Neighborhood Green Space and Objective Measures of Sleep: The Multi-Ethnic Study of Atherosclerosis (MESA) Sleep and MESA-Air

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Abstract

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Background: Sleep-disordered breathing (SDB), including obstructive sleep apnea (OSA), is a prevalent and underdiagnosed condition with significant health and economic consequences. While individual behaviors and environmental exposures are known contributors to poor sleep, the role of neighborhood green space remains underexplored, particularly using objective sleep measures.

Methods: This study investigates the association between residential greenness—measured by the Normalized Difference Vegetation Index (NDVI)—and polysomnography (PSG)-measured sleep outcomes in 1,543 participants from the Multi-Ethnic Study of Atherosclerosis (MESA) Sleep Ancillary Study. NDVI was assessed within 30m and 300m buffers around participants' homes to capture immediate environmental and neighborhood-scale exposures, respectively. The primary outcome was moderate to severe OSA (AHI ≥15 events/hour), with secondary outcomes including wake after sleep onset (WASO), proportion of sleep time when arterial oxygen saturation (SaO2) falls below 90% (T90), nadir oxygen saturation (SpO2), and oxygen desaturation index (4% desaturation) events per hour.

Results: Fully adjusted models revealed that a one interquartile range increase in annual NDVI within a 300m buffer was associated with a 19% lower prevalence of moderate to severe OSA (PR = 0.81; 95% CI: 0.68, 0.98). Associations at smaller buffer sizes were directionally consistent but not statistically significant. No significant associations were observed for secondary sleep outcomes.

Conclusion: These findings suggest that neighborhood-scale greenness may reduce the risk of sleep apnea, potentially through mechanisms involving increased physical activity and reduced environmental stressors. This study underscores the importance of considering spatial scale in sleep and environmental health research and supports the integration of green infrastructure into urban planning to promote sleep health.

Key Words: Sleep-Disordered Breathing, Obstructive Sleep Apnea, Polysomnography, Greenspace, Social Epidemiology, Neighborhood Health

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Introduction

Sleep problems are medically serious and economically costly. In 2015, insufficient sleep cost the U.S. $411 billion (2.28% of GDP), with projections indicating an increase to $467.7 billion by 2030 (1). Workers with sleep problems are more likely to be injured than those without sleep problems, and 13% of workplace injuries can be attributed to insufficient sleep (2).

A 2016 study by the American Academy of Sleep Medicine (AASM) estimates that Obstructive Sleep Apnea (OSA), a condition marked by repeated interruptions in breathing during sleep, affects approximately 30 million Americans (12% of the U.S. adult population). Among patients with cardiovascular disease (CVD), it is estimated that over 40% also have OSA, though the condition frequently remains undiagnosed. The coexistence of OSA and CVD may trigger several downstream mechanisms, including inflammation, disruption of autonomic nervous system function, endothelial dysfunction, and metabolic alterations such as dyslipidemia, insulin resistance, glucose intolerance, and type 2 diabetes (T2DM) (3–6). The interplay of these mechanisms may contribute to damage to the heart and blood vessels (7–9).

Sleep-disordered breathing (SDB), including OSA, is strongly associated with adverse brain health, including an elevated risk of stroke and various forms of dementia (10). A recent study found that 1% decrease in deep sleep each year is associated with a 27% increase in the risk of dementia for people over age 60 (11). These neurological complications are driven by the interplay of physiological and neurological mechanisms associated with SDB, such as repetitive episodes of nocturnal hypoxemia (low oxygen levels during sleep), sympathetic nervous activation, and cortical arousal (12). These disruptions contribute to neural damage through pathways involving oxidative stress and inflammation and often manifest as excessive daytime sleepiness (13–15).

While individual factors like smoking, alcohol use, and obesity are known risks for sleep problems, upstream neighborhood characteristics can exacerbate or mitigate the effect of these behaviors on sleep (16). Previous sleep studies have linked sleep health to environmental factors such as neighborhood walkability and activity levels (17–19) , social environment (17,20,21), built environment (20,22), and other neighborhood features such as redevelopment

and displacement (21,23,24). Chronic exposure to air pollution and traffic noise is associated with a higher risk of OSA possibly due to airway inflammation and disruptions in autonomic nervous system pathways (25–27). Similarly, lower neighborhood safety scores, indicating reduced social cohesion and increased psychological distress, have been associated with poorer sleep outcomes (27–29).

Conversely, urban trees and canopies have been linked to improved sleep outcomes through pathways such as mitigating heat islands (i.e., reducing temperature), improving mental health, reducing stress, reducing noise, and encouraging physical activity (22,30,31). For example, studies show that while reducing physical noise levels to below 35 dB is essential for an optimal sleep environment, non-auditory factors—mediated by the body's stress responses—can also affect susceptibility to noise. These include annoyance, attitudes toward noise and its sources, and perceived control over the environment, all of which affect sleep (32–34). Research also showed that simply having a visual connection to greenspace can alleviate stress because of its calming effects. For example, one study found that adults with views of greenspace from homes are at a lower risk of anxiety and depression (35). Another study revealed that having a bedroom window overlooking a yard, water or green space was associated with a reduced risk of reporting poor sleep quality (36).

Despite extensive research on environmental factors influencing sleep, the specific relationship between urban greenspace and sleep outcomes remains underexplored, with prior studies reporting limited or inconclusive findings (16). Notably, no research to date has investigated the effects of greenspace on OSA or other polysomnography (PSG)-measured sleep-disordered breathing (SDB)—the gold standard for diagnosing sleep-related breathing disorders, including OSA, central sleep apnea, and sleep-related hypoventilation/hypoxia (37). Previous studies examining greenspace and sleep linkage have relied on self-reported measures such as questionnaires and sleep diaries to assess sleep duration and quality (18,20,29,38–40). This study fills a critical knowledge gap by using objectively measured sleep outcomes to assess the greenspace and sleep association.

The aim of this study is to assess the association between green space proximity, measured by the Normalized Difference Vegetation Index (NDVI), and the prevalence of OSA and other PSG-measures of SDB in the Multi-Ethnic Study of Atherosclerosis (MESA). We hypothesize that

individuals living in proximity to more green areas will have lower prevalence and severity of SDB.

This study examines two primary mechanisms through which greenspace exposure may influence sleep: 1) immediate environmental effects, including reduced noise, improved air quality, and exposure to calming visual stimuli; and 2) neighborhood-level effects, such as increased opportunities for physical activity and social interaction. These mechanisms are assessed using NDVI metrics calculated at multiple spatial scales. Smaller buffers are used to represent immediate environmental exposures, while larger buffers capture broader neighborhood-level influences, as detailed in the Exposure Assessment section. See **Figure S2** for the conceptual model of this study.

Findings from this study quantify the impact of green space access on sleep and can inform policies related to urban planning, air quality, noise monitoring, and other initiatives focused on promoting physical exercise and stress reduction.

Data and methods

Study Design, Setting, and Population

We conducted a cross-sectional analysis to evaluate associations between NDVI and PSG-measured sleep outcomes. Data were drawn from MESA, a population-based longitudinal cohort investigating subclinical cardiovascular disease. Between 2000- 2002, MESA enrolled 6,814 adults aged 45–84 years, who were free of clinical cardiovascular disease at baseline and self-identified as White, Black, Hispanic, or Chinese. Participants were recruited from six U.S. sites: New York, NY; Baltimore, MD; Forsyth County, NC; Chicago, IL; St. Paul, MN; and Los Angeles, CA.

Our data are restricted to MESA participants who had geospatial data and participated in the MESA Sleep Ancillary Study during Exam 5 (2010–2013). Participants underwent in-home polysomnogram for one night with a Compumedics Somte system (Compumedics, Abbotsville, Australia). Recorded data was then transmitted to the centralized reading center at Brigham and Women's Hospital and scored by trained technicians (41,42). Eligibility criteria for the sleep sub-study included: enrollment in Exam 5 of the MESA study, willingness to undergo overnight sleep

monitoring and related assessments, and no medical conditions that would make participation in the sleep study impractical or unsafe (e.g., recent major surgery or severe illness). Participants with a prior OSA diagnosis or using sleep-assistive devices (e.g., oral appliances, nocturnal oxygen, or CPAP) were excluded from MESA Sleep to avoid obscuring OSA-related symptoms and PSG results (43). Of the 4,077 Exam 5 participants approached, 147 (6.5%) were ineligible and 141 participants lived too far to participate. Of the remaining 3,789 participants, 2,261 participated in the sleep exam (59.8%) (**Figure S1**).

Exposure Assessment

The Normalized Difference Vegetation Index (NDVI) data used in this study were obtained from satellite imagery compiled by the U.S. Geological Survey (USGS) and serve as a proxy for green space exposure. NDVI values range from -1 to 1 with lower values (≤0.1) corresponding to little or no vegetation, such as barren rock, sand, or snow, moderate values (0.2 to 0.5) reflecting sparse vegetation, including shrubs, grasslands, or crops in decline, and higher values (0.6 to 0.9) corresponding to dense, healthy vegetation such as that found in temperate and tropical forests or crops at peak growth (44).

