Front. Environ. Sci. Eng. 2024, 18(1): 11
https://doi.org/10.1007/s11783-024-1771-z

RESEARCH ARTICLE

Effects of the urban landscape on heatwave-mortality associations in Hong Kong: comparison of different heatwave definitions

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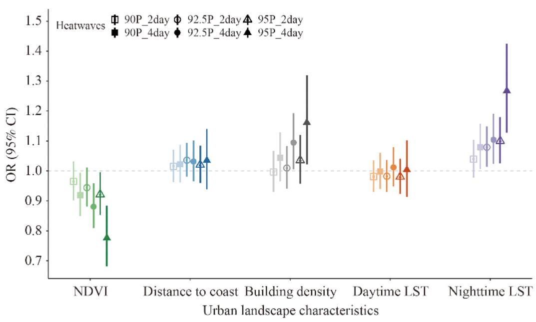
HIGHLIGHTS

• The effect modifications of urban landscape were explored at the intra-urban level.
• Higher levels of green spaces could alleviate adverse health impacts of heatwaves.
• Higher building density and nighttime land surface temperatures aggravate impacts.
• Effects of urban landscape were more significant in older adults and males.
• Pronounced effect modifications were observed under hotter and longer heatwaves.

GRAPHIC ABSTRACT



ARTICLE INFO

Article history:
Received 16 February 2023
Revised 30 July 2023
Accepted 31 July 2023
Available online 4 September 2023

Keywords:
Urban landscape
Heatwave
Mortality
Effect modification
Intra-urban differences
Health risk reduction

ABSTRACT

Despite increased attention given to potential modifiers of temperature-mortality associations, evidence for variations between different urban landscape characteristics remains limited. It is in this context that in this paper effect modifications of multiple urban landscape characteristics are explored under different heatwave definitions for different age groups and gender in Hong Kong, China. Daily meteorological data and heatwave-related mortality counts from 2008 to 2017 were collected from the Hong Kong Census and Statistics Department, China. A case-only design was adopted, combined with logistic regression models to examine the modification effects of five urban landscape characteristics under six heatwave definitions. Stratified analyses were conducted to investigate age- and gender-specific effect modifications. It is found that individuals living in greener areas experienced lower levels of mortality during or immediately after heatwaves. In contrast, a higher building density and nighttime land surface temperature (LST) were associated with a higher heatwave-related mortality risk. Pronounced effect modifications of these urban landscape characteristics were observed under hotter and longer heatwaves, and in older adults (age ⩾ 65 years) and males. The findings provide a scientific basis for policymakers and practitioners when considering measures for coping with hotter, longer, and more frequent heatwaves in the context of global climate change.

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Special Issue—Climate Change and Public Health: emerging impacts and responses (Responsible Editors: Can Wang, Shihui Zhang, Derrick Ho & Miriam Marlier)

1 Introduction

Health impacts of sustained extreme heat (i.e., heatwaves) are observed in cities around the world (D’Ippoliti et al., 2010; Anderson and Bell, 2011; Gasparrini and

Armstrong, 2011; Guo et al., 2017). Due to global climate change, heatwaves are projected to increase in frequency, duration, and intensity (Allen et al., 2018). This is predicted to lead to an aggravation of heatwave-associated morbidity and mortality globally (Gasparrini et al., 2017; Guo et al., 2018; Niu et al., 2023). Future scenarios of socio-economic pathways suggest that adverse health consequences are likely to be exacerbated by both, an aging population (Lee et al., 2019; Liu et al., 2023) and an acceleration of urbanization (Wang et al., 2021). While climate change research is frequently of an international nature, heat mitigation strategies and health interventions are most effectively devised locally (Madrigano et al., 2015). To date, only a few authors have reported on potential effect modifiers of temperature-mortality associations (Schinasi et al., 2018; Son et al., 2019). There are various research gaps, as is subsequently explained.

Most epidemiological studies focus on national and regional levels (Sera et al., 2019; Xu et al., 2020) and few have investigated the impacts of micro-settings on heat-health associations, such as intra-urban characteristics at the census tract level. In those that have, the main focus has been on socio-demographic characteristics, including age, education attainment, wealth and social isolation (Yu et al., 2010; Chen et al., 2016; Hu et al., 2017; Chung et al., 2018; Kim et al., 2020). To date, little attention has been paid to the role of urban landscape characteristics during episodes of extreme heat (Son et al., 2019). Exceptions are studies on urban green (i.e., vegetated) spaces, in particular trees, as these reduce temperatures due to transpiration and shading (Gunawardena et al., 2017; Rahman et al., 2020; Pace et al., 2021). In this context, urban green spaces have been said to alleviate heat-related mortality risk (Xu et al., 2013; Burkart et al., 2015; Gronlund et al., 2015; Pascal et al., 2021). However, green spaces represent only one dimension and other urban landscape characteristics are also likely to be important. For example, blue spaces (i.e. water) can work as thermal buffers (based on enthalpy of vaporization and a high heat capacity) (Oke, 1987; Papanastasiou et al., 2010; Gunawardena et al., 2017).

