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Effects of Heat Exposure

Effects of urbanization on vulnerability to heat-related mortality in urban and rural areas in South Korea: a nationwide district-level time-series study

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Abstract

Background: Although urbanization is often an important topic in climate change studies, the complex effect of urbanization on heat vulnerability in urban and rural areas has rarely been studied. We investigated the disparate effects of urbanization on heat vulnerability in urban and rural areas, using nationwide data.

Methods: We collected daily weather data for all 229 administrative districts in South Korea (2011–17). Population density was applied as an urbanization indicator. We calculated the heat-mortality risk using a distributed lag nonlinear model and analysed the relationship with population density. We also examined district characteristics that can be related to the spatial heterogeneity in heat-mortality risk.

Results: We found a U-shaped association between population density and heat-mortality risk, with the highest risk for rural populations; in urban areas, risk increases with increasing population density. Higher heat-mortality risk was associated with a lower number of hospital beds per person and higher percentage of people requiring recuperation. The association between hospital beds and heat-mortality risk was prominent in high-density urban areas, whereas the association between the percentage of people requiring recuperation and heat-mortality risk was pronounced in rural areas.

Conclusions: Our findings indicate that the association between population density and heat-mortality risk is different in urban and rural areas, and that district characteristics related to heat-mortality risk also differ by urbanicity. These results can contribute to understanding the complex role of urbanization on heat vulnerability and can provide evidence to policy makers for prioritizing resources.

Key words: Urbanization, heat, mortality, urban health, urban policy

Key Messages

- We investigated the effects of urbanization on the heat-mortality risk in South Korea, using nationwide time-series data covering all 229 administrative districts over 2011–17.
- We used population density as the urbanization indicator and found a U-shaped association between population density and heat-mortality risk in South Korea; population density was positively associated with heat-mortality risk in urban areas, whereas in rural areas it was negatively associated with heat-mortality risk.
- In the total population, heat-mortality risk showed a negative association with the number of hospital beds per person and a positive association with the percentage of people requiring recuperation.
- The negative association between heat-mortality risk and the number of hospital beds was pronounced in high-density urban areas; in rural areas, the positive association between heat-mortality risk and the percentage of people requiring recuperation was prominent.
- Our findings show the role of population density in heat-mortality risk varied by regional urbanization level and provides epidemiological evidence for urban-rural differentiated heat action plans.

Introduction

Urbanization is a complex process that affects human lifestyles and demographic and social structures[1]; this global phenomenon has continued for decades in both industrialized and non-industrialized countries and is expected to increase in the near future.[2] Thus, numerous studies have focused on the effects of urbanization on human health,[3] and also a considerable number of climate change studies have discussed the current and potential impacts of urbanization on vulnerability related to high temperatures.[4–8]

Interestingly, however, these studies provided conflicting results regarding the effect of urbanization on heat vulnerability. Studies conducted mostly in industrialized countries reported that urban areas have a higher vulnerability to heat than do rural areas, due to the urban heat island phenomenon.[6–10] By contrast, several studies conducted in China reported that the rural population is more vulnerable to heat, and suggested that limited socioeconomic and health resources, such as air conditioning and medical facilities, may be major factors in the higher heat vulnerability in rural areas.[4,5,11] Examining this inconsistency may contribute to a better understanding of the effect of urbanization on heat vulnerability and to establishing effective policies; however, only a few studies addressed this topic.[4,5]

Urbanization is a multifaceted phenomenon with respect to human health. In general, urbanization is associated with higher income, higher education and access to health care and better health conditions, which may reduce heat vulnerability.[12,13] Concurrently, urbanization increases factors that may alter heat-risk, such as urban heat islands, air quality deterioration, income inequality and housing problems.[14,15] Overall, heat vulnerability has multiple interwoven patterns, indicating that the effects of urbanization can be heterogeneous by degree of urbanization and by urbanicity.

We investigated the complex effect of urbanization on heat vulnerability and examined whether it differs between urban and rural areas, using population-based, nationwide time-series data from all 229 districts in South Korea (hereafter, Korea) over a 7-year period. We also investigated whether demographic, medical and social environmental characteristics could partly explain the underlying effect of urbanization on heat vulnerability. To our knowledge, this is the first nationwide study investigating heat vulnerability and the corresponding effects of urbanization in Korea.

Methods

Ethics approval was not required. The dataset used in this study was open to the general public and completely anonymous, without any personal information.

Study area and population

This study included all the second-level basic local authority districts (shi/gun/gu; 229 districts) in Korea, which covered an area of 100 339.5 km^2 and had a population of 51 269 554 in 2016. In 2016, these districts averaged 438.2 km^2 with population of 223 884.5.

Urbanization indicator

We applied population density (persons per km^2) as an indicator of urbanization level in Korea to approximate the urbanization level of districts. More detailed information on the reasons why population density was selected is provided in Supplementary Information 1: Urbanization indicator, available as Supplementary data at *IJE* online). Population density was obtained from the database of community health outcomes and health determinants for every year for the period ranging over 2011–16.[16]

In addition, for each district, we averaged population density across all years of data during the study period and used the results to categorize districts into quintiles of urbanicity. First, 58 districts whose average population densities ranged 19.8–98.3 persons per km^2 (corresponding to the 0–25th percentiles) were categorized as rural areas, and the 171 remaining districts as urban areas. Then, the urban areas were categorized into three levels of urbanicity based on the population density level: low-density urban (57 districts at population density of 98.3–447.3 persons per km^2; 25th–50th percentiles), mid-density urban (57 districts at population density of 447.3–5725.0 persons per km^2; 50th–75th percentiles) and high-density urban areas (57 districts at population density of 5725.0–28 127.8 persons per km^2; 75th–100th percentiles).

