronic stress, neighborhood deprivation index (NDI), and survey-based scores for neighborhood walkability, safety, and social cohesion in addition to the covariates used in model 2. Model 3 was considered the primary model for these analyses because it is most comprehensive in terms of confounder adjustment.

For the continuous scale NDVI exposure models, HR estimates were calculated for an increase in interquartile range (IQR) with the IQR calculated for each exposure category. For quartile comparison models, quartile 1, the lowest NDVI exposure quartile, was the reference group for all comparisons. A decrease in HR estimates was expected for both comparisons.

Of the initial MESA enrollees, we excluded individuals with prevalent diabetes (n = 883) and individuals with missing NDVI exposure data (n = 71), resulting in a study population of 5,860 individuals.

Sensitivity Analyses:

Based on the skewed distribution of NDVI exposure by quartile and study site

and an *a priori* concern about the more suburban and rural makeup of Forsyth County, NC, sensitivity analyses were conducted excluding participants from this study site. Additional sensitivity analyses were conducted to restrict participants to those who had lived at their residence for at least 2 years. While we are uncertain about the exposure period for any potential protective effect of nearby greenspace, this sensitivity analysis aimed to restrict the analysis to participants with more accurate long-term greenspace exposure data. Lastly, a sensitivity analysis was conducted without adjusting for study site and excluding participants from Forsyth County, NC.

Results:

Among study participants, the mean follow-up time was 7.56 years and there were 659 incident cases of T2DM (11.2% developed T2DM). Incident cases were more likely to have lower incomes, a high school education or less, family history of T2DM, or identify as black or Hispanic (Table 1).

For all NDVI buffer radii, the difference between mean NDVI exposure categories for high-vegetation season median to annual median was approximately 14 index points but varied widely between study sites. The mean and standard deviations were roughly equal across buffer radii of the same period (high-vegetation season vs. annual medians). An IQR increase for the 1km NDVI categories corresponded to a 72- and 56-point increase in NDVI measurement for the high-vegetation season and annual median categories respectively, and similar IQR values were seen for 500m and 2.5km exposure categories (Table 2). NDVI quartile categorization resulted in an unequal distribution by study site (Figure 2). No participants from the Forsyth County, NC study

site had NDVI values below the median NDVI value for any exposure category. While not as extreme as Forsyth County, NC, other sites, like St. Paul, MN, also showed skewed distribution by quartile categorization.

Using the continuous scale with an IQR change in NDVI for 1km buffer radius, estimates were similar across exposure categories with a the high-vegetation median associated with 27% lower risk [HR, 0.73 (CI 95% 0.53 – 1.00)] and annual median association with 23% lower risk [HR, 0.77 (CI 95% 0.59 – 1.01)], but these estimates were not statistically significant (Table 3). Using participants from all study sites and compared across quartiles, the 1km radius high-vegetation season exposure category showed a protective effect for each quartile comparison in the fully adjusted model, but these results were imprecise [HR, Q2 0.92 (CI 95% 0.70-1.21), Q3 0.90 (CI 95% 0.58 – 1.38), and Q4 0.75 (CI 95% 0.43 – 1.38)]. For the 1km buffer radius using annual median exposure category, point estimates also showed a protective effect [Q2 0.78 (CI 95% 0.61 – 0.99), Q3 0.70 (CI 95% 0.52 – 0.94), Q4 0.95 (CI 95% 0.61 – 1.48)]. For sensitivity analyses with exposure categories of 500m and 2.5km, fully adjusted models were similar to 1km estimates, with quartile 4 associated with weaker results than quartile 3 and wide confidence intervals (Table 4).

For NDVI exposure categories using the 1km buffer radius and excluding participants from Forsyth County, NC, fully adjusted models showed narrower confidence intervals for quartile 4 estimates. For 1km annual median estimates, this resulted in an increasing protective effect with increased NDVI quartile by point estimates, but none of the estimates were statistically significant (Table 5). For 500m exposure categories, point estimates decreased for quartile 4, but there was not an

increase in protective effect in the point estimates from quartile 3 to quartile 4 (Table 6). For 2.5km exposure categories, point estimates decreased but confidence intervals remained wide for quartile 4, and there was little change in point estimates from quartile 3 to quartile 4 (Table 6).

Sensitivity analyses excluding participants who reported living at their residence at baseline for less than 2 years and participants from Forsyth County, NC had similar point estimates and CIs to analyses just excluding participants from Forsyth County, NC for 1km NDVI exposure categories (Table 7). Not adjusting for study site and excluding participants from Forsyth County, NC for 1km exposure categories was associated with weaker protective effects for the quartile 4 comparisons and IQR increase than results just excluding Forsyth County, NC participants (Table 8).

