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Impacts of social deprivation on mortality and protective effects of greenness exposure in Hong Kong, 1999–2018: A spatiotemporal perspective

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ABSTRACT

Addressing health inequality is crucial for fostering healthy city development. However, there is a dearth of literature simultaneously investigating the effects of social deprivation and greenness exposure on mortality risks, as well as how greenness exposure may mitigate the adverse effect of social deprivation on mortality risks from a spatiotemporal perspective. Drawing on socioeconomic, remote sensing, and mortality record data, this study presents spatiotemporal patterns of social deprivation, population weighted greenness exposure, and all-cause and cause-specific mortality in Hong Kong. A Bayesian regression model was applied to investigate the impacts of social deprivation and greenness exposure on mortality and examine how socioeconomic inequalities in mortality may vary across areas with different greenness levels in Hong Kong from 1999 to 2018. We observed a decline in social deprivation (0.67–0.56), and an increase in greenness exposure (0.34–0.41) in Hong Kong during 1999–2018. Areas with high mortality gradually clustered in the Kowloon Peninsula and the northern regions of Hong Kong Island. Adverse impacts of social deprivation on all-cause mortality weakened in recent years (RR from 2009 to 2013: 1.103, 95%CI: 1.051–1.159, RR from 2014 to 2018: 1.041 95%CI: 0.950–1.139), while the protective impacts of greenness exposure consistently strengthened (RR from 1999 to 2003: 0.903, 95%CI: 0.827–0.984, RR from 2014 to 2018: 0.859, 95%CI: 0.763–0.965). Moreover, the adverse effects of social deprivation on mortality risks were found to be higher in areas with lower greenness exposure. These findings provide evidence of associations between social deprivation, greenness exposure, and mortality risks in Hong Kong over the past decades, and highlight the potential of greenness exposure to mitigate health inequalities. Our study provides valuable implications for policymakers to develop a healthy city.

1. Introduction

Approximately 70% of the global population is projected to reside in urban areas by 2050, which presents significant challenges in urban development (United Nations, 2018). One of the key goals for achieving sustainable development is building resilient and sustainable cities, with a particular focus on fostering the development of healthy cities (Giles-Corti et al., 2020). Due to the rapid urbanization, uneven socioeconomic status and resources allocation across various areas may lead to health inequalities, which constraints the development of healthy cities (Vlahov et al., 2007). Health inequality is commonly defined as systematic, avoidable, and unfair disparities in health outcomes observed among different sociodemographic groups at both individual and geographic level (McCartney et al., 2019). Researchers have dedicated their efforts to observe and understand health inequalities in cities. For example, a European study identified the socioeconomic inequalities in cause-specific mortality and the disparities in their magnitude across 15 European cities (Marí-Dell'Olmo et al., 2015). A study from China reported that the rapid urbanization resulted in health inequalities in the country due to large-scale migration, pollution, and lifestyle transitions (Yang et al., 2018). Masuda et al. (2012) summarized that health inequalities were associated with differences in social

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and natural environments between less and more affluent neighborhoods based on their observations in Vancouver, Toronto, and Winnipeg, Canada. All the evidence serves as a stark reminder of the persistence of health inequalities in global cities, highlighting the pressing challenge of addressing these issues.

Social deprivation is a frequently used concept to describe the disadvantages faced by a group of individuals in terms of accessing material and social resources (Wang et al., 2021). The existing body of studies has examined the impacts of different aspects of social deprivation on both physiological and psychological health outcomes to illustrate the causes of health inequalities. Socioeconomic inequality has been identified as a significant factor contributing to health inequalities (Pickett and Wilkinson, 2015). People with lower income or those living in less affluent areas tend to experience poor health and well-being (Babones, 2008; Bor et al., 2017; Chetty et al., 2016; Meijer et al., 2012; Rosengren et al., 2019). Besides, some studies demonstrated that people with poorer housing condition, lower education attainment and occupational grade are more likely to experience negative health outcomes (Downing, 2016; Dugravot et al., 2020; Dunn, 2000; Kivimäki et al., 2020; Pevalin et al., 2017; Raghupathi and Raghupathi, 2020; Ross and Mirowsky, 1999; Xie et al., 2015). Moreover, areas with higher unemployment rate and higher proportion of disadvantaged people are presented to be associated with higher rates of morbidity and mortality in previous studies (Drydakis, 2015; Greves Grow et al., 2010; Weimann et al., 2016).

Notably, single socioeconomic factors (e.g., income) are not able to comprehensively represent the social deprivation status in a neighborhood, which is closely linked to the inequalities in public resource allocation. Hence, there is a need to establish a comprehensive social deprivation index by integrating socioeconomic factors from diverse dimensions. Some studies have constructed social deprivation indices to investigate the association between overall social deprivation at neighborhood level and aggregated health outcomes. They found that increase in social deprivation was commonly associated with higher risks of mortality and other negative health outcomes (O'Farrell et al., 2016; Ribeiro et al., 2018; Sánchez-Santos et al., 2013). These studies primarily originated from the Western context, and there is limited evidence in the Asian context with very different welfare systems and social-cultural traditions, except for two recent studies conducted in Hong Kong. These two studies constructed social deprivation indices using various indicators and found that social deprivation were positively associated with cancer mortality and suicide mortality (Wang et al., 2021; Yeung et al., 2022). However, these two studies did not investigate the effects of social deprivation on all-cause and other cause-specific mortality, nor did they explore variations in these effects over time. Hence, further investigation is necessary to enhance the existing evidence. Moreover, the association between neighborhood social deprivation and mortality may exhibit variation in different periods due to socioeconomic development, particularly over a long time period, which has received limited attention in previous studies. Understanding the temporal dynamics of such associations is significant for gaining a comprehensive understanding of the evolution of health inequalities.

Meanwhile, researchers have made efforts to examine the benefits of urban natural environment on urban health issues. Exposure to urban greenness has been identified as having beneficial effects on health in urban settings in extensive previous studies. Researchers found that usage of urban parks, accessibility to urban green spaces, visible urban greenery, and constructions of urban green facilities probably improved both physical and mental health, as well as social well-being (Ayala-Azcárraga et al., 2019; He et al., 2022; Hunter et al., 2019; Labib et al., 2020; Liu et al., 2020; Remme et al., 2021). Some evidence suggests that exposure to greenness had protective effects on all-cause and cause-specific mortality (Barboza et al., 2021; Bauwelinck et al., 2021; Rojas-Rueda et al., 2019). Furthermore, some studies have examined the potential moderating effects of greenness exposure on health inequalities. Mitchell and Popham were the first to observe that the adverse impacts of income deprivation on mortality were less prominent in areas with higher levels of greenness exposure in UK (Mitchell and Popham, 2008). Furthermore, researchers have also discovered the protective effects of greenness exposure on socioeconomic inequalities in various health outcomes including chronic diseases, all-cause mortality, and mental disorder in countries such as the US, UK, Canada, Belgium, and the Netherlands) (Brown et al., 2016; van den Berg et al., 2015). However, the evidence regarding the moderating effects of urban greenness and health inequalities mainly relied on single socioeconomic factors (e.g., income), without considering the overall status of social deprivation.