Weather and mortality data

We collected population-based time-series data on mortality count and mean temperature for each district daily for the period 2011–17. The data were restricted to the summer, identified as the four warmest months (June to September). Mortality data were obtained from the Korea National Statistics Office, and the temperature data from the real-time modelled data provided by the Korea Meteorological Office. These modelled data were based on numerical weather prediction and statistical models with 5 km × 5 km spatial resolution.[17] Owing to the merging and creation of municipal areas, only two districts had different collection periods (missing some years) for temperature data: Cheongju-shi: 2014–17 Sejong-shi: 2012–17. More detailed information on the temperature data is presented in Supplementary Information 2: Real-time modelled temperature data.

District characteristics

To examine the spatial difference in heat-mortality risk according to the urbanization level, we collected data on five district-level characteristics covering demographics, vegetation and levels of health and medical services: (i) percentage of population that is elderly (age 65 years or more); (ii) percentage of houses that are detached; (iii) EVI (Enhanced Vegetation Index) during the summer (June to September) as an indicator of vegetation; (iv) the number of beds in hospitals per 1000 persons (hereafter, the number of hospital beds); and (v) percentage of people requiring recuperation. In this study, we defined the 'percentage of people requiring recuperation' as the percentage of people who responded yes to the question 'Have you spent almost all day lying down due to illnesses or injuries, within in the past 1 month?'. Detailed information on data collection is provided in Supplementary Information 3: Data collection details, available as Supplementary data at *IJE* online. All indicators were recalculated as the average values during the entire study period, and these average values were used as explanatory variables in the meta-regression.

Confounders

We considered confounding variables that could affect the associations between district characteristics and heat-mortality risk. First, annual GRDP (gross regional domestic product) per capita was collected from the Korea Statistical Information Service [http://kosis.kr] and used as an indicator of the economic level of each district. In addition, the average and range of daily mean summer temperatures were included to represent climatic characteristics. All confounding variables were recalculated as average values across the years of the study period, and these average values were used as confounders in the meta-regression.

Statistical analysis

For all statistical analyses, we used R statistical software (version 4.0.2). We calculated district-specific and pooled heat-related mortality risk (hereafter, heat-mortality risk) via two-stage time-series analysis. In the first stage, we estimated the district-specific summer temperature-mortality association, using a generalized linear model with quasi-Poisson distribution and the distributed lag nonlinear model. Modelling conditions were based on previous studies.[10,18,19] We modelled the cross-basis for exposure with a quadratic B-spline for the summer temperature-mortality association, with two internal knots placed at the 50th and 90th percentiles of the city-specific summer temperature distribution for each sub-period, a natural cubic B-spline for the lag response with an intercept, and two internal knots placed at equally spaced values on the log scale. Ten-day lag periods were selected to capture the delayed effects of heat. The temporal trend within a season was controlled using a natural cubic B-spline of day of the summer season (June to September) within a year with equally spaced knots and four degrees of freedom (df). The day of the week was also adjusted as a categorical variable.

In the second stage, we conducted a meta-analysis using a random intercept to obtain the district-specific best linear unbiased predictor (BLUP) and identified the minimum mortality temperature for each district using the BLUPs.[20] We defined the heat-mortality risk based on the relative risk (RR) of mortality for the 99th percentile of the summer temperature distribution based on the temperature distribution across all districts versus the minimum mortality temperature.[18] In addition, using the meta-regression with sub-area indicator variables (i.e. four levels of urbanicity), we calculated the pooled heat-mortality risk separately for the entire study area and for each of the four levels of urbanicity.

Population density and heat-mortality risk

To examine the possibility that population density was nonlinearly associated with heat-mortality risk, we estimated the nonlinear relationship between population density and heat-mortality risk using meta-regression with a spline function. We applied log-transformation for population density in consideration of the right-skewed distributions of population density. A natural cubic spline with three internal knots placed at equally spaced values (25th, 50th, and 75th percentages of each indicator) was used in the model.

Meta-regression for district characteristics

We examined whether the heat-mortality risk was associated with district characteristics (demographics, vegetation and levels of health and medical services) across the total study area and whether this association was heterogeneous among levels of urbanicity. District characteristics were considered simultaneously in the meta-regression models, and all confounders were adjusted in all the meta-regression models. The meta-regression model was performed separately for the total study area (i.e. all districts) and for each level of urbanicity. All associations between district characteristics and heat-mortality risk were presented as a percentage change in RR per interquartile range increase in each district characteristic.

Sub-population and sensitivity analysis

As sub-population analyses, we conducted the same analyses, stratified by sex, age group (age 65+ years, 0–64 years) and causes of death (cardiovascular, respiratory and others). The International Classification of Disease 10th Revision (ICD-10) was used to classify the causes of death (cardiovascular: I00–I99 and respiratory: J00–J99). In addition, for the total population, several sensitivity analyses were performed to examine whether our results were consistent with the modelling specifications (lag period, flexibility of heat-mortality association, and seasonality and long-term trend adjustments), definition of heat-mortality risk, potential outliers and a different classification of urbanicity (districts with population densities within the 0–33.3th/33.3th–66.7th/66.7th–100th percentiles). Details on the sensitivity analysis are presented in the Supplementary Information 4: Sensitivity analysis, available as Supplementary data at *IJE* online.