Discussion:

Overall, the findings showed null results. The exclusion of Forsyth County, NC study participants resulted in HRs in the expected direction of decreased risk with increased quartile of NDVI, but results were not statistically significant. The wide confidence intervals and null results may indicate that there is no association between greenspace and T2DM or may be due to study limitations including insufficient statistical power, NDVI measurement error, the validity of NDVI as a proxy for greenspace, under adjustment for clustering of participants, or the high correlation between greenspace and study site. The imprecise results suggest this study may have been underpowered to detect the association of interest, possibly because this association is weaker in this study population than the power calculation accounted for. The exclusion of Forsyth

County, NC participants in sensitivity analyses further reduced the statistical power.

The stronger protective effect in point estimates after the exclusion of participants from Forsyth County, NC suggests that the inclusion of this more rural and suburban area was biasing the study results. This is in line with existing literature that NDVI is a less reliable proxy for greenspace in non-urban areas (35). While it was known that some participants from Forsyth County, NC lived in more rural areas, some of the other study sites covered wider geographic areas that may have included more suburban areas, like the Baltimore site. This may have reduced the accuracy of the NDVI variable as a proxy for greenspace by capturing non-public greenspace in these more suburban areas. Closer examination of these communities and adjusting for suburban versus urban or further restricting the population to urban areas may increase the accuracy of the NDVI variable. This potential disparity in urban/suburban makeup by study site may also explain some of the skewed distribution of NDVI quartile by study site.
Similarly, this study did not account for spatial clustering among participants within sites. While drawing from several large cities, the study sites had different amounts of clustering among study participants but adjusting for spatial clustering was outside the scope of this study.

The high correlation between study site and greenspace was another possible explanation of the overall null results, prompting the sensitivity analysis without study site adjustment. The reduction of the protective effect towards the null in point estimates for both IQR and quartile 4 comparisons without adjusting for study site suggests that, despite a potentially high correlation with greenspace, study site is confounding this association and should be included in these models.

The 1km and 500m categories had slightly more protective and precise estimates than 2.5km categories, but no clear conclusions about the role of time period or buffer radius can be made due to the overall imprecision of estimates across all categories. Unlike prior studies, this study included participants living across diverse eco-system regions within the US and the range from high-vegetation season median to annual median was highly site-specific. More research is needed to understand how these differences in NDVI calculation impact the potential association with T2DM across different regions in the US and how this interacts with other downstream neighborhood factors and lifestyle choices. As greenspace research is still a burgeoning topic, future research should consider including additional buffer sizes, as this study's estimates were similar across buffer radii and inconclusive.

While this study did not account for changes in NDVI over time, the abundance of greenspace was not expected to vary greatly within the follow-up period for this study because of the urban nature of most of the study sites. But additional questions remain about the temporal relationship between greenspace exposure and T2DM incidence. More research is needed to understand what the appropriate lag time and meaningful exposure time period is for greenspace. This study included a sensitivity analysis restricting to participants who reported living at their baseline residence for at least 2 years to more accurately capture long-term NDVI exposure. But this study could not further explore greenspace exposure and duration earlier in life, which may have a stronger association with T2DM as younger populations may be more likely to make changes to their lifestyle in general and based on nearby greenspace.

Another challenge for this study is the interpretation of greenspace exposure.

This study used NDVI as a proxy for greenspace abundance with the assumption that greenspace abundance is closely related to greenspace usage. While greenspace abundance is hypothesized to be directly connected to potential mediators like air and noise pollution, greenspace abundance and usage are both important factors for potential mediators like exercise and stress reduction. In this study, data on greenspace usage was not available and additional research is needed to detangle the effects of these closely related exposures and these potential mediators. While the inclusion of covariates in models for this study was large driven by the hypothesized causal diagram (Figure 1), this model may represent an overly simplified relationship between key potential mediators and other covariates. Future analyses aimed at understanding the effect of potential mediators need to carefully consider the complex relationship between these mediators and other covariates.

To be more statistically robust, this study could be further improved by accessing for a trend across quartile estimates. Possible trend tests such as the Tarone and Logrank test for hazard models should be considered. To further address the skewed distribution of greenspace exposure by study site, quartiles could be calculated within each study site, rather than for the entire study population. This would reduce the correlation between study site and NDVI quartiles and may reduce the bias in the final estimates.

