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Health effects of greenspace morphology: Large, irregular-shaped, well-connected, and close-clustered greenspaces may reduce mortality risks, especially for neighborhoods with higher aging levels

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A R T I C L E I N F O

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A B S T R A C T

The healthcare burden has intensified with urbanization and aging populations in many global cities. While the health effects of urban greenspaces have been well documented, little is known about the associations between greenspace morphological features and health, especially in a high-density city with significant aging populations. Drawing on land use data with 10-m resolution, we assessed seven greenspace morphological metrics in terms of size (the percentage of greenspace, the largest pixel index, the average greenspace area), fragmentation (the patch density), shape (the average weighted shape index), connectedness (the cohesion index), and proximity (the aggregation index). We further conducted an ecological study to examine their associations with all-cause and three cause-specific (cardiovascular disease, respiratory disease, and cancer) mortality. Results from the negative binomial regression models revealed protective effects of five greenspace morphology metrics, including the percentage of greenspace, the largest pixel index, the average weighted shape index, the cohesion index, and the aggregation index, on mortality. The shape index showed the greatest effects, with every 1 Standard Deviation (SD) increase in the shape index linked to a reduction of 22.1% (95% CI: 22.0%–31.0%) in all-cause mortality, 22.1% (12.2%–30.8%) in mortality from cardiovascular diseases, 25.0% (14.0%–34.6%) in mortality from respiratory diseases, and 22.0% (12.3%–30.6%) in mortality from cancers. Moreover, stratified analyses revealed that the health effects of the cohesion index and the aggregation index were significantly more pronounced in neighborhoods with higher aging levels. Our findings highlight the significance of greenspace morphology features, beyond greenspace quantity, in improving residents' health, particularly for societies with high aging populations.

1. Introduction

Urbanization and aging populations present significant challenges to the health and well-being of urban residents, especially older adults. Environmental degradation and reduced physical activity in urban environment have heightened the risks of diverse non-communicable diseases (NCDs), such as diabetes, cardiovascular diseases, respiratory diseases, and cancers (Katzmarzyk et al., 2022; Prüss-Ustün et al., 2019). These NCDs have emerged as leading causes of mortality in both developing and developed countries (Bennett et al., 2018). Hence, the dual impacts of urbanization and aging populations may further exacerbate the health burden in urban areas, especially for high-density cities with large aging populations. For instance, Hong Kong, ranked as the world's fourth-most densely populated city, is projected to witness a notable aging population. The proportion of individuals aged 65 or above will increase from 19% in 2021 to 31% in 2036, thereby its healthcare burden and expenditure will escalate rapidly (Census and Statistics Department, 2020). Thus, how to use urban environment intervention to mitigate healthcare burden during the course of urban development and aging populations has emerged as an imperative concern for both public health authorities and urban planners.

Urban greenspace, encompassing parks, gardens, greenways, street trees, and other forms of vegetation within urban environments, has been demonstrated to improve residents' well-being and reduce risks of various NCDs and relevant mortality. The health effects of urban greenspaces could be attributed to their social and ecological benefits, such as promoting physical activities, improving social interactions, and mitigating various pollution (Zhang et al., 2017). Most of the existing

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studies measure the quantity of urban greenspace with metrics, e.g., the area of greenspace and Normalized Difference Vegetation Index (NDVI). These studies have shown that increases in the quantity of greenspace provision were associated with reduced life expectancy loss (Wei et al., 2024) and reduced incidence of cardiovascular diseases (Chen et al., 2020), diabetes (Yu et al., 2022), chronic kidney diseases (Lee et al., 2023), and chronic respiratory diseases (Yang and Jiang, 2023). Similarly, urban greenspace has been demonstrated to have protective effects on all-cause and cause-specific mortality, especially mortality attributed to NCDs (Barboza et al., 2021; Crouse et al., 2017; Rojas-Rueda et al., 2019; Zhou et al., 2024). Moreover, some studies focusing on elderly populations have also indicated significant protective effects of urban greenspaces on their health (Ji et al., 2019; Wang et al., 2017; Wei et al., 2023). Further stratified analyses in several studies have revealed that the health effects of urban greenspace may be more pronounced among elderly populations (Besser et al., 2021; Ruijsbroek et al., 2017; Vries et al., 2003), probably due to elderly populations are more sensitive to nearby greenspace due to their limited mobility and activity space.

Another research front has shown that intrinsic characteristics of urban greenspace beyond mere quantity, are also crucial factors associated with urban residents' health. Characteristics of urban greenspaces have the potential to enhance the social and ecological benefits yielded from greenspaces, thereby affecting individual health to varying degrees (Knobel et al., 2019). A systematic review has revealed that different types of urban vegetation (e.g., forests, shrubs, and grasslands) may have various impacts on NCDs including cardiovascular diseases (Astell-Burt et al., 2021), obstructive airway diseases, and asthma (Nguyen et al., 2021). Besides, tree canopy, biodiversity, and amenities have been shown to be associated with risks of hypertension (Astell-Burt and Feng, 2020), cardiovascular diseases (Giacinto et al., 2021), and diabetes (De la Fuente et al., 2021). Regarding ecological studies targeting elderly populations, an international investigation has revealed that the overall quality of urban greenspace may promote walking behavior among the elderly, thereby improving their health (Shuvo et al., 2021). These studies have extensively revealed the health effects of quality of urban greenspace.

Greenspace morphology, which describes both form and spatial patterns of urban greenspace, has also been demonstrated to positively influence residents' health. Greenspace morphology is a landscape concept that measures how greenspaces are structured, organized, and distributed within a city. Unlike other greenspace metrics, such as availability and accessibility, which commonly measure the quantity of greenspace and how easily people can reach it, greenspace morphology provides a deeper understanding of how the spatial configuration of greenspace may deliver social and ecological benefits. Previous studies have well documented the associations between greenspace morphology and its social and ecological functions, such as increase in physical activity (Wang and Tassinary, 2024), reduction in air pollution (Bi et al., 2022), and mitigation of urban heat island effects (Li and Zhou, 2019). These social and ecological benefits of greenspace morphology may consequently improve urban residents' health and wellbeing. Furthermore, several ecological and cross-sectional studies have explicitly demonstrated diverse health effects of various aspects of greenspace morphology. For example, larger and more interconnected greenspaces, as well as greenspaces with complex shapes, have been found to have the potential to reduce the risks of all-cause mortality (Wang and Tassinary, 2019) and mortality attributed to respiratory (Jaafari et al., 2020) and cardiovascular diseases (Shen and Lung, 2016). More fragmented greenspaces have been found to be associated with higher mortality risks (Wang and Tassinary, 2019). Despite the insights, a notable research gap is that there is no comprehensive examination of greenspace morphology and its associations with mortality from various mortality risks simultaneously. Moreover, there has been limited investigation into potential variations in these associations among older populations or within neighborhoods with higher aging levels under the context of aging populations, with the exception of a study conducted in the UK. That study demonstrated the protective effects of greenspace patch size, diversity, and proximity on residents' health in neighborhoods with higher proportions of elderly individuals (Dennis et al., 2020). However, relevant evidence in the Asian context warrants further examination. These gaps underscore the need for nuanced investigations that consider the diverse dimensions of greenspace morphology and their differential impacts on mortality risks under an aging urban context.

Optimizing spatial arrangements of greenspace may represent an effective strategy beyond merely increasing the provision of greenspace to mitigate health-related mortality risks and healthcare burdens in cities. Hence, conducting a comprehensive investigation into the health effects of greenspace morphology from perspectives of different health outcomes and morphological features is warranted, especially in high-density cities characterized by significant aging populations. To bridge the gaps in existing evidence, this ecological study, taking Hong Kong as an example, aims to 1) examine the associations between greenspace morphology and risks of all-cause and cardiovascular disease mortality, respiratory disease mortality, and cancer mortality from the perspectives of size, fragmentation, shape, connectedness, and proximity; and 2) investigate disparities in these associations between neighborhoods with different proportion of aging population. Notably, our study is inspired by, and seeks to build upon, previous research that has highlighted preliminary associations between greenspace morphology and health, as well as their potential disparities. Findings from this study will provide valuable insights for urban planners and policymakers into the implementation of effective and health-promoting design and planning strategies for urban greenspace, ultimately contributing to achieving healthy and sustainable cities and communities.

2. Methods

2.1. Mortality data

The mortality data were obtained from the Registered Death files provided by the Census and Statistics Department of Hong Kong. These files encompass all residents of Hong Kong, including both locals and immigrants. Each record contains detailed information, comprising gender, age, 3-digit codes for place of residence, date of death, and causes of deaths classified by the International Classification of Diseases 10th Revision (ICD-10). Given that mortality from cardiovascular diseases (ICD-10 codes: I10-I69), respiratory diseases (ICD-10 codes: J00-J99), and cancers (ICD-10 codes: C00-C97) account for the majority (76%) of global mortality from NCDs (World Health Organization, 2023), and have been shown to be closely associated with urban greenspace (Yang et al., 2021), this study analyzed mortality attributed to these three causes, along with all-cause mortality.