Results

A total of 590 639 deaths occurred in Korea during the study period. Of these, 493 911 and 96 728 deaths occurred in the urban districts (those with population density above the 25th percentile) and rural districts (those with population density below the 25th percentile), respectively. Figure 1 shows the geographical distributions of the four levels of urbanicity, daily mortality count (median) and average summer temperatures. Table 1 summarizes the descriptive statistics for district characteristics and confounders for the total study area and by the four levels of urbanicity.

Figure 2 shows the nonlinear relationship between population density and the heat-mortality risk in the total population. A nearly ‘U-shaped’ association between population density and the heat-mortality risk was estimated, although a decrease in risk was observed in some districts in mid- or high-density urban areas. The U-shaped curve, together with confidence intervals (CI) and corresponding sub-population results by urbanicity, age group, sex and causes of death, are shown in Supplementary Figures S1–S3, available as Supplementary data at *IJE* online. In addition, the association between the number of hospital beds and population density showed a nearly opposite pattern compared with the association between heat-mortality risk and population density (Supplementary Figure S4, available as Supplementary data at *IJE* online).

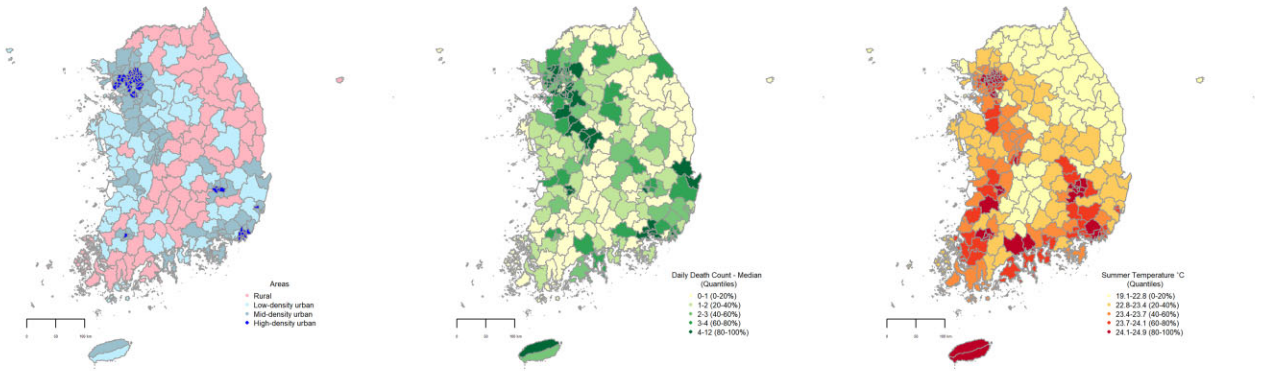

Figure 1 Geographical distributions of urban and rural districts (left), median value of daily mortality count (mid), and average summer temperatures (right) in South Korea during the period 2011–2017.

Table 1 Descriptive statistics district characteristics and confounders; values: median value (10th and 90th percentage of variables; p10, p90)

		Total (229 districts)	Rural (58 districts)	Low-density (57 districts)	Mid-density (57 districts)	High-density (57 districts)
Regional indicators	% population that is elderly	14.2 (9.0, 28.8)	27.8 (20.1, 31.5)	19.1 (12.1, 26.7)	10.4 (7.0, 14)	11.4 (8.9, 15.5)
	% houses that are detached	44.9 (21.8, 83.1)	80.0 (63.2, 86.7)	58.0 (38.7, 78.0)	32.0 (17.7, 41.8)	31.7 (17.1 ,47)
	Enhanced Vegetation Index (EVI)	4.6 (2.5, 5.2)	5.1 (4.9, 5.3)	4.8 (4.5, 5.1)	4.3 (3.4, 4.7)	2.7 (1.6, 3.4)
	Number of beds in hospitals (per 1000 persons)	11.5 (4.9, 22.4)	9.4 (2.6, 21.3)	14.7 (5.4, 27.6)	12.2 (7.3, 21.6)	10.3 (5.8, 21.9)
	% people requiring recuperation	5.2 (3.5, 7.0)	4.4 (2.9, 6.6)	4.8 (3.3, 6.8)	5.4 (4.3, 6.8)	6.3 (4.8, 7.7)
Confounders	GRDP (gross regional domestic product) per capita	22.5 (13.5, 51.2)	22.1 (16.4, 33.7)	25.5 (17.6, 56.7)	24.3 (14.4, 68.6)	17.2 (8.9, 53.0)
	Average summer temperature (°C)	23.5 (22.1, 24.4)	22.6 (21.2, 23.5)	23.3 (22.5, 24.0)	23.7 (23.0, 24.3)	24.1 (23.6, 24.7)
	Range of daily mean summer temperatures (°C)	17.7 (16.1, 18.7)	17.1 (15.4, 18.7)	17.5 (15.7, 18.3)	17.9 (16.3, 18.8)	18.4 (16.2, 18.9)

Elderly: people aged ≥65 years. Percentage of people requiring recuperation: the percentage of people who responded 'Yes' to the question 'Have you spent almost all day lying down due to illnesses or injuries, within in the past 1 month?'.