Despite an increasing number of studies looking at modifiers of heat-mortality associations, little attention has been paid to their effect modifications under heatwaves. Compared with general heat events, heatwaves have specific characteristics with regards to heat intensity (i.e., 92.5th or 95th percentile of temperature as the threshold) and duration (i.e., ⩾ 2, 3, or 4 days) (Nairn and Fawcett, 2014; Xu et al., 2018). While heatwave-related mortality risks have been extensively documented (Gasparrini and Armstrong, 2011; Xu et al., 2016) and evaluated with regards to intensity and duration (Guo et al., 2017), few empirical studies have explored whether and how effect modifications of urban landscape characteristics vary under different heatwave definitions. To date, findings on urban green spaces and heatwave-mortality associations have remained inconsistent. While some observed a protective effect of green spaces on heatwave-related mortality (Madrigano et al., 2015), others have suggested that there are no significant interactions between the two (Xu et al., 2013). While inconsistencies might simply be due to the use of different heatwave definitions, it is also possible that they are associated with effects of urban landscape characteristics under different heatwave conditions (intensity and duration). This is why "one-for-all" heat action plans may not be suitable for dealing with more intense and long-lasting heatwaves.

There is currently little evidence for the modification effects of the urban landscape among different age groups and gender. Those few studies that have touched on this topic have only focused on urban green spaces, with some reporting a significant protective effect only in females and older adults (age ⩾ 65 years) (Bao et al., 2021). Others have suggested that there is no significant disparity across gender and age groups (Son et al., 2016). More empirical evidence is therefore needed to investigate not just green spaces, but also other urban landscape characteristics as modifiers under different heatwave definitions and among different groups of people. To address current research gaps, in this paper we are going:

1) To evaluate the effect modifications of multiple urban landscape characteristics at the intra-urban scale (census tract level),

2) To compare their effect modifications on heatwave-mortality associations under different heatwave definitions, and

3) To explore gender- and age-stratified effect modifications of multiple urban landscape characteristics.

2 Methodology

2.1 Study area

Hong Kong, China, is said to be the world's fourth-most densely populated city. It is located on the south-east coast of China, with a population of 7.3 million and a gross population density of 6603 people per km^2 (Hong Kong Census and Statistics Department, 2006 and 2016). The city's urban landscape extents a complex terrain with mountains and hills. The built up area is characterized by a high-rise and high-density built urban landscape and a significant urban heat island (UHI) effect (Giridharan et al., 2004). Due to the subtropical climate, Hong Kong, China, has a hot and humid summer season (June to September)withaveragetemperaturesrangingbetween26and 29 °C (Hong Kong Observatory, 2021).

Analysis units. In Hong Kong, China, a Tertiary Planning Unit (TPU) is an administrative unit similar to the Census Block Group in the USA. In the investigation, large TPUs are used in which adjacent TPUs with small populations are merged into larger units (Hong Kong Development Bureau, 2004). An average large TPU consists of an area of 7.06 km^2 and a population of 51440 (Hong Kong Census and Statistics Department, 2006 and 2016). Adjacent large TPUs with boundary changes since 2006 were merged in 2016. Consequently, there were 140 large TPUs for further analyses.

2.2 Data collection

Mortality data. Daily mortality data from 2008 to 2017 for large TPUs were obtained from the Census and Statistics Department of Hong Kong. Registered death microdata cover characteristics such as age, gender, date of death, place of residence (in 3-digit TPU codes), the underlying cause of death (according to the International Classification of Disease Tenth Revision, ICD-10), and other information. Registered deaths with an unknown place of residence were excluded and each death record was associated with a large TPU based on its 3-digit TPU code. The underlying causes of deaths included associations with cardiovascular diseases (I00-I99), respiratory diseases (J00-J99), dehydration or volume depletion (E86), hyperpyrexia (R50.9), effects of heat and light (T67), heat stroke (X30) and exposure to sunlight (X32) (Song et al., 2021). Analysis was restricted to the hot season from June to September, i.e., the four hottest adjacent months in Hong Kong, China.

Meteorological data. Daily meteorological data, including daily temperatures and relative humidity, were obtained from the Hong Kong Headquarter station (Hong Kong Observatory, 2023). This is considered to be the most representative urban station (Ho et al., 2020) with a complete record for the study period 2008 to 2017.

Heatwave definitions. A heatwave is composed of several consecutive days with temperatures above an absolute (i.e., 30 °C) or a relative threshold (i.e., 95th percentile of temperatures) (Robinson, 2001). For this analysis, relative thresholds based on long-term daily temperatures were used to allow for regional acclimatization to temperatures, normal to a local population (Anderson and Bell, 2011). Definitions similar to those used before were applied (Hajat et al., 2006; Guo et al., 2017; Zhang et al., 2021), focusing on a combination of intensity (90th, 92.5th, or 95th percentile of daily temperatures in data set) and duration (a minimum of 2 or 4 consecutive days with a temperature above the intensity criterion) to model heatwave periods. In all, six heatwave definitions were included (90P_2day, 90P_4day, 92.5P_2day, 92.5P_4day, 95P_2day and 95P_4day).