To sum up, existing studies provide robust evidence of beneficial effects of greenness exposure and adverse impacts of social deprivation on different health outcomes, as well as the protective effects of greenness exposure on socioeconomic inequalities in health outcomes. However, there are still some gaps that need to be addressed. First, few studies have simultaneously demonstrated the spatiotemporal variations of overall social deprivation, greenness exposure, and mortality. Their associations have yet to be thoroughly discussed under a long-term context in previous studies. Addressing this issue is valuable to reveal a long-term process of changes in social and natural environment and health situations, along with their interplay at the neighborhood level. This contributes significantly to gaining insights for a comprehensive understanding of urban development and implementing tailor-made and sustainable planning strategies to achieve the healthy city goals. Second, studies exploring associations between overall social deprivation and mortality risks are mainly from western countries, with limited exploration focusing on Asian context with different social and welfare conditions, while evidence concerning the extent to which mortality risks arising from overall social deprivation may vary across areas with different levels of greenness exposure remains limited. Addressing this gap not only enhances the evidence of the nexus between overall social deprivation and mortality in the Asian context, but also provides suggestions for policymakers to mitigate health inequalities through effective environmental planning implementations. To fill these gaps, this study aims to (1) construct a comprehensive social deprivation index, evaluate greenness exposure, and calculate all-cause and cause-specific mortality at neighborhood level in Hong Kong, as well as demonstrate their spatiotemporal dynamics; (2) examine independent associations of social deprivation and greenness exposure with all-cause and cause-specific mortality over different periods during 1999–2018; (3) investigate whether greenness exposure could mitigate the adverse impacts of social deprivation on mortality risks in Hong Kong.

2. Methodology

2.1. Study design and participants

This study was carried out in Hong Kong, the world's fourth-most densely populated city, with a population density of over 7000 individuals per square kilometer. Mortality data in Hong Kong from 1999 to 2018 are available for each Tertiary Planning Unit (TPU), which constitutes the third level of planning units as delineated by the geographic reference system of Hong Kong Planning Department. However, the relevant socioeconomic data are only available at the level of Small Tertiary planning Unit Group (STPU), which are amalgamations of one or more TPUs. Consequently, we adopted STPU as the spatial unit for our analyses and aggregated the mortality data from the TPU level to the STPU level. It is worth noting that the boundaries of certain STPUs changed between 2001 and 2016. Specifically, some STPUs with small land areas and low population were merged with the adjacent ones to form larger STPUs during 2001–2006. We thus designated the STPU boundaries in 2016 as the reference, and subsequently merged the STPUs in previous years to ensure consistency of STPU boundaries across all years. Eventually, a total of 179 STPUs were incorporated into this study, and we also aggregated the mortality data and socioeconomic data into the adjusted STPUs for subsequent analyses. These procedures ensure the feasibility of conducting comparisons of social deprivation, greenness exposure, and their associations with mortality risks across space and time.

2.2. Mortality data

The mortality data were acquired from the Registered Death files from the Census and Statistics Department of Hong Kong. These files contain basic information, including3-digit codes of TPUs, date of death, and cause of deaths categorized according to the International Classification of Diseases 9th and 10th Revision (ICD-9 and ICD-10). In this study, we analyzed all-cause mortality, non-accidental mortality (ICD-9 codes: 001–799, icd-10 codes: A00-R99), and cause-specific mortality including cardiovascular diseases (ICD-9 codes: 401–438, ICD-10 codes: I10–I69), respiratory diseases (ICD-9 codes: 460–519, ICD-10 codes: J00-J99), and cancer (ICD-9 codes: 140–208, ICD-10 codes: C00–C97) (Bauwelinck et al., 2021). Based on the matching information between the codes of TPUs and STPUs, we aggregated the annual counts of all-cause and cause-specific deaths from TPUs into each corresponding STPU. Due to the social deprivation indices were only available every five years in 2001, 2006, 2011, and 2016, we assumed that the social deprivation indices for a specific year represented the average status over a 5-year period centered around that specific year. Likewise, we also calculated 5-year average all-cause and cause-specific mortality rate during 1999–2003, 2004–2008, 2009–2013, 2014–2018 for each STPU to show the spatiotemporal patterns.

2.3. Construction of social deprivation

According to previous research and available data, we selected eight representative indicators from five different aspects of social deprivation, which might affect mortality (Messer et al., 2006; Yeung et al., 2022). Specifically, the following indicators were chosen to represent income and poverty situations: the percentage of high-income households and low-income households, personal median income, and household median income. These indicators depict overall income situations of both individual and household at neighborhood level, which are key factors of social deprivation. Besides, to depict the education situation, the percentage of population with secondary education or below were selected. More deprived neighborhoods are usually assumed to have fewer opportunities to access sufficient educational resources. Considering employment and occupation represent the opportunities to engage in socioeconomic activities, we calculated the unemployment rate and the percentage of population with non-professional occupation for representation of the employment and occupation situation, respectively. Lastly, we calculated average room per capita to depict the housing situation as crowded living environment is usually associated with social deprivation. These socioeconomic data at STPU level were derived from census and by-census reports of 2001, 2006, 2011, and 2016 provided by the Census and Statistics Department of Hong Kong.

We employed Principal Component Analysis (PCA) technique to construct social deprivation in this study. PCA is commonly used to derive representative components from a set of correlated variables, based on the total variance explained by the initial variables (Petrişor et al., 2012). Components with an eigenvalue greater than 1 were retained to calculate the social deprivation score. These scores were subsequently normalized to create indices ranging from 0 (least deprived) to 1 (most deprived). Before conducting PCA, we applied the Keiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity to assess the suitability of PCA. The results showed that the KMO value (0.868) exceeded 0.5 and the p-value of Bartlett's test of sphericity (<0.001) was less than 0.05, indicating the necessity of running PCA (Table S1) (Malah and Bahi, 2022). The PCA result indicates that the social deprivation indices can be represented by a single component since the eigenvalue of the second component was less than 1. Specifically, the retained component had an eigenvalue of 5.660, and it explained 70.756% of the total variance, indicating that the social deprivation can be mostly explained by the selected indicators (Table S2). It is worth noting that we used four waves of socioeconomic data from 2001, 2006, 2011, and 2016 to create a panel dataset for conducting PCA analysis comprehensively. This approach enabled the comparison of the temporal variations in social deprivation across the four waves of data.

2.4. Measurement of greenness exposure

In previous studies, greenness exposure was typically quantified by calculating the average Normalized Difference Vegetation Index (NDVI) within a specific urban area using satellite images (Bauwelinck et al., 2021; Ji et al., 2020; Mendoza et al., 2023). However, this approach ignored to consider population distribution, which probably introduce bias in estimating people's exposure to greenness in a particular urban area. To mitigate the potential bias, we estimated population-weighted exposure to greenness in each STPU with combination of NDVI and Population distribution. This approach assigns higher weights proportionally to greenness exposure in areas with denser population distribution (B. Chen et al., 2022). Aligned with the method of Song et al. (2022), annual NDVI was calculated from atmospherically corrected satellite images with a 30-m resolution, obtained from Landsat 8 Collection Tier 2 and Landsat 5 TM Collection Tier 2. The Landsat dataset provides the longest time span of the images, covering the full 20 years of our study period, which has yet to be achieved in other existing remote sensing products. Negative values representing water bodies were set to zero to avoid underestimating the exposure to greenness. Besides, the yearly population distribution of the residents was derived from WorldPop Global Project Population data, which estimated the population residing in each 100 × 100 m grid cell (Sorichetta et al., 2015). We calculated the population-weighted exposure to greenness in each STPU based on the following formula:

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

Where GE denotes the exposure to greenness per person for the given STPU, N denotes the total number of grids for a given STPU, P_i denotes the population of the i^{th} grid, and G_i^b denotes the mean NDVI within a buffer with size of b meters centered on the i^{th} grid (Fig. S1). Referring to the dense pedestrian road network in Hong Kong, we established 400 m buffer and 800 m buffers for each grid to capture the immediate surroundings, accessible within a 5–10 min walk, and the broader surroundings, respectively (Sun et al., 2021). Given the absence of available satellite image for 2012 and population distribution data for 1999, the population-weighted exposure to greenness in these 2 years were supplemented by linear interpolation. All the calculations were conducted in the Google Earth Engine (GEE). We calculated the average population-weighted exposure to greenness for every five years from 1999 to 2018 to represent the average status for corresponding years.

