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Research Paper

The effect of peri-urban parks on life expectancy and socioeconomic inequalities: A 16-year longitudinal study in Hong Kong

Di Wei [a,b,c], Yi Lu [c,*], Yuxuan Zhou [c], Hung Chak Ho [d,e], Bin Jiang [f,g]

[a] School of Architecture and Urban Planning, Huazhong University of Science and Technology, Wuhan, China
[b] Hubei Engineering and Technology Research Center of Urbanization, Wuhan, China
[c] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong SAR, China
[d] Department of Public and International Affairs, City University of Hong Kong, Hong Kong SAR, China
[e] Social Determinants of Health Initiative, City University of Hong Kong, Hong Kong SAR, China
[f] Urban Environments and Human Health Lab, Faculty of Architecture, The University of Hong Kong, Hong Kong SAR, China
[g] Division of Landscape Architecture, Department of Architecture, The University of Hong Kong, Hong Kong SAR, China

HIGHLIGHTS

- Exposure to peri-urban parks (PUPs) was positively linked to life expectancy.
- The life-expectancy benefits of PUP greenery were significant throughout 200–8000 m buffers.
- Higher-SES populations had higher PUP exposure.
- Higher-SES populations gained more life-expectancy benefits from PUPs.

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ABSTRACT

Exposure to greenspaces has well-established benefits for the health and well-being of urban dwellers. Among these greenspaces, peri-urban parks (PUPs), which are human-modified, large-scale, and public-accessible greenspaces located on the urban fringe, have received increasing attention from policymakers and researchers in recent years, as the limited provision of greenspaces in urban areas barely meet the residents' needs for nature engagement. However, the associations between PUPs and life expectancy and their potential socioeconomic inequalities remain unclear. In this study, we employed a longitudinal, territory-wide death-registration dataset to address such research gaps. The results showed that both the area and greenery of PUP significantly decreased life expectancy loss with standardized coefficients of −0.156 ($p = 0.001$) and −0.173 ($p < 0.001$), respectively. The life-expectancy benefits of PUP greenery remain significant throughout 200–8000 m buffer radii. Nevertheless, socioeconomic inequalities were found between PUPs and life expectancy associations. We found that people with higher socioeconomic status (SES) received higher PUP exposure. In addition, contrary to the hypothesis of equigenesis theory, higher-SES populations received greater benefits in life expectancy than lower-SES populations, even after controlling for inequalities in PUP exposure. Our findings uncover a complex relationship between PUPs, life expectancy, and SES, highlighting the need for targeted interventions for people with different SES to ensure equitable health benefits for all.

1. Introduction

Global urbanization has been rapidly advancing. Urban land coverage is expected to expand by roughly 1.5 million km^2 by 2030, marking a 185 % increase since 2000; by then, 60 % of the world's population will reside in urban areas (Seto et al., 2012). Such rapid and large-scale urbanization poses a persistent and ongoing challenge because it reduces people's interaction with nature and reduces the associated health benefits gained from exposure to nature (Markevych et al., 2017).

* Corresponding author.
E-mail addresses: diwei3-c@my.cityu.edu.hk, weidi_0522@foxmail.com (D. Wei), yilu24@cityu.edu.hk (Y. Lu), yuxuzhou3-c@my.cityu.edu.hk (Y. Zhou), hungcho2@cityu.edu.hk (H.C. Ho), jiangbin@hku.hk (B. Jiang).

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Comprehending the benefits of natural environments for urban-population health and maximizing these health effects has consistently been a central issue in several research fields (e.g., public health, urban studies) (Hartig et al., 2014; Liu et al., 2023; Wei, Liu, et al., 2023). Various reviews and meta-analyses have confirmed the multiple significant health benefits of urban greenspaces (Browning et al., 2022; Hartig et al., 2014; Rojas-Rueda et al., 2019). These benefits include increased mental health (Markevych et al., 2017; Yang et al., 2023), reduced obesity (He et al., 2022; Y. Jiang et al., 2022), lower risk of chronic diseases (e.g., cardiovascular disease, respiratory disease) (Orioli et al., 2019; Vienneau et al., 2017; H. Wang & Tassinary, 2019; Yao et al., 2022).

Furthermore, exposure to urban greenspaces is also linked to lower mortality rates and higher life expectancy, which serve as comprehensive measures of population health and well-being (Barboza et al., 2021; Wei, Lu, et al., 2023). Specifically, the majority of evidence suggests that increased urban and neighborhood greenspaces are associated with reduced all-cause mortality rates in North America (Twohig-Bennett & Jones, 2018), the United Kingdom (R. Mitchell & Popham, 2008), and Europe (Barboza et al., 2021). Similar results are also found in China, Australia, and Latin America (Moran et al., 2021; Rojas-Rueda et al., 2019).

In addition, exposure to urban greenspaces, especially nearby greenspaces in neighborhoods, may reduce health disparities and injustices among different population subgroups. Populations with low socioeconomic status (SES) often face worse health status due to insufficient health-related resources (R. Mitchell & Popham, 2008). One potential solution to narrow such inequalities is the provision of neighborhood greenspaces as they serve as public and accessible health-related venues, which is coined as equigenesis theory (R. J. Mitchell et al., 2015; R. Wang et al., 2022). This theory suggests that individuals of lower SES may disproportionately derive more health benefits from urban greenspaces than those of higher SES. The low-SES group may use these greenspaces more often and gain more health benefits than the high-SES group because the latter often has other health-related resources beyond greenspaces (Rigolon et al., 2021). Several empirical studies also confirmed equigenesis theory in mental health (R. J. Mitchell et al., 2015; R. Wang et al., 2022), CVD (Dzhambov et al., 2018), obesity (Villeneuve et al., 2018), general health (Rigolon et al., 2021), and mortality (Rigolon et al., 2021).

However, most of these empirical studies focus on greenspaces in neighborhoods or urban areas, with little evidence focusing on peri-urban greenspaces, which are spaces on the fringe of the city with intricate spatial patterns of landscapes (Žlender & Ward Thompson, 2017). Peri-urban greenspaces have gained increasing attention in urban planning and policymaking due to their pivotal role in meeting rising demands for nature access (Zhang et al., 2021a). Peri-urban parks (PUPs), which refer to human-modified and public-accessible natural or semi-natural areas on the outskirts of urban areas, are arguably the most important component of peri-urban greenspaces (Žlender & Ward Thompson, 2017). Research consistently confirms the high usage of PUPs (Conedera et al., 2015; Lu et al., 2021; Norman & Pickering, 2019; Wu et al., 2023). They provide various functions for urban residents to engage with the natural environment, including leisure, entertainment, travel, sports, and environmental education (Verdú-Vázquez et al., 2021; Zhang et al., 2021b). Compared to urban parks, PUPs offer larger areas, rich landscape assets, valuable cultural heritage properties, more pristine ecological environments, and diverse recreational spaces (Zhang et al., 2021b). In addition, urban residents' acceptable accessibility of PUPs and urban parks varies significantly. Specifically, urban parks located within 300 to 400 m of residential areas are used more frequently, and as the distance increases beyond this threshold, the usage of urban parks declines rapidly (Annerstedt et al., 2012; Zhang et al., 2021b). Conversely, urban residents exhibit greater tolerance to the accessibility of PUPs, as travel time had insignificant effects on PUP use (Gu et al., 2020).

Although PUPs play a crucial role for urban dwellers, there is a notable research gap concerning the effects of PUP on health outcomes and environmental justice. In detail, prior research utilized surveys to examine the health effects of PUPs (Carrus et al., 2015). However, the survey-based research relied on self-reported health status, which is susceptible to recall and social desirability bias (Coughlin, 1990). Also, it employed cross-sectional datasets with relatively small sample sizes and limited spatial coverage, raising concerns about the generalizability of their findings (X. Wang & Cheng, 2020). To our knowledge, no studies have employed longitudinal datasets to examine the health benefits of PUPs with objective indicators (e.g., mortality rate, life expectancy) at a large regional scale (e.g., citywide level).

Furthermore, studies related to environmental justice and socioeconomic inequalities in PUPs have predominantly concentrated on PUP accessibility and PUP exposure, which revealed that SES-advantaged groups had higher PUP exposure (Y. Chen et al., 2020; Suárez et al., 2020; Zhang et al., 2021a). Such inequalities in PUP exposure could be material factors that may contribute to health-related inequalities (Arcaya et al., 2015). To our knowledge, little research has investigated the socioeconomic inequalities in the health effects of PUPs. Lack of the above knowledge may result in ineffective policy and planning as well as inadequate use of PUP resources.