Besides, according to the 3-digit codes for place of residence, the death records can be aggregated into Tertiary Planning Unit (TPU) level. TPUs are the smallest planning units in Hong Kong's town planning system, with an average area of 3.88 km^2 and typically accommodating around 25,000 residents. However, Certain TPUs with relatively smaller populations were frequently amalgamated with adjacent TPUs to create Small Tertiary Planning Unit Groups (STPUGs) in Hong Kong, resulting in an average area of 5.19 km^2 and an average population of 34,277 among the STPUGs. This approach ensures more reliable census statistics. Hence, we aggregated the death records from TPUs to STPUGs based on the matching information for subsequent analyses. Additionally, two STPUGs were excluded from the analyses due to unreliably disproportionate death records in comparison to their total population.

It is important to note that the land use data for calculation of greenspace morphology in Hong Kong is only available starting from 2018. To ensure the consistency with this data, we aggregated the mortality data from 2014 to 2018, assuming little change in land use in Hong Kong during the five years. This approach was taken to enhance the statistical power of the analysis. Consequently, this study encompassed a total of 212 STPUGs, comprising 225,014 records for all-cause deaths, 45,967 records for deaths from cardiovascular diseases, 50,136 records for deaths from respiratory diseases, and 69,393 records for deaths from cancers in Hong Kong from 2014 to 2018. Notably, 73.55% of all-cause mortality in Hong Kong over the five-year period was attributed to these three non-communicable diseases, which is worth of attention.

2.2. Greenspace morphology metrics

Greenspace was defined as any vegetative elements and open space abundant with vegetation in this study. Two datasets were used to extract greenspaces in Hong Kong. Firstly, the Planning Department of Hong Kong provides 10m × 10m land use raster data for 2018, which comprises 11 primary classes and 24 sub-classes of land use. This dataset serves as the highest-resolution land use data in Hong Kong, among which woodlands, shrublands, and grass lands were identified as greenspaces. Besides, vector boundaries of parks and gardens in Hong Kong were rasterized at a resolution of 10m × 10m to merge with land use data. This process supplemented greenspaces identified in the land use dataset with open space with rich vegetations. Considering the edge effect of administrative units, we created buffer zones for each STPUG to assess greenspace morphology within the buffer zones. Given the three-dimensional pedestrian road networks in Hong Kong (Sun et al., 2021), a 400m straight-line distance usually corresponds to approximately 10 min of walking, a duration widely reported as the threshold for residents' willingness to walk to access urban greenspaces (King et al., 2012). Therefore, we created a 400m Euclidean buffer around the boundaries of each STPUG to represent a realistic probability of greenspace exposure for residents within a 10-min walk. Seven greenspace morphology metrics from five dimensions (i.e., size, fragmentation, shape, connectedness, and proximity) were calculated in buffer areas of each STPUG. Specifically, percentage of greenspace (PLAND), largest patch index (LPI), and average greenspace area (AREA_MN) were selected to represent the size of greenspace; patch density (PD) was selected to assess the fragmentation of greenspace; area-weighted shape index (SHAPE_AM) was selected to analyze the shape of greenspace; cohesion index (COHESION) was selected to measure the connectedness of greenspaces, specifically, to what extent urban greenspaces connect with each other; and aggregation index (AI) was selected to assess the proximity between greenspaces, that is, to what extent urban greenspaces locate close to each other (Fig. 1). More details regarding the definition of these metrics are shown in supplementary materials (Table S1). These metrics are among the most commonly used measures of greenspace morphology in existing studies (Wang et al., 2024). The greenspace morphology metrics were calculated on Fragstats software version 4.2 (McGarigal et al., 2023).

2.3. Statistical analysis

Considering overdispersion of the death counts, with variance exceeding the mean, the hypothesis of Poisson regression model is rejected, and instead we fitted a negative binomial regression model to examine the associations between mortality and greenspace morphology metrics. We further tested the spatial dependency of both all-cause and cause-specific mortality, with the results indicating there is no statistically significant spatial autocorrelation for all-cause and cause-specific mortality (Table S2). The negative binomial regression model can be formulated as:

$$\log(death_i) = \beta_0 + \beta_1 GM_i + \sum \beta_n COV_i + offset(personyear_i)$$

In the formula, β_0 is the intercept, while β_1 is the estimated coefficient for greenspace morphology (*GM*) and β_n is the estimated coefficient for a set of covariates (*COV*). In each model, death counts attributed to each cause from 2014 to 2018 served as the response variable, while each greenspace morphology metric was treated as the exposure variable. We conducted a correlation analysis among the greenspace morphology metrics and found significant correlations between each pair of metrics (Fig. S1). Hence, single greenspace morphology metric was separately included in each model to avoid multicollinearity among various greenspace morphology metrics. Additionally, we also added an offset variable $offset(personyear_i)$ based on the person-year in each STPUG, which is typically used in environmental health studies to normalize death counts across spatial units with varying populations in a period.

Moreover, we included different covariates in the model. Specifically, we added the proportion of the population aged 65 or above to represent age structure, the sex ratio to represent gender, the proportion of the population with post-secondary education to represent education level, the unemployment rate to represent employment status, and median household income to represent socioeconomic status. These variables are commonly used in environmental health studies to control for the impacts of demographic and socioeconomic factors. Descriptive summary of control variables is shown in Table S4. The demographic and socioeconomic variables were derived from by-census reports of 2016 provided by the Census and Statistics Department of Hong Kong. We additionally tested the variance inflation factors (VIF) between

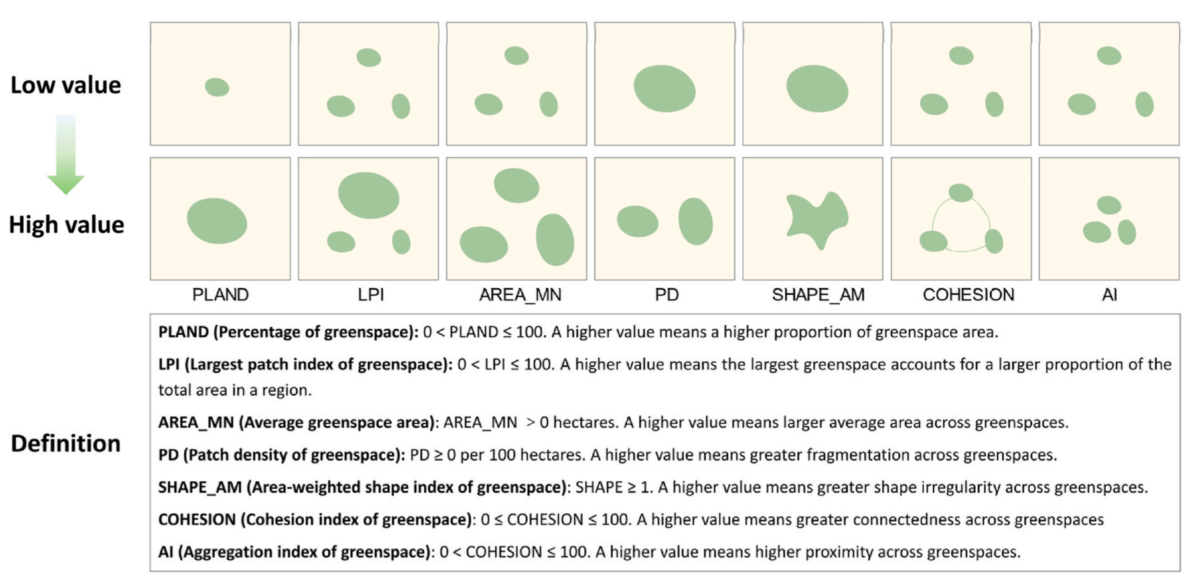

Fig. 1. Conceptual illustration of greenspace morphology metrics adapted from (Wang and Tassinary, 2019).

explanatory variables and control variables for each model; all VIF values are less than four, indicating there were no multicollinearity issues in the models. Notably, the explanatory variables were standardized before the regression analyses, and an exponential transformation was conducted for their regression coefficients to calculate rate ratio (RR) for better interpretation of the results.

We further conducted stratified analyses to investigate whether the effects of greenspace morphology on mortality significantly vary between neighborhoods (defined by STPUGs) with high and low aging levels. The aging level of neighborhoods is defined by the proportion of older adults in a community in this study. Specifically, STPUGs were divided into high and low groups based on the median value of the elderly proportion (16.1%), which closely matches the proportion of individuals aged 65 or above in Hong Kong. Neighborhoods with an elderly proportion greater than 16.1% were classified as having relatively high aging levels, while those with an elderly proportion below 16.1% were classified as having relatively low aging levels. We separately performed the regression analyses for each group and compared the results to explore the disparity of the results between neighborhoods with high and low aging levels. This approach provides a more comprehensive understanding of how the greenspace morphology of neighborhoods with varying aging levels affects mortality, which could capture the broader community context in which older adults reside. The regression analyses in this study were conducted using MASS package in R software version 4.1.1.

