Ecotoxicology and Environmental Safety 304 (2025) 119159

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Effect of built environment on the association between nighttime heat exposure and mortality in stroke patients: A case-crossover study in Shandong Province, China

Qiyong Cao [a,1], Ying Yu [b,c,1], Siyu Sun [a], Qiongqi Zhang [a], Chao Liu [d,e], Wanning Xia [a], Jing Wei [f], Chunxiang Shi [g], Bingyin Zhang [h], Zilong Lu [h], Xiaolei Guo [h], Xianjie Jia [a,*]

[a] *Department of Epidemiology and Statistics, Bengbu Medical University, Bengbu, China*
[b] *Department of Physiology and Pathophysiology, School of Basic Medical Sciences, Cheeloo College of Medicine, Shandong University, Jinan, China*
[c] *Department of Physiology, Bengbu Medical University, Bengbu, China*
[d] *Anhui Campus of the Second Affiliated Hospital, Zhejiang University School of Medicine, Bengbu 233000, China*
[e] *The First Affiliated Hospital of Bengbu Medical College, Bengbu 233000, China*
[f] *Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*
[g] *Meteorological Data Laboratory, National Meteorological Information Center, Beijing, China*
[h] *Shandong Center for Disease Control and Prevention, Jinan, China*

ARTICLE INFO

Edited by: Dr. RENJIE CHEN

Keywords:
Stroke
Nocturnal heat
Case-crossover design
Inverse-probability weighting
Built environment

ABSTRACT

Background: Short-term exposure to extreme heat has been increasingly linked to cardiovascular mortality. However, limited evidence exists regarding the specific impact of nocturnal heat exposure on mortality among stroke patients, and the heterogeneity across residential contexts has not been fully examined.

Methods: Utilizing daily time-series mortality data for stroke patients in Shandong Province, China, we applied a time-stratified case-crossover design with inverse-probability weighting (IPW) to address time-varying confounding, estimating single-day and cumulative lag (0–7 days) associations between nocturnal heat exposure and mortality. Nocturnal heat was defined as the community-specific 95th percentile of mean nighttime temperature (19:00–07:00) during the warm season (May–October). Stratified analyses were conducted by age, sex, stroke subtype, and urban/rural residence. We further examined effect modification of this association by age, sex, stroke subtype, and urban/rural residence, as well as by built environment characteristics including greenness, artificial light at night (ALAN), residential land density, and building volume.

Results: Nocturnal heat exposure was associated with an elevated mortality risk among stroke patients, with the strongest associations at lag 1–2 days. The odds of all-cause, cardiovascular, and stroke-specific mortality increased by 17.6 % (OR 1.18, 95 % CI: 1.12–1.24), 22.1 % (OR 1.22, 95 % CI: 1.15–1.29), and 25.6 % (OR 1.26, 95 % CI: 1.17–1.35), respectively. Elevated risks were more evident among older adults (≥60 years), males, patients with hemorrhagic stroke, and rural residents. High greenness appeared to mitigate the mortality risk associated with nocturnal heat exposure, whereas other built environment factors showed limited modifying effects.

Conclusions: Nocturnal heat exposure was associated with short-term increases in mortality among stroke patients. Neighborhood greenness appeared to mitigate these associations, suggesting that built -environment-based adaptation strategies may help protect vulnerable populations from climate-related health risks.

1. Introduction

Rising global temperatures pose a growing public health concern, with substantial evidence linking extreme heat to increased mortality, particularly from cardiovascular and cerebrovascular conditions (Wu and Liu, 2024; Vicedo-Cabrera et al., 2022, 2021). In China, stroke

* Correspondence to: Department of Epidemiology and Statistics, School of Public Health, Bengbu Medical University, No. 2600 Donghai Avenue, Long zi hu District, Bengbu 233000, China.

E-mail address: jiaxianjie@bbmu.edu.cn (X. Jia).

[1] Qiyong Cao and Ying Yu contributed equally to this work and should be considered as co-first authors

https://doi.org/10.1016/j.ecoenv.2025.119159
Received 4 July 2025; Received in revised form 29 September 2025; Accepted 29 September 2025

remains the leading cause of death and disability-adjusted life years (DALYs), and recent epidemiological evidence suggests that exposure to non-optimal ambient temperatures plays an important role in the stroke burden across China (Tu et al., 2023a, 2023b; Wu and Liu, 2024). While the health effects of daytime heat are well documented, nocturnal heat exposure has been less extensively studied (Iñiguez et al., 2021; Liu et al., 2022). Elevated nighttime temperatures can impede thermoregulation, disrupt sleep-related physiological recovery, and prolong heat stress, potentially exacerbating mortality risk among patients with stroke (Guo and Stein, 2003; Obradovich et al., 2017; Okamoto-Mizuno and Mizuno, 2012). Moreover, most existing studies on nocturnal heat and health outcomes have been conducted in single large metropolitan areas, where sufficient case counts and environmental monitoring systems enable robust analysis (Guo et al., 2024; He et al., 2024; Murage et al., 2017). However, this urban-centric focus limits the generalizability of the findings to smaller cities, towns, and rural areas, which remain largely understudied.

Previous research has underscored the importance of accounting for ambient air pollution when examining the health effects of temperature exposure (Basu, 2009; Stanišić Stojić et al., 2016). Some studies on nocturnal heat have adjusted for air pollutants by including them as covariates; however, this approach may introduce bias when pollution levels are themselves influenced by temperature (Kim et al., 2023; Majeed and Floras, 2022; Murage et al., 2017). High temperatures and air pollution often co-occur due to shared meteorological conditions such as humidity, low wind speed, and atmospheric stagnation. Empirical evidence indicates that temperature increases are frequently accompanied by elevated levels of $PM_{2.5}$ and ozone, making it difficult to disentangle their individual effects (Chen et al., 2024; de Bont et al., 2023). Recent studies have further demonstrated that extreme heat and air pollution may jointly exacerbate stroke mortality risk. Evidence has shown synergistic associations between heat waves and $PM_{2.5}$ constituents, as well as heightened risks of ischemic stroke mortality under combined exposure to heat waves and ozone (Deng et al., 2024; Wang et al., 2025). Motivated by these concerns, we applied a time-stratified case-crossover design combined with inverse-probability weighting (IPW). This approach reweights the data to approximate a pseudo-population in which nocturnal heat exposure is less confounded by observed time-varying factors, thereby strengthening the validity of estimated short-term associations (Clare et al., 2019; Jaakkola, 2003; Qiu et al., 2020).

Although our analytical framework aims to control for both time-invariant and time-varying confounders, differences in residential contexts may still introduce heterogeneity in how individuals respond to nocturnal heat exposure (Coseo and Larsen, 2014; Eisenman et al., 2016). This heterogeneity may be partly explained by characteristics of the built environment, which refers to the physical surroundings that shape and support daily human activity, particularly in outdoor spaces and residential settings (de Bont et al., 2023; Koohsari et al., 2020). It encompasses multiple dimensions, including land use patterns, building configuration, vegetation cover, and transportation infrastructure (Eliasson, 1996; Xi et al., 2023). For instance, dense construction and limited vegetation can amplify the urban heat island (UHI) effect, especially during the night, whereas expanded residential greenness may buffer against thermal stress and has been linked to improved survival among hospitalized patients (Demoury et al., 2022; Lopes et al., 2025; Taylor et al., 2017). Moreover, artificial light at night (ALAN) may compound physiological stress by disrupting circadian regulation (Sun et al., 2021). To date, no research has evaluated whether the built environment modifies the effect of nighttime heat exposure on mortality among stroke patients.

In this study, we aimed to estimate the short-term associations between nighttime heat exposure and mortality among stroke patients in Shandong Province, China. We further examined whether these associations were modified by multidimensional indicators of the built environment and explored potential heterogeneity by stroke subtype, sex, age group, and residential setting.

2. Methods

2.1. Study population

The study population was drawn from the Noncommunicable Disease Registry System maintained by the Shandong Center for Disease Control and Prevention (CDC), which applies standardized diagnostic coding and quality control procedures. Using a geographically stratified sampling approach, we selected permanent residents from 20 counties or districts, ensuring representativeness across urban and rural settings. Eligible individuals were aged 40–99 years and had a newly diagnosed stroke (ICD-10: I60–I63) between January 1, 2013, and December 31, 2019. Stroke diagnoses in this registry have been previously validated with high accuracy (He et al., 2022b; Liu et al., 2024). Mortality outcomes were ascertained from the Shandong Provincial Mortality Surveillance System, with cause of death classified into all-cause (A00–Z99), cardiovascular (I00–I99), and stroke-specific (I60–I63). To focus on the warm season and minimize confounding by cold temperatures or indoor heating, analyses were restricted to deaths occurring between May and October (Guo et al., 2024; He et al., 2024). We excluded individuals with incomplete baseline information, logical inconsistencies, or missing follow-up data. A detailed flowchart of case inclusion is provided in Supplementary Figure S1, and additional methodological details are described elsewhere (Jia et al., 2024; Liu et al., 2023; Zhao et al., 2024).

