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Artificial light at night and social vulnerability: An environmental justice analysis in the U.S. 2012–2019

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A R T I C L E I N F O

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A B S T R A C T

Background: Artificial Light at Night (ALAN) is an emerging health risk factor that has been linked to a wide range of adverse health effects. Recent study suggested that disadvantaged neighborhoods may be exposed to higher levels of ALAN. Understanding how social disadvantage correlates with ALAN levels is essential for identifying the vulnerable populations and for informing lighting policy.
Methods: We used satellite data from the National Aeronautics and Space Administration's (NASA) Black Marble data product to quantify annual ALAN levels (2012–2019), and the Center for Disease Control and Prevention's (CDC) Social Vulnerability Index (SVI) to quantify social disadvantage, both at the US census tract level. We examined the relationship between the ALAN and SVI (overall and domain-specific) in over 70,000 tracts in the Contiguous U.S., and investigated the heterogeneities in this relationship by the rural-urban status and US regions (i.e., Northeast, Midwest, South, West).
Results: We found a significant positive relationship between SVI and ALAN levels. On average, the ALAN level in the top 20% most vulnerable communities was 2.46-fold higher than that in the 20% least vulnerable communities (beta coefficient (95% confidence interval) for log-transformed ALAN, 0.90 (0.88, 0.92)). Of the four SVI domains, minority and language status emerged as strong predictors of ALAN levels. Our stratified analysis showed considerable and complex heterogeneities across different rural-urban categories, with the association between greater vulnerability and higher ALAN primarily observed in urban cores and rural areas. We also found regional differences in the association between ALAN and both overall SVI and SVI domains.
Conclusions: Our study suggested ALAN as an environmental justice issue that may carry important public health implications.
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1. Introduction

The growing field of environmental justice (EJ) research emphasizes understanding the disparate patterns of environmental exposures across different geographic areas and sociodemographic factors, such as race, ethnicity, and socioeconomic status (SES) (Brulle and Pellow, 2006). Decades of EJ research has established that unequal distribution of environmental exposures, specifically a disproportionately high burden of hazardous exposures among disadvantaged populations, is a crucial contributor to health inequity (Brulle and Pellow, 2006).

Artificial Light at Night (ALAN) is an emerging environmental hazard. Excessive exposure to ALAN can disrupt the endogenous circadian rhythm, a master orchestrator of human behaviors and bodily functions. Numerous studies have linked exposure to ALAN with a wide range of

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adverse health outcomes (Lunn et al., 2017). For example, using nighttime satellite imagery, epidemiological studies showed that people living in areas with higher levels of ALAN are more likely to report sleep deficiency (Xiao et al., 2020) and mood disorders (Paksarian et al., 2020), and are at a higher risk to develop obesity (Zhang et al., 2020) and cancer (Xiao et al., 2020; Xiao et al., 2021; Zhang et al., 2021; Xiao et al., 2021; James et al., 2017). Emerging evidence also suggests that ALAN is an important EJ issue: a recent EJ analysis of light pollution in the US reported that racial and ethnic minority groups are exposed to significantly higher levels of ALAN when compared to non-Hispanic White Americans (Nadybal et al., 2020). Moreover, the study reported a positive association between ALAN and the proportion of renter-occupied housing units (an indicator of housing instability), and a curvilinear association between ALAN levels and the median household income (an indicator of neighborhood SES). Finally, the study found that the relationship between ALAN levels and neighborhood attributes were similar across metropolitan, suburban and small city-rural areas.

Although these earlier findings suggested that ALAN levels may be higher in disadvantaged communities, additional and more comprehensive analysis documenting ALAN patterns across American neighborhoods are needed for public health practitioners and policy makers. First, neighborhood social environment is complex and thus require multidimensional measures to capture different domains of neighborhood disadvantage. Second, the previous study investigated the potential moderating effect of rural-urban status on the association between ALAN levels and sociodemographic factors. However, the definition of rural-urban categories was overly simplistic: For example, one category encompassed a heterogeneous mix of micropolitan, small town, and rural areas, each with distinct political, economic, and cultural characteristics that may impact the relationship between ALAN and social disadvantage. Therefore, it is necessary to conduct a more nuanced analysis that considers the diversity of communities along the rural-urban continuum. Moreover, the US is a vast country made of multiple regions that are both geographically and socially different, and yet, no study has examined whether the relationship between ALAN and social disadvantage differs across US regions. Our analysis aims to address these research gaps to provide a more comprehensive understanding of the contextual determinants of ALAN patterns. Such an understanding is crucial to identifying communities that are disproportionately burdened by high levels of ALAN. This knowledge can ultimately guide the development of monitoring and intervention programs to address ALAN-related health disparities.

The objective of this study was to examine ALAN levels across all contiguous US census tracts between 2012 and 2019 in relation to the Social Vulnerability Index (SVI, overall and domain-specific), a recognized measure of neighborhood vulnerability that has been frequently used in environmental and public health research and practice. We also examined the association between ALAN levels and SVI across all 10 categories of the Rural-Urban Commuting Area (RUCA) codes and in four different US regions, the Northeast, Midwest, South and West, as defined by the Census Bureau. We hypothesized that communities facing greater social vulnerability would experience elevated levels of ALAN; however, the specific patterns of the ALAN-SVI relationship would vary across different SVI domains, rural-urban categories and US regions.

2. Methods

2.1. ALAN

We used the VNP46A4 data product in NASA's Black Marble suite to quantify ALAN levels for all US census tracts. Methodological details about this data product have been reported before (Román et al., 2018). Briefly, raw ALAN measure was obtained by the Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) on board the Suomi-National Polar-orbiting Partnership satellite. The VIIRS DNB sensor provides daily measurements of nighttime visible and near-infrared light and is ultra-sensitive in lowlight conditions. Algorithms used to generate the Black Marble data products perform a series of corrections for atmospheric, terrain, lunar, thermal and straylight effects on the raw ALAN values and produce cloud-free nighttime radiance (Román et al., 2018). Yearly composite measures of ALAN were then generated using daily ALAN levels with aforementioned corrections. Finally, because the observation of ALAN by VIIRS DNB is influenced by view angles and snow coverage on the ground, we used the yearly composite measure generated for multiple view-angle categories and upon snow free surfaces. We then derived yearly ALAN measure by each census tract based on the 2010 US census tract boundary, and calculated tract-level average ALAN levels for 2012–2019. Data preparation and mapping was performed in R (Team RDCJhwR-po, 2009).

2.2. SVI

The SVI was developed by the Center for Disease Control and Prevent (CDC) to determine social vulnerability in American neighborhoods and help public health officials to identify communities in need of support when responding to hazardous events (Flanagan et al., 2011). Details about the SVI have been published before (Flanagan et al., 2011). Briefly, the SVI encompasses four domains, where each domain included multiple social determinant measures obtained from the American Community Survey. These four domains include 1) SES (% below poverty, % unemployed, mean household income, and % with no high school diploma); 2) household composition and disability (% below age 17, % above age 65, % with disability, and % male or female householders with children under 18 and no spouse); 3) minority status and language (% minority and % who speak English less than "well"); and 4) housing and transportation (% multi-unit structure, % mobile homes, % household with crowding, % households with no vehicle, and % in group quarters such as correctional institutions, nursing homes, and the military). The SVI was derived by first calculating the percentile ranking of individual measures across US census tracts with a non-zero population. Next, the sum of rankings of relevant individual measure was calculated to generate the domain-specific SVI, and the sum of rankings of all measures was calculated to generate the overall SVI. The SVI, both overall and domain specific, were than scaled to have values between 0 and 1, with higher values indicating higher vulnerability. The SVI has been widely used in public health research to investigate needihood-level disparities in health behaviors and disease outcomes (Bauer et al., 2022; Jain et al., 2022; Khan et al., 2021).

