Associations between residential greenspace exposure and mortality in 4 645 581 adults living in London, UK: a longitudinal study

Samantha Hajna, Vahé Nafilyan, Steven Cummins

Summary

Background Urban greenspaces could reduce non-communicable disease (NCD) risk. The links between greenspaces and NCD-related mortality remain unclear. We aimed to estimate associations between residential greenspace quantity and access and all-cause mortality, cardiovascular disease mortality, cancer mortality, respiratory mortality, and type 2 diabetes mortality.

Methods We linked 2011 UK Census data of London-dwelling adults (aged ≥18 years) to data from the UK death registry and the Greenspace Information for Greater London resource. We calculated percentage greenspace area, access point density (access points per km²), and distance in metres to the nearest access point for each respondent's residential neighbourhood (defined as 1000 m street network buffers) for greenspaces overall and by park type using a geographic information system. We estimated associations using Cox proportional hazards models, adjusted for a range of confounders.

Findings Data were available for 4 645 581 individuals between March 27, 2011, and Dec 31, 2019. Respondents were followed up for a mean of 8·4 years (SD 1·4). All-cause mortality did not differ with overall greenspace coverage (hazard ratio [HR] 1·0004, 95% CI 0·9996–1·0012), increased with increasing access point density (1·0076, 1·0031–1·0120), and decreased slightly with increasing distance to the nearest access point (HR 0·9993, 0·9987–0·9998). A 1 percentage point (pp) increase in pocket park (areas for rest and recreation under 0·4 hectares) coverage was associated with a decrease in all-cause mortality risk (0·9441, 0·9213–0·9675), and an increase of ten pocket park access points per km² was associated with a decreased respiratory mortality risk (0·9164, 0·8457–0·9931). Other associations were observed, but the estimated effects were small (eg, all-cause mortality risk for increases of 1 pp in regional park area were 0·9913, 0·9861–0·9966 and increases of ten small open space access points per km² were 1·0247, 1·0151–1·0344).

Interpretation Increasing the quantity of, and access to, pocket parks might help mitigate mortality risk. More research is needed to elucidate the mechanisms that could explain these associations.

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Introduction

41 million people die each year as a result of non-communicable diseases (NCDs), equivalent to 71% of deaths globally.[1] The four most common NCDs are cardiovascular disease (17·9 million deaths annually), cancers (9·3 million), respiratory disease (4·1 million), and type 2 diabetes (1·5 million).[1,2] In the EU approximately 25% of health-care spending is for the treatment of these four NCDs.[2] To curb the rising costs associated with the treatment of these NCDs, strategies that reduce NCD risk are urgently needed.[1]

People who live in greener neighbourhoods are at lower risk for NCDs and premature mortality.[3–7] This situation has led to calls to explore whether increasing access to greenspace can be used as a population-level NCD prevention strategy. Greenspaces are thought to decrease NCD and mortality risk via a variety of mechanisms that might act both independently and synergistically.[8] These include increasing opportunities for social interactions, promoting exercise, reducing exposure to air pollution and heat, and reducing noise levels,[9] as most cases of cardiovascular disease, cancer, respiratory disease, and type 2 diabetes (the most common type of diabetes) can be prevented via increases in physical activity,[10] reductions in stress,[11] and reductions in air pollution exposure.[12] As these factors have been linked to greenspace exposure,[9] there is reason to believe that greenspaces could potentially modify the risk of mortality from these NCDs.

While there is a growing body of research on the associations between objectively measured greenspace exposure and mortality,[5,13,14] three important gaps in knowledge remain. First, while the links between greenspace quantity and mortality have been assessed in

Research in context

Evidence before this study
Higher levels of greenspace exposure have been linked to reduced risk of all-cause mortality. This is supported by evidence that greenspaces facilitate health behaviours (eg, physical activity) that reduce non-communicable disease risk. Despite this, little is known regarding the links between greenspace quantity and access, and risk of mortality from cardiovascular disease, cancer, respiratory disease, and type 2 diabetes—the most common non-communicable diseases and leading causes of death worldwide.

Added value of this study
Our findings contribute to the literature by demonstrating that not all greenspaces are equal in terms of their potential effects on adult mortality risk. Our results suggest that the effects of greenspaces on mortality risk might vary by park size, with evidence that pocket parks (<0·4 hectares) have beneficial associations for all-cause and respiratory mortality risk. The associations for other park types are less clear.

Implications of all the available evidence
Increasing the quantity of, and access to, small parks might mitigate adult mortality risk in urban areas. To inform the design of more targeted interventions, future research might wish to seek to understand which specific characteristics of small parks facilitate health and mitigate mortality risk.

previous studies,[5] other aspects of greenspaces that might be important for health have not been evaluated. More greenspaces in urban neighbourhoods could improve health by reducing air pollution, but improving access to these greenspaces (eg, increasing the number of entrances) may also improve health via other mechanisms (eg, more opportunities for exercise). Some NCDs have clear hypothesised mechanisms by which greenspaces might mitigate risk. Comparing associations between greenspace quantity and access and all-cause mortality and mortality from the four leading NCDs could shed light on which factors should be prioritised in greenspace interventions. Second, no study has compared how different types of urban greenspaces are associated with mortality risk. Given that smaller parks might encourage exercise and social interactions more than larger regional parks,[15] particularly for older adults who might feel more comfortable in smaller parks, for example believing they are safer, could also be more important for reducing risk of death from NCDs than larger urban greenspaces. Understanding the unique roles of different types of parks on mortality risk would tell us how changes to certain types of parks might plausibly promote health. Third, most previous studies in this area have relied on aggregate area-level measures of exposures, outcomes, or covariates (eg, census tract-level greenspace exposure). Use of individual-level data is much less common, and is needed to estimate greenspace–mortality associations with increased precision and to reduce risk of residual confounding. To explore these questions and address these limitations, we aimed to estimate, using individual-level data, associations between greenspace quantity and access in residential neighbourhoods with all-cause mortality and mortality from the four leading NCDs (cardiovascular disease, cancer, respiratory disease, and type 2 diabetes). We also assessed whether these associations varied by park type, and explored whether there was evidence of effect modification of the greenspaces–mortality associations by age, sex, social grade, and level of education.