2.2. Nocturnal heat exposure

Hourly air temperature, 24-hour relative humidity, and wind speed data were obtained from the China Meteorological Administration Land Data Assimilation System (CLDAS, version 2.0) (Xu et al., 2022). Following previous studies, nighttime was operationally defined as the period from 19:00–07:00, which more aligns closely with human behavioral patterns and periods of thermoregulatory vulnerability than conventional definitions based on astronomical sunrise and sunset. The primary exposure variable was the nighttime mean temperature (°C), calculated by averaging hourly temperatures within this time window for each calendar day(Guo et al., 2024).

To assess the association of nocturnal heat with mortality, we defined hot nights using a percentile-based approach consistent with previous studies (Guo et al., 2024; He et al., 2022a; Liu et al., 2022). Given the substantial climatic variability across Shandong Province, particularly between coastal and inland areas as well as along latitudinal gradients (Figure S2), we applied region-specific thresholds at the community (or village) level. Specifically, for each patient's residing community, we calculated the 95th percentile of nighttime mean temperature during the warm season (May–October) across the study period (2013–2019). A day was classified as a "hot night" (coded as 1) if the nighttime mean temperature in that community exceeded this local threshold; otherwise, it was classified as a "non-hot night" (coded as 0).

2.3. Air pollution

We obtained daily air pollution data for Shandong Province from 2013 to 2019 from the ChinaHighAirPollutant (CHAP) dataset (available at: https://weijing-rs.github.io/product.html). This dataset was generated using the space-time extremely randomized trees (STET) model, an ensemble learning approach that integrates ground monitoring data, remote sensing products, atmospheric reanalysis, and emission inventories(Wei et al., 2023, 2022, 2021).Daily concentrations of nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and sulfur dioxide (SO_2) were estimated at a 10 km spatial resolution, while fine particulate matter ($PM_{2.5}$) concentrations were estimated at a 1 km resolution.

2.4. Built environment indicators

Based on prior research, we focused on four key indicators to characterize the built environment: residential land density, building volume, artificial light at night (ALAN), and greenness, measured by the Normalized Difference Vegetation Index (NDVI) (Sun et al., 2021; Yan et al., 2024). Greenness was assessed using NDVI values derived from MODIS satellite imagery (MOD13A3), averaged over the warm season (May–October) for each year. ALAN, residential land density, and building volume were obtained from the National Earth System Science Data Center (https://www.geodata.cn)(Chen et al., 2021; Yan et al., 2024; Zhang et al., 2024). All built environment variables were expressed as annual averages and assigned to each participant based on their residential location. Additional details on variable construction and data sources are provided in Supplementary Table S1.

2.5. Exposure assessment

To approximate individual-level exposure, each participant was geocoded to one of 11,688 residential communities or villages using official community/village codes. Community-level exposure was then estimated by calculating the area-weighted mean of grid-based values within each community, serving as a proxy for individual-level exposure (Liu et al., 2023).

2.6. Statistical analysis

We employed a time-stratified, bidirectional case-crossover design to estimate the short-term associations between extreme nocturnal heat and mortality among stroke patients. Case days were defined as the date of death (n = 41,417), and control days (n = 142,286) were selected from the same individual by matching on day of the week, month, and year. This strategy inherently controls for confounding by long-term trends, seasonality, and weekly patterns. Because each participant serves as their own control, time-invariant or slowly changing covariates (e.g., age, sex, ethnicity, smoking status, comorbidities) were implicitly adjusted for within the design framework (Jaakkola, 2003; Maclure, 1991).

However, nocturnal heat frequently co-occurs with other environmental conditions, including elevated air pollution and adverse meteorology. Such dependence may introduce time-varying confounding that is not addressed by the case-crossover matching (Figure S3). To mitigate this source of bias, we applied stabilized IPW (Cole and Frangakis, 2009). For each lag day, the probability of hot-night exposure conditional on daily air pollutants ($PM_{2.5}$, NO_2, SO_2, O_3, CO), meteorological factors (relative humidity, wind speed), and calendar month was estimated using a probit propensity score model. Stabilized weights were then computed as

$$SW_i = \frac{P(A_i)}{P(\mathrm{A}_i|\mathrm{L}_i)}$$

Where $P\ (A_i)$ denotes the marginal probability of hot-night exposure in the study population, and $P\ (A_i \mid L_i)$ is the subject- and day-specific propensity score conditional on covariates L_i. This stabilized form prevents unstable estimates that can arise when exposure probabilities are close to zero or one, while retaining the balancing property of IPW.

By construction, applying these weights balances the joint distribution of measured air pollutants and meteorological variables between exposed and unexposed observations, thereby helping to control for measured time-varying confounders (Di et al., 2017). In the weighted pseudo-population, we fitted conditional logistic regression models with strata defined by the matched case–control sets to estimate odds ratios (ORs) and their 95 % confidence intervals for mortality associated with nocturnal heat exposure. Importantly, the weighting is implemented within the matched strata defined by the case-crossover design, so that the self-matched nature of the design is preserved while simultaneously adjusting for environmental time-varying confounding (Abdan et al., 2024; Lee et al., 2020; Qiu et al., 2020).

Analyses were conducted separately for each lag day to characterize both immediate and delayed impacts of nocturnal heat. Following prior literature indicating that temperature-related mortality effects typically attenuate within five days (Gasparrini et al., 2015; Vicedo-Cabrera et al., 2021), the lag period was extended to seven days to evaluate potential delayed associations and mortality displacement(Chen et al., 2019). To address the influence of extreme weights, two-sided truncation at the 1st and 99th percentiles was applied (Cole and Hernán, 2008). Covariate balance before and after weighting was formally assessed using standardized mean differences (SMDs), with values below 0.10 considered to indicate adequate balance (Figures S11–S14).

In subsequent analyses, we performed stratified analyses by stroke subtype, sex, age group, and residential setting (urban vs. rural).

To evaluate whether the built environment modified the association between nocturnal heat exposure and mortality, we included an interaction term (i.e., hot night × built environment [low vs. high]) in the model, interaction *P*-values were obtained using likelihood ratio tests. The built environment indicators were categorized into quartiles, with the first quartile representing the lowest level of exposure, to assess their modifying effects. We then estimated the effects of nocturnal heat exposure in quartiles 2, 3, and 4 relative to quartile 1 (reference), by including interaction terms between heat exposure and built environment quartiles (Sun et al., 2019). Additionally, to assess dose–response trends, we included the median values of the built environment quartiles as a continuous variable in the model (Guo et al., 2022).

2.7. Sensitivity analysis

To assess the robustness of our findings, we conducted a series of sensitivity analyses. First, to evaluate the sensitivity of our findings to the definition of nocturnal heat, we alternatively defined hot nights using thresholds at the 90th, 92.5th, and 97.5th percentiles of nighttime mean temperature. We also re-estimated our primary models using conventional conditional logistic regression without IPW, directly adjusting for all covariates, and compared the results with those obtained from the weighted models. The built-environment metrics were further tested by substituting NDVI with alternative greenness indicators, including the Enhanced Vegetation Index (EVI) and annual averages at varying temporal scales. In addition, we summarized multi-day exposure using an inverse-variance weighted estimate of the cumulative effect across lags 0–7. Finally, daytime mean temperature was included as an additional covariate to distinguish the independent contribution of nocturnal heat from daytime heat and to evaluate potential collinearity.

All analyses were performed with R software, version 4.4.1 (R Foundation for Statistical Computing Vienna, Austria). All tests were two-tailed, and a P value < 0.05 was used as a guide for statistical significance.

3. Results

3.1. Data description

During the entire study period, a total of 41,417 deaths among patients with stroke were recorded. Of these, 29,156 deaths were classified as cardiovascular diseases (CVDs), including 20,034 stroke-specific deaths. Table 1 summarizes the demographic characteristics, air pollution levels, and meteorological conditions of the study population. Overall, females accounted for 45.45 % of deaths. Most deaths occurred among patients aged ≥ 60 years (87.93 %). Urban residents comprised 38.23 % of all deaths. Ischemic stroke was the predominant subtype, accounting for 69.30 % of deaths.

Regarding the built environment, 63.16 % of deaths occurred in

Table 1
Demographic, environmental, and meteorological characteristics of stroke patients who died during the warm season in Shandong Province (2013–2019) *.

