Green space and mortality in European cities: a health impact assessment study

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Summary

Background **Natural outdoor environments including green spaces play an important role in preserving population health and wellbeing in cities, but the number of deaths that could be prevented by increasing green space in European cities is not known. We aimed to estimate the number of natural-cause deaths among adult residents that could be prevented in cities in 31 European countries, if the WHO recommendation for universal access to green space was achieved.**

Methods **In this health impact assessment study we focused on adult residents (aged ≥20 years; n=169 134 322) in 978 cities and 49 greater cities, in 31 European countries. We used two green space proxies: normalised difference vegetation index (NDVI), and percentage of green area (%GA). The exposure was estimated at a fine grid-cell level (250 m×250 m) and the preventable mortality burden for 2015 was estimated at the local city-level.**

Findings **For 2015 we found that meeting the WHO recommendation of access to green space could prevent 42 968 (95% CI 32 296–64 177) deaths annually using the NDVI proxy (ie, 20% [95% CI 15–30] of deaths per 100 000 inhabitants-year), which represents 2·3% (95% CI 1·7–3·4) of the total natural-cause mortality and 245 (95% CI 184–366) years of life lost per 100 000 inhabitants-year. For the %GA proxy 17 947 (95%CI 0–35 747) deaths could be prevented annually. For %GA the number of attributable deaths were half of that of the NDVI and results were non-significant due to the exposure response function considered. The distribution of NDVI and %GA varied between cities and was not equally distributed within cities. Among European capitals, Athens, Brussels, Budapest, Copenhagen, and Riga showed some of the highest mortality burdens due to the lack of green space. The main source of uncertainty for our results was the choice of the age-structures of the population for the NDVI analysis, and exposure-response function for the %GA analysis.**

Interpretation **A large number of premature deaths in European cities could be prevented by increasing exposure to green space, while contributing to sustainable, liveable and healthy cities.**

Funding **GoGreenRoutes, Internal ISGlobal fund, and the United States Department of Agriculture Forest Service.**

Lancet Planet Health 2021; 5: e718–30

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Introduction

Natural outdoor environments including green spaces play an important role in preserving population health and wellbeing in cities[1] and provide ecosystem services and ecological benefits, besides having recreational, social, and cultural values.[2] Many studies have associated green space with beneficial health effects, including enhanced restoration, improved perceived wellbeing and mental health,[3–6] and reduction in cardiovascular disease.[7,8] Additionally, green spaces are associated with decreased natural-cause mortality.[5,9]

75% of the European population lives in urban environments.[10] Large urban populations coupled with the strong epidemiological evidence linking green space and health has put green interventions on the agenda of urban planners and policymakers as a way to promote healthy urban environments. Based on an expert working group report, WHO recommends that green spaces (of at least 0·5 hectares) should be accessible within a 300 m linear distance of residences.[2] The WHO report suggests that the percentage of green area (%GA) retrieved from land cover and land use maps (ie, European Urban Atlas) should be useful as a primary indicator; and the normalised difference vegetation index (NDVI), obtained from satellite imagery, and perception-based measures could also be applicable as secondary indicators.[2] However, urban planners and policy makers seek stronger evidence and quantification to introduce policies and interventions in cities.

It is not clear what kind and what type and quantity of green space could promote better health outcomes. Frequently used proxies are %GA and NDVI. Both proxies show strong associations with mortality,[5,9] but also differ in their way of defining green space. The %GA represents the land use that is officially defined as green space and which is generally publicly accessible (eg, parks, squares, community gardens) and the NDVI detects live vegetation and therefore represents the total amount of green (all types and sizes) of a specific area, capturing general surrounding greenness (eg, street

Research in context

Evidence before this study

We searched for estimates of impacts of green space exposure on health in PubMed, Scopus, and Google Scholar databases until April 28, 2021, without language or publication date restrictions. Our search terms were "green spaces" OR "greenness" OR "NDVI" OR "green area" AND "mortality" OR "premature mortality" AND "impact assessment" OR "health impact". We included all quantitative health impact assessment studies that evaluated green space exposure in the European region up to March 31, 2021. We excluded epidemiological studies (ie, cohort, case-control, cross-sectional, and ecological), studies with only abstracts, and studies not related to urban exposure to green spaces. Three studies analysed the health impacts of green space exposure in one specific city (Barcelona and Vienna), and two other studies analysed the impacts in two cities (Barcelona and Madrid) and six European cities (Barcelona, Athens, Lisbon, London, Stockholm, and Turin). All studies estimated the mortality burden related to the lack of residential exposure to green space based on land use data (ie, percentage of green space area by unit of analysis).

Added value of this study

To our knowledge, our study is the first large study that attempts to estimate the premature mortality burden due to lack of and unequal residential exposure to green spaces in many European cities. We estimated that a high mortality burden could be avoided if the studied European cities achieve the universal residential access to green space. The green space distribution varied between cities and is not equally distributed within cities. The main strengths of the study are the inclusion of a wide range of European cities (978 cities), the use of the same spatial unit of analysis for all cities (grid cells at a fine resolution of 250 m), the use of city-specific mortality rates, the application of several sensitivity analyses, and the estimation of uncertainties of the results for selected cities.

Implications of all the available evidence

Our results showed that a large number of natural-cause deaths in European cities could be prevented annually by increasing green space, which highlights the importance of policy interventions to increase the exposure of green spaces in cities and provide local estimates of the impacts. Urban interventions aiming to increase green space could promote better health and wellbeing, and reduce natural-cause mortality of the population, while contributing to the development of sustainable and healthy cities.

trees, green corridors, private green spaces, and general vegetation). Therefore, each proxy represents different types of exposures to green spaces that can affect health differently, and, consequently, might have a different association with mortality impacts.

In this study, we aimed to estimate the mortality burden that could be prevented in 978 European cities and 49 greater cities in 31 European countries, if these cities achieved the WHO recommendation for access to green space.