Therefore, we evaluated the effects of PUPs on life expectancy and environmental justice via a territory-wide death-registration longitudinal dataset from 2001 to 2016 in Hong Kong. Using territory-wide datasets is a reliable approach; it allows for the direct differentiation of environmental effects across diverse population groups and has the advantages of large sample size, reduced response bias, and generalizability (H.-L. Li et al., 2022). In addition, compared to the cross-sectional dataset used in previous PUP-health research (Carrus et al., 2015), the advantages of our longitudinal research design include enhanced precision in estimating model parameters, revealing dynamic association, and producing more accurate predictions (Hsiao, 2007). Moreover, we chose life expectancy as the health indicator; it has been recognized as an advanced and more informative health indicator than mortality because it considers the time and sex of deaths and places greater emphasis on deaths with younger ages (Moran et al., 2021; Wei, Lu, et al., 2023).

This research extends prior studies in three ways. First, this is among the first studies to assess the effect of PUPs on life expectancy, enhancing the knowledge of health benefits provided by PUPs. Second, it examined the socioeconomic inequalities related to life expectancy, PUP exposure, and the health effects of PUPs. Notably, we revealed an unexpected pattern, which enriched the knowledge of equigenesis theory. Third, it compared the effects of PUPs across varying buffer sizes, shedding light on the effective coverages of PUPs. This provides precise quantitative support for refined urban planning and management.

2. Methodology

2.1. Study design

This research was undertaken in Hong Kong, one of the most densely populated urban centers in the world. The city accommodates a population of 7.48 million residents in 2020 and spans a total land area of 1104 km^2. We chose Hong Kong as the study area due to its advanced urban planning, extensive and well-structured PUP service, providing a strong basis for examining the effect of PUP exposure. PUPs widely include forestry parks, country parks, and other human-modified sites in the peri-urban environment for public recreational purposes (Verdú-Vázquez et al., 2021; Zhang et al., 2021b). Thus, using data from the government (Agriculture, Fisheries and Conservation Department, 2017a), a total of 24 PUPs in Hong Kong were identified, with an average area of 18.658 km^2 (Fig. 1b).

We employed tertiary planning units (TPUs) as the unit of analysis, which are delineated by the Hong Kong Planning Department for urban

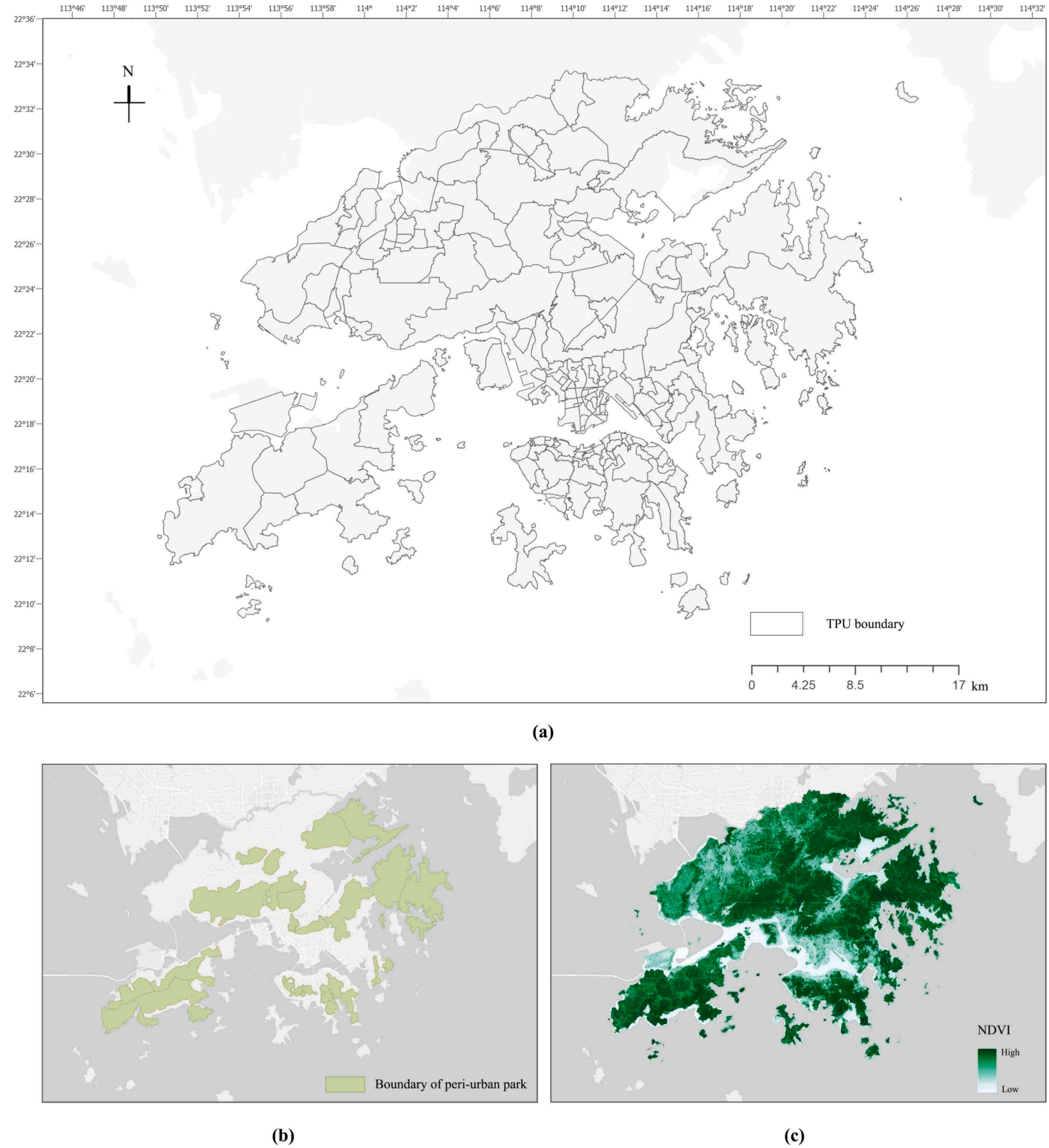

Fig. 1. The map of study area (Hong Kong). (a) TPU boundaries; (b) PUP boundaries; (c) The greenery level of PUPs evaluated by NDVI in Hong Kong.

planning and management purposes. Considering minor changes in TPU boundaries between 2001 and 2016, we merged and matched changing TPU boundaries with neighboring units. This adjustment yielded 179 adjusted TPUs for our study (Fig. 1a), with an average area of 6.198 km^2.

To comprehensively examine the effect of PUPs on life expectancy, we performed three sets of analyses. First, we examined the effects of PUP (i.e., area and greenery of PUP) on life expectancy and compared the effects with those of overall greenery in Hong Kong and greenery in urban areas of Hong Kong. Second, we examined differences in PUP exposure, life expectancy, and the life-expectancy effects of PUPs across SES groups to evaluate environmental justice. This analysis can examine whether PUP can ameliorate socioeconomic inequalities in life expectancy or potentially exacerbate such inequalities. Third, we examined the effects of PUPs and SES moderation across different buffer radii, aiming to determine an appropriate buffer zone and offer clear quantitative guidance for urban planning and public policy initiatives.

2.2. Measures

2.2.1. Life expectancy loss

We acquired anonymized individual mortality records in Hong Kong between 2001 and 2016 from Hong Kong Census and Statistics Department (HKCSD). Such datasets include age at death, residence with TPU code, date of death, and underlying cause based on death certificate codes. We assessed associations for all non-accidental deaths (A00–R99) using Tenth Revision codes (ICD-10) (World Health Organization, 2004) and excluded records outside A00–R99. Furthermore, we excluded records with unknown age at death or residence location. The final mortality dataset encompasses a total of 603,942 deaths.

Following previous research (Cheng et al., 2021; Qi et al., 2020; Wei, Lu, et al., 2023), we calculated years of life lost (YLL) to examine the life expectancy loss. YLL of each death was calculated by matching death year, age, and sex from the life expectancy table provided by HKCSD. We evaluated the annual life expectancy loss at the TPU level for each year from 2001 to 2016 based on the residence with TPU code provided by the individual mortality records. The sum of YLL for each TPU, adjusted for population size, served as the outcome of this study.