Similarly, other approaches could be considered to reduce the bias associated with the Forsyth County, NC site without losing as much statistical power. Possible solutions include an outlier evaluation to exclude individuals with the highest greenspace values, as these participants are most likely to live in rural areas. Another

possible approach would be to restrict Forsyth County, NC participants to those whose exposure values fell within two standards deviations of the mean for the remaining study sites exposure values. These approaches would likely include more study participants than the sensitivity analyses that excluded all Forsyth County, NC participants, increasing study power, and would likely reduce the bias associated with the inclusion of study participants from more rural areas.

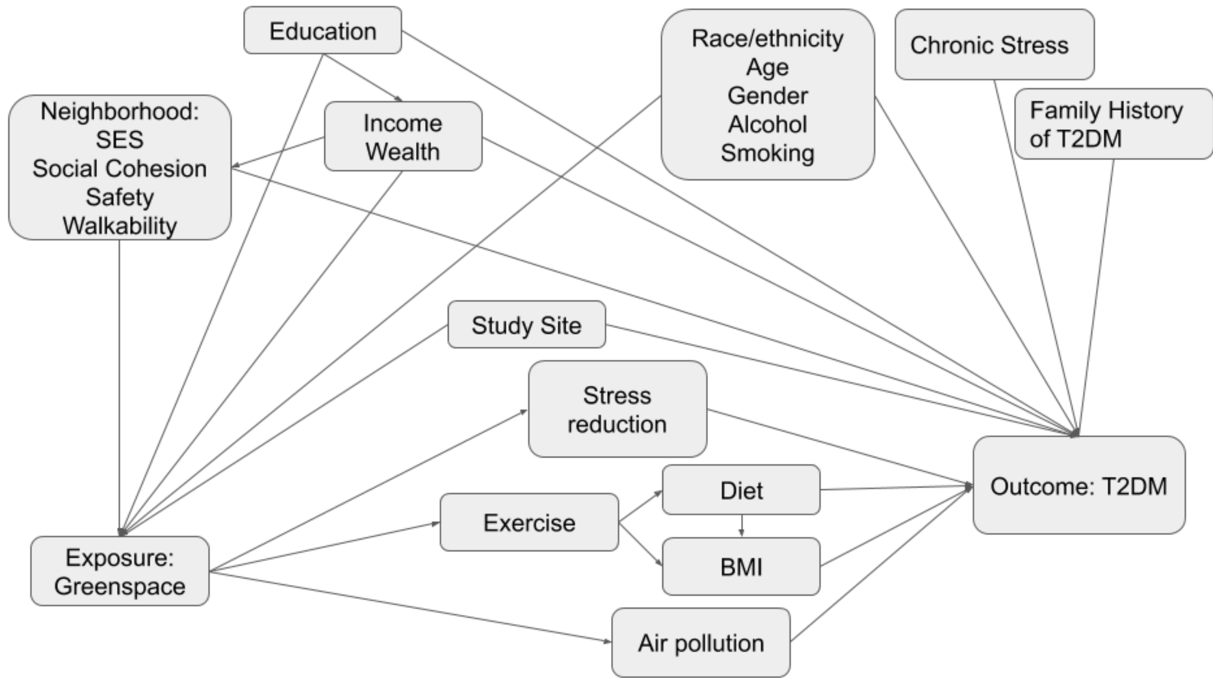
While NDVI as a proxy for greenspace has been used in the past and is considered a validated measure of greenness, other approaches like Light Detection and Ranging (LiDAR) or machinery learning algorithms may be better able to distinguish between parks and vegetation types (35). These approaches may yield more accurate exposure measures than NDVI proxies can offer and have been used in recent greenspace research (36,37). Closer examination of these various exposure measurements is needed to determine the best measure of greenspace for future research questions.

Despite these various limitations, this study has many strengths. It is the first known study to look at this association within the US population. It has a racially and ethnically diverse population and draws from cities across many regions of the US. It also benefited from MESA's rich longitudinal covariate data, including validated measures of neighborhood factors like SES and walkability.

The restriction to existing geocoded variables within the MESA dataset did however limit this study's ability to explore the effect of suburban versus urban areas. It is also possible that the association between greenspace and T2DM is weaker among older adults, who may be less likely to exercise and make changes to their lifestyle.