Methods

We used data from respondents to the 2011 UK Census aged 18 years or older whose home postcode addresses fell within the Greater London Authority (GLA), a geographical area comprised of 33 local government districts (4 645 581 individuals).[13] We linked this data to death registrations for the period March 27, 2011, to Dec 31, 2019, using UK National Health Service (NHS) numbers, obtained by linking 2011 Census respondents to the 2011–13 NHS Patient Register. We derived greenspace measures using data obtained from the Greenspace Information for Greater London environmental records centre. Ethics approval for this study was granted by the London School of Hygiene and Tropical Medicine's Observational Research Ethics Committee (reference number 22868).

Overall greenspace quantity and access

We defined a greenspace as any park or garden that was freely accessible to the public (no monetary barrier to use, open 24 h). The percentage area of residential neighbourhoods covered by freely accessible parks or gardens was used to quantify greenspace quantity. Access point density (number of points of access to freely accessible parks or gardens per km² of the participants' residential neighbourhoods) and distance to the nearest access point (metres via a road or path from the easting [vertical lines dividing a map from west to east] and northing [horizontal lines dividing a map from north to south] point location, corresponding to the centroid of the respondents' residential postcode addresses to the nearest point of access to a freely accessible park or garden) were used to quantify greenspace access. We defined residential neighbourhoods as 1000 m street network-based polygonal buffers, drawn around the easting and northing point location that corresponded to the centroid of each respondents' home postcode address. We selected a 1000 m distance as greenspaces within this distance have been shown to be good predictors of physical health,[16] and because this distance is approximately what people might

Characteristic	
Percentage of residential neighbourhoods covered by freely accessible parks and gardens	3·2% (4·0)
Points of access to freely accessible parks and gardens per km² in residential neighbourhoods	6·3 (8·5)
Distance to the nearest access point to freely accessible parks and gardens from residential address, m	763·1 (603·1)
Outcomes	
All-cause mortality	371 384 (8·0%)
Cardiovascular disease mortality	68 484 (1·5%)
Cancer mortality	99 272 (2·1%)
Respiratory mortality	26 041 (0·6%)
Type 2 diabetes mortality	2291 (<0·1)
Covariates	
Age, years	47·6 (16·5)
Women	2 479 194 (53·4%)
Men	2 166 387 (46·6%)
Ethnicity	
White British	2 368 983 (51·0%)
White other	727 376 (15·7%)
Indian	341 516 (7·4%)
Black African	248 463 (5·3%)
Black Caribbean	204 490 (4·4%)
Mixed	121 215 (2·6%)
Pakistani	110 516 (2·4%)
Bangladeshi	96 527 (2·1%)
Chinese	62 098 (1·3%)
Other	364 397 (7·8%)
Social grade	
Higher and intermediate managerial, administrative, and professional occupations	1 298 353 (27·9%)
Supervisory, clerical and junior managerial, administrative, and professional occupations	1 435 929 (30·9%)
Skilled manual occupations	760 206 (16·4%)
Semi-skilled and unskilled manual occupations	861 789 (18·6%)
Unemployed and lowest grade occupations	246 958 (5·3%)
Not available because living in a communal establishment	42 346 (0·9%)
Family status*	
Not living as part of a family	1 222 306 (26·3%)
Living as part of a two-parent family	2 850 516 (61·4%)
Living as part of a single-parent family	530 413 (11·4%)
Not available because living in a communal establishment	42 346 (0·9%)
Deprivation status†	
Not deprived	1 914 675 (41·2%)
Deprived in one dimension	1 530 412 (32·9%)
Deprived in two dimensions	848 791 (18·3%)
Deprived in three dimensions	273 822 (5·9%)
Deprived in four dimensions	35 535 (0·8%)

(Table continues in next column)

Characteristic	
(Continued from previous column)	
Education‡	
No academic or professional qualifications	918 470 (19·8%)
Level 1	475 600 (10·2%)
Level 2	471 208 (10·1%)
Apprenticeship	82 475 (1·8%)
Level 3	378 341 (8·1%)
Level 4	1 852 193 (39·9%)
Other	467 294 (10·1%)
Household tenure	
Owned outright	1 087 977 (23·4%)
Owned with a mortgage or loan	1 511 207 (32·5%)
Shared ownership (part owned and part rented)	54 679 (1·2%)
Social rented: rented from council (local authority)	516 975 (11·1%)
Social rented: other social rented	403 108 (8·7%)
Private rented	981 170 (21·1%)
Living rent free	48 119 (1·0%)
Communal establishments	42 346 (0·9%)