Earlier MESA studies used NDVI data with relatively large spatial buffers (250m to 2.5km). The MESA Air study later developed annual and summer NDVI measures at finer spatial resolutions (30m, 60m, 120m, 300m, 600m, 900m, and 1200m) for the years 2000, 2005, 2010, 2015, and 2020. These values were calculated over five-year windows centered on each target year and season (e.g., Fall 2000 represents the median of Fall 1998 to Fall 2002). Because exam 5 sleep measurements were collected between 2010 and 2012, and we hypothesized that green space exposure may have long-term effects on sleep outcomes, we estimated individual greenspace exposure using a weighted average of NDVI values from 2003 to 2007. This exposure window precedes exam 5 sleep assessment by at least three years. NDVI values were extracted within 30m, 60m, 300m, and 900m buffers around each participants' geocoded residential address. Additionally, we used the median rather than the mean to mitigate the influence of outliers caused by temporary disturbances such as cloud cover, drought, or land use changes, providing a robust and reliable measure of vegetation exposure by season and location.

We hypothesized two distinct mechanisms by which green space may affect sleep, given that MESA study sites are mostly urban. See **Table 1** comparing the two mechanisms and NDVI buffer selections.

***Mechanism 1**. Immediate Environmental Effects*

We used the annual median NDVI within a 30 m radius as our primary exposure metric, based on prior research suggesting that smaller radial buffers better capture localized benefits of greenery, such as noise reduction, improved air quality, and calming visual stimuli (34,45,46). In sensitivity analyses, we examined annual median NDVI within 60 m, as well as high vegetation season (April 1 – September 30) median NDVI within a 30 m radius. We used these two time periods because NDVI can vary significantly based on season and location.

***Mechanism 2**. Neighborhood-Scale Physical and Social Activity*

We used the annual median NDVI within a 300 m radius as our other primary exposure metric, aligning with previous MESA studies that used 250 m, 500 m, and 1 km to capture neighborhood-level green space and physical movements that may influence sleep outcomes (47–49). In sensitivity analyses, we examined annual median NDVI within 900 m, as well as high vegetation season (April 1 – September 30) median NDVI within a 300 m radius, following the same seasonal approach used in Mechanism 1 (48,50–52).

Table 1: Mechanisms of green space exposure and NDVI buffer selection

Mechanism	Exposure Metric Description	Averaging Time (Median)	Buffer Size	Analysis Type
Immediate Environmental Effects	Annual median NDVI	Annual	30 m	Primary
			60 m	Sensitivity
	High vegetation season median NDVI (Apr 1 – Sep 30)	Summer	30 m	Sensitivity
Neighborhood-Scale Physical and Social Activity	Annual median NDVI	Annual	300 m	Primary
			900 m	Sensitivity
	High vegetation season median NDVI (Apr 1 – Sep 30)	Summer	300 m	Sensitivity

Outcome Assessment

Table 2 describes each sleep outcome, how it is operationalized and the corresponding measure of effect. Briefly the PSG measurements we selected include apnea-hypopnea index (AHI) events per hour and wake after sleep onset (WASO), which we analyzed as both continuous and dichotomous variables based on established clinical cutoffs. Other outcomes examined included PSG-measured proportion of sleep time when arterial oxygen saturation (SaO2) falls below 90% (T90), nadir oxygen saturation (SpO2), and oxygen desaturation index (4% desaturation) events per hour.

We selected AHI and AHI >15 (moderate to severe sleep-disordered breathing) as our primary outcomes, with other sleep-disordered breathing metrics designated as secondary outcomes.

Covariates

Individual-level and neighborhood-level confounders and precision variables were collected at MESA Exam 5 and selected for inclusion in analyses a priori, based on literature review (see **Figure S3** for the directed acyclic graph).

Individual-level sociodemographic covariates included sex, age, race and ethnicity, education, income, and employment status. Individual health status covariates included body mass index (BMI), depressive symptoms, and perceived stress. Perceived stress was measured using the 10-item Perceived Stress Scale (PSS), a validated instrument that measures the degree to which individuals perceive their lives as stressful. Scores were calculated by reverse scoring the positively stated items and summing all responses. Individual health-related behavior covariates included physical activity, alcohol use, and smoking status.

Neighborhood-level covariates included Neighborhood Deprivation Index (NDI)—a census tract level composite index derived from 2010 U.S. Census and American Community Survey data that are mapped to Exam 5 addresses. The NDI is widely used in research on neighborhoods and health, and reflects multiple dimensions of socioeconomic status, including wealth and income, education, occupation, and housing conditions (53). It is also linked to green space availability, with lower NDI scores (indicating higher socioeconomic status) corresponding to more green space availability and potentially fewer sleep disturbances (52,54).

Additional neighborhood-level variables included social cohesion (55–57), safety (17,58), and walkability (22,59) indexes, which were assessed through participant and community surveys conducted in 2004 and aggregated to the census tract level. Distance to major roads (A3) was included, as proximity to major roads is a known source of noise and air pollution, both of which have been associated with adverse sleep outcomes (27,60,61).

The Rural-Urban Commuting Area (RUCA) index classifies U.S. census tracts on a scale of 1 (rural) to 10 (urban) using measures of population density, urbanization, and daily commuting were also included (62). It was initially considered a potential confounder given the expected rural-urban NDVI differences. However, since 99% of MESA participants lived in areas classified as RUCA = 1 (urban), we ended up not adjusting this covariate in our models.

Because MESA did not include a variable indicating the season during which PSG data were collected, we used the midpoint of the month in which Exam 5 was conducted as a reference date and added the number of days between Exam 5 and the sleep study to estimate the sleep study date and season. For example, if a participant completed Exam 5 in April and the interval to the sleep study was 300 days, we added 300 days to April 15, yielding February 9 which is classified as winter (January–March).

Statistical Analysis

The association between greenspace exposure and sleep-related outcomes was evaluated using Multiple Linear Regression and Poisson Regression. As described in table 2, sleep-related outcomes were modelled both as continuous variables and as binary variables, in the setting of clinically meaningful cutoffs. For example, we defined OSA as an apnea-hypopnea index (AHI) >=15 events/hour, indicating moderate to severe OSA. We also modeled AHI as a continuous variable, recognizing that from a public health perspective, individuals with AHI values of 14 and 15 have nearly identical risk profiles, but a dichotomous cutoff classifies one as healthy and the other unhealthy. Including both continuous and categorical versions of AHI allows for a fuller understanding of this sleep measure while maintaining clinical relevance. Similarly, Wake After Sleep Onset (WASO) was analyzed both as a continuous variable and categorical variable (WASO >60 minutes), based on clinical guidelines. Additional sleep measures were selected based on recent MESA Sleep studies examining environmental exposures (25,47).

As shown in **Table 2**, we applied linear regression models to all continuous sleep outcomes. We applied Poisson regression with robust standard errors on dichotomized outcomes after determining the outcomes were common (e.g., 33% of participants had AHI >=15, and 62.6% had WASO >60 minutes—both well above the 10% threshold). Although the log-binomial model is typically recommended for common outcomes, it failed to converge in R, making Poisson regression models the most suitable alternative.

Table 2. Sleep measures

OUTCOME	TYPE	DESCRIPTION	MODEL	MEASURE OF EFFECT
Apnea-Hypopnea Index (AHI) events per hour*	Continuous	# of AHI events per hour that caused a >= 4% decrease in blood oxygen saturation	Linear regression	Coefficient + 95% CI
AHI events per hour >=15*	Binary	Moderate (AHI 15-29) to Severe (AHI >=30) sleep apnea (yes/no)	Poisson Regression	Prevalence ratio + 95% CI
Wake After Sleep Onset (WASO)	Continuous	# of minutes a person is awake after having initially fallen asleep.	Linear regression	Coefficient + 95% CI
WASO >60 min	Binary	# of minutes a person is awake *for more than 60 minutes* after having initially fallen asleep (yes/no)	Poisson Regression	Prevalence ratio + 95% CI
T90	Continuous	% of total sleep time spent below 90% oxygen saturation	Linear Regression	Coefficient + 95% CI
Nadir SpO2**	Count	Lowest oxygen saturation level recorded during the sleep study	Linear Regression	Coefficient + 95% CI

Oxygen desaturation index (ODI) 4% per hour	Continuous	# of times per hour that oxygen levels drop by 4% of more, regardless of cause (i.e., irrespective of whether the drop is associated with an apnea or hypopnea).	Linear Regression	Coefficient + 95% CI

* AHI and AHI >15 are our primary outcomes.

**Unlike AHI and WASO, while nadir SpO2 levels of 80-89% are sometimes considered moderate desaturation and levels below 80% severe desaturation, there are no established clinical reference points for severity. Therefore, we kept nadir SpO2 continuous.