Categories	All-cause mortality	CVD mortality	Stroke mortality
Persons (No.)	41,417	29,156	20,034
Individual Covariates (among all cases) N (%)			
Female	18,884 (45.45 %)	13,684 (46.93 %)	9304 (46.44 %)
age > 60	36,391 (87.93 %)	25,726 (88.24 %)	17,259 (86.15 %)
Urban	15,806 (38.22 %)	10,751 (36.87 %)	7054 (35.21 %)
Ischemic stroke	28,708 (69.30 %)	19,031 (65.27 %)	11,110 (55.46 %)
Case Days			
$PM_{2.5}$ (μg/m³)	45.54 (21.95)	45.96 (21.93)	47.37 (22.31)
CO (mg/m³)	0.89 (0.31)	0.89 (0.31)	0.90 (0.31)
NO_2 (μg/m³)	30.56 (11.74)	30.60 (11.68)	30.79 (11.54)
SO_2 (μg/m³)	20.53 (13.76)	20.87 (13.86)	22.03 (14.44)
O_3 (μg/m³)	136.36 (43.12)	136.45 (42.81)	135.76 (42.35)
Wind speed (m/s)	6.88 (3.86)	6.87 (3.86)	6.87 (3.85)
Relative humidity (%)	70.08 (15.33)	69.84 (15.44)	69.72 (15.48)
Control Days			
$PM_{2.5}$ (μg/m³)	45.19 (21.8)	45.60 (21.81)	47.02 (22.14)
CO (mg/m³)	0.89 (0.31)	0.89 (0.31)	0.90 (0.31)
NO_2 (μg/m³)	30.49 (11.72)	30.50 (11.64)	30.70 (11.52)
SO_2 (μg/m³)	20.47 (13.8)	20.80 (13.93)	21.94 (14.49)
O_3 (μg/m³)	135.38 (42.95)	135.36 (42.67)	134.81 (42.11)
Wind speed (m/s)	6.87 (3.86)	6.87 (3.86)	6.85 (3.85)
Relative humidity (%)	70.06 (15.29)	69.83 (15.42)	69.66 (15.46)
Built Environment (among all cases) N (%)			
Low NDVI	26,155 (63.16 %)	18,305 (62.79 %)	12,353 (61.67 %)
Low ALAN	15,155 (36.60 %)	11,167 (38.31 %)	8210 (40.99 %)
Low Residential Density	17,736 (42.83 %)	12,846 (44.07 %)	9059 (45.22 %)
Low Building Volume	19,084 (46.09 %)	14048 (48.19 %)	9962 (49.73 %)

Case days refer to the date of death among stroke patients, and control days were matched within individuals by year, month, and day of the week using a time-stratified case-crossover design. Data are restricted to the warm season (May to October) from 2013 to 2019.
* Means and standard deviations are reported for continuous variables; counts and percentages are shown for categorical variables. All environmental exposures—including air pollutants and meteorological factors—were assessed at the village or community level based on geocoded residential locations.
Low and high built environment were defined using the median value of built environment indicators calculated within each village or community.Abbreviations: CVD, cardiovascular disease.

areas with low NDVI. Corresponding proportions in areas with low residential density and low building volume were 42.83 % and 46.09 %, respectively. In contrast, 36.60 % of deaths occurred in areas with low ALAN. Additionally, air pollutant concentrations tended to be higher on case days compared with control days. During the study period, the average nighttime temperature in the warm season (May–October) in Shandong Province showed an upward trend, accompanied by an increase in the frequency of extreme nocturnal high-temperature events (Figures S4–S5).

3.2. Main effects of hot night exposure

As shown in Fig. 1, lag-specific associations between nocturnal heat exposure and mortality among stroke patients are presented. Hot-night exposure was associated with an increased mortality risk. Positive associations were observed for all mortality outcomes (all-cause, cardiovascular, and stroke-specific), with the strongest effects at lag days 1–2. At lag day 2, hot-night exposure was associated with elevated risks of all-cause mortality (OR 1.18, 95 % CI: 1.12–1.24), cardiovascular mortality (OR 1.23, 95 % CI: 1.16–1.30), and stroke mortality (OR 1.26, 95 % CI: 1.17–1.35).

3.3. Subgroup analysis

Based on the main findings, stratified analyses at lag days 1–2 are shown in Fig. 2. Higher risks were observed among men, older adults, and patients with hemorrhagic stroke. At lag day 1, these disparities were particularly evident. For example, males showed a stronger association with stroke-specific mortality (OR 1.28, 95 % CI: 1.16–1.41), whereas the estimate for females was weaker and less precise (OR 1.09, 95 % CI: 0.99–1.21). Among patients aged ≥ 60 years, the association was stronger (OR 1.21, 95 % CI: 1.12–1.30), whereas estimates for those aged ≤ 60 years were closer to the null (OR 1.07, 95 % CI: 0.87–1.31). By stroke subtype, patients with hemorrhagic stroke had stronger associations (OR 1.26, 95 % CI: 1.13–1.40) compared with ischemic stroke (OR 1.15, 95 % CI: 1.05–1.25). In urban–rural analyses, differences were observed in both single-day and cumulative lag effects. For all-cause and CVD mortality, urban residents showed higher risks at lag day 1, whereas no clear differences were observed at other lags or in the cumulative analyses (Figures S8–S9). In contrast, stroke mortality showed a distinct pattern: rural residents had higher risks at lag day 0 and again at lag days 4–5 (Figure S10), and their cumulative risk over lag 0–7 was higher than that of urban residents.

3.4. Moderating role of the built environment

As shown in Fig. 3, the built environment appeared to modify the

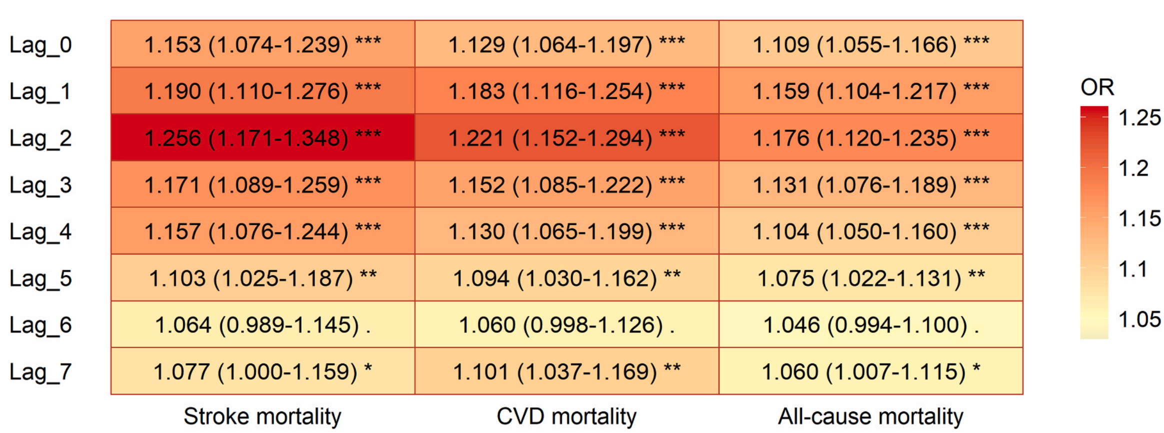

Fig. 1. Lag-specific associations between nocturnal heat exposure (HN 95th) on mortality among stroke patients, Symbols indicate p-value thresholds: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$,. $P < 0.1$.Abbreviations: OR, odds ratio; CI, confidence interval; CVD, cardiovascular disease.

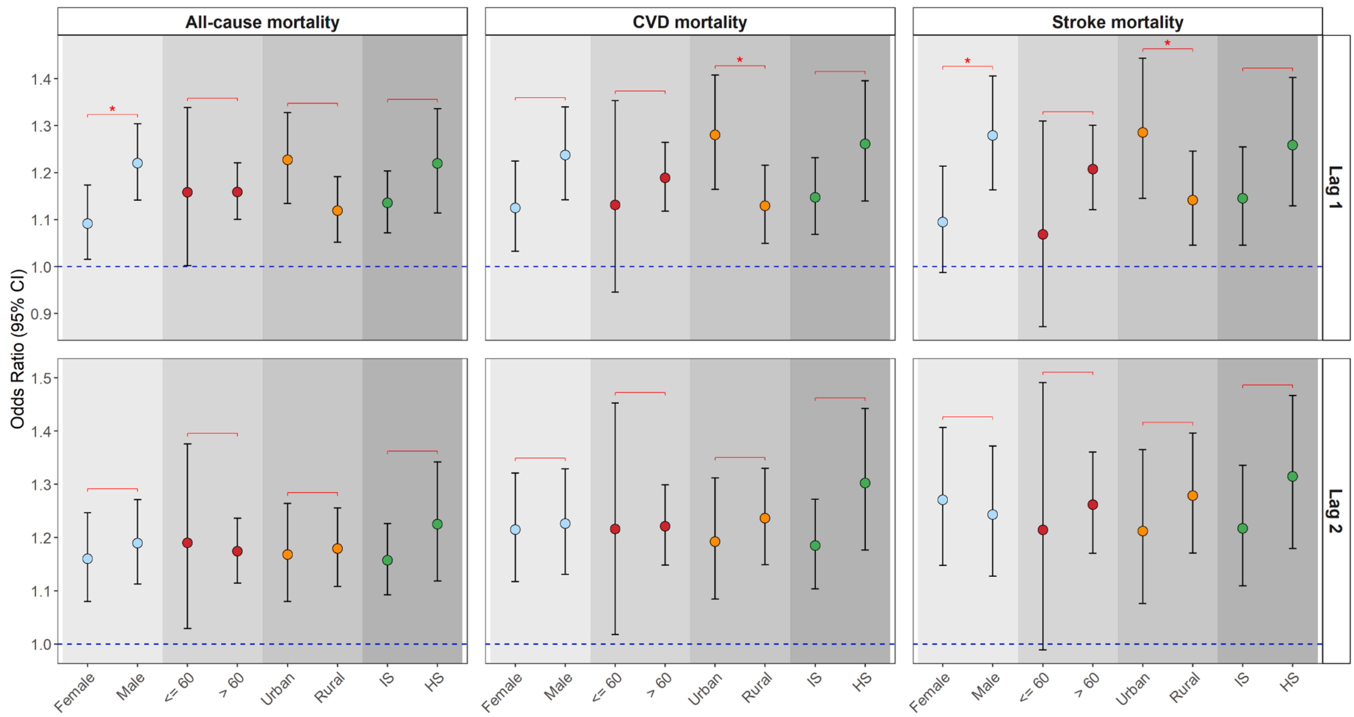

Fig. 2. Stratified associations of nocturnal heat exposure with mortality among stroke patients at lag days 1 and 2 Results are shown for all-cause mortality, cardiovascular disease (CVD) mortality, and stroke-specific mortality. Subgroups include sex (female, male), age group (≤60, >60 years), residential location (urban, rural), and stroke subtype (ischemic stroke [IS], hemorrhagic stroke [HS]). Estimates are derived from IPTW-weighted conditional logistic regression models within a time-stratified case-crossover framework. Error bars represent 95 % confidence intervals. Symbols indicate p-value thresholds for subgroup heterogeneity: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$,. $P < 0.1$., Abbreviations: OR, odds ratio; CI, confidence interval; CVD, cardiovascular disease; IS, ischemic stroke; HS, hemorrhagic stroke.