3. Results

3.1. Descriptive statistics of mortality and greenspace morphology

The descriptive statistics of mortality and greenspace morphology metrics are shown in Table 1. The average all-cause deaths, cardiovascular diseases mortality, respiratory disease mortality, and cancer mortality in Hong Kong during five years were 1061.40 (SD = 1628.95), 216.83 (SD = 326.30), 236.49 (SD = 395.01), 327.33 (SD = 484.57). Mortality from these three NCDs accounted for 73.55% of all-cause mortality, indicating these NCDs caused most of the all-cause mortality in Hong Kong. Over the five-year period, the mortality rate (deaths per 1000 persons) from cardiovascular diseases showed a continuous decreasing trend, declining from 1.35 in 2014 to 1.21 in 2018. In contrast, the all-cause mortality rate, respiratory disease mortality rate, and cancer mortality rate exhibited fluctuations over the same period (Fig. S2). For greenspace morphology metrics, the average values of the percentage of greenspace (PLAND), the largest pixel index of greenspace (LPI), the average greenspace area of greenspace (AREA_MN), the patch density of greenspace (PD), the area-weighted shape index of greenspace (SHAPE_AM), the cohesion index of greenspace (COHESION), and the aggregation index of greenspace (AI) were 42.85% (SD = 24.47), 29.44% (SD = 25.78), 2.01 ha (SD = 2.36), 34.90 per 100 ha (SD = 19.59), 4.15 units (SD = 2.75), 96.46 (SD = 3.73), and 91.05% (SD = 5.59). Notably, the average values of COHESION and AI were relatively high, indicating the urban greenspaces in Hong Kong exhibited high connectedness and proximity. In addition to connectedness and proximity, notable disparities were observed in the maximum and minimum values of other greenspace morphology metrics. These differences suggest that the size, fragmentation, and shape of urban greenspaces vary significantly among neighborhoods in Hong Kong, indicating inequities in spatial configuration of greenspace.

3.2. Effects of greenspace morphology on mortality

Fig. 2 and ***Table S5*** show the independent associations between greenspace morphology metrics and mortality, reported as RR with accompanying 95% confidence intervals (95%). The impacts of greenspace morphology metrics were similar on mortality from each type of causes. For size metrics, PLAND and LPI exhibited significantly negative associations with mortality, while the associations between AREA_MN and mortality were found to be statistically insignificant. For every 1 Standard Deviation (SD) increase in PLAND, the risk of mortality from all-causes, cardiovascular diseases, respiratory diseases, and cancers may decrease by 14.7% (95% CI: 8.1%–27.1%), 17.7% (7.6%–26.7%), 21.7% (10.5%–31.5%), and 13.8% (3.2%–23.2%). LPI demonstrated stronger protective effects compared to PLAND, potentially reducing the risks of mortality by 20.3% (10.0%–29.4%) for all causes, 20.2% (10.4%–28.9%) for cardiovascular diseases, 24.3% (13.5%–33.7%) for respiratory diseases, and 16.8% (6.6%–25.9%) for cancers. In addition, statistically insignificant results of PD indicates that fragmentation of greenspace were not significantly associated with mortality in Hong Kong.

Regarding shape, mortality from all-causes, cardiovascular diseases, respiratory diseases, and cancers were observed to decrease by 22.1% (95% CI: 12.0%–31.0%), 22.1% (12.2%–30.8%), 25.0% (14.0%–34.6%), and 22.0% (12.3%–30.6%) for every 1 SD increase in SHAPE_AM. This suggests that neighborhoods with more complex greenspace shapes tend to have lower mortality risks. Similarly, both the connectedness and proximity of greenspaces were found to be negatively associated with all-cause mortality, mortality from cardiovascular diseases and respiratory diseases. Specifically, every 1 SD increase in COHESION and AI was associated with a reduction of 12.3% (95%CI: 0.7%–22.5%) and 12.8% (1.7%–22.6%) in all-cause mortality, 12.5% (1.6%–22.2%) and 12.3% (1.7%–21.7%) in mortality from cardiovascular diseases, 15.7% (3.4%–26.4%) and 15.8% (4.0%–26.2%) in mortality from respiratory diseases. However, the significantly protective effects of greenspace connectedness and proximity were not observed for mortality from cancers.

3.3. Health effects of greenspace morphology in neighborhoods with different aging level

We further selected greenspace morphology metrics that

Table 1
Descriptive statistics of mortality and greenspace morphology.

	Mean	Median	Std.dev (SD)	Max	Min	units
Mortality (outcome)						
All-cause mortality	1061.40	351.50	1628.95	9258.00	0.00	Numbers
Cardiovascular disease mortality	216.83	68.50	326.30	1881.00	0.00	Numbers
Respiratory disease mortality	236.49	73.00	395.01	2543.00	0.00	Numbers
Cancer mortality	327.33	106.00	484.57	2393.00	0.00	Numbers
Greenspace morphology metrics (exposure)						
The percentage of greenspace (PLAND)	42.85	42.74	24.47	93.82	5.67	Percent
The largest pixel index of greenspace (LPI)	29.44	21.75	25.78	91.76	0.71	Percent
The average greenspace area (AREA_MN)	2.01	1.07	2.36	18.22	0.14	Hectares
The patch density (PD)	34.90	30.07	19.59	102.94	5.06	Number per 100 ha
The area-weighted shape index (SHAPE_AM)	4.15	3.27	2.75	19.69	1.24	units
The cohesion index (COHESION)	96.46	98.09	3.73	99.98	84.75	–
The aggregation index (AI)	91.05	92.12	5.59	98.83	70.55	percent

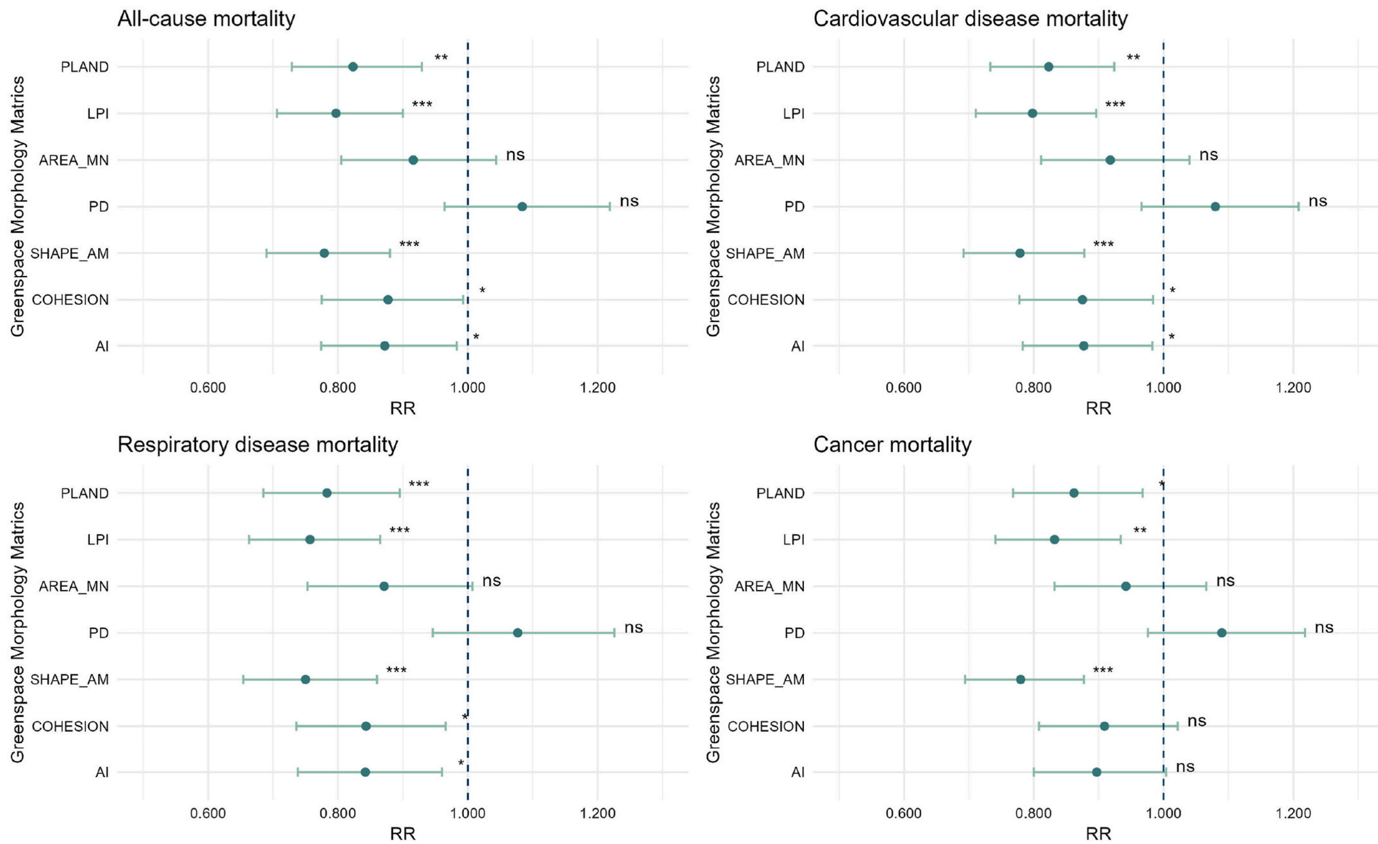

Fig. 2. Associations between greenspace morphology metrics and mortality (ns is not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

