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# Greenspace proximity in relation to sleep health among a racially and ethnically diverse cohort of US women

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A B S T R A C T

Sleep is essential for overall health. Greenspace may contribute to sleep health through, for instance, improving mood, reducing sleep disruptors (e.g., poor air quality), and promoting physical activity. Although greenspace likely differs across populations, few studies have included diverse populations.

To investigate greenspace-sleep health associations, overall and by age, race and ethnicity, and socioeconomic status, we used data collected at enrollment (2003–2009) from women in the Sister Study (n = 1612 Hispanic/Latina, n = 4421 non-Hispanic (NH)-Black, and n = 41,657 NH-White). Participants' geocoded home addresses were linked to NASA's Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index data (250m resolution) to capture greenspace tertiles (further categorized as low/moderate vs. high). Participants reported seven sleep dimensions, which we assessed individually, along with a multidimensional sleep health measure (categories: favorable, moderate, poor). Adjusting for individual- and environmental/neighborhood-level characteristics, we used Poisson regression with robust variance to estimate prevalence ratios and 95 % confidence intervals (PR[CI]). We tested for interaction and estimated age-, race and ethnicity-, and educational attainment category-specific associations.

Among participants (mean ± SD age = 55.7 ± 9.0 years), those with low/moderate vs. high greenspace had a lower prevalence of favorable sleep (58 % vs. 66 %). After adjustment, low/moderate vs. high greenspace was associated with a 32 % higher prevalence of moderate (PR = 1.32 [1.27–1.38]) and 12 % higher prevalence of poor (PR = 1.12 [1.07–1.16]) vs. favorable sleep health. Magnitudes of associations were higher among NH-White women vs. minoritized racial-ethnic groups and women with higher vs. lower educational attainment.

Higher greenspace was associated with favorable sleep, with stronger associations among groups with more social advantages.

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## 1. Introduction

Under-recognition of the importance of sleep health is a global public health problem (Lim et al., 2023) as poor sleep health is highly prevalent and contributes to a host of adverse mental and physical health outcomes, such as depression and poor cardiometabolic health outcomes (Institute of Medicine Committee on Sleep Medicine Research, 2006; Jackson et al., 2015). Favorable sleep health promotes physical and mental health and has been defined as a multidimensional pattern of sleep and wakefulness that is subjectively satisfying, appropriately timed, highly efficient, and adequate in duration, allowing for sustained alertness while awake (Buysse, 2014). Yet in the United States (US), approximately one-third of adults report less than the recommended 7 h of sleep per day (Pankowska et al., 2023), and sleep disorders are estimated to affect 50–70 million adults (Institute of Medicine Committee on Sleep Medicine Research, 2006). Further, sleep health inequities are widely recognized. For example, minoritized racial and ethnic populations experience disproportionately poorer sleep health in the forms of shorter sleep duration and poorer sleep quality in comparison to non-Hispanic White persons (Jackson et al., 2020; Johnson et al., 2019). These sleep disparities are hypothesized to lead to racial and ethnic disparities in, for instance, poor cardiometabolic health (Jackson et al., 2015). Moreover, in addition to race and ethnicity, sleep disparities are also observed by age, sex, and socioeconomic status (SES) (Etindele Sosso et al., 2021; Mander et al., 2017; Zeng et al., 2020). Sleep quality often decreases with age (Mander et al., 2017). Women are more likely to have insomnia and to report more sleep complaints compared to men, while men are more likely to have obstructive sleep apnea (Geer and Hilbert, 2021; Zeng et al., 2020). Additionally, individuals with lower versus higher SES tend to have poorer sleep health (Etindele Sosso et al., 2021). Addressing sleep health and eliminating sleep health disparities may improve overall population health.

To alleviate the burden of poor sleep health, it is essential to consider its physical and social environmental determinants. These are often ubiquitous exposures with potentially wide-ranging impacts on the population (Billings et al., 2020; Jackson and Gaston, 2019). Human contact with the natural environment is decreasing globally; however, experiences with nature have been associated with improved health and well-being, with a hypothesized pathway through positive impacts on sleep health (Bratman et al., 2019; Hartig et al., 2014; Jimenez et al., 2021). As a feature of the natural environment, greenspace (consisting of areas of vegetation, parks, gardens, open fields, etc.) may enhance sleep by improving mental health through physiological stress reduction and restoration in response to being in nature as well as by buffering against sleep disruptors, such as air and noise pollution, and by promoting physical activity (Dzhambov, 2018; Huang et al., 2021; Mytton et al., 2012; Ohly et al., 2016; Tsai et al., 2018; Ulrich et al., 1991). Correspondingly, greenspace exposure has been associated with more favorable sleep duration and quality in the epidemiologic literature (Astell-Burt and Feng, 2020; Jimenez et al., 2021; Li et al., 2022; Parks et al., 2023; Shin et al., 2020; Stenfors et al., 2023; Teixeira et al., 2023; Xie et al., 2020; Yang et al., 2021; Zhong et al., 2022). Nonetheless, literature gaps remain. Most studies among adults were outside of the US and primarily in Europe or were limited in racial and ethnic diversity, mostly among populations of European descent (Hunter and Hayden, 2018; Parks et al., 2023; Shin et al., 2020). It is important to investigate associations with greenspace in diverse US populations because greenspace proximity, access, and quality is not equitably distributed. Minoritized racial and ethnic groups and low-income individuals disproportionately reside where greenspace is either scarce, perceived as unsafe due to factors like crime, or poorly maintained (Casey et al., 2017; Nardone et al., 2021; Wolch et al., 2014). Further, associations between greenspace and sleep were stronger among men and adults aged ≥65 years in a prior study using nationally-representative Behavioral Risk Factor Surveillance System survey data (Grigsby-Toussaint et al., 2015). Associations between greenspace and sleep may vary by key demographic characteristics, but potential modifiers are under-investigated. Moreover, given the higher burden of sleep disturbances among women compared to men (Zeng et al., 2020), the serious health consequences of poor sleep that vary by race among women (Jackson et al., 2020), and that inequitable access to greenspace can exacerbate health disparities (Jennings and Gaither, 2015; Rigolon et al., 2021), research on the interactions between greenspace and social characteristics on sleep health among diverse groups of women is important.

Therefore, the objective of our study was to investigate proximity to greenspace in relation to multiple dimensions of sleep health among a racially and ethnically diverse cohort of US women and to determine whether associations varied by age, race and ethnicity, and educational attainment – a key determinant of SES (Zajacova and Lawrence, 2018). We hypothesized the following: proximity to greenspace is lower among minoritized racial-ethnic and low SES groups; lower proximity to greenspace is associated with short sleep duration and sleep disturbances; and associations are stronger among older compared to younger women, minoritized racial-ethnic groups compared to NH-White women, and individuals with lower versus higher educational attainment. In secondary analyses, we assessed other potential effect modifiers identified in prior literature (e.g., region of residence (Pankowska et al., 2023)) and investigated potential mediation pathways.

## 2. Materials and methods

### 2.1. Data source: The Sister Study cohort

We used cross-sectional data from the Sister Study (data release 11.1), a prospective cohort of women aged 35–74 years living in the US, including Puerto Rico, recruited between 2003 and 2009. The study methods and recruitment strategies have been detailed elsewhere (Sandler et al., 2017). Briefly, women were eligible to participate if they had either a full- or half-sister with a diagnosis of breast cancer but were breast cancer-free themselves at the time of enrollment. Upon enrollment, participants completed mailed questionnaires and a computer-assisted telephone interview to provide information on sociodemographic characteristics, residential history, lifestyle factors, medical history, and occupational and environmental risk factors potentially related to breast cancer risk. The Sister Study was approved and is overseen by the National Institutes of Health Institutional Review Board. The current study is a secondary analysis of de-identified Sister Study data. All participants provided written informed consent.

### 2.2. Study population

A total of 50,884 women were enrolled in the Sister Study cohort at baseline. Participants were excluded from our analytic sample in a stepwise manner for the following reasons (Supplemental Fig. 1): withdrew (n = 5); missing greenspace data (n = 1,849, due to not living in the conterminous US or having an address that could not be geocoded); missing covariates (n = 41); self-identified race and ethnicity other than Hispanic/Latina, non-Hispanic Black, or non-Hispanic White due to small sample size and heterogeneity if groups were combined (n = 1282); or missing sensitivity analysis variables (n = 17). Compared to eligible participants (N = 47,690), excluded participants lived in areas with lower greenspace (or did not have greenspace data), were more likely to identify as a minoritized race or ethnicity, had more risk factors for poor sleep (e.g., lower annual household income), and reported less favorable sleep characteristics (Supplemental Table 1).

### 2.3. Exposure assessment: proximity to greenspace

Greenspace was determined at the residence location at baseline using the National Aeronautic and Space Administration's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite to capture normalized difference vegetation index (NDVI) at a 250m resolution. NDVI values from July were matched to the year of enrollment in the study (e.g., July 2005 data was linked to the geocoded addresses of participants who enrolled in 2005). Consistent with prior literature (James et al., 2017), July MODIS NDVI values were selected to maximize the variability in greenspace, as this was the highest value available, regardless of US census region. NDVI is determined based on the amount of near-infrared light and red wavelength light reflected from the surface of the earth using the following equation: $NDVI = \frac{near\ infrared\ light - red\ light}{near\ infrared\ light + red\ light}$. A plant or tree with a high density of green leaves will reflect a larger proportion of near-infrared light and absorb a larger amount of red light, resulting in an NDVI value closer to 1 (Didan et al., 2015). NDVI values can range from −1 to 1 (unitless), with negative values representing water or cloud coverage and NDVI = 0 representing bare soil (Crouse et al., 2019; Weier and Herring, 2000). Negative NDVI values (n = 37) were recoded as 0 (Klompmaker et al., 2019; Li et al., 2022). NDVI values (mean ± SD = 0.6 ± 0.2, range = 0–1.0) were initially divided into population-based tertiles; however, we later dichotomized NDVI as low/moderate versus high due to small sample sizes among Hispanic/Latina and non-Hispanic Black participants upon stratification by race and ethnicity. This categorization also allows for easier interpretation of our findings, as the raw NDVI values do not directly translate to potential targets for public health intervention. However, we also assessed continuous NDVI values as an exposure.

