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Urban greenspace exposure and inequality are associated with mortality in cities across multiple countries

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Abstract

Background Urban greenspace is recognized as a key component of healthy cities, yet evidence linking greenspace to mortality remains geographically fragmented, while the association between unequal greenspace distribution and mortality remains poorly understood. We aim to examine associations of greenspace exposure and inequality with all-cause, cardiovascular, and respiratory mortality across cities in multiple countries.

Methods We analyzed annual mortality and satellite-derived vegetation data from 624 urban locations across 22 countries during 2001–2020. Greenspace exposure was characterized using the population-weighted Enhanced Vegetation Index, and greenspace inequality using a Gini-based metric. We estimated country-specific associations with all-cause, cardiovascular, and respiratory mortality using negative binomial regression models. Country-specific estimates were pooled using random-effects meta-analysis, and heterogeneity by income level, climate zone, and geographical region was examined.

Results A 0.1-unit increase in greenspace exposure was associated with lower risks of all-cause mortality (RR = 0.89, 95% CI = 0.83–0.95), cardiovascular mortality (0.92, 0.82–1.00), and respiratory mortality (0.89, 0.78–1.01). In contrast, a 0.1-unit increase in greenspace inequality was associated with a higher risk of all-cause mortality (1.14, 0.99–1.31), with no significant associations observed for cardiovascular or respiratory mortality. These associations varied across income levels, climate zones, and geographical regions.

Conclusion Our findings indicate that both the amount and spatial distribution of urban greenspace are associated with population health, underscoring the need for urban planning strategies that prioritize not only greening but also equitable access.

The world has undergone rapid urbanization over the past century. Today, about 55% of the global population lives in cities; this proportion is projected to exceed 68% by 2050[1]. Although urbanization has improved health care, sanitation, and living standards, it introduces public health challenges. Compounded by climate change, urban residents face increasing exposure to heat, air pollution, and chronic psychosocial stress, which contribute to the rising burden of non-communicable diseases, including cardiovascular, respiratory, and mental health disorders[2]. Urban greenspace, as an essential component of healthy and sustainable cities, has been consistently associated with numerous health benefits[3]. Proposed pathways include

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increased physical activity and social interaction, reduced stress, and mitigated adverse environmental exposures (e.g., air pollution, noise, extreme heat)[3]. These mechanisms contribute to improved mental health and well-being and lower risks of adverse outcomes, including mortality[4,5].

Over the past decades, much research has examined associations between greenness and mortality, with most studies conducted in North America, Europe, Asia, and Australia[4,5]. Despite some inconsistent findings, the majority reported inverse associations, indicating lower mortality risk under higher greenness. A global systematic review and meta-analysis of cohort studies estimated that a 0.1 increase in the Normalized Difference Vegetation Index (NDVI) within 500 m of residence was associated with a 4% (95%CI: 3–6%) reduction in all-cause mortality[5]. Large-scale health impact assessments further quantified potential health benefits of greening[6]. In Italy, 28,433 (95% CI: 21,400–42,350) deaths have been associated with greenness levels below those of the 25% most exposed population in 2022, representing about 5% of total mortalities[6]. These findings have strengthened calls to leverage urban nature to address public health challenges. The United Nations emphasized the need for "providing universal access to greenspace for urban residents" in the 11th Sustainable Development Goal[7].

Despite well-documented benefits of greenspace, urban greenness is often unevenly distributed within cities, and access to greenspace can vary substantially across population groups[8–10]. Two related but distinct concepts are important in this context: socio-demographic greenspace inequity and spatial greenspace inequality. Socio-demographic greenspace inequity refers to systematic differences in greenspace exposure or access across population groups defined by income, education, race/ethnicity, or other social characteristics. This represents an environmental justice issue, as "greenspace privilege" can reinforce existing social and health inequalities[11]. Previous studies have shown that disadvantaged groups (e.g., low-income populations, individuals with lower education, racial/ethnic minority populations) generally experience lower exposure or access to greenspace[11–13]. Spatial greenspace inequality, by contrast, refers to the uneven distribution of greenness across urban space. The Gini index has been effectively adopted to quantify inequality in greenspace distribution[8,14–16], with recent applications demonstrating marked disparities at national and global scales. For instance, Song et al. first documented greenspace inequality across Chinese cities[15], and Chen et al. then extended this analysis to a global context[16]. In this study, we focus on spatial greenspace inequality rather than socio-demographic inequity in greenspace access.

Comparisons of studies on greenspace and mortality remain challenging because of variation in exposure metrics, target populations, and modeling approaches. Reliable cross-city and cross-regional assessments require consistent data sources and comparable methods. Research on greenspace inequality has mainly focused on access and socio-demographics disparities, with limited quantitative evaluation of direct health impacts. Moreover, human exposure to greenspace and greenspace inequality has changed over time due to rapid urbanization, climate change, and various policies[14]. Temporal variability in the health impacts of greenspace and greenspace inequality is understudied.

We aim to examine health effects of greenspace and greenspace inequality using a unified framework, with multi-country mortality datasets and satellite-derived greenness data to address three questions: (1) To what extent, do greenspace exposure and its distribution inequality associated with all-cause and cause-specific mortality? (2) Do these associations vary by income level, climate zone, or geographical region? (3) What are the temporal trends in these associations?

Methods

Mortality data and study locations

We analyzed annual mortality data (2001–2020) from all causes (or non-external), cardiovascular causes (International Classification of Diseases, 10th Revision [ICD-10] codes I00–I99), and respiratory causes (ICD-10 codes J00–J99) across 51 countries from the Multi-Country Multi-City (MCC) Collaborative Research Network[17]. All data were aggregated to the annual level. As the MCC dataset includes deaths data for the United States (US) only up to 2006, we replaced the US data with annual county-level death records from 2001 to 2020 obtained from the U.S. Centers for Disease Control and Prevention (CDC). Due to limited location coverage for Australia in the MCC dataset, we substituted the MCC records in Australia with annual deaths data from 2010 to 2020 retrieved from the Australian Institute of Health and Welfare (AIHW). For Canada, annual deaths data for the same period was obtained from the Government of Canada. Mortality rates were calculated as the number of deaths per 1000 population for each location. These rates were crude mortality rates rather than age-standardized rates because age-specific death counts were not consistently available across all study locations. To align mortality data with corresponding geographic units, we acquired administrative boundary data from multiple sources. Specifically, boundaries for Australia, Canada, and the United Kingdom were obtained from the Australian Bureau of Statistics (Local Government Areas), the Government of Canada (2016 Census Tract Boundary Files), and the UK Office for National Statistics (Major Towns and Cities, December 2015 Boundaries, Version 2), respectively. For all other countries, boundary data were sourced from the Database of Global Administrative Areas (GADM, version 4.1). Detailed information on the spatial units and geographical boundary sources for each country is provided in Supplementary Table 1.