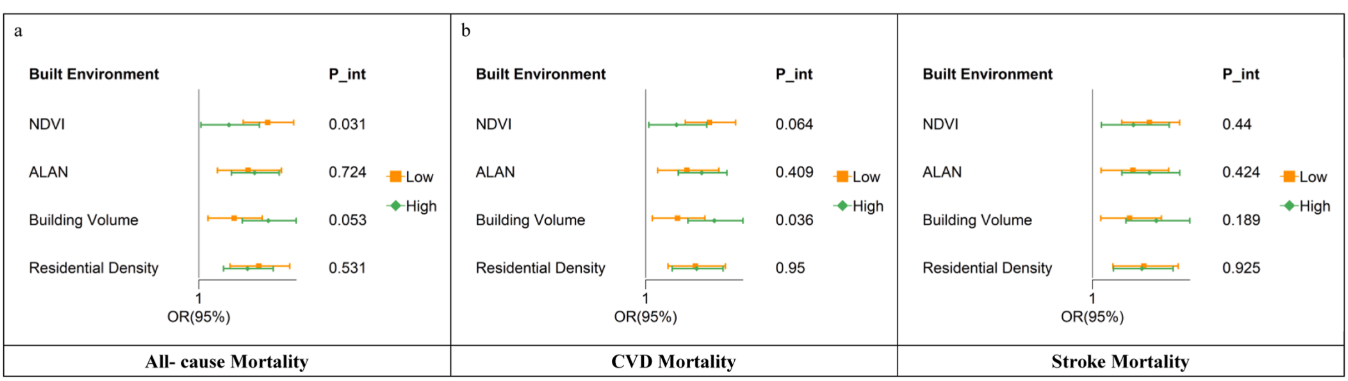

Fig. 3. Effect modification by built environment on the associations between nocturnal heat exposure and mortality outcomes in stroke patients (Lag 1), Associations of nocturnal heat exposure with all-cause, cardiovascular (CVD), and stroke-specific mortality are shown across categories of built environment characteristics, including greenness (NDVI), artificial light at night (ALAN), building volume, and residential density. Odds ratios (ORs) and 95 % confidence intervals (CIs) represent the estimated association within each category of the built environment (Low vs. High). Interaction terms (Hot Night × Built Environment Level) were included in conditional logistic regression models weighted by inverse probability weighting (IPW). *P*_int denotes the p-value for interaction tests.

associations between nocturnal heat exposure and mortality at lag 1. For example, the association with all-cause mortality was stronger in areas with low greenness (OR 1.21, 95 % CI: 1.13–1.28) compared with high-greenness areas (OR 1.09, 95 % CI: 1.01–1.18). Associations were also slightly stronger in areas with higher artificial light at night (ALAN) (OR 1.17, 95 % CI: 1.10–1.24) compared with low-ALAN areas (OR 1.15, 95 % CI: 1.06–1.25). For building volume, ORs were 1.21 (95 % CI: 1.13–1.29) in high-volume areas and 1.11 (95 % CI: 1.03–1.19) in low-volume areas. For residential density, associations were 1.15 (95 % CI: 1.07–1.22) in high-density areas and 1.18 (95 % CI: 1.09–1.27) in low-density areas. The corresponding interaction P-values were 0.031 for NDVI, 0.052 for building volume, 0.723 for ALAN, and 0.531 for residential density.

Differences in associations were also observed across built environment quartiles 2–4 compared with quartile 1 (Table 2). For NDVI, ORs were 1.06 (95 % CI: 0.94–1.20), 0.98 (95 % CI: 0.86–1.12), and 0.85 (95 % CI: 0.73–0.99). For ALAN, ORs were 0.89 (95 % CI: 0.74–1.06), 0.94 (95 % CI: 0.79–1.12), and 0.94 (95 % CI: 0.79–1.10). For residential density, ORs were 0.88 (95 % CI: 0.75–1.02), 0.95 (95 % CI: 0.81–1.10), and 0.86 (95 % CI: 0.74–0.99). For building volume, ORs were 1.14 (95 % CI: 0.98–1.33), 1.01 (95 % CI: 0.87–1.17), and 1.00 (95 % CI: 0.87–1.14). A clear exposure–response trend was observed for greenness (P for trend = 0.049). Similar association patterns were observed for cardiovascular and stroke-specific mortality.

Table 2
Effect modification by built environment quartiles on the associations between nocturnal heat exposure and mortality outcomes in stroke patients (Lag 1).

	Q1 (lowest)	Q2	Q3	Q4 (highest)	*P* for trend
All- cause Mortality					
NDVI	Reference	1.062 (0.938–1.204)	0.982 (0.862–1.119)	0.847 (0.725–0.990)	0.049
ALAN	Reference	0.887 (0.744–1.057)	0.941 (0.794–1.115)	0.935 (0.792–1.103)	0.896
Residential Density	Reference	0.876 (0.752–1.021)	0.948 (0.814–1.104)	0.858 (0.741–0.993)	0.952
Building Volume	Reference	1.139 (0.979–1.325)	1.011 (0.872–1.171)	0.998 (0.874–1.139)	0.125
CVD Mortality					
NDVI	Reference	1.116 (0.962–1.295)	1.005 (0.860–1.174)	0.868 (0.721–1.044)	0.941
ALAN	Reference	0.879 (0.717–1.078)	0.956 (0.785–1.164)	0.964 (0.794–1.171)	0.379
Residential Density	Reference	0.983 (0.820–1.177)	1.029 (0.857–1.236)	0.963 (0.807–1.149)	0.892
Building Volume	Reference	1.162 (0.969–1.394)	1.119 (0.941–1.332)	0.980 (0.834–1.152)	0.165
Stroke Mortality					
NDVI	Reference	1.134 (0.947–1.357)	1.044 (0.865–1.260)	0.958 (0.772–1.188)	0.721
ALAN	Reference	0.877 (0.695–1.107)	0.978 (0.779–1.228)	0.957 (0.764–1.200)	0.818
Residential Density	Reference	1.018 (0.822–1.260)	0.974 (0.780–1.217)	1.030 (0.834–1.273)	0.946
Building Volume	Reference	1.094 (0.880–1.360)	1.028 (0.835–1.266)	0.990 (0.809–1.211)	0.946

Odds ratios (ORs) and 95 % confidence intervals (CIs) are shown for the associations of nocturnal heat exposure with all-cause, cardiovascular (CVD), and stroke-specific mortality across quartiles (Q1–Q4) of built environment indicators: greenness (NDVI), artificial light at night (ALAN), residential density, and building volume. Q1 (lowest quartile) serves as the reference category. Estimates are derived from conditional logistic regression models with interaction terms (Hot Night × Built Environment Quartile), adjusted using inverse probability weighting. P for trend indicates the p-value for a linear trend across quartiles, using the median of each category as a continuous variable.

3.5. Sensitivity analyses

Sensitivity analyses supported the robustness of the main associations. Effect estimates based on alternative thresholds for defining hot nights (90th, 92.5th, and 97.5th percentiles of nighttime mean temperature) were consistent with the main results in both direction and magnitude (Tables S2–S4). Alternative greenness metrics, such as the Enhanced Vegetation Index (EVI) and annual averages at different time scales, showed a consistent protective pattern (Tables S9–S11). Additionally, estimates from conventional covariate-adjusted models without IPW were generally comparable to those from the IPW-weighted models, although the ORs were slightly attenuated (Figure S7). Cumulative estimates from inverse-variance weighted analyses supported persistent elevated risks (Table S19), and further adjustment for daytime mean temperature did not materially change the associations (Table S20). Additional details are provided in the Supplementary Materials.

4. Discussion

Our study, using a time-stratified case-crossover design integrated with IPW, suggests that nocturnal heat exposure was associated with short-term increases in mortality among patients with stroke, with the strongest associations at lag days 1–2. Neighborhood greenness appeared to attenuate these associations, whereas little evidence of modification was observed for artificial light at night (ALAN), residential density, or building volume. Greater vulnerability was observed among men, older adults, rural residents, and patients with hemorrhagic stroke.

From a methodological perspective, conventional case-crossover designs have inherent limitations in adequately addressing time-dependent confounding from air pollutants, which often co-occur with high temperatures due to shared meteorological conditions such as high humidity, low wind speed, and atmospheric stagnation. To address this limitation, we integrated IPW into our case-crossover framework, with the aim of reducing time-dependent confounding induced by air pollution and meteorological factors. This approach creates weighted exposure groups with improved covariate balance across measured factors, thereby providing more robust association estimates that are less sensitive to residual imbalance and more comparable across subgroups than those from conventional conditional models.