significantly associated with mortality for stratified analyses. Significant differences in protective effects of several greenspace morphology metrics on mortality between neighborhoods with different aging levels were found in stratified analyses (Table 2). Specifically, PLAND showed greater protective effects on mortality from cardiovascular diseases (RR: 0.805, 95%CI: 0.665–0.976) in neighborhoods with higher aging levels,

Table 2
Associations between metrics of greenspace morphology and mortality in neighborhood with different aging level.

	All-cause mortality RR (95% CI)	Cardiovascular disease mortality RR (95% CI)	Respiratory disease mortality RR (95% CI)	Cancer mortality RR (95% CI)
PLAND				
Higher aging neighborhoods	0.823 (0.674–1.005)	**0.805[a] (0.665–0.976)**	0.825 (0.671–1.013)	0.850 (0.696–1.038)
Lower aging neighborhoods	**0.853[a] (0.734–0.990)**	0.875 (0.760–1.007)	**0.768[b] (0.647–0.912)**	0.889 (0.774–1.020)
LPI				
Higher aging neighborhoods	**0.779[b] (0.645–0.941)**	**0.765[b](0.638–0.917)**	**0.788[a] (0.648–0.958)**	**0.793[a] (0.656–0.958)**
Lower aging neighborhoods	**0.844[a] (0.726–0.981)**	**0.865[a] (0.751–0.997)**	**0.753[b] (0.634–0.895)**	0.881 (0.767–1.013)
SHAPE_AM				
Higher aging neighborhoods	**0.767[b] (0.643–0.915)**	**0.745[b] (0.623–0.891)**	**0.763[b] (0.631–0.922)**	**0.728[c] (0.606–0.874)**
Lower aging neighborhoods	**0.811[a] (0.692–0.952)**	**0.844[a] (0.726–0.982)**	**0.731[c] (0.608–0.878)**	**0.837* (0.723–0.969)**
COHESION				
Higher aging neighborhoods	**0.787[a] (0.637–0.972)**	**0.775[a] (0.634–0.947)**	**0.774[a] (0.624–0.960)**	0.813 (0.659–1.004)
Lower aging neighborhoods	0.942 (0.813–1.093)	0.950 (0.827–1.091)	0.892 (0.752–1.059)	0.970 (0.847–1.111)
AI				
Higher aging neighborhoods	**0.793[a] (0.660–0.952)**	**0.798[a] (0.670–0.950)**	**0.793[a] (0.657–0.956)**	**0.801[a] (0.667–0.960)**
Lower aging neighborhoods	0.975 (0.839–1.132)	0.979 (0.850–1.127)	0.921 (0.774–1.096)	0.996 (0.868–1.143)

[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

while the protective effects were insignificant in neighborhoods with lower aging levels (RR: 0.875, 95%CI: 0.760–1.007). Inverse results were found for all-cause mortality and mortality from respiratory disease mortality, while the protective effects of PLAND on cancer mortality were insignificant in two groups of neighborhoods. For LPI, both two groups of neighborhoods presented significant results in mortality from different causes, except for cancers. The protective effects of LPI on all-cause mortality and mortality from cardiovascular diseases and cancers were slightly greater in neighborhoods with higher aging levels, even though some of the differences were not statistically significant. In contrast, inverse results were observed for mortality from respiratory diseases. Similar findings were observed for SHAPE_AM, indicating that the shape of greenspaces may be more strongly associated with reduced mortality in neighborhoods with higher aging levels. Interestingly, while the protective effects of greenspace connectedness and proximity were insignificant on mortality from all types of causes in neighborhoods with lower aging levels, they exhibited significant and more pronounced protective effects in neighborhoods with higher levels of aging. Specifically, every 1 SD increase in COHESION, the risk of mortality from all-causes, cardiovascular diseases, and respiratory diseases significantly decreased by 21.3% (95% CI: 2.8%–36.3%), 22.5% (5.3%–36.6%), and 22.6% (4.0%–37.6%). By comparison, every 1 SD increase in AI was associated with a significant reduction of 20.7% (4.8%–34.0%) in all-cause mortality, 20.2% (5.0%–33.0%) in mortality from cardiovascular diseases, 20.7% (4.4%–34.3%) in mortality from respiratory diseases, and 19.9% (4.0%–33.3%) in mortality from cancers. We further included interaction terms in the models to assess whether the health effects of greenspace morphology differ significantly between neighborhoods with varying aging levels (***Tables S6–S10***). The results indicate that the interaction term between COHESION and aging level is significant for all-cause mortality and cardiovascular disease mortality, while the interaction terms between AI and aging level is significant for all-cause mortality, cardiovascular disease mortality, and cancer mortality. These findings suggest that the impact of COHESION on all-cause and cardiovascular disease mortality is significantly more pronounced in neighborhoods with higher aging levels, while the effects of AI on all-cause, cardiovascular disease, and cancer mortality are similarly amplified in these neighborhoods.

3.4. Robustness test

We conducted the first robustness test by reperforming the aforementioned regression analyses using greenspace morphology metrics measured by 200m Euclidean buffers, which correspond to approximately a 5-min walking distance in the Hong Kong context. Descriptive summary of greenspace morphology is depicted in Table S3. The protective effects of PLAND, LPI, SHAPE_AM, COHESION, and AI on all-cause and cause-specific mortality remain statistically significant (Fig. 3, Table S11). Moreover, the health effects of COHESION and AI are more pronounced in neighborhoods with higher aging levels, while these effects are not statistically significant in neighborhoods with lower aging levels (Table S12). These results are consistent with our primary findings. Additionally, we conducted the second robustness test by reperformed the analyses for male and female mortality, respectively. Descriptive summary of mortality by gender is shown in ***Table S4***. The regression results depicted in Fig. 4, Table S1*3 and* Table S14 shows similar patterns compared to full-sample analyses. The protective effects of PLAND, LPI, SHAPE_AM, and AI on all-cause mortality, cardiovascular disease mortality, and respiratory disease mortality remain statistically significant for both male and female. However, while the association between COHESION and all-cause mortality remains statistically significant for male, it is not significant for female. For cancer mortality, the protective effects of PLAND and SHAPE_AM remain statistically significant for both males and females, consistent with the