To focus on urban settings, we restricted the analysis to locations with more than 50% of the population living in urban areas. The following procedure was applied to calculate the proportion of urban population: (1) We obtained the 2020 Global Human Settlement (GHS) settlement model data at a spatial resolution of 1 km. Each grid in the dataset is classified into one of the following categories: 30 (urban center), 23 (dense urban cluster), 22 (semi-dense urban cluster), 21 (suburban), 13 (rural cluster), 12 (low-density rural), 11 (very low-density rural), and 10 (water). (2) these categories were reclassified into three classes: Urban (30, 23, 22), Suburban (21), and Rural (13, 12, 11). (3) By overlaying the new classification with global population data, we estimated the total population residing in 'Urban' areas within each city and calculated the corresponding proportion of urban population. We excluded regional-only locations, locations with <10 consecutive years, and countries with <3 eligible locations. The final dataset included all-cause mortality data (or nonexternal, depending on availability) for 624 locations across 22 countries, cardiovascular-cause mortality data for 456 locations across 12 countries, and respiratory-cause mortality for 449 locations for 11 countries.

Covariates

Daily mean temperature from 2001 to 2020 was calculated using ERA5-Land data (spatial resolution: 9 km) via Google Earth Engine (GEE). Annual mean temperature was then derived for each location. Annual population and age–sex-structured population data from 2001 to 2020 were obtained from the World Pop database. We calculated the percentage of the population that is older adults (≥65 years) for each location by dividing the total number of individuals aged 65 years and older by the total population within the city boundary. Annual $PM_{2.5}$ concentrations (1 km resolution) were obtained from the Atmospheric Composition Analysis Group at Washington University in St. Louis[18]. Gridded GDP data (1 km resolution) were obtained from the global GDP dataset developed by Chen et al.[19]. For each location, we calculated the annual mean $PM_{2.5}$ concentration and GDP by averaging the values of all grid cells within the corresponding geographic boundary.

Greenspace exposure and greenspace inequality

We assessed greenspace with Enhanced Vegetation Index (EVI) and applied population-weighting in this study. EVI corrects for soil and atmospheric influences and is less likely to saturate in high-biomass areas, making it more suitable for urban settings where vegetation is intermixed with impervious surfaces and atmospheric pollution is common. Annual EVI data at 500 m were obtained from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS). EVI values range from −1.0 to 1.0, with negative values representing water bodies and higher positive values indicating higher levels of vegetation density. We recoded negative EVI values as zero.

We use the Gini index metric to estimate inequality in exposure to greenspace[15] as:

$$Gini = 1 - \frac{2 \times \sum_{i=1}^{n} \sum_{i=1}^{i} g_i}{n \times \sum_{i=1}^{n} g_i} \quad (1)$$

where n = number of grid cells in the city; g_i = value of grid-i's greenspace. The Gini index ranges from 0 (absolute equality) to 1 (absolute inequality). Annual greenspace exposure and inequality were computed for all locations. We calculated annual greenspace exposure and greenspace inequality from 2001 to 2020 for all locations included. Data was processed using ArcGIS Pro and R Studio (R version 4.4.2).

Statistical analysis

We linked mortality, greenspace, and covariate data by location and year. For each outcome, we first fitted country-specific negative binomial generalized linear models to quantify the effect of greenspace exposure or greenspace inequality (Eqs. 2–4).

$$Y_{ij} \sim Negative\ Binomial\,(\mu_{ij}, \theta) \quad (2)$$

$$\log\left(\mu_{ij}\right) = \beta_0 + \beta_1 GE_{ij} + \sum_{m=1}^{n} \beta_m Covariate_{ij} + \log(Population_{ij}) + s(Year_c,\ df_c) \quad (3)$$

$$\log\left(\mu_{ij}\right) = \beta_0 + \beta_1 GI_{ij} + \sum_{m=1}^{n} \beta_m Covariate_{ij} + \log(Population_{ij}) + s(Year_c,\ df_c) \quad (4)$$

where Y_{ij} = observed number of deaths (all-cause, cardiovascular, or respiratory) in city i during year j, μ_{ij} = expected count of deaths, log-transformation of $Population_{ij}$ is included as an offset, β_0 = model intercept, β_1 = coefficient, representing greenspace (GE_{ij}) and greenspace inequality (GI_{ij}) for city i and year j. GE and GI were fitted in separate models because of high negative correlations in some countries (Supplementary Table 2). To adjust for area characteristics, we included annual mean temperature, fine particulate matter ($PM_{2.5}$), gross domestic product (GDP), percentage of the population that is >65 years as covariates. Temperature was modeled using a natural spline, and GDP was log-transformed. Country-specific temporal trends were adjusted using a natural spline of year with two degrees of freedom per decade (rounded).

In second-stage analysis, country-specific effect estimates were pooled using a random-effects meta-analysis to account for between-country variability. Effect modification by income level, climate zone, and geographical region was evaluated using multivariate meta-regression models with each classifier as a meta-predictor (Supplementary Table 3). We assessed the significance of these modifiers using Wald chi-square tests. All analyses were conducted in R (version 4.4.2) using the glmmTMB and mixmeta packages.

We examined temporal changes in the associations with period-specific analysis using 5-year intervals (2001–2005, 2006–2010, 2011–2015, and 2016–2020). For each country and each period, we refitted the same model as above but excluded the temporal trend term, thereby obtaining period-specific relative risks.

Model specification selection

Before selecting the final model, we compared alternative specifications for temperature adjustment, including a natural spline of annual mean temperature, a linear temperature term, and the number of heatwave and coldwave days defined using the 90th/10th, 95th/5th, and 99th/1st percentiles; and for socio-economic adjustment, including GDP, GDP per capita, and human development index (HDI) (Supplementary Notes). The Akaike Information Criterion (AIC) was used to evaluate model fit for each country and exposure–outcome pair. For most combinations, the natural spline of annual mean temperature produced the lowest AIC values. GDP provided better AIC than GDP per capita or HDI (Supplementary Tables 4–5, and Supplementary Fig. 8). These specifications were therefore selected for the main analysis, while all alternative specifications were evaluated in sensitivity analyses.

Sensitivity analysis

To evaluate the robustness of our findings, we performed a series of sensitivity analyses. We replaced the natural spline of annual mean temperature with a linear term and the annual number of heat wave and cold wave days for each location's long-term temperature distribution. We substituted socio-economic factors with GDP per capita and HDI to assess the influence of alternative socioeconomic indicators. We replaced annual greenspace exposure and inequality with city-level temporal averages. We introduced city-level random effects. We evaluated a combined specification that included city-level random effects in combination with averaged exposure metrics. We further conducted supplementary non-linear analyses to evaluate potential threshold or saturation patterns. Greenspace exposure and greenspace inequality were transformed into country-specific percentiles to account for differences in their ranges and distributions across countries. Country-specific models were refitted using a natural spline of the exposure percentile with 2 degrees of freedom and an internal knot fixed at the 50th percentile. The spline coefficients and covariance matrices were then pooled using random-effects multivariate meta-analysis to derive overall exposure–response curves, with relative risks centered at the 10th percentile. For the second-stage pooling, we additionally conducted a leave-one-country-out sensitivity analysis to assess the influence of individual countries on the pooled estimates.