The main findings of this study are supported by many other studies. Direct comparison with mortality risk estimates from temperate regions is challenging due to differences in exposure metrics and the limited number of investigations focusing specifically on the vulnerable population of stroke patients. For example, Cheng He et al. employing an individual-level, time-stratified case-crossover design, reported an elevated risk of stroke on days with extreme nighttime heat (97.5th percentile of hot night exposure), with an odds ratio of 1.07 (95 % confidence interval: 1.01–1.15) (He et al., 2024). Similarly, Majeed and Floras (2022) analyzed national time-series data from the UK and US, finding a 3.1–4.8 % increase in cardiovascular mortality per 1°C rise in nighttime surface temperature among males aged 60–64 years (Majeed and Floras, 2022). Furthermore, a multi-city study spanning 15 Chinese cities demonstrated that the relative risk associated with nighttime high temperatures (RR: 1.38; 95 % CI: 1.18–1.61) surpassed that of daytime heat (RR: 1.10; 95 % CI: 1.05–1.15) (Tao et al., 2023).

Most studies have relied on traditional time-series models, such as distributed lag nonlinear models (DLNM), or single-exposure case-crossover designs that typically use city- or region-level average exposure data. These approaches often lack the granularity to capture individual-level exposure variability, which may limit their capacity to provide precise estimates of exposure–response relationships (Kim et al., 2023; Alemayehu Ali et al., 2024). Moreover, the majority of such research has focused on large metropolitan areas to ensure sufficient statistical power and exposure monitoring, leaving the applicability of findings to smaller cities, towns, and rural populations largely unexplored.

In contrast, our study integrates high-resolution satellite remote sensing data with an individual-level case-crossover design, allowing a more refined assessment of personal exposure (Iñiguez et al., 2021; Kim et al., 2023; Murage et al., 2017). This approach improves confidence in the estimated associations between nocturnal heat exposure and stroke mortality risk. By including both coastal and inland counties, and covering diverse levels of urbanization within Shandong Province, our analysis helps fill an important evidence gap and broadens the representativeness of findings across residential settings, particularly in rural areas that are often overlooked in heat-health research.

The detrimental physiological effects of nocturnal heat may be compounded by concurrent exposure to airborne particulate matter, which induces oxidative stress, activates the sympathetic nervous system, and contributes to blood pressure fluctuations and increased cardiovascular strain (Guo and Stein, 2003). For ischemic stroke, the elevated risk may be explained by heat-induced dehydration, increased blood viscosity, and vascular endothelial dysfunction—processes potentially intensified by the rising frequency of extreme nocturnal heat events (Park et al., 2020; Swerdel et al., 2017). Patients with hemorrhagic stroke could be especially vulnerable due to the inherent fragility of cerebral vessels, making them more susceptible to such acute physiological insults (Boehme et al., 2017). Notably, our observation of stronger associations for hemorrhagic stroke contrasts with a German study that reported weaker effects, which may reflect differences in regional climate, population characteristics, or study design (He et al., 2024).

Distinct vulnerability patterns emerged among population subgroups, reflecting a complex interplay of physiological susceptibility and contextual factors. Older adults exhibited an increased risk, likely due to age-related declines in thermoregulatory capacity and heat tolerance (Ye et al., 2012). This physiological vulnerability is often compounded by socioeconomic and behavioral factors, such as limited air conditioning use due to cost constraints, reducing opportunities for nighttime cooling during increasingly frequent hot nights (Hansen et al., 2011). With respect to sex differences, men experienced a greater increase in mortality risk associated with nocturnal heat exposure than women. This pattern may be explained by sex-related physiological differences, including higher rates of cardiovascular comorbidities among men, differences in sweating efficiency, and lifestyle factors such as greater outdoor activity and alcohol consumption, which can exacerbate vulnerability to heat (Charkoudian et al., 2017; Yanovich et al., 2020).

Our analysis revealed notable urban–rural disparities in the impact of nocturnal heat on stroke mortality. In urban areas, the association was most evident at lag day 1, but the cumulative risk did not show clear differences compared with rural areas. In contrast, rural residents experienced higher immediate risks at lag 0, a slight decline at lag 1, and another increase at lag days 4–5, with cumulative risks over the 7-day period remaining consistently elevated, suggesting sustained vulnerability. These differences may reflect variations in heat adaptation behaviors, housing quality, and healthcare access. Limited cooling resources and prolonged physiological stress could further contribute to the excess risks observed in rural settings. Collectively, these findings align with evidence that socioeconomically disadvantaged groups carry a disproportionate burden of heat-related mortality (Guo et al., 2024; Kim et al., 2023). Our results highlight that the increasing frequency of hot nights is likely to impose a greater burden on elderly individuals, men, rural residents, and patients with hemorrhagic stroke.

Extensive research has well documented the modifying effects of the built environment on the association between air pollution and mortality (de Bont et al., 2023; Guo et al., 2022). In contrast, evidence on how the built environment shapes heterogeneity in heat-related health outcomes remains limited and inconsistent. In our study, neighborhood greenness appeared to mitigate the association between nocturnal heat exposure and stroke mortality, suggesting a protective role. At the same time, our subgroup analyses revealed that rural residents, despite generally higher levels of greenness, were disproportionately affected by nocturnal heat. This apparent paradox may reflect structural and contextual disadvantages in rural areas, including poorer housing insulation, markedly lower prevalence of air conditioner ownership (96.1 vs. 32.9 units per 100 households in urban and rural areas, respectively, according to the 2014 Shandong Statistical Bulletin), and limited access to timely healthcare. These regional disparities in infrastructure and resources likely offset the protective benefits of greenness and highlight the importance of considering development inequities when assessing vulnerability. This finding underscores that heat vulnerability is shaped not only by greenness but also by broader social and infrastructural contexts, which should be integrated into interpretations of the built environment's modifying effects. Although interaction analyses for other built environment factors, including ALAN, residential density, and building volume, did not yield strong evidence of effect modification, we observed a trend suggesting that areas with lower ALAN intensity and smaller building volumes exhibited comparatively reduced nighttime stroke mortality risks. While these findings hint at potential protective associations, he absence of strong interaction evidence underscores the need for cautious interpretation. Future studies with larger cohorts and more granular exposure assessments are needed to clarify potential nonlinear or context-dependent effects.

Although epidemiological studies examining built environment variability in heat-related health disparities are scarce, insights from environmental ecology offer valuable mechanistic perspectives. Urban vegetation may contribute to regulating local microclimates; areas with high building density and limited greenness often experience intensified heat stress due to reduced shading and diminished evapotranspiration capacity (Lopes et al., 2025). Green and blue infrastructure can function as natural buffers by facilitating evaporative cooling and providing shaded surfaces, thereby mitigating the urban heat island (UHI) effect and potentially lowering heat exposure among vulnerable populations, including patients with stroke (Hu et al., 2024; Song et al., 2022). The influence of built environment characteristics on urban thermal regimes is highly context dependent, shaped by regional climate, landscape heterogeneity, and complex urban morphology. Structural factors such as building height, street canyon geometry, spatial openness, and orientation can substantially influence patterns of solar radiation absorption, airflow, and convective heat dissipation (Demoury et al., 2022; Eliasson, 1996). For example, tall, densely packed buildings can obstruct ventilation corridors, leading to heat entrapment and localized thermal accumulation that may intensify nighttime warming.

In addition to these microclimatic pathways, artificial light at night (ALAN) may represent a key physiological mechanism linking built environment features to heat-related cardiovascular risks. ALAN disrupts endogenous circadian rhythms, which regulate essential cardiovascular functions including endothelial health and thrombogenesis (Crnko et al., 2019; Martino and Young, 2015). Experimental evidence indicates that circadian disruption may precipitate cardiovascular dysfunction (Anea et al., 2012; Viswambharan et al., 2007). Because nocturnal heat exposure also disturbs sleep and circadian regulation, ALAN penetrating residential bedrooms may synergistically exacerbate circadian misalignment, thereby increasing susceptibility to cardiovascular events and stroke mortality. Furthermore, ALAN has been recognized as an environmental stressor that can trigger inflammatory responses and impair immune function (Bedrosian et al., 2011). Supporting these mechanisms, epidemiological evidence from a prospective cohort of older adults in Hong Kong showed that higher levels of outdoor ALAN at residences were associated with an increased risk of coronary heart disease hospitalizations and mortality (Sun et al., 2021).

This study has several notable strengths. First, it utilized a large-scale, province-wide registry encompassing over 11,000 community-level units, thereby enhancing the representativeness and statistical power of the analysis. Second, we employed a time-stratified case-crossover design integrated with IPW, which offers a framework to address both individual-level and environmental confounders. This approach may improve the robustness and interpretability of association estimates compared with traditional models that rely solely on covariate adjustment. Third, the incorporation of high-resolution built environment indicators, such as greenness and artificial nighttime lighting, enabled a more refined evaluation of potential effect modification.