2.5. Statistical analysis

We aggregated the counts of deaths from 1999 to 2018 into four corresponding 5-year period (i.e., 1999–2003, 2004–2008, 2009–2013, 2014–2018), and their association with social deprivation, and greenness exposure were examined by fitting the following formula with Bayesian modelling technique (Y. Chen et al., 2022):

$$Y_i | death_i, k \sim NegBin(death_i, k)$$

$$\log(death_i) = \beta_0 + \beta_1 SD_i + \beta_2 GE_i + \beta_n COV_i + offset(pop_i) + \varnothing_i + \mu_i$$

To address the overdispersion (k) of death counts (Y_i), we applied a negative binomial distribution for the outcome (mortality). In the formula, β_0 denotes the intercept, while β_1, β_2, β_n denotes the estimated coefficients for social deprivation (*SD*), greenness exposure (*GE*), and a set of covariates (*COV*), respectively. $offset(pop_i)$ denotes the offset variable based on the population in each STPU. $\varnothing_i$ and μ_i denotes spatially structured and unstructured random effects. The contributions of these two random effects were determined by a precision parameter and a mixing parameter in a modified Besag-York-Mollié model (Riebler et al., 2016). Notably, each time period is modeled separately to demonstrate the disparities in the effects of social deprivation and greenness exposure on mortality during each respective period.

We calculated sex ratio, population density, land use mix index, the percentage of non-relative households and the percentage of never-married population to be included in the model as covariates. These variables were used to control the potential influences from some relevant sociodemographic factors and built environment factors on mortality (Patino et al., 2021; Wang et al., 2021; Yeung et al., 2022). We conducted an exponential transformation on the estimated coefficients to calculate rate ratios (RR) to interpret the effects of social deprivation, greenness exposure on mortality. Note that an RR greater than 1 represents adverse effects, while RR less than 1 indicates protective effects. Besides, an RR is considered statistically significant at the 95% level ($p < 0.05$) when it's 95% credible interval does not encompass the value 1 (Habibzadeh, 2017).

To further investigate the potential moderating effects of greenness exposure on the association between social deprivation and mortality risks, we divided the STPU into two groups (high greenness exposure vs. low greenness exposure) based on the median value of greenness exposure. We separately estimated the effects of social deprivation on mortality risks for each group and compared the results to illustrate the differences between the two groups across the four periods. We formulated a hypothesis suggesting that the adverse effects of social deprivation on mortality in areas with high greenness exposure would be less pronounced than in areas with low greenness exposure. The model fitting was conducted using R-INLA package in R software version 4.1.1 (Rue et al., 2017).

3. Results

3.1. Spatiotemporal patterns of mortality, social deprivation, and greenness exposure

Table 1 summarizes the 5-year mean values for all-cause and cause-specific mortality rate, social deprivation, and population-weighted exposure to greenness within 400 m and 800 m buffers, spanning the years 1999–2018. Despite the general rise in all-cause and cause-specific mortality rates from period 1 to period 4, these mortality rates experienced a temporal pattern characterized by an initial increase followed by a subsequent decrease. Notably, the CVD mortality rate declined from 1.26 during period 1 to 1.10 during period 4. Additionally, the standard deviation of five categories of mortality rates continuously increased over the 20 year-period, indicating a widening gap between STPUs with high and low mortality rates. For the social deprivation, the results show that the average score for the whole of Hong Kong remained stable at 0.67 form period 1 to period 2, after which it decreased to 0.60 in period 3 and to 0.56 in period 4. This reveals that Hong Kong society gradually reduced levels of deprivation in recent decade. In addition, the city has been becoming progressively greener, as demonstrated by the upward trend in the population-weighted NDVI (from 0.34 to 0.41 when using 400 m buffers, and from 0.36 to 0.44 when using 800 m buffers).

Fig. 1 and Figs. S2–S5 visualized the spatiotemporal patterns of average mortality rate (expressed by deaths per 1000 persons) in Hong Kong every five year from 1999 to 2018. All-cause mortality and non-accidental mortality exhibited similar patterns. During the year 1999–2008, STPUs with relatively high mortality rate were distributed in the north district, Yuen Long, the Kowloon Peninsula, and the west and north of Hong Kong Island. However, in some STPUs located in the north district, the mortality rate experienced a transition from high to low, while other STPUs remained similar spatial patterns compared with previous periods. Moreover, STPUs with high mortality rates were more densely clustered in the Kowloon Peninsula, and the west and north of Hong Kong Island during the year 2014–2018. Likewise, STPUs with high cause-specific mortality rates also exhibited a concentration from the northern regions towards central Hong Kong, especially the Kowloon Peninsula and the north of Hong Kong Island over the course of two decades.

Table 1
Summary of mortality, social deprivation, and greenness exposure at the STPU level, 1999–2018.

	1999–2003 (Period 1)	2004–2008 (Period 2)	2009–2013 (Period 3)	2014–2018 (Period 4)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
All-cause mortality rate	4.90 (2.62)	5.60 (2.68)	5.81 (3.09)	5.35 (4.71)
Non-accidental mortality rate	4.66 (2.52)	5.39 (2.61)	5.64 (3.03)	5.21 (4.61)
CVD mortality rate	1.26 (0.68)	1.42 (0.73)	1.36 (0.75)	1.10 (0.93)
Respiratory disease mortality rate	0.85 (0.58)	1.06 (0.67)	1.26 (0.88)	1.22 (1.26)
Cancer mortality rate	1.55 (0.88)	1.69 (0.73)	1.76 (0.84)	1.60 (1.30)
Social deprivation	0.67 (0.20)	0.67 (0.17)	0.60 (0.18)	0.57 (0.13)
Greenness exposure (400 m buffer)	0.34 (0.14)	0.33 (0.14)	0.36 (0.14)	0.41 (0.15)
Greenness exposure (800 m buffer)	0.36 (0.14)	0.36 (0.14)	0.38 (0.14)	0.44 (0.15)

Fig. 2 demonstrates the variations of social deprivation and greenness exposure (400 m buffer) over space and time. During the first decade, most high-deprived STPUs (with a deprivation score >0.65), were located in the suburb areas and the Kowloon Peninsula. Furthermore, greener STPUs (with greenness exposure> 0.5) are located in suburb areas such as Yuen Long and the north district, while less greener STPUs are located in the Kowloon Peninsula. Even though there was no significant change in the spatial patterns of the social deprivation during the year 2004–2013, the number of highly deprived STPUs continuously decreased. In the period 2014–2018, deprivation score of STPUs located in the north district exhibited noticeable decrease. The spatial pattern of relatively high deprived STPUs remained consistent with previous periods, while STPUs with least deprivation were primarily concentrated in the central and southern Hong Kong Island. These areas also exhibited relatively high level of greenness exposure throughout two decades.

