Greenspace modifies the associations between heat and mortality: A systematic review and meta-analysis of observational studies

Muhammad Mainuddin Patwary[a,b*], Imran Chowdhury Sakib[a,b], Md Ismay Azam Badhon[a,b], Afif Iftikhar[a,b], Mondira Bardhan[a,c], Mohammad Javad Zare Sakhvidi[d], Dana Sikder[a,b], Payam Dadvand[e,f,g], Michelle L. Bell[h,i], Matthew H. E. M. Browning[c], Thomas Astell Burt[j], Md Pervez Kabir[a,k], Peter James[l,m]

[a] *Environment and Sustainability Research Initiative, Khulna, Bangladesh*
[b] *Environmental Science Discipline, Life Science School, Khulna University, Khulna, Bangladesh*
[c] *Department of Park, Recreation and Tourism Management, Clemson University, Clemson, SC USA*
[d] *Department of Occupational Health, School of Public Health, Yazd Shahid Sadoughi University of Medical Sciences, Yazd, Iran*
[e] *ISGlobal, Barcelona, Spain*
[f] *Universitat Pompeu Fabra (UPF), Barcelona, Spain*
[g] *CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain.*
[h] *Yale School of the Environment, Yale University, New Haven, CT, United States*
[i] *Korea University, Seoul, South Korea*
[j] *School of Architecture, Design and Planning, University of Sydney, NSW 2006, Australia*
[k] *Department of Civil Engineering, University of Ottawa, Ottawa, K1N 6N5, Canada.*
[l] *Division of Environmental and Occupational Health, Department of Public Health Sciences University of California, Davis School of Medicine, Davis, CA 95616, USA*
[m] *Department of Environmental Health, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA*

[*] *corresponding authors: raju.es111012@gmail.com*

Highlights

- First review/meta-analysis on greenspace modifying heat–mortality relationship
- High greenness linked to lower heat-related all-cause mortality risk compared to low greenness
- Limited evidence for greenspace effect on cause-specific heat mortality
- Most studies had low risk of bias in greenspace and heat exposure classification
- Overall quality of evidence rated low due to high heterogeneity and publication bias

Abstract

Greenspace has been increasingly examined for its potential associations with heat-related mortality. However, quantitative synthesis of evidence on this association remains limited. We conducted a systematic review and meta-analysis of observational studies published through July 20, 2025, examining the relationship between effect modification of greenspace on heat-related mortality risk. We systematically searched and synthesized data from 45 studies encompassing over 290 million deaths. A random-effects meta-analysis was conducted, comparing high-greenness areas to low-greenness areas during heat events (≥95th percentile temperature). Risk of bias was assessed using the Office of Health Assessment and Translation (OHAT) tool, and the quality of evidence was evaluated using GRADE criteria. Publication bias was assessed through funnel plots, Egger's test, and the Trim and Fill method. We found that high-greenness areas were associated with a lower risk of all-cause mortality during heat (≥95th percentile), with a pooled relative risk (RR) of 1.09 (95%CI: 1.02–1.17, n=11), compared to low greenness areas (pooled RR: 1.24, 95%CI: 1.11–1.38, n=11) with substantial heterogeneity ($I^2=97\%$). Sensitivity analyses showed consistent associations between high greenness and reduced mortality risk. Funnel plot indicated some asymmetry, and Egger's test suggested publication bias ($p < 0.05$), possibly reflecting small-study effects. Risk of bias assessment showed that 55% of studies had low risk across domains. GRADE evaluation downgraded the overall quality of evidence to "low" due to substantial heterogeneity and publication bias. This quantitative evidence provides suggestive evidence of an association between higher greenspace exposure and reduced heat-related mortality risk. While urban greening initiatives may contribute to mitigating heat-related mortality, the presence of heterogeneity and potential publication bias highlights the need for further research with standardized methods to better characterize this relationship.

Keywords

Extreme heat, greenspace, climate adaptation, meta-analysis, environmental health.

Introduction

Climate change has been intensifying the occurrence of extreme heat events, with 19 of the 20 hottest years on record occurring since 2000 (Zhao et al., 2021). Global temperatures are projected to rise by 1.5°C by 2052 (Tong and Ebi, 2019), leading to more frequent and intense extreme heat events and exposing many more people to their impacts by the end of the century (Gasparrini et al., 2017; Li et al., 2020). Globally, between 2000 and 2019, non-optimal temperature was responsible for approximately 500,000 deaths worldwide annually. Numerous epidemiological studies have reported that non-optimal temperature is increasingly associated with adverse health impacts (Ebi et al., 2021; Gasparrini et al., 2015; Wu et al., 2022), including cardiovascular mortality (Moghadamnia et al., 2017), respiratory mortality (Goggins et al., 2015; Kouis et al., 2019), all-cause mortality (Dimitrova et al., 2021; Kephart et al., 2022; Perry et al., 2023; Zafeiratou et al., 2021; Zhao et al., 2021), emergency department visits, and hospital admissions, (J. Liu et al., 2022; Song et al., 2017). The risk of heat-related mortality is expected to increase by 70% to over 100% by 2050 because of the prolonged frequency of extreme heatwaves (Huang et al., 2011; Li et al., 2013). The impact of heat is particularly pronounced in urban areas with dense populations and high-rise buildings, due to the urban heat island (UHI) effect, mostly caused by human activities (Chen et al., 2016).

Urban greenspace (e.g., urban parks, planting, and street trees) has a significant potential to mitigate temperature-related health risks by improving thermal comfort and safety (Hu and Li, 2020)(Rahman et al., 2020). In shaping the local thermal environment, greenspace may help reduce the perceived temperature up to 2-3ºC (Skarbit et al., 2024) and cool air through evapotranspiration, where heat is converted into latent energy instead of sensible heat (Pearlmutter et al., 2009). Other heat reduction mechanisms included shading (Wang et al., 2008), and humidity regulation (Dalton and Jones, 2020) with tree shading can reduce surface temperature by up to 19ºC (Armson et al., 2012).

The impact of heat on human health, particularly in terms of all-cause and cause-specific mortality, is well-documented (Alahmad et al., 2023; Bunker et al., 2016; Burkart et al., 2021; Zhao et al., 2021). Greenspace may mitigate heat-related health risks by alleviating physical stress and reducing vulnerability to extreme temperatures (Cornu et al., 2024). Current epidemiological studies explored whether greenspace might acts as a protective factor, potentially through mitigating heat-related mortality risk (Denpetkul and Phosri, 2021; He et al., 2022; Qiu et al., 2021; Song et al., 2023). However, existing studies present inconsistent findings. For instance, studies conducted in Australia (Xu et al., 2019) and Hong Kong (Song et al., 2022) found no evidence of a significant effect modification of greenspace on heat-related mortality. Conversely, several studies found significant evidence that a higher level of greenspace may reduce heat-related mortality (Choi et al., 2022; He et al., 2022; Schinasi et al., 2023; Song et al., 2023).

This inconsistency across studies might be understood through a synthesis of the existing literature to reconcile discrepancies and establish more comprehensive understandings of the complex relationships of greenspace with heat and mortality. However, to the best of our knowledge no systematic review has been conducted on this topic. While Cornu et al. (2024) offered valuable qualitative insights into the causal pathways and contextual nuances, they did not provide quantitative analysis of the effect modification of greenspace on heat-related mortality (Cornu et al., 2024).

In the current study, we conduct a systematic review to fill this critical knowledge gap by synthesizing the existing evidence from a wider range of geographic locations and methodological approaches, to evaluate the potential effect modification of greenspace on heat mortality risk, ultimately informing strategies for urban planning and heat mitigation.

2. Methods

This systematic review followed the latest Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The study's protocol was preregistered with the International Prospective Register of Systematic Reviews (PROSPERO) under the ID CRD42022370621.

2.1. Eligibility criteria

Population, exposure, comparator, outcome, and study design and type (PECOS framework), was used to develop the eligibility criteria. This strategy decreased the possibility of bias in our review process and ensured that our chosen papers matched the research question (Hu et al., 2021; Ricciardi et al., 2022; Zare Sakhvidi et al., 2023) (**Table 1**).

Table 1. Eligibility criteria for article inclusion and exclusion in the review.

Research question component	Inclusion Criteria	Exclusion Criteria
Population	Human participants or populations with no age, sex, or gender restrictions	Non-human participants
Exposure	Articles focused on heat related events such as heat wave, hot and extremely hot temperature, etc. and present results on how heat-related mortality was modified by greenspace.	Articles not focused on the effect modification by greenspace on heat-related mortality
Comparator	Articles that compared areas with differing levels of greenspace (e.g., low vs. high greenspace) and evaluated the association between heat exposure and mortality in those areas.	Articles that did not perform such comparisons, including those that did not assess the relationship between greenspace levels and heat-related mortality.
Outcome	Articles that examined the effect modification of greenspace on the association between heat exposure and mortality.	Articles that did not investigate effect modification of greenspace on the association between heat exposure and mortality.
Study design	Observational studies (e.g., cross-sectional, case-control (case-crossover), cohort, or ecological design, time-series, longitudinal)	Qualitative studies, experimental studies.
Study type	Peer reviewed, original articles and articles with full text available.	Materials such as literature reviews, systematic reviews, unpublished data, unpublished theses, duplicate studies, books, conferences, editorials, commentaries, letters to the editor, case reports.
Language	English	Non-English

2.2. Search strategy

Systematic searches were conducted on three electronic databases, including MEDLINE (via PubMed), Scopus (Elsevier), and Web of Science, using search queries constructed based on the study PECOS form databases inception up to July 20, 2025. The detailed search strategies for all databases are presented in

Table S1. We utilized various search terms related to the exposure (temperature, heat, climate, and meteorology, etc.), modifier (green space, greenspace, greenness, greenery, normalized difference vegetation index, vegetation, nature exposure, proximity to nature, etc.), and outcome (mortality, death, etc.) and merged the findings using the Boolean operator AND.

2.3. Selection of studies

We utilized the Rayyan website (https://www.rayyan.ai/), an advanced software for systematic reviews, to screen and select the relevant papers. After duplicate removal, six reviewers (MMP, MB, DS, ICS, IAB, and AI) screened the titles and abstracts of the retrieved studies according to the inclusion/ exclusion criteria. The studies that met the inclusion criteria went to full text assessment step. Any conflicts between reviewers were resolved through discussion.

2.4. Data extraction and data items

After checking of the full text and selection of final eligible papers, the desired details of each article extracted and entered into Google Sheets. The data extraction process focused on various aspects of the studies, such as study general characteristics (e.g., author, publication year, study time, and design), participants' characteristics (e.g., location, sample size, population type and recruitment strategies, sex/gender ratio, age group), exposure description (including time period, data sources, and type of exposure, exposure allocation level [residential address, ecological, etc.]), outcome description (type of reported mortality including cause-specific or all-mortality, outcome data source(s)), and effect modifier description (specifically greenspace or vegetation cover, exposure allocation level [residential address, ecological, etc.]). Data extraction was conducted by six reviewers (MMP, MB, DS, ICS, IAB, AI), and cross-checking was performed by two independent reviewers (MMP, MB) to address any inconsistencies through discussion. Based on the various measures of heat exposure and mortality outcomes analyzed in this review, we concluded that meta-analyses were suitable for the collected data.

2.4. Risk of bias assessment

We applied the Office of Health Assessment and Translation (OHAT) tool to assess the risk of bias (RoB) in the studies included in the systematic review (Buczyłowska et al., 2023; OHAT, 2015). This tool is widely recognized for its structured approach in evaluating risk of bias in observational studies. The assessment concentrated on three key domains of exposure, outcome, and confounding biases, along with five methodological aspects, including selection bias, attrition/exclusion, selective reporting, conflict of interest, and other source of bias. Each domain was rated as "definitely low," "probably low," "probably high," or "definitely high" risk of bias, based on predefined criteria (**Table S2**). The RoB assessment was conducted by two reviewers (MMP and ICS), with any disagreements resolved through discussions mediated by a third reviewer (MHEMB).

2.5. Quality of evidence

The Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) approach was utilized to assess the quality of evidence, categorized into four levels: "high," "moderate," "low," and "very low" (**Table S3 & S4**). Through GRADE, observational studies are generally assigned an initial rating of "moderate," which can be adjusted based on GRADE's systematic evaluation (Woodruff and Sutton, 2014). The rating can be downgraded for one or two levels by five domains such as risk of bias, indirectness, inconsistency, imprecision, or publication bias. On the other hand, upgrades may occur for one or two levels by three domains such as large effect sizes, the presence of a dose-response relationship, or limited confounding (Johnson et al., 2014). Two independent reviewers carried out the assessments, and any differences in judgment were resolved through discussion.