### 2.4. Outcome assessment: multiple dimensions of sleep health

Sleep health is multidimensional (Buysse, 2014); therefore, we assessed several dimensions. Sleep health dimensions were self-reported in the baseline questionnaire (available at https://sisterstudy.niehs.nih.gov/English/researchers.htm). To maximize statistical power, separate analytic samples were used for each of the sleep health dimensions in the analysis. Analytic samples varied (range: n = 30,763 to n = 47,648; sample sizes provided in Supplemental Fig. 1) due to missing sleep data or exclusions, as described below.

Participants reported their sleep and wake patterns over the past six weeks, and questions about sleep duration depended on the type of sleep pattern reported. If consistent daily sleep/wake patterns were reported (Pattern 1), participants were queried on usual (same each day) bed and wake times. If different sleep patterns on work and non-workdays were reported (Pattern 2), participants were queried on usual bed and wake times on work and non-workdays, separately. If different daily sleep patterns were reported (Pattern 3), participants were queried on usual bed and wake times each day of the week. If no consistent sleep/wake pattern was reported (Pattern 4), participants were queried on longest and shortest sleep durations. All participants also reported the average number of hours slept per night. We calculated habitual sleep duration as time between bed and waking, using either reported times (Pattern 1), work and non-workday weighted averages (Pattern 2), a 7-day average (Pattern 3), or self-reported average (Pattern 4). We dichotomized short sleep duration as <7 vs. ≥7 h based on the joint American Academy of Sleep Medicine/Sleep Research Society recommendation for adults (Watson et al., 2015).

Consistent with prior literature (Gaston et al., 2019), we assessed difficulty falling asleep, difficulty staying asleep, insomnia symptoms, short sleep plus insomnia symptoms, frequent napping, and sleep debt. Difficulty falling asleep was categorized as taking >30 min to fall asleep (yes) vs. taking ≤30 min to fall asleep (no). Difficulty staying asleep was categorized as waking up after falling asleep ≥3 times per night or day on ≥3 nights/days each week (yes) vs. waking up after falling asleep <3 times per night or day <3 nights/days after falling asleep (no). Insomnia symptoms were defined as either difficulty falling or staying sleep (yes) vs. neither (no). For short sleep duration plus insomnia symptoms, we compared individuals who reported *both* short sleep duration and insomnia symptoms (yes) to participants who reported recommended sleep duration (7–9 h; excludes n = 1940 participants who reported long sleep duration) and no insomnia symptoms (no) (excludes n = 14,925 participants who reported either short sleep duration *or* insomnia symptoms). We dichotomized frequent napping as ≥3 times per week (yes) vs. <3 times per week (no). We subtracted the reported shortest sleep duration from the longest sleep duration during a week to determine sleep debt, defined as ≥2 h (yes) vs. <2 h (no).

Finally, we used latent class analysis to reflect a multidimensional sleep measure. Indicators included the five primary sleep dimensions (short sleep duration, difficulty falling asleep, difficulty staying sleep, frequent napping, sleep debt), with adjustment for dichotomous greenspace, continuous age, race and ethnicity (Hispanic/Latina, non-Hispanic Black, non-Hispanic White), dichotomous marital status (married, never married/widowed/divorced/separated), and continuous Area Deprivation Index (ADI) (Kind et al., 2014; Xu et al., 2022). Other covariates that were considered but not included due to poorer model fit included dichotomous educational attainment (≤high school or equivalent, at least some college), US census region, and population density. Three latent classes of sleep health (favorable, moderate, and poor) best fit of the data (Supplemental Tables 2–3 and Supplemental Fig. 2–3). In analyses, poor and moderate sleep were separately compared to favorable sleep. Latent class analysis was performed in R (version 4.3.1) using the package polca (https://www.rdocumentation.org/packages/poLCA/versions/1.6.0.1/topics/poLCA); additional details are provided in the supplemental methods.

### 2.5. Potential confounders

We considered several potential confounders that were self-reported at baseline. However, only confounders identified as necessary after construction of directed acyclic graphs were retained. Considered sociodemographic characteristics included age (dichotomized at the population median of 55.6 years); self-identified race and ethnicity defined using US Office of Management and Budget categories (Hispanic/Latina [any race] (hereafter Latina), non-Hispanic Black/African American (hereafter Black), and non-Hispanic White (hereafter White)), marital status (never married, married/living as married, widowed/divorced/separated); and educational attainment (high school or less, some college, bachelor's degree or higher). We also considered health behaviors and clinical characteristics that are described in Table 1 (alcohol consumption, smoking status, physical activity, body mass index category, and healthcare professional-diagnosed depression).

We additionally considered several environmental variables that were based on or linked to primary enrollment addresses. The ADI is a measure of neighborhood deprivation that is based on 17 indicators of poverty, education, housing, and employment from the 2000 US Census, which were weighted to create census block group-level measurements of neighborhood SES (Kind et al., 2014; Xu et al., 2022). Scores range from 1 (low deprivation, i.e., well-off) to 100 (high deprivation) based on national percentiles. Census tract population density was calculated as the number of residents per square mile and dichotomized at the median. Annual average concentrations of $PM_{2.5}$ and $NO_2$ at participants' home addresses were estimated using spatiotemporal models derived from air quality monitors and geographic covariates, as described in prior literature (Brown et al., 2024; Kirwa et al., 2021). Outdoor light at night (LAN) was based on US Defense Meteorological Satellite Program high-dynamic range data for 2003, 2004, and 2006 (only years available that overlapped with our enrollment period) linked to closest historical year of enrollment (e.g., 2006 data was linked to addresses of participants who enrolled from 2006 to 2009) and available at ~1 km resolution (Hsu et al., 2015). Noise levels were based on a land use regression model developed using data from the National Park Service and monitors located in cities and at airports averaged over 2000 to 2014 (Mennitt and Fristrup, 2016). We used mean total anthropogenic and natural nighttime (10:00pm-7:00am) noise in A-weighted decibels (i.e., relative loudness to the human ear), which was available

 

**Table 1**
Baseline sociodemographic characteristics, sleep health dimensions, health behaviors, clinical characteristics, and residential/environmental characteristics of Sister Study participants (N = 47,690) overall and by low/moderate or high greenspace.

| Greenspace, July MODIS NDVI [mean ± SD (range)] [a] | | Total population (n = 47,690) | Greenspace Category | |
|---|---|---|---|---|
| | | | Low/Moderate (n = 31,798; 67 %) | High (n = 15,892; 33 %) |
| | | 0.622 ± 0.182 (0–0.997) | 0.530 ± 0.151 (0–0.729) | 0.808 ± 0.051 (0.729–0.997) |
| **Sociodemographic characteristics** | | | | |
| Age (mean ± SD) | | 55.7 ± 9.0 | 55.7 ± 9.0 | 55.5 ± 8.8 |
| Age (n (%)) | <55.6 years | 23,743 (50) | 15,729 (49) | 8014 (50) |
| | ≥55.6 years | 23,947 (50) | 16,069 (51) | 7878 (50) |
| Race and ethnicity (n (%)) | Hispanic/Latina | 1612 (3) | 1434 (5) | 178 (1) |
| | Non-Hispanic Black | 4421 (9) | 3336 (10) | 1085 (7) |
| | Non-Hispanic White | 41,657 (87) | 27,028 (85) | 14,629 (92) |
| Marital status (n (%)) | Never married | 2572 (5) | 1948 (6) | 624 (4) |
| | Married or living as married | 35,667 (75) | 22,844 (72) | 12,823 (81) |
| | Widowed, divorced, or separated | 9451 (20) | 7006 (22) | 2445 (15) |
| Educational attainment (n (%)) | High school diploma/equivalent or less | 7232 (15) | 4811 (15) | 2421 (15) |
| | Some college or technical school | 16,173 (34) | 11,015 (35) | 5158 (32) |
| | Bachelor's or higher degree | 24,285 (51) | 15,972 (50) | 8313 (52) |
| Annual household income (n (%)) | <$50,000 | 11,839 (25) | 8413 (26) | 3426 (22) |
| | $50,000-$99,999 | 19,738 (41) | 13,170 (41) | 6568 (41) |
| | ≥$100,000 | 16,113 (34) | 10,215 (32) | 5898 (37) |
| **Health behavior characteristics** | | | | |
| Short sleep duration (n (%)) | Yes (<7 h) | 10,363 (22) | 7028 (22) | 3335 (21) |
| | No (recommended [≥7 h]) | 37,285 (78) | 24,737 (78) | 12,548 (79) |
| Difficulty falling asleep (n (%)) | Yes | 8438 (18) | 5819 (18) | 2619 (16) |
| | No | 39,180 (82) | 25,925 (82) | 13,255 (84) |
| Difficulty staying asleep (n (%)) | Yes | 6558 (14) | 4473 (14) | 2085 (13) |
| | No | 41,075 (86) | 27,278 (86) | 13,797 (87) |
| Insomnia symptoms (n (%)) [b] | Yes | 12,903 (27) | 8839 (28) | 4064 (26) |
| | No | 34,701 (73) | 22,892 (72) | 11,809 (74) |
| Short sleep duration and insomnia symptoms (n (%)) [c] | Yes | 3786 (12) | 2637 (13) | 1149 (11) |
| | No | 26,887 (88) | 17,668 (87) | 9219 (89) |
| Frequent napping (n (%)) | Yes | 5119 (11) | 3562 (11) | 1557 (10) |
| | No | 42,559 (89) | 28,227 (89) | 14,332 (90) |
| Sleep debt ≥2 h (n (%)) | Yes | 11,298 (24) | 7611 (25) | 3687 (24) |
| | No | 35,001 (76) | 23,226 (75) | 11,775 (76) |
| Latent class of multidimensional sleep (n (%)) | Favorable | 27,954 (61) | 17,694 (58) | 10,260 (66) |
| | Moderate | 8818 (19) | 6400 (21) | 2418 (16) |
| | Poor | 9378 (20) | 6627 (22) | 2751 (18) |
| Current use of sleep medications (n (%)) | Yes | 746 (3) | 493 (3) | 253 (3) |
| | No | 22,045 (97) | 14,716 (97) | 7329 (97) |
| Alcohol consumption status (n (%)) | Never drinker | 1617 (3) | 1066 (3) | 551 (3) |
| | Former drinker | 7101 (15) | 4864 (15) | 2237 (14) |
| | Current drinker | 38,914 (82) | 25,824 (81) | 13,090 (82) |
| Smoking status (n (%)) | Never smoker | 26,623 (56) | 17,728 (56) | 8895 (56) |
| | Former smoker | 17,174 (36) | 11,417 (36) | 5757 (36) |
| | Current smoker | 3890 (8) | 2652 (8) | 1238 (8) |
| Physical activity (n (%)) | Met CDC recommendation | 26,067 (55) | 17,427 (55) | 8640 (54) |
| | Did not meet CDC recommendation | 21,606 (45) | 14,358 (45) | 7248 (46) |
| **Clinical characteristics** | | | | |
| BMI, $kg/m^2$ (n (%)) | <25.0 | 18,230 (38) | 11,957 (38) | 6273 (39) |
| | 25.0-<30.0 | 15,112 (32) | 9980 (31) | 5132 (32) |
| | ≥30.0 | 14,331 (30) | 9849 (31) | 4482 (28) |
| Depression at baseline (n (%)) | No | 32,141 (76) | 21,337 (76) | 10,804 (77) |
| | Yes | 10,153 (24) | 6923 (24) | 3230 (23) |
| **Environmental characteristics** | | | | |
| ADI (mean ± SD) [d] | | 34.5 ± 24.5 | 34.7 ± 24.8 | 34.1 ± 23.9 |
| Census tract population density, per sq-mile (mean ± SD) [e] | | 3368.8 ± 9360.4 | 4398.5 ± 11,187.0 | 1308.6 ± 2481.6 |
| $PM_{2.5}$, $\mu g/m^3$ (mean ± SD) | | 10.4 ± 2.7 | 10.3 ± 2.7 | 10.6 ± 2.5 |
| $NO_2$, ppb (mean ± SD) | | 9.1 ± 5.0 | 10.1 ± 5.3 | 7.1 ± 3.5 |
| Outdoor LAN, $nW/cm^2/sr$ (mean ± SD) [f] | | 173.4 ± 172.3 | 211.3 ± 185.8 | 97.4 ± 106.6 |
| Noise, dB (mean ± SD) [g] | | 52.3 ± 4.0 | 53.0 ± 4.1 | 50.9 ± 3.4 |
| US census region (n (%)) | Northeast | 8229 (17) | 3411 (11) | 4818 (30) |
| | Midwest | 13,344 (28) | 8832 (28) | 4512 (28) |
| | South | 16,083 (34) | 10,159 (32) | 5924 (37) |
| | West | 10,034 (21) | 9396 (30) | 638 (4) |