Methods

Definition of cities

In this health impact assessment study we retrieved the European cities and greater cities from the Urban Audit 2018 dataset,[11] which follows the city definition from the Organisation for Economic Cooperation and Development and European Commission.[12] The Urban Audit dataset contained 980 cities and 49 greater cities across 31 European countries (appendix 1 p 4). The 49 greater cities covered 161 out of the 980 cities either by including additional surrounding areas or by constituting a combination of several cities (appendix 2 p 2).[12] We excluded Saint-Denis (Réunion, France) and Fort-de-France (Martinique, France) from the study due to their location out of the European region. Our analysis was done for 978 cities and 49 greater cities.

See Online for appendix 1

See Online for appendix 2

Population and age distribution

We retrieved demographic data following the same procedure as described in a previous study published by our research group.[13]

We included all adult inhabitants (aged ≥20 years) in the analysed cities and greater cities. The total number of inhabitants per grid cell was retrieved from the Global Human Settlement Layer (GHSL) for 2015,[14] which was the best and latest available population layer in terms of resolution (ie, 250 m×250 m). We reduced the baseline GHSL dataset to only those grid cells covering residential areas to better represent the population distribution and to avoid misplacing inhabitants into non-residential areas (eg, industrial zones, port areas and water bodies, airports), based on land use data from European Urban Atlas 2012[15] and Corine Land Cover 2012.[16] We re-distributed the population associated with the removed grid cells among the dataset according to the population density reflected in the GHSL to maintain the total city population counts. The GHSL population counts correlated strongly (r=0·99) with the censual city-level total population counts obtained from Eurostat (appendix 2 p 3).[17] The population age distribution for 2015 was obtained from Eurostat at the Nomenclature of Territorial Units for Statistics (NUTS) 3 level.[18,19] We retrieved adult population data by age group (ie, aged ≥20 years, 5-year groupings) and calculated the proportion of the adult population per age group.

We assumed the same age distribution between the NUTS3-level and the corresponding city level (appendix 2 p 4).

Mortality

The total all-cause mortality counts by city were available for 2015 from Eurostat city statistics.[17] For 127 cities and 15 greater cities with missing data, the total all-cause mortality counts were estimated by employing the corresponding NUTS3-level all-cause mortality rates.[18] For eight cities and three greater cities with no data at the NUTS3-level, we used either the NUTS2 or country-level all-cause mortality rates (appendix 2 p 4).[18,20] We calculated the proportion of external deaths (following Eurostat definition) by adult age group and discounted it from the all-cause mortality counts to estimate the natural-cause deaths. We calculated the proportion of natural deaths by adult age group at the NUTS3-level and applied them to the city-level total all-cause mortality counts to estimate the number of natural deaths by adult age group. Finally, we applied the city-level natural-cause mortality rates to the corresponding grid cells to estimate the natural-cause mortality counts by adult age group for each grid cell. The estimated adult natural-cause death counts correlated strongly (r=0·99) with the censual total all-cause mortality counts obtained from Eurostat (appendix 2 pp 4–5).[17]

Quantitative health impact assessment

We conducted a quantitative health impact assessment at the grid-cell level, based on the GHSL population layer,[14] to estimate the impact of the insufficient exposure to green space on natural-cause mortality for the European cities inhabitants (aged ≥20 years). We performed the analysis by city and greater city. We followed the Urban and Transport Planning Health Impact Assessment methodology,[21–26] based on the comparative risk assessment approach in relation to a counterfactual scenario.[27] We defined our counterfactual scenario as compliance with the WHO recommendation of universal residential access to green space, because it is the only internationally recognised recommendation, and retrieved exposure-response functions from the literature, quantifying the strength of association between exposure to green space and mortality. For each grid cell and age group (appendix 2 pp 6–7) we estimated the baseline green space exposure levels (ie, NDVI and %GA; figure 1); determined the exposure level difference between the baseline and the counterfactual levels; estimated the relative risk (RR) associated to the exposure level difference based on the retrieved exposure-response functions; calculated the population attributable fraction for that exposure level difference; and estimated the preventable mortality burden, based on the population attributable fraction and the natural-cause deaths.[28,29] We added up the results by city and greater city and estimated the preventable age-standardised mortality per 100 000 inhabitants, according to the European Standard Population,[30] and the percentage of preventable annual natural-cause deaths. Additionally, we calculated the years of life lost due to premature deaths (appendix 2 pp 6–7). Exposure assignment and data analysis were done using PostGIS (version 2.4), QGIS (version 2.18.27), Python (version 3.7) and R (version 3.6.2).

Baseline levels of exposure to green space

The NDVI generally represents the total amount of surrounding greenness (eg, street trees, green corridors, and general vegetation from public and private spaces). NDVI levels range between –1 and 1, with positive and higher values indicating more greenness.[31] We retrieved the NDVI level for each grid cell using the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) obtained from US Geological Survey[32] and generated every 16 days at a 250 m×250 m resolution. All imagery for Europe between April 1 and June 30, 2015, were collected to ensure the greenest period of the year. Therefore, each grid cell counted up to six images for the calculation of the mean NDVI value. The selected imagery was pre-processed using the quality accuracy information to remove cloudy and snow or ice pixels. Water bodies were masked out from the analysis using the MOD44W.005 data product,[33] which is a combination of MODIS 250 m and SRTM water body data. To reflect the WHO recommendation of residential exposure to green spaces, the total averaged NDVI value was estimated by adding a 300 m buffer around each grid cell to indicate the proximity to greenness (ie, about 5 min walk along walkable pathways).[2]

We retrieved data for %GA using official land use and land cover maps and selected the best available data source in terms of resolution for each city. For 922 cities and 47 greater cities, data were available and obtained from the European Urban Atlas 2012 (0·25 hectare resolution).[15] For 39 cities and one greater city in the UK data were retrieved from the UK Land Cover Map 2015 (LCM 2015) vector (0·5 hectare resolution).[34] For 17 cities and one greater city, data were retrieved from the Corine Land Cover (CLC) 2012 inventory (25 hectare resolution).[16] The estimated %GA with UK LCM 2015 and with Corine Land Cover 2012 correlated strongly at the grid-cell level with the %GA obtained from Urban Atlas (r=0·95 and r=0·91, respectively). Therefore, we assumed that the data retrieved from European Urban Atlas 2012, CLC 2012, and UK LCM 2015 were comparable. Additionally, we applied sensitivity analyses to verify possible changes in outcomes by using each data source. Following the same approach as for NDVI, we estimated the total amount of green area by adding a 300 m buffer around each grid cell (appendix 2 pp 8–10).