2.2.2. Exposure to PUPs

To thoroughly assess the association between PUPs and residents' life expectancy, we calculated the area and greenery of PUPs. In detail, the PUP area was calculated via park boundaries provided by Agriculture, Fisheries and Conservation Department (AFCD). The greenery of PUP was measured via the normalized difference vegetation index (NDVI), a recognized greenery indicator calculated by land surface reflectance at the pixel level based on remote sensing. The NDVI value (Fig. 1c) was calculated using the equation below.

$$NDVI = \frac{NIR - R}{NIR + R}$$

Where NIR denotes the near-infrared band, R denotes the red reflectance.

We calculated NDVI based on Landsat 5 and 8 satellite images (Collection 1, Tier 1, Surface Reflectance) for the entire year from 2001 to 2016 at 30-m resolution. Specifically, we first performed cloud pixel removal on satellite images via the Pixel Quality Assessment Band (PIXEL_QA). To ensure that the values of snow and water did not affect the results, we assigned zero to all pixels having negative NDVI results before performing calculations (Lillesand et al., 2015; Wei, Lu, et al., 2023). Then, we employed an average-value procedure to generate annual NDVI composites. Yearly NDVI was chosen to account for temporal variations in greenspace coverage.

We used two distant methods to measure PUP exposure at the TPU level: normal and population-weighted approaches. First, we calculated the total PUP area and the average NDVI within each TPU boundary. Second, we evaluated population-weighted exposure to PUPs across different buffer sizes (100 m to 4 km) for each TPU. The population-weighted approach represents a bottom-up evaluation (B. Chen et al., 2022). This approach accounted for the spatial interaction between population distribution and allocation of greenspaces, assigning greater weight to areas of higher population density. In addition, it considered not only greenspaces within the grid but also those within a spatial range around the grid (e.g., 400 m, 800 m) (Fig. 2). We computed the population-weighted exposure to greenery for varying buffer sizes within each TPU via the equation below (B. Chen et al., 2022).

$$GA = \frac{\sum_{i=1}^{N} P_i \times G_i^b}{\sum_{i=1}^{N} P_i}$$

Where P_i denotes the population of the ith grid, G_i^b stands for the greenery coverage of the ith grid using a buffer size of b m, N represents the total grid count within a specific TPU, and GA represents the

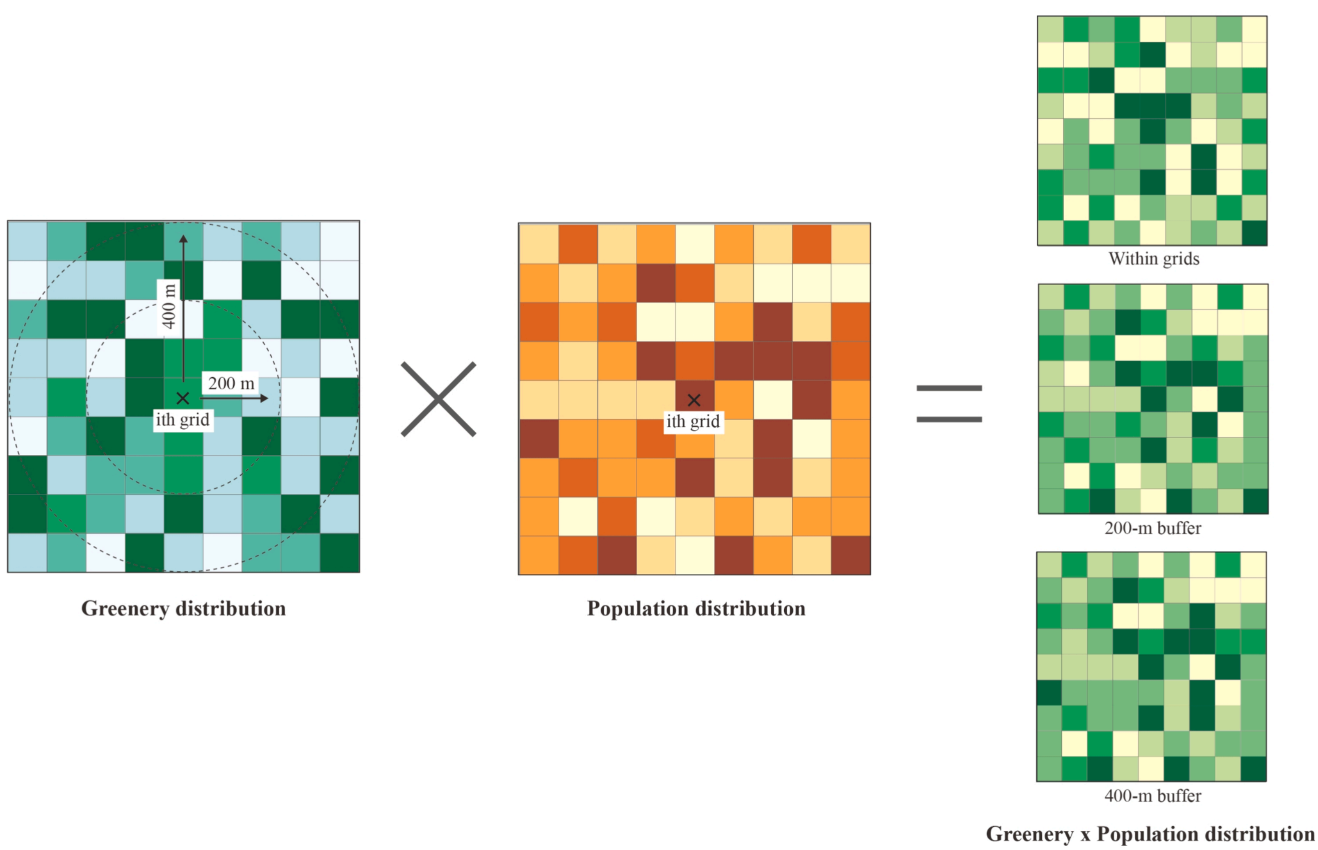

Fig. 2. The illustration of population-weighted exposure model.

estimated greenery exposure per individual within the given TPU.

We employed the WorldPop Global Project Population Dataset from 2001 to 2016 to locate the spatial population distribution within Hong Kong. This dataset provided estimates of the population quantity residing in each 100x100 m grid cell, aligned with the relevant administrative units. To fit the population dataset, the original 30-m NDVI composites were reprojected to 100-m resolution. We calculated the buffer distances from the grid center, and if the center point of the grid lies within the perimeter of the buffer, the grid will be included in the buffer.

Furthermore, the benefits of PUPs derived by residents residing within a grid encompass not only the PUPs within the grid but also PUPs located within a specific spatial range surrounding the residential grid (B. Jiang et al., 2022). Existing research has also confirmed that the effects of greenspace exposure vary significantly with changes in the exposure radius (B. Jiang et al., 2022; Wei, Lu, et al., 2023). Thus, to further investigate the effects of different exposure buffers for PUPs, we chose a 200–4000 m threshold and set a 200-m buffer interval for the buffer distance based on previous research (B. Jiang et al., 2022). For buffer radii exceeding typical walking trips (i.e., > 4000 m), we employed a 500-m buffer interval for analysis.

In addition to the PUP area and greenery, we applied the same methodology through NDVI to assess the exposure to the overall greenery and greenery of urban areas for comparison. The time-series urban boundary data were employed to define urban areas for different time periods (X. Li et al., 2020).

All calculations in Section 2.2.2 were performed in Google Earth Engine (GEE).

2.2.3. Socioeconomic status (SES)

We followed existing research (Arcaya et al., 2015) and employed the median household income of each TPU to evaluate SES. We assessed the median household income based on Population Census data at the TPU level for the years 2001, 2006, 2011, 2016, which were provided by HKCSD. Since the population census is conducted every five years, we employed linear interpolation using available census data to estimate data for intervening years. The mean value of median household income for the 16-year period was 29,651 HKD, with a standard deviation (SD) of 25,056 HKD.

2.2.4. Covariates

Similar to SES, we assessed the covariates based on Population Census data provided by HKCSD. We followed previous studies (Moran et al., 2021; Song et al., 2022) and calculated variables of population density, elderly ratio, sex ratio, marriage ratio, the ratio of individuals with primary education or lower (aged > 15 years), the ratio of individual with post-secondary education or higher (aged > 15 years), labor force ratio, unemployment ratio, average household size. Table S1–S2 in Supplementary Materials reported the definitions of all abbreviations and descriptive statistics for the variables.