The pooled relative risk (RR) for heat-related mortality (mortality risk at the 99% of the summer temperature vs mortality risk at the minimum mortality temperature) across the country was 1.14 (95% CI: 1.10, 1.18) for the total population. The central RR estimate was higher among people age >65 years (RR: 1.15) than those aged 0–64 years (RR: 1.12) and higher for females (RR: 1.18) compared with males (RR: 1.08). Figure 3 shows the pooled RRs by urbanicity for the total population and by age group and sex. The heat-mortality risk was generally lowest in the mid-density urban areas, and the estimated risk pattern for each level of urbanicity generally supported the U-shaped association displayed in Figure 2. The lag-distributed associations between heat and mortality by urbanicity are displayed in Supplementary Figure S5, available as Supplementary data at *IJE* online; the heat-mortality risk was the highest at lag 0–1 days across all areas.

Table 2 provides the associations between district characteristics and the heat-mortality risk for the total population and by urbanicity. For overall results representing the entire area, a higher number of hospital beds was associated with lower heat-mortality risk, and a higher percentage of people requiring recuperation was associated with higher heat-mortality risk. On the other hand, the associations between district characteristics and heat-mortality risk varied according to urbanicity. In rural areas, the positive association between heat-mortality risk and percentage of people requiring recuperation was more pronounced than the overall estimate of the entire nation (based on the central estimates). In the high-density urban areas, the negative association between the number of hospital beds and

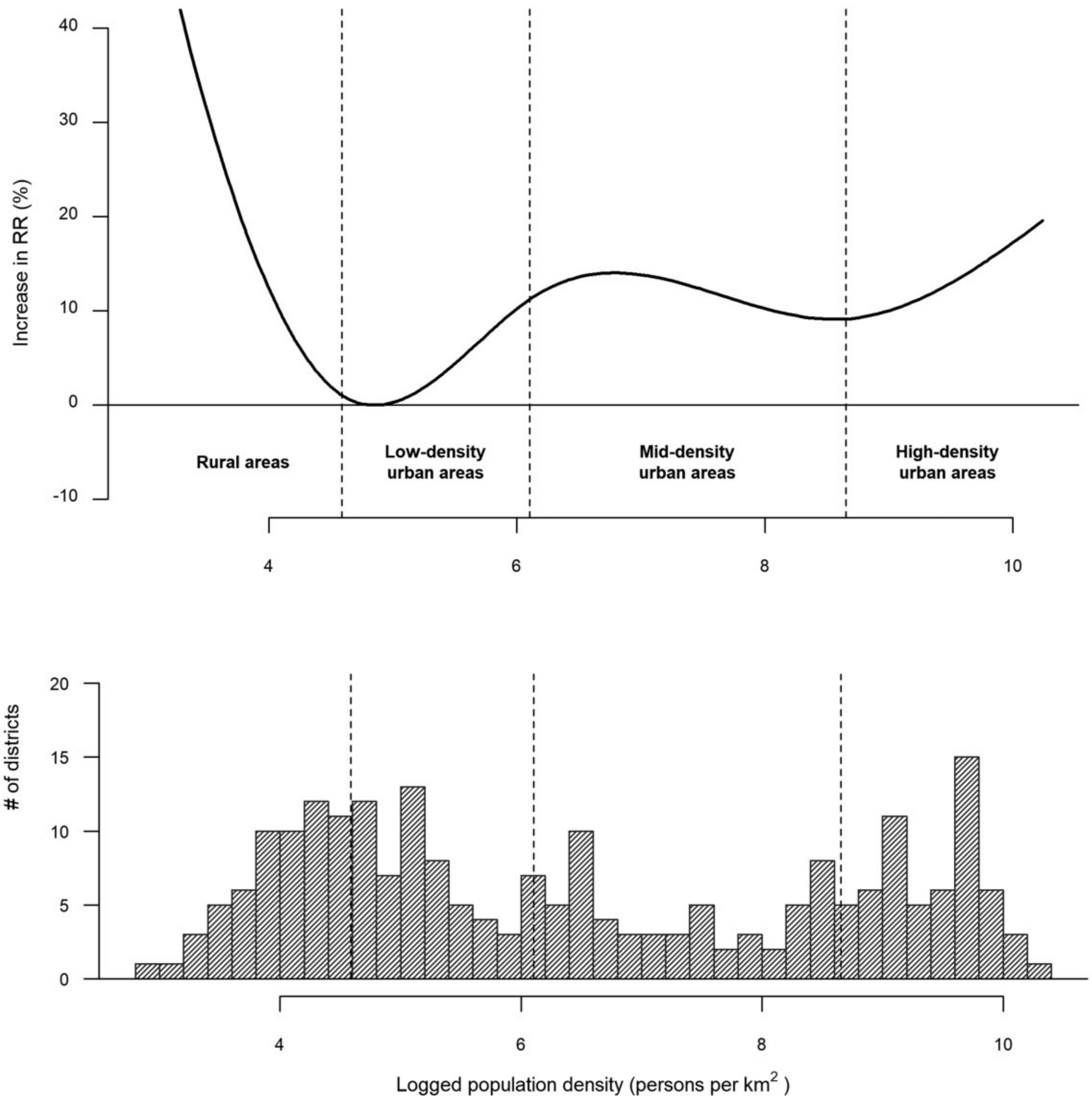

Figure 2 Nonlinear association between population density and heat-mortality risk. Percentile changes in the heat-mortality risk (relative risk of heat; Heat-RR) per one increase in log-population density. The heat-related mortality risk refers to the mortality risk at 99% of the summer temperature vs mortality risk at the minimum mortality temperature. The histogram indicates the number of districts in each category.

heat-mortality risk was more evident than in the total areas (based on the central estimates).