We used the interquartile range (IQR) as the exposure unit due to the narrow range of NDVI values (−1 to 1) and constructed three models with increasing levels of covariate adjustment. Model 1 is minimally adjusted, controlling only for individual sociodemographic characteristics. Model 2, our primary model, included all Model 1 covariates plus major road and season. Model 3 built on Model 2 by further adjusting for covariates that may lie on the causal pathway, including health behaviors, health status, and other neighborhood factors, as identified in prior research (63). For example, greenspace exposure may reduce stress, which can influence smoking and drinking behaviors—both known to affect sleep (64,65). Similarly, greenspace may promote physical activity, leading to lower BMI and, subsequently, improved sleep (66).

Model 1 adjusted for sex, age, race and ethnicity, education, income, neighborhood deprivation index (NDI), and study site. Model 2 adjusted for all Model 1 covariates plus environmental factors, including distance to the nearest major road and season of the sleep study. Model 3 adjusted for all Model 2 covariates plus body mass index (BMI), alcohol consumption, smoking status, depressive symptoms, social cohesion, neighborhood walkability, and safety indexes

Sensitivity Analyses

We conducted several sensitivity analyses to assess the strength of our primary findings. Thesis included assessing the association of AHI >=15 using the 3% oxygen desaturation definition of

hypopnea (U.S. Centers for Medicare and Medicaid [CMS] criteria), and the oxygen desaturation index (ODI) at the 3% threshold.

As described in the Exposure section, we also tested alternative NDVI buffer sizes—300 m and 900 m around each participant's address—as well as high vegetation season (April 1 – September 30) within these radii, to test if seasonal variable or bigger spatial scales change the observed associations.

Results

Study Population

We restricted this study population to the 2,055 participants who completed both the Exam 5 main study and the sleep study. Of these, 1,849 (90%) had complete NDVI and NDI data. After excluding participants with missing covariate data, the final modeling sample included 1,543 individuals (**Figure S1**).

This study sample included slightly more female participants (53.6%) and had a median age of 68. Racial and ethnic composition was predominantly White (36%), and representation within the Asian group was limited to individuals of Chinese descent. This does not reflect the broader diversity of Asian adult populations in the U.S., which includes many other ethnic subgroups. Educational attainment was relatively high, with two thirds of participants held at least some college degrees. Income levels were broadly distributed, with over half of the sample earning between $25,000 and $149,000 annually. Reflecting the older age profile, most participants were not employed (76.4%). The majority were non-smokers (54.4%) and non-drinkers (57.2%), and only 15% screened positive for depressive symptoms. On average, participants lived 155 meters from major roads in their neighborhoods (A3).

Table 2. Participant and neighborhood characteristics at MESA Exam 5 (N = 1849)

Participant Characteristic	n (%) or Mean (SD)
Sex	
Female	991 (53.6%)
Male	858 (46.4%)

Age (years)	
45 – 54	30 (1.6%)
55 – 64	705 (38.1%)
65 – 74	571 (30.9%)
75 – 84	443 (24%)
85 or older	100 (5.4%)
Race and Ethnicity	
Black	495 (26.8%)
Chinese	224 (12.1%)
Hispanic / Latino	464 (25.1%)
White	666 (36%)
Education	
HS/GED or Less	593 (32.1%)
Some College	537 (29%)
Bachelors or Higher	715 (38.7%)
Missing	4 (0.2%)
Income	
< $12,000	176 (9.5%)
$12,000-$24,999	322 (17.4%)
$25,000-$39,999	341 (18.4%)
$40,000-$74,999	470 (25.4%)
$75,000-$149,000	378 (20.4%)
$150,000 or more	118 (6.4%)
Missing	44 (2.4%)
Employment	
Employed	437 (23.6%)
Unemployed	1,412 (76.4%)
BMI, mean ± SD, kg/m2	28.8 (5.6)
Missing	4 (0.2%)
Obesity Status	
BMI >= 30 kg/m2	663 (35.9%)
BMI < 30 kg/m2	1,182 (62.9)
Missing	4 (0.2%)
Depression Status	

CES-D >=16	273 (14.8%)
CES-D <16	1,559 (84.3%)
Missing	17 (0.9%)
Physical Activity Level	
High	617 (33.4%)
Mid	612 (33.1%)
Low	620 (33.5%)
Alcohol Consumption	
Yes	792 (42.8%)
No	1057 (57.2%)
Smoking Status	
Current	137 (7.4%)
Former	855 (46.2%)
Never	857 (46.3%)
Perceived Stress Scale (PSS) tertile	
High	633 (34.2%)
Mid	610 (33%)
Low	606 (32.8%)
Neighborhood Safety	
High	614 (33.2%)
Mid	628 (34%)
Low	607 (32.8%)
Neighborhood Social Cohesion	
High	623 (33.7%)
Mid	606 (32.8%)
Low	620 (33.5%)
Neighborhood Walkability	
High	607 (32.8%)
Mid	632 (34.2%)
Low	610 (33%)
Neighborhood Deprivation Index (NDI) tertile	
High NDI (low SES)	604 (32.7%)
Mid NDI (mid SES)	610 (33%)
Low NDI (high SES)	607 (32.8%)

Missing	28 (1.5%)
Site	
Baltimore, MD	278 (15%)
Chicago, IL	300 (16.2%)
Forsyth County, NC	243 (13.1%)
Los Angeles, CA	325 (17.6%)
New York City, NY	332 (18%)
St. Paul, MN	371 (20.1%)
Distance to Major Roads (meters)	
A3	242 (343)
Season of Sleep Study	
Fall	532 (28.8%)
Winter	412 (22.3%)
Spring	450 (24.3%)
Summer	455 (24.6%)

NDVI Variations by Site

MESA participants generally lived in areas with moderate greenness, with a median NDVI of 0.30 and an interquartile range (IQR) of 0.20 to 0.40, as shown in Figure 1 (a, b). The overall IQR was 0.25 for annual NDVI and 0.35 for summer NDVI.

Forsyth County, NC, had the highest greenness levels (median: 0.54; 25% and 75%: 0.49–0.60), while St. Paul, MN, exhibited the least variability (median: 0.35; 25% and 75%: 0.31–0.39). Median NDVI values were typically higher in summer, with slightly larger IQRs (**Figure S4c**).

The site-based variation in NDVI at 30m and 300m buffers supported our decision to adjust for site as a potential confounder. For a full overview of NDVI distributions across all buffer sizes—including sensitivity buffers (60m for 30m, 900m for 300m) and both annual and summer measurements—see **Figure S4 (a, b)**.

Figure 1 (a). Histograms of annual 30m and 300m NDVI values by MESA site

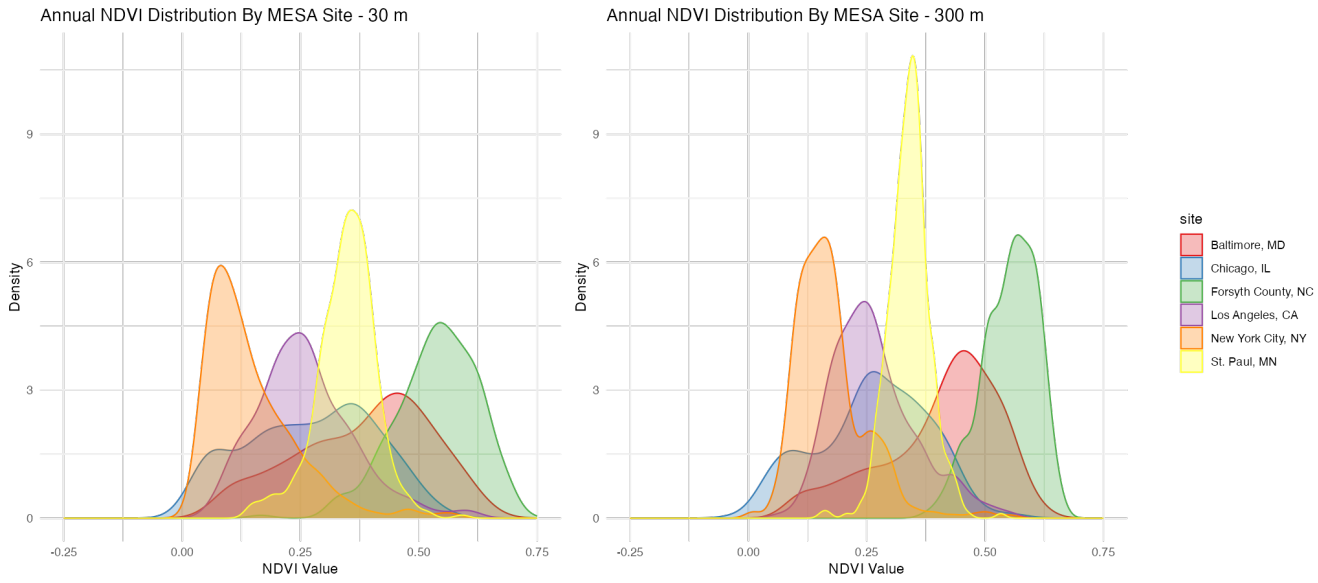
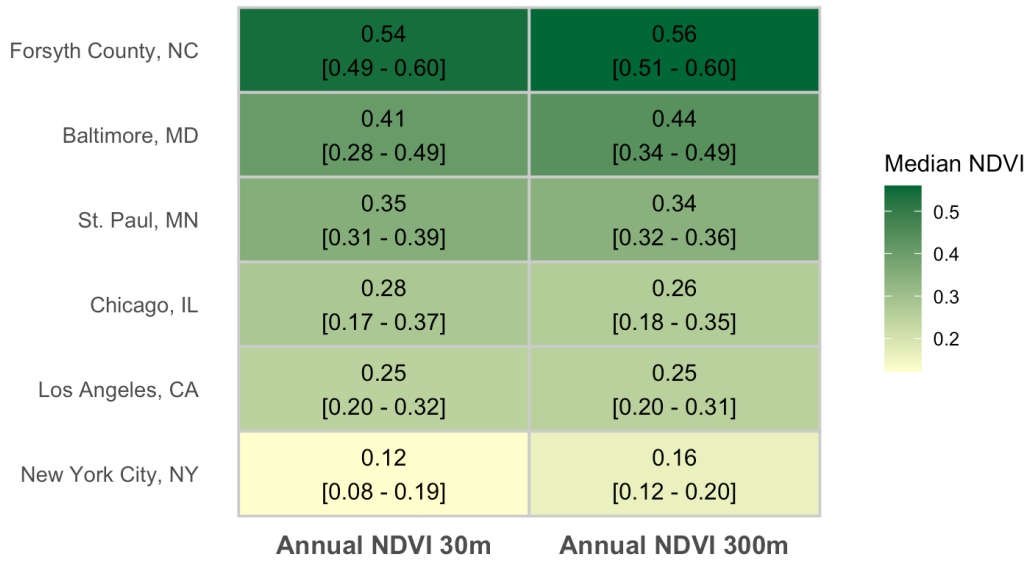