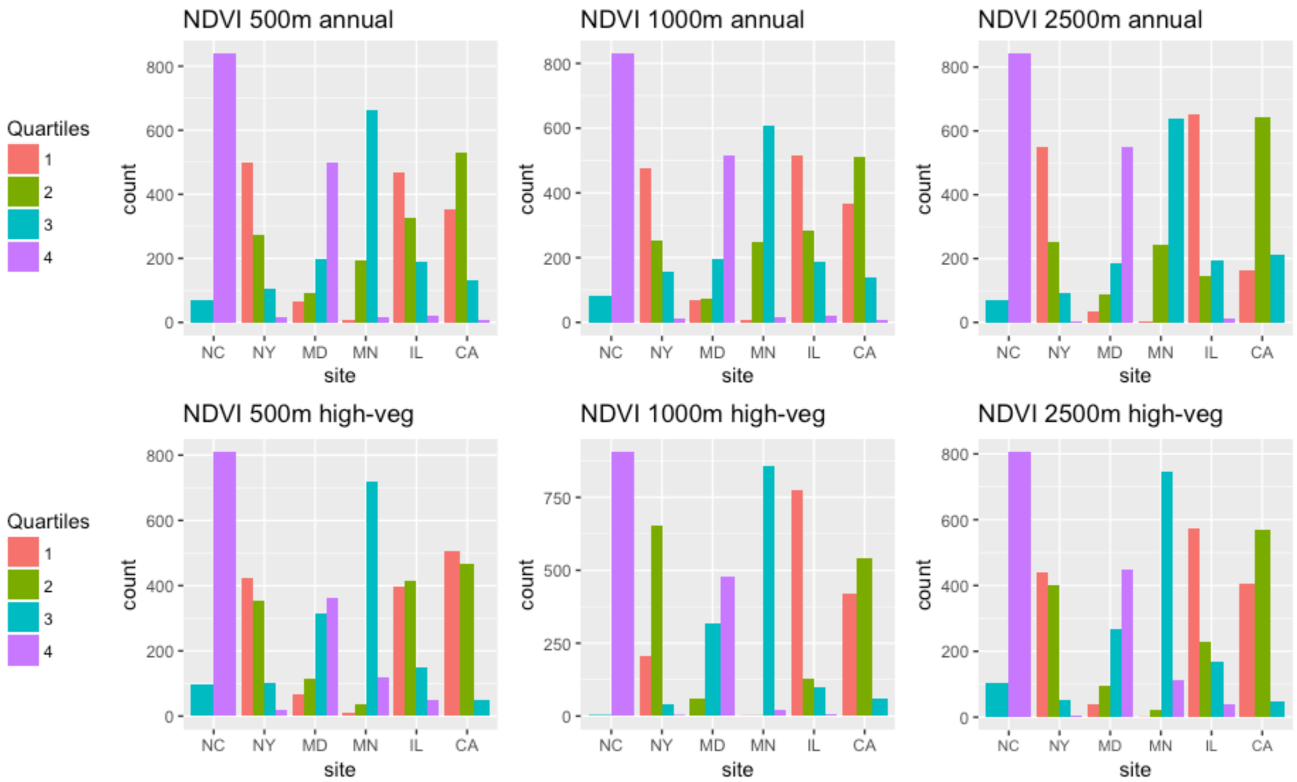
Furthermore, repeating this study in a nationwide population with more urban areas across the country would increase the exposure variability and accuracy of NDVI as a proxy for greenspace and give a better estimate of the true effect of greenspace on T2DM.

Figure 1: Causal diagram depicting potential confounders, precision variables, and mediators for the greenspace and type 2 diabetes mellitus (T2DM) association



SES: Socioeconomic status

Figure 2: Distribution of study participants by study site and Normal Difference Vegetation Index (NDVI) quartile for each NDVI exposure category



NC: Forsyth County, NC
NY: New York, New York
MD: Baltimore, Maryland
MN: St. Paul, Minnesota
IL: Chicago, Illinois
CA: Los Angeles, California
High-veg: High-vegetation season defined as April 1st – September 30th

Table 1: Characteristics of total population at baseline exam and participants who did and did not develop type 2 diabetes mellitus (T2DM) during study period