2.3. Statistical analysis

Considering the structure of our dataset (with repeated measurements over time, nested within diverse TPU), we utilized mixed-effects models to analyze the longitudinal changes in life expectancy and to investigate the effect of PUPs on YLL. The mixed-effects model has gained wide use in longitudinal analysis. It handles missing data efficiently and robustly and can model a wide range of time variations, including nonlinear variations such as quadratic and cubic trends. The corresponding equations of the mixed-effects model are provided below (Lairdl & Warel, 1982):

$$Y_i = X_i\beta + Z_i b_i + \varepsilon_i$$

$$b_i \sim N_q(0, \Psi)$$

$$\varepsilon_i \sim N_{n_i}\left(0, \sigma^2\Lambda_i\right)$$

Y_i represents the response vector, with dimensions $n_i \times 1$, containing YLL observations within the i^{th} TPU, and n_i denotes the count of observations for i^{th} TPU. The model matrix X_i, measuring $n_i \times p$, encompasses fixed effects for YLL in TPU i, while p is the number of fixed-effect parameters in the model. Our focus is on the $p \times 1$ vector (β) representing the fixed-effects coefficients. The random effects for YLL observations in TPU i are characterized by Z_i ($n_i \times q$ model matrix), while q is the count of random effects, consisting of the intercept, time, and time-squared of each TPU. b_i refers to the $q \times 1$ vector containing random-effect coefficients for TPU i. ε_i represents the $n_i \times 1$ vector of errors for YLL observations of TPU i. The random effects are further characterized by the $q \times q$ covariance matrix (Ψ). The errors in TPU i are delineated by the $n_i \times n_i$ covariance matrix ($\sigma^2\Lambda_i$).

Three sets of models were employed to comprehensively examine the effects of PUPs on life expectancy. First, we modeled life expectancy using PUP exposure (i.e., PUP area and PUP greenery) and other types of greenery exposure (overall greenery and greenery in urban areas), as well as covariates (Models 1 and 2). Linear and quadratic time trends were also controlled in the model to assess both the linear and nonlinear longitudinal patterns in life expectancy. Models 1 and 2 examined the effects of PUP exposure with normal and population-weighted methods, respectively (see Section 2.2.2 for details). Second, Models 3 and 4 added interaction terms (i.e., PUP exposure x SES). Third, Models 5 and 6 evaluated the dose–response effects of PUPs and interaction terms, with radii of buffer set between 200 and 4000 m. For variables that remained significant at the 4000-m buffer radius, we would extend the buffer radius to 8000-m to further investigate their dose–response effects.

We employed the natural logarithm to fit the outcome into a normal distribution (Benoit, 2011). Also, we standardized all variables by centering and scaling them with their mean and SD values. The reported coefficients of PUP exposure can be explained as the change in log YLL for each SD change in PUP exposure. Statistical analyses were conducted in R v4.2.2 (Bates, 2010; Nagle, 2018).

3. Results

3.1. The relationship between PUP exposure and life expectancy

Tables 1 and 2 present the effects of PUP area, PUP greenery, overall greenery, and greenery in urban areas on life expectancy loss. Specifically, both PUP greenery and overall greenery were significant in both the average calculation (normal method) (Model 1) and population-weighted method (Model 2). The PUP area was significant in Model 2 but not in Model 1, probably because the population-weighted method is more accurate than the normal method, as the population-weighted method considers both the distribution of greenspaces and population. We noted that PUP greenery showed the highest negative coefficient on life expectancy loss (-0.173, $p < 0.001$), followed by PUP area (-0.156, $p = 0.001$) and overall greenery (-0.139, $p < 0.001$) (Table 2). Conversely, the greenery in urban areas was insignificant on life expectancy in either Model 1 or Model 2.

3.2. The socioeconomic inequalities of PUP exposure and life expectancy

We revealed significant socioeconomic inequalities between PUPs and life expectancy; Fig. 3 depicted the differences between SES quartile groups. In detail, Fig. 3a illustrated that higher-SES populations had lower life expectancy loss (i.e., higher life expectancy). The Kruskal-Wallis test (McKight & Najab, 2010) demonstrated significant differences in life expectancy among the four SES groups ($p < 0.001$). Also, higher-SES groups showed higher PUP exposure than lower-SES groups (Fig. 3b). The Kruskal-Wallis test indicated significant differences in both the exposure of the PUP area and greenery between the highest SES

Table 1
Regression results of predicting life expectancy loss. The greenspace exposure was measured using the normal method (Model 1).

Model Predictors	Model 1a		Model 1b		Model 1c		Model 1d	
	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values
Fixed Effects								
Greenspace exposure with average calculation								
PUP area	−0.075 (0.047)	0.109						
PUP NDVI			−0.142 (0.044)	0.001 **				
Overall NDVI					−0.147 (0.035)	< 0.001 ***		
NDVI in urban area							0.056 (0.036)	0.121
SES variables								
Median household income	−0.032 (0.054)	0.555	−0.017 (0.054)	0.748	−0.036 (0.053)	0.498	−0.022 (0.054)	0.682
Control variables								
Elderly ratio	0.263 (0.046)	< 0.001 ***	0.257 (0.045)	< 0.001 ***	0.26 (0.045)	< 0.001 ***	0.267 (0.046)	< 0.001 ***
Sex ratio	−0.107 (0.034)	0.002 **	−0.099 (0.034)	0.003 **	−0.103 (0.033)	0.002 **	−0.112 (0.034)	0.001 **
Marriage ratio	−0.145 (0.03)	< 0.001 ***	−0.144 (0.029)	< 0.001 ***	−0.152 (0.029)	< 0.001 ***	−0.145 (0.03)	< 0.001 ***
Ratio of primary diploma or below	0.021 (0.076)	0.784	0.028 (0.075)	0.711	0.065 (0.075)	0.388	0.031 (0.076)	0.678
Ratio of post-secondary diploma or above	−0.34 (0.077)	< 0.001 ***	−0.336 (0.076)	< 0.001 ***	−0.301 (0.076)	< 0.001 ***	−0.339 (0.077)	< 0.001 ***
Labor ratio	0.174 (0.041)	< 0.001 ***	0.169 (0.041)	< 0.001 ***	0.183 (0.04)	< 0.001 ***	0.182 (0.041)	< 0.001 ***
Unemployment ratio	−0.074 (0.027)	0.006 **	−0.076 (0.027)	0.005 **	−0.076 (0.027)	0.005 **	−0.076 (0.027)	0.005 **
Mean household size	−0.041 (0.039)	0.299	−0.032 (0.039)	0.412	0.004 (0.04)	0.914	−0.04 (0.039)	0.304
Population density	0.057 (0.053)	0.277	0.051 (0.052)	0.327	0.046 (0.051)	0.368	0.06 (0.053)	0.252
Year	0.387 (0.067)	< 0.001 ***	0.392 (0.067)	< 0.001 ***	0.383 (0.067)	< 0.001 ***	0.391 (0.067)	< 0.001 ***
Year_square	−0.443 (0.075)	< 0.001 ***	−0.44 (0.074)	< 0.001 ***	−0.401 (0.075)	< 0.001 ***	−0.459 (0.075)	< 0.001 ***
Random Effects								
σ2	0.204		0.204		0.204		0.204	
τ00 TPU	0.393		0.381		0.357		0.386	
τ11 TPU.year	0.442		0.440		0.441		0.442	
τ11 TPU.year_square	0.720		0.717		0.715		0.715	
ρ01	−0.025		−0.051		0.015		−0.008	
	0.259		0.281		0.235		0.244	
ICC	0.728		0.723		0.714		0.725	
N TPU	179		179		179		179	
Observations	2835		2835		2835		2835	
Marginal R^2 / Conditional R^2	0.245 / 0.795		0.263 / 0.796		0.266 / 0.790		0.243 / 0.792	

groups and the other groups ($p < 0.001$).

Moreover, Model 3 (Table 3) and Model 4 (Table 4) illustrated significant interaction terms between SES and PUP area/ greenery after controlling for the exposure of PUP area/ greenery. Fig. 4 & Fig. S1 and Figs. S2–S3 visualized the interaction effects via the population-weighted method and normal method, respectively. The results in both methods indicated that populations with higher SES benefit more from PUPs than populations with lower SES. The results related to PUPs were in direct contrast to the equigenesis hypothesis.