Tract-level overall and domain-specific SVI for 2014, 2016, and 2018 were downloaded from the CDC's website (https://www.atsdr.cdc.gov/placeandhealth/svi/index.html). For the main analysis, we first computed the average SVI (overall and specific domains) across years 2014, 2016, and 2018, and then divided these into quintiles. For the sensitivity analysis focusing on year-specific ALAN-SVI relationship, we used year-specific quintiles of overall SVI and SVI domains and the ALAN levels of the corresponding year.

2.3. Rural-urban status and US regions

Census tract rural-urban status was defined by the 2010 RUCA Codes developed by the U.S. Department of Agriculture (https://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes/documentation/). We used the primary RUCA categories, including metropolitan area core, metropolitan area high commuting, metropolitan area low commuting, micropolitan area core, micropolitan high commuting, micropolitan low commuting, small town core, small town high commuting, small town low commuting, and rural areas. We used the Census Regions and Divisions to define different regions in the contiguous US, including the Northeast (CT, ME, MA, NH, RI, VI, NJ, NY, PA), Midwest (IN, IL, MI, OH, WI, IA, KS, MN, MO, NE, ND, SD), South (DE, DC, FL, GA, MD, NC, SC, VA, WV, AL, KY, MS, IN, AR, LA, OK, TX) and West (AZ, CO, ID, NM, MT, UT, NV, WY, CA, OR, WA).

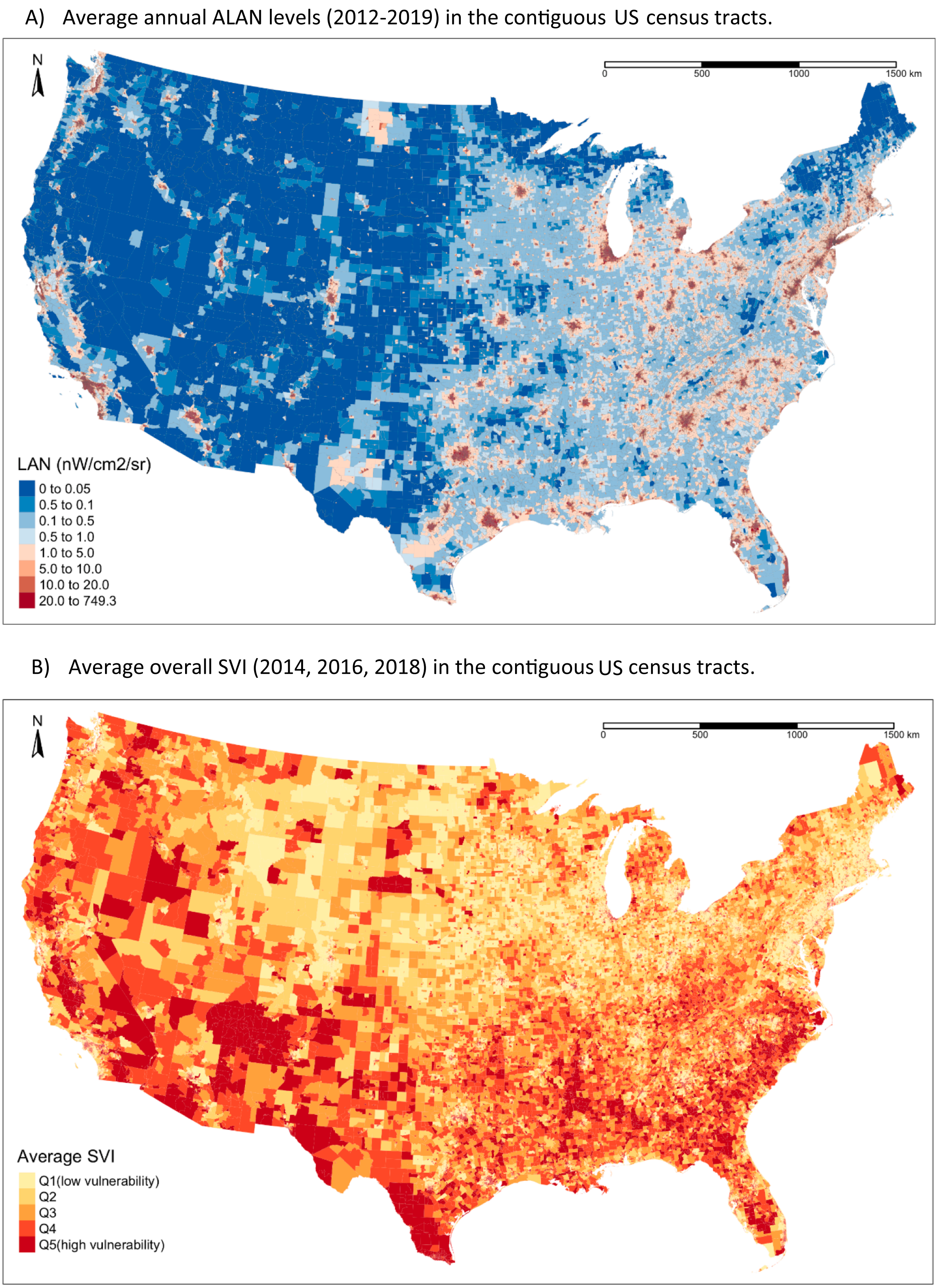

Fig. 1. Average ALAN (A) levels and overall SVI (B) in the in the contiguous US census tracts. Redder/warmer colors indicate higher ALAN levels and social vulnerability. Abbreviations: ALAN, artificial light at night; SVI, Social Vulnerability Index.

Table 1
Distribution of selected characteristics of US census tracts (N = 71,651) according to quintiles of average SVI (2014, 2016, 2018).