3.2. Independent effects of social deprivation and greenness exposure on mortality

We firstly conducted baseline models including solely social deprivation and solely greenness exposure, respectively (Tables S5–S7). Significant adverse effects of social deprivation on all-cause mortality and cause-specific mortality were observed across the previous three periods (i.e., 1999–2003, 2004–2008, 2009–2013), while the protective effects of greenness exposure on mortality exhibited statistically significant throughout four periods. Furthermore, we constructed models including both social deprivation and greenness exposure to examine their independent effects on mortality. Table 2 and Table 3 demonstrate

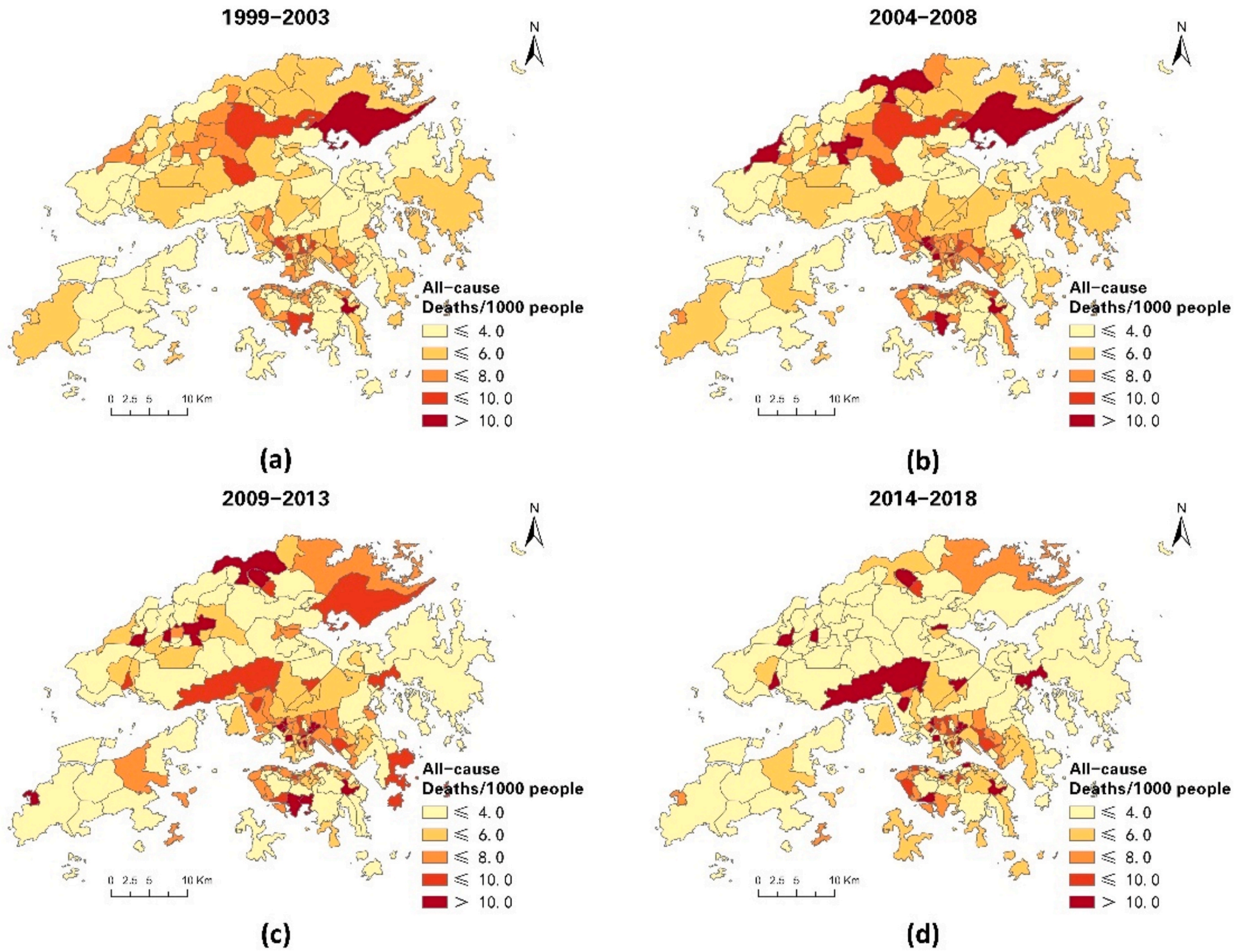

Fig. 1. Spatiotemporal variations of all-cause mortality, 1999–2018.

the independent associations between social deprivation, greenness exposure, and mortality across the four periods, reported as RR with corresponding 95% credible intervals (95% CI). Overall, the results are consistent with those of the baseline models.

During 1999–2003, the risk of all-cause mortality, non-accidental mortality, mortality from CVD, respiratory disease, and cancer increased by 7.1% (95% CI: 2.1%–12.2%), 6.7% (95% CI: 1.6%–11.9%), 6.0% (95% CI: 0.9%–11.3%), 7.4% (95% CI: 1.6%–13.5%), and 7.8% (95% CI: 3.2%–12.6%) for every 10% increase in deprivation score. These adverse effects increased during the year 2004–2008. However, the effects of social deprivation on all-cause mortality, and mortality from respiratory disease exhibited slight attenuation in the period 2009–2013, with a reduction in RR from 1.106 (95% CI: 1.058–1.157) to 1.103 (95% CI: 1.051–1.159) and from 1.131 (95% CI: 1.067–1.199) to 1.106 (95% CI: 1.093–1.177), respectively. In contrast, the effects on mortality from CVD and cancer continuously intensified, with an RR increasing from 1.111 (95% CI: 1.060–1.163) to 1.117 (95% CI: 1.066–1.171), and from 1.103 (95% CI: 1.061–1.147) to 1.111 (95% CI: 1.065–1.159), respectively. Interestingly, these adverse effects of social deprivation on mortality from all causes were no longer statistically significant during the period 2014–2018, which was probably attributed to the improved social deprivation situation in Hong Kong during that period.

Greenness exposure was shown to have significantly protective effects on mortality risks. Specifically, mortality risks decreased noticeably with the increase in the greenness exposure. In the period 1999–2003, RR of all-cause mortality, non-accidental mortality, CVD mortality, respiratory disease mortality, and cancer mortality were 0.910 (95% CI: 0.835–0.991), 0.907 (95% CI: 0.831–0.990), 0.889 (95% CI: 0.815–0.969), 0.888 (95% CI: 0.803–0.982), 0.914 (95% CI: 0.848–0.984), respectively. Despite the fluctuation during 2004–2013, the protective effects on all-cause and cause-specific mortality significantly enhanced in the period 2014–2018, achieving their highest level. The risk of all-cause mortality, non-accidental mortality, mortality from CVD, respiratory disease, and cancer decreased by 14.8% (95% CI:4.5%–24.2%), 15.3% (95% CI: 4.9%–24.7%), 16.7% (95% CI: 7.1%–25.6%), 19.9% (95% CI: 8.0%–30.7%), and 16.3% (95% CI: 6.2%–25.6%) for every 10% increase in greenness exposure. We substituted the exposure variable with population-weighted exposure to greenness within 800 m buffers and obtained similar results, indicating the robustness of the results (Table 3).