	Total population	T2DM Case	
		Yes	**No**
	(N= 5,860)	(n= 659)	(n= 5,201)
Age (years) – n (%)			
45-54	1,757 (30)	205 (31)	1,552 (30)
55-64	1,607 (27)	202 (31)	1,405 (27)
65-74	1,692 (29)	187 (28)	1,505 (29)
75-84	804 (14)	65 (10)	739 (14)
Race/Ethnicity – n (%)			
White NH	2,422 (41)	202 (31)	2,220 (43)
Chinese NH	690 (12)	79 (12)	611 (12)
Black NH	1,532 (26)	203 (31)	1,329 (26)
Hispanic	1,216 (21)	175 (27)	1,041 (20)
Sex – n (%)			
Female	3,141 (54)	340 (52)	2,801 (54)
Education – n (%)			
HS degree/GED or less	2,002 (34)	250 (38)	1,752 (34)
Some college[1]	1,678 (29)	199 (30)	1,479 (29)
Bachelors' or more	2,159 (37)	209 (32)	1,950 (38)
Missing	*21*	*1*	*20*
Alcohol Use[2] – n (%)			
Never/not current drinker	2,449 (42)	301 (46)	2,148 (42)
Moderate	2.485 (43)	271 (41)	2,214 (43)
Heavy	888 (15)	84 (13)	804 (16)
Missing	*38*	*3*	*35*
Smoking Status – n (%)			
Never	2,767 (47)	301 (46)	2,466 (48)
Former	2,190 (38)	259 (39)	1,931 (37)
Current	881 (15)	98 (15)	783 (15)
Missing	*22*	*1*	*21*
Family History of T2DM – n (%)			
Yes	1,772 (33)	296 (46)	1,476 (31)
No	3,598 (67)	351 (54)	3,247 (69)
Missing	*490*	*12*	*478*
Participant Income[3] – n (%)			
<$12,000	1,576 (28)	185 (30)	1,391 (28)
$12,000-$24,999	1,629 (29)	201 (32)	1,428 (29)
$25,000-$39,999	1,146 (20)	135 (22)	1,011 (20)
$40,000-$74,999	1,085 (19)	96 (15)	989 (20)
$75,000+	165 (3)	9 (1)	156 (3)
Missing	*259*	*33*	*226*
Wealth Index[4] – n (%)			
Low	638 (11)	68 (10)	570 (11)
Moderate	1,832 (32)	233 (36)	1,599 (32)
High	3,177 (56)	458 (54)	2,819 (57)
Missing	*213*	*0*	*213*
Chronic Stress[5] – n (%)			
Yes	3,525 (61)	400 (61)	3,125 (61)

No	2,276 (39)	257 (39)	2,019 (39)
Missing	*59*	*2*	*57*
Neighborhood Factors – mean (SD)			
Social Cohesion Score[7]	3.54 (0.22)	3.53 (0.25)	3.55 (0.22)
Safety Score[8]	3.63 (0.38)	3.61 (0.38)	3.63 (0.38)
Walkability Score[9]	3.92 (0.31)	3.86 (0.29)	3.93 (0.31)
Neighborhood SES Score[10]	-0.33 (1.38)	-0.06 (1.25)	-0.38 (1.39)

Percentages may not add up to 100% because of rounding
1: Some college includes associate's degree, technical degree and some college and no degree
2: Heavy alcohol use define as more than 14 of drinks per week or more than 4 drinks in one day in last 30 days for males and more than 7 of drinks per week or more than 3 drinks in one day in last 30 days for females. Moderate alcohol use defined as reported alcohol consumption, but under heavy use thresholds.
3: Participant income calculated from total household income divided by number of household members
4: Wealth Index created from self-reported investment, home, land, and car ownership
5: Chronic stress defined as 6+ months of medical related problems for self or someone close or 6+ months of relationship, job, or financial related strain/difficulties
6: Social Cohesion score based on survey responses to 4 questions on neighborhood social cohesion on a 1 to 5 scale and averaged across all responses within the participants' census tract
7: Safety score based on survey responses to 2 questions on neighborhood safety on a 1 to 5 scale and averaged across all responses within the participants' census tract
8: Walkability score based on survey responses to 4 questions on neighborhood walkability on a 1 to 5 scale and averaged across all responses within the participants' census tract
9: Neighborhood socioeconomic score (SES) was derived from weighted scores of census tract level-measure of education attainment, employment, wealth, poverty, and housing characteristics

Table 2: Descriptive statistics of neighborhood abundance of nearby greenspace measured by Normal Difference Vegetation Index (NDVI) by quartile of study participants at baseline exam

	Overall	Lowest Quartile	Quartile 2	Quartile 3	Highest Quartile	Interquartile Range (IQR)
NDVI[1] Category	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Index Points
500m buffer radius[2,3]						
High-Vegetation median[4]	141.77 (39.86)	93.97 (11.67)	122.09 (14.56)	160.07 (15.25)	192.93 (11.80)	72
Annual Median	127.07 (33.57)	87.67 (11.94)	112.37 (6.70)	136.79 (9.39)	174.48 (9.69)	56
1km buffer radius[5,6]						
High-Vegetation median[4]	141.10 (39.30)	91.05 (12.85)	122.97 (14.75)	158.34 (15.30)	191.61 (10.76)	71
Annual Median	126.48 (32.77)	87.91 (13.53)	113.03 (6.35)	136.81 (9.62)	173.21 (9.04)	54
2.5km buffer radius[2,7]						
High-Vegetation median[4]	137.18 (39.39)	91.31 (12.86)	116.81 (12.97)	155.49 (16.72)	189.09 (9.42)	72
Annual Median	138.06 (39.71)	83.15 (13.66)	109.13 (6.12)	134.62 (10.88)	171.55 (7.47)	58