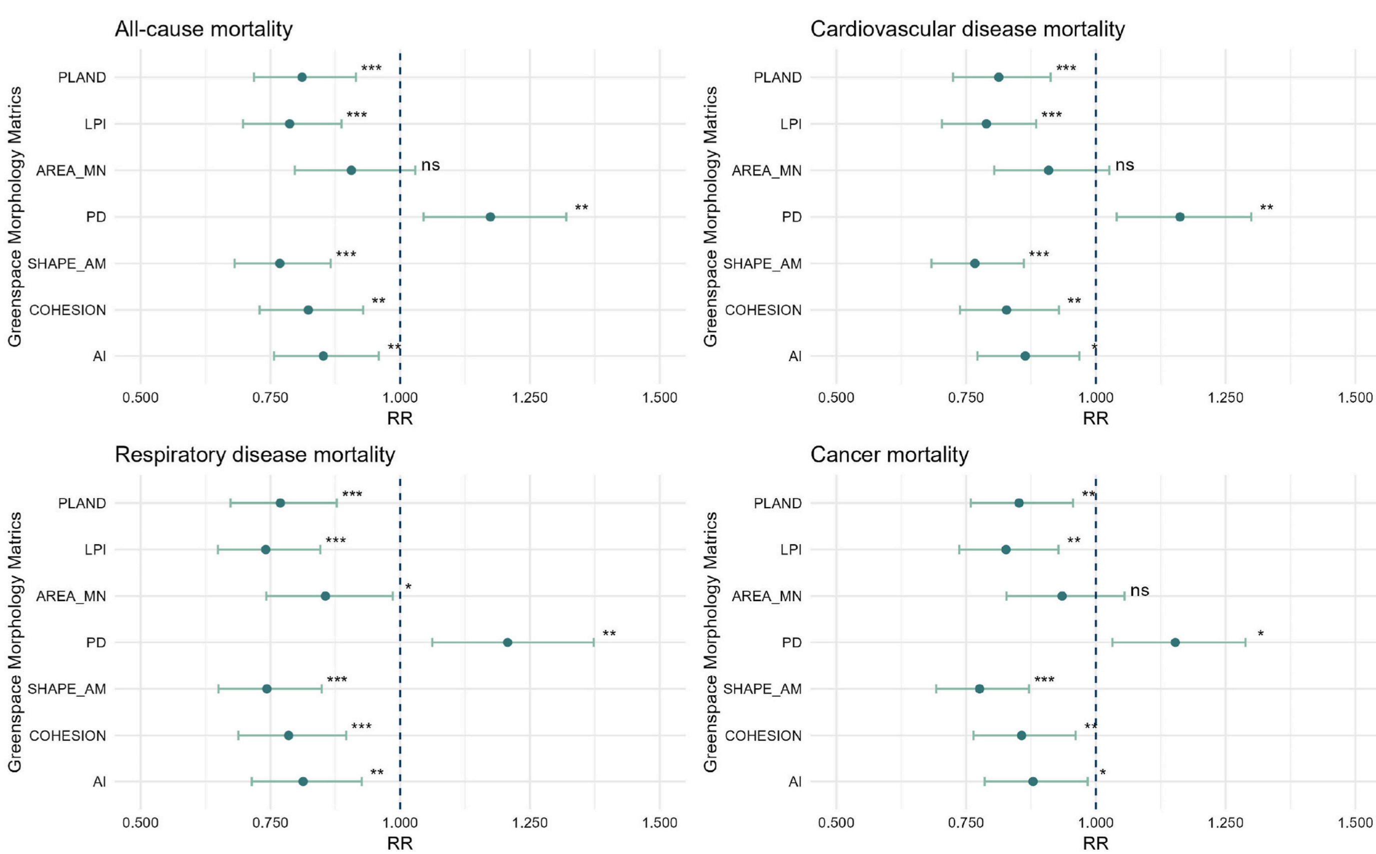

Fig. 3. Associations between metrics of greenspace morphology (measured by 200m buffer) and mortality (ns is not significant, *p < 0.05, **p < 0.01, ***p < 0.001).

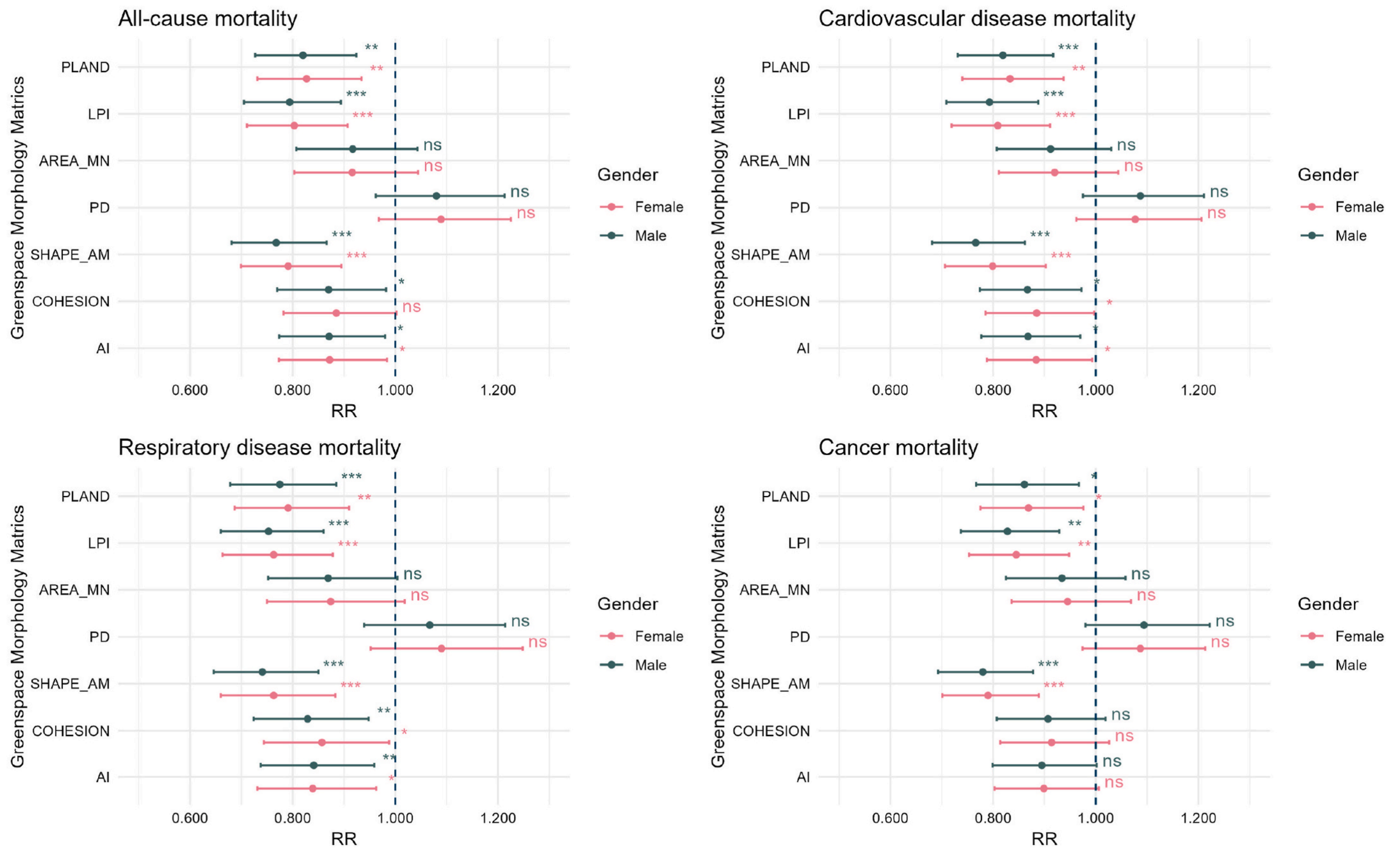

Fig. 4. Associations between metrics of greenspace morphology and mortality by gender (ns is not significant, *p < 0.05, **p < 0.01, ***p < 0.001).

main findings of the full-sample analyses. Additionally, neighborhoods with higher aging levels show greater protective effects of COHESION and AI on mortality for both males and females, except for cancer mortality for male. Overall, the main findings in our study remain largely consistent, suggesting that the primary analyses in our study are robust.

4. Discussion

In this ecological study, we examined the associations between greenspace morphology and mortality from all causes and three non-communicable diseases in Hong Kong. Greenspace morphology metrics from five dimensions (i.e., size, fragmentation, shape, connectedness, and proximity) were considered in this study, providing a comprehensive description of form and spatial configuration of greenspaces. In addition, we conducted stratified analyses to detect the variations in these associations between neighborhoods with high and low aging levels. This study extends to existing studies by providing robust evidence on the protective effects of greenspace morphology on mortality risks in a high-density Asian city (i.e. Hong Kong) from various aspects. The findings of this study underscore the significance of spatial structure and organization of greenspace for health, extending beyond simply increasing the quantitative provision of greenspace, particularly for society with high aging populations.

4.1. Principle findings and interpretation

By performing the negative binomial regression, we identified varying effects of size, fragmentation, shape, connectedness, and proximity of greenspaces on different types of mortality. For greenspace size, a higher proportion of greenspace area and a larger area of the largest greenspace in neighborhoods were associated with reduced risks of all-cause mortality and mortality from cardiovascular diseases, respiratory diseases, and cancers. These results are aligned with many previous studies, suggesting the protective effects of greenspace quantity on residents' health (Yang et al., 2021). By comparison, we also performed the analysis for normalized difference vegetation index (NDVI), a metric commonly used to quantify the magnitude of urban greenspaces. The results reveal significant associations between NDVI and reduced mortality risks (Table S15). It has been demonstrated that quantity metrics of greenspace, such as NDVI, accessibility, and availability are tightly associated with improving ecological environments, increasing physical activity, and promoting social interaction, thereby contributing to improvements in various health outcomes (Browning et al., 2022). Our findings contribute additional evidence on the potential health effects of greenspace quantity, specifically from a landscape perspective, particularly highlighting the importance of the largest greenspace area. The findings are aligned with existing evidence, which has demonstrated that larger parks tend to offer a wider range of recreational opportunities compared to smaller parks, thereby potentially offering greater health benefits (Sugiyama et al., 2010). Interestingly, the associations between average areas of greenspaces in neighborhoods and all types of mortality were found to be statistically insignificant, which is contradicted with previous evidence (Wang and Tassinary, 2019). A possible explanation is that greenspaces in the downtown areas of Hong Kong are typically small since its high-density nature. Thus, the general small size and limited variation in greenspace area may reduce the statistical power to detect such effect.