The associations between district characteristics and heat-mortality risk by age group (0–64 years and 65+ years) and sex for the total study area are displayed in Table 3. The positive association between heat-mortality risk and percentage of people requiring recuperation occurred in people age 65+ years. Females showed the negative association between heat-mortality risk and the number of hospital beds. Results by urbanicity that correspond with the results in Table 2 are presented in Supplementary Table S1, available as Supplementary data at *IJE* online. In addition, the cause-specific relationship between district characteristics and heat-mortality risk is reported in Supplementary Table S2, available as Supplementary data at *IJE* online; the negative association with the number of beds in hospitals was observed in cardiovascular disease deaths and in non-cardiorespiratory disease, based on the central estimates.

In addition, based on the directionality of association with heat-mortality risk, the results of our sensitivity analysis (Supplementary Tables S3–S5, available as Supplementary data at *IJE* online) were generally robust with respect to the modelling specifications, definition of heat-mortality risk, potential outliers and criteria of urbanicity classification.

Discussion

In this study, we investigated the effect of urbanization on heat-related mortality risk using high spatial resolution data covering all administrative districts in Korea. We

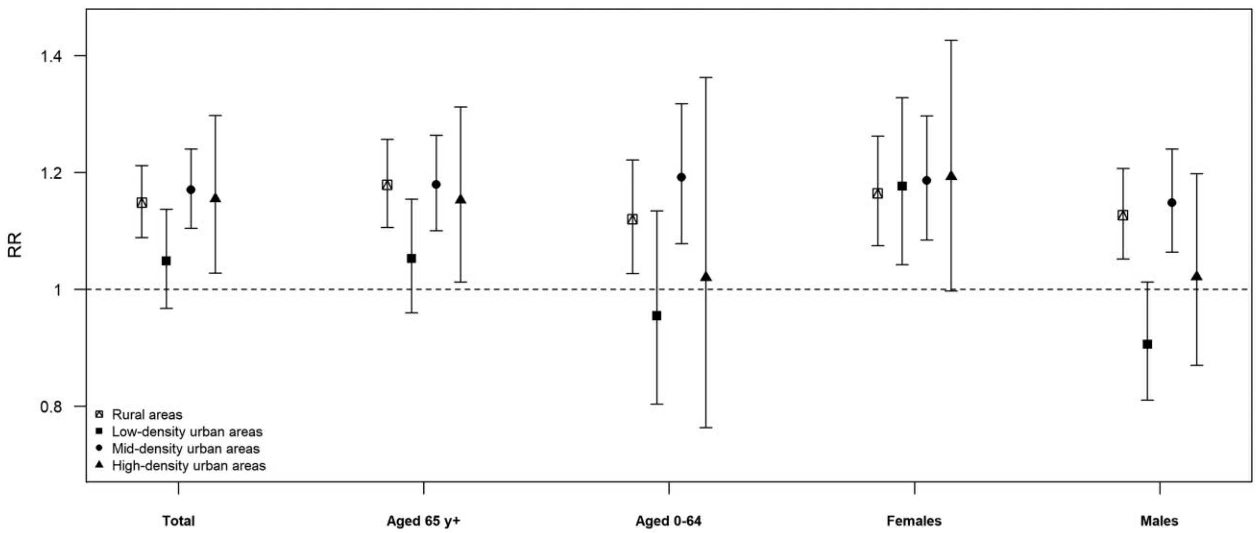

Figure 3 Pooled heat-mortality risks (relative risks; RRs) for the total and sub-population by urbanicity. The heat-related mortality risk refers to the mortality risk at the 99% of the summer temperature vs mortality risk at the minimum mortality temperature. Quintiles of urbanicity: rural areas (58 districts) with the average population density 19.8–98.3 persons/km^2 (corresponding to 0th–25th percentiles), low-density urban (57 districts) with the average population density of 98.3–447.3 persons/km^2 (25th–50th percentiles), mid-density urban (57 districts) with average population density 447.3–5725.0 persons/km^2 (50th–75th percentiles) and high-density urban areas (57 districts) with average population density of 5725.0–28127.8 persons/km^2 (75th–100th percentiles).

Table 2 Associations between district characteristics and heat-related mortality risk for the total population and by urbanicity

	Total (229 districts)	Rural (58 districts)	Low-density (57 districts)	Mid-density (57 districts)	High-density (57 districts)
% population that is elderly	−6.1 (−20.8, 11.2)	4.2 (−56.8, 151.2)	−0.4 (−44.9, 80.0)	−31.8 (−54.5, 2.1)	5.9 (−33.5, 68.9)
% houses that are detached	8.4 (−7.7, 27.3)	51.0 (−50.6, 361.2)	17.6 (−40.5, 132.2)	23.7 (−12.2, 74.3)	−8.1 (−28.4, 17.8)
Enhanced Vegetation Index (EVI)	−0.6 (−7.8, 7.3)	36.7 (−54.3, 308.8)	27.6 (−28.4, 127.6)	2.9 (−15.6, 25.5)	−11.4 (−24.5, 4.0)
Number of beds in hospitals (per 1000 persons)	−5.3 (−9.8, −0.6)	−9.9 (−23.4, 6.0)	−6.6 (−16.2, 4.1)	4.8 (−6.4, 17.4)	−10.4 (−19.2, −0.6)
% people requiring recuperation	6.2 (0.2, 12.6)	33.8 (10.0, 62.8)	12.6 (−1.0, 28)	6.9 (−4.8, 20.1)	−5.1 (−13.8, 4.4)

Elderly: people aged ≥65 years. Percentage of people requiring recuperation: the percentage of people who responded 'Yes' to the question 'Have you spent almost all day lying down due to illnesses or injuries within in the past 1 month?'.