2.6. Data synthesis and analysis

We conducted a meta-analysis to assess the association between heat exposure which was defined based on temperature percentiles—and all-cause mortality at different levels of greenspace exposure. We limited our analysis to all-cause mortality due to the insufficient number of studies on cause-specific mortality outcomes (e.g., respiratory, cardiovascular), which prevented meaningful meta-analytical synthesis. However, we included these studies in a narrative review to provide a broader contextual understanding. Given the methodological differences among different study designs, we restricted our meta-analysis to time-series, case-time series and case-crossover studies, as all are well-established designs for assessing the short-term effects of environmental exposures on mortality. Despite differences in methodology, they share a common focus on short-term risk estimation using time-varying exposure data. These designs produce comparable effect estimates and are often combined in earlier quantitative syntheses (Atkinson et al., 2014; Gasparrini, 2014).

These studies predominantly report relative risks (RRs) as the effect measure. Effect sizes were reported across studies in different formats, including percentage change, regression coefficients (β), odds ratio (OR) and direct RRs. When necessary, we standardized these metrics as follows: percentage changes were converted to RRs using the formula: RR = 1 + (% change)/100; regression coefficients (β) were transformed using the exponential function: RR = exp (β). We used the natural logarithm of RRs (logRR) in our meta-analysis to stabilize variances and enable linear modeling, which is standard practice in random-effects meta-analysis. When a meta-analysis was not feasible due to limited number of studies on a specific outcome, we provided narrative descriptions of the findings.

We focused on heat exposure estimates defined at the 95th or 99th percentiles of daily temperature relative to the median or a fixed reference value (e.g., 25 °C), as these thresholds are more representative of extreme heat exposure. Estimates based on other percentiles (e.g., 75th, 25th, or 1st) were excluded because, in the context of the included studies' climate distributions, these percentiles typically corresponded to cooler temperature conditions rather than the extreme heat thresholds of interest. Additionally, we excluded studies that defined heat exposure based on heatwaves, as definitions varied and could not be harmonized with percentile-based temperature exposures. Regarding exposure–outcome effect modification, we extracted association estimates reported across different levels of greenness, most commonly measured using the Normalized Difference Vegetation Index (NDVI). Although some studies also used other metrics such as the Soil-Adjusted Vegetation Index (SAVI) and the Enhanced Vegetation Index (EVI), NDVI was the predominant measure across the included studies. To ensure consistency, we categorized greenness into three groups—low, moderate, and high—based on reported NDVI levels. Specifically, we defined the first NDVI quartiles as low, the middle quartiles as moderate, and the highest quartile as high. In cases where studies reported four NDVI categories (Q1:Q4), we classified the first category as low, two middle categories (Q2 and Q3) as moderate, and the last category (Q4) as high.

Since meta-analysis requires the assumption of approximate normality, we log-transformed RRs (logRR) and calculated standard errors (SE) based on the reported 95% confidence intervals. We then performed a subgroup meta-analysis according to the three greenness levels (low, moderate, high). A random-effects meta-analysis was conducted using the *metagen* function from the meta package in R, employing the Paule–Mandel estimator for between-study heterogeneity (Veroniki et al., 2016). Studies were visually summarized using forest plots, sorted by greenness subgroup to facilitate comparison. Each plot displayed study-specific estimates along with pooled RRs and 95% confidence intervals.

Statistical heterogeneity was assessed using the I² statistic, interpreted as follows: ≤25%: low heterogeneity, 25%–50%: low to moderate, 50%–75%: moderate to high, ≥75%: high heterogeneity (Higgins et al., 2003). To ensure robustness, we conducted sensitivity analyses excluding case-crossover and case-time series studies. We visually evaluated publication bias using funnel plots, and employed the trim-and-fill method to estimate the influence of potentially missing studies on the reported pooled estimates. Where applicable, imputed pseudo-studies were added to estimate adjusted pooled effects. All analyses were performed in R version 4.1.0 (R Foundation for Statistical Computing, Vienna, Austria) using the meta package (version 5.5-0) for meta-analyses and the *metafor* package (version 4.2-0) for publication bias assessments.

3. Results

3.1. Study selection

The PRISMA flow diagram (Figure 1) outlines the systematic process of selecting studies for inclusion in the review. Initially, 13,976 records were identified through database searches (PubMed, Web of Science, and Scopus) and manual reference checks. After removing 3,106 duplicates, 10,870 records underwent title and abstract screening, resulting in the exclusion of 10,589 records. The remaining 281 full-text articles were assessed for eligibility. Ultimately, 45 studies were included in the final analysis.

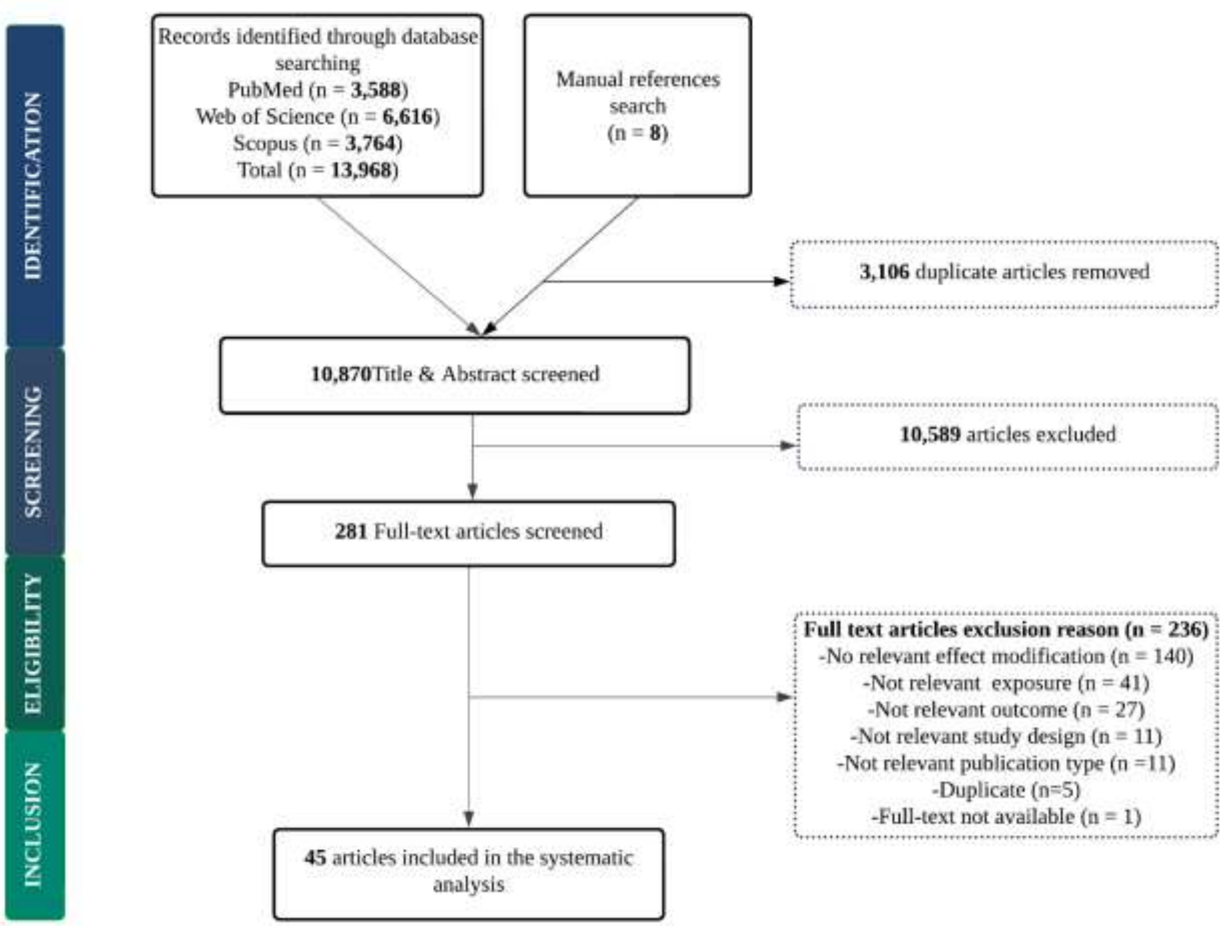

Figure 1. PRISMA flow chart of study selection process.

3.2. Characteristics of the included studies

The systematic review included studies published between 2013 and 2025, with the majority (n=30) published between 2020 and 2025. Geographically, most studies were from the USA (n=7), followed by China (n=7), Hong Kong (n=5), multiple countries (n=8), South Korea (n=4), the UK (n=2), Thailand (n=2), Australia (n=2), and one each from France, Finland, India, Jordan, Portugal, Spain, Switzerland, and Vietnam. Over half of the studies employed a time-series design (n=23), followed by case-crossover (n=10), cohort (n=4), case-only (n=4), and ecological designs (n=4). Most studies focused on the general population (all ages) (n=30), with others on the elderly (65 years and older) (n=13), infants (n=1), and cancer patients (n=1). The total sample size exceeded 290 million deaths from 1985 to 2020. The most commonly used statistical methods were the Distributed Lag Non-Linear Model (DLNM) (n=24) and conditional logistic regression (n=11). The frequently adjusted confounders for heat effects in included studies were time-related factors like time trends, seasonality, day of the week, and holidays, and environmental factors such as air pollutants (e.g., $PM_{2.5}$, NO_2, O_3, PM_{10}), relative humidity and temperature. Additionally, studies commonly considered demographic characteristics such as age, sex, race, income, education level, population density, urbanization, gross domestic project (GDP), unemployment and area-level socio-economic status (SES) variables (Table 2).

The included studies analyzed various aspects of temperature, with continuous temperature effects (n=24), often during warm months (n=16), being a dominant focus, followed by heat effects (n=9), heatwaves days (n=7), extreme heat (n=2), heat index (n=1), urban thermal climate index (n=1) and hot night durations and hot night excess (n=1). Most studies collected data from national meteorological stations such as the United States National Oceanic and Atmospheric Administration (NOAA) (n=7), other national government agencies (n=28), European Centre for Medium-Range Weather Forecasts (ECMWF) (n=5), and others (n=5). Various greenspace indicators were used as effect modifiers in the included studies. Vegetation indices appeared in 30 studies, with the most commonly used index being the NDVI (n=29), followed by EVI (n=4) and SAVI (n=1). Ten studies measured the percent cover of greenspace, eight used land use land cover classifications of greenspace, three used tree cover, three used street view greenery, and one reported on perceived greenness. Common data sources were from satellite-based systems, with MODIS (250–1000 m resolution) being the most frequently used, followed by Landsat (30 m resolution) (Table 2).

3.3. Effect modification of greenness on ambient heat and mortality

Eleven studies were included in the meta-analysis. The results indicated that high greenness areas [pooled RR (95% CI) = 1.09 (1.02–1.17), n = 11] had a lower risk of all-cause mortality during heat (≥95th percentile) compared to areas with lower greenness [pooled RR (95% CI) = 1.24 (1.11–1.38), n = 11], with substantial heterogeneity (I^2 = 97%) (Figure 2). We conducted sensitivity analyses by excluding studies with case time-series and case-crossover design and results indicated that the association between high greenness and lower risk of mortality compared to medium and low greenness remained consistent (Figure 3).

Visual inspection of the funnel plot indicated some asymmetry (Figure S1), and Egger's regression test suggested potential publication bias ($p < 0.05$), possibly reflecting small-study effects. To explore this further, we applied the Trim and Fill method, which imputed 12 potentially missing studies and indicating that the overall estimate may be influenced by publication patterns and should be interpreted with appropriate caution (Figure S2).