Abbreviations: ADI, Area Deprivation Index; BMI, body mass index; CDC, Centers for Disease Control and Prevention; HS, high school; LAN, light at night; MODIS, Moderate Resolution Imaging Spectroradiometer; NDVI, Normalized Difference Vegetation Index; $NO_2$, nitrogen dioxide; $PM_{2.5}$, particulate matter with aerodynamic diameter <2.5 μm; SD, standard deviation.

[a] NDVI values from July were available for 2000–2010 and were matched to participant addresses by year of enrollment.

[b] Presence of insomnia symptoms defined as a report of either difficulty falling asleep or difficulty staying asleep.
[c] Reference group is comprised of participants who reported neither short sleep nor insomnia symptoms; participants who reported either were excluded from this analysis.
[d] The ADI is a measure of neighborhood deprivation that is based on 17 indicators of poverty, education, housing, and employment from the 2000 US Census, which were weighted to create census block group-level measurements of neighborhood socioeconomic status.
[e] Census tract population density was based on the 2000 US Census.
[f] Participants who enrolled in 2003 were linked to 2003 LAN data, in 2004–2005 to 2004 data, and 2006–2009 to 2006 data due to the availability of LAN data.
[g] Predicted mean 24-h noise level based on monitoring data, averaged over the time period 2000–2014.

at a 270-m resolution. US census region was categorized based on state of enrollment address as Northeast, Midwest, South, or West.

### 2.6. Potential modifiers

We considered age, race and ethnicity, and educational attainment as potential modifiers (Etindele Sosso et al., 2021; Jackson et al., 2020; Li et al., 2018). In secondary analyses, we considered other potential modifiers. Prior studies suggest that sleep outcomes differ by annual household income (Etindele Sosso et al., 2021), use of sleep medication (Zee et al., 2023), depression (Riemann et al., 2001), and neighborhood SES (Etindele Sosso et al., 2021). Greenspace differs by both population density (i.e., urban areas have less greenspace than rural areas) and US census region (i.e., most of the US desert regions are in the West). Thus, we considered several additional potential modifiers in sensitivity analyses: annual household income (<$50,000, $50,000-$99,999, ≥$100,000), recent use of sleep medications (self-report of yes vs. no to the use of over the counter or prescription sleep medications over the past 6 weeks or to current use of antihistamines or melatonin), healthcare professional-diagnosed depression (yes, no), ADI (<75th vs. ≥75th percentile), population density (divided at the median of 1513.85 residents per square mile), and US census region.

### 2.7. Potential mediators

Greenspace may impact sleep through several mechanisms. Individuals who live in areas with more greenspace may be more likely to participate in physical activity (Kondo et al., 2018) and may be at lower risk of depression (Chen et al., 2024; Geneshka et al., 2021). Both lower physical activity and depression have been associated with poorer sleep quality (Kimura et al., 2014; Zhao et al., 2023). Additionally, prior research demonstrates greenspace as protective against air pollutants, which have been associated with sleep health (Liu et al., 2020). Therefore, we considered three potential mediators of the association between greenspace and sleep: physical activity (met Department of Health and Human Services recommendation of ≥7.5 MET-hours per week (DHHS, 2018)), healthcare professional-diagnosed depression at baseline (yes, no), and $NO_2$ dichotomized at the median value (8.10 ppb).

### 2.8. Statistical analysis

#### 2.8.1. Main analysis

Descriptive statistics (frequencies/percentages for categorical variables and means/standard deviations for continuous variables) were presented, overall and by dichotomous greenspace category (low/moderate vs. high).

We evaluated whether multilevel models that account for potential clustering in the data were appropriate. Using an intercept-only hierarchical generalized linear model with a Poisson distribution and Laplace estimation (Ene et al., n.d.) with US census region – the geographical unit available for this dataset – as the random intercept/cluster variable, we calculated the intraclass correlation coefficients (ICCs) for each sleep dimension. The ICCs ranged from 0.003 to 0.01, suggesting no homogeneity/clustering within regions (Fenn et al., 2004); therefore, we deemed a multilevel model as unnecessary for this analysis. Using Poisson regression with robust variance, we calculated prevalence ratios (PRs) and 95 % confidence intervals (CIs) for the cross-sectional associations between categorical greenspace or a one standard deviation decrease in greenspace and dimensions of sleep health. Two primary adjustment sets were considered. Model 1 was minimally adjusted for age (dichotomized at the median) and race and ethnicity (Latina, Black, White). Fully-adjusted Model 2 covariates were selected based on a directed acyclic graph (Greenland et al., 1999) and included age, race and ethnicity, marital status, educational attainment, population density, ADI, and US census region.

#### 2.8.2. Stratified analyses/assessment of effect measure modification

Effect measure modification (EMM) of the greenspace-sleep associations was evaluated in the fully-adjusted model (Model 2) by Wald tests of interaction terms for greenspace by the following potential modifiers, as previously described: age, race and ethnicity, and educational attainment. We also present results for each level of the potential modifier to show any differences in relative associations between groups. Lastly, we compared absolute differences in prevalence of sleep dimensions for low/moderate vs. high greenspace proximity by assessing the adjusted (for Model 2 covariates) population attributable risk (PAR) within each subgroup. Prior cross-sectional analyses of sleep disparities have used PAR approaches (Sweeney et al., 2024). The PAR combines both the effect size and exposure prevalence to compare health outcomes between two scenarios: the observed, or “factual”, scenario compared to the “counterfactual scenario” in which the exposure has been removed from the entire population (Northridge, 1995). Therefore, we assumed associations were true and that all low/moderate greenspace was replaced with high greenspace. Confidence intervals for the PARs were calculated using bootstrapping with 1000 repetitions and the percentile method (Jung et al., 2019).

#### 2.8.3. Secondary and sensitivity analyses

In addition to the primary EMM assessment, we considered annual household income, sleep medication use, depression, ADI, population density, and US census region as potential modifiers in sensitivity analyses by using the same approach described above.

We evaluated mediation by physical activity, depression, and $NO_2$ both individually and jointly. We used the inverse odds ratio weighting method, which allows multiple mediators to be evaluated simultaneously when considering continuous or categorical exposures (Nguyen et al., 2015). Briefly, inverse odds ratio weights were generated by fitting a linear regression model for the exposure given the mediator(s) and covariates. The calculated weights were then incorporated into the fully-adjusted Poisson model with robust variance to estimate the direct effect of greenspace on sleep health. The total effect was estimated using a modified Poisson model without the weights, and the indirect effect was determined by subtracting the direct effect from the total effect. CIs for the indirect effects were obtained using a bootstrapping approach with 1000 repetitions and the percentile method (Jung et al., 2019).

To evaluate our fully-adjusted model (Model 2) for potential over-adjustment and residual confounding, we estimated four additional models, separately. We (1) removed population density from the adjustment; (2) evaluated whether other factors related to urbanicity were confounding the greenspace-sleep association by additionally adjusting Model 2 for outdoor LAN, $PM_{2.5}$, $NO_2$, and noise; (3) additionally adjusted Model 2 for meteorological season of sleep questionnaire completion as a proxy for outdoor temperature, which is associated with sleep (Chevance et al., 2024), and because sleep varies by season (Karunanayake et al., 2021; Titova et al., 2022); and (4) additionally adjusted Model 2 for meteorological season and its interaction with region of residence because of variation in greenness and sleep by region (Grandner et al., 2015; Pankowska et al., 2023).

Lastly, we conducted additional sensitivity analyses to assess associations with annual average greenspace (averaged across January, April, July, and September) and associations by season of questionnaire completion.