Remote sensing data. Data of green spaces and land surface temperatures (LSTs) were obtained from satellite images. The amount of green space was assessed, using the Normalized Difference Vegetation Index (NDVI), a widely-used satellite-based index of vegetation presence and density (Tucker, 1979; Rhew et al., 2011; James et al., 2015). NDVI is calculated with: NDVI = (NIR − Red)/(NIR + Red), where NIR is the near-infrared band and Red is the visible red band. The values of NDVI range from −1 to 1, with a higher value indicating a high density of vegetation (Weier and Herring, 2000). All available Landsat images (30 m × 30 m) from 2008 to 2017 were collected and the annual NDVI composite calculated, using the Maximum Value Compositing (MVC) technique (Holben, 1986). All Landsat images were obtained and processed by Google Earth Engine. After truncating the NDVI scale by setting negative values to zero, the mean NDVI value of each large TPU was calculated by averaging the pixel values within the large TPU boundary for each year. By averaging all annual NDVI at the area level for the period of 2008 to 2017, a single long-term average NDVI was produced for each large TPU. Daily LST data from two widely used satellite image products were also collected via the Moderate Resolution Imaging Spectroradiometer (MODIS), MOD11A1 (daytime), and MYD11A1 (nighttime) at a resolution of 1 km. All LST data products were distributed by the National Aeronautics and Space Administration (NASA)'s Land Processes Distributed Active Archive Center (LP DAAC). These were downloaded and processed through the R package "Modistsp". The average LSTs at daytime and nighttime were calculated for each large TPU, based on daily daytime and nighttime LST during the hot season (June to September) from 2008 to 2017.

Buildings and land use data. Data on buildings and land use information were obtained from the iB5000 Topographical Data set of the Hong Kong Lands Department in 2014. This data set was acquired from government records of buildings and land-use zoning information. Based on the data of building footprints, building density was calculated by the Kernel Density tool in ArcGIS (10.5.1, ESRI). Calculation results were then averaged and aggregated at the large TPU level. Exposure to blue space was assessed by using population-weighted distances to coasts as inland water bodies are limited in Hong Kong, China (Hong Kong Planning Department, 2016), extracting coastlines from the iB5000 Topographical Data Set (2014). Annual 100 m × 100 m population grids were obtained from the WorldPop Data Set (Tatem, 2017). Values of each population grid were averaged for 2008–2017. Population grids and the shapefile of large TPUs were inputted into the Mean Center tool in ArcGIS in order to identify population-weighted centroids for each large TPU. Distances to the coast were estimated by the Euclidean distance between the population-weighted centroids and the nearest coastal lines of each large TPU, using the Near tool in ArcGIS.

2.3 Statistical analysis

A case-only design was used to examine the modification effect of each urban landscape characteristic on heatwave-mortality associations. A case-only design is an efficient, precise, and robust method to analyze a time-fixed modifier of a given time-dependent environmental exposure in a set of cases over time (Armstrong, 2003; Schwartz, 2005; Dastgiri, 2010). Exposure variables were heatwaves, and cases were represented by heatwave-related mortality. Modifier variables were urban landscape characteristics that appeared to modify heatwave-mortality associations (Xu et al., 2013; Madrigano et al., 2015), including green space exposure, proximity to water, building density, daytime and nighttime LSTs. The case-only design hypothesizes that if an urban landscape characteristic increases, the risk of heatwave-related mortality will be higher on heatwave days than on non-heatwave days during the hot season.

Each urban landscape characteristic was characterized, using quartiles as cut-off values and each large TPU was assigned to one category. The thresholds (25th and 75th percentiles) used to categorize low and high levels of each indicator were similar to those applied in most recent intra-urban studies in order to facilitate a comparison across different studies (Heo et al., 2021; Qiu et al., 2021). Individuals were defined as having/not having a characteristic, based on whether they lived in a large TPU with that characteristic. Multinomial logistic regressions were then fitted with each categorized urban landscape characteristic as the dependent variable and “heatwave day” was used as the independent variable. To account for lag (delayed) effects of a heatwave, the four days after a heatwave were included as heatwave days, as there is a delayed effect of almost all heatwaves on mortality, which lasts three to four days (Guo et al., 2017). To determine whether an urban landscape characteristic has a positive or negative effect on deaths during heatwave days, the focus was on the odds ratio (OR) between the top quartile (above the 75th percentile) and the bottom quartile (below the 25th percentile) of that characteristic. An OR less than 1 indicates that high values of that characteristic might alleviate the impacts of heatwaves on observed deaths and vice versa.

Regression analyses were performed for six heatwaves, one at a time, to examine the effect modification of each urban landscape characteristic under different heatwave definitions. Separate models were fitted for two age groups, young people (0–64 years) and older adults (age $\geqslant$ 65 years), and for males and females to determine sensitive populations.

To investigate whether effect modification of each urban landscape characteristic varies over different heatwave definitions, a meta-regression was conducted for the OR values of heatwaves, differing in intensity or duration, or both. Age- and gender-stratified meta-regression analyses were also conducted to investigate whether the difference in OR values across heatwave definitions was significant among any specific age and gender group. All meta-regression analyses were conducted, using the “metaphor” package (Viechtbauer, 2010).

To explore the potential effects of the socioeconomic status (SES), a Pearson’s correlation analysis was conducted between each urban landscape variable and variables related to age, education and income for proxies of SES (Burkart et al., 2015; Son et al., 2016; Song et al., 2022). Details on data sources and definitions are provided in the appendix (Table A1). Sensitivity analyses were conducted by changing the lag effect from 4 to 3 days (Guo et al., 2017); including daily relative humidity in order to take account of the effect of humidity; and including O_3 and PM_{10} at 0–1 lag days to control the impact of air pollution (Burkart et al., 2015). The “nnet” package was applied to create these models (Ripley et al., 2016). All analyses were performed, using the R software (v. 4.0.4). Two-tailed $p < 0.05$ were considered to be statistically significant.