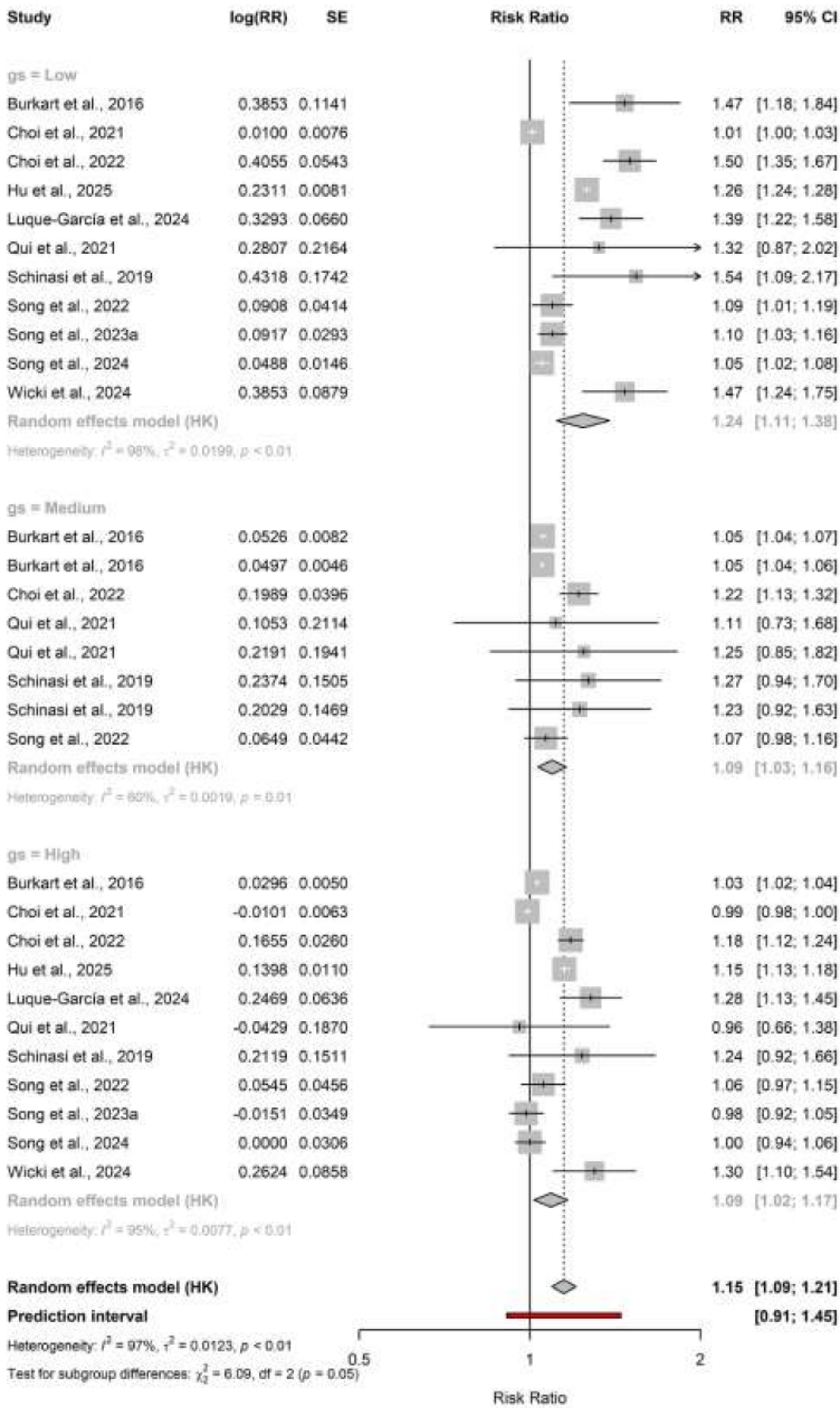
Study log(RR) SE Risk Ratio RR 95% CI
gs = Low
Burkart et al., 2016 0.3853 0.1141 1.47 [1.18; 1.84]
Choi et al., 2021 0.0100 0.0076 1.01 [1.00; 1.03]
Choi et al., 2022 0.4055 0.0543 1.50 [1.35; 1.67]
Hu et al., 2025 0.2311 0.0081 1.26 [1.24; 1.28]
Luque-García et al., 2024 0.3293 0.0660 1.39 [1.22; 1.58]
Qui et al., 2021 0.2807 0.2164 1.32 [0.87; 2.02]
Schinasi et al., 2019 0.4318 0.1742 1.54 [1.09; 2.17]
Song et al., 2022 0.0908 0.0414 1.09 [1.01; 1.19]
Song et al., 2023a 0.0917 0.0293 1.10 [1.03; 1.16]
Song et al., 2024 0.0488 0.0146 1.05 [1.02; 1.08]
Wicki et al., 2024 0.3853 0.0879 1.47 [1.24; 1.75]
Random effects model (HK) 1.24 [1.11; 1.38]
Heterogeneity: I^2 = 98%, τ^2 = 0.0199, p < 0.01
gs = Medium
Burkart et al., 2016 0.0526 0.0082 1.05 [1.04; 1.07]
Burkart et al., 2016 0.0497 0.0046 1.05 [1.04; 1.06]
Choi et al., 2022 0.1989 0.0396 1.22 [1.13; 1.32]
Qui et al., 2021 0.1053 0.2114 1.11 [0.73; 1.68]
Qui et al., 2021 0.2191 0.1941 1.25 [0.85; 1.82]
Schinasi et al., 2019 0.2374 0.1505 1.27 [0.94; 1.70]
Schinasi et al., 2019 0.2029 0.1469 1.23 [0.92; 1.63]
Song et al., 2022 0.0649 0.0442 1.07 [0.98; 1.16]
Random effects model (HK) 1.09 [1.03; 1.16]
Heterogeneity: I^2 = 60%, τ^2 = 0.0019, p = 0.01
gs = High
Burkart et al., 2016 0.0296 0.0050 1.03 [1.02; 1.04]
Choi et al., 2021 -0.0101 0.0063 0.99 [0.98; 1.00]
Choi et al., 2022 0.1655 0.0260 1.18 [1.12; 1.24]
Hu et al., 2025 0.1398 0.0110 1.15 [1.13; 1.18]
Luque-García et al., 2024 0.2469 0.0636 1.28 [1.13; 1.45]
Qui et al., 2021 -0.0429 0.1870 0.96 [0.66; 1.38]
Schinasi et al., 2019 0.2119 0.1511 1.24 [0.92; 1.66]
Song et al., 2022 0.0545 0.0456 1.06 [0.97; 1.15]
Song et al., 2023a -0.0151 0.0349 0.98 [0.92; 1.05]
Song et al., 2024 0.0000 0.0306 1.00 [0.94; 1.06]
Wicki et al., 2024 0.2624 0.0858 1.30 [1.10; 1.54]
Random effects model (HK) 1.09 [1.02; 1.17]
Heterogeneity: I^2 = 95%, τ^2 = 0.0077, p < 0.01
Random effects model (HK) 1.15 [1.09; 1.21]
Prediction interval [0.91; 1.45]
Heterogeneity: I^2 = 97%, τ^2 = 0.0123, p < 0.01
Test for subgroup differences: χ^2_2 = 6.09, df = 2 (p = 0.05)
0.5
1
2
Risk Ratio

Figure 2. Forest plot for the pooled estimate of the overall effect of ambient heat (≥95th percentile) on all-cause mortality when modified by different level of greenness (NDVI).

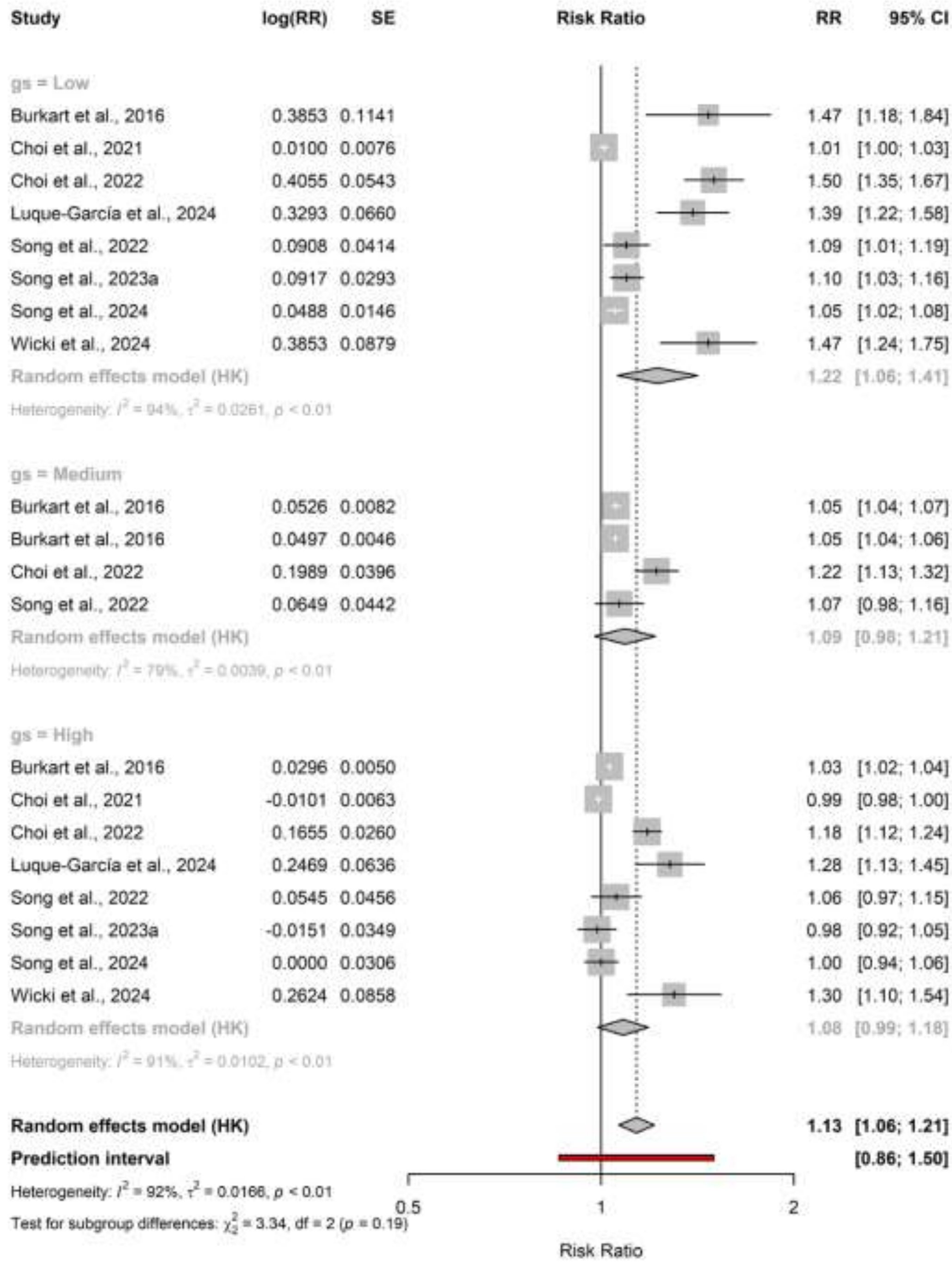

Figure 3. Forest plot for the sensitivity analysis by removing studies with case time-series and case-crossover deisgn on the effect modification of NDVI on heat and all-cause mortality.

Other greenspace indicators, such as high levels of EVI and SAVI were found to be protective against extreme heat (95th-99th percentile temperature)-induced all-cause mortality (Choi et al., 2022; Choi et al., 2023; Wu et al., 2025), cardio-respiratory mortality (Choi et al., 2022), and stroke, including ischemic stroke mortality (He et al., 2022). Additionally, three studies reported that higher tree coverage was associated with a lower risk of all-cause mortality during high-temperature events (Murage et al., 2019; Xu et al., 2013; Williams et al., 2020).

Two studies identified green land cover as an effect modifier, demonstrating its protective effects against all-cause (Avashia et al., 2021) and cardiovascular mortality during high temperatures (Zhang et al., 2023). When greenspace area was used as a modifier, a higher proportion of greenspace was associated with lower risks of all-cause (Dang et al., 2018; Sera et al., 2019), cardiovascular (Gronlund et al., 2014), respiratory (Sofia et al., 2023), and total mortality (Zanobetti et al., 2013) during high heat.

Overall greenspace, forests, parks, and nature reserves were associated with reduced risk of all-cause mortality (Hu et al., 2025) and cardiovascular mortality (Hu et al., 2024). Street greenery showed a positive association with reduced risk of all-cause (Song et al., 2023a) and cardiovascular mortality (Hu et al., 2024) during high-temperature periods. At mean temperature, three studies reported protective effects of high greenness on all-cause mortality (Labib et al., 2024), mental disorder mortality (Ho and Wong, 2019), and cancer mortality (Yi et al., 2021). However, meta-analysis was not feasible due to the heterogeneity in exposure-outcome measures (Table 2).

3.4. Effect modification of greenness on heatwaves and mortality

Six studies investigated the effect modification of greenness in the association between heatwaves and mortality (Benmarhnia et al., 2017; Kim and Kim, 2017; Madrigano et al., 2015; Song et al., 2023b; Wang, 2023; Xu et al., 2019; Zhang et al., 2021). Among these, three studies reported that high NDVI levels were associated with low risk of all-cause mortality (Song et al., 2023b; Zhang et al., 2021) and cardio-respiratory and hypertensive mortality (Wang, 2023) during heatwaves. Additionally, two studies utilized greenspace area as a modifier, reporting that a higher proportion of green areas conferred protection against all-cause mortality during heatwave days (Benmarhnia et al., 2017; Kim and Kim, 2017).