1: NDVI: Normal Difference Vegetation Index (possible range from 0-255)
2: NDVI categories used in sensitivity analyses
3: 500m buffer radius quartiles for high-vegetation season were: Q1 <107, Q2 107-140, Q3 141-178, Q4 >178 and for annual median were: Q1 <102 Q2 102-124, Q3 125-157, Q4 >157
4: High-vegetation season defined as April 1st – September 30th
5: NDVI categories used in primary analysis
6: 1km buffer radius quartiles for high-vegetation season were: Q1 <107, Q2 107-138, Q3 139-177, Q4 >177 and for annual median were: Q1 <103, Q2 103-124, Q3 125-156, Q4 >156
7: 2.5km buffer radius quartiles for high-vegetation season were: Q1 <105, Q2 105-137, Q3 138-176, Q4 >176 and for annual median were: Q1 <99, Q2 99-119, Q3 120-156, Q4 >156

Table 3: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 1km buffer radius exposures

NDVI Exposure Category	**IQR** [1] HR (95% CI)	**Quartile 2** HR (95% CI)	**Quartile 3** HR (95% CI)	**Quartile 4** HR (95% CI)
1km radius – high vegetation season [2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1 [3]	0.89 (0.69 – 1.13)	0.96 (0.72 – 1.21)	1.01 (0.67 – 1.52)	0.89 (0.53 – 1.50)
Model 2 [4]	0.85 (0.65 – 1.11)	0.98 (0.75 – 1.27)	0.97 (0.64 – 1.47)	0.94 (0.55 – 1.60)
Model 3 [5]	0.73 (0.53 – 1.00)	0.92 (0.70 – 1.21)	0.90 (0.58 – 1.38)	0.77 (0.43 – 1.38)
1km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1 [3]	0.90 (0.74 – 1.11)	0.81 (0.64 – 1.00)	0.76 (0.58 – 0.99)	1.05 (0.73 – 1.51)
Model 2 [4]	0.88 (0.70 – 1.10)	0.79 (0.63 – 0.99)	0.72 (0.54 – 0.95)	1.07 (0.73 – 1.58)
Model 3 [5]	0.77 (0.59 – 1.01)	0.78 (0.61 – 0.99)	0.70 (0.52 – 0.94)	0.95 (0.61 – 1.48)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles
2: High-vegetation season defined as April 1st – September 30th
3: Model 1 adjusting for greenspace, sex, age, race/ethnicity, and study site
4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes
5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

Table 4: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 500m and 2.5km buffer radii exposures

NDVI Exposure Category	IQR[1] HR (95% CI)	Quartile 2 HR (95% CI)	Quartile 3 HR (95% CI)	Quartile 4 HR (95% CI)
500m radius – high vegetation season[2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.89 (0.70 – 1.13)	0.88 (0.71 – 1.10)	0.73 (0.54 – 1.00)	0.98 (0.69 – 1.39)
Model 2[4]	0.86 (0.66 – 1.11)	0.86 (0.69 – 1.07)	0.70 (0.51 – 0.96)	0.93 (0.64 – 1.35)
Model 3[5]	0.75 (0.55 – 1.01)	0.87 (0.69 – 1.09)	0.63 (0.45 – 0.90)	0.79 (0.52 – 1.20)
500m radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.91 (0.73 – 1.24)	0.90 (0.72 – 1.12)	0.72 (0.54 – 0.96)	1.06 (0.73 – 1.52)
Model 2[4]	0.89 (0.70 – 1.12)	0.88 (0.70 – 1.10)	0.67 (0.50 – 0.90)	1.06 (0.72 – 1.57)
Model 3[5]	0.80 (0.61 – 1.04)	0.88 (0.69 – 1.11)	0.64 (0.47 – 0.87)	0.92 (0.59 – 1.44)
2.5km radius – high vegetation season		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	1.03 (0.78 – 1.06)	0.98 (0.78 – 1.22)	0.81 (0.58 – 1.15)	0.17 (0.80 – 1.71)
Model 2[4]	1.01 (0.75 – 1.35)	0.98 (0.78 – 1.23)	0.77 (0.54 – 1.10)	0.16 (0.78 – 1.74)
Model 3[5]	0.87 (0.61 – 1.25)	1.05 (0.83 – 1.33)	0.69 (0.47 – 1.03)	1.02 (0.63 – 1.64)
2.5km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	1.02 (0.79 – 1.30)	0.80 (0.76 – 1.26)	0.80 (0.60 – 1.07)	1.11 (0.73 – 1.69)
Model 2[4]	1.00 (0.77 – 1.30)	0.96 (0.74 – 1.23)	0.75 (0.55 – 1.01)	1.12 (0.71 – 1.76)
Model 3[5]	0.88 (0.64 – 1.20)	0.95 (0.73 – 1.23)	0.70 (0.51 – 0.97)	0.92 (0.55 – 1.55)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles
2: High-vegetation season defined as April 1st – September 30th
3: Model 1 adjusting for greenspace, sex, age, race/ethnicity, and study site
4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes
5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