Counterfactual levels of exposure to green space

Based on previous studies,[22,23,25] we established that each residential grid cell needs to have 25%GA to provide

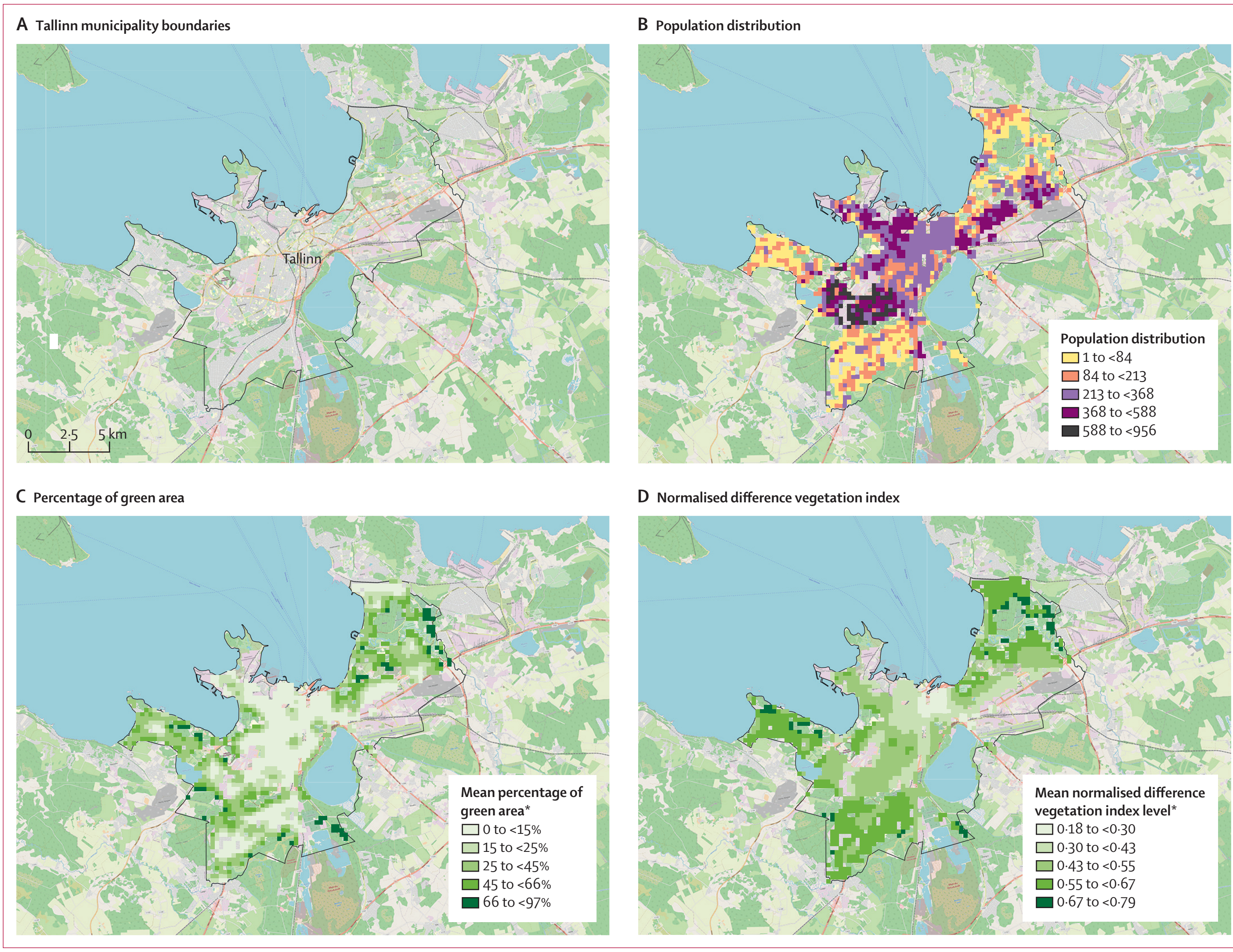

Figure 1: **Population and exposure level distribution for percentage of green area and normalised difference vegetation index at the grid-cell level for the city of Tallinn, Estonia**
The underlying map used in this figure is © OpenStreetMap contributors (www.openstreetmap.org) under a CC BY-SA 2.0 license. *250 m grid cells plus 300 m surrounding area.

universal access to a green space within 300 m. These studies correlated geolocation data of cohort study participants that reported to have access to a green space within 300 m from their residences with the %GA of the studied unit area (ie, census tract and sub-district level) and found that, with a 25%GA, universal access to green space for residents was provided.[22,23,25]

We translated the WHO recommendation of residential access to green space into a counterfactual target NDVI and applied it at the grid-cell level. To do so, we modelled the association between the %GA and NDVI for each city and established the target NDVI as the NDVI value associated to 25%GA (ie, target for %GA analysis), based on a similar approach of a health impact assessment green space study for the city of Philadelphia.[26] Most of the cities (768 [89%] of 866) showed strong non-linear correlation (Spearman $\rho>0{\cdot}7$) between %GA and NDVI, and only 12 cities showed non-linear correlations with Spearman $\rho<0{\cdot}4$ (figure 2). To allow for non-linear relationships, we used a generalised additive model (GAM) employing the grid-cell level %GA as predictor variable and the grid-cell level NDVI as the outcome variable. The fitted GAM was used to estimate the target NDVI separately for each city (appendix 2 pp 11–13), given that natural characteristics (eg, latitude, type of landscape) can influence their NDVI values (ie, by variations in type and density of vegetation) and the shape of the relationship. We ran Leave Group Out cross-validation (Monte Carlo CV) to get estimates of model performance using 90% of grid cells as the training dataset and repeating the resampling 100 times (appendix 1 p 1; appendix 2 pp 11–13). Furthermore, we applied sensitivity analyses to verify possible changes in outcomes by using alternative counterfactuals.