Nonetheless, several limitations should be acknowledged. The validity of IPW depends on correct specification of the propensity score model; although covariates were selected based on prior knowledge, residual confounding from unmeasured factors, such as indoor cooling behaviors or access to emergency healthcare, may persist. IPW can also challenge the positivity assumption by heavily down-weighting observations with very low exposure probabilities, potentially reducing the effective sample size and precision of estimates. Additionally, exposure misclassification is possible due to discrepancies between outdoor ambient temperatures and individual indoor microenvironments or personal pollutant exposures. Greenness was assessed solely by NDVI, without accounting for aspects such as accessibility or vegetation type that may influence its protective potential; future studies should incorporate more comprehensive greenness metrics. Finally, caution is warranted when extrapolating these findings beyond the climatic and geographic context of Shandong Province.

Future research should incorporate more detailed built environment characteristics, including street orientation, canyon geometry, proximity to water bodies, and vegetation quality, to clarify their effects on microclimate regulation and related health outcomes. Combining high-resolution spatial data with personal exposure metrics and physiological measurements may improve exposure assessment accuracy. In addition, examining the interactions between urban morphology, hydrological features, and social determinants could provide deeper insights into how built environments shape heat-related health risks, thereby supporting more targeted strategies for urban planning and climate adaptation. Given that nocturnal heat disrupts sleep and impairs physiological recovery, future studies should also integrate sleep quality metrics (e.g., from wearable devices) to explore their potential mediating role in the association between nocturnal heat and stroke mortality.

In conclusion, this study suggests that nocturnal heat exposure is associated with short-term increases in mortality risk among stroke patients, while neighborhood greenness appears to have a protective role. These findings highlight the importance of integrating built environment characteristics, urban greening, and meteorological factors into comprehensive climate and public health strategies. Such an integrated approach may be crucial for designing effective interventions to alleviate heat-related health burdens, particularly among vulnerable populations in the context of global climate change.

Funding

This work was supported by the Natural Science Research Program for Universities in Anhui Province (2023AH040288); the Key Support Project of Bengbu Medical University (2023bypy015); the Open Research Program of the Anhui Institute of Territorial Spatial Planning and Ecology (GTY2024KF01); and the University Research Project of Anhui Province (2024AH051241).

CRediT authorship contribution statement

Qiongqi Zhang: Investigation, Data curation. **Ying Yu:** Writing – review & editing, Methodology. **Siyu Sun:** Investigation, Data curation. **Jing Wei:** Data curation. **Chunxiang Shi:** Data curation. **Chao Liu:** Visualization, Formal analysis. **Wanning Xia:** Resources, Funding acquisition. **Xiaolei Guo:** Supervision, Resources. **Xianjie Jia:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Qiyong Cao:** Writing – original draft, Formal analysis, Data curation. **Bingyin Zhang:** Supervision, Investigation. **Zilong Lu:** Supervision, Resources.

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.

Acknowledgements

We would like to thank the Shandong Centers for Disease Control and Prevention (CDC), the National Earth System Science Data Center, the National Science & Technology Infrastructure of China (http://www.geodata.cn), Dr. Jing Wei's team, Prof. Chunxiang Shi's team, and the U.S. Geological Survey for providing onset, air pollution, meteorological, and built environment data, respectively, used in all analyses of the present study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2025.119159.

Data availability

The authors do not have permission to share data.

References

Abdan, L., Nematollahi, S., Masoudkabir, F., Jalali, A., Pashang, M., Vasheghani-Farahani, A., Hosseini, K., Pourhosseini, H., 2024. Investigating the relationship between opium use and coronary slow flow: a propensity score matched case-control study. BMJ Open 14, e090471. https://doi.org/10.1136/bmjopen-2024-090471.

Alemayehu Ali, E., Cox, B., Van de Vel, K., Verachtert, E., Vaes, B., Gabriel Beerten, S., Duarte, E., Scheerens, C., Aerts, R., Van Pottelbergh, G., 2024. Associations of heat with diseases and specific symptoms in flanders, belgium: An 8-year retrospective study of general practitioner registration data. Environ. Int. 193, 109097. https://doi.org/10.1016/j.envint.2024.109097.

Anea, C.B., Cheng, B., Sharma, S., Kumar, S., Caldwell, R.W., Yao, L., Ali, M.I., Merloiu, A.M., Stepp, D.W., Black, S.M., Fulton, D.J.R., Rudic, R.D., 2012. Increased superoxide and endothelial NO synthase uncoupling in blood vessels of Bmal1-knockout mice. Circ. Res. 111, 1157–1165. https://doi.org/10.1161/CIRCRESAHA.111.261750.

Basu, R., 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ. Health 8, 40. https://doi.org/10.1186/1476-069X-8-40.

Bedrosian, T.A., Fonken, L.K., Walton, J.C., Nelson, R.J., 2011. Chronic exposure to dim light at night suppresses immune responses in siberian hamsters. Biol. Lett. 7, 468–471. https://doi.org/10.1098/rsbl.2010.1108.

Boehme, A.K., Esenwa, C., Elkind, M.S.V., 2017. Stroke risk factors, genetics, and prevention. Circ. Res. 120, 472–495. https://doi.org/10.1161/CIRCRESAHA.116.308398.

de Bont, J., Pickford, R., Åström, C., Coloma, F., Dimakopoulou, K., de Hoogh, K., Ibi, D., Katsouyanni, K., Melén, E., Nobile, F., Pershagen, G., Persson, Å., Samoli, E., Stafoggia, M., Tonne, C., Vlaanderen, J., Wolf, K., Vermeulen, R., Peters, A., Ljungman, P., 2023. Mixtures of long-term exposure to ambient air pollution, built environment and temperature and stroke incidence across Europe. Environ. Int. 179, 108136. https://doi.org/10.1016/j.envint.2023.108136.

Charkoudian, N., Hart, E.C.J., Barnes, J.N., Joyner, M.J., 2017. Autonomic control of body temperature and blood pressure: influences of female sex hormones. Clin. Auton. Res. 27, 149–155. https://doi.org/10.1007/s10286-017-0420-z.

Chen, K., Breitner, S., Wolf, K., Hampel, R., Meisinger, C., Heier, M., von Scheidt, W., Kuch, B., Peters, A., Schneider, A., Study Group, K.O.R.A., 2019. Temporal variations in the triggering of myocardial infarction by air temperature in augsburg, Germany, 1987-2014. Eur. Heart J. 40, 1600–1608. https://doi.org/10.1093/eurheartj/ehz116.

Chen, Z., Yu, B., Yang, C., Zhou, Y., Yao, S., Qian, X., Wang, C., Wu, B., Wu, J., 2021. An extended time series (2000–2018) of global NPP-VIIRS-like nighttime light data from a cross-sensor calibration. ESSD 13, 889–906. https://doi.org/10.5194/essd-13-889-2021.

Chen, B., Zhen, L., Wang, L., Zhong, H., Lin, C., Yang, L., Xu, W., Huang, R.-J., 2024. Revisiting the impact of temperature on ground-level ozone: a causal inference approach. Sci. Total Environ. 953, 176062. https://doi.org/10.1016/j.scitotenv.2024.176062.

Clare, P.J., Dobbins, T.A., Mattick, R.P., 2019. Causal models adjusting for time-varying confounding-a systematic review of the literature. Int. J. Epidemiol. 48, 254–265. https://doi.org/10.1093/ije/dyy218.

Cole, S.R., Frangakis, C.E., 2009. The consistency statement in causal inference: a definition or an assumption? Epidemiology 20, 3–5. https://doi.org/10.1097/EDE.0b013e31818ef366.

Cole, S.R., Hernán, M.A., 2008. Constructing inverse probability weights for marginal structural models. Am. J. Epidemiol. 168, 656–664. https://doi.org/10.1093/aje/kwn164.

Coseo, P., Larsen, L., 2014. How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain urban heat islands in Chicago. Landsc. Urban Plan 125, 117–129. https://doi.org/10.1016/j.landurbplan.2014.02.019.

Crnko, S., Du Pré, B.C., Sluijter, J.P.G., Van Laake, L.W., 2019. Circadian rhythms and the molecular clock in cardiovascular biology and disease. Nat. Rev. Cardiol. 16, 437–447. https://doi.org/10.1038/s41569-019-0167-4.

Demoury, C., De Troeyer, K., Berete, F., Aerts, R., Van Schaeybroeck, B., Van Der Heyden, J., De Clercq, E.M., 2022. Association between temperature and natural mortality in Belgium: effect modification by individual characteristics and residential environment. Sci. Total Environ. 851, 158336. https://doi.org/10.1016/j.scitotenv.2022.158336.

Deng, B., Zhu, L., Zhang, Yuanyuan, Tang, Z., Shen, J., Zhang, Yalin, Zheng, H., Zhang, Yunquan, 2024. Short-term exposure to PM2.5 constituents, extreme temperature events and stroke mortality. Sci. Total Environ. 954, 176506. https://doi.org/10.1016/j.scitotenv.2024.176506.

Di, Q., Dai, L., Wang, Y., Zanobetti, A., Choirat, C., Schwartz, J.D., Dominici, F., 2017. Association of short-term exposure to air pollution with mortality in older adults. JAMA 318, 2446–2456. https://doi.org/10.1001/jama.2017.17923.

Eisenman, D., Wilhalme, H.M., Tseng, C., Chester, M., English, P., Pincetl, S., Fraser, A. M., Vangala, S., Dhaliwal, S.K., 2016. Heat death associations with the built environment, social vulnerability and their interactions with rising temperature. Health Place 41, 89–99. https://doi.org/10.1016/j.healthplace.2016.08.007.