	Average SVI (2014, 2016, 2018), quintiles				
	Q1 (Least Vulnerable)	Q2	Q3	Q4	Q5 (Most Vulnerable)
ALAN, nW/cm^2/sr, median (IQR)	10.56 (3.15, 22.31)	11.76 (1.76, 26.83)	12.59 (1.28, 30.18)	19.82 (2.79, 39.34)	35.18 (15.86, 56.17)
Overall SVI, median (IQR)	0.11 (0.06, 0.16)	0.30 (0.26, 0.35)	0.50 (0.45, 0.55)	0.70 (0.65, 0.75)	0.89 (0.85, 0.94)
SVI domain, median (IQR)					
Socioeconomic status	0.12 (0.06, 0.21)	0.31 (0.22, 0.41)	0.5 (0.4, 0.6)	0.68 (0.59, 0.77)	0.88 (0.81, 0.94)
Household composition/Disability	0.23 (0.14, 0.35)	0.39 (0.22, 0.54)	0.55 (0.34, 0.7)	0.66 (0.45, 0.81)	0.80 (0.63, 0.91)
Minority status/Language	0.29 (0.16, 0.45)	0.37 (0.18, 0.58)	0.44 (0.22, 0.67)	0.6 (0.37, 0.8)	0.83 (0.65, 0.94)
Housing/Transportation	0.14 (0.07, 0.25)	0.36 (0.24, 0.52)	0.52 (0.36, 0.68)	0.66 (0.49, 0.8)	0.82 (0.68, 0.92)
Tract-level characteristics [a], median (IQR)					
Population density, per km^2	701.24 (186.26, 1451.82)	681.91 (77.1, 1678.74)	646.77 (47.82, 1858.18)	959.07 (96.61, 2399.68)	1682.86 (528.69, 3729.00)
% households living below poverty level	2.50 (1.20, 4.30)	5.00 (2.90, 7.50)	8.20 (5.40, 11.80)	13.00 (9.00, 18.00)	23.70 (17.10, 32.00)
% persons 16 or older unemployed	2.20 (1.50, 3.10)	2.70 (1.80, 3.80)	3.20 (2.20, 4.40)	4.00 (2.70, 5.50)	5.50 (3.80, 7.70)
% persons 25 or older without high school diploma	3.50 (2.00, 5.40)	6.60 (4.40, 9.20)	10.10 (7.30, 13.60)	14.80 (11.00, 20.00)	24.50 (18.40, 32.80)
% persons 65 or older	16.10 (12.10, 20.10)	16.80 (12.70, 21.00)	16.40 (12.30, 20.60)	14.90 (10.90, 19.10)	11.80 (8.50, 16.00)
% persons 17 or younger	21.80 (18.20, 25.30)	20.70 (17.10, 23.80)	21.00 (17.60, 24.20)	22.50 (19.00, 26.00)	26.40 (22.40, 30.40)
% persons 5 or older with disability	8.80 (6.70, 11.10)	11.60 (9.00, 14.40)	13.70 (10.50, 17.20)	15.00 (11.20, 19.10)	15.50 (11.60, 20.00)
% persons not non-Hispanic White	14.70 (7.80, 25.00)	18.80 (8.30, 34.90)	24.10 (10.10, 44.90)	41.65 (20.50, 69.10)	79.50 (55.80, 93.40)
% persons 5 or older speaking English less than well	2.00 (0.80, 4.20)	2.60 (0.90, 6.00)	3.10 (0.90, 8.20)	4.80 (1.30, 13.50)	13.10 (3.30, 27.20)
% occupied housing units with > 1 occupant/room	0.50 (0.00, 1.20)	1.10 (0.40, 2.40)	1.90 (0.70, 3.60)	3.00 (1.30, 5.70)	5.90 (2.90, 11.20)
% occupied housing units renter occupied	14.40 (8.70, 24.30)	23.70 (16.00, 37.40)	29.40 (20.50, 43.70)	39.20 (27.40, 54.00)	56.40 (42.6, 71.40)
% persons with no health insurance	3.40 (2.00, 5.40)	5.50 (3.50, 8.40)	7.80 (5.20, 11.50)	10.60 (7.10, 15.20)	14.30 (9.70, 20.60)
Primary RUCA code (2010), %					
Metropolitan area core (RUCA code = 1)	81.30	70.25	62.61	65.33	79.05
Metropolitan area high commuting (RUCA code = 2)	11.80	12.48	11.15	8.08	3.58
Metropolitan area low commuting (RUCA code = 3)	0.58	1.06	1.42	1.00	0.50
Micropolitan area core (RUCA code = 4)	1.51	3.96	6.72	8.78	7.98
Micropolitan area high commuting (RUCA code = 5)	1.64	3.42	4.41	3.13	1.00
Micropolitan area low commuting (RUCA code = 6)	0.24	0.69	0.95	0.70	0.27
Small town core (RUCA code = 7)	0.36	1.42	3.29	5.34	4.46
Small town high commuting (RUCA code = 8)	0.55	1.37	1.95	1.37	0.47
Small town low commuting (RUCA code = 9)	0.17	0.57	0.85	0.68	0.12
Rural (RUCA code = 10)	1.86	4.77	6.65	5.59	2.56
US regions					
Northeast	22.90	22.39	17.71	14.92	15.15
Midwest	28.41	26.58	24.76	21.38	17.02
South	29.73	30.56	37.54	42.59	40.67
West	18.96	20.47	19.98	21.11	27.15

Abbreviations: ALAN, artificial light at night; IQR, interquartile range; RUCA, rural-urban commuting area codes; SVI, social vulnerability index.
[a]all tract-level measures were based on 5-year estimates of the American Community Survey (2014–2018).

2.4. Statistical analysis

The analysis included 71,651 tracts with no missing data for ALAN, SVI or RUCA. We presented descriptive statistics (median and interquartile range for continuous variables and percentage for categorical variables) of census tract ALAN levels, along with various census tract characteristics by quintiles of the average overall SVI. Correlation among overall SVI and individual SVI domains was determined by the Spearman correlation coefficient. Tract-level ALAN was highly skewed to the right and was log-transformed to improve normality. To assess the tract-level geographic variation of ALAN levels explained by the SVI and RUCA, we applied linear mixed effect regression models with a county-level random intercept to account for clustering effects. We developed a series models to investigate the impact of each explanatory variable on the ALAN level as follows: For the analysis focusing on the overall SVI, we presented results from three models: Model 1 included SVI quintiles alone; Model 2 additionally included population density and state, both as fixed effects; and Model 3 further included the primary RUCA code (10 groups) as fixed effects. For the analysis focusing on individual SVI domains, we performed similar linear mixed effect regression analysis which included each SVI domain separately (Model 4), or all four domain SVI domains simultaneously (Model 5), adjusting for population density, state and RUCA. Then we performed subgroup analysis to determine the ALAN-SVI relationship within each RUCA category and US region. Finally, to evaluate whether and to what degree this relationship changed over the years, we conducted sensitivity analysis using ALAN and SVI values for 2014, 2016, and 2018 separately. All statistical analyses were performed by R or SAS 9.4 (SAS Inc. Cary, North Carolina).

3. Results

Maps presenting the average ALAN levels (2012–2019) and SVI values (2014–2018) at census tracts are depicted in Fig. 1, and specific SVI domains are depicted in **Supplementary** Fig. 1**.** Table 1 presents the census-tract average ALAN levels and other attributes by quintiles of average overall SVI. There was a monotonic increase in ALAN levels with higher quintiles of SVI. When compared to tracts in the lowest quintile of social vulnerability, tracts with higher vulnerability had higher rates of poverty, unemployment, disability, non-White

Table 2
Association between average ALAN levels (2012–2019) and neighborhood characteristics among US census tracts.

	Average ALAN, log-transformed, β (95% CI)		
	Model 1	Model 2	Model 3
SVI, average, 2014–2018			
Q1	ref	ref	ref
Q2	0.27 (0.24, 0.29)	0.25 (0.22, 0.27)	0.26 (0.24, 0.28)
Q3	0.56 (0.53, 0.58)	0.52 (0.49, 0.55)	0.48 (0.46, 0.50)
Q4	0.92 (0.89, 0.95)	0.85 (0.82, 0.88)	0.68 (0.66, 0.70)
Q5	1.29 (1.26, 1.32)	1.17 (1.14, 1.19)	0.90 (0.88, 0.92)
Population density, 1000 [a]		0.075 (0.072, 0.078)	0.059 (0.057, 0.061)
Primary RUCA code (2010)			
Metropolitan area core (RUCA code = 1)			ref
Metropolitan area high commuting (RUCA code = 2)			−2.27 (−2.29, −2.24)
Metropolitan area low commuting (RUCA code = 3)			−2.90 (−2.97, −2.83)
Micropolitan area core (RUCA code = 4)			−0.51 (−0.55, −0.46)
Micropolitan area high commuting (RUCA code = 5)			−3.07 (−3.12, −3.01)
Micropolitan area low commuting (RUCA code = 6)			−3.19 (−3.28, −3.10)
Small town core (RUCA code = 7)			−1.40 (−1.45, −1.34)
Small town high commuting (RUCA code = 8)			−3.54 (−3.61, −3.46)
Small town low commuting (RUCA code = 9)			−3.43 (−3.53, −3.32)
Rural (RUCA code = 10)			−3.59 (−3.64, −3.54)