Exposure response functions

The association between residential exposure to green space and the risk of natural-cause mortality was estimated using two previously published systematic reviews and meta-analyses.

The NDVI systematic review and meta-analysis included only cohort studies and found that for a 0·1 unit increase in green exposure (including a buffer zone of 500 m or less from the place of residence) there was a statistically significant reduction in the risk of mortality by 4% (RR=0·96 [95% CI 0·94–0·97]).[9]

The %GA systematic review and meta-analysis included cohort, cross-sectional, and ecological studies and found that for a 10% increase in GA there was a statistically non-significant reduction in the risk of mortality by 1% (RR=0·99 [95% CI 0·98–1·01]).[5]

City comparisons

To explore which cities had the highest and lowest mortality impacts, we ranked and ordered the cities in quintiles, from highest (first position, first quintile) to the lowest (866th position, fifth quintile) mortality burden, based on the mortality burden score calculated through a principal component analysis. We present the rank and quintile distribution for 31 European capital cities. We used three measures (preventable age-standardised mortality rate, percentage of preventable natural-cause mortality, and years of life lost) in the principal component analysis and assigned the coordinate values for each city alongside the principal component. We conducted one principal component analysis for each proxy. We kept all the greater cities (n=49) and only cities that were not included in a greater city (n=817) to avoid double counting cities (appendix 2 p 14).

Uncertainty analyses

We performed uncertainty analyses for 20 selected cities to evaluate the impact of the uncertainty distributions of the parameters included in the health impact assessment for NDVI and %GA on the confidence intervals of our results. The parameters considered in the uncertainty analyses were exposure-response functions, city-specific mortality rates and population age structures, NDVI data error, and the city-target NDVI estimated with the GAM. We propagated the uncertainty of each parameter to the final results using Monte Carlo simulations, with 500 simulations for each city. We conducted a first round of Monte Carlo simulations to assess the overall uncertainty impact due to all parameters. Afterwards, we performed new rounds of Monte Carlo sampling to assess the uncertainty impact due to each of the parameters separately (appendix 2 pp 15–17).

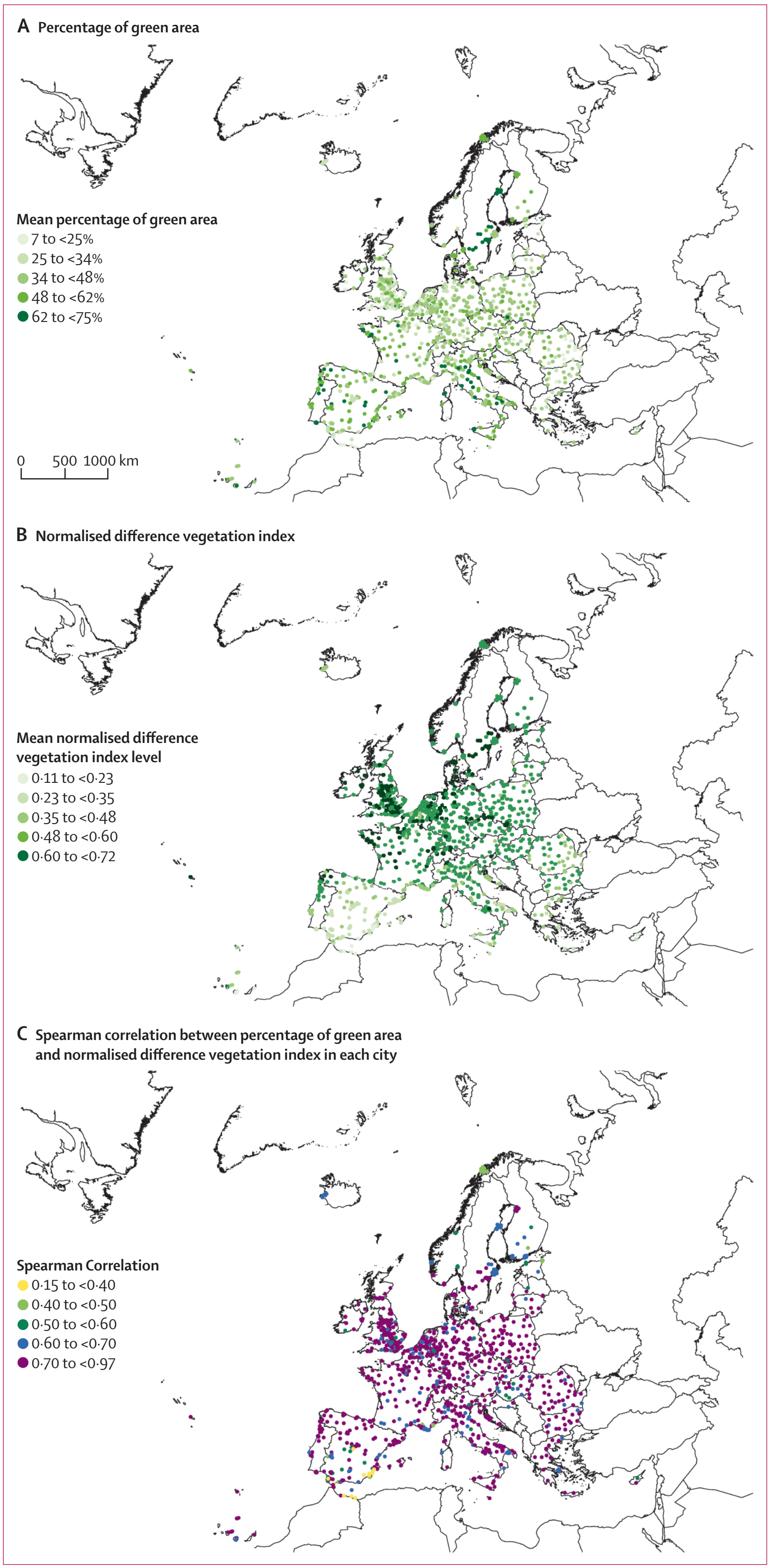

Figure 2: Distribution of average exposures among European cities and correlation between exposures by city