Table 5: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 1km buffer radius exposures excluding study participants from the Forsyth County, NC study site

NDVI Exposure Category	**IQR**[1] HR (95% CI)	**Quartile 2** HR (95% CI)	**Quartile 3** HR (95% CI)	**Quartile 4** HR (95% CI)
1km radius – high vegetation season[2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.88 (0.70 – 1.10)	0.82 (0.73 – 1.16)	0.81 (0.61 – 1.07)	0.89 (0.61 – 1.07)
Model 2[4]	0.84 (0.67 – 1.06)	0.91 (0.72 – 1.15)	0.77 (0.58 – 1.03)	0.83 (0.58 – 1.18)
Model 3[5]	0.80 (0.61 – 1.06)	0.95 (0.74 – 1.21)	0.78 (0.57 – 1.07)	0.82 (0.55 – 1.24)
1km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.92 (0.79 – 1.06)	0.91 (0.71 – 1.16)	0.84 (0.64 – 1.11)	0.83 (0.61 – 1.13)
Model 2[4]	0.89 (0.76 – 1.04)	0.87 (0.68 – 1.12)	0.78 (0.59 – 1.04)	0.76 (0.55 – 1.04)
Model 3[5]	0.86 (0.72 – 1.05)	0.93 (0.72 – 1.20)	0.79 (0.58 – 1.07)	0.72 (0.50 – 1.06)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles
2: High-vegetation season defined as April 1st – September 30th
3: Model 1 adjusting for greenspace, sex, age, race/ethnicity, and study site
4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes
5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

Table 6: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 500m and 2.5km buffer radii exposures excluding study participants from the Forsyth County, NC study site

NDVI Exposure Category	**IQR**[1] HR (95% CI)	**Quartile 2** HR (95% CI)	**Quartile 3** HR (95% CI)	**Quartile 4** HR (95% CI)
500m radius – high vegetation season[2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.89 (0.72 – 1.10)	0.93 (0.73 – 1.17)	0.76 (0.58 – 1.00)	0.86 (0.58 – 1.19)
Model 2[4]	0.85 (0.68 – 1.06)	0.93 (0.73 – 1.17)	0.72 (0.54 – 0.95)	0.82 (0.58 – 1.14)
Model 3[5]	0.81 (0.63 – 1.06)	0.94 (0.74 – 1.21)	0.72 (0.53 – 0.97)	0.79 (0.54 – 1.17)
500m radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.92 (0.79 – 1.08)	1.04 (0.82 – 1.32)	0.77 (0.58 – 1.32)	0.87 (0.65 – 1.18)
Model 2[4]	0.89 (0.75 – 1.06)	0.99 (0.78 – 1.26)	0.74 (0.55 – 0.99)	0.82 (0.59 – 1.13)
Model 3[5]	0.87 (0.72 – 1.07)	1.03 (0.80 – 1.32)	0.75 (0.54 – 1.02)	0.78 (0.54 – 1.13)
2.5km radius – high vegetation season		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.96 (0.75 – 1.22)	1.03 (0.79 – 1.34)	0.83 (0.61 – 1.13)	0.87 (0.60 – 1.26)
Model 2[4]	0.95 (0.73 – 1.23)	1.04 (0.79 – 1.36)	0.82 (0.60 – 1.14)	0.87 (0.58 – 1.28)
Model 3[5]	0.90 (0.66 – 1.23)	1.09 (0.82 – 1.43)	0.82 (0.58 – 1.16)	0.79 (0.50 – 1.26)
2.5km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.97 (0.81 – 1.17)	0.96 (0.74 – 1.25)	0.85 (0.62 – 1.17)	0.95 (0.68 – 1.32)
Model 2[4]	0.97 (0.79 – 1.18)	0.93 (0.71 – 1.21)	0.85 (0.62 – 1.17)	0.88 (0.62 – 1.24)
Model 3[5]	0.93 (0.73 – 1.18)	0.93 (0.70 – 1.22)	0.87 (0.62 – 1.23)	0.85 (0.57 – 1.27)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles
2: High-vegetation season defined as April 1st – September 30th
3: Model 1 adjusting for greenspace, sex, age, race/ethnicity, and study site
4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes
5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

