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Urban Shade Shelter and Reduction in Heat-Related Mortality Across 25 Districts of Seoul, South Korea

Ayoung Kim
Seoul National University
Jisung Choi
Seoul National University
Seohyeon Park
Seoul National University
Cinoo Kang
Seoul National University
Ejin Kim
Seoul National University
Ho Kim
hokim@snu.ac.kr

Seoul National University https://orcid.org/0000-0001-7472-3752

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Abstract

The climate crisis has significantly increased the frequency and intensity of extreme heat events. While the Seoul Metropolitan Government has deployed shade shelters as a key heat adaptation strategy, empirical evidence linking shade shelters to reductions in urban mortality remains limited. This study evaluates the public health impact of Seoul's shade shelter policy on heat-related mortality. We conducted an extended two-stage meta-analysis using daily mortality and temperature data across 25 districts in Seoul from 2017 to 2022. At the first stage, district-specific associations between extreme heat and mortality were estimated using distributed lag non-linear models. Then, at the second stage, meta-regression was employed to assess effect modification by shade shelter density. We further performed counterfactual scenario analysis to quantify the number of deaths averted by the expansion of shelters compared to a hypothetical 2017 baseline. A total of 88,266 deaths were analyzed. Districts with high shade shelter coverage showed attenuated mortality risks during extreme heat compared to low-coverage districts. The protective effect was most pronounced among working-age adults (< 65 years) and for respiratory-related mortality. Counterfactual analysis indicated that the progressive expansion of shelters significantly reduced relative risks over time, whereas risks remained elevated in the static-coverage scenario. Given their cost-effectiveness, rapid deployability, and demonstrated benefits particularly for younger adults, shade shelters represent a practical and scalable adaptation strategy for cooling warming cities.

Introduction

The climate crisis has emerged as a preeminent threat to global public health, characterized by an unprecedented increase in the frequency, intensity, and duration of extreme heat events (1, 2). According to the Intergovernmental Panel on Climate Change (IPCC) AR6 report, it is virtually certain that the scale of recent changes across the climate system is unprecedented over many centuries to millennia (2). In the Western Pacific region, these shifts are particularly alarming; South Korea has observed an annual average temperature increase of approximately 1.6°C over the past 30 years (1991–2020) compared to the early 20th century (1912–1940), a warming rate that significantly exceeds the global average (3).

The health implications of such rapid warming are profound. Heatwaves are established drivers of excess mortality, primarily through the exacerbation of cardiovascular and respiratory diseases (4). The World Health Organization (WHO) emphasizes that heat stress is a leading cause of weather-related death and can trigger severe exhaustion and heatstroke, particularly among vulnerable urban populations (5). In South Korea, heat-related fatalities have become a recurring national crisis, with over 250 deaths recorded in the past decade attributable to extreme heat events [4]. As the "urban heat island" phenomenon intensifies within densely populated metropolises like Seoul, the necessity for robust, evidence-based adaptation strategies has never been more urgent (6). Importantly, urban heat exposure is not uniformly distributed across populations, with pedestrians and individuals with greater outdoor mobility often experiencing disproportionate exposure to extreme heat.

In response, the South Korean government has integrated heat adaptation into its national policy framework, notably through the "The Enhanced 3rd National Climate Crisis Adaptation Plan"(3). A cornerstone of this localized response is the deployment of "shade shelters"—fixed or smart canopy structures installed at pedestrian crossings and traffic islands to provide immediate thermal relief as a street-level climate adaptation strategy within public spaces. Since 2018, Seoul has aggressively expanded this infrastructure to mitigate the direct heat exposure of citizens (3). While microclimatic evidence from field studies indicates that both natural and artificial shade can improve subjective thermal sensation by approximately one point on a 9-point scale and significantly reduce Mean Radiant Temperature (MRT), empirical evidence linking such urban shade infrastructure to actual reductions in population-level mortality remains scarce (7).

This study aims to bridge this critical knowledge gap by evaluating the public health impact of Seoul's shade shelter policy. Utilizing longitudinal data from 2017 to 2022, we analyze the association between shelter density and heat-related mortality across Seoul. Furthermore, we conducted a counterfactual analysis to estimate the extent to which the expansion of shade shelters may have prevented deaths compared with a hypothetical scenario in which shelter coverage remained at 2017 levels.