	Exposure-response function	Annual preventable deaths (n; 95% CI)	Annual preventable mortality rate (deaths per 100 000 inhabitants; 95% CI)	Annual preventable age-standardised mortality rate (deaths per 100 000 inhabitants; 95% CI)	Annual preventable impact on deaths (%; 95% CI)	Years of life lost (per 100 000 inhabitants; 95% CI)	Change (%)
Main analyses							
NDVI	Rojas-Rueda et al (2019)	42 968 (32 296–64 177)	22·08 (16·60–32·96)	19·90 (14·94–29·77)	2·25% (1·69–3·36)	245 (184–366)	..
%GA	Gascon et al (2016)	17 947 (0–35 747)	10·61 (0–21·14)	9·19 (0–18·31)	0·94% (0–1·87)	102 (0–204)	..
Sensitivity using city average values							
NDVI	Rojas-Rueda et al (2019)	4939 (3691–7462)	2·92 (2·18–4·41)	1·49 (1·12–2·25)	0·26% (0·39–0·19)	28·51 (21·30–43·07)	–89%*
%GA	Gascon et al (2016)	1254 (0–2512)	0·74 (0–1·48)	0·01 (0–0·03)	0·07% (0–0·13)	7 (0–14)	–93%†
Sensitivity using NDVI data retrieved from April to August							
Mean NDVI	Rojas-Rueda et al (2019)	41 941 (31 520–62 657)	24·80 (18·64–37·05)	19·37 (14·54–28·98)	2·20% (1·65–3·28)	240 (180–358)	–2%*
Maximum NDVI	Rojas-Rueda et al (2019)	48 075 (36 160–71 704)	28·42 (21·38–42·39)	22·45 (16·87–33·54)	2·52% (1·89–3·76)	274 (206–409)	+12%*
Sensitivity by employing different counterfactual exposures							
30%GA	Gascon et al (2016)	24 378 (0–48 463)	14·41 (0–28·65)	12·60 (0–25·04)	1·28% (0–2·54)	139 (0–276)	+36%†
NDVI reference for 30% GA	Rojas-Rueda et al (2019)	51 814 (38 962–77 314)	30·63 (23·04–45·71)	24·45 (18·37–36·55)	2·71% (2·05–4·05)	296 (222–441)	+21%*
Target NDVI reference 25% GA, based on an alternative GAM with biome, latitude, and precipitation	Rojas-Rueda et al (2019)	51 667 (38 851–77 098)	30·55 (22·97–45·58)	28·18 (21·18–42·09)	2·70% (2·04–4·04)	295 (222–440)	+20%*
Mean NDVI by biome	Rojas-Rueda et al (2019)	62 682 (47 182–93 343)	37·06 (27·89–55·19)	30·52 (45·53–22·96)	3·28% (2·47–4·89)	359 (270–534)	+46%*
Median NDVI by biome	Rojas-Rueda et al (2019)	64 753 (48 745–96 412)	38·28 (28·82–57·00)	31·76 (23·89–47·37)	3·39% (2·55–5·05)	370 (279–551)	+51%*
NDVI 0·2	Rojas-Rueda et al (2019)	808 (604–1219)	0·48 (0·36–0·72)	0·44 (0·33–0·66)	0·04% (0·03–0·06)	5 (4–7)	–98%*
NDVI 0·3	Rojas-Rueda et al (2019)	7733 (5798–11 605)	4·57 (3·43–6·86)	3·39 (2·54–5·09)	0·41% (0·30–0·61)	44 (33–67)	–82%*
NDVI 0·4	Rojas-Rueda et al (2019)	25 432 (19 122–37 956)	15·04 (11·31–22·44)	11·07 (8·32–16·52)	1·33% (1·00–1·99)	145 (109–217)	–41%*
NDVI 0·5	Rojas-Rueda et al (2019)	58 850 (44 362–87 383)	34·79 (26·23–51·66)	27·62 (20·81–41·05)	3·09% (2·32–4·58)	336 (253–499)	+37%*
Sensitivity by employing different sources of data for percentage of GA (cities with Urban Atlas and Corine Land Cover or UK Land Cover Map data)							
Corine *vs* Urban Atlas	Gascon et al (2016)	23 956 *vs* 15 561	16·2 *vs* 10·5	14·36 *vs* 9·16	1·42% *vs* 0·92%	156 *vs* 101	+54%†
UK Land Cover Map *vs* Urban Atlas	Gascon et al (2016)	3339 *vs* 2365	14·2 *vs* 10·0	14·61 *vs* 10·46	1·36% *vs* 0·96%	137 *vs* 97	+41%†

NDVI=normalised difference vegetation index. %GA=percentage of green area. GAM=generalised additive model. *In relation to the main analysis of NDVI reference for 25% of greenness. †In relation to the main analysis of 25% of green area based on land cover.

Table 1: **Results of the health impact assessment for main analysis and sensitivity analyses by employing distinct spatial level of analysis (ie, city-level), counterfactual scenarios, and sources of data**

Sensitivity analyses

We ran sensitivity analyses to evaluate the impact of changes in input variables for the health impact assessment on the magnitude of our final mortality burden estimations.