Results

Study characteristics and spatial distribution

Our analysis included about 56 million all-cause deaths from 624 locations across 22 countries, 13.5 million cardiovascular deaths from 456 locations across 12 countries, and 4.6 million respiratory deaths for 449 locations for 11 countries (Table 1, Fig. 1a and Supplementary Figs. 1, 2). Mean greenspace exposure ranged from 0.15 (SD 0.03) in cities in Mexico to 0.28 (SD 0.05) in Switzerland, while greenspace inequality was lowest in Australia (0.09, SD 0.02) and highest in Japan (0.29, SD 0.03) (Table 1). Regions in western Europe, the eastern US, and Australia had higher greenspace exposure, whereas South Africa, the central US, and parts of South America showed lower levels (Fig. 1b, c). Greenspace inequality was greater in Japan, South Korea, and parts of Europe, and lower in the central US and Australia. Joint spatial distributions of greenspace exposure and inequality with mortality are shown in Supplementary Fig. 3.

Associations of greenspace exposure and inequality with mortality

Overall, higher greenspace exposure was associated with reduced mortality risks (Fig. 2a). A 0.1-unit increase in greenspace corresponded to lower risks of all-cause mortality (Relative Risk [RR] = 0.89, 95% Confidence Interval [CI]: 0.83–0.95), cardiovascular mortality (0.92, 0.82–1.00), and respiratory mortality (0.89, 0.78–1.01). Substantial heterogeneity was observed in these associations across countries, with $I^2 > 90\%$ for all three outcomes ($p < 0.001$). Protective associations across all outcomes were evident in some countries (South Africa, Spain, UK, US). For example, in the UK, greenspace exposure was associated with lower risks of all-cause mortality (0.94, 0.92–0.97), cardiovascular mortality (0.96, 0.94–0.99), and respiratory mortality (0.87, 0.84–0.90). In the US, the corresponding associations were RR = 0.96 (0.95–0.98), 0.99 (0.98–1.00), and 0.88 (0.86–0.89), respectively. By contrast, in South Korea, opposite associations were observed.

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Table 1 | Summary of the number of locations, study periods, number of deaths, mortality, greenspace, greenspace inequality, and urban population by countries.

Country	locations	Study period	Total deaths			Mortality (deaths/1000)			Greenspace exposure	Greenspace inequality	Urban Population (%)
			all-cause	cvd	resp	all-cause	cvd	resp			
Argentina	3	2005–2015	686,333	NA	NA	10.6 ± 2.14 (7.93–14.43)	NA	NA	0.22 ± 0.06 (0.12–0.29)	0.17 ± 0.02 (0.14–0.21)	84.57 ± 12.88 (68.92–100)
Australia	100	2010–2020	846,031	NA	NA	6.39 ± 1.78 (1.95–12.64)	NA	NA	0.25 ± 0.04 (0.13–0.37)	0.09 ± 0.02 (0.04–0.18)	81.23 ± 13.80 (50.23–100)
Belgium	4	2001–2020	2,128,450	NA	NA	10.61 ± 1.32 (7.53–13.63)	NA	NA	0.25 ± 0.05 (0.16–0.33)	0.21 ± 0.04 (0.14–0.26)	70.90 ± 17.49 (55.48–99.98)
Brazil	18	2001–2018	3,247,414	1,006,691	387,961	6.97 ± 1.85 (3.28–12.58)	2.13 ± 0.63 (0.78–3.89)	0.80 ± 0.24 (0.27–1.65)	0.25 ± 0.06 (0.16–0.39)	0.15 ± 0.03 (0.09–0.22)	88.82 ± 11.36 (61.77–99.20)
Canada	47	2001–2020	2,731,923	775,460	236,080	3.06 ± 3.62 (0.02–18.37)	0.87 ± 1.02 (0.01–5.54)	0.26 ± 0.32 (0.00–1.64)	0.20 ± 0.04 (0.06–0.30)	0.13 ± 0.03 (0.08–0.23)	74.03 ± 14.56 (50.63–99.91)
Estonia	3	2001–2020	128,062	65,110	4,025	12.31 ± 2.62 (7.06–16.84)	6.43 ± 1.48 (3.90–9.13)	0.38 ± 0.11 (0.16–0.71)	0.19 ± 0.02 (0.15–0.25)	0.12 ± 0.03 (0.08–0.16)	79.64 ± 7.38 (73.28–89.9)
France	17	2001–2017	1,737,850	NA	NA	7.00 ± 4.28 (2.31–21.62)	NA	NA	0.25 ± 0.05 (0.10–0.33)	0.18 ± 0.03 (0.13–0.26)	67.56 ± 15.15 (50.04–100)
Germany	12	2001–2020	2,597,878	NA	NA	11.74 ± 1.68 (8.77–15.98)	NA	NA	0.27 ± 0.02 (0.20–0.32)	0.15 ± 0.02 (0.11–0.20)	82.59 ± 8.74 (57.62–93.53)
Israel	3	2001–2020	354,682	NA	NA	5.72 ± 1.74 (3.33–8.95)	NA	NA	0.19 ± 0.02 (0.17–0.23)	0.15 ± 0.01 (0.13–0.17)	77.46 ± 17.30 (57.47–99.36)
Italy	12	2001–2015	693,174	NA	NA	4.30 ± 2.69 (1.65–11.77)	NA	NA	0.23 ± 0.03 (0.16–0.29)	0.18 ± 0.03 (0.11–0.26)	74.36 ± 10.76 (51.77–90.94)
Japan	3	2001–2020	4,081,683	1,105,480	612,825	8.49 ± 1.04 (6.89–10.36)	2.32 ± 0.22 (1.95–2.74)	1.28 ± 0.22 (0.92–1.71)	0.16 ± 0.02 (0.15–0.20)	0.29 ± 0.03 (0.25–0.35)	90.74 ± 9.43 (77.66–98.97)
Mexico	7	2001–2020	1,532,601	412,140	NA	5.46 ± 4.93 (3.50–23.19)	2.23 ± 1.54 (0.89–7.99)	NA	0.15 ± 0.03 (0.09–0.20)	0.15 ± 0.02 (0.11–0.19)	95.21 ± 3.84 (87.92–99.61)
Philippines	9	2006–2019	581,326	212,905	84,593	5.71 ± 1.02 (4.31–8.14)	2.09 ± 0.43 (1.30–3.04)	0.77 ± 0.30 (0.41–1.82)	0.17 ± 0.05 (0.07–0.25)	0.15 ± 0.03 (0.10–0.22)	100 ± 0 (100–100)
Romania	8	2001–2019	788,271	NA	NA	10.34 ± 1.30 (8.26–13.43)	NA	NA	0.20 ± 0.02 (0.15–0.24)	0.15 ± 0.02 (0.10–0.18)	85.71 ± 6.11 (77.88 – 97.11)
Serbia	3	2001–2020	519,930	NA	NA	12.07 ± 0.84 (10.30–14.89)	NA	NA	0.24 ± 0.01 (0.20–0.27)	0.13 ± 0.01 (0.11–0.16)	73.92 ± 0.86 (73.16 – 75.33)
South Africa	23	2001–2013	3,967,144	630,712	485,763	12.36 ± 3.38 (4.85–23.52)	2.01 ± 0.55 (0.82–4.16)	1.67 ± 0.82 (0.33–4.66)	0.21 ± 0.05 (0.12–0.34)	0.12 ± 0.03 (0.06–0.24)	72.35 ± 14.86 (50.07–97.63)
South Korea	18	2001–2018	2,097,553	480,919	153,301	5.51 ± 1.40 (3.38–8.98)	1.24 ± 0.35 (0.66–2.18)	0.43 ± 0.21 (0.16–1.33)	0.22 ± 0.03 (0.13–0.28)	0.19 ± 0.03 (0.12–0.27)	72.92 ± 17.19 (51.35–98.86)
Spain	17	2001–2014	1,195,037	384,260	143,107	3.64 ± 1.64 (0.98–7.27)	1.08 ± 0.53 (0.30–2.62)	0.39 ± 0.19 (0.08–0.96)	0.20 ± 0.02 (0.09–0.33)	0.20 ± 0.04 (0.15–0.33)	63.94 ± 11.77 (51.65–85.76)
Sweden	3	2001–2016	425,806	168,968	30,440	16.89 ± 3.06 (11.66–21.91)	6.72 ± 1.41 (4.20–9.43)	1.22 ± 0.26 (0.76–1.77)	0.20 ± 0.02 (0.16–0.24)	0.19 ± 0.01 (0.16–0.20)	89.04 ± 5.64 (84.57 – 98)
Switzerland	6	2001–2018	170,916	NA	NA	7.67 ± 2.89 (4.13–14.59)	NA	NA	0.28 ± 0.05 (0.18–0.37)	0.18 ± 0.01 (0.13–0.19)	77.62 ± 19.23 (51.46 – 100)
UK	112	2001–2020	4,259,934	1,292,082	592,330	10.70 ± 2.20 (5.42–19.37)	3.26 ± 1.04 (1.35–8.53)	1.46 ± 0.37 (0.62 –2.77)	0.27 ± 0.03 (0.19–0.34)	0.12 ± 0.03 (0.04–0.26)	96.18 ± 3.21 (84.13–100)
US	196	2001–2020	21,219,701	6,966,964	1,888,349	7.56 ± 2.09 (1.46–20.33)	2.39 ± 0.75 (0.64–5.78)	0.71 ± 0.25 (0.18 –2.09)	0.24 ± 0.05 (0.09–0.37)	0.11 ± 0.04 (0.03–0.30)	70.11 ± 14.99 (50.02–100)