Eliasson, I., 1996. Urban nocturnal temperatures, street geometry and land use. Atmos. Environ. Conf. Urban Therm. Environ. Stud. Tohwa 30, 379–392. https://doi.org/10.1016/1352-2310(95)00033-X.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M.L., Guo, Y.-L.L., Wu, C., Kan, H., Yi, S.-M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Honda, Y., Kim, H., Armstrong, B., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386, 369–375. https://doi.org/10.1016/S0140-6736(14)62114-0.

Guo, Y.T., Chan, K.H., Qiu, H., Wong, E.L., Ho, K.F., 2024. The risk of hospitalization associated with hot nights and excess nighttime heat in a subtropical metropolis: a time-series study in Hong Kong, 2000–2019. Lancet Reg. Health West. Pac. 51, 101168. https://doi.org/10.1016/j.lanwpc.2024.101168.

Guo, Y. i-Fang, Stein, P.K., 2003. Circadian rhythm in the cardiovascular system: chronocardiology. Am. Heart J. 145, 779–786. https://doi.org/10.1016/S0002-8703(02)94797-6.

Guo, C., Yu, T., Lin, C., Chang, L.-Y., Bo, Y., Wong, M.C.S., Tam, T., Lau, A.K.H., Lao, X. Q., 2022. Habitual exercise, air pollution, and pneumonia mortality: a longitudinal cohort study of approximately 0.4 million adults. Am. J. Epidemiol. 191, 1732–1741. https://doi.org/10.1093/aje/kwac113.

Hansen, A., Bi, P., Nitschke, M., Pisaniello, D., Newbury, J., Kitson, A., 2011. Perceptions of heat-susceptibility in older persons: barriers to adaptation. Int. J. Environ. Res. Public Health 8, 4714–4728. https://doi.org/10.3390/ijerph8124714.

He, C., Breitner, S., Zhang, S., Huber, V., Naumann, M., Traidl-Hoffmann, C., Hammel, G., Peters, A., Ertl, M., Schneider, A., 2024. Nocturnal heat exposure and stroke risk. Eur. Heart J. 45, 2158–2166. https://doi.org/10.1093/eurheartj/ehae277.

He, C., Kim, H., Hashizume, M., Lee, W., Honda, Y., Kim, S.E., Kinney, P.L., Schneider, A., Zhang, Y., Zhu, Y., Zhou, L., Chen, R., Kan, H., 2022. The effects of night-time warming on mortality burden under future climate change scenarios: a modelling study. Lancet Planet. Health 6, e648–e657. https://doi.org/10.1016/S2542-5196(22)00139-5.

He, F., Wei, J., Dong, Y., Liu, C., Zhao, K., Peng, W., Lu, Z., Zhang, B., Xue, F., Guo, X., Jia, X., 2022. Associations of ambient temperature with mortality for ischemic and hemorrhagic stroke and the modification effects of greenness in shandong province, China. Sci. Total Environ. 851, 158046. https://doi.org/10.1016/j.scitotenv.2022.158046.

Hu, K., Wang, S., Fei, F., Song, J., Chen, F., Zhao, Q., Shen, Y., Fu, J., Zhang, Y., Cheng, J., Zhong, J., Yang, X., Wu, J., 2024. Modifying temperature-related cardiovascular mortality through Green-blue space exposure. Environ. Sci. Ecotechnol. 20. https://doi.org/10.1016/j.ese.2024.100408.

Iñiguez, C., Royé, D., Tobías, A., 2021. Contrasting patterns of temperature related mortality and hospitalization by cardiovascular and respiratory diseases in 52 spanish cities. Environ. Res 192, 110191. https://doi.org/10.1016/j.envres.2020.110191.

Jaakkola, J.J.K., 2003. Case-crossover design in air pollution epidemiology. Eur. Respir. J. 21, 81s–85s. https://doi.org/10.1183/09031936.03.00402703.

Jia, X., Zhang, B., Yu, Y., Xia, W., Lu, Z., Guo, X., Xue, F., 2024. Greenness mitigate cause-specific mortality associated with air pollutants in ischemic and hemorrhagic stroke patients: an ecological health cohort study. Environ. Res. 251, 118512. https://doi.org/10.1016/j.envres.2024.118512.

Kim, S.E., Hashizume, M., Armstrong, B., Gasparrini, A., Oka, K., Hijioka, Y., Vicedo-Cabrera, A.M., Honda, Y., 2023. Mortality risk of hot nights: a nationwide population-based retrospective study in Japan. Environ. Health Perspect. 131, 57005. https://doi.org/10.1289/EHP11444.

Koohsari, M.J., McCormack, G.R., Nakaya, T., Oka, K., 2020. Neighbourhood built environment and cardiovascular disease: knowledge and future directions. Nat. Rev. Cardiol. 17, 261–263. https://doi.org/10.1038/s41569-020-0343-6.

Lee, H.-S., Lynch, K.F., Krischer, J.P., Study Group, T.E.D.D.Y., 2020. Nested case-control data analysis using weighted conditional logistic regression in the environmental determinants of diabetes in the young (TEDDY) study: a novel approach. Diabetes Metab. Res. Rev. 36, e3204. https://doi.org/10.1002/dmrr.3204.

Liu, J., Varghese, B.M., Hansen, A., Zhang, Y., Driscoll, T., Morgan, G., Dear, K., Gourley, M., Capon, A., Bi, P., 2022. Heat exposure and cardiovascular health outcomes: a systematic review and meta-analysis. Lancet Planet. Health 6, e484–e495. https://doi.org/10.1016/S2542-5196(22)00117-6.

Liu, Chao, Yu, Y., Liu, Chengrong, Tang, L., Zhao, K., Zhang, P., He, F., Wang, M., Shi, C., Lu, Z., Zhang, B., Wei, J., Xue, F., Guo, X., Jia, X., 2023. Effect of neighbourhood greenness on the association between air pollution and risk of stroke first onset: a case-crossover study in shandong province, China. Int. J. Hyg. Environ. Health 254, 114262. https://doi.org/10.1016/j.ijheh.2023.114262.

Liu, Chengrong, Zhang, B., Liu, Chao, Zhang, Y., Zhao, K., Zhang, P., Tian, M., Lu, Z., Guo, X., Jia, X., 2024. Association of ambient ozone exposure and greenness exposure with hemorrhagic stroke mortality at different times: a cohort study in shandong province, China. Ecotoxicol. Environ. Saf. 278, 116356. https://doi.org/10.1016/j.ecoenv.2024.116356.

Lopes, H.S., Vidal, D.G., Cherif, N., Silva, L., Remoaldo, P., 2025. Green infrastructure and its influence on urban heat island, heat risk, and air pollution: a case study of porto (Portugal). J. Environ. Manag. 376. https://doi.org/10.1016/j.jenvman.2025.124446.

Maclure, M., 1991. The case-crossover design: a method for studying transient effects on the risk of acute events. Am. J. Epidemiol. 133, 144–153. https://doi.org/10.1093/oxfordjournals.aje.a115853.

Majeed, H., Floras, J.S., 2022. Warmer summer nocturnal surface air temperatures and cardiovascular disease death risk: a population-based study. BMJ Open 12, e056806. https://doi.org/10.1136/bmjopen-2021-056806.

Martino, T.A., Young, M.E., 2015. Influence of the cardiomyocyte circadian clock on cardiac physiology and pathophysiology. J. Biol. Rhythms 30, 183–205. https://doi.org/10.1177/0748730415575246.

Murage, P., Hajat, S., Kovats, R.S., 2017. Effect of night-time temperatures on cause and age-specific mortality in London. Environ. Epidemiol. 1, e005. https://doi.org/10.1097/EE9.0000000000000005.

Obradovich, N., Migliorini, R., Mednick, S.C., Fowler, J.H., 2017. Nighttime temperature and human sleep loss in a changing climate. Sci. Adv. https://doi.org/10.1126/sciadv.1601555.

Okamoto-Mizuno, K., Mizuno, K., 2012. Effects of thermal environment on sleep and circadian rhythm. J. Physiol. Anthr. 31, 14. https://doi.org/10.1186/1880-6805-31-14.

Park, S., Kario, K., Chia, Y.-C., Turana, Y., Chen, C.-H., Buranakitjaroen, P., Nailes, J., Hoshide, S., Siddique, S., Sison, J., Soenarta, A.A., Sogunuru, G.P., Tay, J.C., Teo, B. W., Zhang, Y.-Q., Shin, J., Van Minh, H., Tomitani, N., Kabutoya, T., Sukonthasarn, A., Verma, N., Wang, T.-D., Wang, J.-G., Network, the, H.A., 2020. The influence of the ambient temperature on blood pressure and how it will affect the epidemiology of hypertension in Asia. J. Clin. Hypertens. 22, 438–444. https://doi.org/10.1111/jch.13762.

Qiu, X., Wei, Y., Wang, Y., Di, Q., Sofer, T., Awad, Y.A., Schwartz, J., 2020. Inverse probability weighted distributed lag effects of short-term exposure to PM2.5 and ozone on CVD hospitalizations in new england Medicare participants - exploring the causal effects. Environ. Res. 182, 109095. https://doi.org/10.1016/j.envres.2019.109095.