3 Results

3.1 Descriptive statistics

A total of 423135 deaths had residential location information (3-digit TPU code) during the study period (2008–2017) in Hong Kong, China. Restricting the data set to heatwave-related mortality during the hot season (June to September) resulted in the inclusion of 55154 deaths for regression analysis. Over half of the deaths occurred among males (54.3%), and most deaths occurred in individuals over 65 years old (89.0%). The 90th, 92.5th, and 95th percentiles of daily temperature distributions were 29.6, 29.8, and 30.1 °C. The number of heatwaves, the number of heatwave days, and deaths on heatwave days during the study periods are listed in Table A2. Summary statistics for five urban landscape characteristics were shown in Table 1. Each of these was categorized in quartiles (25th, 50th, and 75th percentiles) as cut-off values for multinomial models.

3.2 Effect modifications of urban landscape characteristics stratified by heatwave definitions

Figure 1 shows results for the examined urban landscape

Table 1 Summary statistics of urban landscape characteristics

Urban landscape Characteristics	Mean ± SD	25%	Median	75%
NDVI	0.48 ± 0.18	0.34	0.52	0.64
Proximity to water (km)	1.59 ± 1.84	0.35	0.88	1.90
Building density	81.04 ± 61.98	21.88	66.01	134.00
Daytime LST (°C)	29.45 ± 1.82	27.88	29.10	30.78
Nighttime LST (°C)	24.00 ± 0.90	23.33	24.01	24.67

Notes: LST is short for Land Surface Temperature. The daytime and nighttime LSTs were the average daily daytime and nighttime LSTs in hot seasons from 2008 to 2017.

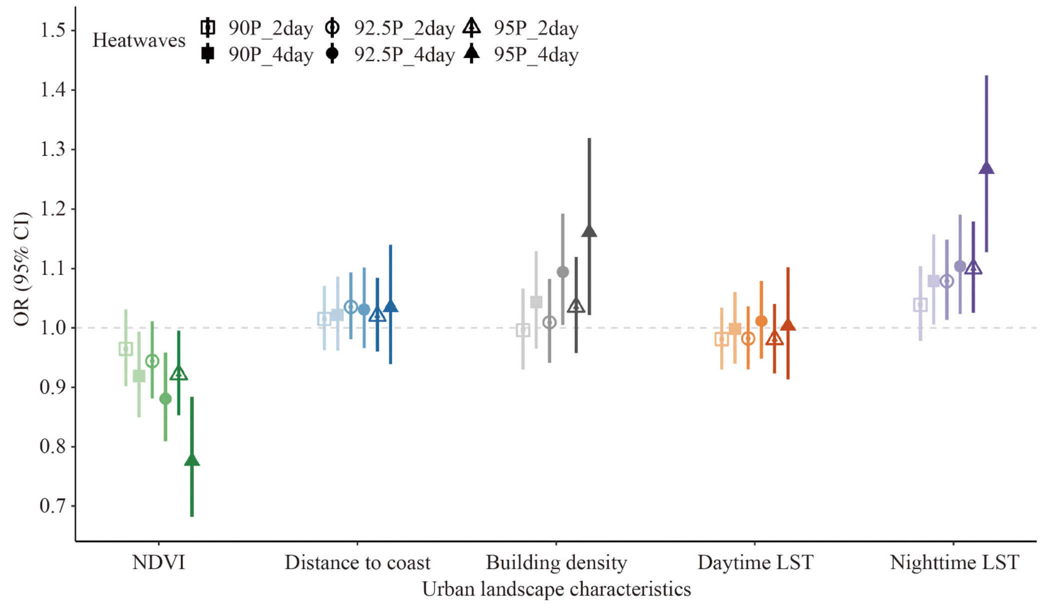

Fig. 1 Effect modifications of urban landscape characteristics on the associations between mortality and heatwaves with different specifications of intensity and duration.

characteristics. Generally speaking, high values of building density and nighttime LST are associated with an aggravation of mortality rates during intensive and long-lasting heatwaves. There are also indications that high values of NDVI alleviate adverse health impacts. No significant effect modifications were found with regards to proximity to water and daytime LST.

Table 2 shows the OR values for each urban landscape characteristic stratified by heatwave definitions and p-value for the difference in OR values between heatwaves, differentiated according to intensity or duration or both. This shows that individuals living in "greener" areas of the city were less likely to pass away during and immediately after longer heatwaves (based on longer duration days; ⩾ 4 days). Moreover, a significant difference in OR values remained for longer heatwaves (p-value < 0.05). For shorter heatwaves (⩾ 2 days), significant effect modifications were only observed for the most intensive events (based on a higher temperature threshold; ⩾ 95th percentile). No differences were observed for the three shorter heatwaves. For each pair of shorter and longer heatwaves, a significant difference in OR values was observed only between the two most intensive heatwaves (i.e., 95P_2day versus 95P_4day, p-value < 0.05). In addition, a statistically significant difference was observed in OR values between two heatwaves that differed in terms of both, intensity and duration (i.e., 90P_2day versus 95P_4day, p-value < 0.01).