Model 1: linear mixed effect model including SVI quintiles as the predictor, and county as a random effect variable.
Model 2: linear mixed effect model including SVI (quintiles), population density (continuous), and state (results not shown), and county as a random effect variable.
Model 3: linear mixed effect model including SVI (quintiles), population density (continuous), Primary RUCA code (10 groups as shown), and state (results not shown), and county as a random effect variable.
[a] measured based on 5-year estimates of the American Community Survey (2014–2018).
Abbreviations: ALAN, artificial light at night; CI, confidence interval, RUCA, rural-urban commuting area codes; SVI, social vulnerability index.

population, crowding housing units, renter-occupied housing, and lower education level, English proficiency, and health insurance coverage. Population density was noticeably higher in the upper two quintiles of SVI than in the lower three quintiles. The vast majority of census tracts (n = 51,379, 71.7%) were located in metropolitan area cores, and neighborhoods in both the lowest and highest quintiles of the SVI were more likely to be located in metropolitan cores compared to neighborhoods in the middle quintiles. We also observed higher social vulnerability (Q4 and Q5 of SVI) in the South region. Correlations between the overall SVI and four domains ranged from 0.56 (overall SVI and minority status and language) to 0.92 (overall SVI and SES). Correlations among SVI domains were generally weaker, ranging from 0.02 to 0.62 (**Supplementary Table 1**).

Table 2 presents the regression analysis results on the estimated associations of the averaged ALAN levels with quintiles of overall SVI, as well as associations with population density and the RUCA code. Higher social vulnerability was significantly associated with higher ALAN levels with an apparent dose-dependent relationship. Adjusting for population density, state, and RUCA categories only moderately reduced effect sizes associated with the SVI, and all beta coefficients as well as the overall trend remained statistically significant. In the fully adjusted models (**Model 3**), the difference in log-transformed ALAN values between the highest and lowest quintile of SVI was 0.90 (95% confidence interval (CI), 0.88, 0.92)). This suggested that the average ALAN level in the top 20% most vulnerable communities was 2.46-fold higher than that in the bottom 20%. Year-specific analyses using data from 2014, 2016 and 2018 produced results largely similar (**Supplementary Table 2**), showing <10% difference in effect estimates compared to the main results.

The association between ALAN levels and social vulnerability varied across different SVI domains (Table 3). From the results where each domain was assessed individually (Model 4), the minority status and language domain showed the strongest association with ALAN level ($\beta_{Q5\ vs\ Q1}$ (95% CI), 1.10 (1.07, 1.13)), equivalent to a 2.72-fold increase). The household composition and disability domain showed the weakest association with ALAN level (0.35 (0.32, 0.37), or 42% increase). After simultaneously including all four SVI domains (Model 5), ALAN level remained positively associated with three of the four SVI domains (i.e., SES, minority status and language, and housing and transportation), despite attenuated estimated effect sizes. In contrast, the simultaneously adjusted model showed a *negative* relationship between household composition/disability and ALAN level, suggesting increased vulnerability in this domain was associated with *lower* levels of ALAN after accounting for vulnerability in other domains. Year-specific results for individual SVI domains from Model 4 and Model 5 were presented in **Supplementary Table 3 and 4**, respectively. Overall the findings were similar across years, and consistent with those in the main analysis.

Stratified analyses by the RUCA code showed that the ALAN-SVI relationships varied substantially across the rural-urban continuum (Fig. 2 and Table 4). For overall SVI, the positive association with ALAN levels was generally strong in the cores of metropolitan, micropolitan and small-town areas, but weaker-to-null in commuting areas surrounding these cores. We also observed a strong positive relationship between overall SVI and ALAN levels in rural tracts. For the SES domain, we observed a positive association with ALAN levels only in metropolitan and micropolitan cores, and a strong *negative* association in areas with high commuting to metropolitan cores. The household composition and disability domain exhibited mixed patterns of association with ALAN, showing a negative association among metropolitan cores areas, but a positive association among areas with high commuting to metropolitan cores, cores of micropolitan and small-town areas, and rural areas. For the minority status and language domain, the positive relationship with higher levels of ALAN was only observed in areas of metropolitan cores and with high commuting to metropolitan cores. Finally, the housing/transportation domain was positively associated with ALAN levels in most of the RUCA categories, except for the micropolitan low commuting, and small-town core and low commuting areas. Year-specific relationships between SVI and ALAN by RUCA categories were largely similar (data not shown).

Table 5 presents the associations between ALAN and overall SVI and SVI domains across the four US regions. Although we observed a relationship between higher ALAN and higher overall SVI in all four US regions, the relationship appeared to be the most pronounced in the Northeast and the least pronounced in the South, when judged by effect size. Regional differences in the SVI-ALAN relationship varied across SVI domains. For example, the association with the housing and transportation domain was largely similar across regions. In contrast, a significant trend between higher ALAN and the socioeconomic domain was

Table 3
Association between individual SVI domains and averaged ALAN levels (2012–2019) among US census tracts.

	Average SVI domains, 2014–2018, quintiles					
	Q1	Q2	Q3	Q4	Q5	*p trend*
Socioeconomic status						
ALAN, nW/cm^2/sr, median (IQR)	12.58 (4.71, 24.96)	12.33 (2.16, 27.31)	12.55, 1.33, 30.17)	16.76 (1.56, 37.51)	34.57 (13.85, 55.71)	
β (95% CI)						
Model 4	ref	0.25 (0.23, 0.27)	0.43 (0.41, 0.45)	0.62 (0.60, 0.64)	0.83 (0.81, 0.85)	*<0.0001*
Model 5	ref	0.13 (0.10, 0.15)	0.19 (0.17, 0.21)	0.26 (0.24, 0.29)	0.36 (0.32, 0.39)	*<0.0001*
Household composition/Disability						
ALAN, nW/cm^2/sr, median (IQR)	24.79 (9.71, 47.52)	15.20 (4.18, 31.75)	13.78 (1.98, 33.27)	11.24 (1.07, 30.95)	16.28 (2.32, 35.89)	
β (95% CI)						
Model 4	ref	−0.16 (−0.19, −0.14)	−0.06 (−0.08, −0.04)	0.07 (0.05, 0.09)	0.35 (0.32, 0.37)	*<0.0001*
Model 5	ref	−0.21 (−0.23, −0.19)	−0.25 (−0.27, −0.23)	−0.25 (−0.27, −0.23)	−0.12 (−0.15, −0.10)	*<0.0001*
Minority status/Language						
ALAN, nW/cm^2/sr, median (IQR)	1.52 (0.45, 7.69)	8.33 (1.75, 21.02)	16.93 (6.03, 32.80)	25.10 (12.31, 41.96)	40.48 (25.06, 59.80)	
β (95% CI)						
Model 4	ref	0.37 (0.35, 0.39)	0.67 (0.65, 0.69)	0.91 (0.88, 0.93)	1.10 (1.07, 1.13)	*<0.0001*
Model 5	ref	0.28 (0.26, 0.30)	0.46 (0.43, 0.48)	0.58 (0.55, 0.60)	0.59 (0.56, 0.63)	*<0.0001*
Housing/Transportation						
ALAN, nW/cm^2/sr, median (IQR)	11.17 (3.32, 22.26)	11.78 (1.48, 28.06)	16.02 (1.98, 34.62)	20.96 (3.41, 42.29)	29.78 (8.39, 54.81)	
β (95% CI)						
Model 4	ref	0.22 (0.20, 0.24)	0.39 (0.37, 0.41)	0.60 (0.58, 0.62)	0.88 (0.86, 0.90)	*<0.0001*
Model 5	ref	0.12 (0.10, 0.14)	0.22 (0.20, 0.24)	0.37 (0.34, 0.39)	0.57 (0.55, 0.59)	*<0.0001*