One study evaluated the effect modification of green land cover, characterized by the prevalence of grass and shrubs, and found that it was associated with a reduced risk of mortality from cardiovascular disease (CVD), myocardial infarction, congestive heart failure (CHF), and chronic obstructive pulmonary disease (COPD) during or immediately following heatwave days (Madrigano et al., 2015). However, meta-analysis was not feasible due to heterogeneity in exposure-outcome definitions (Table 2).

Table 2. Characteristics of the included studies (n = 45).

Author (s), Publication Year; Country	**Study design; Study Population (age); Sample size**	**Statistical methods**	**Time period**	**Heat/Temperature**	**Greenness**	**Mortality outcome**	**Main findings**	**Confounder adjusted**
Avashia et al., 2021; India	Time-series; General population (All ages); 554,553	Generalized additive model (GAM), DLNM; GLM	2001-2015	Continuous temperature	Green land use	All-cause	An increase in relative risk of mortality as non-built-up spaces (e.g., green space) decrease in the land-use mix.	Time-trend, seasonality, day of the week; Age, gender, underlying health conditions, income levels and access to preventive as well as palliative healthcare measures
Benmarhnia et al., 2017; France	Time-series; Elderly (65 years and older); 7,376	Bernoulli probability model; Meta-regression	2004-2009	Heatwave days	Greenspace proportion	All-cause	Greenspace density showed protective effect on heatwave-mortality.	Time-trend; annual $PM_{2.5}$, NO, PM_{10}; social deprivation, % foreign people; %unemployed, % elderly, education, median income, people with stable jobs
Burkart et al., 2015; Portugal	Time-series; Elderly (65 years and older); 218,764	GAM, DLNM	1998-2008	Urban Thermal Climate index (equivalent temperature)	NDVI	All-cause	A 1°C rise in UTCI above 24.8°C increased the mortality risk by 14.7% (95% CI: 1.9, 17.5%) in areas with the least vegetation compared to areas with the most vegetation (3.0% increase, 95% CI: 2.0, 4.0%)	Time trend, Day of the week, average daily mean PM_{10}, O_3 concentrations (lag 0–1), percentage of the parish population > 65 years of age, Building density (number of buildings per km²), percentage of college graduates, proportion of inhabitants receiving social benefits
Choi et al., 2021; USA	Time-series; General population (All ages); 1,208,766	GAM, Bayesian hierarchical modeling	2000-2016	Heat effects	NDVI	All-cause	Higher relative cold risk to mortality was attributable to counties with less greenness.	Time-trend, seasonality, day of the week, daily dew point temperature; Population density, $PM_{2.5}$, education level, residential segregation, income inequality, income
Choi et al., 2022; Multi country	Time-series; General population (All ages); Daily mean death 53.93	Quasi-Poisson regression, DLNM	2000-2018	Continuous temperature (warm months)	NDVI, EVI	All-cause; Cardiovascular ; Respiratory	Heat related relative mortality risk was low in areas with high greenspace. A 1% to 20% increase in greenness (NDVI) across was expected to	Time-trend, seasonality, day of the week, latitude, summer mean temperature, temperature range, , humidity, $PM_{2.5}$, GDP, population density, and unemployment

							reduce the heat-related attributable fraction by approximately 0.5% to 9.2%.	
Choi et al., 2023; USA	Time-series; General population (All ages); 444,854	Quasi-Poisson regression, DLNM	2000-2016	Continuous temperature (warm months)	NDVI, EVI	All-cause	The heat-mortality relative risk was 8% higher in areas with low greenspace at the 99th temperature percentile compared to the MMT.	Time-trend, seasonality; Race, place of region
Dang et al., 2018; Vietnam	Time-series; General population (All ages); 101,897	Quasi-Poisson regression, DLNM	2010-2013	Continuous temperature	Greenspace area per 1000 people	All-cause	For every increase of 1 square kilometer of green space per 1,000 people, the number of heat-attributable mortalities was estimated to decrease by 7.4 (95% CI: 1.3, 13.5) in Ho Chi Minh City.	Time-trend, day of the week; Population density
Denpetkula and Phosri, 2021; Thailand	Case-crossover; General population (All ages); 2,891,407	Conditional Poisson regression model, DLNM	2010-2017	Heat effects	NDVI	All-cause; Cardiovascular; Respiratory	A 0.1-unit increase in NDVI was linked to decreases in all-cause deaths by 0.81% and 0.60% due to non-optimum and hot temperatures, respectively. It also led to a decrease in cardiovascular and respiratory deaths by 0.47% and 0.98% for non-optimum temperatures, and by 0.32% and 0.84% for hot temperatures.	Time-trend, seasonality, day of the week; temperature, proportion of elderly, proportion of higher education, income, and population density
Dimakopoulou et al., 2024; Multi country	Cohort; General population (37 years and older); 27,788,811	Cox proportional hazard model	Administrative cohort: Baseline: 2010-2014,	Continuous temperature	NDVI	All-cause	There was no significant evidence reported on changes in	Age, sex, sub-cohort, baseline year, marital status, BMI, Smoking duration and intensity, employment status,

			Follow-up: 2018/2019; Traditional cohort: Baseline: 1992-2004, Follow-up: 2011-2015				greenness and reduction of heat-mortality.	education level, area-level SES variables
Gronlund et al., 2014; USA	Case-crossover; Elderly (65 years and older); Mean daily death 133.22	Conditional logistic regression	1990-2007	Extreme heat	Greenspace area	Cardiovascular ; Respiratory	The risk of cardiovascular mortality due to extreme heat were 17% higher for individuals living in ZIP codes with a high proportion (91%) of non-green space (95% CI: 6% to 29%).	Time variation; personal marital status, age, race, sex and education, income, education, living alone, and housing age (U.S. Census).
He et al., 2019; Thailand	Case-crossover; General population (All ages); 59,836	Conditional logistic regression, DLNM	2000-2008	Heat (90th percentile of temperature) & Extreme heat (99th percentile of temperature)	NDVI	Diabetes mortality	A 1-unit increase in NDVI was associated with a 40% reduction in the odds of diabetes mortality due to heat and an 80% reduction due to extreme heat.	Time-trend, daily relative humidity and diurnal temperature variation, GDP, education, proportion of elderly
He et al., 2022; China	Time-series; General population (All ages); 138,749	DLNM	2013-2019	Heat effects	NDVI, EVI, SAVI	Stroke mortality; Ischemic stroke mortality; Hemorrhagic stroke mortality	For each 0.1-unit increase in NDVI, SAVI, and EVI, the relative risk of overall stroke mortality from extreme heat decreased by 0.162, 0.194, and 0.107, respectively, and the risk of ischemic stroke mortality decreased by 0.239, 0.296, and 0.168, respectively.	Time-trend, seasonality, day of the week, holiday (public holidays), relative humidity, $PM_{2.5}$, SO_2, NO_2, CO, GDP, Population density, road proximity
Ho and Wong, 2019; Hong Kong	Ecological; General population (All ages); 133,359	Poisson regression; Linear regression	2007-2014	Continuous temperature	Vegetation cover (%)	All-cause; Respiratory; Cardiovascular ;Mental	The mortality risk of mental disorder in high temperature days was higher in the area with	Time-trend, seasonality, weekend effect, demographic factors, air quality, occupational effect

						disorder mortality	lower percentage of vegetation cover.	
Hu et al., 2024; China	Time-series; Elderly (65 years and older); 902,193	Quasi-Poisson regression, DLNM	2009-2020	Heat effects	Overall greenspace, Farms, Nature Reserves, Forests, Scrubs, Grasses, Parks, Street Greenery	Cardiovascular	Overall greenspace, forests, parks, nature reserves, and street greenery were linked with lower heat-related cardiovascular mortality	Long-term and seasonal trends, day-of-week effects, relative humidity (0–3 lag days), percentage of older adults (65+), sex ratio, per capita disposable income.
Hu et al., 2025; China	Case time-series; Elderly (65 years and older); 2,778,865	Fixed-effects conditional quasi-Poisson regression, DLNM	2009-2020	Daily ambient mean temperature	Overall greenspace, Farms, Nature Reserves, Forests, Scrubs, Grasses, Parks, Street Greenery; GVI; NDVI	All-cause	A 10%, 20%, and 30% increase in overall green space exposure was projected to reduce heat-related mortality burden by approximately 1.6%, 3.2%, and 4.8%, respectively. At the 95th and 99th temperature percentiles, higher green space exposure (NDVI) was associated with lower heat-related all-cause mortality risks.	Long-term and seasonal trends and the day-of-the-week effects, year, month, and day of the week, percentages of population over 65 y of age, sex ratios, and illiteracy rates in people over 15 y of age.
Jang et al., 2020; South Korea	Time-series; General population (All ages); Mean death count 5 per buffer	GLM with a quasi-Poisson distribution, DLNM	2011-2017	Continuous temperature (summer months) at 30km, 35km, 40km buffer	LULC indicators (green coverage, woodland, urban forest, crop field)	All-cause	There was no significant association between any LULC indicators and mortality.	Time-trend, seasonality, day of the week, GRDP per capita, Local tax per capita, sex, Percentage of individuals aged ≥ 65 years, Percentage of detached houses, Percentage of apartments, Number of hospital beds per 1,000 people
Kim and Kim, 2017; South Korea	Case-crossover; General population (All ages); 33,554	Conditional logistic regression	2009-2012	Heatwave days	Park area per 1 person, Green area, Green area around public buildings, Roof green area	All-cause	The death during heat waves was more likely to occur in low proportion of green area around public buildings and low roof green area.	Time-trend, day of the week, relative humidity, PM10, deprivation index, income level, financial independence, occupation, living floor area
Kivimäki et al., 2023; Finland	Cohort; General population (All ages); 8,818	Conditional logistic regression	2000-2018	Heat index	NDVI	Cardiovascular	There were no significant differences between surrounding	Time-trend, calendar year, age, sex, education, population density, obesity, smoking,

							greenness level on reducing heat-related mortality.	high alcohol intake, physical inactivity
Labib, 2024; UK	Ecological; General population (<75 years older); Mean premature mortality rate 74.47	Spatial and non-spatial random forest model	2008-2013	Continuous temperature	NDVI	All-cause	High greenness exposure (e.g., NDVI >0.6) interacted with high temperature exposure (e.g., 19°C) was associated with reduced risks of premature mortality.	Income deprivation, barriers to housing, crime scores, density of people, distance to nearest general medical practice, average Distance to fast food outlets, land use diversity
Luque-García et al., 2024; Jordan	Time-series; General population (all ages); 171,284	Quasi-Poisson regression, DLNM	2000-2020	Continuous temperature	NDVI	All-cause	The low greenness area had a high risk of heat-related mortality.	Time-trend, season, day of the week, urbanization, population density.
Madrigano et al., 2015; USA	Case-only; General population (>19 years of age); 232,572	Multinomial logistic regression	2000-2011	Heatwave days	Land cover (Trees, Grass, Shrubs)	CVD, myocardial infarction, congestive heart failure, and COPD	Living in "greener" areas, characterized by more grass and shrubs, was associated with a 4% lower risk of death during or immediately after heat waves.	Time-trend, season, race/ethnicity, place of death, and socioeconomic measures (e.g., public assistance)
Murage et al., 2019; UK	Case-crossover; General population (All ages); 185,397	Conditional logistic regression	2007-2016	Continuous temperature (Summer months)	Land cover (forested and agricultural land, green urban land), Tree cover, NDVI-300m, Garden	All-cause	High-vegetation areas showed a stronger reduction in heat-related mortality compared to low-vegetation areas.	Day of the week, age-group, sex, land-use categories, by LSOAs and by quartiles of socio-economic, natural and built environment
Park et al., 2024; South Korea	Time-stratified case-crossover; General population (All ages); 14,693	Quasi-Poisson regression, DLNM	2000-2020	Hot night duration (%); Hot night excess (>25 ◦C) (warm season)	NDVI	Suicide	For a 10% increase in hot night duration, the suicide mortality risk increased by approximately 5.9% in areas with low NDVI compare to high NDVI.	Time-trend, calendar year, day of the week, daily mean temperature, relative humidity, age, sex,
Qui et al., 2021; China	Time-stratified case-crossover; Elderly (65 years and older); 21,775	DLNM	2000-2014	Heat effects	NDVI-250m	All-cause	Higher levels of greenness were associated with a reduced risk of heat-related mortality compared to lower	Time-trend, calendar year, day of the week, relative humidity, age, sex, and health status.