## 3. Results

### 3.1. Study population characteristics

Among 47,690 participants with a mean age ± standard deviation of 56 ± 9.0 years, 3 % identified as Latina, 9 % as Black, and 87 % as White (Table 1). Most were married or living as married (75 %), completed at least some college or a technical degree (85 %), and had an annual household income of ≥$50,000 (75 %). Approximately a quarter of participants reported short sleep duration (22 %), insomnia symptoms (27 %), sleep debt (24 %), and belonged to the poor sleep latent class (20 %). Combined short sleep and insomnia (12 %) and frequent napping (11 %) were less prevalent. Over half met physical activity guidelines (55 %), approximately a quarter reported a healthcare professional diagnosis of depression (24 %), and 17 % of participants resided in the Northeast US region.

There was a higher proportion of Latina and Black participants in areas within proximity to low/moderate (5 % and 10 %) vs. high (1 % and 7 %) greenspace. Participants with low/moderate vs. high greenspace had comparable educational attainment, annual household income, most sleep dimensions (except sleep latent class membership), physical activity, and depression. Participants with low/moderate vs. high greenspace were more likely to live in the West (30 % vs. 4 %) and less likely to live in the Northeast (11 % vs. 30 %). The distributions of NDVI values overall and across categories of potential modifiers are presented in Supplemental Table 4.

### 3.2. Associations between greenspace and multiple sleep dimensions in the overall population

After adjustment for age and race and ethnicity, low to moderate (mean NDVI ± SD = 0.5 ± 0.2) compared to high (mean NDVI ± SD = 0.8 ± 0.1) greenspace proximity was not associated with short sleep duration or sleep debt but was associated with a higher prevalence of insomnia symptoms (PR = 1.06 [95 % CI:1.03–1.10]), frequent napping (PR = 1.11 [1.05–1.18]), and poorer multidimensional sleep as well as a marginally higher prevalence of combined short sleep plus insomnia (PR = 1.07 [1.00–1.14]); Table 2). After additional adjustment for sociodemographic characteristics, ADI, population density, and region of residence, associations were attenuated (e.g., $PR_{\text{insomnia symptoms}}$ = 1.03 [1.00–1.07]; $PR_{\text{short sleep and insomnia symptoms}}$ = 1.03 [0.96–1.11]; $PR_{\text{frequent napping}}$ = 1.06 [1.00–1.13]). Associations with continuous greenspace were generally consistent with the associations observed for categorical greenspace, except for the marginal association between a one SD-decrease in greenspace and a higher prevalence of short sleep (Model 2 - PR = 1.02 [1.00–1.04]).

### 3.3. Fully-adjusted associations between greenspace and multiple sleep dimensions: EMM by age, race and ethnicity, and educational attainment

Low/moderate vs. high greenspace proximity was associated with a higher prevalence of difficulty falling asleep only among younger (<55.6 years vs. ≥55.6 years) participants (*p*-interaction = 0.02; Table 3). Although EMM was not observed for continuous greenspace (*p*-interaction = 0.09), associations were consistent with results for categorical greenspace; higher prevalence of difficulty falling asleep was only observed among younger participants. For difficulty staying asleep,

**Table 2**
Prevalence ratios and 95 % confidence intervals for associations between low or moderate compared to high greenspace exposure and sleep health dimensions among women in the Sister Study.

| | | | Model 1 [a] | Model 2 [b] |
|---|---|---|---|---|
| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/N* | *PR (95 % CI)* | *PR (95 % CI)* |
| Short sleep duration (<7 h vs. ≥7 h) (n = 47,648) | Low/ moderate | 7028/ 31,765 | 1.00 (0.96, 1.03) | 0.98 (0.94, 1.02) |
| | High | 3335/ 15,883 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 10,363/ 47,648 | 1.01 (0.99, 1.03) | 1.02 (1.00, 1.04) |
| Difficulty falling asleep (yes vs. no) (n = 47,618) | Low/ moderate | 5819/ 31,744 | 1.06 (1.02, 1.11) | 1.04 (0.99, 1.09) |
| | High | 2619/ 15,874 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 8438/ 47,618 | 1.03 (1.01, 1.05) | 1.02 (1.00, 1.05) |
| Difficulty staying asleep (yes vs. no) (n = 47,633) | Low/ moderate | 4473/ 31,751 | 1.08 (1.03, 1.13) | 1.03 (0.98, 1.09) |
| | High | 2085/ 15,882 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 6558/ 47,633 | 1.04 (1.02, 1.07) | 1.02 (0.99, 1.05) |
| Insomnia symptoms [d] (yes vs. no) (n = 47,604) | Low/ moderate | 8839/ 31,731 | 1.06 (1.03, 1.10) | 1.03 (1.00, 1.07) |
| | High | 4064/ 15,873 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 12,903/ 47,604 | 1.03 (1.02, 1.05) | 1.02 (1.00, 1.03) |
| Short sleep and insomnia symptoms (yes for both vs. no for both) (n = 30,673) | Low/ moderate | 2637/ 20,305 | 1.07 (1.00, 1.14) | 1.03 (0.96, 1.11) |
| | High | 1149/ 10,368 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 3786/ 30,673 | 1.03 (1.00, 1.06) | 1.02 (0.99, 1.06) |
| Frequent napping (yes vs. no) (n = 47,678) | Low/ moderate | 3562/ 31,789 | 1.11 (1.05, 1.18) | 1.06 (1.00, 1.13) |
| | High | 1557/ 15,889 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 5119/ 47,678 | 1.05 (1.02, 1.08) | 1.04 (1.01, 1.07) |
| Sleep debt ≥2 h (vs. <2 h) (n = 46,299) | Low/ moderate | 7611/ 30,837 | 1.01 (0.98, 1.05) | 0.99 (0.95, 1.03) |
| | High | 3687/ 15,462 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 11,298/ 46,299 | 1.01 (0.99, 1.02) | 1.00 (0.98, 1.02) |
| Moderate sleep (vs. favorable sleep) (n = 36,772) | Low/ moderate | 6400/ 24,094 | 1.33 (1.29, 1.38) | 1.32 (1.27, 1.38) |
| | High | 2418/ 12,678 | 1.0 (ref) | 1.0 (ref) |
| | Per SD-decrease [c] | 8818/ 36,772 | 1.11 (1.09, 1.12) | 1.11 (1.09, 1.13) |
| Poor sleep (vs. favorable sleep) (n = 37,332) | Low/ moderate | 6627/ 24,321 | 1.16 (1.12, 1.20) | 1.12 (1.07, 1.16) |
| | High | 2751/ 13,011 | 1.0 (ref) | 1.0 (ref) |

(continued on next page)

**Table 2** (*continued*)

| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/N* | Model 1 [a] *PR (95 % CI)* | Model 2 [b] *PR (95 % CI)* |
|---|---|---|---|---|
| | Per SD-decrease [c] | 9378/37,332 | 1.05 (1.04, 1.07) | 1.05 (1.03, 1.07) |

Abbreviations: ADI, Area Deprivation Index; CI, confidence interval; NDVI, normalized difference vegetation index; PR, prevalence ratio; SD, standard deviation.

[a] Model 1 adjusted for age (dichotomized at the median) and race and ethnicity (Hispanic/Latina, non-Hispanic Black, non-Hispanic White).

[b] Model 2 adjusted for age (dichotomized at the median), race and ethnicity (Hispanic/Latina, non-Hispanic Black, non-Hispanic White), marital status (married/living as married, widowed/divorced/separated, never married), educational attainment (high school or less, some college/technical, bachelor's or higher), ADI (continuous), census tract population density (dichotomized at the median), and census region (Northeast, Midwest, South, West).

[c] SD = 0.182.

[d] Presence of insomnia symptoms defined as a report of either difficulty falling asleep or difficulty staying asleep.

even though EMM by age was only observed for continuous greenspace (p-interaction = 0.01), patterns of associations were similar whether greenspace was measured categorically or continuously, suggesting no association among the younger age group but a higher prevalence among the older age group. For moderate vs. favorable multidimensional sleep, associations with lower greenspace were stronger among younger participants whether greenspace was assessed categorically (p-interaction = 0.003) or continuously (p-interaction = 0.01). Further, PARs for moderate sleep differed among younger (PAR = 32.98 [23.34–42.89]) compared to older (16.70 [14.35–18.95]) participants, suggesting that if 100 younger aged women moved from areas within low/moderate greenspace proximity to areas with high greenspace proximity, approximately 33 would be expected to have favorable vs. moderate sleep, while a lower frequency (~17) would be expected among older aged women (Supplemental Table 5). Conversely, PRs for associations between lower greenspace and poor multidimensional sleep were larger among older participants; however, EMM was observed only for continuous greenspace (p-interaction = 0.01) and PARs overlapped across age groups (Table 3 and Supplemental Table 5).

Associations with multidimensional sleep also varied by race and ethnicity (Table 4). For instance, low/moderate greenspace was most strongly associated with poor vs. favorable sleep among White women: $PR_{Latina}$ = 0.93 [0.75–1.15]; $PR_{Black}$ = 1.02 [0.97–1.08]; $PR_{White}$ = 1.16 [1.11–1.22] (p-interaction<0.01). Results were consistent when greenspace was measured continuously. PARs for associations with poor vs. favorable sleep varied by race and ethnicity with suggestion of additive associations only among White women ($PAR_{White}$ = 9.22 [6.35–12.23]; Supplemental Table 6).

Associations between low/moderate vs. high greenspace and moderate vs. favorable multidimensional sleep varied by educational attainment (p-interaction = 0.04; Table 5). Specifically, the magnitudes of associations increased within increasing educational attainment ($PR_{\leq \text{high school}}$ = 1.23 [1.15–1.32], $PR_{\text{some college}}$ = 1.31 [1.24–1.40], $PR_{\geq \text{Bachelor's degree}}$ = 1.38 [1.30–1.46]). Associations with a SD decrease in greenspace were consistent with the categorical greenspace results. CIs for PARs of moderate vs. favorable sleep overlapped across educational attainment categories but were highest among participants who attained a bachelor's degree or higher (20.12 [16.57–23.74]) and lowest among participants who attained high school or less (13.32 [8.94–17.93]; Supplemental Table 7).