Individuals living in areas where building density was above the top quartile had an increased relative risk of passing away during or immediately after longer heatwaves except for the one which was mild (⩾ 90th percentile), compared with those living in areas of the bottom quartile. However, no significant effect modification of building density under any shorter heatwaves was observed (Table 2). The results of the meta-regression analyses indicate that there was no difference in OR values among heatwaves of different intensities or durations. However, the difference in OR values between the two heatwaves that differed in intensity and duration was statistically significant (p-value < 0.05, Table 2).

For nighttime LST, statistically significant effect modifications were observed for almost all heatwaves, except for the one which was shorter and milder (i.e., 90P_2day). For three longer heatwaves, there was a trend of pronounced effect modifications of nighttime LST for more intensive heatwaves (p-value < 0.05, Table 2). The results of the meta-regression analyses showed a significant difference in OR values between shorter and longer heatwaves with a high intensity (⩾ 95th percentile). Significantly different estimates were also established for two heatwaves differing in intensity and duration (p-value < 0.01, Table 2).

3.3 Age and gender stratified effect modifications of urban landscape characteristics

Figure 2 displays age and gender stratified effect modifications for each urban landscape characteristic on heatwave-mortality associations by heatwave definitions. While nighttime LST is a significant modifier of heat-wave-mortality associations among older adults (age ⩾ 65 years), both males and females, green space and building density showed significant effect modifications only among older adults and males. In addition, age- and gender-specific effect modifications of these urban

Table 2 Effect modifications of urban landscape characteristics on the associations between total mortality and heatwaves differing in temperature thresholds or durations or both, and *p*-values for the difference in OR values for six heatwave definitions, with 95% confidence intervals

Urban landscape characteristics	Heatwave definitions	2 day	4 day	*p*-value[a]
NDVI	90P	0.96 (0.90, 1.03)	**0.92 (0.85, 0.99)**	0.355
	92.5P	0.94 (0.88, 1.01)	**0.88 (0.81, 0.96)**	0.213
	95P	0.92 (0.85, 1.00)	**0.78 (0.68, 0.88)**	**0.026**
	p-value[b]	0.382	**0.04**	**0.0043**[c]
Proximity to water	90P	1.02 (0.96, 1.07)	1.02 (0.96, 1.09)	0.868
	92.5P	1.04 (0.98, 1.09)	1.03 (0.97, 1.10)	0.926
	95P	1.02 (0.96, 1.08)	1.03 (0.94, 1.14)	0.811
	p-value[b]	0.873	0.815	0.737[c]
Building density	90P	1.00 (0.93, 1.07)	1.04 (0.96, 1.13)	0.380
	92.5P	1.01 (0.94, 1.08)	**1.09 (1.00, 1.19)**	0.151
	95P	1.04 (0.96, 1.12)	**1.16 (1.02, 1.32)**	0.133
	p-value[b]	0.469	0.154	**0.038**[c]
Daytime LST	90P	0.98 (0.93, 1.03)	1.00 (0.94, 1.06)	0.667
	92.5P	0.98 (0.93, 1.04)	1.01 (0.95, 1.08)	0.489
	95P	0.98 (0.92, 1.04)	1.00 (0.91, 1.10)	0.681
	p-value[b]	0.991	0.872	0.679[c]
Nighttime LST	90P	1.04 (0.98, 1.10)	**1.08 (1.01, 1.16)**	0.425
	92.5P	**1.08 (1.01, 1.15)**	**1.10 (1.02, 1.19)**	0.645
	95P	**1.10 (1.03, 1.18)**	**1.27 (1.13, 1.42)**	**0.041**
	p-value[b]	0.221	**0.039**	**0.003**[c]

Notes: a) *p*-value for the difference between shorter and longer heatwaves with the same intensity. b) *p*-value for the difference among heatwaves with the same duration but differing in intensity. c) *p*-value for the difference between heatwaves differing in both intensity and duration (i.e., 90P_2day versus 95P_4day).