Figure 1 (b). Median (with IQR) of annual 30m and 300m NDVI values by MESA site



Similarly, we created maps of all road types (**Figure S5**) to highlight differences in potential noise exposure across study sites. Among the road categories presented in our data, we adjusted only for A3 major roads—excluding highways—because their average distance to participants' addresses (242 m) fell within the 300 m buffer zone—our primary exposures of interest, capturing neighborhood-scale physical and social activity as a potential mechanism linking greenspace exposure to sleep outcomes.

Outcomes

As shown in Table 3, the median AHI was 9.1 (IQR: 3.3—19.7). One-third of the participants met criteria for moderate to severe sleep apnea, and nearly two-thirds experienced prolonged wakefulness after sleep onset (WASO >60 minutes). Despite these sleep disturbances, most participants maintained relatively stable overnight oxygen levels, with less than 1% of time spent below 90% saturation and a median nadir SpO2 of 85%.

Table 3. MESA Sleep characteristic at MESA Exam 5 (N = 1849)

	% (n) or median (25%, 75% values)
AHI (4% desaturation) events per hour	9.1 (3.3 – 19.7)
OSA, AHI (4%) >=15 by AASM (n)	33.4% (568)
AHI (3% desaturation) events per hour*	18.2 (9.2 – 33)
OSA, AHI (3%) >=15 by AASM (n)*	59.6% (1000)
WASO (min)	78 (45.5 - 122.5)
Percentage WASO > 60 min (n)	62.6% (1064)
ODI (4% desaturation) events per hour	8.3 (3.1 – 18.9)
ODI (3% desaturation) events per hour*	15.9 (7.4 – 30.2)
Nadir SpO2	85 (80 – 89)
Percentage sleep time with <90% saturation	0.6 (0- 3.1)
Total Sleep hours	6.2 (5.2 – 7)

Definition of abbreviation: AASM = American Academy of Sleep Medicine; IQR = interquartile range; AHI = apnea–hypopnea index; OSA = obstructive sleep apnea; WASO = wake after sleep onset; ODI = oxygen desaturation index

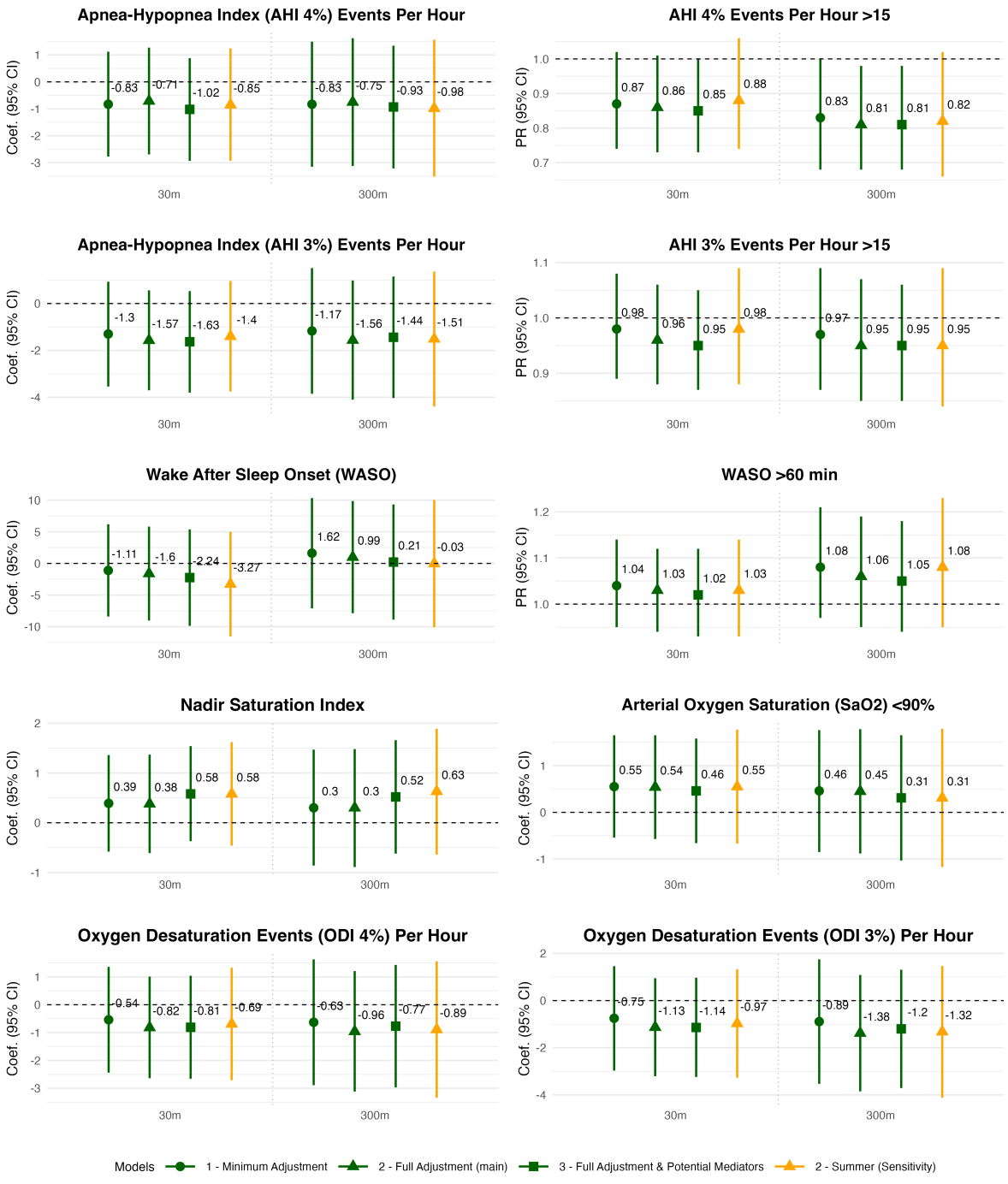
*Sensitivity analyses

Primary and Sensitivity Analyses

As shown in **Figure 2** and **Table S1,** a one IQR increase in annual NDVI within a 300 m buffer (IQR ≈ 0.25) was associated with a 19% lower prevalence of moderate to severe sleep apnea (PR = 0.81; 95% CI: 0.68, 0.98), our primary outcome, in the fully adjusted main model (Model 2). This association was statistically significant.

At smaller buffer sizes (30m and 60m), associations were directionally consistent but attenuated and not statistically significant. Models treating AHI as a continuous variable showed similar trends but with wide confidence intervals. No significant associations were observed for other secondary sleep outcomes, including WASO, nadir SpO2, time with SaO2 < 90%, and ODI. Results were also null for sensitivity analyses using AHI and ODI at the 3% desaturation threshold. Full results are presented in **Figure 2** (primary buffer sizes: 30m and 300m) and **Table S1** (all buffer sizes).