**Table 3**
Prevalence ratios and 95 % confidence intervals for associations between low or moderate compared to high greenspace exposure and sleep health dimensions among women in the Sister Study by age.

| | | Age | | | | |
|---|---|---|---|---|---|---|
| | | <55.6 years | | ≥55.6 years | | |
| Greenspace, July MODIS NDVI [mean ± SD (range)] | | 0.624 ± 0.182 (0–0.982) | | 0.621 ± 0.183 (0–0.997) | | |
| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/N* | *PR (95 % CI)* [a] | *Cases/N* | *PR (95 % CI)* [a] | *p-int* [b] |
| Short sleep duration (<7 h vs. ≥7 h) (n = 47,648) | Low/moderate | 3630/15,716 | 0.97 (0.92, 1.02) | 3398/16,049 | 0.99 (0.94, 1.05) | 0.57 |
| | High | 1753/8010 | 1.0 (ref) | 1582/7873 | 1.0 (ref) | |
| | Per SD-decrease [c] | 5383/23,726 | 1.01 (0.98, 1.04) | 4980/23,922 | 1.04 (1.01, 1.06) | 0.12 |
| Difficulty falling asleep (yes vs. no) (n = 47,618) | Low/moderate | 2797/15,715 | 1.09 (1.02, 1.16) | 3022/16,029 | 0.99 (0.93, 1.05) | 0.02 |
| | High | 1209/8008 | 1.0 (ref) | 1410/7866 | 1.0 (ref) | |
| | Per SD-decrease [c] | 4006/23,723 | 1.04 (1.01, 1.07) | 4432/23,895 | 1.01 (0.98, 1.04) | 0.09 |
| Difficulty staying asleep (yes vs. no) (n = 47,633) | Low/moderate | 1978/15,714 | 1.00 (0.93, 1.08) | 2495/16,037 | 1.05 (0.98, 1.13) | 0.31 |
| | High | 970/8011 | 1.0 (ref) | 1115/7871 | 1.0 (ref) | |
| | Per SD-decrease [c] | 2948/23,725 | 0.98 (0.95, 1.02) | 3610/23,908 | 1.04 (1.01, 1.08) | 0.01 |
| Insomnia symptoms [d] (yes vs. no) (n = 47,604) | Low/moderate | 4123/15,708 | 1.05 (1.00, 1.10) | 4716/16,023 | 1.02 (0.97, 1.06) | 0.32 |
| | High | 1893/8009 | 1.0 (ref) | 2171/7864 | 1.0 (ref) | |
| | Per SD-decrease [c] | 6016/23,717 | 1.02 (0.99, 1.04) | 6887/23,887 | 1.01 (0.99, 1.04) | 0.98 |
| Short sleep and insomnia symptoms (yes for both vs. no for both) (n = 30,673) | Low/moderate | 1274/10,094 | 1.00 (0.91, 1.10) | 1363/10,211 | 1.07 (0.97, 1.18) | 0.31 |
| | High | 590/5350 | 1.0 (ref) | 559/5018 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1864/15,444 | 0.99 (0.95, 1.04) | 1922/15,229 | 1.05 (1.00, 1.10) | 0.05 |
| Frequent napping (yes vs. no) (n = 47,678) | Low/moderate | 1307/15,726 | 0.99 (0.90, 1.09) | 2255/16,063 | 1.11 (1.02, 1.19) | 0.07 |
| | High | 621/8014 | 1.0 (ref) | 936/7875 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1928/23,740 | 1.01 (0.96, 1.06) | 3191/23,938 | 1.06 (1.02, 1.10) | 0.09 |
| Sleep debt ≥2 h (vs. <2 h) (n = 46,299) | Low/moderate | 4138/15,064 | 0.99 (0.95, 1.04) | 3473/15,773 | 0.98 (0.93, 1.04) | 0.76 |
| | High | 2026/7723 | 1.0 (ref) | 1661/7739 | 1.0 (ref) | |
| | Per SD-decrease [c] | 6164/22,787 | 1.00 (0.98, 1.02) | 5134/23,512 | 0.99 (0.97, 1.02) | 0.70 |
| Moderate sleep (vs. favorable sleep) (n = 36,772) | Low/moderate | 428/11,757 | 1.75 (1.44, 2.13) | 5972/12,337 | 1.30 (1.25, 1.35) | 0.003 |
| | High | 129/6397 | 1.0 (ref) | 2289/6281 | 1.0 (ref) | |
| | Per SD-decrease [c] | 557/18,154 | 1.21 (1.13, 1.30) | 8261/18,618 | 1.11 (1.09, 1.13) | 0.01 |

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**Table 3** (*continued*)

| | | Age | | | | |
|---|---|---|---|---|---|---|
| | | <55.6 years | | ≥55.6 years | | |
| Greenspace, July MODIS NDVI [mean ± SD (range)] | | 0.624 ± 0.182 (0–0.982) | | 0.621 ± 0.183 (0–0.997) | | |
| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/ N* | *PR (95 % CI)* [a] | *Cases/ N* | *PR (95 % CI)* [a] | *p-int* [b] |
| Poor sleep (vs. favorable sleep) (n = 37,332) | Low/ moderate | 3273/ 14,602 | 1.09 (1.03, 1.15) | 3354/ 9719 | 1.14 (1.09, 1.20) | 0.21 |
| | High | 1314/ 7582 | 1.0 (ref) | 1437/ 5429 | 1.0 (ref) | |
| | Per SD-decrease [c] | 4587/ 22,184 | 1.03 (1.00, 1.06) | 4791/ 15,148 | 1.07 (1.05, 1.10) | 0.01 |

Abbreviations: ADI, Area Deprivation Index; CI, confidence interval; NDVI, normalized difference vegetation index; p-int, p-interaction; PR, prevalence ratio.

[a] Model adjusted for race and ethnicity (Hispanic/Latina, non-Hispanic Black, non-Hispanic White), marital status (married/living as married, widowed/divorced/separated, never married), educational attainment (high school or less, some college/technical, bachelor's or higher), ADI (continuous), census tract population density (dichotomized at the median), and census region (Northeast, Midwest, South, West).

[b] p-interaction determined using the Wald statistic.

[c] SD = 0.182.

[d] Presence of insomnia symptoms defined as a report of either difficulty falling asleep or difficulty staying asleep.

### 3.4. Secondary and sensitivity analyses

In the secondary analysis that included assessment of EMM by other potential modifiers after full adjustment, no associations varied by sleep medication use or depression, but certain associations varied by annual household income, ADI, population density, and US Census region (Supplemental Tables 8–13). Consistent with EMM results by educational attainment, associations between low/moderate greenspace and higher prevalence of moderate vs. favorable sleep were stronger as annual household income increased ($PR_{<\$50,000}$ = 1.23 [1.17–1.30], $PR_{\$50,000\text{-}\$99,999}$ = 1.36 [1.28–1.44], $PR_{\geq\$100,000}$ = 1.43 [1.31–1.57]; p-interaction = 0.003). However, when greenspace was measured continuously, there was a u-shaped relationship suggesting stronger associations in the highest and lowest compared to middle-income category (p-interaction = 0.003). ADI consistently modified associations with several sleep dimensions, including short sleep, difficulty falling asleep, insomnia symptoms, combined short sleep plus insomnia, and poorer multidimensional sleep (all p-interactions <0.05). Generally, both low/moderate vs. high greenspace and a one SD decrease in greenspace were associated with a higher prevalence of unfavorable sleep dimensions among participants in the least deprived neighborhoods (ADI<75th percentile) while low/moderate greenspace was associated with a lower or suggestively lower prevalence of unfavorable sleep dimensions among participants in the most deprived neighborhoods (ADI≥75th percentile). For instance, low/moderate vs. high greenspace proximity was associated with a 19 % higher prevalence (PR = 1.19 [1.14–1.24]) of poor vs. favorable sleep in the least deprived neighborhoods and with a 6 % marginally lower prevalence (PR = 0.94 [0.87–1.02]) in the most deprived neighborhoods (p-interaction <0.0001). Moreover, low/moderate greenspace was associated with either marginally higher or higher prevalence of short sleep duration (p-interaction = 0.03), short sleep plus insomnia symptoms (p-interaction = 0.03), and sleep debt (p-interaction = 0.02) only among participants living in areas with high population density. Associations with higher prevalence of moderate (p-interaction = 0.05) and poor (p-interaction<0.01) multidimensional sleep were stronger in these high vs. low density areas. These patterns were consistent when continuous greenspace was assessed. Relatedly, associations between low/moderate greenspace and higher prevalence of short sleep as well as poor vs. favorable sleep were strongest in the densely populated Northeast region (e.g., poor sleep: $PR_{Northeast}$ = 1.32 [1.21–1.45], $PR_{Midwest}$ = 1.10 [1.02–1.19], $PR_{South}$ = 1.05 [1.00–1.11]), $PR_{West}$ = 1.24 [1.00–1.54]; p-interaction <0.0001), and EMM by region was consistent for continuous greenspace.

Physical activity, depression, and $NO_2$ generally did not individually or jointly mediate associations between greenspace and sleep dimensions (Supplemental Table 14).

In models assessing the sensitivity of our confounder adjustment among the overall population, results were largely unchanged when we (1) removed population density from models, (2) additionally adjusted for other ambient environmental exposures (LAN, air pollutants, noise), and (3) additionally adjusted for season of sleep questionnaire completion as well as (4) the interaction between questionnaire season and region of residence (Supplemental Table 15). In models assessing the stability of our greenspace measure (measuring annual average greenspace and testing for season of sleep questionnaire completion*-greenspace interaction), results were comparable and consistent with the main analysis, except for a weaker association with moderate vs. favorable multidimensional sleep (PR = 1.19 [1.14–1.23] for annual greenspace vs. PR = 1.32 [1.27–1.38] for July greenspace), and there was no evidence of seasonal variation except for a weaker association between continuous greenspace and moderate multidimensional sleep when the sleep questionnaire was completed in the spring versus the winter (Supplemental Tables 15–16).