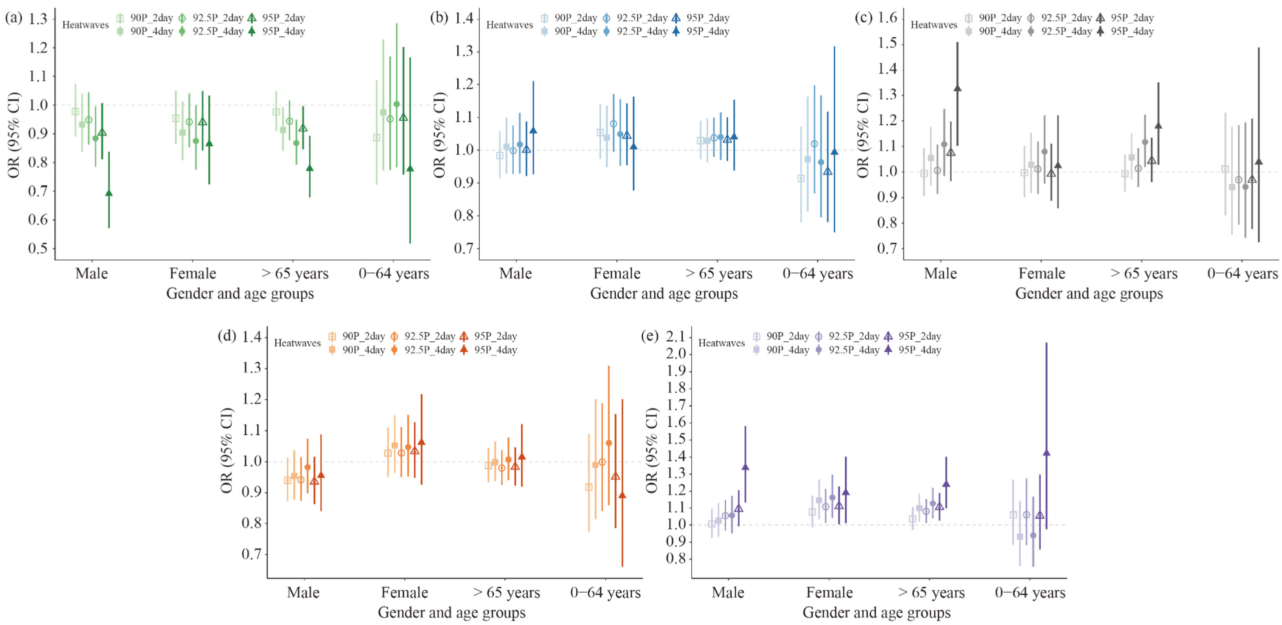

Fig. 2 Relative odds of dying during or 4-days following a heatwave versus dying on other days during hot season for people who live at the top quartile, compared with those living at the bottom quartile of (a) NDVI; (b) Proximity to water; (c) Building density; (d) Daytime Land Surface Temperature (LST); (e) Nighttime LST.

landscape characteristics varied over different heatwave definitions, with a trend of pronounced effect for longer and more intensive heatwaves.

Age and gender stratified OR values for six heatwave definitions are shown in Tables A3–A6. As for green space, older adults living in greener areas were less likely to die during or immediately following longer heatwaves, with OR values of 0.91 (0.84, 0.99) for 90P_4day, 0.87 (0.79, 0.95) for 92.5P_4day, and 0.78 (0.68, 0.89) for 95P_4day, respectively (Table A4). However, effect modifications of green space were not significantly different across these longer heatwaves (p-value > 0.05). For each pair of shorter and longer heatwaves with the same intensity, a significant difference was observed only for the pair of most intensive heatwaves, with OR values of 0.92 (0.85, 1.00) for 95P_2day and 0.78 (0.68, 0.89) for 95P_4day (p-value < 0.05). In addition, the effect modifications of green spaces were significantly different for heatwaves differing in both, intensity and duration (i.e., p-value < 0.01). For males (Table A5), green space was a significant modifier only for the longer and most intensive heatwave, with an OR value of 0.69 (0.57, 0.84) for 95P_4day. There was a significant difference in OR values across the three longer heatwaves (i.e., p-value < 0.05), and a substantial difference was also observed for two heatwaves that differed in intensity and duration (p-value < 0.01).

As for building density, significant effect modifications were found for older adults during or immediately after a longer and intensive heatwave, with OR values of 1.12 (1.02, 1.22) for 92.5P_4day and 1.18 (1.03, 1.35) for 95P_4day (Table A4); and significant effects in males for the most intensive heatwaves, with an OR value of 1.33 (1.10, 1.60) for 95P_4day (Table A5). Effect modifications of building density in both, males and older adults were significantly different between the two heatwaves that differed in intensity and duration (i.e., p-value < 0.01 for males, p-value < 0.05 for older adults) (Tables A3 and A4).

According to Tables A3 and A4, significant effect modifications of nighttime LSTs were located in older adults but were not observed in young people. High values of nighttime LST may exacerbate the adverse impact of almost all types of heatwaves on older adults, except for shorter and milder ones (i.e., 90P_2day). A significant difference in OR values was also established for two heatwaves that differed in intensity and duration (i.e., p-value < 0.05, Table A4). Similar results were found in females (Table A6), which showed significant effect modifications of nighttime LST for almost all types of heatwaves, except for 90P_2day. However, no significant difference was found for different heatwave definitions (p-values > 0.05). In males (Table A5), effect modifications of nighttime LST were only significant for the longer and most intensive heatwaves, with an OR value of 1.34 (1.13, 1.58) for 95P_4day. The estimates for the three longer heatwaves were significantly different from each other (p-value < 0.05). A significant difference was also observed for shorter and longer heatwaves with a high intensity (p-value < 0.05); and for two heatwaves that differed in intensity and duration (i.e., p-value < 0.01).

3.4 Results of correlation and sensitivity analyses

According to the results of Pearson's correlation analysis, there was a weak to non-explicit association between urban landscape characteristics and SES variables (Fig. A1). Weak correlations indicate impacts of SES variables to be minimal. Sensitivity analyses show that effect modifications of urban landscape characteristics are generally similar, when using three days for the lag effect (Figs. A2 and A3), including a variable for relative humidity (Figs. A4 and A5), and controlling for the impacts of air pollution by including O_3 and PM_{10} at 0–1 lag days (Figs. A6 and A7). This suggests the robustness of the analyses.