For the NDVI we assessed the impacts of employing the average city-level values instead of the grid-cell level values. We assessed the changes for the impacts of using two different NDVI exposures datasets, (1) the mean NDVI and (2) the maximum NDVI values from April 1 to Aug 31, 2015, to consider the NDVI estimates within the summer months. We applied counterfactual exposures based on discrete values between 0·2 and 0·5 NDVI because they usually represent sparse to dense vegetation—ie, vegetation levels that we considered applicable to urban settings. Additionally, we applied three different counterfactual exposures based on the European biome's distribution (ie, natural regions which comprise different landscapes and ecosystems with similar characteristics, mainly regarding vegetation and climate).[35,36] These exposures are the mean NDVI level by European biome; the median NDVI level by European biome; and an alternative GAM for all cities, employing the city-level %GA, biome category, latitude, and annual mean precipitation as predictor variables and the city-level NDVI as the outcome variable (appendix 2 pp 27–30). The mean and median NDVI levels were chosen to account for potential differences in NDVI levels within and between cities in each European biome. The alternative GAM was performed considering variables that contribute to the variability of green spaces; so, we predicted an alternative NDVI counterfactual exposure related to 25%GA by applying this alternative GAM.

For %GA we assessed the impacts of employing the average city-level values instead of the grid-cell level values. We analysed the impacts of using distinct %GA data sources for those cities with data retrieved from Urban Atlas and data also available through CLC (n=927 cities) and UK LCM (n=135 cities). We applied alternative counterfactual exposure level for %GA by using 30%GA as an even more ambitious target, guided by strategic action plans for green cities.[37,38]

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

In total, we included 169 134 322 adults aged 20 years or older who resided in the 978 European cities and 49 greater cities from Jan 1 to Dec 31, 2015, representing 32·2% of the population in the 31 European countries. The 2015 natural-cause mortality count among this population was 1 908 520 deaths (1128 deaths per 100 000 inhabitants-year). The average baseline NDVI was 0·52 (city range 0·11–0·72) and %GA was 41·2% (city range 7·6–75·4%; figure 2).

For NDVI, we estimated that 62% of the population (city range 15–97%) had residences in areas where the NDVI level was below the city-target NDVI. An increase in NDVI could prevent 42 968 (95% CI 32 296–64 177) deaths annually (ie, 20% [95% CI 15–30] of deaths per 100 000 inhabitants-year), which represents 2·3% (95% CI 1·7–3·4) of the total natural-cause mortality and 245 (95% CI 184–366) years of life lost per 100 000 inhabitants-year (table 1). For %GA, we estimated that 65% of the population (city range of 4% to 100%) had not enough access to green spaces within 300 m linear distance from their residences. Achieving the WHO recommendations by increasing the %GA to 25% could result in the prevention of 17 947 (95%CI 0–35 747) deaths annually (ie, 9 [0–18]) deaths per 100 000 inhabitants-year), which represents 0·9% (0–1·9) of total natural-cause mortality and 102 (0–204) years of life lost per 100 000 inhabitants-year (table 1; figure 3).

We found great variability in the preventable mortality burden among the European cities with both proxies, NDVI (city range 0·2–5·5% of total mortality; 1–59 deaths per 100 000 inhabitants-year) and %GA (city range 0–2% of total mortality; 0–28 deaths per 100 000 inhabitants-year). The number of preventable deaths for NDVI and %GA were strongly linearly correlated (r=0·98); however, preventable age-standardised mortality rates (r=0·74), years of life lost (r=0·74), and the percentage of preventable deaths (r=0·67) were not as strongly correlated (appendix 2 p 36).

We found that the first principal component of the data could explain 95% and 92% of the total variance among the cities' mortality burden outcomes, for NDVI and %GA, respectively, in which all the three measures of mortality burden contributed similarly (appendix 2 p 14). For both analyses, cities located in Greece, Bulgaria, Romania, Hungary, Lithuania, Latvia, Estonia, northern and southern Italy, northern France, Belgium, in the UK, big cities in central Europe were in quintiles one and two, presenting high attributable mortality burdens (figure 3; appendix 1 pp 2,3; appendix 2 p 36). Most European capitals also showed a high mortality burden (21 [68%] of 31 were in quintiles one and two; tables 2, 3), and we found that an increase in greenness could prevent 2·9% (95% CI 2·2–4·3) of the total natural-cause mortality in the European capitals.