## 4. Discussion

Among a racially and ethnically diverse cohort of US women, we investigated proximity to greenspace in relation to multiple dimensions of sleep health. We also determined whether age, race and ethnicity, and educational attainment acted as modifiers of associations. Consistent with our hypotheses, low-to-moderate versus high proximity to greenspace, which was more prevalent among Black and Latina women, was associated with a higher prevalence of sleep disturbances, including insomnia symptoms and poorer multidimensional sleep. However, greenspace proximity was generally not associated with short sleep duration. These results were robust when greenspace was measured continuously and after sensitivity analyses related to confounder adjustment. Age, race and ethnicity, and educational attainment – a marker of SES – generally modified the greenspace proximity-sleep relationship in directions that did not align with our hypotheses. Specifically, lower greenspace proximity was more strongly associated with moderate versus favorable multidimensional sleep among younger versus older aged women while associations with difficulty staying asleep were stronger among older women. Moreover, lower greenspace proximity was more strongly associated with poor multidimensional sleep among White compared to racially and ethnically minoritized women. Also, lower greenspace proximity was more strongly associated with moderate multidimensional sleep among women who attained higher versus lower levels of education. Results were consistent when we used annual household income rather than educational attainment as the indicator of SES while evaluating EMM. Additionally, while low-to-moderate compared to high greenspace proximity was associated with a higher prevalence of unfavorable sleep among women in the least deprived/disadvantaged neighborhoods, it was marginally associated with a lower prevalence of multidimensional unfavorable sleep in the most deprived/disadvantaged neighborhoods. These findings demonstrate that proximity to greenspace may be associated with better sleep health; however, the benefits appear inequitably distributed in that socially-advantaged populations appear to benefit the most.

Our observations of lower proximity to greenspace being associated with sleep disturbances are consistent with most prior studies. In a recent review of the greenspace and sleep literature, 11 of 13 studies

**Table 4**
Prevalence ratios and 95 % confidence intervals for associations between low or moderate compared to high greenspace exposure and sleep health dimensions among women in the Sister Study by race and ethnicity.

| | | Race and ethnicity | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Hispanic/Latina | | Non-Hispanic Black | | Non-Hispanic White | | |
| Greenspace, July MODIS NDVI [mean ± SD (range)] | | 0.477 ± 0.187 (0–0.920) | | 0.604 ± 0.162 (0–0.984) | | 0.630 ± 0.182 (0–0.997) | | |
| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/N* | *PR (95 %CI)* [a] | *Cases/N* | *PR (95 %CI)* [a] | *Cases/N* | *PR (95 %CI)* [a] | *p-int* [b] |
| Short sleep duration (<7 h vs. ≥7 h) (n = 47,648) | Low/moderate | 385/1430 | 1.02 (0.78, 1.33) | 1518/3329 | 0.93 (0.86, 1.01) | 5125/27,006 | 0.99 (0.95, 1.04) | 0.38 |
| | High | 45/177 | 1.0 (ref) | 499/1082 | 1.0 (ref) | 2791/14,624 | 1.0 (ref) | |
| | Per SD-decrease [c] | 430/1607 | 1.03 (0.95, 1.12) | 2017/4411 | 0.99 (0.96, 1.03) | 7916/41,630 | 1.03 (1.00, 1.05) | 0.28 |
| Difficulty falling asleep (yes vs. no) (n = 47,618) | Low/moderate | 382/1431 | 1.10 (0.82, 1.46) | 934/3329 | 0.95 (0.85, 1.06) | 4503/26,984 | 1.05 (1.00, 1.10) | 0.24 |
| | High | 39/178 | 1.0 (ref) | 308/1084 | 1.0 (ref) | 2272/14,612 | 1.0 (ref) | |
| | Per SD-decrease [c] | 421/1609 | 0.98 (0.91, 1.06) | 1242/4413 | 0.97 (0.92, 1.03) | 6775/41,596 | 1.03 (1.01, 1.06) | 0.08 |
| Difficulty staying asleep (yes vs. no) (n = 47,633) | Low/moderate | 182/1430 | 0.75 (0.52, 1.09) | 436/3327 | 1.12 (0.93, 1.36) | 3855/26,994 | 1.03 (0.97, 1.09) | 0.17 |
| | High | 27/178 | 1.0 (ref) | 120/1084 | 1.0 (ref) | 1938/14,620 | 1.0 (ref) | |
| | Per SD-decrease [c] | 209/1608 | 0.91 (0.80, 1.03) | 556/4411 | 1.02 (0.94, 1.11) | 5793/41,614 | 1.02 (0.99, 1.05) | 0.18 |
| Insomnia symptoms [d] (yes vs. no) (n = 47,604) | Low/moderate | 481/1429 | 0.95 (0.76, 1.19) | 1169/3325 | 0.99 (0.90, 1.09) | 7189/26,977 | 1.04 (1.00, 1.08) | 0.49 |
| | High | 57/178 | 1.0 (ref) | 370/1084 | 1.0 (ref) | 3637/14,611 | 1.0 (ref) | |
| | Per SD-decrease [c] | 538/1607 | 0.96 (0.89, 1.02) | 1539/4409 | 0.99 (0.94, 1.03) | 10,826/41,588 | 1.02 (1.00, 1.04) | 0.07 |
| Short sleep and insomnia symptoms (yes for both vs. no for both) (n = 30,673) | Low/moderate | 168/862 | 0.91 (0.60, 1.39) | 615/1802 | 0.95 (0.83, 1.08) | 1854/17,641 | 1.06 (0.98, 1.15) | 0.29 |
| | High | 20/110 | 1.0 (ref) | 193/577 | 1.0 (ref) | 936/9681 | 1.0 (ref) | |
| | Per SD-decrease [c] | 188/972 | 0.96 (0.85, 1.09) | 808/2379 | 0.97 (0.90, 1.03) | 2790/27,322 | 1.04 (1.00, 1.08) | 0.09 |
| Frequent napping (yes vs. no) (n = 47,678) | Low/moderate | 176/1434 | 0.90 (0.59, 1.38) | 501/3335 | 1.04 (0.87, 1.23) | 2885/27,020 | 1.07 (1.00, 1.14) | 0.71 |
| | High | 21/178 | 1.0 (ref) | 147/1085 | 1.0 (ref) | 1389/14,626 | 1.0 (ref) | |
| | Per SD-decrease [c] | 197/1612 | 1.03 (0.90, 1.17) | 648/4420 | 1.00 (0.92, 1.09) | 4274/41,646 | 1.05 (1.01, 1.08) | 0.55 |
| Sleep debt ≥2 h (vs. <2 h) (n = 46,299) | Low/moderate | 417/1370 | 1.00 (0.78, 1.28) | 1082/3188 | 0.96 (0.87, 1.06) | 6112/26,279 | 0.99 (0.95, 1.03) | 0.84 |
| | High | 49/170 | 1.0 (ref) | 353/1039 | 1.0 (ref) | 3285/14,253 | 1.0 (ref) | |
| | Per SD-decrease [c] | 466/1540 | 1.02 (0.95, 1.10) | 1435/4227 | 0.96 (0.92, 1.01) | 9397/40,532 | 1.00 (0.98, 1.02) | 0.28 |
| Moderate sleep (vs. favorable sleep) (n = 36,772) | Low/moderate | 267/902 | 0.91 (0.66, 1.25) | 307/1164 | 1.49 (1.20, 1.86) | 5826/22,028 | 1.32 (1.27, 1.38) | 0.04 |
| | High | 23/114 | 1.0 (ref) | 56/421 | 1.0 (ref) | 2339/12,143 | 1.0 (ref) | |
| | Per SD-decrease [c] | 290/1016 | 1.04 (0.96, 1.12) | 363/1585 | 1.14 (1.05, 1.23) | 8165/34,171 | 1.12 (1.10, 1.14) | 0.17 |
| Poor sleep (vs. favorable sleep) (n = 37,332) | Low/moderate | 459/1094 | 0.93 (0.75, 1.15) | 2009/2866 | 1.02 (0.97, 1.08) | 4159/20,361 | 1.16 (1.11, 1.22) | 0.0009 |
| | High | 55/146 | 1.0 (ref) | 615/980 | 1.0 (ref) | 2081/11,885 | 1.0 (ref) | |
| | Per SD-decrease [c] | 514/1240 | 1.01 (0.95, 1.08) | 2624/3846 | 1.01 (0.98, 1.03) | 6240/32,246 | 1.07 (1.05, 1.10) | 0.0008 |

Abbreviations: ADI, Area Deprivation Index; CI, confidence interval; NDVI, normalized difference vegetation index; p-int, p-interaction; PR, prevalence ratio.
[a] Model adjusted for age (dichotomized at the median), marital status (married/living as married, widowed/divorced/separated, never married), educational attainment (high school or less, some college/technical, bachelor's or higher), ADI (continuous), census tract population density (dichotomized at the median), and census region (Northeast, Midwest, South, West).
[b] p-interaction determined using the Wald statistic.
[c] SD = 0.182.
[d] Presence of insomnia symptoms defined as a report of either difficulty falling asleep or difficulty staying asleep.

found that higher greenspace was associated with better sleep quantity and quality (Shin et al., 2020). Studies among adults published after this review have been mixed but mostly demonstrate greenspace as associated with recommended sleep duration, better sleep quality, and less sleep disturbance (Astell-Burt and Feng, 2020; Li et al., 2022; Parks et al., 2023; Stenfors et al., 2023; Teixeira et al., 2023; Xie et al., 2020; Yang et al., 2020; Zhong et al., 2022). In the study with the most comparable population of 51,562 women (mean age = 66.9 ± 10.9 years; 88 % White) who resided in California, more greenspace access was associated with lower odds of both short sleep duration and longer sleep

**Table 5**
Prevalence ratios and 95 % confidence intervals for associations between low or moderate compared to high greenspace exposure and sleep health dimensions among women in the Sister Study by educational attainment.