3.3. Mortality risks associated with social deprivation by exposure levels to greenness

Fig. 3 depicts differences in adverse effects of social deprivation on mortality risks stratified by high and low levels of greenness exposure within 400 m buffers. During the period 1999–2003, the difference in adverse effects of social deprivation on all-cause mortality risks was minimal between STPUs with high and low exposure levels to greenness. However, STPUs with high exposure levels to greenness exhibited lower adverse effects of social deprivation on cause-specific mortality risks, even though such differences are not statistically significant. Similarly, this pattern persisted in the following three periods not only for most cause-specific mortality risks, but also for all-cause mortality risks. The difference was especially noticeable for the CVD mortality. During

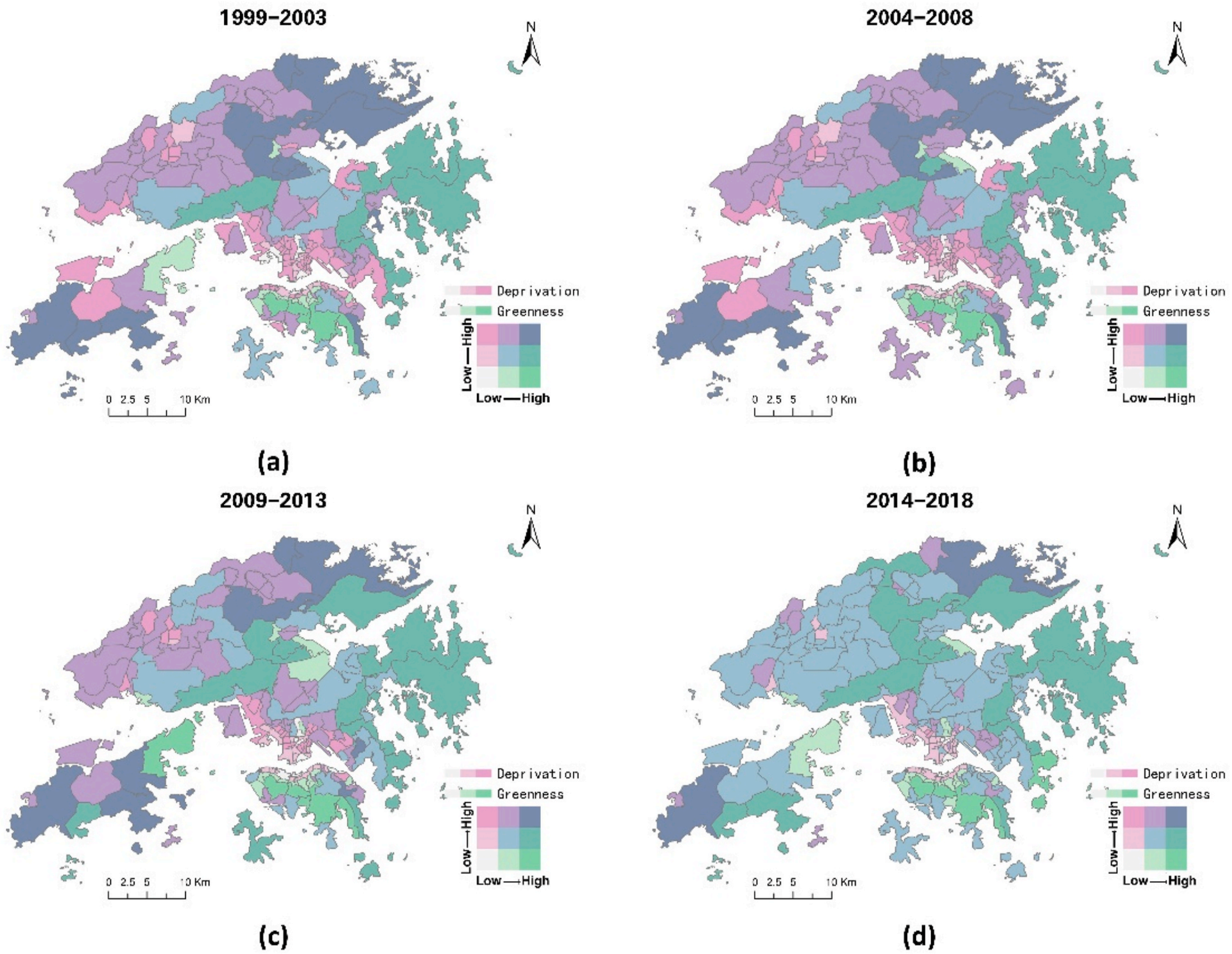

Fig. 2. Spatiotemporal variations of social deprivation and greenness exposure, 1999–2018 (note: Social deprivation and greenness exposure are respectively classified into three classes based on their low, medium, and high values, resulting in a total of nine classes in each bivariate map. These classes depict the spatial relationships between two variables, ranging from low-low values to high-high values. Specifically, the ranges for the three classes of social deprivation are <0.40, 0.40–0.65, and ≥0.65, while the ranges for the three classes of greenness exposure are <0.30, 0.30–0.50, and ≥0.50.).

Table 2
Effects of social deprivation and greenness exposure (population-weighted exposure within 400 m buffers) on mortality, 1999–2018.

	1999–2003 R R (95%CI)	2004–2008 R R (95%CI)	2009–2013 R R (95%CI)	2014–2018 R R (95%CI)
All-cause Mortality				
Deprivation	**1.071 (1.021–1.122)**	**1.106 (1.058–1.157)**	**1.103 (1.051–1.159)**	1.041 (0.950–1.139)
Greenness	**0.910 (0.835–0.991)**	**0.889 (0.828–0.953)**	**0.890 (0.820–0.966)**	**0.852 (0.758–0.955)**
Non-accidental Mortality				
Deprivation	**1.067 (1.016–1.119)**	**1.103 (1.053–1.154)**	**1.103 (1.050–1.158)**	1.037 (0.946–1.136)
Greenness	**0.907 (0.831–0.990)**	**0.888 (0.826–0.954)**	**0.888 (0.817–0.964)**	**0.847 (0.753–0.951)**
Cardiovascular disease Mortality				
Deprivation	**1.060 (1.009–1.113)**	**1.111 (1.060–1.163)**	**1.117 (1.066–1.171)**	1.043 (0.956–1.136)
Greenness	**0.889 (0.815–0.969)**	**0.874 (0.812–0.940)**	**0.895 (0.826–0.969)**	**0.833 (0.744–0.929)**
Respiratory disease Mortality				
Deprivation	**1.074 (1.016–1.135)**	**1.131 (1.067–1.199)**	**1.106 (1.039–1.177)**	1.036 (0.932–1.150)
Greenness	**0.888 (0.803–0.982)**	**0.853 (0.776–0.937)**	**0.845 (0.758–0.939)**	**0.801 (0.693–0.920)**
Cancer Mortality				
Deprivation	**1.078 (1.032–1.126)**	**1.103 (1.061–1.147)**	**1.111 (1.065–1.159)**	1.034 (0.946–1.128)
Greenness	**0.914 (0.848–0.984)**	**0.895 (0.841–0.951)**	**0.886 (0.825–0.951)**	**0.837 (0.744–0.938)**

2009–2013, a 10% increase in social deprivation score was associated with an 8.6% (95%CI: 1.3%–16.2%) increase in CVD mortality in high greenness exposure group and a 12.5% (95%CI: 5.6%–19.7%) increase in CVD mortality in the low group. Unexpectedly, a stronger adverse effect of social deprivation on cancer mortality risks exhibited in STPUs with high exposure to greenness, even though the difference was insignificant (RR of high greenness exposure group: 1.102, 95%CI: 1.036–1.172, RR of low greenness exposure group: 1.095, 95%CI: 1.033–1.160). During the year 2014–2018, the associations between social deprivation and mortality risks were no longer statistically significant in both groups, despite exhibiting similar trends to previous periods. The findings were similar when using population-weighted exposure to greenness within 800 m buffers to define greenness exposure (Fig. 4). The results for non-accidental mortality are also similar to

Table 3
Effects of social deprivation and greenness exposure (population-weighted exposure within 800 m buffers) on mortality, 1999–2018.