Regarding other morphology metrics, fragmentation of greenspaces in Hong Kong were found to be not statistically associated with mortality, probably due to relatively high proportion of small-size gardens in the urban settings (Tian et al., 2014). For the shape of greenspaces, our findings reveal the greatest protective effects of the shape index on all types of mortality compared to other greenspace morphology metrics.

Previous studies have also demonstrated the protective effects of the shape index on health (Wang and Tassinary, 2019). Greenspaces with more complex shapes may tend to be more connected to nearby residential areas and feature a greater variety of functional amenities and entrances, thereby facilitating residents' access to these greenspaces (Li et al., 2020; Rigolon, 2016). Also, previous evidence has shown that parks with more complex shapes may increase accessibility compared to parks with regular shapes (e.g., compact shapes) (Ngom et al., 2016). These, in turn, contribute to improving residents' health-related behaviors, such as social interaction and physical activity, thereby improving their health outcomes (Huang and Lin, 2023).

In addition, we further observed significant protective effects of connectedness and proximity of greenspaces on mortality from all-causes, cardiovascular diseases, and respiratory diseases, while such effects were not statistically significant for cancer mortality. These findings, however, remain inconsistent in previous studies, with some demonstrating significant protective effects while others have found insignificant associations (Jaafari et al., 2020; Shen and Lung, 2017; Wang and Tassinary, 2019). In a high-density environment (i.e., Hong Kong), interconnected small greenspaces like rest gardens or sitting-out areas, located closely to each other, could potentially enhance residents' accessibility, and extend their stay, thereby amplifying the health benefits associated with such greenspaces. Besides, some connected greenspaces along streets may provide residents with passive exposure to urban greenery during their commutes, thereby indirectly contributing to health benefits. Moreover, greenspaces characterized by higher levels of connectedness and proximity may have greater capacity to mitigate pollution and provide shading effects, thereby reducing risks of heat-related, respiratory, and other heart-related health issue (Liu et al., 2021; Wang and Tassinary, 2024). These findings and potential mechanisms extend beyond existing studies that focus solely on the health effects of greenspace quantity using traditional metrics such as accessibility and availability. While previous research has illustrated mechanisms linking urban greenspaces with health, such as reducing air pollution, promoting physical activity, and enhancing social interactions, these mechanisms also merit investigation in the context of greenspace morphology and its association with mortality. However, this falls outside the scope of our current study and is recommended as a direction for future studies.

Based on the stratified analyses, we observed that the protective effects of greenspace morphology on mortality risks tend to be higher in neighborhoods with higher aging levels than those with lower aging levels. Previous studies have suggested that neighborhoods with a higher proportion of elderly residents or an aging population may derive greater physical health from urban greenspaces (Besser et al., 2021; Ruijsbroek et al., 2017). Our study confirms and extends these findings from previous research by assessing such health effects of greenspaces from a perspective of their morphological features. While the disparities in the health effects of greenspace size and shape between neighborhoods with different aging levels were not statistically significant, the connectedness and proximity of greenspaces were found to significantly reduce mortality risks only in neighborhoods with higher aging levels. These findings are consistent with a previous study (Wang and Tassinary, 2019). An ecological study conducted in the UK has also found protective effects of greenspace proximity on health outcomes in neighborhoods characterized by higher proportion of older adults (Dennis et al., 2020), which supports our results to some extent. Higher levels of connectedness and proximity of urban greenspaces may make it more convenient for the elderly with limited mobility to access urban greenspaces, extend their stay, and increase their willingness to engage in health-related activities in these urban greenspaces, especially in a high-density urban environment (Ali et al., 2022). Hence, the connectedness and proximity of greenspaces may exhibit greater health effects in neighborhoods with higher aging level. By comparison, NDVI did not demonstrate a similar disparity in mortality, as indicated by the insignificant interaction terms (Table S16). These findings underscore the need for equitable and reliable landscape design of greenspaces in neighborhoods with higher aging levels.

4.2. Policy implications

Insights from our study provide several policy implications for urban planning and design, as well as public health policies. First, we highlight the importance of urban greenspace morphology besides greenspace quantity on mortality outcomes. Our findings suggest that large, irregular-shaped (high shape index), well-connected (high connectedness) and close-clustered (high proximity) greenspaces may effectively reduce all-cause and cause-specific mortality. Based on the findings, policymakers are suggested to prioritize these spatial structure characteristics when constructing new network of urban greenspaces. In high-density area with limited land resource, it is recommended to develop small- or medium-size greenspaces, such as rest gardens and pocket parks, to enhance the proximity between urban greenspaces within neighborhoods. Also, urban planners are recommended to enhance the connectivity of existing greenspaces using other vegetative elements, such as tree-lined streets or greenways, to improve the connectedness of urban greenspaces within neighborhoods. Moreover, it is advisable to incorporate diverse functional facilities, amenities, and vegetation arrangements in existing urban greenspaces with irregular shapes to enhance their quality, thereby maximizing their health effects. This approach may serve as an alternative intervention strategy for the existing urban greenspaces. Considering more pronounced health effects of greenspace connectedness and proximity in neighborhoods with higher aging levels, these two characteristics of greenspace morphology should be considered as two primary metrics to provide their health effects in neighborhoods with high aging levels. Urban planners and policymakers are suggested to prioritize the improvement of greenspace connectedness and proximity in neighborhoods with higher aging levels. In addition, our study also revealed the health effects of greenspaces with large size. Given there is limited available land in a high-density city to construct large greenspaces, it is recommended to effectively improve transportation infrastructure in these areas to enhance accessibility to existing large-scale but remote greenspaces (e.g., puri-urban parks) for elderly populations. We believe that these implications would be beneficial for policymakers in designing environmental interventions aimed at promoting urban residents' health.

4.3. Limitations and future directions

Several limitations in this study may introduce bias on the results, which requires to be addressed in future studies. First, the land use data with 10-m resolution may result in inaccurate identification of urban greenspace. Even though this is public-available data with the sufficient resolution to detect most small-scale greenspaces, this resolution may still not accurately capture small landscape elements, potentially introducing bias in the calculation of landscape metrics for greenspaces. Future studies are recommended to make an effort to develop land use data with higher resolution and conduct more nuanced analyses. For example, classifying the land use types from high-resolution satellite images using geospatial artificial intelligence (GeoAI) techniques may serve as a helpful approach (Tong et al., 2020).

Second, the residence-based paradigm of this ecological study may introduce spatiotemporal uncertainty of environmental exposure assessment. While the death records are at individual-level, the information regarding their residential locations is only available at the TPU level for the purpose of privacy protection. Additionally, the available census data finally constrained our study to the STPUG level, which served as neighborhoods in this study. The neighborhood-based paradigm of environmental health may be susceptible to the Uncertain Geographic Context Problem (UGCoP) as the spatiotemporal uncertainty in the given geographic units when measuring environmental exposure for individuals (Kwan, 2012). Moreover, the records lack information on the duration of residency, preventing us from distinguishing between long-term or short-term residents before their deaths. This limitation also introduces spatiotemporal uncertainty in measuring environmental exposure, potentially leading to the UGCoP. Hence, if individual-level data with more precise mobility information is available, future studies are recommended to conduct individual-level analyses to mitigate UGCoP and validate results found in this study.

Third, the absence of longitudinal data limits our study to revealing correlations between greenspace morphology and mortality, rather than establishing causal relationships. It should be acknowledged that we only conducted a cross-sectional ecological analysis to examine the health effects of greenspace morphology, primarily due to the unavailability of longitudinal land use data. Hence, the interpretation of our findings needs to be approached with caution, as they represent correlations rather than causal relationships (van den Berg et al., 2015). We call for further studies to conduct longitudinal analyses, if relevant data is available, to generate more compelling evidence regarding the link between urban greenspace morphology and diverse health outcomes.

Finally, the lack of a more nuanced classification of cause-specific mortality may limit our ability to distinguish results within broader categories of causes. For example, while our study suggests positive health effects of greenspace morphology on mortality from respiratory diseases, existing studies have demonstrated that the health impacts of greenspaces may differ between lung function and asthma. In our dataset, asthma cases were sparse, with 99 neighborhoods reporting zero cases and 29 reporting only one case. Besides, we also conducted a correlation analysis between respiratory disease records with and without asthma, finding a very strong correlation (Fig. S3). Given the ecological nature of our study, excluding asthma is unlikely to change the overall results significantly. Hence, we included the broader category of respiratory diseases in the analyses, consistent existing studies (Bauwelinck et al., 2021). The same issue applies to cancer mortality, where distinguishing between cancer subtypes could lead to sparse records and reduced statistical power. However, existing research indicates that associations between greenspace and cancer mortality may vary across different cancer types (Zare Sakhvidi et al., 2022). This limitation in our study, or in many ecological studies could be addressed by conducting individual-level studies. Where data is available, such studies could better distinguish the nuanced associations between greenspace morphology and health outcomes in individuals with different types of diseases.