Methods

Data source

We collected daily mortality data, including total deaths and cause-specific deaths (cardiovascular diseases: ICD-10 I00–I99; respiratory diseases: J00–J99), from the Statistics Korea database from January 1, 2017, to December 31, 2022, in Seoul, South Korea (8). For the same period, we obtained meteorological data, including daily mean temperature (°C) from the Automated Surface Observing System (ASOS) operated by the Korea Meteorological Administration (9). To assess the implementation of heat adaptation strategies, we compiled a comprehensive dataset on "Shade Shelters" (fixed and smart canopies) from the administrative records of the Seoul Metropolitan Government, which included the installation date and geographic coordinates (district-level) for all shelters across the 25 second-level districts of Seoul.

Ethical statement

This study used aggregated national death registry data and public weather records. As the dataset consisted of strictly de-identified and publicly accessible information for research purposes, this study did not require formal informed consent or Institutional Review Board approval under the national ethical guidelines for secondary data analysis.

Study design and exposure definition

This study utilized a time-series design to evaluate the effectiveness of urban shade infrastructure in mitigating heat-related mortality. The primary exposure of interest was extreme heat, defined based on daily mean temperatures. The intervention variable was the number of shade shelters per district. We

categorized the 25 districts of Seoul into two groups based on their shade shelter coverage to compare the protective impacts: the high-coverage group (top 20% of districts by shelter count) and the low-coverage group (bottom 20%) (10).

Statistical modeling

We employed an extended two-stage longitudinal meta-analysis to estimate the association between extreme heat and mortality and to evaluate the potential modification impacts of shade shelters (10).

In the first stage, a time-series analysis was performed for each district. To focus on the impact of extreme heat, the analysis was restricted to the summer months (June to September) from 2017 to 2022. We employed a time-series model with a quasi-Poisson distribution. To account for the non-linear and delayed health impacts of temperature, we used a distributed lag non-linear model (DLNM). The exposure–response relationship was modeled using a natural cubic spline of daily maximum temperature percentiles (knots at the 10th and 90th percentiles), and the lag–response relationship was modeled with a natural cubic spline over a lag period of up to 5 days. The model adjusted for the day of the week and long-term temporal trends (using a natural cubic spline of time with 2 degrees of freedom per period). We divided the study duration into three sub-periods (2017–2018, 2019–2020, and 2021–2022) (10).

In the second stage, we used a multivariate meta-regression to pool district-specific estimates and to examine the effect modification by shade shelters. The meta-predictor, "shade shelter coverage," was defined as the number of shelters installed in each district in each year. To handle potential measurement errors and missing values in the shelter data, we applied a linear mixed-effects model (LME) to predict the smooth trend of shelter expansion using a B-spline of the calendar year with district-specific random intercepts. The final meta-regression model included the predicted shelter density and a natural cubic spline of the year (knots at 2020) as fixed effects, with district-level random effects using a diagonal covariance structure (10).

To quantify the public health benefits of the policy, we performed a counterfactual scenario analysis. We estimated the Relative Risks (RRs) at the 99th percentile of temperature (using the 75th percentile as the centering point). We compared two scenarios: (1) the "Actual trend" scenario, reflecting the real-world expansion of shade shelters from 2017 to 2022; and (2) the "Hypothetical trend constant at 2017 level" scenario, where the number of shade shelters was fixed at 2017 levels. The mortality risk reduction was visualized by plotting the annual RR trends for both scenarios (10).

To assess the robustness of our findings, we conducted several sensitivity analyses by varying the internal knot positions (25th and 75th percentiles) and extending the maximum lag period to 7 days. Additionally, we evaluated the stability of the protective benefit by re-estimating mortality risks the contrast of shade shelter density, comparing the 10th and 90th percentiles of the distribution.

We conducted statistical analysis with R (version 4.0.3; R development Core Team) with the packages “mixmeta”, “nlme”, “survival,” “tsModel” and “splines”.