Model 4: linear mixed effect model including each domain-specific SVI (quintiles), population density (continuous), Primary RUCA code (1–10), and state, and county as a random effect variable.
Model 5: linear mixed effect model including all four domain-specific SVI domains (quintiles), population density (continuous), Primary RUCA code (1–10), and state, and county as a random effect variable.
Abbreviations: ALAN, artificial light at night; CI, confidence interval, RUCA, rural-urban commuting area codes; SVI, social vulnerability index.

only in the Northeast and Midwest, not in the South or West regions.

4. Discussions

In this nationwide analysis with over 70,000 US census tracts, we found a strong positive association between overall SVI and ALAN levels, confirming our hypothesis that communities of higher social vulnerability have a higher burden of light pollution. Our analysis on individual domains of SVI and by rural-urban status and regions revealed a considerably more complex relationship between neighborhood disadvantage and ALAN levels than previously documented. These findings suggested that burdens of ALAN exposure in EJ communities may not be homogenous nationwide, and are likely shaped by an array of social, economic, cultural, and environmental factors.

The observed relationship between higher social vulnerability and ALAN levels was generally consistent with the previous EJ analysis on light pollution inequalities in the US (Nadybal et al., 2020). In particular, our finding for the SVI domain on minority status and language confirmed the previously reported higher levels of ALAN among racial/ethnic minority groups when compared to White Americans. In fact, of all four SVI domains, the minority status and language component emerged as the strongest predictor of higher ALAN levels, with a statistically significant association after simultaneously adjusting for other SVI components. This suggests that this SVI domain plays an important and distinct role in shaping ALAN disparities that cannot be fully explained by other social factors (e.g., SES). In the US, decades of structural racism has led to race- and place-based policy and practices (e.g., Jim Crow laws in the South, race-based mortgage lending and zoning codes, land-use and transportation decisions) that created racially segregated neighborhoods with uneven distributions of environmental hazards and substantial health disparities across the country (Lee et al., 2022; Swope et al., 2022; Krieger et al., 2014; Dannenberg et al., 2003). For example, previous research has consistently reported that historical redlining, a discriminative practice that restricted access to mortgage based on neighborhood racial composition, was associated with higher air pollution, lack of green space, and adverse outcomes in cardiovascular disease, cancer, asthma, and preterm birth (Yitshak-Sade et al., 2020; Jones et al., 2014; Nardone et al., 2021; Nardone et al., 2020; Krieger et al., 2020; Krieger et al., 2020). Our study extended this research by showing that neighborhoods with dominantly racial/ethnic minority populations are also exposed to higher levels of ALAN, an emerging risk factor for many diseases that has potentially important public health implications (Lunn et al., 2017).

Previous research reported a curvilinear relationship between median household income and ALAN levels at the tract level, with lower levels of ALAN associated with both low and high income levels (Nadybal et al., 2020).In contrast, we found a monotonic increase in ALAN levels with lower SES. The discrepancy between the previous finding and ours may be explained by differences in the SES measures: while the previous study focused on income alone, the SES domain of the SVI provides a more comprehensive measurement of SES, including multiple variables on income, unemployment and education levels. The positive association between ALAN levels and the SVI domain of housing and transportation (which includes measures of housing quality and ownership of automobiles) is a novel finding that has not been reported before. Although crowing, multi-unit housing and low rate of car ownership are more common in densely populated urban cores, the positive relationship with ALAN observed in our study remained after adjustment for population density and rural-urban status, suggesting that the finding cannot be entirely attributed to the correlation between ALAN levels and population density and urbanicity. Finally, although the results for the household composition and disability domain appeared to be weak-to-null in the overall analysis, this does not suggest a lack of association between this domain and ALAN levels. Instead, the finding, when combined with the RUCA-stratified results, suggested that differences in the ALAN-SVI relationship along the rural-urban continuum cannot be ignored (see below for detailed discussions on the role of rural-urban status). Taken together, our findings highlight the varying contribution both regarding the magnitude and direction by different domains of social vulnerability, and emphasize the importance of considering social vulnerability as a multi-dimension measure in future research.

A rather complex picture emerged in our analysis on SVI and ALAN levels by rural-urban status and US regions. Previous study employed crude rural-urban classifications (i.e., combining RUCA codes 2–3 and 4–10 into single categories) and found a consistent positive association