Song, J., Lu, Y.-L., Zhao, Q., Zhang, Y., Yang, X., Chen, Q., Guo, Y., Hu, K., 2022. Effect modifications of Green space and blue space on heat-mortality association in Hong Kong, 2008-2017. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2022.156127.

Stanišić Stojić, S., Stanišić, N., Stojić, A., 2016. Temperature-related mortality estimates after accounting for the cumulative effects of air pollution in an urban area. Environ. Health 15, 73. https://doi.org/10.1186/s12940-016-0164-6.

Sun, S., Cao, W., Ge, Y., Ran, J., Sun, F., Zeng, Q., Guo, M., Huang, J., Lee, R.S.-Y., Tian, L., Wellenius, G.A., 2021. Outdoor light at night and risk of coronary heart disease among older adults: a prospective cohort study. Eur. Heart J. 42, 822–830. https://doi.org/10.1093/eurheartj/ehaa846.

Sun, S., Tian, L., Cao, W., Lai, P.-C., Wong, P.P.Y., Lee, R.S., Mason, T.G., Krämer, A., Wong, C.-M., 2019. Urban climate modified short-term association of air pollution with pneumonia mortality in Hong Kong. Sci. Total Environ. 646, 618–624. https://doi.org/10.1016/j.scitotenv.2018.07.311.

Swerdel, J.N., Janevic, T.M., Kostis, W.J., Faiz, A., Cosgrove, N.M., Kostis, J.B., The Myocardial Infarction Data Acquisition System (MIDAS 27) Study Group, 2017. Association between dehydration and short-term risk of ischemic stroke in patients with atrial fibrillation. Transl. Stroke Res. 8, 122–130. https://doi.org/10.1007/s12975-016-0471-9.

Tao, J., Zhang, Y., Li, Z., Yang, M., Huang, C., Hossain, M.Z., Xu, Y., Wei, X., Su, H., Cheng, J., Zhang, W., 2023. Daytime and nighttime high temperatures differentially increased the risk of cardiovascular disease: a nationwide hospital-based study in China. Environ. Res. 236, 116740. https://doi.org/10.1016/j.envres.2023.116740.

Taylor, J., Wilkinson, P., Picetti, R., Symonds, P., Heaviside, C., Macintyre, H., Davies, M., Mavrogianni, A., Hutchinson, E., 2017. Comparison of built environment adaptations to heat exposure and mortality during hot weather, west midlands region, UK. Environ. Int. 111, 287–294. https://doi.org/10.1016/j.envint.2017.11.005.

Tu, W.-J., Wang, L.-D., Yan, F., Peng, B., Hua, Y., Liu, M., Ji, X.-M., Ma, L., Shan, C.-L., Wang, Y.-L., Zeng, J.-S., Chen, H.-S., Fan, D.-S., Gu, Y.-X., Tan, G.-J., Hu, B., Kang, D.-Z., Liu, J.-M., Liu, Y.-L., Lou, M., Luo, B.-Y., Pan, S.-Y., Wang, L.-H., Wu, J., on behalf of the Special Writing Group of China Stroke Surveillance Report, 2023a. China stroke surveillance report 2021. Mil. Med. Res. 10, 33. https://doi.org/10.1186/s40779-023-00463-x.

Tu, W.-J., Xu, Y., Fan, Y., Zeng, X., Zhao, J., 2023b. Impacts of exposure to ambient temperature and altitude on the burden of stroke. J. Neurol. 270, 4214–4218. https://doi.org/10.1007/s00415-023-11742-x.

Vicedo-Cabrera, A.M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D.M., Abrutzky, R., Tong, S., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Lavigne, E., Correa, P.M., Ortega, N. V., Kan, H., Osorio, S., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Jaakkola, J.J. K., Ryti, N., Pascal, M., Schneider, A., Katsouyanni, K., Samoli, E., Mayvaneh, F., Entezari, A., Goodman, P., Zeka, A., Michelozzi, P., de'Donato, F., Hashizume, M., Alahmad, B., Diaz, M.H., De La Cruz Valencia, C., Overcenco, A., Houthuijs, D., Ameling, C., Rao, S., Ruscio, F.D., Carrasco-Escobar, G., Seposo, X., Silva, S., Madureira, J., Holobaca, I.H., Fratianni, S., Acquaotta, F., Kim, H., Lee, W., Iniguez, C., Forsberg, B., Ragettli, M.S., Guo, Y.L.L., Chen, B.Y., Li, S., Armstrong, B., Aleman, A., Zanobetti, A., Schwartz, J., Dang, T.N., Dung, D.V., Gillett, N., Haines, A., Mengel, M., Huber, V., Gasparrini, A., 2021. The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Chang 11, 492–500. https://doi.org/10.1038/s41558-021-01058-x.

Vicedo-Cabrera, A.M., Tobias, A., Jaakkola, J.J.K., Honda, Y., Hashizume, M., Guo, Y., Schwartz, J., Zanobetti, A., Bell, M.L., Armstrong, B., Katsouyanni, K., Haines, A., Ebi, K.L., Gasparrini, A., 2022. Global mortality burden attributable to non-optimal temperatures. Lancet 399, 1113. https://doi.org/10.1016/S0140-6736(22)00179-9.

Viswambharan, H., Carvas, J.M., Antic, V., Marecic, A., Jud, C., Zaugg, C.E., Ming, X.-F., Montani, J.-P., Albrecht, U., Yang, Z., 2007. Mutation of the circadian clock gene Per2 alters vascular endothelial function. Circ. https://doi.org/10.1161/CIRCULATIONAHA.106.653303.

Wang, Z., Zhu, L., Peng, M., Zheng, H., Zhang, Y., 2025. Summer heatwave, ozone pollution and ischemic stroke mortality: an individual-level case-crossover study. Environ. Res. 268, 120818. https://doi.org/10.1016/j.envres.2025.120818.

Wei, J., Li, Z., Li, K., Dickerson, R.R., Pinker, R.T., Wang, J., Liu, X., Sun, L., Xue, W., Cribb, M., 2022. Full-coverage mapping and spatiotemporal variations of ground-level ozone (O3) pollution from 2013 to 2020 across China. Remote Sens. Environ. 270, 112775. https://doi.org/10.1016/j.rse.2021.112775.

Wei, J., Li, Z., Lyapustin, A., Sun, L., Peng, Y., Xue, W., Su, T., Cribb, M., 2021. Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens. Environ. 252, 112136. https://doi.org/10.1016/j.rse.2020.112136.

Wei, J., Li, Z., Wang, J., Li, C., Gupta, P., Cribb, M., 2023. Ground-level gaseous pollutants (NO_2, SO_2, and CO) in China: daily seamless mapping and spatiotemporal variations. Atmos. Chem. Phys. 23, 1511–1532. https://doi.org/10.5194/acp-23-1511-2023.

Wu, S., Liu, M., 2024. Global burden of stroke: dynamic estimates to inform action. Lancet Neurol. 23, 952–953. https://doi.org/10.1016/S1474-4422(24)00363-6.

Xi, Z., Li, C., Zhou, L., Yang, H., Burghardt, R., 2023. Built environment influences on urban climate resilience: evidence from extreme heat events in Macau. Sci. Total Environ. 859, 160270. https://doi.org/10.1016/j.scitotenv.2022.160270.

Xu, R., Wang, Q., Wei, J., Lu, W., Wang, R., Liu, T., Wang, Y., Fan, Z., Li, Y., Xu, L., Shi, C., Li, G., Chen, G., Zhang, L., Zhou, Y., Liu, Y., Sun, H., 2022. Association of short-term exposure to ambient air pollution with mortality from ischemic and hemorrhagic stroke. Eur. J. Neurol. 29, 1994–2005. https://doi.org/10.1111/ene.15343.

Yan, W., Wu, Jianping, Zhang, Chaoqun, Chen, Xiuzhi, Ren, Jiashun, Xiao, Zhenzhen, Liao, Ziyin, Lafortezza, Raffaele, Li, Xueyan, Su, Y., 2024. Developing an annual building volume dataset at 1-km resolution from 2001 to 2019 in China. Int. J. Digit. Earth 17, 2330690. https://doi.org/10.1080/17538947.2024.2330690.

Yanovich, R., Ketko, I., Charkoudian, N., 2020. Sex differences in human thermoregulation: relevance for 2020 and beyond. Physiology. https://doi.org/10.1152/physiol.00035.2019.

Ye, X., Wolff, R., Yu, W., Vaneckova, P., Pan, X., Tong, S., 2012. Ambient temperature and morbidity: a review of epidemiological evidence. Environ. Health Perspect. 120, 19–28. https://doi.org/10.1289/ehp.1003198.

Zhang, X., Zhang, D., Wang, X., Peng, J., Li, Y., Li, S., 2024. A dataset of 1km-grid comprehensive indexes of land use degree density in China (2020). CSD 9, 1–10. https://doi.org/10.11922/11-6035.csd.2022.0100.zh.

Zhao, K., He, F., Zhang, B., Liu, Chengrong, Hu, Y., Dong, Y., Zhang, P., Liu, Chao, Wei, J., Lu, Z., Guo, X., Huang, Q., Jia, X., Mi, J., 2024. Short-term ozone exposure on stroke mortality and mitigation by greenness in rural and urban areas of shandong province, China. BMC Public Health 24, 2955. https://doi.org/10.1186/s12889-024-20454-4.