							greenness. In contrast, higher level of greenness were associated with high risk of heat-related mortality compared to lower greenness.	
Schinasi et al., 2019; USA	Case-crossover; Infants (<12 months older); 1,522	Conditional logistic regression	2000-2015	Continuous temperature (warm months)	NDVI-250m	All-cause	There was no significant evidence on the effect modification role of greenness on heat-related mortality.	Time-trend, seasonality, day of the week, age, sex, and race.
Schinasi et al., 2023; Multi country	Time-series; General population (All ages); NR	Conditional Poisson regression, DLNM	2002-2015	Continuous temperature (warm months)	NDVI	All-cause	Higher greenness area had significantly lower heat excess death fractions than lower greenness.	Time-trend, seasonality, PM2.5, social environment index (education, sewage access, piped water, crowding)
Sera et al., 2019; Multi country	Ecological time-series; General population (All ages); 50,000,000	Quasi-Poisson regression, DLNM	1985-2014	Heat effects	Green area (m^2 per million persons)	All-cause	Higher greenness area showed lower heat-related AF%.	Seasonality, day of the week, population density, PM2.5, GDP and Gini index (a measure of income inequality)
Sofia et al., 2023; Multi country	Ecological; General population (All ages); 1,394 Mortality per 100,000 inhabitants	Poisson regression, DLNM	1996-2018	Continuous temperature	Green area per 100,000 (low vs high)	Respiratory	High green areas had lower risk of heat-related mortality than lower green.	Time-trend, population density, urban type, and employment
Son et al., 2016; South Korea	Ecological time-series; General population (All ages); NR	Poisson generalized linear model	2000-2009	Continuous temperature (warm months)	NDVI	All-cause	The risk of total mortality from heat was highest in low NDVI compared medium and high group.	Time trends, day of the week, relative humidity, daily PM10 and O3 concentrations, NDVI group, percentage of persons >65, percentage receiving social benefits (SES proxy), population size.
Song et al., 2021; Multi country	Time-series; Elderly (65 years and older); 67,871,077 deaths per	Linear regression, Fixed effect model	1990-2019	Continuous temperature (warm months)	NDVI	All-cause	High surrounding greenness showed lower heat-related mortality across countries.	PM2.5, population density, the proportion of the population aged 65 years older (%) and the proportion of man (%), GDP per capita, GDP growth

	100,000 population							(annual%), life expectancy at birth (years), Gini index, physicians (per 1000 people) and educational level; Urban characteristics: including urban population and urban population growth.
Song et al., 2022; Hong Kong	Time-series; Elderly (65 years and older); 421,979	Quasi-Poisson generalized linear model, DLNM	2008-2017	Continuous temperature (warm months)	NDVI	All-cause	Areas with lower and medium levels of greenness experienced a significant increase in mortality risk due to higher temperatures compared to areas with higher levels of greenness.	Time-trend, public holidays and days of the week, population density, sex ratio, percentage of older adults, educational attainment, poverty levels, and household size.
Song et al., 2023a; Hong Kong	Time-series; Elderly (65 years and older); 221,919	DLNM	2005-2018	Continuous temperature (warm months)	NDVI, greenspace, street greenery	All-cause	Areas with higher levels of urban greenery showed lower relative risks of mortality. Eye-level street greenery was the most effective at reducing mortality risk during high-temperature periods.	Days of the year, days of the week, holidays, and baseline risks across different time scales, relative humidity, air pollutants (O_3, PM_{10}), age, sex
Song et al., 2023b; Hong Kong	Case-only; Elderly (65 years and older); 55,154	Multinomial logistic regression	2008-2017	Heatwave days	NDVI	All-cause	Higher level of greenness was associated with reduced mortality during or after immediate heatwaves.	Relative humidity, O3, PM10, age, sex.
Song et al., 2024; Hong Kong	Time-series; General population (All ages); 221,919	Conditional Poisson regression, DLNM	2005-2018	Continuous temperature (warm months)	Population-weighted NDVI 200-4000m, Land cover (Overall greenspace, forest, shrub, grassland)	All-cause	Areas with lower levels of greenness within 1-km could face increase in mortality risk due to higher temperatures compared to areas with higher levels of greenness.	Temporal trends, day of the week, holidays, relative humidity, daily ozone, PM10, age, education, income, and blue space exposure.
Wang, 2023; China	Time-series; General	DLNM, Mediation analysis	2007-2015	Heatwave days	NDVI	Non-accidental, all Cardio-	Cooling services of the city (e.g., NDVI) was associated with reduced	Time-trend, day of the week, relative humidity, age, sex.

	population (All ages); NR					respiratory, hypertensive, IHD, stroke, COPD	heat-related mortality risk.	
Wicki et al., 2024; Switzerland	Time-series; General population (All ages); 53,593	Conditional logistic regression models, DLNM	2003-2016	Continuous temperature (warm months)	NDVI-500m	All-cause	Living in high greenness areas were associated with lower heat-related mortality risk than low greenness areas.	Time-trends, seasonality, day of the week, age, sex
Williams et al., 2020; USA	Case-only; General population (<81 years old); 40,506	Logistic regression and GLM with Poisson distribution	2000-2015	Continuous temperature (warm months)	Street tree	All-cause	Street trees were associated with a reduction in the relative odds of death during warm days both within and outside the home.	Time-trend, seasonality, Impervious surface fraction, population density, proportion of disability, proportion of older, proportion of low income people
Wu et al, 2025; 830 locations in 53 countries	Ecological; General population (All ages); 127,179,341	Random forest, GLM with quasi-Poisson, DLNM, multivariate meta-regression, and Monte Carlo simulations	2000-2019	Daily mean temperature (warm months)	EVI	All-cause	A 10%, 20%, and 30% increase in EVI decreased the attributable fraction of heat-related deaths by 0.67%, 0.80%, and 0.91%, respectively.	Time-trend, seasonality, long-term trends, day of the week, and seasonality-year interaction, GDP, age structure
Xu et al., 2013; Spain	Case-crossover; Elderly (65 years and older); 52,806	Conditional logistic regression	1999-2006	Continuous temperature (warm months)	Perceived greenness, Tree cover-500m	All-cause	Higher tree covered area was associated with a lower risk of heat-related mortality compared to lower tree cover.	Time-trend, seasonality, day of the week, manual labor, unemployment, education, age, building age, air conditioning, surrounding greenness perception, and housing type.
Xu et al., 2019; Australia	Cohort; General population (All ages); 513	Conditional logistic regression	2005-2014	Heatwave days	NDVI	Diabetes mortality	There was no significant evidence on urban vegetation and heat-mortality reduction.	Time-trend, public holidays, seasonality, PM10, NO2, relative humidity, age, gender, socioeconomic advantage & disadvantage

Xu et al., 2024; Australia	Time-series; General population (All ages); NR	Poisson fixed-effects regression model	2006-2016	Continuous temperature	NDVI	Suicides per 100,000	Greenspace coverage moderated the suicides rate during hot temperature.	Seasonality, age, gender, household annual income, indigenous population, unemployment, farmers per labor force, and the proportion of health professionals
Yi et al., 2021; China	Case-crossover; Cancer patients (All ages); 303,670	Conditional logistic regression	2016-2017	Continuous temperature	Green area per capita	Cancer mortality	Cities with less green space per person were more susceptible to the cancer mortality due to temperature variability.	Time-trend, season, day of the week, relative humidity, rainfall, and air pollutants (PM2.5, SO2, NO2, O3), age, sex, income, GDP
Zanobetti et al., 2013; USA	Case-only; Elderly (65 years and older); 7,204,031	Conditional logistic regression	1985-2006	Heat effects	Proportion of green space	Total mortality	Living in areas with less green space was associated with increased odds of mortality during warm months when exposed to high temperatures.	Time-trend, seasonality, sex, race, pre-existing conditions, education level, poverty levels, and population density.
Zhang et al., 2021; China	Cohort; Elderly (65 years and older); 20,758	Cox proportional hazard models	2000-2014	Heatwave days	NDVI-500m	All-cause	For each 0.1-unit decrease in cumulative NDVI corresponding to a 6% increase in mortality risk during hot days.	Time-trend, age, gender, geographic region, ethnicity, marital status, residence, education, occupation, smoking status, alcohol consumption, physical activity, and one-year annual PM2.5 levels.
Zhang et al., 2023; Multi country	Time-series; General population (All ages); 2,842,043	Quasi-Poisson regression, DLNM	1996-2018	Continuous temperature (warm months)	Land cover (green areas)	Cardiovascular	Lower greenspace coverage was associated with higher heat-mortality risk than higher greenspace coverage.	Time-trend, year, month, day of the week, and area-level characteristics (population density, socioeconomic status, and land use).

3.6. Risk of bias assessment

Table S5 presents the risk of for individual studies included in the review. Overall, 25 (55%) studies had a 'Definitely low' or 'Probably low' risk of bias across all dimensions, while the remaining 20 (45%) studies showed a 'Probably high' bias for one or more dimensions of the bias assessment. The risk of bias varied across individual domains. Exposure classification exhibited a 'Probably low' risk in 71% of studies, with 22% showing a 'Probably high' risk. Outcome bias was consistently rated 'Definitely low' in all studies. Confounding bias presented a higher risk, with 40% of studies marked as 'Probably high.' In contrast, selection bias was rated as 'Definitely low' in 87% of studies, while attrition/exclusion bias, selective reporting bias, conflict of interest, and other bias had similarly strong results, with more than 90% of studies rated as 'Definitely low' in these domains (Figure 4). The details of risk of bias for individual studies are presented in Table S6.

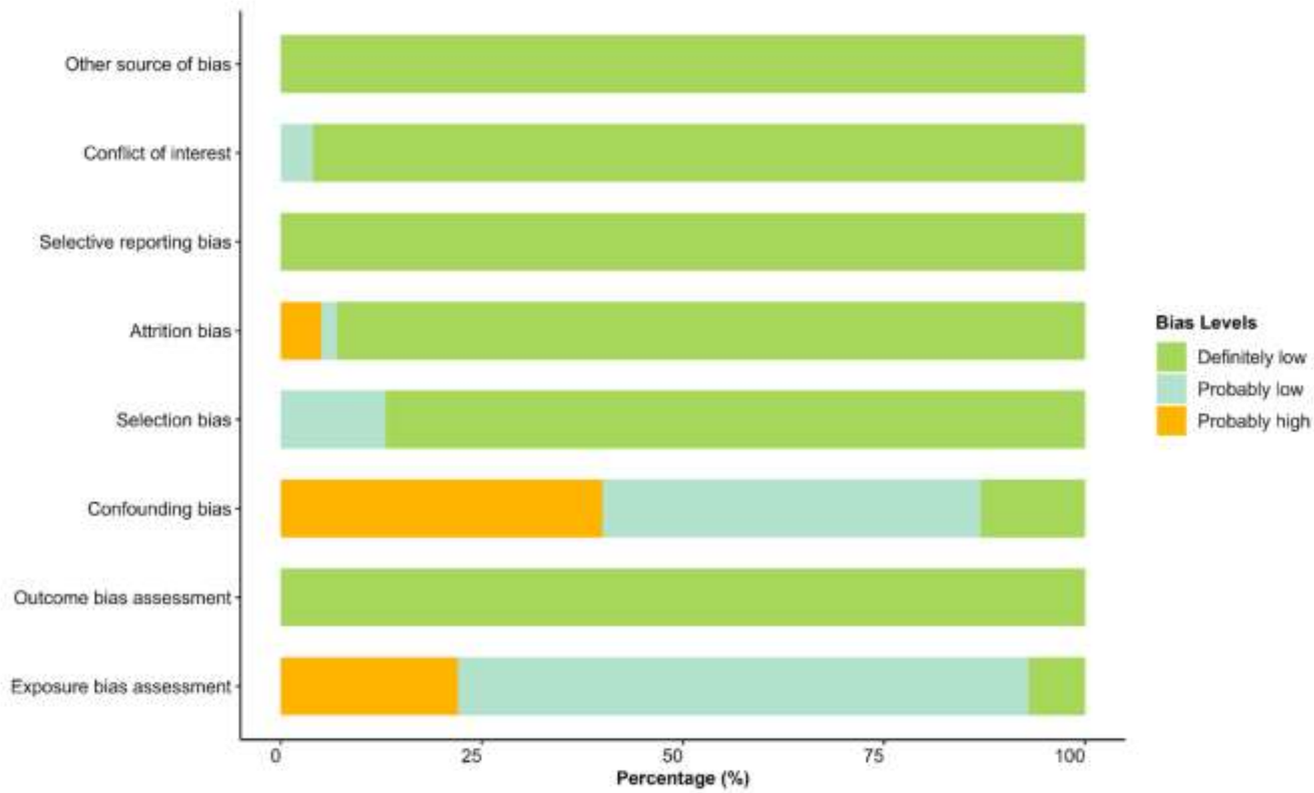

Figure 4. Summary of risk of bias assessment of individual studies.