Data are mean (SD) or n (%). *Family status classifications were defined based on the following categories—not living as part of a family: aged 65 years or older, or other; two-parent family: member of couple, dependent child of one or both members of the couple, non-dependent child of one or both members of the couple; single-parent family: parent, dependent child of a parent, non-dependent child of parent; or living in communal establishments: living in a care home, hospice, prison, or other communal establishment. †Deprivation status was defined based on the following four dimensions—employment: at least one household member is unemployed or long-term sick, excluding full-time students; education: no household members have at least level 2 education, and no one aged 16–18 years is a full-time student; health and disability: at least one household member reported their health as being bad or very bad or has a long-term health problem; and housing: the household's accommodation is overcrowded, with an occupancy rating of –1 or less, or is in a shared dwelling, or has no central heating. ‡Education level was defined based on the following categories—no academic or professional qualifications: no qualifications obtained; level 1: 1–4 O Levels/CSEs/GCSEs (any grades), Entry Level, Foundation Diploma, NVQ level 1, Foundation GNVQ, or Basic/Essential skills; level 2: ≥5 O Levels (passes)/CSEs (Grade 1)/GCSEs Level 2 (Grades A*–C), School Certificate, 1 A Level, or 2–3 AS Levels or VCEs, Intermediate or Higher Diploma, Welsh Baccalaureate Intermediate Diploma, NVQ level 2, Intermediate GNVQ, City and Guilds Craft, BTEC First or General Diploma, or RSA Diploma; any apprenticeship; level 3: ≥2 A Levels or VCEs, ≥4 AS Levels, Higher School Certificate, Progression or Advanced Diploma, Welsh Baccalaureate Advance Diploma, NVQ Level 3, Advanced GNVQ, City and Guilds Advanced Craft, ONC, OND, BTEC National, pr RSA Advanced Diploma; level 4: degree (eg, BA, BSc), higher degree (eg, MA, PhD, Level ≥4 PGCE), NVQ level 4–5, HNC, HND, RSA Higher Diploma, BTEC Higher level, Foundation degree (NI), or Professional qualifications (eg, teaching, nursing, accountancy); and other: vocational or work-related qualifications, foreign qualifications and qualifications gained outside the UK, or not stated or level unknown.

Table: **Descriptive characteristics of the exposures, outcomes, and covariates of interest for the study population (n=4 645 581)**

be expected to walk to access nearby amenities, including the different types of parks that we assessed as part of this study.[17]

We used the May, 2011, Office for National Statistics Postcode Directory (ONSPD) to identify the eastings and northings point locations corresponding to the centroid of each home postcode address, and Integrated Transport Network road data from the Ordnance Survey to derive residential neighbourhood buffers around these point locations and to calculate the distance to the nearest access point. Postcodes that could not be found in the ONSPD were obtained using Grid Reference Finder. We obtained all of the geospatial greenspace data from the Greenspace Information for Greater London service, and we derived the greenspace measures of interest using ArcMap 10.8.1 (ESRI; Redlands, CA, USA).

For the **Grid Reference Finder** see http://www.gridreferencefinder.com

Park-specific greenspace quantity and access

Using the methods mentioned previously, we assessed quantity and access for six types of parks, including regional parks, metropolitan parks, district parks, local parks, small open spaces, and pocket parks.[18] Park types were defined based on the public open space categorisations outlined in the 2011 London Plan.[18] Regional parks were defined as large areas (>400 hectares [ha]) that include facilities and features that offer recreational and ecological benefits. Metropolitan parks are similar to regional parks, but smaller (ranging between 60 ha and 400 ha). District parks are open spaces between 20 ha and 60 ha that provide a range of natural features and facilities for both sports and recreation. Local parks are areas between 2 ha and 20 ha that provide spaces for recreation, sitting, and nature conservation. Small open spaces (ranging between 0·4 ha and 2 ha) and pocket parks (<0·4 ha) are smaller than local parks, but similar in form and function.

All-cause and cause-specific mortality

Deaths occurring between March 27, 2011, and Dec 31, 2019, from all causes and from cardiovascular disease (International Classification of Disease 10th revision [ICD-10] codes I20–I49), cancer (C00–D48), respiratory disease (J00–J18, J20–J22, J40–J47, J80–J84, or J96), and type 2 diabetes (E11) were included in our analyses. We chose to examine the links between greenspaces and these specific causes of death because they are the most common NCDs in the UK, account for a large burden of mortality, and the risk of mortality from these causes might be modifiable via greenspace interventions, given the causal pathway hypothesised to link greenspaces to health.

Moderators and covariates

We adjusted for factors that were likely to confound the association between greenspaces and mortality that were assessed as part of the 2011 UK Census. These included age, sex, ethnicity, social grade, family status, household deprivation status, education, and household tenure (appendix p 2).