cvd refers to cardiovascular; resp refers to respiratory. Values for mortality, greenspace exposure, greenspace inequality, and urban population are presented as mean ± standard deviation (range: minimum–maximum). For Argentina, Brazil, Spain, and Mexico, all-cause refer to non-external causes.

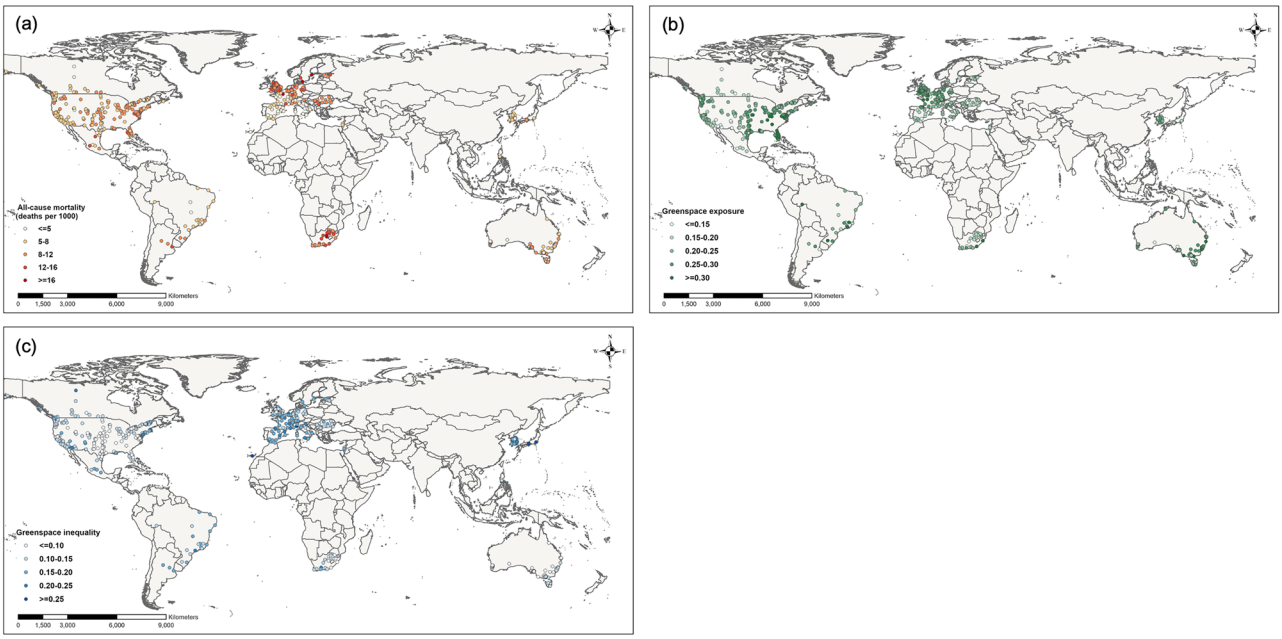

Fig. 1 | Geographical patterns of all-cause mortality, greenspace exposure and inequality across study locations. Geographical distribution of all-cause mortality (**a**), greenspace exposure (**b**), and greenspace inequality (**c**) across 624 study locations. In (**a**), colors indicate categories of all-cause mortality rates (per 1000 population), with darker colors representing higher mortality. In (**b**), colors represent levels of greenspace exposure, with darker green indicating higher exposure. In (**c**), colors denote degrees of greenspace inequality, with darker blue indicating greater inequality. Maps were generated using ArcGIS Pro. Country boundary data were obtained from the GADM database (Global Administrative Areas).