4 Discussion and conclusions

In this paper, effect modifications of several urban landscape characteristics on heatwave-mortality associations were examined. Higher values of building density and nighttime LST were found to be likely explanations for an exacerbation of harmful human health impacts of heatwaves. Furthermore, green spaces were found to likely be able to alleviate negative consequences. However, effect modifications of different urban landscape characteristics vary across different heatwave definitions, with pronounced effects likely to be associated with longer and more intensive heatwaves. Significant effect modifications were mainly located in older adults (age ⩾ 65 years) and males.

Significant effect modifications of green spaces on heatwave-mortality associations were similar as those established in other studies (Madrigano et al., 2015; Kim and Kim, 2017). Importantly, a pronounced protective effect was established for green spaces under conditions of longer and more intensive heatwaves. Substantial health benefits of green spaces were associated with high temperatures, confirming findings from past studies. In Lisbon, Portugal, the difference in heat-related mortality risk between regions at the top and bottom quartiles of NDVI was more significant in temperatures over the 99th percentile than in temperatures over the 95th percentile (Burkart et al., 2015). Similar results were reported in a recent publication on Paris, France (Pascal et al., 2021). This established a larger disparity in relative mortality risk between neighborhoods with high and low levels of green spaces under conditions of extreme heatwaves, compared with non-extreme heatwaves. Findings confirm the results of a recent study in Hong Kong, China, which did not identify significant effect modifications of green space under moderate heat (days with the daily temperatures > 90th percentile of temperature distribution) or heat (days with the daily temperature > 95th percentile), or any substantial difference between moderate heat and heat (Song et al., 2022).

Currently, underlying reasons for the more apparent health benefits of green space during more intense and longer heatwaves are not entirely clear. Several reasons are possible. First, the evapotranspiration rate of vegetation tends to increase as temperatures rise (Ziter et al., 2019), leading to more potent cooling effects and less heat stress for people living in areas close to green spaces during episodes of extreme heat. Second, a recent study in India found that high temperatures would discourage people's physical activities in greener areas (Ho et al., 2021). As such, individuals living near greener spaces would be less likely to be exposed to high temperatures, particularly during the extreme heat events.

For Hong Kong, China, it was established that people in areas with a higher building density are more likely to pass away during or immediately following a heatwave than those in low-density areas. High-density buildings absorb more solar energy, block breezeway, trap heat, and consequently intensify the local UHIs (Johansson and Emmanuel, 2006). This exacerbates heat stress from heatwaves in wet climates (Zhao et al., 2014; Founda and Santamouris, 2017). In a study of neighborhoods in New York City, USA, a higher value of building density was positively associated with an increased mortality risk on heatwave days compared with other days during warm summer months (Madrigano et al., 2015). A study on Alabama, USA, found that the association between non-accidental deaths and heatwaves was consistently positive in high-density areas but not in medium- or low-density areas (Kent et al., 2014). Kent et al. (2014) also found a more apparent disparity, albeit insignificant, between high and low-density areas under most intensive heatwaves (> 98th percentile) compared with mild heatwaves (> 90th percentile).

The research described in this paper is one of the first to have observed a pronounced effect modification of building density under longer and hotter heatwaves, although the underlying mechanism is not yet well understood. Impacts are likely driven by processes of urban warming that mainly occur in dense urban areas, evolving over time during heatwaves (Lemonsu et al., 2012). Under the cumulative effect of urban warming, thermal comfort is found to deteriorate over time during long-lasting heatwaves, as buildings are progressively warming up (Lemonsu et al., 2015).

High values of nighttime LST were established as likely causes for an aggravation of the negative effects of heatwaves on mortality, with no significant effect modification being established in daytime LST. This is different from findings of an earlier study in New York City, USA, which marked a significant mortality increase associated with daytime LST during heatwaves (Madrigano et al., 2015). However, it is consistent with findings of a recent study in Shenzhen, China, a city adjacent to Hong Kong, China. This established an increased risk of heat stroke morbidity associated with a higher nighttime LST (Bao et al., 2021). There are several underlying reasons for this. Firstly, the UHI phenomenon that mainly occurs at night can interact with heatwaves, leading to more prolonged urban warming (He et al., 2021). As a marker of UHI, nighttime LST is likely to have more substantial effects on residents' thermal comfort and heat health risk than daytime LST. Secondly, since urban characteristics were matched with death records based on the residential addresses, daytime activity trajectories of residents with a separation of work and residence may lead to a biased estimation of their daytime exposure to heat stress.

For Hong Kong, China, increased effect modifications were observed for nighttime LST under longer and hotter heatwaves. While the exact reasons for this are currently not known, Laaidi et al. (2012) suggested that higher nighttime temperatures could lead to a decrease in sleeping comfort. There are indications that effects amplify during prolonged and intensive heatwaves (Wilhelm, 2012) when urban infrastructure cannot completely cool off at night and the cumulative heat stored in the urban structures and materials increases, both indoor and outdoor (Lemonsu et al., 2015). This strengthens UHIs at night during heatwave days (Tian et al., 2021) and is likely to aggravate the harmful health impacts of heatwaves, particularly in areas with higher nighttime LST.