See Online for appendix

Statistical analysis

We produced descriptive statistics for all variables of interest. Before modelling, correlation and univariate analyses were conducted to check for collinearity between the independent variables of interest. The associations between the three greenspace measures and mortality, both overall and by park type, were estimated using Cox proportional hazards models. Differences in mortality risk were estimated for every 1 percentage point increase in greenspace coverage in residential neighbourhoods, for every additional ten access points per km² in residential neighbourhoods, and for every 100 m increase in distance between the residential address and the nearest access point. We fitted separate models for each of the greenspace measures, due to high correlations between these measures. First, we fitted partially adjusted models with age and sex included as covariates. Age and sex were interacted to allow for different effects of age on mortality in men and women. Second, we fitted maximally adjusted models that included all variables specified a priori as important covariates or potential confounders. These included age, sex, ethnicity, social grade, family status, deprivation status, level of education, household tenure, and GLA borough. All factors were introduced in the models as independent variables, except GLA borough, where borough-specific baseline hazards were computed to account for different trends in mortality in different boroughs. We explored whether there was evidence of effect modification of the greenspaces–mortality associations with four variables identified a priori as potential modifiers of the greenspaces–mortality relationship: age (<65 *vs* ≥65 years), sex (male *vs* female), social grade (high: higher and intermediate managerial, administrative, and professional occupations *vs* low: junior administrative, professional occupations, skilled manual occupations, semi-skilled and unskilled manual occupations, unemployed, and lowest grade occupations; not available because living in a communal establishment), and level of education (degree *vs* no degree). We did this by testing whether the interactions between the exposure to greenspace and the potential modifier were significant, and for those that were we fitted stratified models. We used Schoenfeld residuals from the fitted Cox models, smoothed using generalised additive models, to assess whether the hazard ratios (HR) for the exposure of interest changed over time. All of the analyses were based on complete case data and conducted in R version 3.5.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Of the 52 637 675 adults who responded to the 2011 Census in England and Wales and were usual residents (anyone who, on census day, March 27, 2011, was in the UK and has stayed, or intended to stay, in the UK for 12 months or more, had a permanent UK address and was outside the UK for less than 12 months), 5 060 056 (9·6%) lived in the GLA area. Data for 4648087 of census respondents could be linked to NHS records via the 2011–13 NHS Patient Register (91·9% linkage rate). Of the respondents with linked census and mortality data, 99·9% (n=4645581) had valid greenspace measures and were included in our final analyses. Descriptive characteristics of the exposure, outcome, and covariate variables of interest are provided in the table. In brief, 8·0% of the sample died over the follow-up period (mean 8·4 years [SD 1·4]: 1·5% from cardiovascular disease, 2·1% from cancer, 0·6% from respiratory disease, and <0·1% from type 2 diabetes). On average, 3·2% (SD 4·0) of residential neighbourhoods were covered by freely accessible parks and gardens, they had an average of 6·3 access points per km² (8·5), and were located an average of 763·1 m (603·1) from the nearest park or garden access point. The locations of the freely accessible parks and gardens in the GLA area are shown in figure 1.

The maximally adjusted associations between greenspace quantity and greenspace access are described below. No important differences were observed between the partially and maximally adjusted models (data not shown).

No important associations were observed between overall greenspace coverage and risk of all-cause mortality or mortality from the four leading NCDs (figure 2). Some associations were observed when examining the associations by park type (figure 3). Specifically, 1 percentage point increases in regional and pocket park areas in residential neighbourhoods were associated with reductions in all-cause mortality risk (regional parks: [HR] 0·9913, 95% CI 0·9861–0·9966; pocket parks: 0·9441, 0·9213–0·9675). By contrast, 1 percentage point increases in small open spaces were associated with increases in all-cause mortality risk (1·0137, 1·0082–1·0192) and cancer mortality risk (1·0160, 1·0055–1·0266). A negligible association was also observed between local park coverage and all-cause mortality risk (1·0004, 0·9996–1·0012).

Every ten additional greenspace access points per km² in residential neighbourhoods were associated with an increased all-cause mortality risk (HR 1·0076, 95% CI 1·0031–1·0120) and cancer mortality risk (1·0118, 1·0034–1·0203). No important associations were observed between greenspace access point density and risk of mortality from cardiovascular disease, respiratory disease, or type 2 diabetes (figure 2). When examining the access point and mortality associations by park type (figure 4), every ten additional access points per km² for pocket parks was associated with a decreased respiratory mortality risk (0·9164, 0·8457–0·9931). By contrast, every ten additional access points per km² for small open spaces was associated with an increased risk of all-cause mortality (1·0247, 1·0151–1·0344), cardiovascular disease mortality (1·0237, 1·0015–1·0464), and cancer mortality (1·0267, 1·0085–1·0452).

No associations were observed between distance to the nearest greenspace access point and risk of cardiovascular disease, cancer, respiratory, or type 2 diabetes mortality (figure 2). A negligible association was observed for all-cause mortality, where living 100 m further away from the nearest greenspace access point was associated with a small decreased risk of all-cause mortality (HR 0·9993, 95% CI 0·9987–0·9998). Some associations were observed when examining the associations by park type (figure 5), but these were also probably not clinically relevant (eg, living 100 m further away from a local park access point was associated with a decreased risk of respiratory mortality (0·9984, 0·9968–0·9999).

For all-cause mortality, the smoothed Schoenfeld residuals (appendix p 1) indicated violation of the proportional hazard assumption for greenspace coverage and access point density. For greenspace coverage, the estimated log-hazard ratio was not contained within the 95% CI around the smoothed Schoenfeld residuals for the first 700 days at risk, and the residuals suggested a positive association between mortality and greenspaces coverage in the first 700 days, which is probably due to unmeasured confounding. For access point density, the deviation from the estimated log-hazard ratio was small, and the 95% CI around the smoothed Schoenfeld residuals always included the estimated log-hazard ratio, suggesting that violation of the proportional hazard assumption was unlikely to substantially affect our main results.

Some interactions by age, sex, social grade, or level of education for the greenspace–mortality associations were significant (p<0·05; appendix p 3). Stratified analyses of these interactions, however, revealed that most of these hazard ratios were indicative of no or negligible associations (appendix p 4).