5. Conclusion

In conclusion, we observed potentially protective effects of greenspace morphology metrics including size, shape, connectedness, and proximity on different types of mortality in Hong Kong. Concurrently, more pronounced protective effects of connectedness and proximity were found in neighborhoods with higher aging levels. Our study highlights the significance of greenspace morphology on improving urban residents' health in a high-density Asian city with high aging populations. Findings from this study provide valuable insights for policymakers and urban planners to prioritize the design of large-scale, irregular, connected, and close-clustered greenspaces in urban settings, particularly in neighborhoods with higher aging levels, with the aim of achieving a healthy aging society.

CRediT authorship contribution statement

Yuxuan Zhou: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Yi Lu:** Writing – review & editing, Validation, Supervision, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120095.

References

Ali, MdJ., Rahaman, M., Hossain, SkI., 2022. Urban green spaces for elderly human health: a planning model for healthy city living. Land Use Pol. 114, 105970. https://doi.org/10.1016/j.landusepol.2021.105970.

Astell-Burt, T., Feng, X., 2020. Urban green space, tree canopy and prevention of cardiometabolic diseases: a multilevel longitudinal study of 46 786 Australians. Int. J. Epidemiol. 49, 926–933. https://doi.org/10.1093/ije/dyz239.

Astell-Burt, T., Navakatikyan, M.A., Walsan, R., Davis, W., Figtree, G., Arnolda, L., Feng, X., 2021. Green space and cardiovascular health in people with type 2 diabetes. Health Place 69, 102554. https://doi.org/10.1016/j.healthplace.2021.102554.

Barboza, E.P., Cirach, M., Khomenko, S., Iungman, T., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., Kondo, M., Nieuwenhuijsen, M., 2021. Green space and mortality in European cities: a health impact assessment study. Lancet Planet. Health 5, e718–e730. https://doi.org/10.1016/S2542-5196(21)00229-1.

Bauwelinck, M., Casas, L., Nawrot, T.S., Nemery, B., Trabelsi, S., Thomas, I., Aerts, R., Lefebvre, W., Vanpoucke, C., Van Nieuwenhuyse, A., Deboosere, P., Vandenheede, H., 2021. Residing in urban areas with higher green space is associated with lower mortality risk: a census-based cohort study with ten years of follow-up. Environ. Int. 148, 106365. https://doi.org/10.1016/j.envint.2020.106365.

Bennett, J.E., Stevens, G.A., Mathers, C.D., Bonita, R., Rehm, J., Kruk, M.E., Riley, L.M., Dain, K., Kengne, A.P., Chalkidou, K., Beagley, J., Kishore, S.P., Chen, W., Saxena, S., Bettcher, D.W., Grove, J.T., Beaglehole, R., Ezzati, M., 2018. NCD Countdown 2030: worldwide trends in non-communicable disease mortality and progress towards Sustainable Development Goal target 3.4. Lancet 392, 1072–1088. https://doi.org/10.1016/S0140-6736(18)31992-5.

Besser, L.M., Lovasi, G.S., Michael, Y.L., Garg, P., Hirsch, J.A., Siscovick, D., Hurvitz, P., Biggs, M.L., Galvin, J.E., Bartz, T.M., Longstreth, W.T., 2021. Associations between neighborhood greenspace and brain imaging measures in non-demented older adults: the Cardiovascular Health Study. Soc Psychiatry Psychiatr Epidemiol 56, 1575–1585. https://doi.org/10.1007/s00127-020-02000-w.

Bi, S., Dai, F., Chen, M., Xu, S., 2022. A new framework for analysis of the morphological spatial patterns of urban green space to reduce PM2.5 pollution: a case study in Wuhan, China. Sustain. Cities Soc. 82, 103900. https://doi.org/10.1016/j.scs.2022.103900.

Browning, M.H.E.M., Rigolon, A., McAnirlin, O., Yoon, H. (Violet), 2022. Where greenspace matters most: a systematic review of urbanicity, greenspace, and physical health. Landsc. Urban Plann. 217, 104233. https://doi.org/10.1016/j.landurbplan.2021.104233.

Census and Statistics Department, 2020. Hong Kong Population Projections 2020-2069.

Chen, H., Burnett, R.T., Bai, L., Kwong, J.C., Crouse, D.L., Lavigne, E., Goldberg, M.S., Copes, R., Benmarhnia, T., Ilango, S.D., van Donkelaar, A., Martin, R.V., Hystad, P., 2020. Residential greenness and cardiovascular disease incidence, readmission, and mortality. Environmental Health Perspectives 128, 087005. https://doi.org/10.1289/EHP6161.

Crouse, D.L., Pinault, L., Balram, A., Hystad, P., Peters, P.A., Chen, H., Donkelaar, A. van, Martin, R.V., Ménard, R., Robichaud, A., Villeneuve, P.J., 2017. Urban greenness and mortality in Canada's largest cities: a national cohort study. Lancet Planet. Health 1, e289–e297. https://doi.org/10.1016/S2542-5196(17)30118-3.

De la Fuente, F., Saldías, M.A., Cubillos, C., Mery, G., Carvajal, D., Bowen, M., Bertoglia, M.P., 2021. Green space exposure association with type 2 diabetes mellitus, physical activity, and obesity: a systematic review. Int. J. Environ. Res. Publ. Health 18, 97. https://doi.org/10.3390/ijerph18010097.

Dennis, M., Cook, P.A., James, P., Wheater, C.P., Lindley, S.J., 2020. Relationships between health outcomes in older populations and urban green infrastructure size, quality and proximity. BMC Publ. Health 20, 626. https://doi.org/10.1186/s12889-020-08762-x.

Giacinto, J.J., Fricker, G.A., Ritter, M., Yost, J., Doremus, J., 2021. Urban forest biodiversity and cardiovascular disease: potential health benefits from California's street trees. PLoS One 16, e0254973. https://doi.org/10.1371/journal.pone.0254973.

Huang, W., Lin, G., 2023. The relationship between urban green space and social health of individuals: a scoping review. Urban For. Urban Green. 85, 127969. https://doi.org/10.1016/j.ufug.2023.127969.

Jaafari, S., Shabani, A.A., Moeinaddini, M., Danehkar, A., Sakieh, Y., 2020. Applying landscape metrics and structural equation modeling to predict the effect of urban green space on air pollution and respiratory mortality in Tehran. Environ. Monit. Assess. 192, 412. https://doi.org/10.1007/s10661-020-08377-0.