Figure 2. Coefficients or prevalence ratios (95% CI) per IQR increase in annual and summer NDVI at 30m and 300m buffers



Model 1 (● dark green): minimum adjustment for sex, age, race and ethnicity, education, income, neighborhood deprivation index (NDI), and study site.
Model 2 (▲ dark green): full adjustment (main model), adding distance to the nearest major road and season of the sleep study.
Model 3 (● dark green): full adjustment plus potential mediators, including BMI, alcohol consumption, smoking status, depressive symptoms, social cohesion, neighborhood walkability, and safety indexes.
Summer sensitivity model (▲ orange): same as Model 2, but using summer-only NDVI exposure.

Discussion

In this cross-sectional analysis of the MESA cohort, we found that greater residential greenness was associated with a lower risk of moderate to severe sleep apnea (AHI >=15) and a trend toward lower apnea-hypopnea index (AHI). Notably, we observed the strongest associations when greenspace was estimated within a 300 m radius of participants' residential addresses, rather than within a 30 m radius. This suggests that neighborhood-scale greenspace may improve sleep outcomes and be protective against sleep-disordered breathing by promoting physical activity (mechanism 2) and other healthy behaviors in the built environment.

Associations observed at smaller buffer sizes—intended to capture more immediate environmental effects such as noise reduction and improved air quality—were directionally consistent but weaker and not statistically significant. Similarly, summer NDVI models used in sensitivity analyses showed trends consistent with annual NDVI models, though with wider confidence intervals, likely reflecting greater seasonal variability and shorter exposure windows.

The null findings for other sleep outcomes and sensitivity analyses suggest that the observed associations may not be generalizable across all forms of sleep-disordered breathing. They may be attributable to limited statistical power or selection bias, as the analytic sample skewed towards healthier, older adults—who are at a higher risk for OSA than younger people—from selected U.S. cities who were eligible to participate in the follow-up exam 10 years after baseline. These results may also reflect limitations in the exposure and outcome measurements, which are explored in detail in the Limitations section below.

Our findings align with prior research linking greenspace exposure to improved sleep outcomes, while addressing a critical gap by using PSG—the clinical gold standard for sleep assessment. Prior studies that reported positive, negative, or no null associations between greenspace and sleep replied on self-reported sleep questionnaires and actigraphy data (16). These methods, while useful, are inherently subjective and susceptible to recall bias, misreporting, and other transient influences. In contrast, PSG provides objective, high-resolution data by directly measuring physiological parameters as summarized in **Table 2**.

Discrepancies in outcomes using the same study population such as WASO could be due to differences in measurement methods, with actigraphy averaging sleep over multiple nights and PSG capturing a single night, which is discussed in detail in the Limitations below (25).

Overall, these results underscore the importance of spatial scale in environmental exposure assessments and support further research to confirm these associations, explore longitudinal patterns, and identify mediating environmental factors such as air quality and noise.

Strengths and Limitations

This study has several notable strengths. It draws on a large and geographically diverse sample from the MESA cohort, with sophisticated estimates of greenspace exposure at individual residential address. These estimates were averaged over a five-year period to account for people moving, and were assessed at least three years prior to sleep measurement, supporting our hypothesis of a long-term effect of greenspace on sleep.

Greenspace exposure was quantified across multiple spatial scales—30 m and 300 m buffers as primary measures, with 60 m and 900 m buffers included in sensitivity analyses—in both annual and summer-specific timeframes. This multi-scale, multi-seasonal approach enabled a nuanced assessment of greenspace's potential influence on sleep, capturing both immediate environmental surroundings and broader neighborhood-level vegetation during peak (summer) and average (annual) greenness periods.

The MESA cohort is exceptionally well-characterized, allowing for robust adjustment for a wide range of potential confounders, including individual health behaviors and status, neighborhood built and social environments, and site and season. Sleep outcomes were measured using in-home PSG, the clinical gold standard for diagnosing SDB, providing objective, high-quality data that improve upon the self-reported sleep measures commonly used in prior studies.

Study Design and Sample Selection

This study may be affected by attrition bias due to loss to follow-ups between earlier MESA exams and the Exam 5 sleep study. This attrition likely resulted in a healthier sample with different individual or neighborhood characteristics—as individuals with more severe health

issues were more likely to have died or dropped out before Exam 5—compared to the general U.S. adult population.

The ancillary sleep study had substantial missing data, primarily because some Exam 5 participants were ineligible or lived too far from the sleep study sites (see *Study Design, Setting, and Population* and **Figure S1** for details on how we arrived at our final sample of 2,260 out of 4,077 Exam 5 participants). As a result, our sample excluded individuals with moderate to severe OSA who use CPAP or other sleep-assisting technologies. This exclusion may introduce bias toward the null, as those with more symptomatic or severe OSA were more likely to be receiving treatment and thus were not included in the study. Additionally, individuals with medical conditions that made participation impractical or unsafe, as well as those living outside urban centers where sleep data were collected, were excluded, resulting in a sample biased toward urban, healthy residents. In future analysis, we plan to address missing data through imputation.

Selection bias may also be present, as the MESA Sleep ancillary study included only a subset of Exam 5 participants who met specific eligibility criteria and were willing to undergo overnight PSG. Individuals with severe illnesses or those using sleep-assisting technologies such as CPAP were excluded, resulting in a healthier and potentially more health-conscious sample. This may limit the generalizability of our findings to the broader population, particularly those with more severe sleep disorders or comorbidities. It can also impact validity and could explain some of our null results, although we would need to do further analyses to confirm.

Exposure Measurement

We used NDVI as a proxy for residential greenness. While NDVI effectively captures vegetation density, it does not reflect actual access to or use of greenspace. Individual engagement with greenspace can be influenced by contextual factors such as neighborhood walkability, safety, work schedules, transportation availability, and seasonal variation. In some urban environments, visible vegetation may be separated from residential areas by roads, fences, or other physical barriers, making it less accessible. These limitations can lead to exposure misclassification since NDVI is used as a proxy for access to greenspace.

Additionally, this study was designed to evaluate long-term associations between greenspace exposure and sleep outcomes, with greenspace data preceding sleep measures by at least three years. However, some proposed pathways, such as noise reduction within a 30 m NDVI buffer, may operate on much shorter timescales. For instance, the impact of noise reduction on sleep is likely immediate, affecting sleep the same night rather than years later. Moreover, the use of averaged NDVI values over a five-year period may limit the accuracy of exposure estimates for the specific night of PSG assessment, especially in regions with pronounced seasonal changes.

Outcome Measurement

MESA sleep outcomes were assessed using a single night of in-home polysomnography (PSG), which provides high-quality, objective data commonly used to diagnose sleep apnea and other clinical sleep disorders. Although the MESA Sleep Study also collected actigraphy data over a seven-day period to capture night-to-night variability in sleep patterns, these data were not included in our analysis. As a result, our findings reflect a single-night snapshot of sleep, which may differ from studies using actigraphy data. For example, 10.8% of the MESA Exam 5 population had wake after sleep onset (WASO) >60 minutes based on actigraphy data (25), compared to 62.6% based on PSG data for the same population.

In addition, our single-night findings may be influenced by transient factors unrelated to long-term environmental exposures—such as acute physical activities, sleep deprivation, and the use of alcohol or medications (64,67,68). Future research that incorporates both PSG and actigraphy could provide a more robust assessment of both short- and long-term sleep patterns and their associations with exposure to greenspace.

Future Directions

Given the number of sleep outcomes and buffer sizes examined, there may be an increased risk of Type I error. To address this, our next step may involve applying formal multiple comparison correction methods—such as the Bonferroni adjustment—to reduce the likelihood of falsely rejecting the null hypothesis when no true association exists.

We could also explore gender as a potential modifier of the effects of greenspace exposure on sleep. Prior studies suggest that women and men may respond differently to environmental settings, with women potentially being more sensitive to environmental stressors such as noise and visual disorder. Depending on the quality of their surroundings, women may exhibit stronger stress responses—either positive or negative—compared to men (69–71). Physical activity may also play a modifying role, as individuals with higher baseline activity levels are more likely to use neighborhood greenspace for exercise and recreation, thereby deriving greater benefit from mechanism 2 (72,73).

For future work, we plan to incorporate data from the newly collected Exam 7, which includes approximately 600 participants who also took part in Exam 5, and a total of 893 participants with at least minimal PSG data. Our proposed repeated cross-sectional design will allow us to maximize both sample size and exposure variability by including all participants with sleep outcomes measured at least once.

Conclusion

This study demonstrates and association of neighborhood greenness with sleep apnea. Chronic exposure to greener environments may contribute to a lower prevalence and severity of sleep apnea and other SDB. These findings underscore the potential of greenspace as a productive environmental factor that supports healthier sleep patterns, with broader implications for cognitive and cardiovascular health. Future research should consider mitigating missing data with imputation, apply formal multiple comparison correction methods to minimize falsely positives, and incorporate real-time data from in-home sensors or wearable devices to better capture the immediate environmental effect of greenery on sleep.