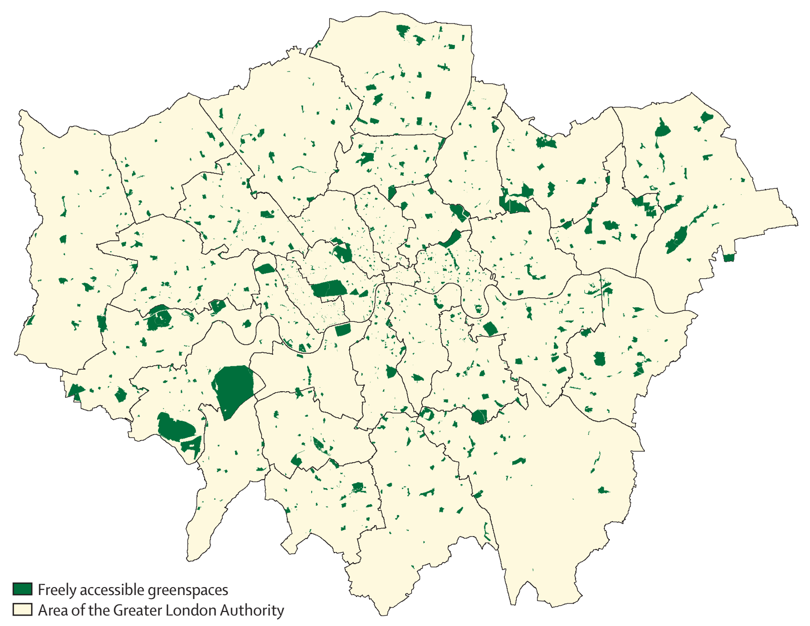

Figure 1: **Locations of freely accessible parks or gardens in the Greater London Authority area**

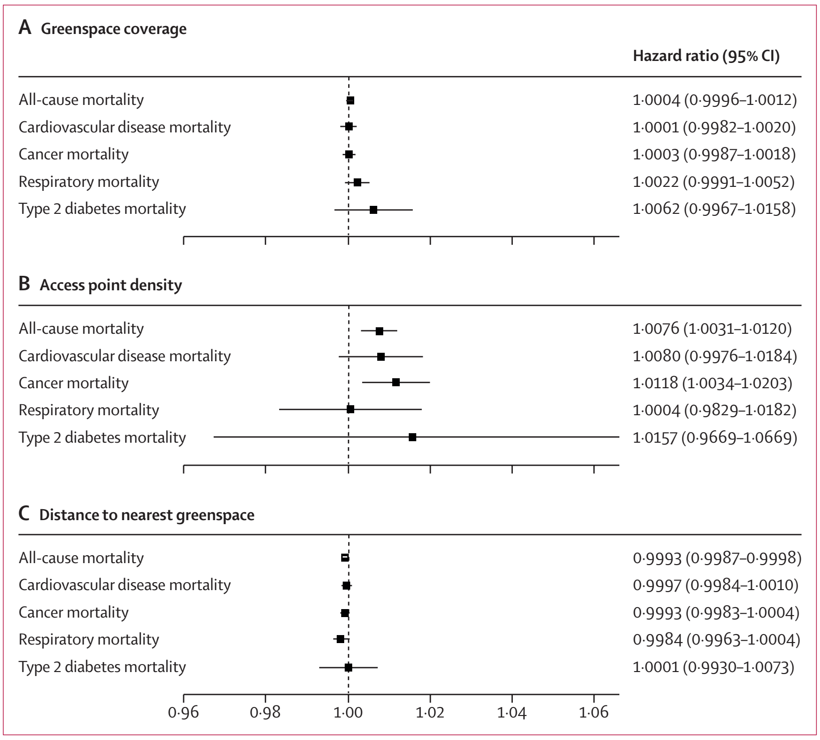

Figure 2: **Risk of all-cause mortality and mortality from the four leading non-communicable diseases**
(A) Every percentage point increase in greenspace coverage in residential neighbourhoods. (B) Each additional ten access points per km² in residential neighbourhoods. (C) Every 100 m increase in distance away from the nearest greenspace access point in residential neighbourhoods. Data for 4 645 581 individuals. Models are adjusted for age, sex, ethnicity, social grade, family status, deprivation status, level of education, and household tenure.

Discussion

When examining greenspaces overall, we found small positive and negative associations between different measures of urban greenspace exposure and all-cause mortality and cause-specific mortality. Evidence of effect modification of these associations by age, social grade, and level of education was limited. We also found positive and negative associations when examining associations by park subtype. Specifically, reductions in all-cause mortality were observed for more regional (large) park and pocket (small) park coverage in home neighbourhoods, and reductions in respiratory mortality were observed for increasing access to pocket parks. Conversely, small increases in all-cause mortality and cancer mortality were observed for increases in small open space (mid-sized parks) coverage and access, small increases in cardiovascular disease mortality were observed for increases in small open space access, and small increases in all-cause mortality were observed for increases in local park (large-to-mid-sized parks) coverage in home neighbourhoods.

Our findings of negative associations between greenspaces and mortality are supported by previous studies that have also found small associations between higher greenspace exposure and lower risk of all-cause mortality and mortality from leading causes of NCDs.[14,19–21] In an analysis of a large prospective cohort of 2 185 170 urban-dwelling Belgian adults (mean follow-up 9·4 years), an interquartile increase in residential greenness (using the Normalised Difference Vegetation Index [NDVI]) was associated with a decreased risk of non-accidental mortality (HR 0·97, 95% CI 0·96–0·98) and respiratory mortality (0·95, 0·93–0·98).[22] Findings of meta-analyses also suggest there are small negative associations between greenspaces and risk of mortality. In their meta-analysis of studies from North America, Europe, Asia, and Australia, Rojas-Rueda and colleagues found that an NDVI increment of 0·1 in residential neighbourhoods was associated with a 4% decrease in all-cause mortality risk (0·96, 95% CI 0·94–0·97).[5] Similarly, in their systematic review of studies in North America, Europe, and New Zealand, Gascon and colleagues found that adults living in neighbourhoods characterised by high levels versus low levels of greenness had an 8% reduced risk of all-cause mortality (risk ratio 0·92, 95% CI 0·87–0·97) and a 4% reduced risk of cardiovascular disease mortality (0·96, 0·94–0·97).[13] When examining greenness as a continuous exposure measure, Gascon and colleagues did not find evidence of important associations between greenness and all-cause or cardiovascular disease mortality risk, suggesting that while there might be small negative associations between some measures of greenspace and mortality, exposure measurement might play a role in the size of the observed effects.[14]