	1999–2003 R R (95%CI)	2004–2008 R R (95%CI)	2009–2013 R R (95%CI)	2014–2018 R R (95%CI)
All-Cause Mortality				
Deprivation	**1.071 (1.021–1.122)**	**1.105 (1.056–1.155)**	**1.102 (1.049–1.157)**	1.036 (0.946–1.134)
Greenness	**0.903 (0.827–0.984)**	**0.890 (0.829–0.956)**	**0.900 (0.828–0.978)**	**0.859 (0.763–0.965)**
Non-accidental Mortality				
Deprivation	**1.066 (1.016–1.119)**	**1.101 (1.051–1.152)**	**1.101 (1.048–1.157)**	1.035 (0.945–1.134)
Greenness	**0.900 (0.824–0.983)**	**0.889 (0.826–0.956)**	**0.897 (0.825–0.975)**	**0.859 (0.762–0.965)**
Cardiovascular disease Mortality				
Deprivation	**1.058 (1.007–1.110)**	**1.109 (1.059–1.161)**	**1.115 (1.064–1.169)**	1.040 (0.953–1.133)
Greenness	**0.878 (0.804–0.958)**	**0.872 (0.809–0.939)**	**0.898 (0.829–0.973)**	**0.838 (0.747–0.936)**
Respiratory disease Mortality				
Deprivation	**1.073 (1.014–1.133)**	**1.128 (1.064–1.196)**	**1.102 (1.034–1.175)**	1.032 (0.928–1.146)
Greenness	**0.879 (0.793–0.972)**	**0.858 (0.779–0.943)**	**0.857 (0.768–0.955)**	**0.803 (0.694–0.925)**
Cancer Mortality				
Deprivation	**1.078 (1.032–1.126)**	**1.101 (1.059–1.145)**	**1.109 (1.063–1.157)**	1.030 (0.941–1.125)
Greenness	**0.911 (0.845–0.983)**	**0.900 (0.846–0.957)**	**0.902 (0.839–0.968)**	**0.849 (0.753–0.953)**

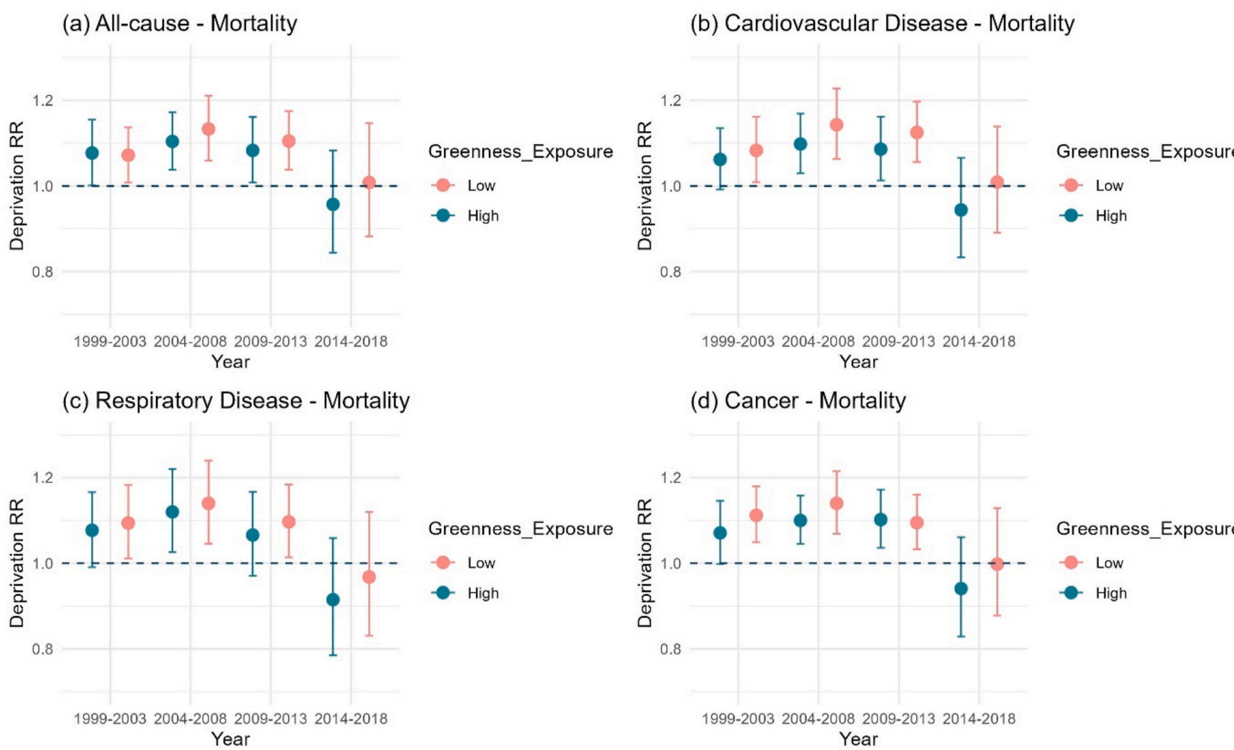

Fig. 3. Rate ratios (RR) with 95% credible intervals (95% CI) of social deprivation on mortality between high and low greenness exposure groups (400 m buffers), 1999–2018.

those of all-cause mortality, as shown in Fig. S6.

4. Discussion

In this study, we measured and visualized the spatiotemporal dynamics of social deprivation, greenness exposure, as well as all-cause and cause-specific mortality in Hong Kong during the year 1999–2018. It contributes to a comprehensive understanding of socio-economic development, environmental changes, and health disparities in the city. Additionally, we examined the independent effects of social deprivation and greenness exposure on mortality risks, offering valuable insights into the influences of socioeconomic factors and environmental factors on mortality in Hong Kong. Furthermore, we found out the adverse effects of social deprivation on mortality risks differ across areas with varying levels of greenness exposure. To the best of our knowledge, this is the first attempt to explore the complex interplay between social deprivation and greenness exposure in affecting mortality risks in Hong Kong. The results highlight that greenness exposure may mitigate socioeconomic inequalities in health outcomes in this densely populated Asian city.