Results

A total of 88,266 deaths were recorded in Seoul, South Korea, during 2017–2022 (Table 1). Males and females accounted for 57.0% and 43.0% of the total mortality, respectively, while individuals aged 65 years or older represented 76.3% of all cases. Regarding cause-specific mortality, cardiovascular and respiratory diseases accounted for 18.9% and 8.7% of all deaths, respectively.

Between 2017 and 2022, the number of shade shelters increased substantially across all districts; however, their spatial distribution remained heterogeneous (Fig. 1; Supplementary Fig. 1). Districts in the southeastern region consistently exhibited higher coverage of shade shelters, whereas northern and western districts showed relatively lower coverage. This spatial heterogeneity is further illustrated in Supplementary Fig. 1, which shows distinct distribution patterns between conventional fixed shade shelters and smart shade shelters. In addition, Supplementary Fig. 2 indicates that the annual average number of shade shelters increased steadily across districts over the study period. Overall, this expansion pattern suggests both a general scaling of shade shelters and the persistence of inter-district disparities over time.

Fig. 2a illustrates the exposure–response relationship between temperature percentiles and mortality for districts with the lowest (bottom 20%) and the highest (top 20%) shade shelter coverage. In both groups, the association exhibited a non-linear pattern, with RRs referenced at the 75th percentile. Mortality risk increased at higher temperature percentiles, particularly under extreme heat conditions. When stratified by shade shelter coverage, districts with higher coverage showed a slightly attenuated increase in RR at higher temperature percentiles compared to those with lower coverage. This divergence became more pronounced in the upper range of the temperature distribution. However, the 95% confidence intervals (CIs) overlapped across most of the temperature range, indicating that these observed differences should be interpreted with caution.

In the counterfactual analysis, the RRs of mortality under extreme heat conditions declined over time in the observed scenario, which reflected the actual expansion of shade shelters (Fig. 2b). In contrast, under the hypothetical scenario where shelter coverage remained fixed at 2017 levels, the risk reduction was less pronounced. By 2022, a divergence between the two scenarios emerged, with the observed scenario showing a lower RR compared to the fixed-coverage scenario.

Fig. 3 summarizes the RRs under extreme heat conditions across population subgroups. Overall, districts with lower shade shelter coverage exhibited consistently higher RRs compared to those with higher shade coverage. This disparity was more evident among individuals aged <65 years and in cause-specific mortality, particularly for respiratory diseases.

Sensitivity analyses using alternative model specifications—including alternative knot placements, lag structures, and definitions of shade shelter density—yielded consistent results (Supplementary Table 1). The associations remained robust, with broadly similar effect estimates across all specifications. In particular, elevated risks were consistently observed in districts with lower shade shelter coverage, whereas estimates for districts with higher shade shelter coverage were attenuated and did not reach statistical significance.

Discussion

Our findings indicate a potential attenuating impact of urban shade shelters on heat-related mortality, providing a basis for further evaluation of their protective benefits. Across 25 districts of Seoul over six years, we found that districts with higher shade shelter coverage experienced lower mortality during extreme heat compared to those with lower shade shelters; notably, this protective benefit strengthened as the city progressively expanded its shade shelters. The benefit was consistent across multiple mortality outcomes and population subgroups, with working-age adults showing the most pronounced risk reduction. Importantly, our counterfactual analysis revealed that had shelter deployment remained static at 2017 levels, mortality during extreme heat would have been notably higher than observed. These results suggest that ongoing policy investment in shade shelters has likely translated into a tangible reduction in heat-related fatalities.

The reason shade shelters work is that they lower the heat load people experience outdoors. When people walk in direct sunlight, their bodies absorb solar radiation that dramatically increases thermal stress (11, 12). Shade shelters block this incoming radiation, creating cooler local environments where people can move through the city (13, 14). Studies show that shaded areas can improve thermal sensation by about one point on standard comfort scales compared to sun-exposed locations (7). This translates into real physiological benefits: people in shaded environments show reduced heart rate and blood pressure compared to those in direct sun (15). When outdoor temperatures are high, this reduction in physiological stress can prevent the progression from heat discomfort to heat exhaustion or heat stroke (16, 17). The artificial canopies Seoul installed could work as well as natural tree shade in reducing these health risks.