Our findings of positive associations between greenspace and mortality were unexpected based on the associations reported in the greenspace–mortality literature. While greenspace exposure has generally been found to be associated with reduced mortality risk,[3,5,13] our findings suggest that some types or aspects of greenspaces might be linked to higher mortality risk, and that targeting the improvement of these factors could need to be the focus of future greenspace interventions. For example, access points to mid-sized urban parks (which we found were associated with a small increased risk of all-cause mortality) might attract more criminal activity or anti-social behaviours, such as selling and purchasing illegal drugs, due to being a good meeting spot and facilitating easy exit if required. This could lead mid-sized parks to be perceived as less safe by neighbourhood residents. Furthermore, access to these parks could be more difficult than small parks (eg, located closer to busier main roads with poor pedestrian crossings and more traffic).[23] In combination, these factors could reduce the use of these spaces for health promoting behaviours. Therefore, greenspace interventions might also require improvements to public perception of these spaces, rather than solely increasing the number of access points.[24]

Although most previous studies have found protective effects for greenspaces on health, some studies have found null or unexpected associations.[25–27] For example, in an analysis of data from a nationally representative sample of the English population, adults living in the most green neighbourhoods compared with the least green neighbourhoods were found to have a 12% increased risk

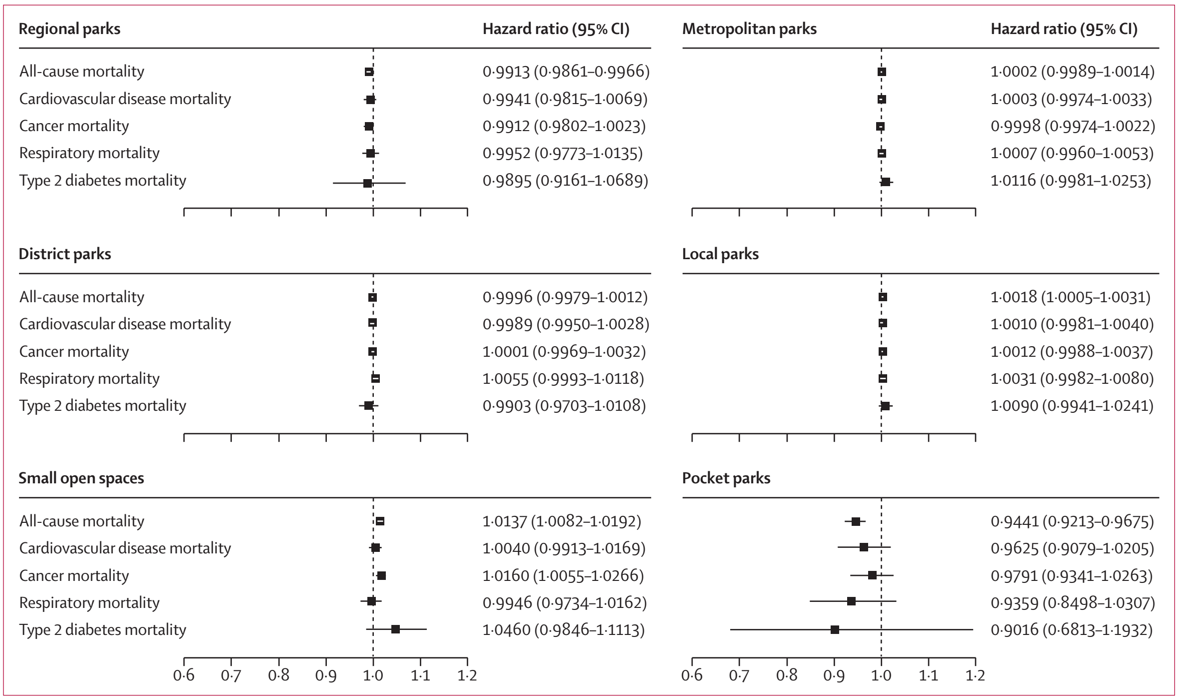

Figure 3: **Risk of all-cause and cause-specific mortality for every percentage point increase in greenspace coverage**
Data for 4 645 581 individuals. Models are adjusted for age, sex, ethnicity, social grade, family status, deprivation status, level of education, and household tenure.