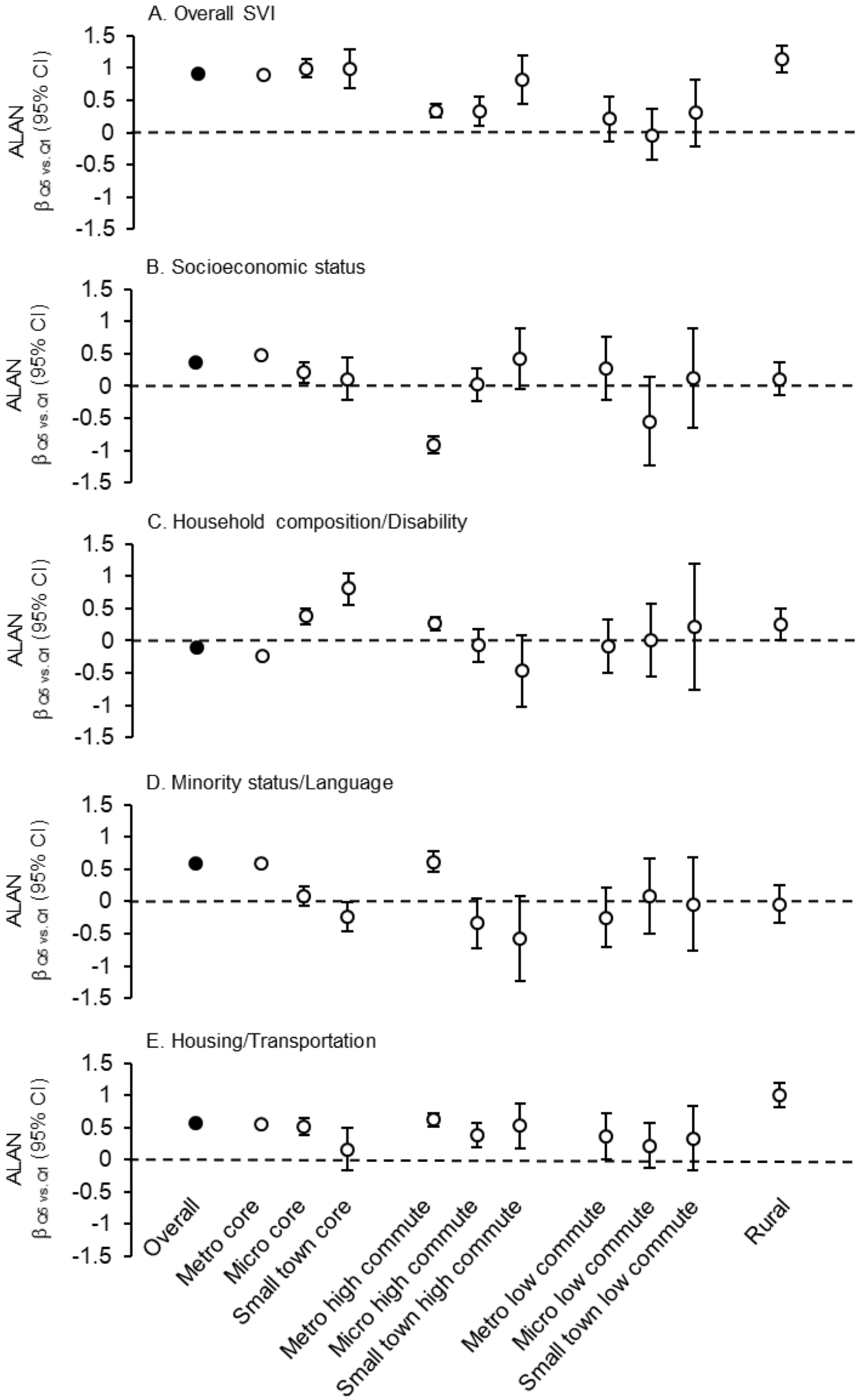

Fig. 2. Associations between ALAN levels and overall SVI and SVI domains in the overall sample and according to different RUCA categories. [a] Associations are expressed as β (95% CI) comparing the highest quintile of the SVI variable to the lowest, derived from multiple linear regression models including all four SVI domains (quintiles) and population density (continuous). Abbreviations: ALAN, artificial light at night; CI, confidence interval, RUCA, rural-urban commuting area codes; SVI, social vulnerability index.

between ALAN levels and sociodemographic and socioeconomic characteristics across different rural-urban areas. In contrast, our analysis that stratified by the 10 original RUCA codes revealed considerable heterogeneity along the rural-urban continuum. Specifically, higher overall SVI was consistently associated with higher ALAN level across all urban cores, regardless of population size (i.e., metropolitan, micropolitan and small-town cores). These results suggest that socially vulnerable communities in urban cores are exposed to higher levels of ALAN, even in small cities and towns that have been largely overlooked in light pollution studies. Conversely, the ALAN-SVI association appeared weaker in surrounding commuting areas of urban cores, suggesting that characteristics unique to suburban areas may influence the distribution of ALAN and its relationship with social vulnerability. This finding provides nuanced information for policy makers and urban planners to design place-based smart lighting solutions to mitigate the adverse health consequences associated with ALAN levels. Interestingly, we discovered a strong relationship between ALAN levels and social vulnerability among rural areas. Despite the lower ALAN in rural areas

Table 4
Associations [a] between average overall SVI and SVI domains and average ALAN according to different RUCA categories.

	ALAN, log-transformed, β (95% CI)									
	Core areas			High commute areas			Low commute areas			
	Metro	Micro	Small town	Metro	Micro	Small town	Metro	Micro	Small town	Rural
Overall SVI										
Q1	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Q2	0.31 (0.29, 0.33)	0.25 (0.11, 0.40)	0.47 (0.16, 0.79)	−0.06 (−0.12, 0.01)	0.00 (−0.15, 0.14)	−0.06 (−0.34, 0.23)	−0.08 (−0.35, 0.19)	−0.19 (−0.51, 0.13)	0.53 (0.15, 0.90)	0.31 (0.14, 0.48)
Q3	0.52 (0.50, 0.55)	0.43 (0.29, 0.57)	0.67 (0.37, 0.98)	0.00 (−0.07, 0.07)	0.14 (−0.01, 0.29)	0.26 (−0.02, 0.54)	0.00 (−0.27, 0.27)	−0.27 (−0.59, 0.05)	0.42 (0.05, 0.80)	0.58 (0.41, 0.75)
Q4	0.70 (0.68, 0.72)	0.70 (0.56, 0.84)	0.72 (0.42, 1.02)	0.08 (−0.01, 0.16)	0.17 (0.00, 0.33)	0.60 (0.29, 0.90)	0.16 (−0.13, 0.44)	−0.02 (−0.35, 0.31)	0.43 (0.05, 0.82)	0.86 (0.68, 1.04)
Q5	0.90 (0.88, 0.92)	0.99 (0.85, 1.14)	0.99 (0.69, 1.29)	0.34 (0.23, 0.45)	0.33 (0.11, 0.55)	0.83 (0.45, 1.20)	0.21 (−0.14, 0.56)	−0.04 (−0.43, 0.36)	0.31 (−0.22, 0.83)	1.14 (0.93, 1.34)
p-trend	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0003*	*<0.0001*	*0.05*	*0.39*	*0.6*	*<0.0001*
Socioeconomic status										
Q1	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Q2	0.14 (0.12, 0.16)	0.02 (−0.13, 0.16)	−0.01 (−0.31, 0.29)	−0.21 (−0.29, −0.13)	−0.03 (−0.22, 0.16)	−0.09 (−0.49, 0.30)	0.31 (−0.06, 0.69)	−0.42 (−1.04, 0.20)	0.20 (−0.48, 0.87)	−0.06 (−0.26, 0.13)
Q3	0.24 (0.22, 0.26)	0.04 (−0.11, 0.18)	−0.10 (−0.40, 0.21)	−0.40 (−0.48, −0.31)	−0.13 (−0.34, 0.08)	−0.12 (−0.54, 0.30)	0.21 (−0.19, 0.62)	−0.56 (−1.20, 0.07)	0.18 (−0.53, 0.88)	0.01 (−0.20, 0.22)
Q4	0.34 (0.32, 0.37)	0.12 (−0.03, 0.27)	−0.08 (−0.39, 0.23)	−0.60 (−0.70, −0.49)	−0.15 (−0.38, 0.07)	0.07 (−0.36, 0.51)	0.20 (−0.24, 0.63)	−0.49 (−1.15, 0.17)	0.07 (−0.65, 0.80)	−0.06 (−0.29, 0.17)
Q5	0.48 (0.45, 0.51)	0.21 (0.04, 0.37)	0.11 (−0.22, 0.44)	−0.91 (−1.05, −0.78)	0.02 (−0.24, 0.28)	0.43 (−0.05, 0.90)	0.28 (−0.21, 0.77)	−0.55 (−1.24, 0.14)	0.12 (−0.64, 0.89)	0.11 (−0.15, 0.36)
p-trend	*<0.0001*	*0.0003*	*0.21*	*<0.0001*	*0.79*	*0.004*	*0.87*	*0.37*	*0.67*	*0.11*
Household composition/Disability										
Q1	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Q2	−0.22 (−0.24, −0.20)	0.10 (−0.04, 0.24)	0.39 (0.10, 0.68)	−0.03 (−0.11, 0.05)	−0.33 (−0.56, −0.09)	−0.97 (−1.53, −0.42)	0.13 (−0.23, 0.48)	0.21 (−0.33, 0.75)	0.05 (−0.90, 0.99)	−0.12 (−0.36, 0.13)
Q3	−0.26 (−0.28, −0.24)	0.12 (−0.01, 0.25)	0.54 (0.27, 0.80)	−0.01 (−0.10, 0.08)	−0.18 (−0.42, 0.05)	−0.67 (−1.22, −0.13)	−0.15 (−0.52, 0.22)	0.09 (−0.45, 0.62)	0.08 (−0.88, 1.04)	−0.20 (−0.43, 0.04)
Q4	−0.29 (−0.31, −0.27)	0.22 (0.09, 0.34)	0.57 (0.32, 0.82)	0.04 (−0.05, 0.14)	−0.13 (−0.37, 0.10)	−0.60 (−1.15, −0.05)	−0.10 (−0.47, 0.27)	0.08 (−0.47, 0.63)	0.16 (−0.81, 1.13)	−0.03 (−0.26, 0.21)
Q5	−0.24 (−0.27, −0.22)	0.38 (0.25, 0.50)	0.81 (0.56, 1.05)	0.27 (0.16, 0.37)	−0.07 (−0.32, 0.18)	−0.47 (−1.02, 0.09)	−0.08 (−0.49, 0.32)	0.01 (−0.56, 0.58)	0.22 (−0.76, 1.20)	0.25 (0.01, 0.50)
p-trend	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.22*	*0.12*	*0.45*	*0.43*	*0.36*	*<0.0001*
Minority status/Language										
Q1	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Q2	0.35 (0.32, 0.37)	0.11 (0.02, 0.19)	0.05 (−0.06, 0.17)	0.19 (0.13, 0.25)	0.00 (−0.11, 0.11)	0.28 (0.07, 0.48)	0.12 (−0.08, 0.31)	0.24 (0.04, 0.44)	0.06 (−0.18, 0.30)	−0.10 (−0.21, 0.01)
Q3	0.52 (0.49, 0.54)	0.11 (0.02, 0.21)	0.09 (−0.05, 0.24)	0.39 (0.31, 0.47)	−0.04 (−0.19, 0.11)	0.17 (−0.08, 0.43)	0.20 (−0.05, 0.46)	0.42 (0.07, 0.77)	0.25 (−0.07, 0.58)	−0.07 (−0.22, 0.09)
Q4	0.61 (0.58, 0.64)	0.22 (0.11, 0.33)	−0.06 (−0.23, 0.10)	0.56 (0.45, 0.66)	−0.17 (−0.38, 0.04)	−0.19 (−0.54, 0.16)	0.27 (−0.07, 0.61)	0.28 (−0.10, 0.66)	0.19 (−0.34, 0.71)	−0.10 (−0.29, 0.08)
Q5	0.60 (0.57, 0.64)	0.08 (−0.07, 0.24)	−0.24 (−0.46, −0.02)	0.61 (0.45, 0.78)	−0.34 (−0.72, 0.04)	−0.57 (−1.23, 0.09)	−0.25 (−0.71, 0.21)	0.08 (−0.51, 0.67)	−0.04 (−0.77, 0.69)	−0.04 (−0.33, 0.25)
p-trend	*<0.0001*	*0.004*	*0.27*	*<0.0001*	*0.11*	*0.86*	*0.24*	*0.03*	*0.18*	*0.63*
Housing/Transportation										
Q1	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Q2	0.16 (0.14, 0.18)	0.11 (−0.03, 0.25)	−0.18 (−0.54, 0.17)	−0.02 (−0.08, 0.05)	0.13 (0.00, 0.26)	0.07 (−0.17, 0.30)	0.06 (−0.18, 0.30)	0.04 (−0.23, 0.30)	0.10 (−0.22, 0.42)	0.31 (0.14, 0.49)
Q3	0.27 (0.25, 0.29)	0.10 (−0.03, 0.24)	0.04 (−0.29, 0.37)	0.06 (−0.01, 0.13)	0.12 (−0.02, 0.25)	−0.04 (−0.28, 0.21)	0.07 (−0.19, 0.33)	0.15 (−0.13, 0.44)	0.00 (−0.33, 0.33)	0.40 (0.23, 0.57)
Q4	0.39 (0.37, 0.41)	0.32 (0.18, 0.45)	0.08 (−0.24, 0.40)	0.18 (0.10, 0.26)	0.21 (0.06, 0.36)	0.12 (−0.16, 0.41)	0.13 (−0.15, 0.41)	0.27 (−0.04, 0.58)	0.06 (−0.30, 0.43)	0.62 (0.45, 0.79)
Q5	0.56 (0.54, 0.59)	0.51 (0.38, 0.65)	0.16 (−0.16, 0.49)	0.62 (0.52, 0.72)	0.39 (0.20, 0.58)	0.53 (0.18, 0.88)	0.37 (0.00, 0.73)	0.22 (−0.12, 0.57)	0.33 (−0.17, 0.83)	1.01 (0.82, 1.20)
p-trend	*<0.0001*	*<0.0001*	*0.001*	*<0.0001*	*<0.0001*	*0.04*	*0.11*	*0.03*	*0.56*	*<0.0001*