| | | Educational attainment | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | High school diploma or equivalent | | Some college or technical school | | Bachelor's or higher degree | | |
| Greenspace, July MODIS NDVI [mean ± SD (range)] | | 0.625 ± 0.180 (0–0.994) | | 0.616 ± 0.184 (0–0.997) | | 0.626 ± 0.182 (0–0.982) | | |
| *Sleep dimension* | *Greenspace (NDVI)* | *Cases/N* | *PR (95 %CI)* [a] | *Cases/N* | *PR (95 %CI)* [a] | *Cases/N* | *PR (95 %CI)* [a] | *p-int* [b] |
| Short sleep duration (<7 h vs. ≥7 h) (n = 47,648) | Low/moderate | 1150/4803 | 0.96 (0.88, 1.06) | 2683/11,000 | 1.00 (0.94, 1.06) | 3195/15,962 | 0.97 (0.92, 1.03) | 0.76 |
| | High | 557/2417 | 1.0 (ref) | 1162/5155 | 1.0 (ref) | 1616/8311 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1707/7220 | 0.99 (0.95, 1.04) | 3845/16,155 | 1.04 (1.01, 1.08) | 4811/24,273 | 1.02 (0.99, 1.04) | 0.12 |
| Difficulty falling asleep (yes vs. no) (n = 47,618) | Low/moderate | 1113/4799 | 0.97 (0.89, 1.07) | 2346/10,995 | 1.07 (1.00, 1.15) | 2360/15,950 | 1.03 (0.96, 1.11) | 0.24 |
| | High | 538/2416 | 1.0 (ref) | 960/5156 | 1.0 (ref) | 1121/8302 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1651/7215 | 1.00 (0.95, 1.04) | 3306/16,151 | 1.04 (1.00, 1.07) | 3481/24,252 | 1.02 (0.99, 1.05) | 0.30 |
| Difficulty staying asleep (yes vs. no) (n = 47,633) | Low/moderate | 837/4801 | 0.98 (0.88, 1.10) | 1688/10,999 | 1.02 (0.94, 1.10) | 1948/15,951 | 1.06 (0.98, 1.15) | 0.49 |
| | High | 415/2419 | 1.0 (ref) | 753/5157 | 1.0 (ref) | 917/8306 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1252/7220 | 0.99 (0.94, 1.04) | 2441/16,156 | 1.02 (0.98, 1.06) | 2865/24,257 | 1.03 (0.99, 1.07) | 0.43 |
| Insomnia symptoms [d] (yes vs. no) (n = 47,604) | Low/moderate | 1635/4797 | 0.98 (0.92, 1.06) | 3406/10,995 | 1.03 (0.98, 1.09) | 3798/15,939 | 1.05 (1.00, 1.11) | 0.29 |
| | High | 798/2416 | 1.0 (ref) | 1476/5155 | 1.0 (ref) | 1790/8302 | 1.0 (ref) | |
| | Per SD-decrease [c] | 2433/7213 | 0.98 (0.95, 1.02) | 4882/16,150 | 1.02 (0.99, 1.05) | 5588/24,241 | 1.02 (1.00, 1.05) | 0.12 |
| Short sleep and insomnia symptoms (yes for both vs. no for both) (n = 30,673) | Low/moderate | 503/2865 | 0.95 (0.83, 1.09) | 1115/6825 | 1.07 (0.96, 1.19) | 1019/10,615 | 1.05 (0.94, 1.17) | 0.37 |
| | High | 246/1483 | 1.0 (ref) | 442/3266 | 1.0 (ref) | 461/5619 | 1.0 (ref) | |
| | Per SD-decrease [c] | 749/4348 | 0.98 (0.92, 1.06) | 1557/10,091 | 1.05 (1.00, 1.10) | 1480/16,234 | 1.01 (0.96, 1.07) | 0.25 |
| Frequent napping (yes vs. no) (n = 47,678) | Low/moderate | 661/4811 | 1.05 (0.92, 1.19) | 1317/11,009 | 1.06 (0.96, 1.17) | 1584/15,969 | 1.07 (0.98, 1.16) | 0.98 |
| | High | 294/2421 | 1.0 (ref) | 541/5156 | 1.0 (ref) | 722/8312 | 1.0 (ref) | |
| | Per SD-decrease [c] | 955/7232 | 1.05 (0.99, 1.12) | 1858/16,165 | 1.05 (1.00, 1.10) | 2306/24,281 | 1.03 (0.99, 1.08) | 0.83 |
| Sleep debt ≥2 h (vs. <2 h) (n = 46,299) | Low/moderate | 1270/4714 | 0.97 (0.89, 1.05) | 2868/10,636 | 1.03 (0.97, 1.10) | 3473/15,487 | 0.96 (0.91, 1.01) | 0.16 |
| | High | 630/2363 | 1.0 (ref) | 1250/5020 | 1.0 (ref) | 1807/8079 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1900/7077 | 1.00 (0.96, 1.04) | 4118/15,656 | 1.01 (0.99, 1.04) | 5280/23,566 | 0.98 (0.95, 1.01) | 0.17 |
| Moderate sleep (vs. favorable sleep) (n = 36,772) | Low/moderate | 1324/3496 | 1.23 (1.15, 1.32) | 2246/7944 | 1.31 (1.24, 1.40) | 2830/12,654 | 1.38 (1.30, 1.46) | 0.04 |
| | High | 529/1835 | 1.0 (ref) | 834/4001 | 1.0 (ref) | 1055/6842 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1853/5331 | 1.11 (1.08, 1.14) | 3080/11,945 | 1.09 (1.06, 1.12) | 3885/19,496 | 1.13 (1.11, 1.16) | 0.06 |
| Poor sleep (vs. favorable sleep) (n = 37,332) | Low/moderate | 1193/3365 | 1.06 (0.98, 1.15) | 2650/8348 | 1.13 (1.07, 1.20) | 2784/12,608 | 1.13 (1.07, 1.20) | 0.35 |
| | High | 519/1825 | 1.0 (ref) | 1012/4179 | 1.0 (ref) | 1220/7007 | 1.0 (ref) | |
| | Per SD-decrease [c] | 1712/5190 | 1.03 (0.99, 1.07) | 3662/12,527 | 1.06 (1.04, 1.10) | 4004/19,615 | 1.05 (1.02, 1.08) | 0.33 |

Abbreviations: ADI, Area Deprivation Index; CI, confidence interval; NDVI, normalized difference vegetation index; p-int, p-interaction; PR, prevalence ratio.
[a] Model adjusted for age (dichotomized at the median), race and ethnicity (Hispanic/Latina, non-Hispanic Black, non-Hispanic White), marital status (married/living as married, widowed/divorced/separated, never married), ADI (continuous), census tract population density (dichotomized at the median), and census region (Northeast, Midwest, South, West).
[b] p-interaction determined using the Wald statistic.
[c] SD = 0.182.
[d] Presence of insomnia symptoms defined as a report of either difficulty falling asleep or difficulty staying asleep.

latency (Zhong et al., 2022). Our study extends this prior literature by including women from across the US, supporting that associations persisted even after adjustment for other geographically based exposures, and by investigating and demonstrating effect modification by age, race and ethnicity, and SES. These findings related to EMM contrast some prior literature but are consistent with other literature. For instance, county-level access to greenspace was more protective against insufficient sleep among adults aged 65 years and older versus those younger than 65 years in a nationally representative study of US men and women (Grigsby-Toussaint et al., 2015). We observed similar EMM by age for difficulty staying asleep and poor multidimensional sleep but the opposite (i.e., stronger associations among younger participants) for other sleep dimensions (e.g., difficulty falling asleep, moderate multidimensional sleep). These and our other contrasting findings may be related to differences in geographical area (i.e., county vs. home address) used to determine greenspace exposure and the composition of study populations since, for instance, our population comprised only women.

Our findings related to EMM of associations by age that varied by sleep dimension may be explained by biological, behavioral, and clinical factors. As described in prior literature, certain sleep characteristics change with age. Specifically, aging is associated with increased difficulty in maintaining sleep due to factors like decreases in deep or slow wave sleep along with increases in lighter sleep stages where awakenings are more likely; increased napping frequency that can affect nighttime sleep continuity; and clinical factors such as use of medications, chronic conditions (e.g., pain), and sleep disorders that can lead to disrupted sleep after onset (Li et al., 2018). Generally poorer sleep maintenance and related factors such as sleep disorders that were not observable may have exacerbated the greenspace proximity–difficulty staying asleep as well as greenspace proximity–poor multidimensional sleep associations observed among older women in the current study. In contrast, the magnitude of changes to sleep latency or difficulty falling asleep are modest as age increases (Li et al., 2018). Lower underlying differences in difficulty falling asleep between younger and older women may have allowed for a more accurate assessment of potential EMM by age that is directly related to greenspace rather than to age-related changes to sleep. However, more research is necessary to explore and explain why associations between greenspace proximity and difficulty falling asleep was stronger among younger women.

Since most studies were either limited in racial and ethnic diversity or were outside of the US, we are the first, to our knowledge, to demonstrate potentially stronger positive impacts of greenspace proximity on sleep among White (non-Hispanic) women compared to women of other races and ethnicities. This finding may be related to processes like greenspace gentrification that can unintentionally negatively impact minoritized racial-ethnic groups in myriad ways that reduce use (e.g., decreased sense of belonging in neighborhoods/greenspaces) (Jelks et al., 2021; Jennings et al., 2024; Williams et al., 2021; Wolch et al., 2014). Moreover, although prior nationally representative studies described disparities in greenspace (Casey et al., 2017; Klompmaker et al., 2023), few studies considered SES differences in associations between greenspace and sleep. Like these descriptive studies (Casey et al., 2017; Klompmaker et al., 2023), we found higher greenspace proximity among higher SES individuals and among White compared to Black women. However, greenspace proximity was, on average, higher in our sample than in Klompmaker et al.'s nationally representative sample, which may reflect the higher SES in the Sister Study cohort. Of two prior studies of SES differences in greenspace-sleep associations among adults, one in Canada indicated no differences by SES as measured by low versus high annual household income (Parks et al., 2023); however, consistent with our study, Xie et al. reported stronger associations among individuals with higher versus lower SES, as measured by educational attainment and income, in China (Xie et al., 2020). Replication across populations with racial and ethnic, SES, and geographic diversity is warranted.