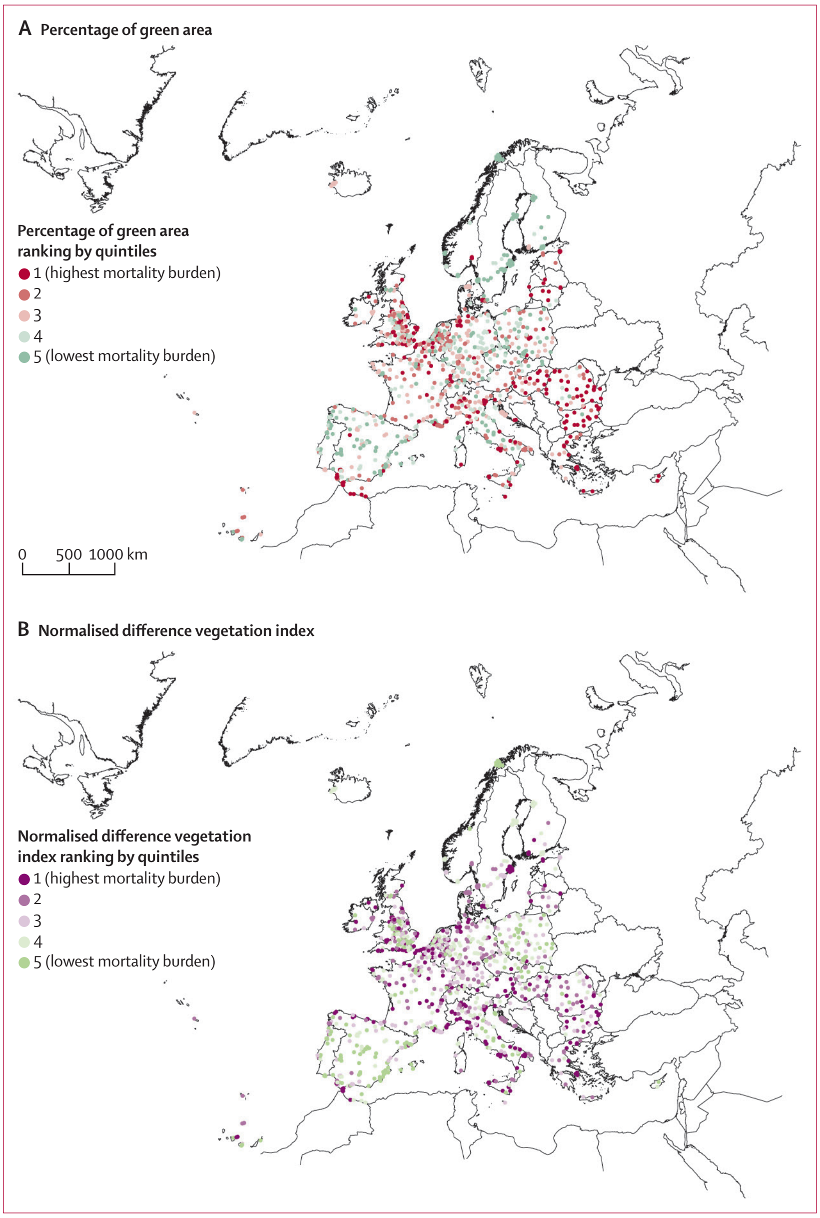

Figure 3: **Cities and greater cities ranked from highest (first quintile) to the lowest (fifth quintile) mortality burdens based on the principal component analysis score**

For NDVI, the main source of uncertainty was the age structure of the city population, followed by the city-specific mortality rates, the exposure response function, the error associated with the NDVI data, and finally, the GAM applied to define the city-target NDVI. For %GA, uncertainty analysis indicated that the most

	Impact group (quintile)	City ranking	NDVI level (mean)	Target NDVI	Population below target NDVI (%)	Annual preventable deaths (n; 95% CI)	Annual preventable age-standardised mortality rate (deaths per 100 000 inhabitants; 95% CI)	Annual preventable impact on deaths (%; 95% CI)	Years of life lost (per 100 000 inhabitants; 95% CI)
Brussels (Belgium)	1	5	0·47	0·52	78·5	426 (321–632)	54 (41–80)	5·0% (3·8–7·4)	464 (350–688)
Copenhagen (Denmark; greater city)	1	9	0·53	0·55	76·5	437 (329–649)	46 (35–69)	4·0% (3·0–5·9)	462 (348–685)
Budapest (Hungary)	1	12	0·49	0·51	76·6	746 (562–1109)	50 (37–74)	3·5% (2·6–5·2)	450 (339–669)
Paris (France; greater city)	1	17	0·42	0·48	86·4	1918 (1446–2850)	36 (27–53)	4·9% (3·7–7·3)	378 (285–561)
Athens (Greece; greater city)	1	18	0·29	0·32	87·7	1431 (1074–2141)	42 (32–63)	3·5% (2·6–5·2)	485 (364–7269)
Riga (Latvia)	1	28	0·50	0·50	72·4	227 (170–338)	42 (32–63)	2·9% (2·2–4·3)	432 (325–644)
Tallinn (Estonia)	1	61	0·51	0·51	70·8	108 (81–161)	37 (28–55)	2·8% (2·1–4·2)	355 (267–529)
Vienna (Austria)	1	69	0·47	0·49	61·4	464 (349–690)	34 (26–51)	3·0% (2·3–4·5)	322 (242–479)
London (UK; greater city)	1	72	0·52	0·54	76·6	1712 (1288–2550)	33 (25–49)	3·6% (2·7–5·3)	266 (200–397)
Bucharest (Romania)	1	77	0·40	0·44	78·5	470 (353–703)	38 (29–57)	2·7% (2·1–4·1)	301 (226–451)
Amsterdam (Netherlands)	1	108	0·49	0·51	69·5	187 (141–279)	33 (25–49)	3·0% (2·3–4·5)	255 (192–381)
Sofia (Bulgaria)	1	146	0·48	0·48	73·7	247 (185–371)	35 (26–52)	2·2% (1·6–3·2)	269 (202–403
Stockholm (Sweden; greater city)	1	150	0·58	0·54	65·5	329 (248–490)	28 (21–42)	2·9% (2·2–4·3)	237 (179–353)
Rome (Italy)	1	155	0·47	0·44	68·5	649 (488–970)	26 (20–39)	2·6% (2·0–3·9)	287 (215–428)
Berlin (Germany)	1	168	0·53	0·54	65·2	763 (573–1139)	28 (21–42)	2·4% (1·8–3·6)	274 (206–409)
Oslo (Norway)	2	239	0·53	0·53	55·3	105 (79–156)	29 (22–43)	2·1% (1·6–3·1)	198 (149–295)
Zurich (Switzerland; greater city)	2	268	0·56	0·55	60·1	107 (81–160)	22 (17–33)	2·4% (1·8–3·6)	205 (155–306)
Vilnius (Lithuania)	2	269	0·55	0·50	52·4	99 (75–148)	26 (19–38)	1·9% (1·4–2·8)	230 (173–344)
Dublin (Ireland; greater city)	2	282	0·62	0·57	58·8	174 (131–259)	26 (19–38)	2·2% (1·7–3·3)	177 (133–262)
Lisbon (Portugal; greater city)	2	301	0·38	0·35	72·1	355 (266–533)	22 (16–33)	1·9% (1·5–2·9)	234 (176–351)
Bratislava (Slovakia)	2	314	0·51	0·51	61·2	68 (51–102)	26 (19–39)	1·8% (1·4–2·7)	200 (150–299)
Luxembourg (Luxembourg)	3	359	0·52	0·49	50·8	14 (11–21)	21 (16–31)	2·1% (1·6–3·2)	180 (135–269)
Zagreb (Croatia)	3	366	0·60	0·53	52·7	143 (107–214)	23 (18–35)	1·7% (1·3–2·6)	195 (146–292)
Warsaw (Poland)	3	495	0·49	0·47	62·6	271 (203–406)	18 (14–27)	1·5% (1·2–2·3)	187 (140–281)
Valletta (Malta)	3	518	0·24	0·25	75·0	24 (18–37)	19 (14–28)	1·6% (1·2–2·4)	162 (121–244)
Helsinki (Finland; greater city)	4	521	0·52	0·47	55·3	128 (96–191)	17 (13–26)	1·7% (1·3–2·6)	153 (115–228)
Madrid (Spain; greater city)	4	538	0·32	0·32	66·6	620 (465–932)	15 (12–23)	1·7% (1·3–2·5)	156 (117–235)
Ljubljana (Slovenia)	4	561	0·58	0·51	49·0	34 (26–51)	15 (11–23)	1·6% (1·2–2·4)	148 (111–221)
Prague (Czech Republic)	4	562	0·55	0·51	44·1	175 (132–262)	17 (13–26)	1·4% (1·1–2·2)	147 (110–219)
Reykjavik (Iceland)	4	616	0·37	0·38	64·9	20 (15–29)	15 (11–23)	1·6% (1·2–2·4)	120 (90–181)
Lefkosia (Cyprus)	5	835	0·23	0·23	68·2	11 (8–17)	8 (6–12)	0·7% (0·5–1·0)	52 (39–79)