In addition, both Model 3 and Model 4 found insignificant moderating effects of SES on associations between overall greenery and life expectancy, as well as greenery in urban areas and life expectancy.

3.3. Effects of population-weighted exposure to greenspaces at different buffer distances

Considering the insignificant effect of greenery in urban areas, we focused on examining the effects of PUP area, PUP greenery, and overall greenery on life expectancy within different buffer ranges (200 m–4000 m) that represent typical walking distances in Model 5 (Table S3). We detected that the significant effects of PUP area and overall greenery decrease as the buffer radius increases; their effects persisted up to 1800 m and 2400 m, respectively (Fig. 5). In contrast, the effect of PUP greenery was not only higher than that of PUP area across all buffers but also significant throughout 200–4000 m buffers. To further investigate the effect of PUP greenery, we extended the buffer radius to 4000–8000 m. It is worth noting that PUP greenery exhibited significant effects on life expectancy across the entire range of 200–8000 m (Fig. 5), nearly covering the entirety of Hong Kong area.

Furthermore, considering the insignificant interaction terms related to overall greenery and greenery in urban areas, we focused on examining the interacting effects of SES and PUP area/greenery on life expectancy within different buffer ranges (200 m–4000 m) in Model 6 (Table S4). Notably, we observed that the interaction effects of SES with PUP area and PUP greenery persisted up to 4500 m and 4000 m, with the highest interaction effect in 2600 m and 2200 m, respectively (Fig. 6). This indicated that the differences in the effects of PUP area and PUP greenery on life expectancy were highest between high SES groups and low SES groups in 2600 m and 2200 m, respectively. Figs. S4 and S5 clearly depicted the highest moderating effects of SES.

4. Discussion

4.1. Key findings

4.1.1. Effects of PUPs

We found that the exposure of PUP area, PUP greenery, and overall greenery of Hong Kong had significantly positive effects on life expectancy. This aligns with existing research that has consistently demonstrated the association between neighborhood urban greenspaces and various health outcomes (Orioli et al., 2019; Vienneau et al., 2017; R. Wang et al., 2021, 2022). Compared to the mortality rate used in

Table 2
Regression results of predicting life expectancy loss. The exposure was assessed by the population-weighted method (Model 2).

Model Predictors	Model 2a		Model 2b		Model 2c		Model 2d	
	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values
Fixed Effects								
Greenspace exposure with population-weighted model								
PUP area	−0.156 (0.047)	0.001 **						
PUP NDVI			−0.173 (0.046)	< 0.001 ***				
Overall NDVI					−0.139 (0.034)	< 0.001 ***		
NDVI in urban area							0.026 (0.033)	0.419
SES variables								
Median household income	0.002 (0.055)	0.966	−0.004 (0.054)	0.944	−0.031 (0.053)	0.561	−0.026 (0.054)	0.629
Control variables								
Elderly ratio	0.249 (0.046)	< 0.001 ***	0.252 (0.046)	< 0.001 ***	0.265 (0.045)	< 0.001 ***	0.271 (0.046)	< 0.001 ***
Sex ratio	−0.09 (0.034)	0.009 **	−0.084 (0.034)	0.014 *	−0.1 (0.033)	0.002 **	−0.113 (0.034)	0.001 **
Marriage ratio	−0.15 (0.03)	< 0.001 ***	−0.148 (0.029)	< 0.001 ***	−0.152 (0.029)	< 0.001 ***	−0.145 (0.03)	< 0.001 ***
Ratio of primary diploma or below	0.025 (0.075)	0.739	0.03 (0.075)	0.692	0.06 (0.075)	0.425	0.025 (0.076)	0.74
Ratio of post-secondary diploma or above	−0.34 (0.076)	< 0.001 ***	−0.328 (0.076)	< 0.001 ***	−0.299 (0.076)	< 0.001 ***	−0.339 (0.077)	< 0.001 ***
Labor ratio	0.163 (0.041)	< 0.001 ***	0.163 (0.041)	< 0.001 ***	0.181 (0.04)	< 0.001 ***	0.181 (0.041)	< 0.001 ***
Unemployment ratio	−0.08 (0.027)	0.003 **	−0.08 (0.027)	0.003 **	−0.074 (0.027)	0.006 **	−0.074 (0.027)	0.007 **
Mean household size	−0.039 (0.039)	0.322	−0.036 (0.039)	0.349	0.0 (0.039)	0.995	−0.042 (0.039)	0.29
Population density	0.058 (0.052)	0.269	0.056 (0.052)	0.277	0.04 (0.051)	0.431	0.061 (0.053)	0.248
Year	0.391 (0.067)	< 0.001 ***	0.388 (0.067)	< 0.001 ***	0.376 (0.067)	< 0.001 ***	0.387 (0.067)	< 0.001 ***
Year_square	−0.443 (0.075)	< 0.001 ***	−0.437 (0.074)	< 0.001 ***	−0.394 (0.075)	< 0.001 ***	−0.454 (0.075)	< 0.001 ***
Random Effects								
σ2	0.204		0.204		0.204		0.204	
τ00 TPU	0.377		0.373		0.352		0.391	
τ11 TPU.year	0.446		0.444		0.444		0.442	
τ11 TPU.year_square	0.725		0.717		0.717		0.717	
ρ01	−0.019		−0.016		0.023		−0.021	
	0.251		0.249		0.225		0.257	
ICC	0.723		0.720		0.713		0.727	
N TPU	179		179		179		179	
Observations	2835		2835		2835		2835	
Marginal R^2 / Conditional R^2	0.263 / 0.796		0.270 / 0.796		0.254 / 0.782		0.238 / 0.792	

previous studies (R. Mitchell & Popham, 2008), our study measured more reliable overall health and well-being via life expectancy, as it considered the weighting of death-age and sex (Cheng et al., 2021; Moran et al., 2021).

Notably, we noticed that PUP area and greenery had higher effects than overall greenery, highlighting the enhanced life-expectancy benefits offered by PUPs to residents. We inferred that the higher effects might be attributed to the high usage rate of PUPs (Conedera et al., 2015; Lu et al., 2021; Norman & Pickering, 2019), especially in Hong Kong, where approximately 13 million visits to PUPs occur annually (Agriculture, Fisheries and Conservation Department, 2017b). Residents engage in activities in PUPs to enjoy the life-expectancy benefits conferred by these natural environments, which can be explained by three reasons. First, PUPs featuring extensive natural greenery can mitigate various environmental hazards, including pollutants, high temperatures, and noise (Markevych et al., 2017). Second, the diverse landscape resources and abundant natural greenery of PUP can enhance mental well-being by aiding in stress-recovery processes (R. J. Mitchell et al., 2015). Third, PUPs provide expansive outdoor public spaces, enchanting scenery, and cultural heritage resources. They attract urban residents to engage in physical activity (e.g., hiking, camping, and cycling) and foster social connections for prolonged durations, ultimately resulting in enhanced physical and mental well-being (Lu et al., 2021).

However, we observed an insignificant effect of greenery in urban areas on life expectancy, which appears inconsistent with other studies that have demonstrated significant health benefits (e.g., lower mortality, obesity, mental health) (He et al., 2022; R. Wang et al., 2022). We speculated that this inconsistency may be due to Hong Kong's high-density urban environment with relatively less urban greenery (mean urban-area NDVI=0.127). Less urban greenery per capita may lead people to choose other public facilities for their health-promoting activities, e.g., public gyms and sports stadiums. This also highlights the indispensable role of PUPs in meeting residents' demands for accessing nature in high-density cities (e.g., Hong Kong).