Our findings align with research showing that shade and cooling interventions reduce heat-related deaths at the city level. Multiple studies across different countries have found that areas with more shade coverage show lower mortality during heat events (18-20). A global analysis using data from 830 cities in 53 countries estimated that increasing urban vegetation by 30% could have prevented roughly 1.16 million heat-related deaths worldwide between 2000 and 2019 (21). A health impact study of 93 European cities found that raising tree canopy to 30% could prevent about one-third of deaths linked to urban heat islands (22). Research in Los Angeles showed that increasing tree cover and reflective surfaces could reduce heat-related emergency room visits by 25-50% during moderate heat events (23). What makes our study different is that we directly linked actual built shade shelters to observed mortality data. We used administrative records showing exactly where and when shelters were installed,

rather than satellite estimates or computer models. This provides real-world policy evidence supporting the potential effectiveness of urban shade shelters.

Considering age groups, adults under 65 showed stronger protection from shade shelters than older adults did. This might seem backward since older people are more vulnerable to heat due to weaker temperature regulation and more chronic health problems (18). But vulnerability and exposure are different things. Shade shelters are placed at pedestrian crossings and traffic islands—locations used mainly by working-age people commuting to work, outdoor workers doing their jobs, and people moving through the city during the day (24). Younger adults are more likely to be in these exact outdoor spaces that the shelters protect (25). Older adults, despite being more fragile, tend to spend more time indoors where many have air conditioning (18). Research shows that outdoor workers and people in physically demanding jobs face high risk for heat illness (26). Heat exposure can cause cardiovascular strain, reduced work capacity, and increased injury risk in these groups (27). Younger adults make up most of these outdoor workers (25, 28). The age difference we found likely reflects who is actually outside and exposed to the heat, not a difference in how much the body benefits from shade

The most important finding for policy is that mortality risk decreased as shelter coverage expanded over time. As Seoul added more shelters across its districts, deaths during extreme heat dropped further than they would have if the city had stopped building after 2017. This means each wave of new shelter installations translated into measurable lives saved during the hottest days. Shade shelters are relatively cheap, quick to install, and work without requiring behavior change—people benefit just by walking through them (29). Compared to long-term strategies like planting trees that take years to mature, shade shelters offer a fast way to reduce heat deaths now (23, 30). Urban planning research increasingly recognizes shade shelters as a critical component of heat mitigation policy (11). As extreme heat events become more common due to climate change, cities face urgent pressure to implement rapid cooling strategies (1, 2). Many cities in Asia share Seoul's characteristics: high population density, heavy pedestrian activity, and intense summer heat (6). Evidence suggests that each 0.1 increase in vegetation index can reduce heat-related mortality by 6-10%, showing the power of green and shade shelters (31). Our findings suggest that street-level shade shelters may provide meaningful public health benefits beyond thermal comfort, particularly when implemented at broader urban scale.

This study has some important strengths. First, we used six years of data across all 25 districts of Seoul, which gave us enough variation in both shelter coverage and temperature conditions to detect meaningful differences in mortality. Second, we based the analysis on actual shelter installation records rather than estimated or modeled green space data, which means the exposure measure is grounded in what the city actually built. Third, the counterfactual analysis—asking what would have happened without further investment—also makes the findings easier to interpret from a policy standpoint. However, there are limitations. Because our analysis used district-level data, we cannot say which individual people benefited or how often they used the shelters. Also, we measured shelter coverage simply as the number per district, which does not tell us how accessible or well-placed those shelters were for the people who needed them most.

In conclusion, this study shows that expanding shade shelter shelters in Seoul was associated with fewer heat-related deaths—a pattern that became clearer and stronger as more shelters were installed over time. This benefit was most visible during the hottest days, and most pronounced among working-age adults who spend more time outdoors. Shade shelters are cheap, fast to install, and easy for people to use without any effort on their part. At a time when heat is becoming more dangerous in cities across the world, this kind of simple, street-level shade shelter deserves serious attention as a practical way to protect lives.