We assessed associations between greenspace inequality and mortality (Fig. 2b). A 0.1-unit increase in greenspace inequality is associated with higher risk of all-cause mortality (1.14, 0.99–1.31). Null or weak associations were observed for cardiovascular mortality (1.00, 0.86–1.17) and respiratory mortality (1.04, 0.87–1.25). However, these overall estimates showed substantial heterogeneity across countries. For all-cause mortality, while a strong positive association was evident in 12 of the 22 countries, with the largest risk in Switzerland, a null association was found in seven countries. Protective associations were observed in Mexico, Japan and South Africa. For cardiovascular and respiratory mortality, pooled estimates were close to the null with wide confidence intervals. Although not statistically significant, the direction of the associations suggested that higher inequality tended to be linked with higher respiratory mortality.

Variation across income levels, climate zones, and geographical regions

We analyzed heterogeneity in the associations of greenspace metrics and mortality across income levels, climate zones, and geographical regions (Fig. 3, Supplementary Fig. 4). For income levels (Fig. 3a, b), results showed no significant differences in RRs for greenspace exposure and inequality across mortality outcomes (all $p > 0.1$). Nevertheless, we observed significant protective effect for greenspace exposure on all-cause mortality in high-income settings, with a 0.1-unit increase associated with a reduced risk (0.88, 0.81–0.95), whereas a protective but non-significant association was observed in non-high-income settings (0.91, 0.82–1.02). Cardiovascular and respiratory mortality estimates were not statistically significant in both income groups but consistently suggested protective effects. For greenspace inequality (Fig. 3b), a significant positive association was observed with all-cause mortality in high-income countries (1.22, 1.04–1.44); largely null associations were found in non-high-income group (0.98, 0.78-1.25). Across climate zones (Fig. 3c, d), greenspace exposure was significantly protective for all-cause mortality in temperate (0.90, 0.83–0.97) and cold (0.81, 0.70–0.94) climates, but not in tropical climates (0.96, 0.81–1.13). Borderline significant heterogeneity across zones was detected for inequality–all-cause ($p = 0.10$) and inequality–respiratory ($p = 0.05$) associations. We estimated harmful effects in cold climates, but not other climates. Across geographical regions, borderline significant heterogeneity was observed for the greenspace–cardiovascular mortality ($p = 0.10$) and inequality–respiratory mortality ($p = 0.05$) associations. Protective associations of greenspace exposure were evident in Europe for all mortality outcomes, but not other regions. For greenspace inequality, significant associations were limited to Europe, and only for all-cause mortality (Supplementary Fig. 4).

Temporal variation in associations

We assessed temporal variation in the associations of greenspace exposure and inequality with mortality during 2001–2020 (Supplementary Tables 6–8). Pooled associations generally remained stable across the study period. For example, for all-cause mortality, the relative risks of greenspace exposure ranged from 0.89 to 0.90, while those for greenspace inequality ranged from 1.15 to 1.19. Across the periods, most countries showed similarly stable associations, although the magnitude and direction varied somewhat by country and period.

Sensitivity analyses

Sensitivity analyses indicated that pooled estimate for greenspace exposure and greenspace inequality remained robust across alternative temperature and socio-economic adjustments (Supplementary Figs 5–7). When incorporating city as random effect in the main model, we observed attenuated estimates of both greenspace exposure and greenspace inequality on mortality, with greenspace inequality attenuated more and crossed the nulls. Results based on averaged exposure metrics (time-invariant) were generally stable regardless of whether city-level random effects were included. The pooled non-linear analyses were broadly consistent with the main linear models (Supplementary Fig. 9). For greenspace exposure, the pooled curve for all-cause mortality decreased across the percentile distribution, while the curves for cardiovascular and respiratory mortality showed similar patterns but with wide confidence interval. For greenspace inequality, the relative risk for all-cause mortality increased from low to moderate inequality percentiles and then plateaued. The curves for cardiovascular and respiratory mortality suggested possible inverted-U patterns, however, confidence intervals were wide and largely overlapped the null. Country-specific curves suggested non-linear exposure–response patterns in some countries, particularly