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Appendices

Figure S1: A flowchart detailing the Exam 5 samples included in this study

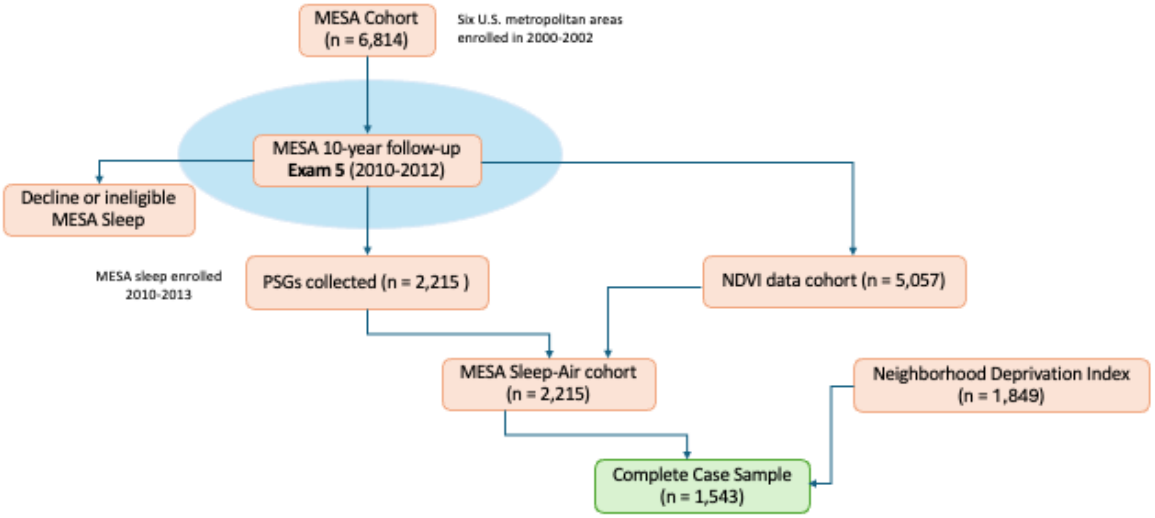

Figure S1. flow chart detailing the sample included in this study from Exam 5 cohort. PSG = polysomnography. NDVI = Normalized Difference Vegetation Index. SDB = sleep disordered breathing

Figure S2. Conceptual model depicting the relationship between green space and sleep disordered breathing