Table 7: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 1km buffer radius exposures excluding study participants from the Forsyth County, NC study site and those who reported living at residence at baseline exam for less than 2 years

NDVI Exposure Category	**IQR**[1] HR (95% CI)	**Quartile 2** HR (95% CI)	**Quartile 3** HR (95% CI)	**Quartile 4** HR (95% CI)
1km radius – high vegetation season[2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.91 (0.73 – 1.14)	0.93 (0.72 – 1.19)	0.85 (0.64 – 1.14)	0.92 (0.65 – 1.31)
Model 2[4]	0.88 (0.69 – 1.13)	0.92 (0.72 – 1.19)	0.82 (0.61 – 1.11)	0.97 (0.60 – 1.26)
Model 3[5]	0.81 (0.61 – 1.08)	0.96 (0.74 – 1.26)	0.81 (0.58 – 1.13)	0.81 (0.52 – 1.24)
1km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	0.94 (0.91 – 1.11)	0.91 (0.70 – 1.17)	0.88 (0.66 – 1.18)	0.89 (0.65 – 1.24)
Model 2[4]	0.93 (0.78 – 1.10)	0.88 (0.67 – 1.14)	0.82 (0.60 – 1.11)	0.84 (0.59 – 1.18)
Model 3[5]	0.88 (0.72 – 1.07)	0.93 (0.71 – 1.22)	0.81 (0.59 – 1.11)	0.75 (0.50 – 1.12)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles

2: High-vegetation season defined as April 1st – September 30th

3: Model 1 adjusting for greenspace, sex, age, race/ethnicity, and study site

4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes

5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

Table 8: Hazard ratios (HRs) for type 2 diabetes mellitus (T2DM) incidence corresponding to an interquartile range (IQR) change in normal difference vegetation index (NDVI) and by quartile for 1km buffer radius exposures excluding study participants from the Forsyth County, NC study site and without adjusting for study site

NDVI Exposure Category	**IQR**[1] HR (95% CI)	**Quartile 2** HR (95% CI)	**Quartile 3** HR (95% CI)	**Quartile 4** HR (95% CI)
1km radius – high vegetation season[2]		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	1.02 (0.88 – 1.19)	0.89 (0.69 – 1.15)	0.90 (0.69 – 1.17)	1.03 (0.80 – 1.34)
Model 2[4]	0.96 (0.81 – 1.13)	0.89 (0.68 – 1.15)	0.88 (0.67 – 1.15)	0.97 (0.73 – 1.28)
Model 3[5]	0.91 (0.75 – 1.11)	0.91 (0.69 – 1.20)	0.90 (0.68 – 1.20)	0.94 (0.68 – 1.30)
1km radius – annual median		Reference Category – Quartile 1 (lowest) NDVI exposure		
Model 1[3]	1.04 (0.93 – 1.16)	0.95 (0.75 – 1.20)	0.90 (0.70 – 1.14)	1.03 (0.70 – 1.31)
Model 2[4]	0.99 (0.88 – 1.12)	0.90 (0.71 – 1.14)	0.81 (0.63 – 1.04)	0.93 (0.72 – 1.21)
Model 3[5]	0.96 (0.82 – 1.12)	0.92 (0.71 – 1.18)	0.78 (0.59 – 1.03)	0.86 (0.63 – 1.18)

1: IQR increase is an increase NDVI equivalent to the different between the values of the 25th and 75th percentiles
2: High-vegetation season defined as April 1st – September 30th
3: Model 1 adjusting for greenspace, sex, age, and race/ethnicity
4: Model 2 adjusting for same as model 1 and education level, income, smoking status, alcohol consumption, and family history of diabetes
5: Model 3 adjusting for same as model 2 and chronic stress, neighborhood deprivation index, and neighborhood scores for walkability, safety, and social cohesion

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