3.7. Overall quality of the evidence

Table S7 presents the GRADE evaluation of greenspaces as an effect modifier in the relationship between heat exposure and mortality. Initially, the body of evidence was rated "moderate" given that all included studies were observational in nature. However, the confidence level was reduced due to substantial heterogeneity across the pooled studies and publication bias. Despite this, the evidence was not downgraded for concerns related to risk of bias, indirectness, or imprecision. Additionally, no upgrades were applied for factors such as the large magnitude of effect, presence of a dose-response effect, or adjustment for potential confounders. As a result, the overall confidence in the effect modification of greenspace on heat-related mortality was downgraded to "low" based on the GRADE criteria (Table S8).

4. Discussion

In this systematic review and meta-analysis, we evaluated the relationship between ambient temperature, greenspace, and mortality, and synthesized the evidence from 45 original studies published from 2013 to 2025. To the best of our knowledge, this is the first systematic review and meta-analysis to quantitatively analyze the effect modification of greenness on heat-related mortality. Our findings suggest a potential positive association of greenspace in modifying the effects of heat on mortality. The meta-analysis of 11 studies found that areas with increased greenness, as measured by NDVI, were associated with low risk of all-cause mortality during high heat periods compare to low greenness area. Our findings further suggest that while greenness suggests protective association with all-cause mortality during high temperature, its relationship in modifying cause-specific mortality, such as respiratory, cardiovascular, cancer, and mental disorder-related deaths, remains unclear due to limited and inconsistent evidence. However, it is essential to interpret these findings with caution due to the generally low level of evidence across the few studies examined, which may influence the reliability of our conclusions. Therefore, while we highlight potential associations, the evidence does not yet provide a definitive stance on this relationship.

4.1. Potential mechanisms

Although the exact biological mechanisms are not fully understood, several interrelated mechanisms could explain the effect modification of greenspace on association between heat and mortality. Greenspaces may play a vital role in alleviating the UHI effect, where urban areas become significantly warmer than their rural surroundings due to human activities (e.g., pavement) (Hamada and Ohta, 2010; Kuang et al., 2015; W. Liu et al., 2022). Urban greenspace, in particular trees potentially reduces heat stress by providing shade (Armson et al., 2012) and cooling through transpiration (Konarska et al., 2016). Studies showed that as the amount of greenspace increases, indicated by higher NDVI values, surface temperatures decrease (Kuang et al., 2015). Additionally, research indicates that an increase in leaf area index is associated with a significant drop in temperature, with some studies estimating reductions of around 1 °C (Hardin and Jensen, 2007). Similarly, increases in tree cover are linked to measurable daytime and nighttime cooling effects, highlighting the effect of urban vegetation in mitigating heat (Yan and Dong, 2015). Vegetation cools the air through evapotranspiration, releasing moisture and lowering ambient temperatures, which is particularly beneficial during heatwaves by creating more comfortable conditions and reducing heat-related health risks (Anderson and Gough, 2022). Studies reported that greenspaces are protective against the risk of all-cause mortality (Rojas-Rueda et al., 2019), cardiovascular mortality (X. X. Liu et al., 2022), respiratory mortality (Mueller et al., 2022), cancer mortality (Zare Sakhvidi et al., 2022) and suicide mortality (Bolanis et al., 2024)

Greenspaces may improve air quality by filtering pollutants and particulate matter. Vegetation can absorb harmful gases, such as carbon dioxide and nitrogen dioxide, and trap particulate matter on leaf surfaces (Kumar et al., 2019; Wróblewska and Jeong, 2021). Better air quality contributes to respiratory health, which is particularly important during heatwaves when air quality may deteriorate due to increased temperatures and pollution (Kalisa et al., 2018). Earlier studies revealed that higher level of air pollution elevated the risk of heat-related mortality (Hu et al., 2022).

Another potential mechanism could be the incorporation of greenery into the indoor environment such as green roofs and vertical gardens, which can further reduce indoor temperatures, offering refuge from external heat (Visvanathan et al., 2024). Green roofs can reduce indoor temperature up to 15 °C (Mihalakakou et al., 2023). This aspect is particularly important for vulnerable populations, such as the elderly and those with preexisting health conditions, who may be more susceptible to heat-related illnesses (Marvuglia et al., 2020).

4.2. Limitations of existing studies

Significant heterogeneity was observed among the included studies in this review, indicated by high I^2 values, complicating interpretation. This variability could result from differences in exposure measurement, categorizations, and the demographic or geographical context of each study. These findings align with previous systematic reviews on air pollution, temperature, and health outcomes, which also reported significant I^2 values (Bunker et al., 2016). As Bunker et al. (2016) noted, conventional I^2 thresholds are better suited for controlled epidemiological studies and may not fully capture the variability present in environmental health research, where methodological flexibility is common (Bunker et al., 2016).

One of the main limitations was the inconsistent use of temperature metrics—ranging from mean, median, or different percentiles—added complexity to these comparisons. Additionally, many studies relied on fixed meteorological stations or modelled temperatures to assess temperature, which may not accurately represent individual heat exposure, as heterogeneous heat exposure is common within urban neighborhoods. Outdoor temperatures measured by these stations often misrepresent the temperatures felt by individuals during both normal summer conditions and heatwaves (Kim and Kim, 2017), and similarly modelled data do not reflect personal exposures. To improve comparability and ensure more reliable synthesis of results, there is an urgent need for application of consistent methods on exposure and analytical design and use of individual-level exposure, as well as studies to better understand the relationship between ambient and personal exposure across locations and subpopulations. While the impact of heat on health varies by location and population, use of consistent methods would aid understanding of the true impact of heat on health.

Regarding effect modifiers, commonly used greenspace metrics (e.g., street trees, satellite-derived indices like NDVI and EVI, and land-use data) reflect overall vegetation levels but may not fully represent important aspects of greenspace such as quality, accessibility, or distinctions between types of vegetation (e.g., agricultural land, forests, urban parks), which could be relevant to health outcomes (Sanders et al., 2015). In this review, none of the studies accounted for greenspace quality or proximity as modifiers, both of which are important for health outcomes (Ye et al., 2022), as such greenspace metrics are challenging to assess for an epidemiological study. Additionally, only a limited number of studies assessed greenspace using tree canopy coverage or land cover data. While indices like NDVI and EVI perform well in epidemiological studies (Huete et al., 2002), they and other measures of greenspace often overlook key factors like human interaction with greenspace, such as walkability or shade provided by trees (Choi et al., 2022). Therefore, future research should prioritize more nuanced assessments of greenspace, incorporating factors that directly affect health outcomes, such as accessibility, proximity, safety, type of vegetation, and specific greenspace features. Another key limitation in the current body of literature is the temporal assessment of greenspace. While most studies account for average greenspace coverage over time, they often do not address how greenspace changes dynamically, particularly in response to urbanization or policy interventions (Wu et al., 2023). Future research should incorporate longitudinal greenspace data to better understand how changes in greenspace availability and quality over time influence health outcomes, particularly as cities continue to evolve. Moreover, the majority of studies included in this review were conducted in urban environments, with limited investigation into suburban or rural areas, where the availability and types of greenspace may differ considerably. A finer, neighborhood-level analysis would offer more insights into how greenspace modifies heat-related health risks within cities and across different socio-economic groups (Song et al., 2024). Understanding intra-urban variability in greenspace distribution, as well as its interaction with community characteristics like income or air pollution exposure, is crucial for designing targeted public health interventions (Hong et al., 2021; Rigolon et al., 2021).

Regarding adjustment for confounders, behavioral factors such as air conditioning usage and structural factors like housing insulation was not consistently considered across the studies, which further limits the accuracy of heat exposure assessments, as it can significantly modify the relationship between temperature and health outcomes, particularly in urban settings (Zanobetti et al., 2013). Air pollution is another important confounder that was often not considered with the analysis of greenspace exposure for effect modification. Greenspaces may potentially mitigate the harmful effects of air pollution by improving air quality and reducing pollution levels. However, without considering the interaction between air pollution and greenspace, studies may miss the combined or synergistic effects these factors have on health outcomes.

Another key limitation was the predominant focus on high-income countries (HICs) in the literature, particularly in Europe and America, overlooking low- and middle-income countries (LMICs) where healthcare access is limited. This is concerning given that the poorest populations face significantly higher heatwave exposure and have lower ability to respond to environmental stressors. As climate change worsens these conditions, the vulnerability of these communities to heat-related illnesses will likely increase (Alizadeh et al., 2022). There is an urgent need for more research and policy attention in LMICs and Latin America to address these specific health risks, with future studies prioritizing these regions for a better understanding of how greenspace mitigates heat-related health outcomes across varying socio-economic contexts.

While our findings suggest a consistent association between higher greenspace exposure and lower heat-related mortality risk, it is important to consider the potential influence of publication bias. Funnel plot asymmetry and Egger’s test indicated possible small-study effects. The application of the Trim and Fill method resulted in slightly attenuated but still consistent estimates, suggesting that the observed associations may be influenced by selective publication of studies with significant results. Therefore, while the direction of the association remains supportive of a protective link between greenspace and heat-related mortality, the magnitude of the effect should be interpreted with caution.

4.3. Policy implications and future research direction

To effectively mitigate heat-related mortality, policymakers should prioritize urban planning strategies that incorporate greenspace development to enhance heat resilience, particularly in low-income neighborhoods. Equitable access to greenspaces, such as parks and urban forests, should be ensured, as they provide natural cooling during heatwaves (Li et al., 2024). Policies promoting the creation of shaded zones and expanding urban forestry can reduce temperatures and protect vulnerable populations (Mihalakakou et al., 2023). Public health authorities should conduct health impact assessments for new developments to ensure that greenspace is integrated into urban designs. Additionally, public awareness campaigns are needed to educate communities about the health benefits of greenspace and their role in mitigating heat stress.

Based on the current evidence, future research should focus on several key areas to better understand the relationship between greenspace and heat-related mortality. A primary recommendation is to harmonize methods (e.g., for temperature metrics and greenspace exposure) across studies, moving towards a standardized assessment of exposure that accounts for individual-level heat, although the relationships between heat and health and the nature of greenspace will vary by location and subpopulation. Moreover, future studies should incorporate behavioral factors such as air conditioning usage and its protective roles in urban environments, as it has been shown to significantly reduce heat-related mortality risks (Zanobetti et al., 2013). More refined methods to assess greenspace quality, accessibility, and proximity should be prioritized over simple indices like NDVI (Astell-Burt and Feng, 2022), alongside longitudinal data capturing dynamic changes in greenspace availability, although such assessments are more complex and will not be available for all studies. Additionally, variables such as air pollution should be systematically examined with greenspace indicators, as greenspaces can potentially mitigate the adverse effects of pollution, and due to the relationship between temperature and air pollution (e.g., higher levels of O_3 under conditions of high temperature) yet this relationship was often omitted from the existing studies.

Future research must also broaden its geographical scope, focusing on LMICs and lower income areas in high-income countries (HICs), where populations are disproportionately vulnerable to heat exposure and have limited access to healthcare and greenspace. Investigating differences between urban and rural areas, and performing neighborhood-level analyses that consider socio-economic status and air pollution exposure, will provide critical insights into designing targeted public health interventions. Incorporating behavioral factors, such as daily activity patterns and the use of greenspace, will help to explore how individuals interact with their environments, further clarifying the health benefits of greenspace in mitigating the risks of heat and other environmental stressors. Future studies could place greater emphasis on exploring how greenspace characteristics may be associated with variations in heat-related, cause-specific mortality, particularly in relation to cardiovascular, respiratory, cancer-related, and pregnancy-related outcomes.

4.4. Limitations of the current review

There are several limitations to this review. First, the inclusion of studies was restricted to those published in English, potentially overlooking relevant research published in other languages. Additionally, the databases used for the literature search (e.g., PubMed, Scopus, Web of Science) may not have captured all relevant grey literature or studies published in non-indexed journals, which could have provided further insights. Another limitation is the methodological heterogeneity across studies arising from differences in study design, exposure assessment methods, and outcome measurements that could impacts the overall reliability of the conclusions. Furthermore, the review predominantly included studies from high-income countries, with limited representation from LMICs, could complicate the generalizability of the findings to global populations. The association between heat and mortality can differ dramatically by location and population, and this review did not investigate whether the potential effect modification of greenspace on this association could have similar variation. Finally, we were unable to distinguish the impacts by different types of greenspace.