All associations between district characteristics and heat-mortality risk were presented as a percentage change in RR per interquartile range increase in the district characteristics, where heat-related mortality risk refers to the mortality risk at the 99% of the summer temperature vs mortality risk at the minimum mortality temperature; values: a percentage change in RR (95% confidence interval).

found a U-shaped association between population density and heat-mortality risk, with the highest risk for rural populations, and then within urban areas increasing risk with increasing population density. In the entire population, a lower number of hospital beds and higher percentage of people requiring recuperation were associated with higher heat-mortality risk. The association with number of hospital beds was evident in high-density urban areas, whereas that with higher percentage of people requiring recuperation was prominent in the rural areas.

The major finding of this study, the U-shaped association between population density and heat-mortality risk (i.e. the heat-mortality risk generally increased with higher urbanicity in urban areas; however, in rural areas, it increased with lower urbanicity) can partly explain the conflicting results of previous studies. Previous studies conducted in urban cities (mostly in industrialized countries) showed that higher heat-mortality risk was associated with increasing urbanicity.[9,21,22] By contrast, studies conducted in China reported that rural counties had higher

Table 3 Associations between district characteristics and heat-mortality risk in the total population by sub-populations for age and sex

	People aged 65+ years	People aged 0–64 years	Females	Males
% population that is elderly	−0.4 (−18.4, 21.5)	−27.3 (−46.5, −1.3)	−2.5 (−24.5, 25.8)	−14.5 (−31.8, 7.2)
% houses that are detached	1.0 (−16.5, 22.1)	21.5 (−7.5, 59.5)	5.0 (−17.7, 33.9)	15.1 (−6.7, 41.8)
Enhanced Vegetation Index (EVI)	−2.9 (−11.2, 6.1)	0.6 (−12.4, 15.5)	−7.0 (−17.0, 4.1)	2.7 (−7.2, 13.7)
Number of beds in hospitals (per 1000 persons)	−4.0 (−9.3, 1.6)	−6.0 (−14.9, 3.8)	−7.9 (−14.4, −0.8)	−3.1 (−9.4, 3.6)
% people requiring recuperation	8.4 (1.2, 16.0)	−3.1 (−12.6, 7.4)	1.8 (−6.7, 11.2)	5.3 (−2.6, 13.9)

Elderly: people aged ≥65 years. Percentage of people requiring recuperation: the percentage of people who responded 'Yes' to the question 'Have you spent almost all day lying down due to illnesses or injuries within in the past 1 month?'.

All associations between district characteristics and heat-mortality risk were presented as a percentage change in RR per interquartile range increase in the district characteristics, where heat-related mortality risk refers to the mortality risk at the 99% of the summer temperature vs mortality risk at the minimum mortality temperature; values: a percentage change in RR (95% confidence interval).

heat-mortality risk than did urban areas, under conditions of lower levels of educational attainment and lower levels of medical infrastructure that can be interpreted as major characteristics of the lower urbanicity.[4,5] We conjecture that these seemingly conflicting findings of existing studies might be attributed to the different urbanization levels of each study area, and our findings suggest that the influence of urbanization on heat-related mortality are not uniform and may depend on the degree of regional urbanicity. Additional research should further explore the heat-mortality association in relation to urbanicity including different types of urbanicity and urban/rural characteristics.

Our results reveal that a lower number of hospital beds per population was associated with higher heat-mortality risk, and that this association was more evident in high-density urban areas. Moreover, we found that the hospital bed accessibility declined with population density in rural areas and also within the high-density urban areas (see Supplementary Figure S5). In particular, despite high-density urban areas (i.e. metropolitan areas) generally having a higher absolute number and higher quality of medical infrastructures than other areas, they also have lower accessibility to hospital beds, resulting in a trade-off of the benefits of these urban areas. We speculate that a similar paradoxical phenomenon may occur in other industrialized countries with a high concentration of the population in metropolitan areas. In addition, although previous studies suggested that the heat island phenomenon was the major factor affecting the higher heat vulnerabilities in urban areas,[7,8,21] our results indicate that limited medical infrastructure in highly urbanized areas may contribute to the higher heat risk in urban areas.

Our study found that links between district characteristics and heat vulnerability were heterogeneous across levels of urbanicity. In particular, the association between heat-mortality risk and the percentage of people requiring recuperation was pronounced in rural areas, compared with the entire areas. We postulate that this result may relate to the population and socioeconomic characteristics in less urbanized areas. Along with steep depopulation due to rapid urbanization, the percentage of the elderly population in Korean rural areas has increased rapidly over recent decades,[23] and thus the poor health conditions of the rural elderly have been recognized as an important social problem in Korea.[23,24] Moreover, rural or low-density urban areas have medical infrastructures that are generally poorer than metropolitan areas.[25] Therefore, the average baseline health level of individuals may be more importantly related to heat vulnerability in less urbanized areas, having a different impact than in more urbanized areas, although this should be investigated further.