4.1.2. *Socioeconomic inequalities between PUPs and life expectancy*

Our study revealed significant socioeconomic inequalities in life expectancy, PUP exposure, and PUPs' life-expectancy benefits. Although the finding that higher-SES groups had better life expectancy and PUP exposure aligns with previous studies (Y. Chen et al., 2020; R. Mitchell & Popham, 2008), the unexpected socioeconomic inequalities in PUPs'

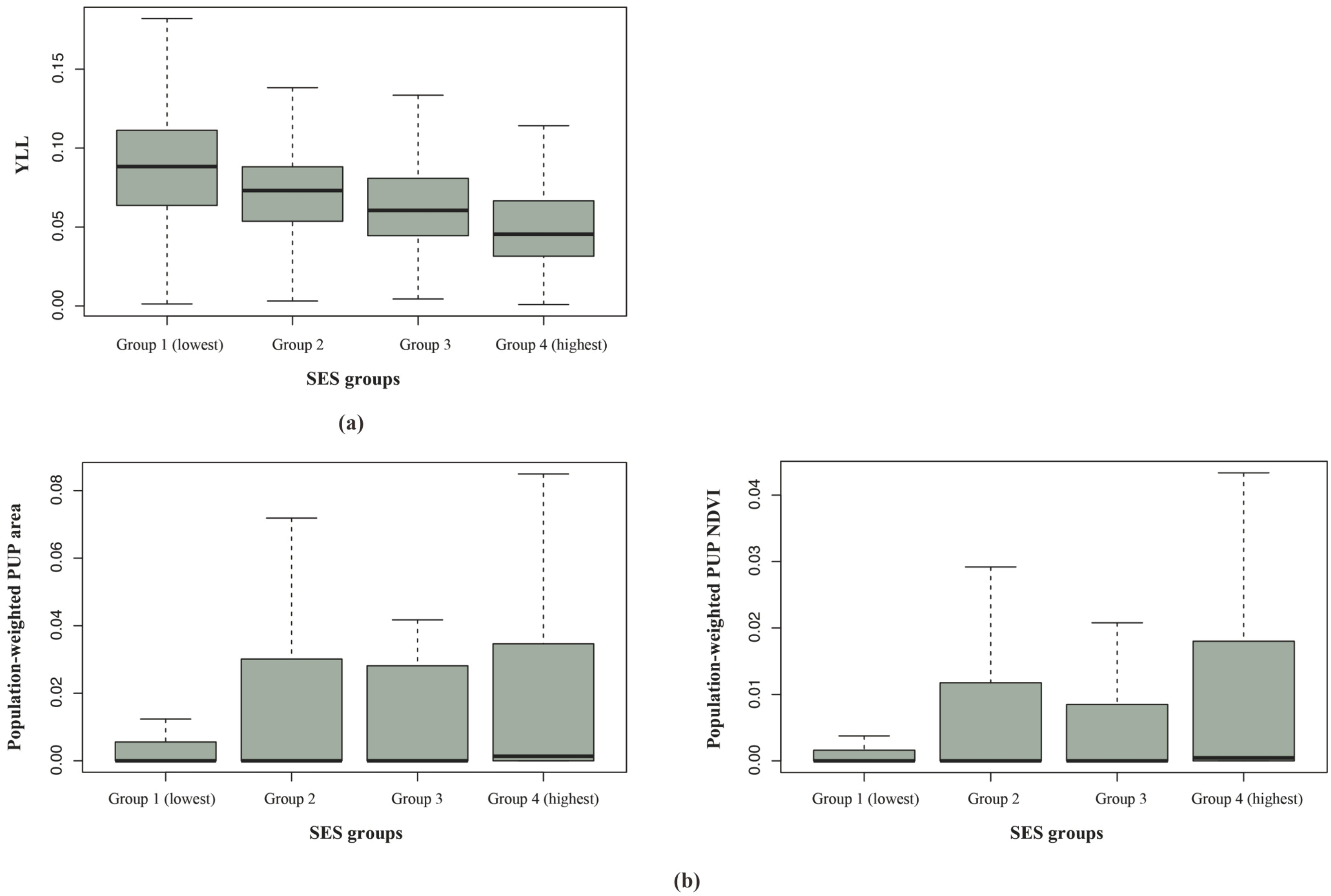

Fig. 3. Descriptive boxplots for different SES groups. (a) Life expectancy loss for different SES groups; (b) Population-weighted exposure of PUP area and PUP greenery for different SES groups. Higher SES groups had significantly lower life expectancy loss and better PUP exposure compared to lower SES groups.

life-expectancy benefits were observed in our study. We found that the population with higher SES gained greater life-expectancy benefits from PUPs. This finding contradicted the equigenesis theory, which suggests that greenspaces can be considered an effective pathway for mitigating socioeconomic inequalities because low SES groups can derive greater benefits from greenspaces (Rigolon et al., 2021; R. Wang et al., 2022; Wei, Lu, et al., 2023).

The inconsistency may be because previous studies primarily concentrated on examining the equigenic effects of urban greenspaces (Rigolon et al., 2021). One suggested mechanism explaining the equigenesis theory of greenspace is that, in comparison to people with higher SES, those with lower SES tend to have less mobility and disposable time, making them more likely to use and benefit from nearby greenspaces within their neighborhoods (R. Wang et al., 2022). In contrast, PUPs typically require longer travel distances and visit times (Žlender & Ward Thompson, 2017), which may result in fewer visits from lower-SES groups. Such behavioral differences between different SES groups are one of the pathways leading to health inequalities, as evidenced in other health-related research (Arcaya et al., 2015). Another pathway that may cause health inequalities is the inequalities in PUP exposure. The favorable PUP exposure of higher-SES groups is confirmed in our findings (Fig. 3b) and previous research (Y. Chen et al., 2020; Zhang et al., 2021a). Notably, in our model, even after controlling for PUP exposure, the interaction terms (i.e., the inequalities of PUPs' life-expectancy effects) remain significant. This to some extent indicated that both the behavioral differences (due to time availability and financial resources) and environmental injustice (due to inequalities in PUP exposure) may lead to socioeconomic inequalities in the associations of PUP and life expectancy.

Furthermore, we found no significant variation in the life-expectancy effects of overall greenery and greenery in urban areas among different SES groups. This may be because our study city (i.e., Hong Kong) has a highly developed urban area that has robust social safety nets and public service infrastructures (e.g., government-subsidized low-cost sports facilities, gyms, etc.). This allows residents, especially those in lower SES groups, to access other avenues for health benefits beyond public urban greenspaces. This also aligns with existing research indicating that the disparity in health effects of urban greenspaces between different SES groups tends to be smaller in more developed regions (Rigolon et al., 2021).

4.1.3. Optimal buffer radius for PUP exposure and environmental justice

Our finding suggested the PUP buffer ranges where the highest life expectancy effects and the most pronounced socioeconomic inequalities occur. In detail, the effect size of PUP greenery was significantly higher than that of the PUP area. This aligns with existing research, emphasizing that the quality of greenspaces, such as plant types, vegetation density, or landscaping, exerts a more significant influence on health benefits than the sheer size of greenspaces (Rojas-Rueda et al., 2019; R. Wang et al., 2022). Notably, PUP greenery showed significant effects in buffer sizes ranging from 200 to 8000 m, covering almost the entire area of Hong Kong. This is a noteworthy result as it implies that PUP greenery contributes to improved life expectancy across most areas of the city, potentially benefiting a considerable portion of the population. In contrast, overall greenery has significant effects in the buffer size only up to 2400 m, which is roughly equivalent to a 30-minute walking distance, similar to previous research findings (B. Jiang et al., 2022).

Moreover, the socioeconomic inequalities of PUPs' life-expectancy

Table 3
Regression results for the moderating effect of SES on the association between greenspaces and life expectancy. The greenspace exposure was measured using the normal method (Model 3).