5. Conclusions

This systematic review and meta-analysis offer the first synthesis of quantitative data examining the relationship between greenspace and heat-related mortality. The findings suggest an association between higher greenspace exposure and reduced all-cause mortality during periods of high temperature. These results contribute to the broader dialogue on urban greening strategies and their potential relevance to addressing heat-related health outcomes. However, the evidence is suggestive and should be interpreted with caution, given the low confidence level determined by the GRADE criteria due to heterogeneity and study limitations. Critical gaps in the literature remain, including the inconsistent effects on cause-specific mortality. The heterogeneity of exposure assessments and methodologies further complicates direct comparisons between studies. Future research should address these gaps by harmonizing temperature metrics, accounting for individual-level exposure, and incorporating more nuanced measures of greenspace, such as proximity, quality, and specific vegetation types. Expanding research in LMICs and lower income areas in HICs, where vulnerable populations are disproportionately affected by heat-related risks, is also critical. As climate change intensifies the frequency and severity of heatwaves and extreme temperatures, developing resilient, green urban environments will be essential to reducing mortality and protecting vulnerable populations worldwide.

Conflicts of interest

No authors report conflicts of interest.

Author contributions

M.M.P., M.B., M.H.E.B., P.D., M.J.Z.S., M.L.B., & T.A.B. conceptualized the study, created the methodology; M.M.P., ICS., M.I.A.B., M.A.I., M.B., & D.S., conducted data curation; M.M.P., I.C.S., M.I.A.B., M.A.I., & M.B., wrote the original draft. M.M.P., & M.J.Z.S. conducted analysis; M.M.P., & I.C.S. created visualizations. All other authors contributed to reviewing and editing.

References:

Alahmad, B., Khraishah, H., Royé, D., Vicedo-Cabrera, A.M., Guo, Y., Papatheodorou, S.I., Achilleos, S., Acquaotta, F., Armstrong, B., Bell, M.L., Pan, S.C., De Sousa Zanotti Stagliorio Coelho, M., Colistro, V., Dang, T.N., Van Dung, D., De' Donato, F.K., Entezari, A., Guo, Y.L.L., Hashizume, M., Honda, Y., Indermitte, E., Íñiguez, C., Jaakkola, J.J.K., Kim, H., Lavigne, E., Lee, W., Li, S., Madureira, J., Mayvaneh, F., Orru, H., Overcenco, A., Ragettli, M.S., Ryti, N.R.I., Saldiva, P.H.N., Scovronick, N., Seposo, X., Sera, F., Silva, S.P., Stafoggia, M., Tobias, A., Garshick, E., Bernstein, A.S., Zanobetti, A., Schwartz, J., Gasparrini, A., Koutrakis, P., 2023. Associations Between Extreme Temperatures and Cardiovascular Cause-Specific Mortality: Results From 27 Countries. Circulation 147, 35–46. https://doi.org/10.1161/CIRCULATIONAHA.122.061832

Alizadeh, M.R., Abatzoglou, J.T., Adamowski, J.F., Prestemon, J.P., Chittoori, B., Akbari Asanjan, A., Sadegh, M., 2022. Increasing Heat-Stress Inequality in a Warming Climate. Earth's Futur. 10. https://doi.org/10.1029/2021EF002488

Anderson, V., Gough, W.A., 2022. Nature-based cooling potential: a multi-type green infrastructure evaluation in Toronto, Ontario, Canada. Int. J. Biometeorol. 66, 397–410. https://doi.org/10.1007/s00484-021-02100-5

Armson, D., Stringer, P., Ennos, A.R., 2012. The effect of tree shade and grass on surface and globe temperatures in an urban area. Urban For. Urban Green. 11, 245–255. https://doi.org/10.1016/j.ufug.2012.05.002

Astell-Burt, T., Feng, X., 2022. Paths through the woods. Int. J. Epidemiol. https://doi.org/10.1093/ije/dyab233

Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C., Walton, H.A., 2014. Epidemiological time series studies of $PM_{2.5}$ and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax 69, 660–665. https://doi.org/10.1136/thoraxjnl-2013-204492

Bolanis, D., Vergunst, F., Mavoa, S., Schmelefske, E., Khoury, B., Turecki, G., Orri, M., Geoffroy, M.C., 2024. Association between greenspace exposure and suicide-related outcomes across the lifespan: A systematic review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2023.167451

Buczyłowska, D., Zhao, T., Singh, N., Jurczak, A., Siry, A., Markevych, I., 2023. Exposure to greenspace and bluespace and cognitive functioning in children – A systematic review. Environ. Res. 222, 115340. https://doi.org/10.1016/j.envres.2023.115340

Bunker, A., Wildenhain, J., Vandenbergh, A., Henschke, N., Rocklöv, J., Hajat, S., Sauerborn, R., 2016. Effects of Air Temperature on Climate-Sensitive Mortality and Morbidity Outcomes in the Elderly; a Systematic Review and Meta-analysis of Epidemiological Evidence. EBioMedicine 6, 258–268. https://doi.org/10.1016/j.ebiom.2016.02.034

Burkart, K.G., Brauer, M., Aravkin, A.Y., Godwin, W.W., Hay, S.I., He, J., Iannucci, V.C., Larson, S.L., Lim, S.S., Liu, J., Murray, C.J.L., Zheng, P., Zhou, M., Stanaway, J.D., 2021. Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the Global Burden of Disease Study. Lancet 398, 685–697. https://doi.org/10.1016/S0140-6736(21)01700-1

Chen, K., Zhou, L., Chen, X., Ma, Z., Liu, Y., Huang, L., Bi, J., Kinney, P.L., 2016. Urbanization level and vulnerability to heat-related mortality in Jiangsu Province, China. Environ. Health Perspect. 124, 1863–1869. https://doi.org/10.1289/EHP204

Choi, H.M., Lee, W., Roye, D., Heo, S., Urban, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Gasparrini, A., Analitis, A., 2022. Effect modification of greenness on the association between heat and mortality: a multi-city multi-country study. EBioMedicine 84.

Cornu, T., Marchal, B., Renmans, D., 2024. How do urban green spaces influence heat-related mortality in elderly? A realist synthesis. BMC Public Health 24, 457. https://doi.org/10.1186/s12889-024-17973-5

Dalton, A.M., Jones, A.P., 2020. Residential neighbourhood greenspace is associated with reduced risk of cardiovascular disease: A prospective cohort study. PLoS One 15, e0226524. https://doi.org/10.1371/journal.pone.0226524

Denpetkul, T., Phosri, A., 2021. Daily ambient temperature and mortality in Thailand: estimated effects, attributable risks, and effect modifications by greenness. Sci. Total Environ. 791, 148373.

Dimitrova, A., Ingole, V., Basagaña, X., Ranzani, O., Milà, C., Ballester, J., Tonne, C., 2021. Association between ambient temperature and heat waves with mortality in South Asia: Systematic review and meta-analysis. Environ. Int. https://doi.org/10.1016/j.envint.2020.106170

Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R.S., Ma, W., Malik, A., Morris, N.B., Nybo, L., Seneviratne, S.I., Vanos, J., Jay, O., 2021. Hot weather and heat extremes: health risks. Lancet. https://doi.org/10.1016/S0140-6736(21)01208-3

Gasparrini, A., 2014. Modeling exposure-lag-response associations with distributed lag non-linear models. Stat. Med. 33, 881–899. https://doi.org/10.1002/sim.5963

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

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A.M., Huber, V., Tong, S., de Sousa Zanotti Stagliorio Coelho, M., Nascimento Saldiva, P.H., Lavigne, E., Matus Correa, P., Valdes Ortega, N., Kan, H., Osorio, S., Kyselý, J., Urban, A., Jaakkola, J.J.K., Ryti, N.R.I., Pascal, M., Goodman, P.G., Zeka, A., Michelozzi, P., Scortichini, M., Hashizume, M., Honda, Y., Hurtado-Diaz, M., Cesar Cruz, J., Seposo, X., Kim, H., Tobias, A., Iñiguez, C., Forsberg, B., Åström, D.O., Ragettli, M.S., Guo, Y.L., Wu, C. fu, Zanobetti, A., Schwartz, J., Bell, M.L., Dang, T.N., Van, D. Do, Heaviside, C., Vardoulakis, S., Hajat, S., Haines, A., Armstrong, B., 2017. Projections of temperature-related excess mortality under climate change scenarios. Lancet Planet. Heal. 1, e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0

Goggins, W.B., Yang, C., Hokama, T., Law, L.S.K., Chan, E.Y.Y., 2015. Using Annual Data to Estimate the Public Health Impact of Extreme Temperatures. Am. J. Epidemiol. 182, 80–87. https://doi.org/10.1093/aje/kwv013

Hamada, S., Ohta, T., 2010. Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. Urban For. Urban Green. 9, 15–24. https://doi.org/10.1016/j.ufug.2009.10.002

Hardin, P.J., Jensen, R.R., 2007. The effect of urban leaf area on summertime urban surface kinetic temperatures: A Terre Haute case study. Urban For. Urban Green. 6, 63–72. https://doi.org/10.1016/j.ufug.2007.01.005

He, F., Wei, J., Dong, Y., Liu, C., Zhao, K., Peng, W., Lu, Z., Zhang, B., Xue, F., Guo, 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.

Higgins, J.P.T., Thompson, S.G., Deeks, J.J., Altman, D.G., 2003. Measuring inconsistency in meta-analyses. BMJ 327, 557–560. https://doi.org/10.1136/BMJ.327.7414.557

Hong, A., Martinez, L., Patino, J.E., Duque, J.C., Rahimi, K., 2021. Neighbourhood green space and health disparities in the global South: Evidence from Cali, Colombia. Heal. Place 72. https://doi.org/10.1016/j.healthplace.2021.102690

Hu, L., Li, Q., 2020. Greenspace, bluespace, and their interactive influence on urban thermal environments. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/ab6c30

Hu, X., Han, W., Wang, Y., Aunan, K., Pan, X., Huang, J., Li, G., 2022. Does air pollution modify temperature-related mortality? A systematic review and meta-analysis. Environ. Res. 210. https://doi.org/10.1016/j.envres.2022.112898

Huang, C., Barnett, A.G., Wang, X., Vaneckova, P., Fitzgerald, G., Tong, S., 2011. Projecting Future heat-related mortality under climate change scenarios: A systematic review. Environ. Health Perspect.

https://doi.org/10.1289/ehp.1103456

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Johnson, P.I., Sutton, P., Atchley, D.S., Koustas, E., Lam, J., Sen, S., Robinson, K.A., Axelrad, D.A., Woodruff, T.J., 2014. The Navigation guide—evidence-based medicine meets environmental health: Systematic review of human evidence for PFOA effects on fetal growth. Environ. Health Perspect. 122, 1028–1039. https://doi.org/10.1289/EHP.1307893

Kalisa, E., Fadlallah, S., Amani, M., Nahayo, L., Habiyaremye, G., 2018. Temperature and air pollution relationship during heatwaves in Birmingham, UK. Sustain. Cities Soc. 43, 111–120. https://doi.org/10.1016/j.scs.2018.08.033

Kephart, J.L., Sánchez, B.N., Moore, J., Schinasi, L.H., Bakhtsiyarava, M., Ju, Y., Gouveia, N., Caiaffa, W.T., Dronova, I., Arunachalam, S., Diez Roux, A. V., Rodríguez, D.A., 2022. City-level impact of extreme temperatures and mortality in Latin America. Nat. Med. 28, 1700–1705. https://doi.org/10.1038/s41591-022-01872-6

Kim, E.J., Kim, H., 2017. Effect modification of individual- and regional-scale characteristics on heat wave-related mortality rates between 2009 and 2012 in Seoul, South Korea. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.03.248

Konarska, J., Uddling, J., Holmer, B., Lutz, M., Lindberg, F., Pleijel, H., Thorsson, S., 2016. Transpiration of urban trees and its cooling effect in a high latitude city. Int. J. Biometeorol. 60, 159–172. https://doi.org/10.1007/s00484-015-1014-x

Kouis, P., Kakkoura, M., Ziogas, K., Paschalidou, A., Papatheodorou, S.I., 2019. The effect of ambient air temperature on cardiovascular and respiratory mortality in Thessaloniki, Greece. Sci. Total Environ. 647, 1351–1358. https://doi.org/10.1016/j.scitotenv.2018.08.106