Furthermore, we found vegetation level and heat-mortality risk in high-density urban areas to be negatively associated, and this relationship was more pronounced in the elderly population (see Supplementary Table S1). These results are consistent with previous studies reporting that the urban vegetation is associated with reduced heat in urban areas,[26–28] and thus we infer that this advantage may be related to the beneficial effect of vegetation on heat-mortality risk in high-density areas. Meanwhile, previous studies reported that living in apartments may lead to increased social isolation, and thus living in houses that are detached may be more beneficial for reducing heat vulnerability.[29,30] However, we observed no apparent relationship between residence in houses that are detached and heat-mortality risk, which may imply that medical accessibility and individual health level may be more strongly associated with heat vulnerability than residence type in Korea. Moreover, apartments are the most common and preferred housing type in Korea, and also associated with higher income and more educational and medical facilities.[31] Thus, housing type (e.g. detached house, apartment) has complex links to various socioeconomic and health-related factors, as well as social isolation. Therefore, we recommend future studies with more differentiated and detailed indicators to investigate the complex relationships of housing type, social isolation and socioeconomic disparities with heat vulnerability in Korea.

The association between district characteristics and heat-related mortality risk differed by age groups; the relationship between heat-mortality and the percentage of people requiring recuperation was observed in the older group. We speculate that these results may be associated with a generally poorer health condition and higher heat vulnerability in the elderly group than in the younger group. The district characteristics related to heat-mortality risk were also heterogeneous by sex. In particular, the association between the number of hospital beds and heat-mortality risk was evident only in females. We postulate that the higher proportion of females in the elderly population (national sex ratio: 72.7)[31] and the higher heat vulnerability of females were linked to the result; however, further studies are required. Finally, unlike other causes of death, respiratory disease mortality did not show a positive association between heat-mortality risk and population density in urban areas, and it only showed a negative association between population density and heat-mortality risk in rural areas. We conjecture that the cause-specific results might be associated with the different characteristics of the rural population including different industries (e.g. agriculture). Previous studies reported that rural residents have been exposed to moulds, dust, animal products and pesticides more frequently than urban residents, and the higher exposures affect the higher vulnerability to respiratory disease in the rural population.[32,33] Our data also showed that the percentage of respiratory disease mortality was higher in rural areas (11.0%) than in high- or mid-density urban areas (5.7-8.3%), unlike the percentage of cardiovascular disease mortality which was consistent across all areas (rural: 21.4% and high- or mid-density urban: 20.2-20.4%).

Several limitations of this study should be acknowledged. First, although we consider different levels of urbanicity, future work should investigate more detailed characteristics of rural and urban environments, including how urban settings impact on the heat island effect. In addition, owing to data limitations, we could not consider air conditioner prevalence, which could influence heat-mortality risk. However, because the prevalence of air conditioning in Korea is high across all areas (prevalence of 78% for the nation and 74% for Seoul in 2013),[34] there is a possibility that regional variation in air conditioner prevalence might not be highly influential. Nevertheless, these possible factors should be explored in future studies.

Despite these limitations, our findings have important implications for current and future studies and public health interventions. The main contribution of this study is the evidence on the effect of urbanization on heat-mortality risk using high spatial resolution nationwide data. We found a U-shaped association between population urbanicity and heat-mortality risk, and the availability of medical facilities in rural and metropolitan areas may play an important role to reduce heat-mortality risk. This evidence supports the theory of higher heat-mortality risk in urban areas than in rural areas, along with the urban heat island which has been suggested as the major factor of the higher heat-mortality risk in urban areas by the previous studies.[7,9,35] With respect to policy, our findings suggest that area-specific public health interventions may be more effective if they are developed with consideration of urbanicity, and that a given policy (e.g. heat warning system) may be more effective in some areas than others as the influence of heat on mortality differs by level of urbanicity. Specifically, the impact of heat on mortality was highest in the most rural areas, and secondly in high-density urban areas (see Figure 2), suggesting the potential for multiple mechanisms and pathways through which heat affectscts health. In metropolitan areas, administrative supports to increase the availability of medical resources and green spaces may be effective in reducing the heat vulnerability of their population; in rural areas, policy supports for enhancing individual health (e.g. expanding rural health care providers) could be important to mitigate heat vulnerability.

In conclusion, this nationwide study provides evidence on the complex effects of urbanization on heat vulnerability in Korea. Our results can help policy makers prioritize resources to provide area-customized heat action plans and urban development policies. In a rapidly changing climate, our study also may provide implications for climate change response strategies in industrialized countries dealing with a population concentrated in urban areas, as well as for non-industrialized countries as they experience rapid urbanization.

Supplementary Data

Supplementary data are available at *IJE* online.

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Author contributions

WL conceived the idea, designed the research, analysed data and wrote the paper. MC collected and analysed data and wrote the paper. MB and KE reviewed and revised all parts of the manuscript. CK, JJ, IS and YK contributed to data collection. HK supported and counselled all processes of this study.

Conflict of interest

None declared.