4.1. Social deprivation, urban greenness, and mortality risks

Our findings show that the 5-year average all-cause and cause-specific mortality rates in Hong Kong increased from 1999 to 2013, then decreased during the period 2014–2018. Besides, the differences between STPUs with high and low mortality rates gradually widened. The spatiotemporal patterns reveal that STPUs with relatively high mortality rates gradually shift from the northern regions towards central Hong Kong, particularly in the highly urbanized areas such as the Kowloon Peninsula and the northern part of Hong Kong Island. This raised concerns of growing health burden in the high-density areas in Hong Kong. Regarding social deprivation, the average social deprivation score in Hong Kong has decreased noticeably during the past two

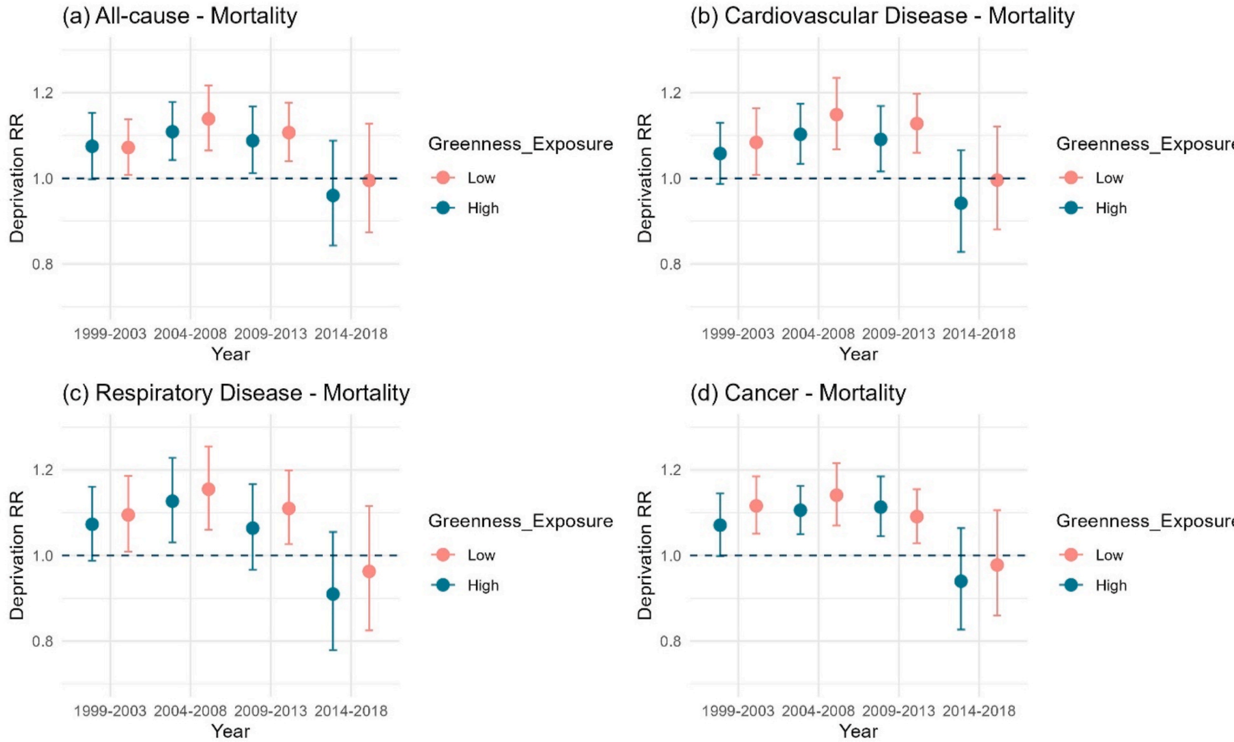

Fig. 4. Rate ratios (RR) with 95% credible intervals (95% CI) of social deprivation on mortality between high and low greenness exposure groups (800 m buffers), 1999–2018.

decades, especially for STPUs located in the suburb areas (i.e., the north district and the island district). This indicates a trend of decreasing social deprivation in Hong Kong, and a reduction in the number of areas with extreme deprivation, which is aligned with the findings of a previous study (Yeung et al., 2022). For greenness exposure, we found that the overall greenness exposure in Hong Kong has increased over the past two decades, indicating that people have had increasing access to urban greenness. The spatial disparity of greenness exposure, however, remained relatively stable, with lower values observed in the Kowloon Peninsula and the northern part of Hong Kong Island. In sum, the areas with higher social deprivation and lower greenness exposure, also tend to have relatively high mortality rates.

We further identified significant adverse impacts of social deprivation on mortality risks based on the Bayesian spatial model. We observed that the areas with higher deprivation were more likely to have higher mortality risks. The finding revealed the socioeconomic inequalities on health outcomes also existed in Hong Kong, which is consistent with many cities worldwide (Chan et al., 2018; Hatch et al., 2011; Jacquet et al., 2018; Lin et al., 2019; Safaei, 2007). We also found that the adverse effects of social deprivation on mortality from CVD and cancer continuously strengthened during the period 1999–2013, possibly because of the heavy financial burdens associated with CVDs and cancers, while the effects on all-cause, non-accidental, and respiratory disease mortality gradually weakened after the second period. However, to our surprise, all the adverse effects of social deprivation are statistically insignificant in the period 2014–2018. There are two possible explanations. First, the substantial reduction in social deprivation in Hong Kong may alleviate the socioeconomic inequalities of health in Hong Kong in recent years. Hence, we assume that there might be a threshold effects between social deprivation and mortality risks (Rehkopf et al., 2008). When social deprivation diminishes in a society, the association between social deprivation and the mortality risks might be attenuated accordingly. Second, the consistent improvement of health resources and the development of community-based medical services in the areas with high social depravation may be reducing the risks of mortality and morbidity, thereby reducing the adverse effects of social deprivation in Hong Kong (Cheung et al., 2020). For example, Hong Kong is equipped with 2519 automated external defibrillators (AEDs) strategically covering urban centers and public housing estates so far(Fig. S7) (Fire Services Department Hong Kong SAR, 2021). Moreover, over 92.5% of ambulance responses could occur within 12 min from call to arrival in Hong Kong, ensuring timely assistance in emergent situations across communities (Fire Services Department Hong Kong SAR, 2022).

Moreover, our study revealed a gradual increase in the protective effects of greenness exposure for two decades. The protective effects of greenness exposure in Hong Kong were documented in a previous work, revealing an association between higher NDVI and reduced mortality from CVD and diabetes (Xu et al., 2017). Our study further observed significant protective effects of population-weighted greenness exposure on all-cause mortality, non-accidental mortality, CVD mortality, respiratory disease mortality, and cancer mortality. For comparison, we further conducted a sensitivity analysis using traditional NDVI measures. The results show similar trends, although outcomes from some years exhibited insignificant (Table S8 and Table S9). A potential explanation for this difference could be our unique approach to measuring greenness exposure in our study, specifically, the use of population-weighted greenness exposure. This approach has been identified as a more reliable measurement of greenness exposure in other environmental health studies (Jiang et al., 2022). There is a possible interpretation regarding the potential mechanism of the protective effects of greenness exposure on mortality, i.e., greenness may mitigate pollution and mental stress, encourage physical activities, social interactions, and active transport and lifestyles, all of which contribute to better health outcomes (Fernández Núñez et al., 2022; Lu, 2019; Remme et al., 2021; Tsai et al., 2019; Yang et al., 2019).