Kuang, W., Liu, Y., Dou, Y., Chi, W., Chen, G., Gao, C., Yang, T., Liu, J., Zhang, R., 2015. What are hot and what are not in an urban landscape: quantifying and explaining the land surface temperature pattern in Beijing, China. Landsc. Ecol. 30, 357–373. https://doi.org/10.1007/s10980-014-0128-6

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K. V., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A.C., de Lusignan, S., Morawska, L., 2019. The nexus between air pollution, green infrastructure and human health. Environ. Int. https://doi.org/10.1016/j.envint.2019.105181

Li, D., Yuan, J., Kopp, R.E., 2020. Escalating global exposure to compound heat-humidity extremes with warming. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/ab7d04

Li, T., Horton, R.M., Kinney, P.L., 2013. Projections of seasonal patterns in temperature- related deaths for

Manhattan, New York. Nat. Clim. Chang. 3, 717–721. https://doi.org/10.1038/nclimate1902

Li, Y., Svenning, J.C., Zhou, W., Zhu, K., Abrams, J.F., Lenton, T.M., Ripple, W.J., Yu, Z., Teng, S.N., Dunn, R.R., Xu, C., 2024. Green spaces provide substantial but unequal urban cooling globally. Nat. Commun. 2024 151 15, 1–13. https://doi.org/10.1038/s41467-024-51355-0

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. Heal. 6, e484–e495. https://doi.org/10.1016/S2542-5196(22)00117-6

Liu, W., Zhao, H., Sun, S., Xu, X., Huang, T., Zhu, J., 2022. Green Space Cooling Effect and Contribution to Mitigate Heat Island Effect of Surrounding Communities in Beijing Metropolitan Area. Front. Public Heal. 10. https://doi.org/10.3389/fpubh.2022.870403

Liu, X.X., Ma, X.L., Huang, W.Z., Luo, Y.N., He, C.J., Zhong, X.M., Dadvand, P., Browning, M.H.E.M., Li, L., Zou, X.G., Dong, G.H., Yang, B.Y., 2022. Green space and cardiovascular disease: A systematic review with meta-analysis. Environ. Pollut. https://doi.org/10.1016/j.envpol.2022.118990

Marvuglia, A., Koppelaar, R., Rugani, B., 2020. The effect of green roofs on the reduction of mortality due to heatwaves: Results from the application of a spatial microsimulation model to four European cities. Ecol. Modell. 438. https://doi.org/10.1016/j.ecolmodel.2020.109351

Mihalakakou, G., Souliotis, M., Papadaki, M., Menounou, P., Dimopoulos, P., Kolokotsa, D., Paravantis, J.A., Tsangrassoulis, A., Panaras, G., Giannakopoulos, E., Papaefthimiou, S., 2023. Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives. Renew. Sustain. Energy Rev. 180, 113306. https://doi.org/10.1016/J.RSER.2023.113306

Moghadamnia, M.T., Ardalan, A., Mesdaghinia, A., Keshtkar, A., Naddafi, K., Yekaninejad, M.S., 2017. Ambient temperature and cardiovascular mortality: A systematic review and meta-analysis. PeerJ 2017, 3574. https://doi.org/10.7717/peerj.3574

Mueller, W., Milner, J., Loh, M., Vardoulakis, S., Wilkinson, P., 2022. Exposure to urban greenspace and pathways to respiratory health: An exploratory systematic review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2022.154447

OHAT, 2015. Handbook for Conducting a Literature-Based Health Assessment Using OHAT Approach for Systematic Review and Evidence Integration March. Natl. Toxicol. Progr. 1–98.

Pearlmutter, D., Krüger, E.L., Berliner, P., 2009. The role of evaporation in the energy balance of an open-air scaled urban surface. Int. J. Climatol. 29, 911–920. https://doi.org/10.1002/joc.1752

Perry, T., Obolski, U., Peretz, C., 2023. The Association Between High Ambient Temperature and Mortality in the Mediterranean Basin: a Systematic Review and Meta-analysis. Curr. Environ. Heal. Reports. https://doi.org/10.1007/s40572-022-00386-0

Qiu, C., Ji, J.S., Bell, M.L., 2021. Effect modification of greenness on temperature-mortality relationship among older adults: a case-crossover study in China. Environ. Res. 197, 111112.

Rahman, M.A., Stratopoulos, L.M.F., Moser-Reischl, A., Zölch, T., Häberle, K.H., Rötzer, T., Pretzsch, H., Pauleit, S., 2020. Traits of trees for cooling urban heat islands: A meta-analysis. Build. Environ. https://doi.org/10.1016/j.buildenv.2019.106606

Rigolon, A., Browning, M.H.E.M., McAnirlin, O., Yoon, H., 2021. Green Space and Health Equity: A Systematic Review on the Potential of Green Space to Reduce Health Disparities. Int. J. Environ. Res. Public Heal. 2021, Vol. 18, Page 2563 18, 2563. https://doi.org/10.3390/IJERPH18052563

Rojas-Rueda, D., Nieuwenhuijsen, M.J., Gascon, M., Perez-Leon, D., Mudu, P., 2019. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. Lancet Planet. Heal. 3, e469–e477. https://doi.org/10.1016/S2542-5196(19)30215-3

Sanders, T., Feng, X., Fahey, P.P., Lonsdale, C., Astell-Burt, T., 2015. Greener neighbourhoods, slimmer children? Evidence from 4423 participants aged 6 to 13 years in the Longitudinal Study of Australian children. Int. J. Obes. 39, 1224–1229. https://doi.org/10.1038/ijo.2015.69

Schinasi, L.H., Bakhtsiyarava, M., Sanchez, B.N., Kephart, J.L., Ju, Y., Arunachalam, S., Gouveia, N., Teixeira Caiaffa, W., O'Neill, M.S., Dronova, I., Diez Roux, A. V., Rodriguez, D.A., 2023. Greenness and excess deaths from heat in 323 Latin American cities: Do associations vary according to climate zone or green space configuration? Environ. Int. 180. https://doi.org/10.1016/j.envint.2023.108230

Skarbit, N., Unger, J., Gál, T., 2024. Evaluating the Impact of Heat Mitigation Strategies Using Added Urban Green Spaces during a Heatwave in a Medium-Sized City. Sustainability 16, 3296.

Song, J., Gasparrini, A., Fischer, T., Hu, K., Lu, Y., 2023. Effect Modifications of Overhead-View and Eye-Level Urban Greenery on Heat–Mortality Associations: Small-Area Analyses Using Case Time Series Design and Different Greenery Measurements. Environ. Health Perspect. 131, 97007. https://doi.org/10.1289/EHP12589

Song, J., Gasparrini, A., Wei, D., Lu, Y., Hu, K., Fischer, T.B., Nieuwenhuijsen, M., 2024. Do greenspaces really reduce heat health impacts? Evidence for different vegetation types and distance-based greenspace exposure. Environ. Int. 191, 108950. https://doi.org/10.1016/J.ENVINT.2024.108950

Song, J., Lu, Y., 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. 838, 156127.

Song, X., Wang, S., Hu, Y., Yue, M., Zhang, T., Liu, Y., Tian, J., Shang, K., 2017. Impact of ambient temperature on morbidity and mortality: An overview of reviews. Sci. Total Environ. 586, 241–254. https://doi.org/10.1016/j.scitotenv.2017.01.212

Tong, S., Ebi, K., 2019. Preventing and mitigating health risks of climate change. Environ. Res.

https://doi.org/10.1016/j.envres.2019.04.012

Veroniki, A.A., Jackson, D., Viechtbauer, W., Bender, R., Bowden, J., Knapp, G., Kuss, O., Higgins, J.P., Langan, D., Salanti, G., 2016. Methods to estimate the between-study variance and its uncertainty in meta-analysis. Res. Synth. Methods 7, 55–79. https://doi.org/10.1002/jrsm.1164

Visvanathan, G., Patil, K., Suryawanshi, Y., Meshram, V., Jadhav, S., 2024. Mitigating urban heat island and enhancing indoor thermal comfort using terrace garden. Sci. Reports 2024 141 14, 1–14. https://doi.org/10.1038/s41598-024-60546-0

Wang, J., Endreny, T.A., Nowak, D.J., 2008. Mechanistic simulation of tree effects in an urban water balance model. J. Am. Water Resour. Assoc. 44, 75–85. https://doi.org/10.1111/j.1752-1688.2007.00139.x

Woodruff, T.J., Sutton, P., 2014. The navigation guide systematic review methodology: A rigorous and transparent method for translating environmental health science into better health outcomes. Environ. Health Perspect. 122, 1007–1014. https://doi.org/10.1289/EHP.1307175

Wróblewska, K., Jeong, B.R., 2021. Effectiveness of plants and green infrastructure utilization in ambient particulate matter removal. Environ. Sci. Eur. https://doi.org/10.1186/s12302-021-00547-2

Wu, S., Chen, B., Webster, C., Xu, B., Gong, P., 2023. Improved human greenspace exposure equality during 21st century urbanization. Nat. Commun. 14. https://doi.org/10.1038/s41467-023-41620-z

Wu, Y., Li, S., Zhao, Q., Wen, B., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.C., Íñiguez, C., Ameling, C., De la Cruz Valencia, C., Åström, C., Houthuijs, D., Van Dung, D., Royé, D., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., de'Donato, F., Rao, S., Sera, F., Carrasco-Escobar, G., Kan, H., Orru, H., Kim, H., Holobaca, I.H., Kyselý, J., Madureira, J., Schwartz, J., Jaakkola, J.J.K., Katsouyanni, K., Hurtado Diaz, M., Ragettli, M.S., Hashizume, M., Pascal, M., de Sousa Zanotti Stagliorio Coélho, M., Ortega, N.V., Ryti, N., Scovronick, N., Michelozzi, P., Correa, P.M., Goodman, P., Nascimento Saldiva, P.H., Abrutzky, R., Osorio, S., Dang, T.N., Colistro, V., Huber, V., Lee, W., Seposo, X., Honda, Y., Guo, Y.L., Bell, M.L., Guo, Y., 2022. Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study. Lancet Planet. Heal. 6, e410–e421. https://doi.org/10.1016/S2542-5196(22)00073-0

Yan, H., Dong, L., 2015. The impacts of land cover types on urban outdoor thermal environment: the case of Beijing, China. J. Environ. Heal. Sci. Eng. 13. https://doi.org/10.1186/s40201-015-0195-x

Ye, T., Yu, P., Wen, B., Yang, Z., Huang, W., Guo, Y., Abramson, M.J., Li, S., 2022. Greenspace and health outcomes in children and adolescents: A systematic review. Environ. Pollut. 314, 120193. https://doi.org/10.1016/j.envpol.2022.120193

Zafeiratou, S., Samoli, E., Dimakopoulou, K., Rodopoulou, S., Analitis, A., Gasparrini, A., Stafoggia, M., De' Donato, F., Rao, S., Monteiro, A., Rai, M., Zhang, S., Breitner, S., Aunan, K., Schneider, A., Katsouyanni, K., 2021. A systematic review on the association between total and cardiopulmonary mortality/morbidity or cardiovascular risk factors with long-term exposure to increased or decreased ambient temperature. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2021.145383

Zare Sakhvidi, M.J., Yang, J., Mehrparvar, A.H., Dzhambov, A.M., Ebrahimi, A.A., Dadvand, P., Jacquemin, B., 2022. Exposure to greenspace and cancer incidence, prevalence, and mortality: A systematic review and meta-analyses. Sci. Total Environ. 838, 156180. https://doi.org/10.1016/J.SCITOTENV.2022.156180

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.C., Íñiguez, C., Ameling, C., De la Cruz Valencia, C., Åström, C., Houthuijs, D., Dung, D. Van, Royé, D., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., de'Donato, F., Di Ruscio, F., Sera, F., Carrasco-Escobar, G., Kan, H., Orru, H., Kim, H., Holobaca, I.H., Kyselý, J., Madureira, J., Schwartz, J., Jaakkola, J.J.K., Katsouyanni, K., Hurtado Diaz, M., Ragettli, M.S., Hashizume, M., Pascal, M., de Sousa Zanotti Stagliorio Coélho, M., Valdés Ortega, N., Ryti, N., Scovronick, N., Michelozzi, P., Matus Correa, P., Goodman, P., Nascimento Saldiva, P.H., Abrutzky, R., Osorio, S., Rao, S., Fratianni, S., Dang, T.N., Colistro, V., Huber, V., Lee, W., Seposo, X., Honda, Y., Guo, Y.L., Bell, M.L., Li, S., 2021. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. Lancet Planet. Heal. 5, e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4