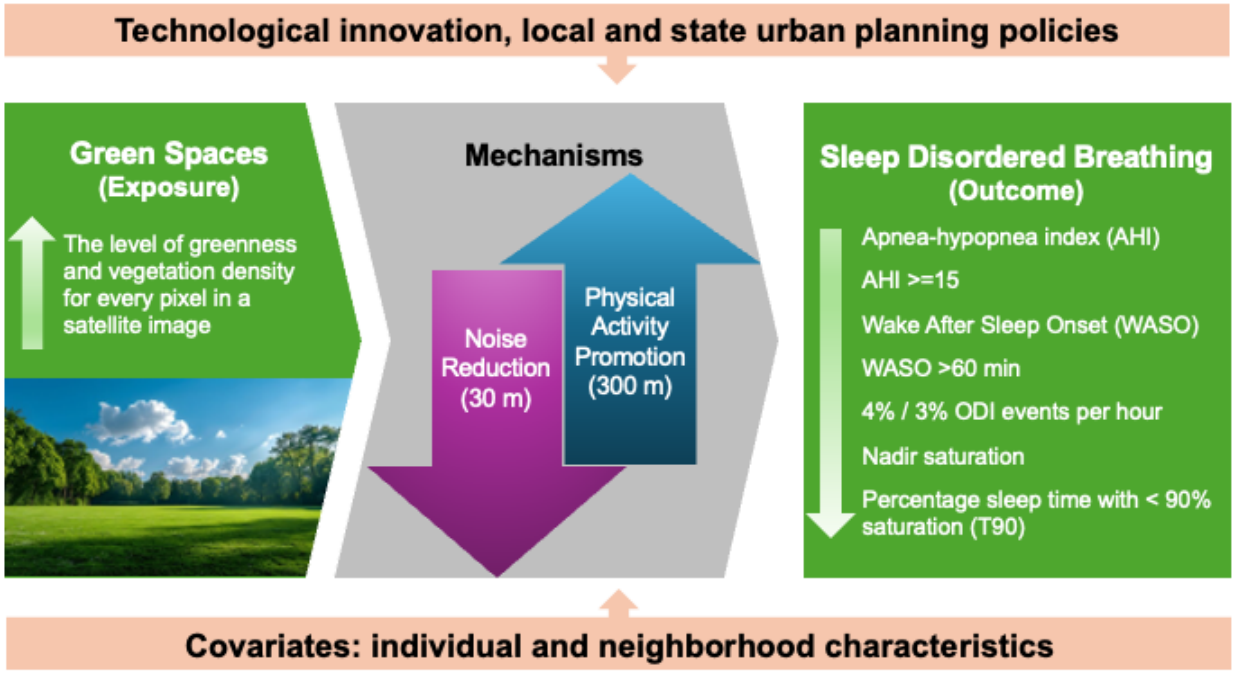

Figure S3. DAG for this study

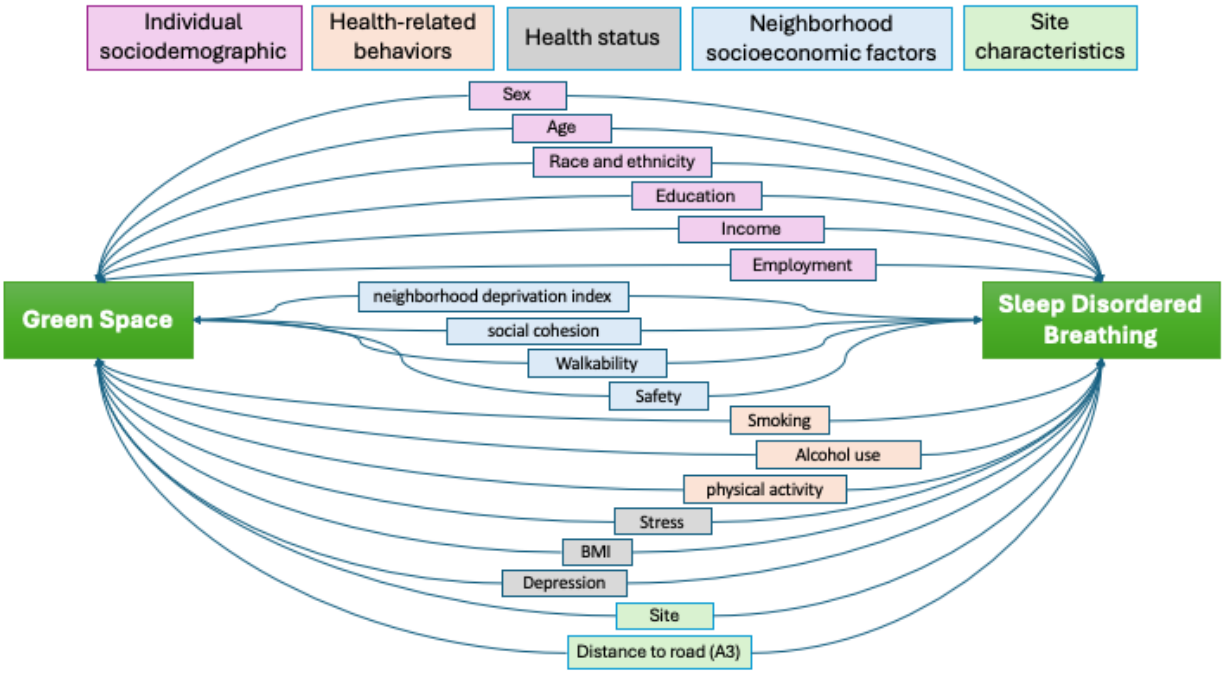

Figure S4 (a). Histograms of annual NDVI values by MESA site

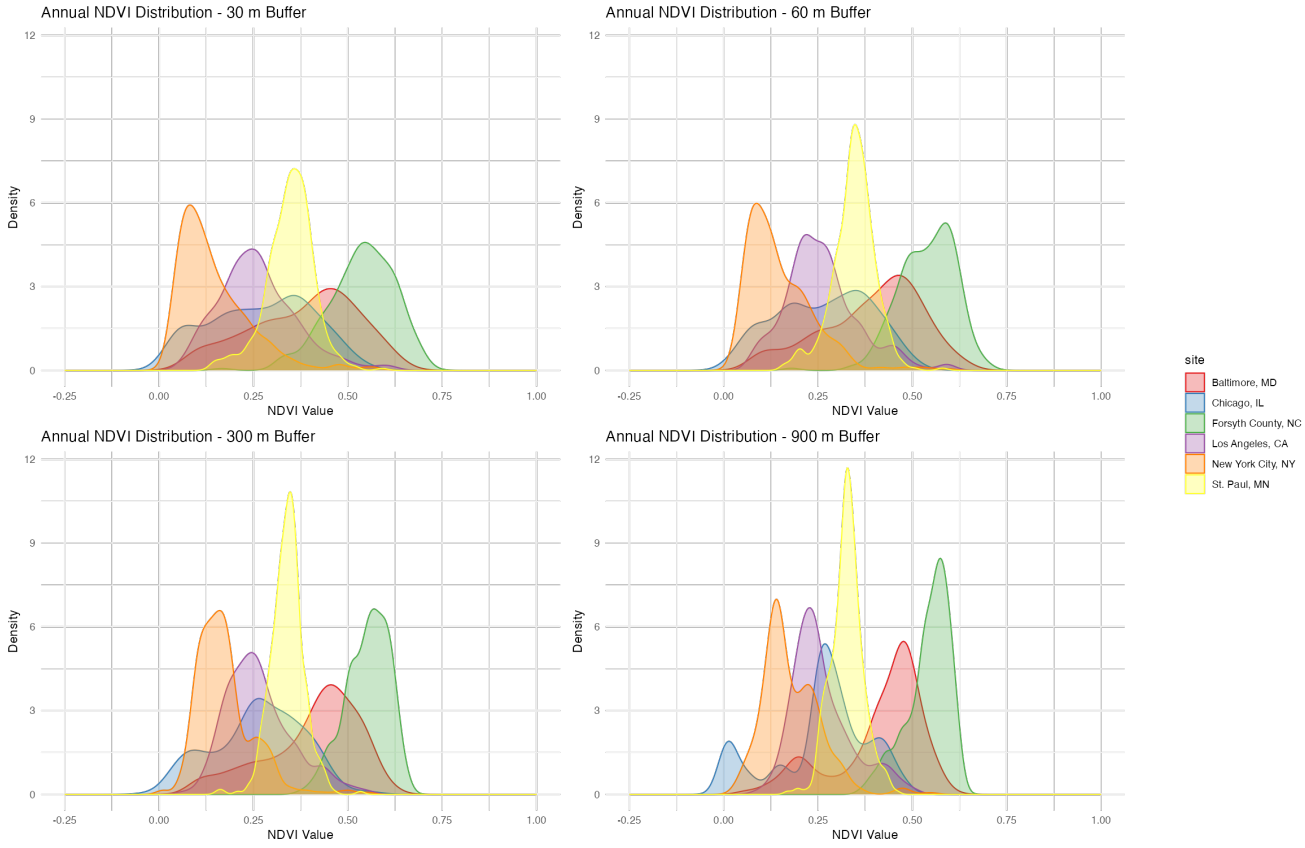

Figure S4 (b). Histograms of summer NDVI values by MESA site

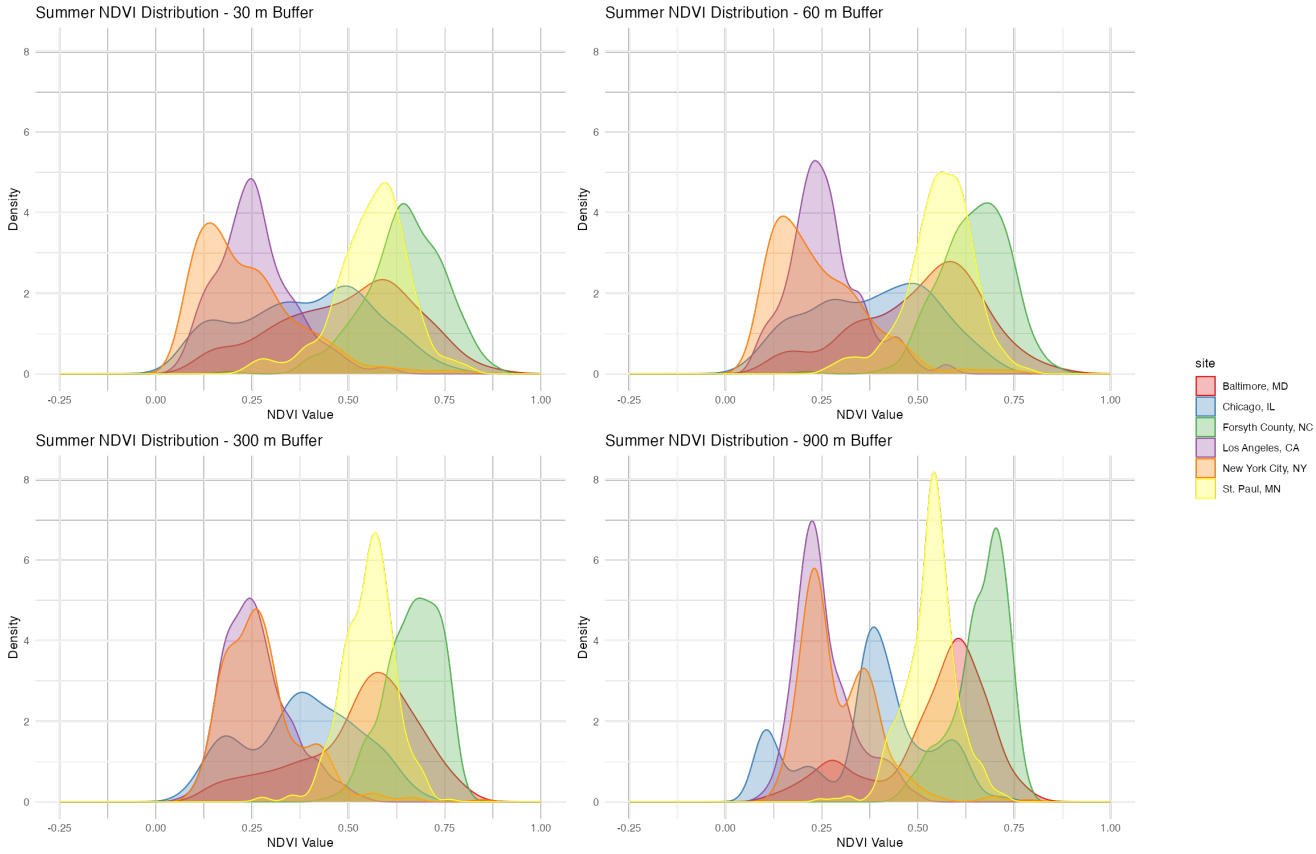

Figure S5. Roads by MESA site

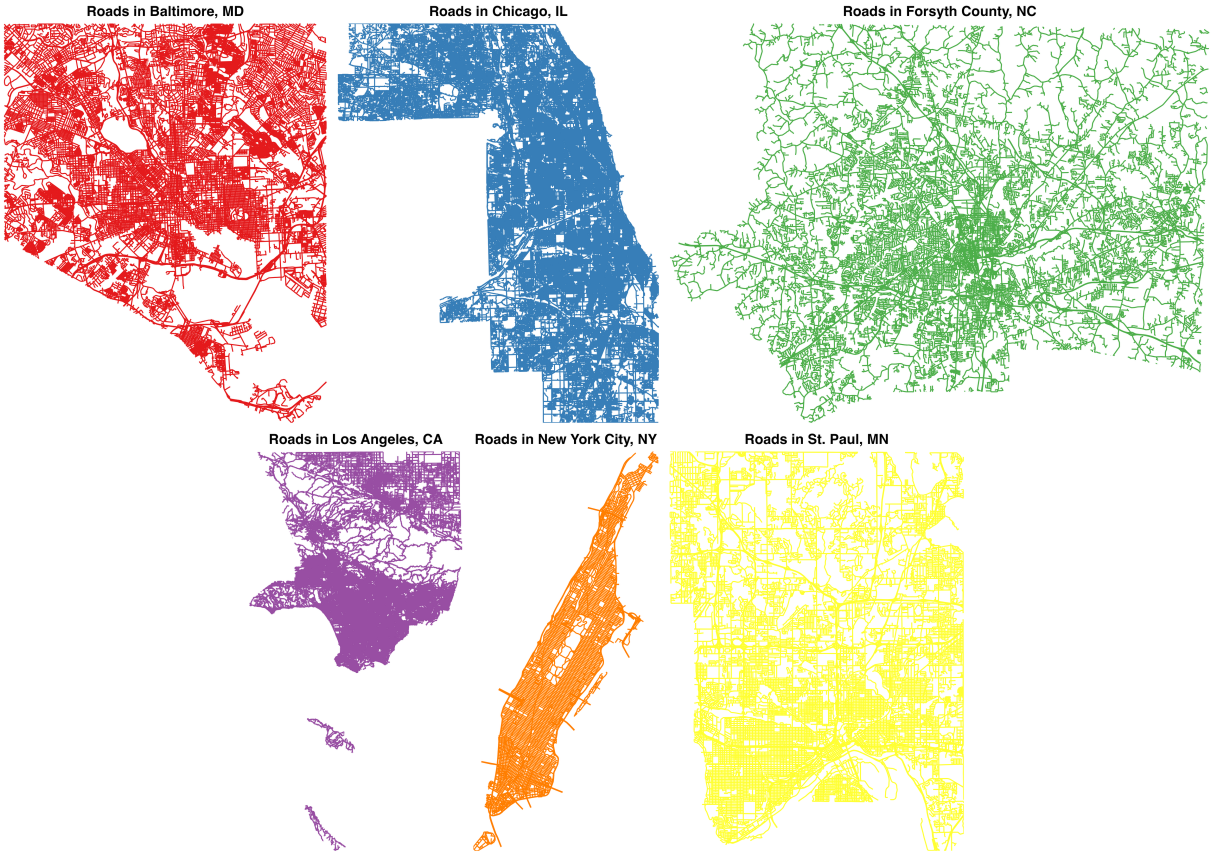

Table S1. Coefficient (β) or prevalence ratios (PRs) and 95% confidence intervals of five sleep disordered breathing measures corresponding to an interquartile range (IQR) increase in annual (models 1, 2, and 3) and summer (model 2 only) Normalized Difference Vegetation Index (NDVI)