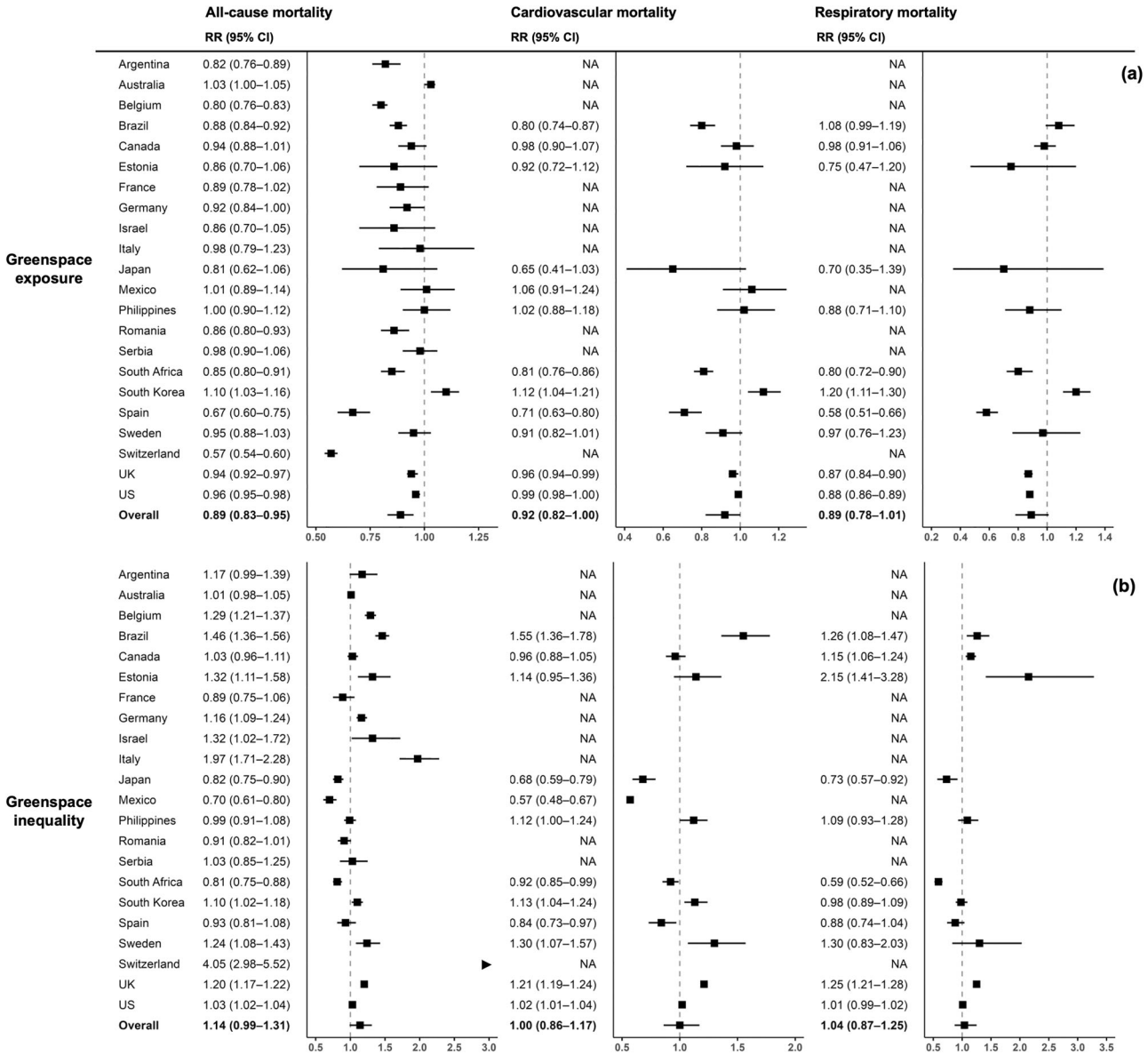

Fig. 2 | Associations of greenspace exposure and greenspace inequality with mortality. Country-specific and overall relative risks (RR) of all-cause, cardiovascular, and respiratory mortality per 0.1-unit increase in greenspace exposure (**a**) and in greenspace inequality (**b**). The center of each error bar represents the point estimates of RRs, and horizontal error bars represent the corresponding 95% confidence intervals (CIs). The dashed vertical line indicates the null value (RR = 1). For all-cause mortality, $n = 624$ independent study locations across 22 countries; for cardiovascular mortality, $n = 456$ independent study locations across 12 countries; and for respiratory mortality, $n = 449$ independent study locations across 11 countries.

where the corresponding linear associations were not statistically significant (Supplementary Figs. 10–15). Leave-one-country-out analyses showed that the pooled estimates for greenspace exposure and mortality remained generally stable in magnitude and direction across country exclusions (Supplementary Fig. 16). Importantly, excluding countries contributing the largest numbers of locations did not materially alter the pooled estimates. For greenspace inequality, the positive association with all-cause mortality remained largely unchanged, whereas estimates for cardiovascular and respiratory mortality showed greater variability across country exclusions, with confidence intervals generally overlapping the null.

Discussion

This study provides global evidence linking urban greenspace exposure and its inequality with mortality. Higher greenspace exposure was associated with lower mortality risk, while higher greenspace inequality was associated with increased all-cause mortality risk. In subgroup analyses, statistically significant protective associations of greenspace were observed in temperate and cold climates and in European regions, while statistically significant adverse associations of greenspace inequality were observed in high-income countries and Europe. However, these subgroup-specific findings do not necessarily indicate stronger associations than those observed in other groups.

The health benefits of greenspace are well established and mediated through multiple mechanisms, including mitigation of urban heat, reduced air and noise pollution, promotion of physical activity, strengthened social cohesion, and reduced psychological stress, all of which lower mortality risks[4,5,20]. Our pooled estimates for greenspace and all-cause mortality are consistent with a meta-analysis reporting a pooled hazard ratio (HR) of 0.96 (95% CI: 0.94–0.97) for a 0.1-unit increase in NDVI for all-cause/non-injury mortality[4]. Our findings in Canada, Belgium, and the UK were consistent with large cohort studies in these countries. For example, although the study designs and exposure metrics differ, our findings for the UK were consistent

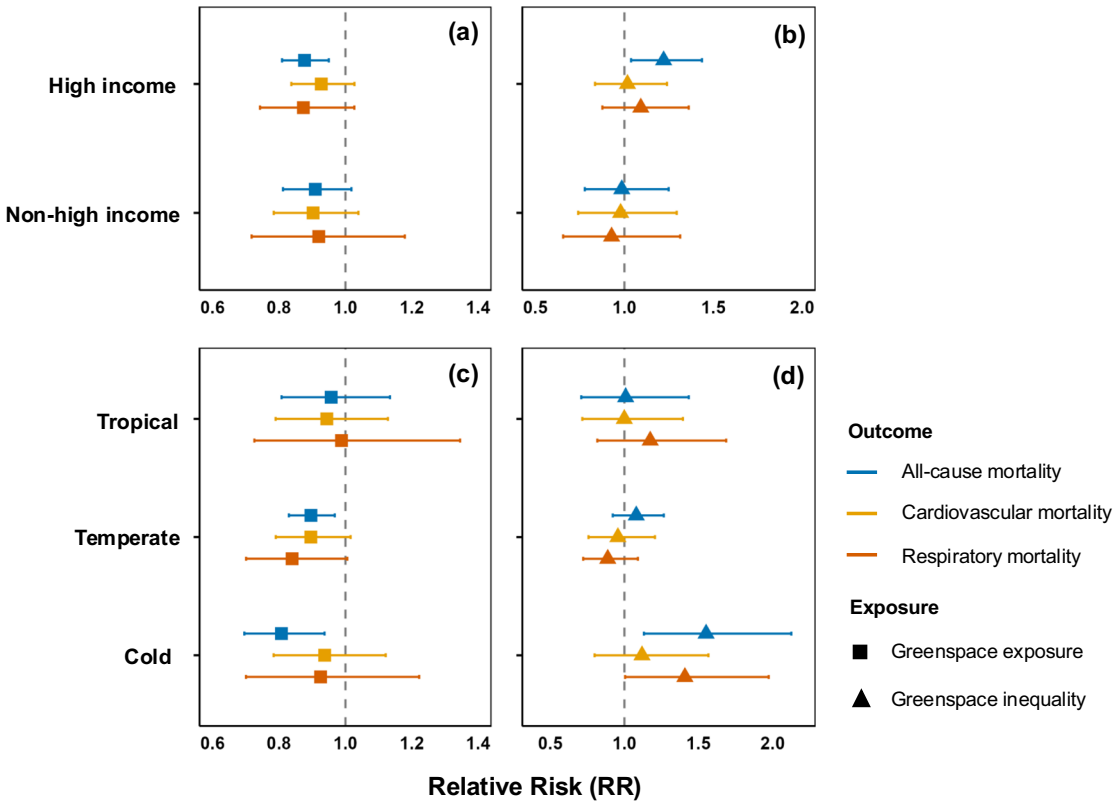

Fig. 3 | Associations of greenspace exposure and inequality with mortality by income level and climate zone. Pooled relative risks of mortality per 0.1-unit increase in greenspace exposure (**a**, **c**) and greenspace inequality (**b**, **d**), stratified by income level (**a**, **b**) and by climate zone (**c**, **d**). Colors represent mortality outcomes (all-cause, cardiovascular, respiratory), and shapes indicate exposure types, with squares denoting greenspace exposure and triangles denoting greenspace inequality. The center of each error bar represents the point estimates of RRs, and horizontal error bars represent the corresponding 95% confidence intervals (CIs). Income level and climate zone were included as meta-predictors in separate meta-regression models. For these analyses, $n = 624$, 456, and 449 independent study locations for all-cause, cardiovascular, and respiratory mortality, respectively.