Model Predictors	Model 3a		Model 3b		Model 3c		Model 3d	
	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values
Fixed Effects								
Greenspace exposure with average calculation								
PUP area	−0.1 (0.048)	0.037 *						
PUP NDVI			−0.114 (0.044)	0.01 *				
Overall NDVI					−0.145 (0.035)	< 0.001 ***		
NDVI in urban area							0.058 (0.036)	0.113
SES variables								
Median household income	−0.033 (0.054)	0.539	0.061 (0.057)	0.287	−0.05 (0.058)	0.384	−0.005 (0.067)	0.94
Control variables								
Elderly ratio	0.254 (0.046)	< 0.001 ***	0.261 (0.045)	< 0.001 ***	0.26 (0.045)	< 0.001 ***	0.266 (0.046)	< 0.001 ***
Sex ratio	−0.126 (0.035)	< 0.001 ***	−0.117 (0.034)	0.001 **	−0.102 (0.033)	0.002 **	−0.113 (0.034)	0.001 **
Marriage ratio	−0.145 (0.03)	< 0.001 ***	−0.153 (0.029)	< 0.001 ***	−0.15 (0.029)	< 0.001 ***	−0.145 (0.03)	< 0.001 ***
Ratio of primary diploma or below	0.027 (0.076)	0.727	0.034 (0.075)	0.651	0.066 (0.075)	0.378	0.03 (0.076)	0.692
Ratio of post-secondary diploma or above	−0.347 (0.077)	< 0.001 ***	−0.357 (0.076)	< 0.001 ***	−0.294 (0.077)	< 0.001 ***	−0.345 (0.078)	< 0.001 ***
Labor ratio	0.177 (0.041)	< 0.001 ***	0.179 (0.041)	< 0.001 ***	0.182 (0.04)	< 0.001 ***	0.181 (0.041)	< 0.001 ***
Unemployment ratio	−0.072 (0.027)	0.008 **	−0.071 (0.027)	0.009 **	−0.077 (0.027)	0.004 **	−0.075 (0.027)	0.006 **
Mean household size	−0.037 (0.039)	0.342	−0.029 (0.039)	0.452	0.005 (0.04)	0.904	−0.042 (0.04)	0.285
Population density	0.067 (0.053)	0.203	0.062 (0.052)	0.231	0.045 (0.051)	0.38	0.061 (0.053)	0.245
Year	0.394 (0.068)	< 0.001 ***	0.402 (0.068)	< 0.001 ***	0.383 (0.067)	< 0.001 ***	0.394 (0.068)	< 0.001 ***
Year_square	−0.445 (0.075)	< 0.001 ***	−0.453 (0.075)	< 0.001 ***	−0.401 (0.075)	< 0.001 ***	−0.464 (0.076)	< 0.001 ***
Interaction terms								
PUP area x Median household income	−0.118 (0.049)	0.017 *						
PUP NDVI x Median household income			−0.105 (0.026)	< 0.001 ***				
Overall NDVI x Median household income					0.02 (0.032)	0.529		
NDVI in Urban area x household house income							0.017 (0.037)	0.651
Random Effects								
σ2	0.203		0.203		0.204		0.204	
τ00 TPU	0.388		0.375		0.358		0.387	
τ11 TPU.year	0.466		0.454		0.440		0.443	
τ11 TPU.year_square	0.741		0.725		0.716		0.715	
ρ01	−0.011		−0.056		0.015		−0.012	
	0.238		0.287				0.247	
ICC	0.727		0.723		0.715		0.726	
N TPU	179		179		179		179	
Observations	2835		2835		2835		2835	
Marginal R^2 / Conditional R^2	0.250 / 0.795		0.276 / 0.799		0.264 / 0.790		0.241 / 0.792	

effects persisted up to 4000–4500 m, with the highest injustice in 2200–2600 m. This suggested that the phenomenon of significant difference between high-SES and low-SES groups was not limited to the immediate vicinity of PUPs. Instead, it extended quite a distance away from PUPs, reaching up to 4000–4500 m, with the most significant disparities emerging at approximately a 30-minute walking range (2200–2600 m). In conclusion, the socioeconomic inequalities of PUPs' health benefits underscore the urgent need for comprehensive, equitable solutions to address this pressing issue.

4.2. Implication

Our findings hold several implications for urban design and management. First, creating more PUPs may be a widely effective way to enhance the life expectancy of residents in high-density cities. PUPs not only significantly enhanced life expectancy but also had an effect radius extending to 8000 m, covering nearly the entire area of densely populated cities like Hong Kong. In high-density cities with limited urban green spaces, it is crucial to prioritize the establishment and management of PUPs because the PUPs may offer alternative venues for people to access nature. Second, urban designers and policymakers should not only focus on expanding PUP areas but also pay attention to the quality of PUP greenery, such as vegetation types, density, and landscaping (Carrus et al., 2015). Third, it is worth noting that, unlike neighborhood/ urban greenery, PUP was not a pathway to overcome SES inequalities in Hong Kong. In contrast, it was found to exacerbate the SES inequalities of life expectancy. It should be acknowledged increasing PUP exposure of low-SES groups is hard due to existing urban and social contexts in Hong Kong. Therefore, we recommend that future efforts should focus on changing perceptions, attitudes, and visitation towards PUPs of low-SES groups, with an emphasis on improving public transport and promotion for low-SES groups.

4.3. Limitations

Several limitations should be noted for future studies. First, although

Table 4
Regression results for the moderating effect of SES on the association between greenspaces and life expectancy. The greenspace exposure was measured using the population-weighted method (Model 4).

Model Predictors	Model 4a		Model 4b		Model 4c		Model 4d	
	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values	Coefficient (SE)	p-values
Fixed Effects								
Greenspace exposure with population-weighted model								
PUP area	−0.095 (0.049)	0.053						
PUP NDVI			−0.128 (0.048)	0.007 **				
Overall NDVI					−0.139 (0.034)	< 0.001 ***		
NDVI in urban area							0.028 (0.033)	0.383
SES variables								
Median household income	0.101 (0.059)	0.088	0.069 (0.058)	0.232	−0.036 (0.058)	0.54	0.042 (0.065)	0.516
Control variables								
Elderly ratio	0.253 (0.046)	< 0.001 ***	0.253 (0.046)	< 0.001 ***	0.265 (0.045)	< 0.001 ***	0.268 (0.046)	< 0.001 ***
Sex ratio	−0.123 (0.035)	0.001 **	−0.11 (0.035)	0.002 **	−0.099 (0.033)	0.003 **	−0.118 (0.034)	< 0.001 ***
Marriage ratio	−0.157 (0.03)	< 0.001 ***	−0.153 (0.03)	< 0.001 ***	−0.152 (0.029)	< 0.001 ***	−0.148 (0.03)	< 0.001 ***
Ratio of primary diploma or below	0.039 (0.076)	0.604	0.039 (0.075)	0.609	0.06 (0.075)	0.423	0.02 (0.076)	0.788
Ratio of post-secondary diploma or above	−0.362 (0.077)	< 0.001 ***	−0.35 (0.077)	< 0.001 ***	−0.297 (0.076)	< 0.001 ***	−0.362 (0.078)	< 0.001 ***
Labor ratio	0.178 (0.041)	< 0.001 ***	0.175 (0.041)	< 0.001 ***	0.18 (0.04)	< 0.001 ***	0.18 (0.041)	< 0.001 ***
Unemployment ratio	−0.069 (0.027)	0.012 *	−0.072 (0.027)	0.008 **	−0.075 (0.027)	0.006 **	−0.069 (0.027)	0.011 *
Mean household size	−0.035 (0.039)	0.371	−0.032 (0.039)	0.407	0.0 (0.039)	0.992	−0.047 (0.04)	0.239
Population density	0.071 (0.052)	0.172	0.066 (0.052)	0.205	0.04 (0.051)	0.438	0.065 (0.053)	0.216
Year	0.407 (0.068)	< 0.001 ***	0.401 (0.068)	< 0.001 ***	0.376 (0.067)	< 0.001 ***	0.403 (0.068)	< 0.001 ***
Year_square	−0.464 (0.075)	< 0.001 ***	−0.453 (0.075)	< 0.001 ***	−0.394 (0.075)	< 0.001 ***	−0.472 (0.076)	< 0.001 ***
Interaction term								
PUP area x Median household income	−0.096 (0.022)	< 0.001 ***						
PUP NDVI x Median household income			−0.081 (0.023)	< 0.001 ***				
Overall NDVI x Median household income					0.006 (0.028)	0.844		
NDVI in Urban area x household house income							0.058 (0.03)	0.15
Random Effects								
σ2	0.202		0.203		0.204		0.204	
τ00 TPU	0.374		0.370		0.353		0.388	
τ11 TPU.year	0.467		0.458		0.444		0.446	
τ11 TPU.year_square	0.737		0.725		0.718		0.717	
ρ01	−0.029		−0.026		0.023		−0.037	
	0.253		0.255		0.225		0.267	
ICC	0.723		0.720		0.713		0.726	
N TPU	179		179		179		179	
Observations	2835		2835		2835		2835	
Marginal R^2 / Conditional R^2	0.272 / 0.798		0.278 / 0.798		0.264 / 0.789		0.234 / 0.790	

we obtained the individual-level longitudinal data, the residential location data for individuals was limited to the TPU level because of HKCSD's privacy protection policies. This constraint forced us to aggregate our data and conduct longitudinal analyses at the TPU level, potentially exposing our study to ecological fallacy issues. Hence, future studies should use territory-wide register-based datasets at detailed residential locations to validate our results. In addition, although noise, air pollution, and other environmental factors may also influence residents' life expectancy, relevant time-series data at the TPU level were unavailable for this study. Also, given that population census data is conducted every five years, linear interpolation was utilized to estimate data for intervening years. The absence of such data may introduce bias. Hence, future studies should validate our results when fine-grained data are available. Second, we only used data from Hong Kong, a high-density and high-socioeconomic city with abundant and well-established PUP resources. Whether our findings are generalizable to other cities, especially those with different social, urban, and PUP contexts, requires further validation. Third, although our longitudinal data allowed us to infer a relatively robust life-expectancy effect of PUPs, their effect may still be influenced by unobserved confounders. Therefore, future research should consider well-controlled interventions or natural experiments to further examine this causal relationship.