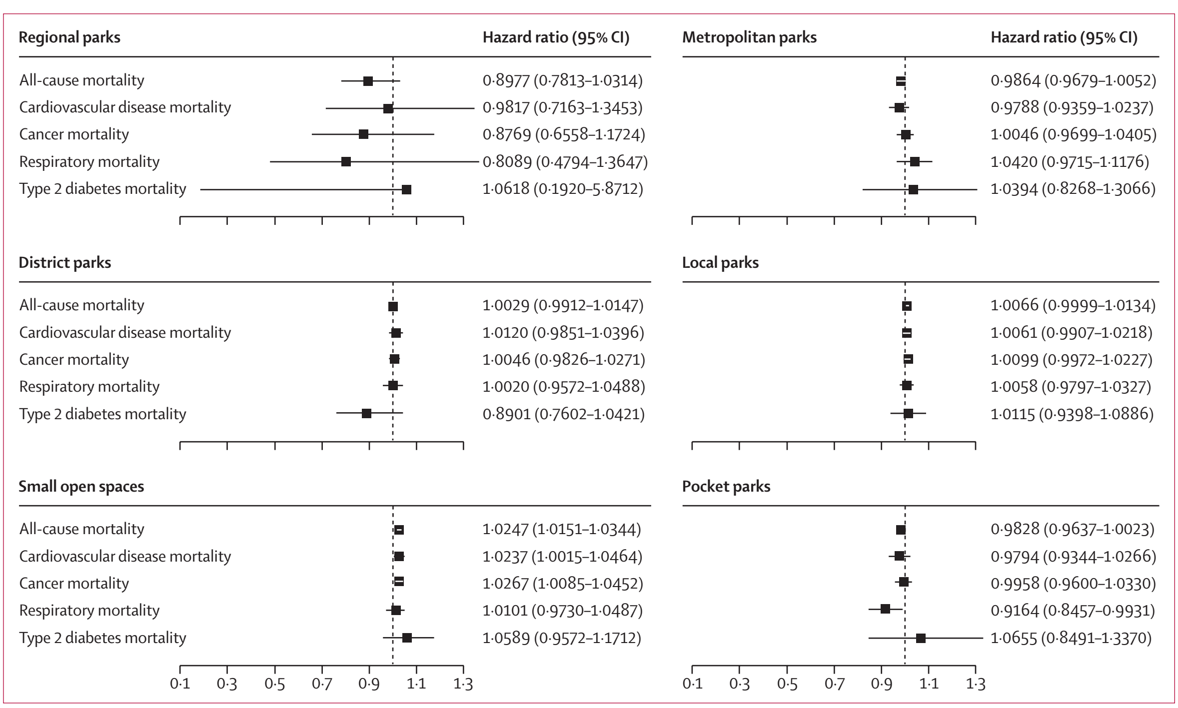

Figure 4: **Risk of all-cause and cause-specific mortality for each additional ten access points per km²**
Data for 4 645 581 individuals. Models are adjusted for age, sex, ethnicity, social grade, family status, deprivation status, level of education, and household tenure.

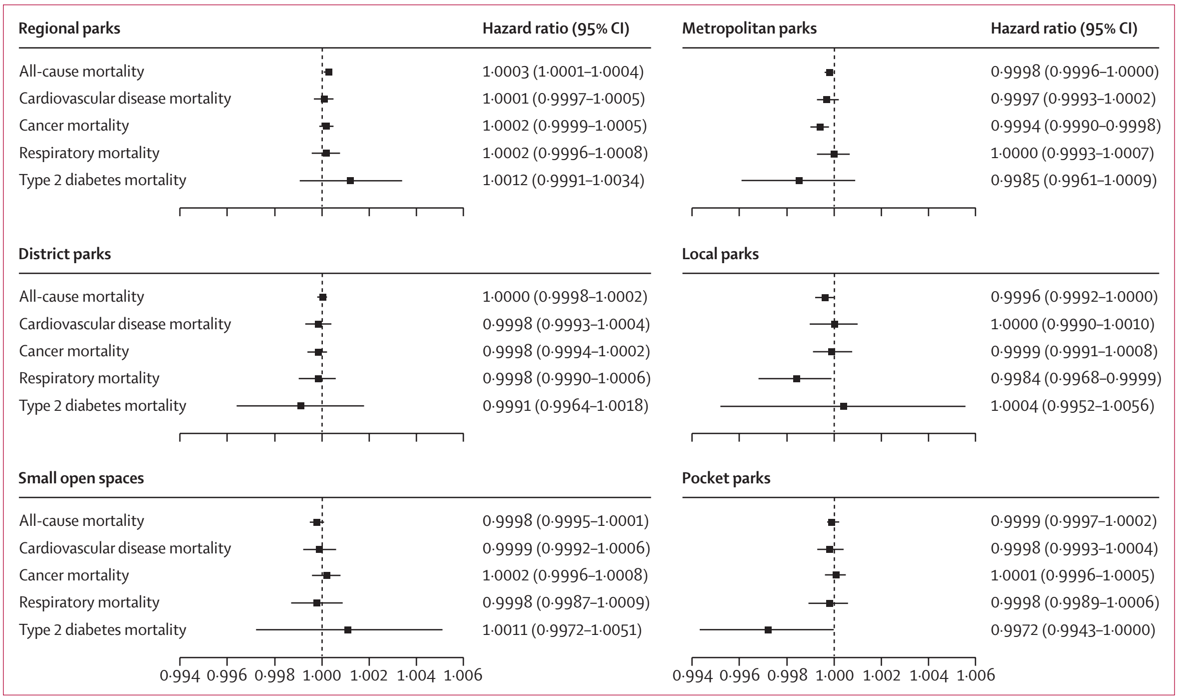

***Figure 5:* Risk of all-cause and cause-specific mortality for every 100 m increase in distance from the nearest greenspace access point**
Data for 4 645 581 individuals. Models are adjusted for age, sex, ethnicity, social grade, family status, deprivation status, level of education, and household tenure.