with a national cohort study finding inverse associations for all-cause, cardiovascular, and respiratory mortality, with HR of 0.94 (0.91–0.97), 0.92 (0.86–0.98), and 0.87 (0.78–0.98), respectively, per interquartile range (IQR) increase in private residential garden cover (within 100 m buffer)[21]. Our ecological estimates using EVI are not directly comparable, but show similar patterns. Similarly, national cohort studies in Canada's 30 largest cities and Belgium's five largest urban areas reported inverse associations between greenness and mortality[22,23]. The relationship between greenness and mortality in the US and Spain has been characterized by differing evidence. Cohort studies, including those of US nurses and Barcelona residents[24,25], reported protective associations, whereas large-scale ecological analyses yielded conflicting results[26,27]. Our study, using an ecological design, was consistent with the cohort evidence, reporting a significant inverse association between greenspace and mortality in both countries. Although greenspace exposure showed a generally protective association across most countries, we observed positive associations in a few countries, particularly in South Korea. Our supplementary non-linear analyses suggested U-shaped associations between greenspace exposure and all-cause and cause-specific mortality in South Korea, indicating that higher satellite-derived greenness was not uniformly associated with lower mortality risk (Supplementary Figs. 10–12). This pattern may partly reflect differences in vegetation composition, greenspace accessibility, and urban morphology. Certain vegetation types may emit biogenic volatile organic compounds (BVOCs) that can increase ozone and secondary $PM_{2.5}$, impacting respiratory and cardiovascular mortality[28,29]. Depending on the type of vegetation, dense tree cover in urban area can lead to high pollen levels, exacerbating respiratory symptoms or triggering allergic reactions. In addition, a study in Seongnam City, South Korea, found that residents in an older town visited parks less frequently and reported lower satisfaction with neighborhood and park environments than those in a newer town, even though the older town contained a larger total area of neighborhood parks[30]. This pattern was attributed to parks in older towns being more likely to be located on steep slopes or at the urban fringe, as well as to the fragmented distribution of other park types, which limited accessibility and routine use. Moreover, if some parks or park facilities require admission or user fees, even small costs could further reduce accessibility and routine use, particularly for residents with fewer economic resources. Because our EVI-based metric captures all vegetation, including both accessible, high-quality greenspaces and less accessible or lower-quality vegetation, it may not fully represent health-relevant greenspace exposure. In areas where high greenness reflects vegetation with limited accessibility or poor quality, the expected health benefits may be attenuated or absent.

We observed generally protective effect of greenspace in high-income and non-high-income countries, but the effect was only significant in high-income settings. This may reflect disparities in greenspace quality, maintenance, and accessibility, which are typically higher in high-income settings and enhance health benefits[31]. In lower-income settings, competing health risks (e.g., infectious diseases, limited healthcare resources, poor sanitation) may overshadow the comparatively modest benefits of greenspace. We also observed that the protective associations between greenspace exposure and mortality were more pronounced in cold and temperate climates than in tropical climate regions. Several mechanisms may explain this pattern. The benefits of urban greenspace may differ by vegetation characteristics, urban morphology, and background climatic conditions[32]. A recent study in India reported that higher canopy cover was associated with a higher heat index, particularly in humid urban cores[33].. In addition, greenspace benefits may

depend on actual physical use, and high heat and humidity have been shown to reduce the recreational value of urban green spaces[34].

Our study offers a contribution by analyzing the health impact of greenspace inequality. Recent evidence suggests that greenspace morphology and configuration may have health implications beyond greenspace quantity alone[35], further supporting the importance of evaluating not only how much greenspace exists within a city, but also how it is spatially distributed. Consistent with our hypothesis, we found that greater greenspace inequality was associated with higher all-cause mortality risk. This may be due to higher greenspace inequality reflecting higher socioeconomic disparities, as supported by previous studies[9,36]. For example, studies conducted in the U.S. indicated that people of color and low-income populations typically live in less green environments than White or higher-income populations[36]. Moreover, improved urban greening can sometimes produce unintended social consequences through "green gentrification" when the creation or enhancement of urban green spaces increases property values and living costs, leading to displacement of marginalized residents[37,38]. Such processes can reinforce existing inequalities, lessening the health benefits of greening to more disadvantaged populations. As a result, such inequities may contribute to widening health disparities or increased mortality risks among marginalized populations[38]. It should be noted that we observed substantial variations across countries in the association between greenspace inequality and risk of mortality. The adverse associations of greenspace inequality are most pronounced in high-income countries, particularly in Europe. This suggests that in high-income settings, where urban design and healthcare systems are further developed, the deprivation of greenspace exposure may occur as a more salient determinant of health. Thus, urban greening and urban forestry initiatives should be paired with affordable housing protections and anti-displacement policies to ensure that the health benefits of greenspace improvements are retained by existing residents rather than contributing to displacement through green gentrification[39]. In contrast, we observed null or protective associations in some non-high-income countries, such as Mexico and South Africa. Greenspace in these nations can be scarce resources given their arid climate and dense urban development. In such settings, areas with more greenery often coincide with higher economic development and improved living conditions, which could partly explain the protective signal. We also observed that compared with cardiovascular and respiratory mortality, the association between greenspace inequality and all-cause mortality was stronger. One possible explanation is that psychosocial stress related to environmental injustice may have broader systemic impacts on health, affecting multiple disease pathways simultaneously. Such broad effects may be more clearly captured by all-cause mortality than by specific cause-specific outcomes.

For all exposure–outcome combinations, the wide confidence intervals observed in some countries, such as Estonia, Israel, Japan, and Mexico, should be interpreted cautiously. These wide intervals may partly reflect the small number of eligible locations in some countries, particularly Estonia, Israel, and Japan, each of which included only three locations. Limited numbers of independent spatial units, restricted within-country variation in greenspace exposure or greenspace inequality, and adjustment for multiple covariates and temporal trends may have further reduced statistical precision. More broadly, high-income countries contributed a larger number of locations to the dataset, which may have increased statistical power in these settings. Therefore, the observation that statistically significant associations were mainly found in high-income countries should be interpreted cautiously, as it may partly reflect differences in statistical power in addition to potential true effect heterogeneity.

Our sensitivity analysis including city-level random effects resulted in attenuated associations between greenspace or greenspace inequality and mortality. This pattern is likely due to that most variability in our exposure metrics occurs between cities, whereas within-city temporal variability is small. Introducing a random-effects structure shifts the model to some extent away from capturing these between-city contrasts and toward relying more on within-city temporal deviations, which in our dataset are limited. To explore this explanation, we compared models using averaged (time-invariant) exposure metrics with and without city-level random effects. Results were consistent across these specifications, supporting the interpretation that the attenuation arises from limited temporal variability. Therefore, including city-level random effects in our main model could obscure between-city associations. However, random-effects modeling is more informative in other settings, whereas this approach is limited by the characteristics of our dataset, 20 years of data with relatively low temporal changes. The non-linear analyses suggested that exposure–response patterns may vary across countries and may not always be fully captured by a linear specification. This was particularly evident in some countries where the linear associations were weak or statistically non-significant. Although these analyses provide additional evidence of potential non-linear patterns in some countries, country-specific curves should be interpreted cautiously because some countries had few eligible locations or limited within-country exposure variability.