5. Conclusion

This study employed a territory-wide register-based longitudinal dataset from 2001 to 2016 in Hong Kong to comprehensively assess the effects of PUPs on life expectancy. Our findings showed that exposure to

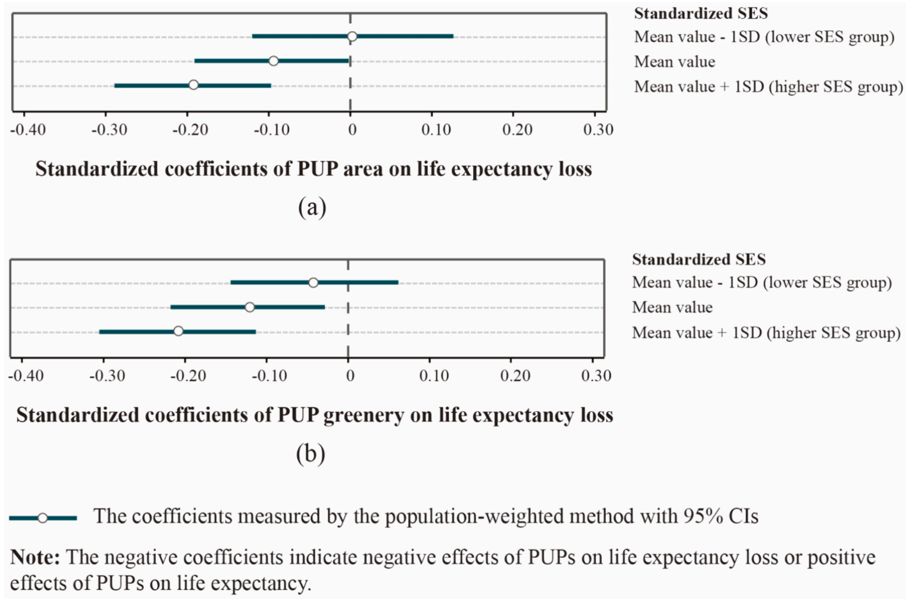

Fig. 4. SES moderated the relationship between PUP area and life expectancy ($p < 0.001$) as well as PUP greenery and life expectancy ($p < 0.001$) with the population-weighted method. (a) The standardized coefficients of PUP area on life expectancy loss among different SES levels in Model 4a; (b) The standardized coefficients of PUP greenery on life expectancy loss among different SES levels in Model 4b. The higher-SES group had negative coefficients with a larger magnitude than the lower-SES group.

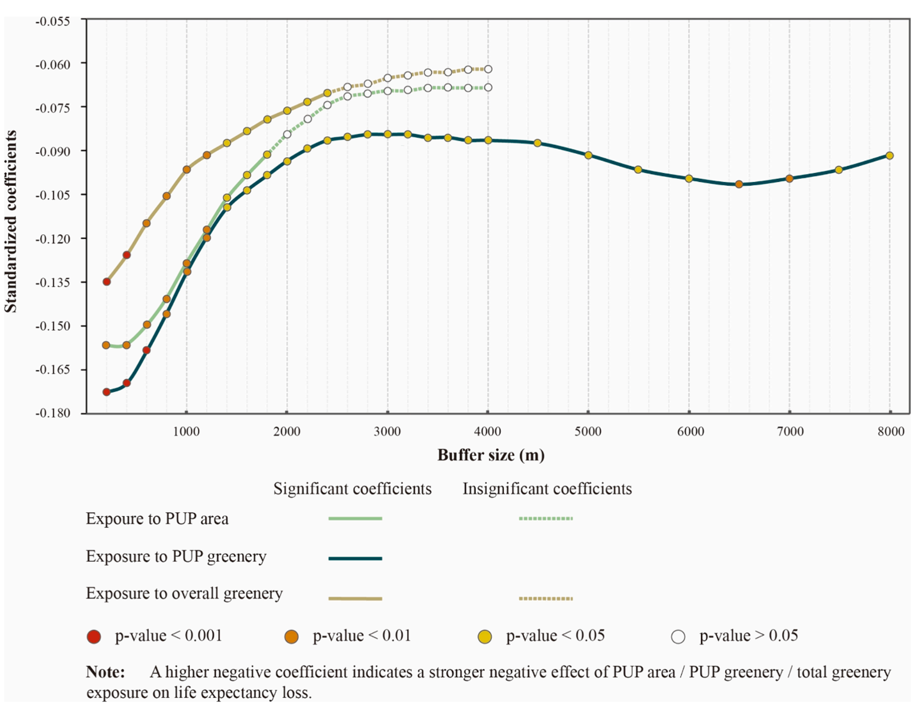

Fig. 5. Visualization of the effects of PUP area, PUP greenery, and overall greenery across 200–8000 m buffer distances after accounting for the control variables and random effects (Model 5). The effect of PUP greenery persisted throughout the 200–8000 m.

PUPs significantly enhanced life expectancy, with significant effect buffers from 200 to 8000 m. Compared to the PUP area, increasing PUP greenery exhibited a greater effect on improving life expectancy. However, PUP exposure may exacerbate socioeconomic inequalities in life expectancy. In summary, our study emphasizes the significant health benefits of PUPs and highlights their socioeconomic inequalities, offering both encouraging insights and challenges for urban design and management.

CRediT authorship contribution statement

Di Wei: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yi Lu:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Yuxuan Zhou:** Visualization, Data curation. **Hung Chak Ho:** Resources, Data curation. **Bin Jiang:** Supervision.

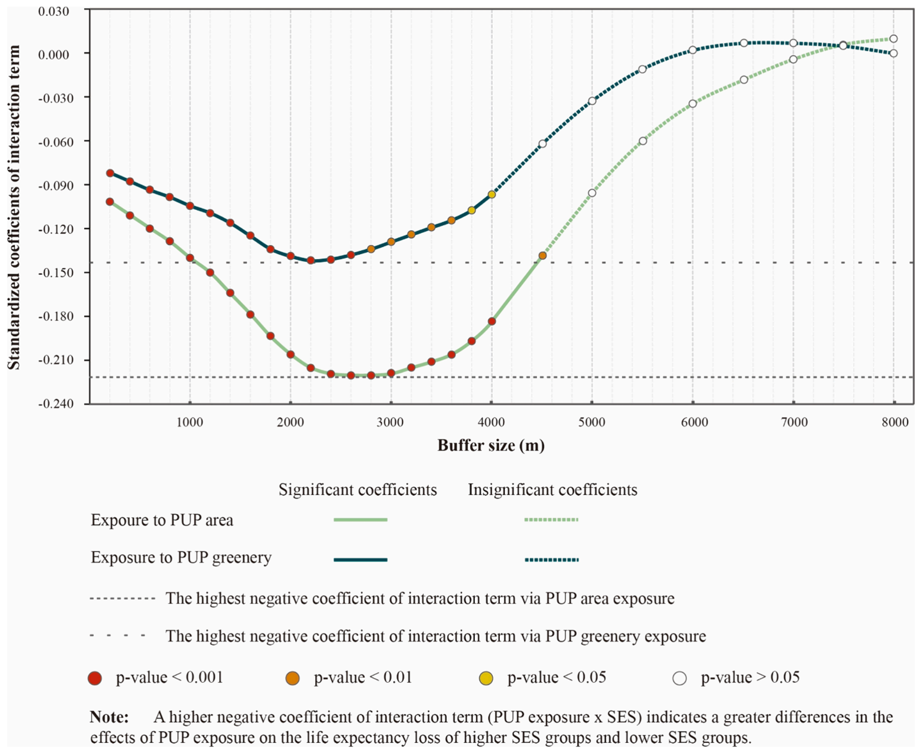

Fig. 6. Visualization of the moderating effects of SES (i.e., PUP area x SES and PUP greenery x SES) (Model 6) across 200–8000 m buffer distances after accounting for the control variables and random effects. The highest moderating effects related to PUP area and PUP greenery were within 2600 m and 2200 m buffer distances, respectively.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105192.

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