Ji, J.S., Zhu, A., Bai, C., Wu, C.-D., Yan, L., Tang, S., Zeng, Y., James, P., 2019. Residential greenness and mortality in oldest-old women and men in China: a longitudinal cohort study. Lancet Planet. Health 3, e17–e25. https://doi.org/10.1016/S2542-5196(18)30264-X.
Katzmarzyk, P.T., Friedenreich, C., Shiroma, E.J., Lee, I.-M., 2022. Physical inactivity and non-communicable disease burden in low-income, middle-income and high-income countries. Br. J. Sports Med. 56, 101–106. https://doi.org/10.1136/bjsports-2020-103640.
King, T.L., Thornton, L.E., Bentley, R.J., Kavanagh, A.M., 2012. Does parkland influence walking? The relationship between area of parkland and walking trips in Melbourne, Australia. Int. J. Behav. Nutr. Phys. Activ. 9, 115. https://doi.org/10.1186/1479-5868-9-115.
Knobel, P., Dadvand, P., Maneja-Zaragoza, R., 2019. A systematic review of multi-dimensional quality assessment tools for urban green spaces. Health Place 59, 102198. https://doi.org/10.1016/j.healthplace.2019.102198.
Kwan, M.-P., 2012. The Uncertain geographic context Problem. Ann. Assoc. Am. Geogr. 102, 958–968. https://doi.org/10.1080/00045608.2012.687349.
Lee, W., Heo, S., Stewart, R., Wu, X., Fong, K.C., Son, J.-Y., Sabath, B., Braun, D., Park, J. Y., Kim, Y.C., Lee, J.P., Schwartz, J., Kim, H., Dominici, F., Bell, M.L., 2023. Associations between greenness and kidney disease in Massachusetts: the US Medicare longitudinal cohort study. Environ. Int. 173, 107844. https://doi.org/10.1016/j.envint.2023.107844.
Li, Fangzheng, Li, Fengyi, Li, S., Long, Y., 2020. Deciphering the recreational use of urban parks: experiments using multi-source big data for all Chinese cities. Sci. Total Environ. 701, 134896. https://doi.org/10.1016/j.scitotenv.2019.134896.
Li, X., Zhou, W., 2019. Optimizing urban greenspace spatial pattern to mitigate urban heat island effects: extending understanding from local to the city scale. Urban For. Urban Green. 41, 255–263. https://doi.org/10.1016/j.ufug.2019.04.008.
Liu, J., Zhang, L., Zhang, Q., Zhang, G., Teng, J., 2021. Predicting the surface urban heat island intensity of future urban green space development using a multi-scenario simulation. Sustain. Cities Soc. 66, 102698. https://doi.org/10.1016/j.scs.2020.102698.
McGarigal, K., Cushman, S., Ene, E., 2023. FRAGSTATS V4: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors.
Ngom, R., Gosselin, P., Blais, C., 2016. Reduction of disparities in access to green spaces: their geographic insertion and recreational functions matter. Appl. Geogr. 66, 35–51. https://doi.org/10.1016/j.apgeog.2015.11.008.
Nguyen, P.-Y., Astell-Burt, T., Rahimi-Ardabili, H., Feng, X., 2021. Green space quality and health: a systematic review. Int. J. Environ. Res. Publ. Health 18, 11028. https://doi.org/10.3390/ijerph182111028.
Prüss-Ustün, A., Deventer, E. van, Mudu, P., Campbell-Lendrum, D., Vickers, C., Ivanov, I., Forastiere, F., Gumy, S., Dora, C., Adair-Rohani, H., Neira, M., 2019. Environmental risks and non-communicable diseases. BMJ 364, l265. https://doi.org/10.1136/bmj.l265.
Rigolon, A., 2016. A complex landscape of inequity in access to urban parks: a literature review. Landsc. Urban Plann. 153, 160–169. https://doi.org/10.1016/j.landurbplan.2016.05.017.
Rojas-Rueda, D., Nieuwenhuijsen, M.J., Gascon, M., Perez-Leon, D., Mudu, P., 2019. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. Lancet Planet. Health 3, e469–e477. https://doi.org/10.1016/S2542-5196(19)30215-3.
Ruijsbroek, A., Droomers, M., Kruize, H., Van Kempen, E., Gidlow, C.J., Hurst, G., Andrusaityte, S., Nieuwenhuijsen, M.J., Maas, J., Hardyns, W., Stronks, K., Groenewegen, P.P., 2017. Does the health impact of exposure to neighbourhood green space differ between population groups? An explorative study in four European cities. Int. J. Environ. Res. Publ. Health 14, 618. https://doi.org/10.3390/ijerph14060618.
Shen, Y.-S., Lung, S.-C.C., 2017. Mediation pathways and effects of green structures on respiratory mortality via reducing air pollution. Sci. Rep. 7, 42854. https://doi.org/10.1038/srep42854.
Shen, Y.-S., Lung, S.-C.C., 2016. Can green structure reduce the mortality of cardiovascular diseases? Sci. Total Environ. 566–567, 1159–1167. https://doi.org/10.1016/j.scitotenv.2016.05.159.
Shuvo, F.K., Feng, X., Astell-Burt, T., 2021. Urban green space quality and older adult recreation: an international comparison. Cities & Health 5, 329–349. https://doi.org/10.1080/23748834.2020.1766781.
Sugiyama, T., Francis, J., Middleton, N.J., Owen, N., Giles-Corti, B., 2010. Associations between recreational walking and attractiveness, size, and proximity of neighborhood open spaces. Am J Public Health 100, 1752–1757. https://doi.org/10.2105/AJPH.2009.182006.
Sun, G., Webster, C., Zhang, X., 2021. Connecting the city: a three-dimensional pedestrian network of Hong Kong. Environ. Plan. B Urban Anal. City Sci. 48, 60–75. https://doi.org/10.1177/2399808319847204.
Tian, Y., Jim, C.Y., Wang, H., 2014. Assessing the landscape and ecological quality of urban green spaces in a compact city. Landsc. Urban Plann. 121, 97–108. https://doi.org/10.1016/j.landurbplan.2013.10.001.
Tong, X.-Y., Xia, G.-S., Lu, Q., Shen, H., Li, S., You, S., Zhang, L., 2020. Land-cover classification with high-resolution remote sensing images using transferable deep models. Remote Sensing of Environment 237, 111322. https://doi.org/10.1016/j.rse.2019.111322.
van den Berg, M., Wendel-Vos, W., van Poppel, M., Kemper, H., van Mechelen, W., Maas, J., 2015. Health benefits of green spaces in the living environment: a systematic review of epidemiological studies. Urban For. Urban Green. 14, 806–816. https://doi.org/10.1016/j.ufug.2015.07.008.
Vries, S. de, Verheij, R.A., Groenewegen, P.P., Spreeuwenberg, P., 2003. Natural environments—healthy environments? An exploratory analysis of the relationship between greenspace and health. Environ. Plann. A. https://doi.org/10.1068/a35111.
Wang, D., Lau, K.K.-L., Yu, R., Wong, S.Y.S., Kwok, T.T.Y., Woo, J., 2017. Neighbouring green space and mortality in community-dwelling elderly Hong Kong Chinese: a cohort study. BMJ Open 7, e015794. https://doi.org/10.1136/bmjopen-2016-015794.
Wang, H., Gholami, S., Xu, W., Samavatekbatan, A., Sleipness, O., Tassinary, L.G., 2024. Where and how to invest in greenspace for optimal health benefits: a systematic review of greenspace morphology and human health relationships. Lancet Planet. Health 8, e574–e587. https://doi.org/10.1016/S2542-5196(24)00140-2.
Wang, H., Tassinary, L.G., 2024. Association between greenspace morphology and prevalence of non-communicable diseases mediated by air pollution and physical activity. Landsc. Urban Plann. 242, 104934. https://doi.org/10.1016/j.landurbplan.2023.104934.
Wang, H., Tassinary, L.G., 2019. Effects of greenspace morphology on mortality at the neighbourhood level: a cross-sectional ecological study. Lancet Planet. Health 3, e460–e468. https://doi.org/10.1016/S2542-5196(19)30217-7.
Wei, D., Lu, Y., Wu, X., Ho, H.C., Wu, W., Song, J., Wang, Y., 2023. Greenspace exposure may increase life expectancy of elderly adults, especially for those with low socioeconomic status. Health Place 84, 103142. https://doi.org/10.1016/j.healthplace.2023.103142.
Wei, D., Lu, Y., Zhou, Y., Ho, H.C., Jiang, B., 2024. The effect of peri-urban parks on life expectancy and socioeconomic inequalities: a 16-year longitudinal study in Hong Kong. Landsc. Urban Plann. 252, 105192. https://doi.org/10.1016/j.landurbplan.2024.105192.
World Health Organization (WHO), 2023. Non communicable diseases [WWW Document]. URL. https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases, 4.9.24.
Yang, B.-Y., Zhao, T., Hu, L.-X., Browning, M.H.E.M., Heinrich, J., Dharmage, S.C., Jalaludin, B., Knibbs, L.D., Liu, X.-X., Luo, Y.-N., James, P., Li, S., Huang, W.-Z., Chen, G., Zeng, X.-W., Hu, L.-W., Yu, Y., Dong, G.-H., 2021. Greenspace and human health: an umbrella review. Innovation 2, 100164. https://doi.org/10.1016/j.xinn.2021.100164.
Yang, Y., Jiang, B., 2023. Green spaces in highly urbanized tracts tied to lower prevalence of chronic respiratory diseases: a nationwide study across levels of urbanicity. Urban For. Urban Green. 90, 128149. https://doi.org/10.1016/j.ufug.2023.128149.
Yu, L., Li, T., Yang, Z., Zhang, X., Xu, L., Wu, Y., Yu, Z., Shen, P., Lin, H., Shui, L., Tang, M., Jin, M., Chen, K., Wang, J., 2022. Long-term exposure to residential surrounding greenness and incidence of diabetes: a prospective cohort study. Environmental Pollution 310, 119821. https://doi.org/10.1016/j.envpol.2022.119821.
Zare Sakhvidi, M.J., Yang, J., Mehrparvar, A.H., Dzhambov, A.M., Ebrahimi, A., Dadvand, P., Jacquemin, B., 2022. Exposure to greenspace and cancer incidence, prevalence, and mortality: a systematic review and meta-analyses. Sci. Total Environ. 838, 156180. https://doi.org/10.1016/j.scitotenv.2022.156180.
Zhang, L., Tan, P.Y., Diehl, J.A., 2017. A conceptual framework for studying urban green spaces effects on health. Journal of Urban Ecology 3, jux015. https://doi.org/10.1093/jue/jux015.
Zhou, Y., Lu, Y., Wei, D., He, S., 2024. Impacts of social deprivation on mortality and protective effects of greenness exposure in Hong Kong, 1999–2018: a spatiotemporal perspective. Health Place 87, 103241. https://doi.org/10.1016/j.healthplace.2024.103241.