Declarations

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Contributors

Conceptualization: Kim A, Choi J. Data curation: Choi J, Kang C. Formal analysis: Kim A, Park S. Funding acquisition: Kim H. Visualization: Kim A, Choi J. Writing – original draft: Kim A, Choi J. Writing – review & editing: Kim H, Choi J, Kang C, Park S, Kim E

Disclosure and Conflict of Interests

The authors declare no conflicts of interest. All authors have read the manuscript, agree that the work is ready for submission to the journal, and accept responsibility for its content

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Table

Table 1
Summary statistics for mortality from 2017 to 2022 between June and September in Seoul, South Korea

Category, n (%)		**No. of Deaths**
Total		88,266
Sex		
	Male	50,314 (57.00)
	Female	37,952 (43.00)
Age (years)		
	< 65	20,898 (23.68)
	≥ 65	67,361 (76.32)
Cause of Deaths		
	Cardiovascular disease (I00–I99)	16,708 (18.93)
	Respiratory disease (J00–J99)	7,654 (8.67)

Figures

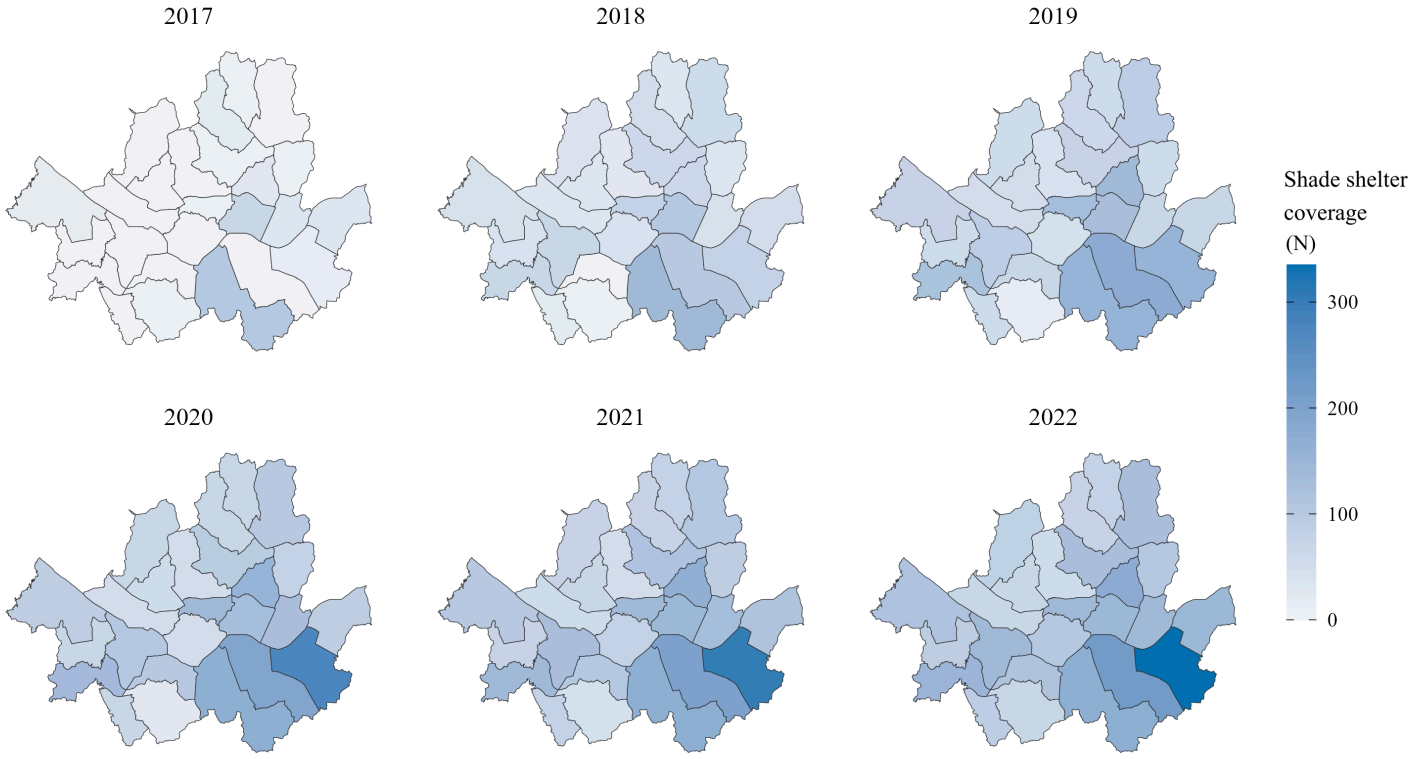
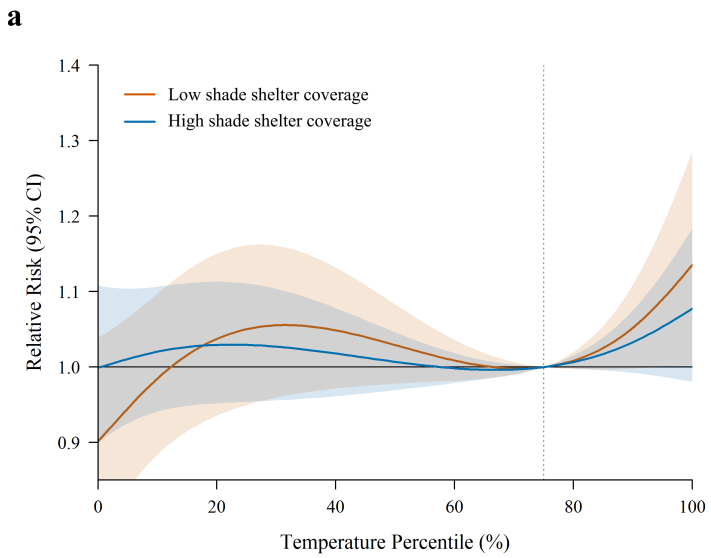