References

1. United Nations (UN). *World Urbanization Prospects: The 2018 Revision.* New New ork, NY: United Nations, Department of Economic and Social Affairs, Population Division, 2018.
2. Organisation for Economic Cooperation and Development (OECD). *Competitive Cities in the Global Economy*. Paris: Organisation for Economic Cooperation and Development, 2006.
3. World Health Organization (WHO). *Global Report on Urban Health: Equitable Healthier Cities for Sustainable Development*. Geneva: World Health Organization, 2016.
4. Hu K, Guo Y, Hochrainer-Stigler S *et al.* Evidence for urban–rural disparity in temperature–mortality relationships in Zhejiang Province, China. *Environ Health Perspect* 2019;**127**:37001.
5. Chen K, Zhou L, Chen X *et al.* Urbanization level and vulnerability to heat-related mortality in Jiangsu Province, China. *Environ Health Perspect* 2016;**124**:1863–69.
6. Hajat S, Kosatky T. Heat-related mortality: a review and exploration of heterogeneity. *J Epidemiol Community Health* 2010; **64**:753–60.
7. Hajat S, Kovats RS, Lachowycz K. Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 2007;**64**:93–100.
8. Gabriel KM, Endlicher WR. Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 2011;**159**:2044–50.
9. Anderson BG, Bell ML. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology* 2009;**20**:205–13.
10. Lee W, Ebi KL, Kim Y *et al.* Heat-mortality risk and the population concentration of metropolitan areas in Japan: a nationwide time-series study. *Int J Epidemiol* 2021;**50**:602–12.
11. Zeng W, Lao X, Rutherford S *et al.* The effect of heat waves on mortality and effect modifiers in four communities of Guangdong Province, China. *Sci Total Environ* 2014;**482-3**: 214–21.
12. Kamal-Chaoui L. and Robert A. (eds.) "Competitive cities and climate change", *OECD Regional Development Working Papers N° 2, 2009*, Paris, France: OECD publishing, 2009.
13. Kamal-Chaoui L, Sanchez-Reaza J. Urban trends and policies in OECD countries. In: *Organisation for Economic Cooperation and Development (OECD) Regional Development Working Papers, Paris, France*, 2012.
14. Chen G, Glasmeier AK, Zhang M, Shao Y. Urbanization and income inequality in post-reform China: a causal analysis based on time series data. *PloS One* 2016;**11**:e0158826.
15. Calì M. *Urbanization, Inequality and Economic Growth: Evidence from Indian States and Towns*. Washington: World Bank, 2008.
16. Kim D, Jeong J, Ko Y, Kwon Y, Kim Y. The construction of database of community health outcomes and health determinants in the Republic of Korea. *Public Health* Wkly Rep KCDC 2018;11:979–83.
17. Jang J, Lee W, Choi M, Kang C, Kim H. Roles of urban heat anomaly and land-use/land-cover on the heat-related mortality in the national capital region of South Korea: a multi-districts time-series study. *Environ Int* 2020;**145**:106127.
18. Gasparrini A, Guo Y, Hashizume M *et al.* Temporal variation in heat–mortality associations: a multicountry study. *Environ Health Perspect* 2015;**123**:1200–07.
19. Lee W, Choi HM, Kim D, Honda Y, Guo Y-LL, Kim H. Temporal changes in mortality attributed to heat extremes for 57 cities in Northeast Asia. *Sci Total Environ* 2018;**616–17**: 703–09.
20. Chung Y, Yang D, Gasparrini A *et al.* Changing susceptibility to non-optimum temperatures in Japan, 1972–2012: the role of climate, demographic, and socioeconomic factors. *Environ Health Perspect* 2018;**126**:057002.
21. Sera F, Armstrong B, Tobias A *et al.* How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *Int J Epidemiol* 2019;**48**:1101–12.
22. Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occup Environ Med* 2007;**64**: 827–33.
23. Jang I-Y, Jung H-W, Lee CK *et al.* Rural and urban disparities in frailty and aging-related health conditions in Korea. *J Am Geriatr Soc* 2016;**64**:908–11.
24. Kim IK, Liang J, Rhee K-O, Kim C-S. Population aging in Korea: changes since the 1960s. *J Cross Cult Gerontol* 1996;**11**:369–88.
25. Kang C, Park C, Lee W *et al.* Heatwave-related mortality risk and the risk-based definition of heat wave in South Korea: a nationwide time-series study for 2011–2017. *Int J Environ Res Public Health* 2020;**17**:5720.
26. Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 2001;**70**:295–310.
27. Son J-Y, Lane KJ, Lee J-T, Bell ML. Urban vegetation and heat-related mortality in Seoul, Korea. *Environ Res* 2016;**151**: 728–33.

28. Susca T, Gaffin SR, Dell'osso GR. Positive effects of vegetation: urban heat island and green roofs. *Environ Pollut* 2011;**159**: 2119–26.
29. Vandentorren S, Bretin P, Zeghnoun A *et al.* August 2003 heat wave in France: risk factors for death of elderly people living at home. *Eur J Public Health* 2006;**16**:583–91.
30. Kilbourne EM, Choi K, Jones TS, Thacker SB. Risk factors for heatstroke: a case-control study. *JAMA* 1982;**247**: 3332–36.
31. Korean Population Census. *Korean Population Census 2015*. Seoul: Statistics Korea, 2015.
32. Gomez MI, Hwang SA, Lin S, Stark AD, May JJ, Hallman EM. Prevalence and predictors of respiratory symptoms among New York farmers and farm residents. *Am J Ind Med* 2004;**46**:42–54.
33. Lee SJ. The occupational diseases of agricultural workers. *Hanyang Med Rev* 2010;**30**:305–12.
34. Korea Power Exchange. *Survey on Electricity Consumption Characteristics of Home Appliances*. Seoul: Statistics Korea, 2013.
35. Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occup Environ Med* 2007;**64**:827–33.