Findings of significant effect modifications of green space, building density, and nighttime LST on older adults are consistent with those of the recent study in Shenzhen mentioned above (Bao et al., 2021). Age differences in effect modifications may be down to several reasons. Firstly, while almost all heat-adaptation strategies appear to be under-used by older adults, younger people tend to engage in more heat-adaptive behaviors, for example, turning fans on with the windows opened, changing clothes, taking a shower, or leaving the house (White-Newsome et al., 2011). As such, the urban landscape's effect modifications on young people's heat hazards might be weakened. Secondly, while most young people in Hong Kong, China have a separation of work and residence (around 82.6%, Hong Kong Census and Statistics Department (2006 and 2016)), older adults mainly conduct their daily activities in areas within or close to their residential addresses (Lo and Jim, 2010; Jim and Shan, 2013; Ambrey and Fleming, 2014). The estimated urban landscape characteristics of residents, using area-level attributes of the units they live in are therefore more likely to modify the heatwave-mortality associations among older people.

As for the analyses of gender-specific effect modifications, green space and building density were found to be significant modifiers in males under longer and more intensive heatwaves. No substantial effect modifications were observed in females. This finding might be due to the difference in the occupational exposure and adaptation behavior between males and females. Due to the differences in gender distributions in industrial sectors, males usually work more hours per day outdoors (Spector et al., 2019). They are therefore more likely to be affected by the outdoor thermal environment than females. Besides, a recent survey in the USA suggested a higher risk perception of extreme heat among women than men (Howe et al., 2019). This may encourage spontaneous coping strategies and self-protective behaviors to heat stress (i.e., staying indoors, taking shaded walks) (Subiza-Pérez et al., 2020). Therefore, effect modifications of urban landscape characteristics might be weakened among women who have higher risk perceptions and thus tend to engage in more heat adaptive behaviors. Regular education and training activities could support spontaneous adjustment behaviors of both, males and females in their daily lives in response to heatwaves (Ban et al., 2019).

The authors acknowledge a number of limitations of their research. Firstly, it would be advantageous to have data on individual activity trajectories for a more accurate exposure assessment to match urban landscape characteristics with death records. Secondly, while the case-only design can identify groups with relatively higher risks of heatwave-related mortality, it cannot identify groups with the highest absolute excess risk. For example, females living in areas with a shortage of green spaces have much higher daily mortality rates and may have a higher absolute excess risk than males living in the same areas despite not having a higher relative risk than females living in greener areas. Thirdly, due to a shortage of relevant data, personal heatwave adaptive behaviors could not be accounted for, such as the use of air conditioning. Fourthly, outdoor ambient temperatures were used to assess personal heat exposure, but the amount of time that residents spend indoors might contribute to biased estimations.

Furthermore, due to the data acquisition difficulty, fine-scale spatial variations and temporal changes in urban landscape characteristics could not be accounted for. These should be considered in the future if data are available. Recently launched satellites that provide high-resolution remote sensing images, such as Sentinel-1 with a resolution of 10 m, could be a data source for future studies. Single sources of air temperatures might be another limitation for intra-urban studies. Even though between-area variations within a city are likely to be smaller when compared with the temporal variation of air temperatures, the latter is expected to result in more precise estimates. Further studies are thus needed to address this issue in case of high-resolution temperature data being available. The study presented in this paper derives risks at different levels of urban landscape characteristics by using univariate models. In this context, other factors that might partially explain differences in the heatwave-mortality associations within typologies are not accounted for (e.g., socioeconomic status). But the weak correlations between urban landscape characteristics and SES variables shown in Fig. A1 indicate that the confounding effects of the former would be, if present, minimal to the latter. Nevertheless, continued work on more advanced models are needed to disentangle the effect modifications of different variables.

Overall, this paper offers several contributions to existing research. Firstly, as a fine-scale study it contributes to precedent studies by identifying the intra-urban modifiers of heatwave-mortality associations in a high-density and high-rise city. Secondly, additional evidence for the effect modifications of specific urban landscape characteristics is provided (i.e., green space, building density, nighttime LST) on heatwave-mortality associations. It is found that urban landscape may matter more under longer and hotter heatwaves are established. Thirdly, findings extend the existing research by observing particular population groups (i.e., older adults and males) that were more sensitive to effect modifications of these urban landscape characteristics during heatwave days. Furthermore, since extreme heat events are projected to increase in frequency, duration, and intensity (Allen et al., 2018; Qing and Wang, 2021), valuable information is provided for the formulation and implementation of heat mitigation strategies and health interventions.

Acknowledgement **Jinglu Song:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing-original draft, Writing-review and editing, Funding acquisition. **Yi Lu:** Writing-review and editing, Funding acquisition. **Thomas Fischer:** Writing-review and editing. **Kejia Hu:** Data curation, Writing-review and editing, Funding acquisition. The study was supported by the National Natural Science Foundation of China (Nos. 42007421 and 42001013), the General Research Project Fund of Hong Kong Research Grants Council (Hong Kong, China) (No. 11207520), the Key Program Special Fund (China) (No. KSF-E-43) and the Research Development Fund (China) (No. RDF-19-02-13) of XJTLU, and the Zhejiang Provincial Natural Science Foundation of China (No. Y23D050006). The authors thank the efforts of the Hong Kong Census and Statistics Department (Hong Kong, China) in collecting and processing the census and mortality data, and declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11783-024-1771-z and is accessible for authorized users.

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