Figure 1

Spatial distribution of shade shelter coverage across 25 districts in Seoul, South Korea, from 2017 to 2022. Each map displays the number of shade shelters (N) installed per district for the respective year. The color gradient indicates shelter density, with darker blue representing higher coverage (up to 300 shelters) and lighter shades indicating lower coverage. The maps demonstrate progressive expansion of shade shelter infrastructure over time, with southeastern districts consistently exhibiting higher coverage compared to northern and western districts



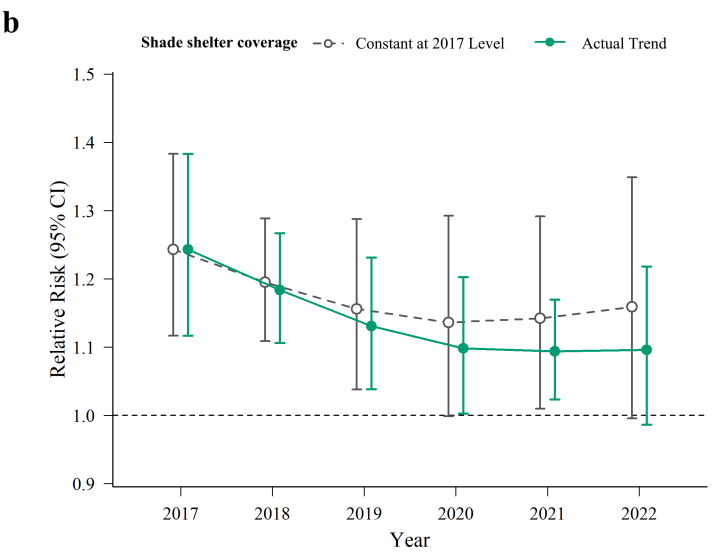


Figure 2

Association between temperature and mortality by shade shelter coverage and temporal trends in heat-related mortality risk. Panel a shows the exposure–response relationship between temperature percentiles and relative risk (RR) of mortality, stratified by low (orange line) and high (blue line) shade shelter coverage districts. The reference point is set at the 75th temperature percentile (vertical dashed line). Shaded areas represent 95% confidence intervals. Panel b presents counterfactual analysis of mortality risk under extreme heat conditions from 2017 to 2022, comparing the actual trend of shade shelter expansion (solid green line with filled circles) versus a hypothetical scenario with shelter coverage constant at 2017 levels (dashed gray line with open circles). Error bars indicate 95% confidence intervals