		*AHI (4%)**	*AHI >=15 (4%)**	*AHI (3%)***	*AHI >=15 (3%)***
30m	M 1***	-0.83 (-2.77, 1.12)	0.87 (0.74, 1.02)	-1.30 (-3.54, 0.93)	0.98 (0.89, 1.08)
	M 2 (Main)***	-0.71 (-2.69, 1.27)	0.86 (0.73, 1.01)	-1.57 (-3.70, 0.56)	0.96 (0.88, 1.06)
	M 3***	-1.02 (-2.93, 0.88)	0.85 (0.73, 1.00)	-1.63 (-3.80, 0.53)	0.95 (0.87, 1.05)
	Summer (Sensitivity)	-0.85 (-2.93, 1.24)	0.88 (0.74, 1.06)	-1.40 (-3.75, 0.96)	0.98 (0.88, 1.09)
60m	M 1	-0.95 (-3.06, 1.17)	0.88 (0.74, 1.04)	-1.25 (-3.68, 1.18)	0.98 (0.89, 1.09)
	M 2 (Main)	-0.84 (-2.99, 1.31)	0.87 (0.73, 1.03)	-1.50 (-3.82, 0.82)	0.97 (0.87, 1.07)
	M 3	-1.02 (-3.10, 1.06)	0.87 (0.73, 1.03)	-1.45 (-3.81, 0.92)	0.96 (0.87, 1.06)
	Summer (Sensitivity)	-0.96 (-3.25, 1.32)	0.89 (0.74, 1.09)	-1.42 (-4.01, 1.17)	0.98 (0.87, 1.09)
300m	M 1	-0.83 (-3.15, 1.49)	0.83 (0.68, 1.00)	-1.17 (-3.85, 1.51)	0.97 (0.87, 1.09)
	M 2 (Main)	-0.75 (-3.12, 1.62)	0.81 (0.68, 0.98)	-1.56 (-4.10, 0.98)	0.95 (0.85, 1.07)
	M 3	-0.93 (-3.21, 1.34)	0.81 (0.68, 0.98)	-1.44 (-4.03, 1.15)	0.95 (0.85, 1.06)
	Summer (Sensitivity)	-0.98 (-3.51, 1.56)	0.82 (0.66, 1.02)	-1.51 (-4.39, 1.36)	0.95 (0.84, 1.09)
900m	M 1	-0.09 (-2.44, 2.27)	0.90 (0.74, 1.09)	-0.38 (-3.09, 2.33)	1.01 (0.90, 1.13)
	M 2 (Main)	-0.03 (-2.41, 2.36)	0.88 (0.73, 1.07)	-0.75 (-3.31, 1.81)	0.98 (0.88, 1.10)
	M 3	-0.32 (-2.61, 1.97)	0.88 (0.73, 1.07)	-0.78 (-3.38, 1.82)	0.98 (0.87, 1.10)

	Summer (Sensitivity)	-0.14 (-2.70, 2.42)	0.91 (0.73, 1.13)	-0.64 (-3.54, 2.26)	0.99 (0.87, 1.13)		

		WASO	*WASO >60 min*	*Nadir*	*T90*	*ODI (4%)*	*ODI (3%)**
30m	M 1	-1.11 (-8.40, 6.19)	1.04 (0.95, 1.14)	0.39 (-0.58, 1.36)	0.55 (-0.54, 1.65)	-0.54 (-2.44, 1.36)	-0.75 (-2.97, 1.46)
	M 2 (Main)	-1.60 (-9.03, 5.82)	1.03 (0.94, 1.12)	0.38 (-0.61, 1.37)	0.54 (-0.57, 1.65)	-0.82 (-2.64, 1.01)	-1.13 (-3.21, 0.95)
	M 3	-2.24 (-9.87, 5.38)	1.02 (0.93, 1.12)	0.58 (-0.37, 1.54)	0.46 (-0.66, 1.58)	-0.81 (-2.66, 1.04)	-1.14 (-3.24, 0.97)
	Summer (Sensitivity)	-3.27 (-11.54, 4.99)	1.03 (0.93, 1.14)	0.58 (-0.46, 1.62)	0.55 (-0.67, 1.77)	-0.69 (-2.71, 1.33)	-0.97 (-3.27, 1.33)
60m	M 1	-0.10 (-8.02, 7.83)	1.07 (0.97, 1.17)	0.48 (-0.58, 1.54)	0.47 (-0.72, 1.65)	-0.77 (-2.83, 1.29)	-0.99 (-3.39, 1.42)
	M 2 (Main)	-0.66 (-8.73, 7.41)	1.05 (0.95, 1.16)	0.47 (-0.61, 1.55)	0.46 (-0.75, 1.67)	-0.98 (-2.96, 1.01)	-1.32 (-3.58, 0.95)
	M 3	-1.64 (-9.96, 6.68)	1.05 (0.95, 1.16)	0.62 (-0.42, 1.67)	0.44 (-0.78, 1.67)	-0.87 (-2.88, 1.15)	-1.20 (-3.50, 1.10)
	Summer (Sensitivity)	-2.53 (-11.62, 6.55)	1.07 (0.95, 1.19)	0.68 (-0.46, 1.82)	0.49 (-0.85, 1.83)	-0.84 (-3.05, 1.37)	-1.18 (-3.70, 1.35)
300m	M 1	1.62 (-7.11, 10.34)	1.08 (0.97, 1.21)	0.30 (-0.86, 1.47)	0.46 (-0.85, 1.76)	-0.63 (-2.89, 1.63)	-0.89 (-3.53, 1.75)
	M 2 (Main)	0.99 (-7.87, 9.86)	1.06 (0.95, 1.19)	0.30 (-0.89, 1.48)	0.45 (-0.88, 1.78)	-0.96 (-3.12, 1.21)	-1.38 (-3.85, 1.09)
	M 3	0.21 (-8.90, 9.32)	1.05 (0.94, 1.18)	0.52 (-0.62, 1.66)	0.31 (-1.03, 1.65)	-0.77 (-2.97, 1.43)	-1.20 (-3.71, 1.31)
	Summer (Sensitivity)	-0.03 (-10.10, 10.05)	1.08 (0.95, 1.23)	0.63 (-0.64, 1.89)	0.31 (-1.17, 1.79)	-0.89 (-3.34, 1.56)	-1.32 (-4.12, 1.47)
900m	M 1	2.70 (-6.13, 11.54)	1.10 (0.99, 1.23)	0.19 (-0.99, 1.37)	0.62 (-0.70, 1.95)	0.08 (-2.21, 2.37)	-0.14 (-2.81, 2.54)
	M 2 (Main)	2.21 (-6.73, 11.16)	1.09 (0.98, 1.22)	0.18 (-1.02, 1.38)	0.62 (-0.73, 1.96)	-0.25 (-2.43, 1.93)	-0.63 (-3.12, 1.86)
	M 3	0.94 (-8.21, 10.10)	1.09 (0.97, 1.22)	0.42 (-0.73, 1.56)	0.58 (-0.76, 1.93)	-0.20 (-2.41, 2.01)	-0.56 (-3.08, 1.96)

Summer (Sensitivity)	0.39 (-9.77, 10.55)	1.12 (0.98, 1.27)	0.49 (-0.79, 1.76)	0.53 (-0.97, 2.02)	-0.11 (-2.58, 2.36)	-0.48 (-3.30, 2.34)

* AHI and AHI >15 are primary outcomes. The other measures of sleep-disordered breathing are secondary outcomes.

** AHI 3%, AHI 3% >15, ODI 3% are sensitivity analyses.

*** Models (M)

- M1: controlled for sex, age, race and ethnicity, education, income, neighborhood deprivation index (NDI), and study site
- M2: controlled for all M1 covariates plus distance to the nearest major road and season of the sleep study
- M3: controlled for all M2 covariates plus body mass index (BMI), alcohol consumption, smoking status, depressive symptoms, social cohesion, neighborhood walkability, and safety indexes