There are several limitations in this study. First, although the MCC Collaborative Research Network provides one of the largest multi-location mortality datasets and enables standardized analyses across countries, it is based on a collaborative data-sharing framework rather than a globally representative sampling design. Most included locations were from high-income countries, and coverage in Africa and other underrepresented regions was limited. Uneven numbers of locations across countries may have influenced the precision and statistical weight of country-specific estimates, although the two-stage random-effects meta-analysis reduced the direct influence of countries with many locations. Second, we used satellite-derived EVI as the measurement of greenspace. Although EVI is widely used and offers globally consistent with high-resolution coverage, it captures only the quantity of vegetation. It does not distinguish between different types, qualities, or spatial configurations of greenspace, which may have distinct effects on health outcomes and may have different patterns of inequality. It may also assign low values to arid, semi-arid, or desert landscapes, despite their potential role as natural open spaces. Therefore, our findings should be interpreted as associations with vegetation-based greenspace rather than with all natural environments. We also acknowledge that the 500 m spatial resolution may smooth fine-scale heterogeneity in urban greenspace and potentially underestimate Gini-based greenspace inequality compared with estimates derived from finer-resolution such as 30 m. Future studies using finer-resolution greenness data, together with more spatially granular mortality data, are warranted. In addition, fixed administrative boundaries were used to calculate greenspace exposure and inequality, whereas the geographic units used for mortality reporting may have changed over time, potentially introducing minor spatial mismatches in some locations.

Third, this study used an ecological design, aimed at assessing associations between city-level greenspace characteristics and population health outcomes, rather than individual-level relationships such as in cohort or case-control studies. As such, our findings may be subject to ecological fallacy, provide limited causal inference, and should not be used to predict individual health outcomes. For example, an individual living in a green pocket of an unequal city might still benefit, even if the city-level inequality is higher. Our analysis does not capture between-community differences or individual-level exposures and outcomes. Despite adjustment for key city-level covariates, the possibility of residual confounding remains a limitation. Cross-national and cross-city heterogeneity in demographic structure, healthcare systems, coding practices, and baseline risk may have influenced the estimated associations. In addition, although we adjusted for the proportion of the population aged ≥65 years, this adjustment only partially accounts for differences in population age structure and does not eliminate potential residual confounding arising from the use of non-age-standardized mortality data.

Moreover, urban density and compactness may be associated with both greenspace distribution and population health. Compact cities may have more spatially concentrated greenspaces and higher Gini values, whereas sprawling cities may have more evenly distributed vegetation through private yards or peri-urban greenery. Therefore, residual confounding by urban form may have influenced the estimated associations between greenspace inequality and mortality. We used Gini index to

quantify greenspace inequality, which reflects spatial inequality rather than socioeconomic inequality. We did not consider socio-demographic inequality due to data limitations. Therefore, a low greenspace Gini index does not necessarily translate to equitable greenspace access across population groups. Finally, although we examined heterogeneity by geographical region, income level, and climate zone, differences in statistical power and geographical coverage across subgroups should be acknowledged. In addition, country-level comparisons may mask substantial within-country variation, particularly in large and ecologically diverse countries. Future studies should consider more refined city-level stratifications, such as income-based clusters, coastal versus inland cities, or other ecological and urban characteristics, to better characterize spatial heterogeneity in the associations between greenspace, greenspace inequality, and mortality.

In conclusion, based on a multi-country analysis of 624 locations across 22 countries, we found that higher greenspace exposure was generally associated with lower mortality risk, whereas greater greenspace inequality was associated with higher all-cause mortality risk. These associations also varied across income levels and climate zones, with statistically significant associations observed in high-income settings, cold climates, and European regions. Our findings have implications for urban planning and public health policy, suggesting that urban greening strategies aimed at supporting population health should not only expand overall greenspace coverage but also reduce spatial inequalities in greenspace and improve the quality and configuration of greenspace to maximize population health gains. This study also provides a standardized framework for jointly assessing greenspace exposure, greenspace inequality, and mortality across diverse urban settings, while highlighting important challenges in cross-country comparisons, including differences in data availability, city representation, administrative boundaries, mortality reporting practices, and baseline population characteristics. Future research should further investigate how different types of vegetation and socio-demographic disparities in greenspace access shape these relationships. Additionally, examining the potential interaction between greenspace exposure and greenspace inequality may yield deeper insights into how their combined effects influence human health.

Data availability

Mortality data for most countries were obtained through the Multi-Country Multi-City (MCC) Collaborative Research Network under data-sharing agreements and cannot be made publicly available. Researchers interested in accessing these data may contact the relevant MCC country representatives or the MCC Collaborative Research Network (https://mccstudy.lshtm.ac.uk/contact-us/) for information on data access. Access is subject to approval by the original data providers and the terms of the applicable data-sharing agreement. U.S. mortality data were obtained from the U.S. Centers for Disease Control and Prevention (CDC) and are publicly available. Australian mortality data were obtained from the Australian Institute of Health and Welfare (AIHW) and are publicly available through the AIHW data portal. Canadian mortality data were provided by co-author Eric Lavigne and are subject to the terms and conditions governing their use and redistribution. EVI data were obtained from NASA MODIS, and population and age–sex-structured population data from WorldPop; both are publicly available. Derived data that do not contain or permit reconstruction of restricted mortality data may be requested from the corresponding author; provision is subject to the terms of the original data-sharing agreements and any applicable restrictions imposed by the data providers.

Code availability

Custom R scripts used for the statistical analyses in this study are publicly available at https://github.com/Tian519/urban-greenspace-mortality. The repository includes code for the country-specific analyses and second-stage meta-analysis, together with demonstration data illustrating the structure of the analytical dataset. Analyses were conducted using R version 4.4.2. The original mortality data required to reproduce the full analyses are subject to data-sharing agreements and are not included in the repository; data access is described in the Data availability statement.

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Author contributions

T.M. and M.L.B. conceived the idea and designed the study. T.M. performed the methodology and analysis, produced the original figures, and drafted the manuscript. B.A., E.L., A.G., P.M. and M.L.B. contributed to the methodology. E.L., B.A., P.M., A.G., F.S., R.R., A.S., V.H., F.D.D., P.L.C.C., M.S.Z.S.C., M.M., A.Z., J.S., M.L.B. provided the data. All authors contributed to interpretation of the results and revised the manuscript. T.M. and M.L.B. accessed and verified the data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Competing interests

The authors declare no competing interests.

Additional information

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