[a] For overall SVI, the results were derived from linear mixed effect model including population density (continuous), and state, and county as a random effect variable. For SVI domains, the models additionally included all four SVI domains (quintiles), but not the overall SVI.

Abbreviations: ALAN, artificial light at night; CI, confidence interval, RUCA, rural-urban commuting area codes; SVI, social vulnerability index.

Table 5
Associations [a] between average overall SVI and SVI domains and average ALAN according to US regions.

	ALAN, log-transformed, β (95% CI)			
	Northeast	**Midwest**	**South**	**West**
Overall SVI				
Q1	ref	ref	ref	ref
Q2	0.39 (0.35, 0.43)	0.28 (0.24, 0.31)	0.11 (0.08, 0.15)	0.26 (0.21, 0.31)
Q3	0.71 (0.67, 0.76)	0.53 (0.49, 0.57)	0.19 (0.15, 0.22)	0.47 (0.42, 0.53)
Q4	1.01 (0.96, 1.05)	0.79 (0.74, 0.83)	0.34 (0.31, 0.37)	0.64 (0.58, 0.69)
Q5	1.32 (1.27, 1.37)	0.95 (0.91, 1.00)	0.60 (0.57, 0.64)	0.81 (0.76, 0.87)
p-trend	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Socioeconomic status				
Q1	ref	ref	ref	ref
Q2	0.16 (0.12, 0.20)	0.15 (0.11, 0.19)	−0.01 (−0.05, 0.03)	0.13 (0.08, 0.18)
Q3	0.23 (0.18, 0.28)	0.31 (0.27, 0.36)	−0.02 (−0.06, 0.02)	0.11 (0.04, 0.17)
Q4	0.40 (0.34, 0.46)	0.45 (0.40, 0.50)	−0.03 (−0.07, 0.02)	0.17 (0.10, 0.24)
Q5	0.59 (0.52, 0.66)	0.63 (0.57, 0.70)	0.08 (0.03, 0.13)	0.14 (0.06, 0.23)
p-trend	*<0.0001*	*<0.0001*	*0.07*	*0.68*
Household composition/Disability				
Q1	ref	ref	ref	ref
Q2	−0.17 (−0.21, −0.13)	−0.20 (−0.24, −0.16)	−0.20 (−0.23, −0.17)	−0.15 (−0.2, −0.11)
Q3	−0.19 (−0.23, −0.15)	−0.22 (−0.26, −0.18)	−0.26 (−0.30, −0.23)	−0.16 (−0.21, −0.11)
Q4	−0.15 (−0.20, −0.10)	−0.21 (−0.26, −0.17)	−0.27 (−0.31, −0.23)	−0.17 (−0.23, −0.12)
Q5	−0.02 (−0.07, 0.04)	−0.11 (−0.16, −0.06)	−0.18 (−0.22, −0.14)	0 (−0.06, 0.07)
p-trend	*0.0024*	*<0.0001*	*<0.0001*	*0.02*
Minority status/Language				
Q1	ref	ref	ref	ref
Q2	0.44 (0.40, 0.48)	0.28 (0.25, 0.32)	0.17 (0.13, 0.21)	0.39 (0.32, 0.47)
Q3	0.72 (0.66, 0.77)	0.38 (0.34, 0.42)	0.33 (0.29, 0.37)	0.66 (0.58, 0.74)
Q4	0.92 (0.86, 0.98)	0.41 (0.36, 0.46)	0.45 (0.41, 0.50)	0.76 (0.68, 0.85)
Q5	0.95 (0.88, 1.03)	0.30 (0.23, 0.37)	0.45 (0.40, 0.51)	0.78 (0.69, 0.88)
p-trend	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Housing/Transportation				
Q1	ref	ref	ref	ref
Q2	0.15 (0.10, 0.19)	0.12 (0.08, 0.16)	0.11 (0.08, 0.14)	0.07 (0.01, 0.12)
Q3	0.27 (0.23, 0.31)	0.17 (0.13, 0.21)	0.21 (0.17, 0.24)	0.19 (0.14, 0.25)
Q4	0.40 (0.35, 0.45)	0.32 (0.28, 0.37)	0.34 (0.31, 0.38)	0.34 (0.28, 0.40)
Q5	0.55 (0.50, 0.61)	0.46 (0.41, 0.51)	0.56 (0.52, 0.59)	0.60 (0.54, 0.66)
p-trend	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