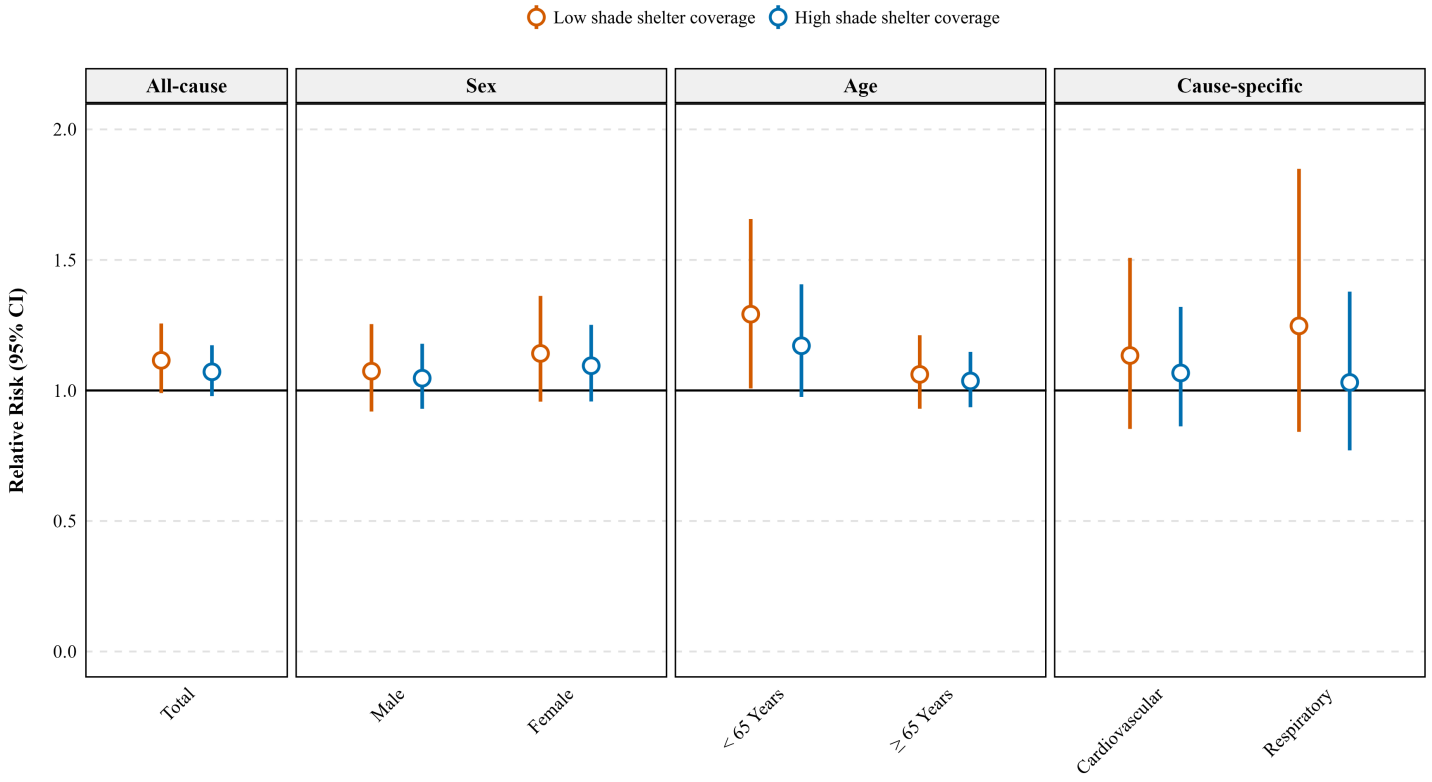


Figure 3

Relative risks of mortality under extreme heat conditions (99th temperature percentile) stratified by shade shelter coverage and population subgroups. Results are presented for all-cause mortality (Total), sex-specific mortality (Male, Female), age-specific mortality (<65 Years, ≥65 Years), and cause-specific mortality (Cardiovascular, Respiratory). Orange markers with error bars represent districts with low shade shelter coverage (bottom 20%), while blue markers represent districts with high shade shelter coverage (top 20%). All relative risks are referenced to the 75th temperature percentile. Error bars represent 95% confidence intervals

Supplementary Files

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- Supplementarymaterial.docx