4.2. *Potential moderating effects of urban greenness on health inequality*

Based on the stratified analyses (Figs. 3 and 4), we observed that the RRs of mortality caused by social deprivation were higher in the low-greenness STPUs than that in the high-greenness STPUs in most periods. Even though the differences are not statistically significant, probably due to the relatively small sample size, we revealed an interesting trend warranting further studies. The potential moderating effect of greenness exposure on health inequalities is supported by the 'Equigenesis' theory (Moran et al., 2021; Schinasi et al., 2023), which suggests that the positive health effects of greenness are more prominent among socially deprived populations and areas. Some empirical evidence also supports this theory. For example, Mitchell and Popham (2008) identified lower health inequalities in populations residing in areas with most greenness. Additionally, Yao et al. (2022) observed that the protective effects of street view greenness on ischemic heart diseases were more pronounced among patients residing in low-income neighborhood. As mentioned in the previous section, green environments can enhance opportunities for engaging in health-promoting activities and mitigate pollution and stress, potentially reducing the risks of negative health outcomes for socially deprived populations. This effect might counterbalance the health risks associated with limited medical services in deprived areas. On the other hand, socially advanced populations may access other relatively high-cost health-promoting venues and resources beyond greenspaces, such as gyms. Therefore, greenness exposure may have a larger marginal effect for socially deprived populations. In Hong Kong, basic medical services (e.g., AEDs and timely ambulance services) are widely available in most communities, which partially ensures access to healthcare for socially deprived populations. This abundance of medical services may result in statistically insignificant moderating effects of greenness exposure in our case. However, the observed higher adverse health impacts of social deprivation in areas with lower greenness exposure highlights that increasing greenness exposure may be a low-cost and effective solution for mitigating social and health inequalities.

4.3. Planning implications for a healthy city

Examining the associations between social deprivation and mortality risks can provide critical insights for the evidence-based policymaking. Despite the gradual reduction in social deprivation over the past two decades and the attenuation of its adverse effects on mortality risks in recent years, we highlight the ongoing importance of continuous monitoring of local socioeconomic development and health situation in Hong Kong. It is worth noting that special attention should be directed toward densely populated areas, particularly the Kowloon Peninsula and the northern areas of Hong Kong Island, due to relatively high mortality rates in these locations. These monitoring should involve the utilization of more comprehensive indices of social deprivation and health outcomes at finer planning units, facilitating the timely acquisition of more precise information on socioeconomic disparities and health inequalities. Using this information, the government can prioritize the allocation of medical services and health-promoting resources in the relatively deprived areas. Meanwhile, enhancement of health literacy, job security, housing condition, and income levels are suggested as key measures to reduce relevant health risks, with a particular focus on relatively deprived areas.

Drawing from the protective effects of greenness exposure on mortality risks and its potential to mitigate socioeconomic inequalities in mortality, we recommend government should pay attention to the role of green spaces in improving health. Specifically, urban planners should prioritize promoting the equitable distribution of urban green spaces, rather than solely emphasizing the overall quantity of green areas, to ensure the equal opportunities for residents to be exposed to urban greenness. For example, more green spaces should be created in densely populated areas and relatively deprived areas, as green exposure is proven to be a low-cost and effective solution to mitigate health inequalities. Since Hong Kong is a high-density city, we recommend the government to consider increasing the quantity and quality of street greeneries and pocket parks to accommodate the intensive land use (D. Liu et al., 2023; Lu, 2019; Yang et al., 2021). Meanwhile, as suggested by The Green and Blue Space Conceptual Framework in Hong Kong (2030)+, it is essential to develop more recreational and supporting facilities within existing and new green spaces to increase people's motivation to engage in health-promoting activities (HKGSAR, 2021). Furthermore, we also suggest that the government should improve transportation infrastructures from relatively deprived areas to large and remote green spaces, e.g., country parks. It is worth noting that these implications may also be applicable to other high-density cities aiming to mitigate health inequalities.

4.4. Limitations

There are several limitations in this study. Firstly, we should acknowledge that we only selected eight indicators for calculating social deprivation due to the limitation of available data. However, it is worth noting that the eight selected indicators are encompassed within five basic dimensions which are most comprehensively associated with social deprivation, which ensures the representativeness of the social deprivation indices. In addition, due to the models employed in this study are period-specific, it is essential to interpret the results with caution, considering each specific period independently. Whether changes in mortality risks are really associated with the changes in social deprivation and greenness exposure requires further verification by using temporal statistical methodology when more temporal data points are available.

Secondly, it is important to note that we solely quantified the overall greenness exposure using the NDVI in this study, due to the absence of relevant data with temporal information on other indicators of greenness exposure including the proximity to parks, and the density of green spaces (Bancroft et al., 2015; Lee et al., 2019; Zijlema et al., 2019). Even though NDVI has been widely used to represent greenness levels in many environmental health studies, it is important to acknowledge that it is a product of image enhancement techniques, which may not fully reflect the ecological services provided by green space (Liu et al., 2023a). We recommend future study to conduct more rigorous environmental health studies by using more accurate measurements of greenness, such as ratio of green space, when longitudinal data with high spatiotemporal resolution is available. In addition, previous studies have suggested that the quality of greenness can be also associated with health outcomes (Akpinar, 2016; Shuvo et al., 2020). However, the limited data available constrained our ability to measure the quality of greenness throughout Hong Kong. We also recommend that future studies could make efforts to examine the effort of other aspects of greenness on mortality risks and health inequality.

Thirdly, given the socioeconomic data and mortality data are only available at STPU-level, we aggregated all the other data from different resolutions into the STPU-level. Consequently, our study employed a residence-based measurement of environmental exposure. Previous studies in health geography have suggested that modelling the health effects of environments may be affected by various measurements of environmental exposure derived from different geographic context, which refers to the Uncertain Geographic Context Problem (UGCoP) (Kwan, 2012). The UGCoP is more likely occur when measuring environmental exposure using residence-based measurements due to the spatial uncertainty in the given geographic units and the temporal uncertainty regarding the timing and duration of individuals' exposure to diverse environments within their residence (Liu et al., 2023b). Therefore, our study might be susceptible to the UGCoP as our study follows a population-level residence-based paradigm. Mobility data provides great promise in addressing the UGCoP as it enables the assessment of individuals' actual exposure to environments, thereby largely mitigating the relevant spatial and temporal uncertainty. Hence, further studies could be conducted at the individual level to offer more strong evidence in the association between social deprivation, greenness exposure, and mortality in Hong Kong upon the data availability.

5. Conclusion

In this study, we observed a decline of social deprivation and an increase in greenness exposure in Hong Kong from 1999 to 2018. Concurrently, we noted the areas with higher mortality rates gradually concentrated in the Kowloon Peninsula and the northern regions of Hong Kong Island. Our statistical analyses unveiled that the adverse effect of social deprivation on mortality risks weakened in recent years, coupled with a progressive strengthening of the protective effects of greenness exposure during the period 1999–2018. Importantly, it is worth highlighting that greenness exposure may mitigate the negative impacts of social deprivation on mortality risks. Our recommendation to urban planners and policymakers is to maintain continuous monitoring of social deprivation and health status, while also enhancing efforts to implement equitable green space access, particularly in relatively deprived areas.

CRediT authorship contribution statement

Yuxuan Zhou: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yi Lu:** Writing – review & editing, Validation, Supervision. **Di Wei:** Writing – review & editing, Validation, Data curation. **Shenjing He:** Writing – review & editing, Validation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.healthplace.2024.103241.

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