[a] For overall SVI, the results were derived from linear mixed effect model including population density (continuous), and state, and county as a random effect variable. For SVI domains, the models additionally included all four SVI domains (quintiles), but not the overall SVI.
[b] Regions are defined based on census regions and divisions. Northeast: CT, ME, MA, NH, RI, VI, NJ, NY, PA; Midwest: IN, IL, MI, OH, WI, IA, KS, MN, MO, NE, ND, SD; South: DE, DC, FL, GA, MD, NC, SC, VA, WV, AL, KY, MS, IN, AR, LA, OK, TX; West: AZ, CO, ID, NM, MT, UT, NV, WY, CA, OR, WA.
Abbreviations: ALAN, artificial light at night; CI, confidence interval, RUCA, rural-urban commuting area codes; SVI, social vulnerability index.

in general, a recent analysis by our group showed increases in ALAN at alarming rates in some rural areas (unpublished data). Specifically, using the same Black Marble data source, we characterized temporal trend at the county level between 2012 and 2019 in the contiguous US, and we found that the top 10 counties with the most rapid increase in ALAN were all rural counties in the state of Texas. Moreover, we identified that housing and transportation domain was the primary driver of this relationship, a novel finding that has not been reported before. Future research should investigate the implication of high ALAN levels on rural health, particularly in areas with escalating ALAN levels and among populations with suboptimal housing and transportation conditions. Finally, our region-specific analysis provided additional insight in the complex SVI-ALAN relationship across the country. Although higher overall SVI was associated with higher ALAN in all US regions, the main driver for this association appeared to be different for different regions. For example, socioeconomic vulnerability appeared to be a strong predictor of ALAN in the Northeast and Midwest, but not in the South or West. On the other hand, vulnerabilities in the minority status and housing and transportation domains exhibited more consistent associations with ALAN across all four regions. Taken together, our findings from subgroup analysis provide potentially important insight in identifying EJ communities with high burdens of ALAN.

Although electric lighting has tremendous benefits, including promoting commerce activities, enhancing social interactions and improving public safety, these benefits are also accompanied by serious ecological, economical and public health consequences. Growing research has linked higher levels of light exposure at nighttime with adverse health outcomes. In particular, large epidemiological studies using satellite data to estimate outdoor ALAN levels have linked ALAN with sleep deficiency and mood disorders (Xiao et al., 2020; Paksarian et al., 2020), obesity (Zhang et al., 2020), diabetes (Amini et al., 2020), and cancer (Xiao et al., 2020; Zhang et al., 2021; Xiao et al., 2021; James et al., 2017).Most, if not all, of these adverse health outcomes also exhibit substantial disparities across different neighborhoods, often with more disadvantaged communities showing disproportionately high burdens. Thus, future research should investigate disparate ALAN exposure as a contributing factor to health disparities across American neighborhoods. However, it is also important to note that satellite-based estimate of ALAN levels may not accurately reflect individual-level exposures to ALAN (Rea et al., 2011; Huss et al., 2019). While satellite imagery offers a convenient data source as proxy measures of ALAN in large studies, it may not accurately reflect individual-level exposures, particularly among individuals who stay indoors at night and have access to window treatments to block outdoor light. Another potential limitation of satellite-based ALAN measure is its potentially high correlation with other urban environmental hazards. A recent study found that after accounting for multiple other environmental factors (e.g., noise, greenspace, air pollution), there was no association between outdoor ALAN and breast cancer risk, while indoor light was still associated with an increased risk (Sweeney et al., 2022). Therefore, future investigations focusing on the public health implications of ALAN exposure should consider collecting light exposure data at the individual level, such as using bedroom light sensors or from wearable devices. Finally, the validity of satellite data in ALAN measurement may be influenced by a wide range of factors including light intensity, living environment, housing conditions, occupation and work schedule, and other sociobehavioral factors. Thus, an important area of research is to comprehensively evaluate whether and to what degree satellite-based ALAN estimates may serve as a valid proxy measure of light exposure at the individual level in diverse populations.

Moreover, it is important to acknowledge that not only can *uneven distribution* of environmental risk factors such as ALAN contribute to health disparities, *differential responses* to environmental hazard across communities may also play a role in this regard. A study found that the association between high ALAN levels and short sleep was up to 50% greater among adults living in areas with higher poverty rate than among those in lower poverty areas (Xiao et al., 2020). Similarly, we also found that the relationship between higher levels of ALAN and increased breast cancer incidence was stronger among women living in higher poverty neighborhoods (Xiao et al., 2020). The larger adverse effects of ALAN in poor neighborhoods may be due to limited knowledge and resources for preventive measures (e.g. lack of window treatments to block outdoor light), poor living conditions exacerbating sleep problems and circadian disruptions (e.g. bedroom crowding, noise), unfavorable work schedules that increase ALAN exposure (e.g. shift work), and chronic stress prevalent among residents of disadvantaged neighborhoods. On the other hand, it is worth noting that in this study (Xiao et al., 2020), a similar pattern was not observed according to individual-level education, an important measure of SES, suggesting that the interaction between ALAN and neighborhood- and individual-level factors is likely complex and warrants further investigation. Therefore, investigating the combined effects and potential interactions of different hazardous exposures is crucial to design interventions that mitigate associated health effects in these populations.

In conclusion, our study confirmed that ALAN is an important EJ issue with potential public health consequences. Furthermore, our findings revealed a complex relationship between social vulnerability and ALAN levels, suggesting that multiple social and environmental forces may contribute to ALAN patterns in the US. Future research should focus on investigating the impact of ALAN exposure on health disparities and evaluating policies related to urban planning, housing and land use to address the disproportionate burden of ALAN exposure and associated health risks in disadvantaged populations.

CRediT authorship contribution statement

Qian Xiao: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft. **Yue Lyu:** Data curation, Formal analysis, Visualization. **Meng Zhou:** Data curation, Writing – review & editing. **Jiachen Lu:** Data curation, Formal analysis. **Kehe Zhang:** Data curation, Formal analysis, Visualization. **Jun Wang:** Data curation, Supervision. **Cici Bauer:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108096.

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