of overweight (relative risk ratios 1·12, 95% CI 1·03–1·22) and 23% increased risk of obesity (1·23, 1·11–1·37).[25] In an analysis of British adults who participated in the Whitehall II cohort, long-term greenspace exposure was not associated with arterial stiffness, a prognostic marker of cardiovascular health that might be impacted by greenspaces (eg, via reductions in stress and increases in opportunities for exercise).[6] Findings such as these indicate that the relationship between greenspaces and health are complex. Our study highlights complexities in three key areas. First, by contrast with earlier work, in which greenspaces have been shown to mitigate income-related inequalities in health including all-cause mortality and mortality from circulatory diseases,[28] we found limited evidence of effect modification of the greenspace–mortality associations by sociodemographic factors including age, sex, social grade, and level of education. More research is needed to further understand the modifiers of the greenspace–mortality relationships, and to understand why sociodemographic factors seem to be important effect modifers in some populations and not in others. A more nuanced understanding of effect modifiers would help inform the development of effective greenspace intervention. Second, we found that the greenspace–mortality associations differed by some specific NCD mortalities. This suggests that the mechanisms linking greenspaces to mortality could be unique for different types of NCD mortalities (eg, physical activity might be more important for cardiovascular disease-related mortality, whereas air pollution could be more important for respiratory-related mortality). Future studies should explore the causal mechanisms linking greenspaces and mortality outcomes. Third, we found that not all greenspaces are equal in terms of their potential effects on health, and that pooling different types of greenspaces in analyses might potentially mask heterogeneity in exposure–outcome associations. Different types of parks could be better than others at facilitating health-promoting behaviours (eg, exercise) or mitigating health-related risks (eg, lower levels of air pollution or ambient heat in regional parks). This is in line with evidence from our study that the provision of pocket parks in residential neighbourhoods might be particularly important for mitigating mortality risk. Based on previous qualitative work on park or greenspace use,[29] pocket parks could better facilitate social interactions and physical activity opportunities associated with health than larger parks, as they tend to be more convenient to use by the public. They might also be perceived as safer (eg, better lighting, fewer unkept areas, less crime, fewer opportunities for children to get lost, easier to take shelter from poor weather), more usable in terms of availability of park furniture (eg, benches, water fountains, play areas for children), more accessible (more readily identifiable entry and exit points), and more aesthetically pleasing than larger parks. Pocket parks also could provide ecological corridors when dotted throughout cities, allowing for a greater diversity of flora and fauna to flourish in cities, which in turn could have important benefits to human health (eg, via the calming effects of nature). To elucidate the causal pathways linking greenspaces and health, and to inform the design of effective greenspace interventions, future studies should consider other features of greenspaces (eg, their shapes and sizes) that could be relevant to health.[14,20] This is in line with evidence that greenspace morphology is a predictor of mortality regardless of the level of greenness.[14] Additional research on patterns of park use, and residents' perceptions of different types of parks, and their links with mortality risk are also needed to explain the potential reasons for the differences across park types and mortality risk that we observed.[29]

Strengths of our study include the use of a large administrative dataset (n=4 645 581) that contained individual-level data and the use of objectively assessed measures of greenspaces. Most previous studies have been relatively small or have relied on area-level measures of exposures, outcomes, or covariates.[5,13,14,19] By using individual-level and objectively assessed greenspace data in a large sample, with a long follow-up period, we have been able to estimate the associations between greenspaces and mortality risk with increased precision and a reduced risk of residual confounding. Some important limitations should also be noted when interpreting our study findings. First, London is ranked as the greenest city in the UK, and one of the greenest cities in Europe.[30] This probably reduced heterogeneity in exposure measures and might therefore have reduced our ability to detect effects. Second, it is possible that some people could have moved soon after the census was conducted and as such the greenspace exposure measurement for this subsample might not be representative of their actual greenspace exposure. There is also a possibility that this residential mobility might differ by sociodemographic characteristics (eg, young adults might be more likely to move than older adults). Nevertheless, because the number of movers is expected to be small, and there is evidence that people tend to move to better or worse neighbourhoods in similar proportions,[31] we expect that the bias arising from selective residential mobility is probably minimal. Third, the possibility of bias arising from leisure time mobility cannot be excluded. People might travel long distances to visit greenspaces far away from home,[32] and thus, even though greenspaces in specific locations might matter for health, greenspaces in home neighbourhoods might not matter as much. Our results can only be generalised to greenspace quantity and access within home neighbourhoods. Fourth, we did not examine the causal mechanisms linking greenspace exposure to mortality risk. Future research should investigate the potential mediating roles of factors such as air pollution, heat, and noise exposure. Fifth, the possibility of unmeasured or residual confounding cannot be excluded. While we adjusted for the main potential confounders, some of these variables were proxies for the confounders of interest (eg, household deprivation as a measure of person-level comorbidities) and thus might not have been perfect measures of the confounders of interest. Last, while our overall sample size was large, the number of deaths from some of the NCD-specific causes was small, leading to wide variance estimates for some of the outcomes of interest.

In conclusion, we found positive and negative associations between greenspace quantity and access and mortality risk. Many of the observed associations were small or negligible in magnitude. Clear associations, however, did appear for the smallest parks and all-cause and respiratory mortality risk. Our findings suggest that increasing the quantity of and access to pocket parks (<0·4 ha) might help mitigate mortality risk in adults in urban settings. To inform the design of more targeted interventions, future research might wish to identify which specific characteristics of these small parks mitigate mortality risk.

Contributors
SH and VN accessed and verified the underlying data. SH derived the greenspace measures. VN conducted the statistical analyses. SH, SC, and VN contributed to the writing of the manuscript, interpretation of the results, and approval of the final manuscript. All authors had full access to the data in the study and accept responsibility for submission of the paper for publication.

Declaration of interests
We declare no competing interests.

Data sharing
The greenspace measures were derived using data provided by the Ordnance Survey and the Greenspace Information for Greater London resource under licence. The derived measures will be shared on reasonable request to the corresponding author. The mortality and covariate data were obtained from the Office for National Statistics (ONS). The authors are unable to provide access to these data, but interested parties are advised to contact the ONS directly.

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