Notably, our results do not support the hypothesized equigenic effects of greenspace suggested in prior literature (Brown et al., 2018; Mitchell and Popham, 2008; Moran et al., 2021). The "equigenesis hypothesis" posits that access to greenspace could contribute to attenuated health inequities by supporting the health of less advantaged populations as much as or more than the more advantaged populations in a geographical area (Mitchell, 2013; Mitchell and Popham, 2008). However, we observed that associations between lower greenspace proximity and poorer multidimensional sleep were strongest among participants with higher versus lower social advantages, suggesting potentially greater sleep health benefits among more advantaged participants. Our findings are likely related to unintended consequences that may promote sleep disparities. Williams et al. and Wolch et al. previously demonstrated that greenspace redevelopment can inadvertently negatively impact minoritized racial and ethnic groups through processes like gentrification (Williams et al., 2021; Wolch et al., 2014). For instance, greenspace development efforts in Atlanta neighborhoods were associated with stressors (e.g., financial strain, likely related to increases in property values and ultimately, property tax) and fear of displacement, which were associated with short sleep duration and sleep disturbances among Black residents (Williams et al., 2022). These findings contrast with a systematic review suggesting that the protective effects of greenspace against some poor health outcomes (e.g., cardiovascular disease) are stronger among lower compared to higher SES individuals; however, this finding was more evident in studies in Europe vs. the US, which differ from each other in SES and racialized contexts (Rigolon et al., 2021). Our findings are also supported by a recent scoping review that showed that greenspace gentrification can result in differential health benefits where marginalized groups fare the worst (Jelks et al., 2021).

Relatedly, we consistently observed stronger associations between greenspace proximity and sleep among higher versus lower SES groups across SES measures (i.e., educational attainment and annual household income). Further, low/moderate versus high greenspace proximity was associated with a higher prevalence of multiple dimensions of poor sleep health in the least deprived neighborhoods but was associated with a lower prevalence of poor sleep health in the most deprived neighborhoods. This may be related to the likelihood of higher access and more well maintained greenspace that may have beneficial effects in more advantaged neighborhoods (Nardone et al., 2021; Wolch et al., 2014) as well as differences between advantaged and disadvantaged groups. For instance, individuals with higher versus lower SES are more likely to engage in leisure-time physical activity (Sturm and Cohen, 2019), a health behavior associated with better sleep health (Zhao et al., 2023) that may occur outdoors. Higher SES individuals may also have other resources (e.g., perceived safety) that allow for higher accessibility and use of greenspace areas (Jelks et al., 2021). Such factors can contribute to SES differences in the potential sleep health benefits, or lack thereof, of greenspace.

Despite potential differences in relationships by social factors, the proposed mechanisms through which greenspace may promote sleep health include fostering improved mental health, promotion of physical activity, and buffering against environmental hazards such as noise pollution (Dzhambov, 2018; Huang et al., 2021; Mytton et al., 2012; Ohly et al., 2016; Ulrich et al., 1991). For instance, higher objective measures of greenspace were previously associated with lower noise annoyance, which can improve sleep quality as noise is a known sleep disruptor (Dzhambov, 2018; Jackson and Gaston, 2019). By absorbing and reducing ambient air pollutants, greenspace can also improve air quality, an additional environmental contributor to sleep health (Jackson and Gaston, 2019). Further, greenspace can provide an accessible area for multiple types of recreation, thus promoting physical activity (Mytton et al., 2012), which has been associated with improved sleep quality and subjective sleep (De Nys et al., 2022; Kelley and Kelley, 2017). Green spaces have also been suggested to promote health through increased social connections and social cohesion (Hartig et al., 2014; Jennings and Bamkole, 2019), which has been associated with favorable sleep health (Alhasan et al., 2020; Gaston et al., 2024). Related to mental health, the attention-restorative theory (ART) and the stress recovery theory (SRT) support the sleep health benefits of greenspace. ART posits that natural environments improve cognitive function through the engagement of "soft fascination" which can replenish directed attention after mental fatigue (Ohly et al., 2016). SRT contends that humans are physiologically attuned to nature, with exposure to natural surroundings resulting in overall positive affective responses through an engagement of the parasympathetic nervous system (Ulrich et al., 1991). In a study investigating SRT and ART in physiological responses to urban greenspace, exposure to greenspace, particularly in areas of diverse plant species, led to significant decreases in physiological measures of stress (Huang et al., 2021). In combination, these findings along with evidence of bidirectional associations between stress and sleep regulation (Hirotsu et al., 2015) corroborate the potentially restorative influence of greenspace on sleep.

Our observations must be considered in the context of several limitations. The cross-sectional study design limits causal inference. Related to our measurement of greenspace, we used a 250m resolution to capture residential greenness. Larger buffer sizes (e.g., up to 2000m) are suggested as better predictors of physical health (Browning and Lee, 2017); however, more data are needed to determine the best buffer sizes for determining relationships with sleep health. Additionally, the exposure assessment only included residential greenness; however, exposures at other locations (e.g., workplace) are also relevant. Relatedly, our greenspace measure captured proximity to greenspace, but our findings suggest that access to greenspace may vary by sociodemographic group (e.g., race and ethnicity) even when groups are within the same proximity of greenspace. Additionally, data on greenspace type (e.g., tree canopy, grass) are not available in the NDVI and most data did not become available from other sources until after enrollment in Sister Study ended. With newer data, more detailed greenspace assessments can better inform potential sleep interventions (Astell-Burt and Feng, 2020). Further, as stated in prior literature, ideal greenspace assessment over time would include multiple dimensions, including greenspace type and biodiversity; quantity; quality; visual, auditory, olfactory, and physical accessibility; and actual use by study participants (Bratman et al., 2024; Yang et al., 2021). Only subjective sleep data were available, and prior studies show moderate correlations between subjective and objective sleep (Jackson et al., 2018; Lauderdale et al., 2008). Moreover, although we captured several dimensions of sleep health, data on other aspects of sleep health such as satisfaction with sleep are needed. Also related to our assessment of sleep debt, we assumed that longest sleep duration reflected the amount of sleep needed to feel rested and shortest sleep duration reflected the usual amount of sleep obtained. However, direct measurements are necessary to capture sleep debt. Future studies can overcome our and prior study limitations by employing longitudinal designs and capturing multidimensional, objective along with subjective (e.g., satisfaction) measures of both greenspace and sleep. Moreover, future studies are needed to further elucidate relationships among men and gender diverse individuals. Additionally, residual confounding related to unmeasured factors (e.g., crime in neighborhoods) is possible. Future analyses are warranted, including those considering additional confounders, longitudinal studies of other potential mediators (e.g., temperature), and causal inferences studies that can better approximate PARs. Lastly, our relatively high SES sample comprised women who had sisters with breast cancer who may differ and engage in more positive health behaviors than women in the general population, thus limiting generalizability. However, a prior study showed Black and White women in the Sister Study data cohort no more likely to engage in healthy behaviors than the general population (Spector et al., 2011).

Nonetheless, strengths include our large sample size; a racially and ethnically as well as socioeconomically diverse study population of US women; use of objective satellite imagery to capture greenspace; and robust findings after adjustment for important environmental and individual-level factors and other sensitivity analyses. Also, our novel findings expand the prior literature by demonstrating that benefits of greenspace on sleep may be more pronounced among socially advantaged populations in the US, thus revealing interactions between physical and social environments. As described in a prior review of the literature, future studies should also consider the interplay of social and physical environments in addition to individual-level risk factors in investigations of sleep health (Hunter and Hayden, 2018). Moreover, our study included greenspace proximity; however, as highlighted in a recent review, natural landscapes are composed of plants, water, and rocks and minerals, each of which have possible health benefits that require further investigation (Li et al., 2023). Incorporating other components of natural landscapes in future studies could better inform potential public health interventions.

Although further research is warranted to provide additional evidence on associations between greenspace and sleep among socially diverse populations, our observations of disparities in the greenspace and sleep association highlight potential concerns that may warrant public health initiatives. Attending to multiple aspects of the social and physical environment may help address the observed inequity in the greenspace and sleep relationship. For instance, as described by Jennings et al., addressing built environment features (e.g., walkability), safety concerns (e.g., crime, nearby traffic), and effective maintenance of spaces while incorporating cultural preferences in greenspace design may promote greenspace utilization among diverse communities inclusive of groups with social disadvantages (Jennings et al., 2024). Furthermore, given that gentrification and greenspace gentrification processes have been found to contribute to loss of social cohesion, lower perceptions of safety (often related to stigmatization), and decreased feelings of belonging in newly created spaces among long-time residents (Jelks et al., 2021), fostering community in greenspaces may encourage use of proximate and accessible greenspace among socially disadvantaged populations. In turn, use of shared greenspace across diverse groups can result in increased neighborhood social cohesion (Jennings and Bamkole, 2019), which has been previously associated with propitious sleep health (Alhasan et al., 2020; Gaston et al., 2024).

## 5. Conclusions

In conclusion, in this cross-sectional study of proximity to greenspace in relation to sleep among a racially and ethnically and socioeconomically diverse cohort of US women, low/moderate compared to high greenspace proximity was associated with poorer multidimensional sleep health, with the largest magnitudes of associations among women with social advantages. Additionally, lower greenspace proximity was associated with better sleep health among women in neighborhoods with higher levels of deprivation. These findings may be linked to the inadvertent consequences related to greenspace development (e.g., gentrification) that negatively impact socially vulnerable groups. While replication is warranted, these findings demonstrate the need to consider both social and physical environments while incorporating a health equity lens in investigations of environmental determinants of sleep. Such approaches can guide intervention development to address sleep health – a fundamental contributor to overall health and well-being – and sleep health disparities.

## CRediT authorship contribution statement

**Symielle A. Gaston:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Marina Sweeney:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Shubhangi Patel:** Writing – original draft. **Viniece Jennings:** Writing – review & editing. **Gregory N. Bratman:** Writing – review & editing. **Erline Martinez-Miller:** Writing – review & editing, Methodology, Formal analysis. **W. Braxton Jackson:** Writing –

review & editing, Supervision, Project administration. **Rena R. Jones:** Writing – review & editing, Resources. **Peter James:** Writing – review & editing, Resources. **Diana Grigsby-Toussaint:** Writing – review & editing. **Dale P. Sandler:** Writing – review & editing, Resources, Funding acquisition. **Chandra L. Jackson:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

## Non-financial disclosure:

None

## Data statement

Data, including anonymized data for replication, are available as described on the Sister Study website (https://sisterstudy.niehs.nih.gov/English/coll-data.htm). Data use is restricted to replication, only. New analyses must be approved after a proposal process. Code can be requested from the corresponding author.

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The Sister Study was approved and is overseen by the National Institute of Environmental Health Sciences (NIEHS) Institutional Review Board. The NIEHS Institutional Review Board waived approval of this secondary analysis of de-identified data. All participants provided written informed consent.

## Financial disclosure:

None

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121698.

## Data availability

Data will be made available on request.

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