NDVI=normalised difference vegetation index.

Table 2: **Preventable mortality burden due to the increase in normalised difference vegetation index (NDVI) in the 31 European capitals, from highest (top) to lowest (bottom) burden**

important uncertainty source was the exposure response function, followed by the age structures of the city population and the city-specific mortality rates. The quantitative details on how the different sources of error affected the precision of the impact assessment are shown in appendix 2 (pp 18–26).

For the NDVI, we observed the greatest change in the total mortality burden estimations with the use of NDVI 0·2 (–98%) and NDVI 0·3 (–82%) as alternative counterfactuals and with the city-level analysis (–89%), suggesting that these levels are not sufficient to prevent deaths and that the geographical distribution of NDVI and population within the cities is important, respectively. The largest increases in the mortality burden were found with the use of median (+51%) and mean (+46%) NDVI level by biome as counterfactuals, which suggests a high variability of NDVI levels within and between the cities in each biome. The smallest changes in the mortality burden estimations were found with the use of the alternative dataset with the mean NDVI (–2%) and the maximum NDVI (+12%) values based on imagery from April to August, 2015, followed by the use of the target NDVI based on an alternative GAM model considering biome, latitude and precipitation data (+20%), and the use of the NDVI reference for 30%GA (+21%; table 1; appendix 2 pp 31–35).

	Impact group (quintile)	City Ranking	Percentage of GA (mean)	Population below 25% GA (%)	Annual preventable deaths (n; 95% CI)	Annual preventable age-standardised mortality rate (deaths per 100 000 inhabitants; 95% CI)	Annual preventable impact on deaths (%; 95% CI)	Years of life lost (per 100 000 inhabitants; 95% CI)
Athens (Greece; greater city)	1	10	20·38	85·88	643 (0–1279)	19 (0–38)	1·56% (0–3·10)	218 (0–434)
Bucharest (Romania)	1	12	16·44	85·30	272 (0–540)	22 (0–44)	1·59% (0–3·15)	174 (0–346)
Budapest (Hungary)	1	13	20·03	84·52	316 (0–629)	21 (0–42)	1·49% (0–2·96)	191 (0–380)
Riga (Latvia)	1	29	26·80	77·36	97 (0–192)	18 (0–36)	1·22% (0–2·43)	184 (0–366)
Copenhagen (Denmark; greater city)	1	35	22·05	83·68	154 (0–306)	16 (0–33)	1·39% (0–2·77)	162 (0–323)
Brussels (Belgium)	1	46	17·37	86·06	125 (0–249)	16 (0–31)	1·46% (0–2·91)	136 (0–270)
Valletta (Malta)	1	68	25·15	76·21	20 (0–40)	15 (0–30)	1·29% (0–2·57)	132 (0–262)
Sofia (Bulgaria)	1	81	27·85	73·13	121 (0–241)	17 (0–34)	1·06% (0–2·11)	131 (0–262)
Paris (France; greater city)	1	84	14·34	90·67	614 (0–1222)	11 (0–23)	1·58% (0–314)	121 (0–241)
Oslo (Norway)	1	126	27·42	76·39	57 (0–115)	16 (0–31)	1·15% (0–2·29)	109 (0–216)
Lefkosia (Cyprus)	1	138	28·99	75·59	21 (0–41)	14 (0–29)	1·30% (0–2·59)	98 (0–195)
London (UK; greater city)	1	159	22·29	82·83	645 (0–1285)	12 (0–25)	1·34% (0–2·67)	100 (0–200)
Berlin (Germany)	1	164	22·72	75·23	347 (0–691)	13 (0–25)	1·10% (0–2·19)	125 (0–248)
Lisbon (Portugal; greater city)	2	214	34·98	70·36	185 (0–368)	11 (0–23)	1·01% (0–2·01)	122 (0–243)
Amsterdam (Netherlands)	2	215	23·11	73·91	70 (0–140)	12 (0–25)	1·13% (0–2·25)	96 (0–191)
Tallinn (Estonia)	2	217	28·80	67·05	36 (0–72)	12 (0–25)	0·94% (0–1·87)	119 (0–238)
Vienna (Austria)	2	276	27·76	70·08	148 (0–295)	11 (0–22)	0·96% (0–1·91)	103 (0–205)
Warsaw (Poland)	2	314	35·77	62·94	154 (0–306)	10 (0–21)	0·88% (0–1·75)	106 (0–212)
Rome (Italy)	2	334	43·03	65·20	232 (0–462)	9 (0–19)	0·94% (0–1·87)	102 (0–204)
Reykjavik (Iceland)	3	380	30·94	66·99	13 (0–25)	10 (0–19)	1·01% (0–2·01)	77 (0–154)
Madrid (Spain; greater city)	3	396	27·03	69·72	349 (0–695)	9 (0–17)	0·95% (0–1·90)	88 (0–175)
Zurich (Switzerland; greater city)	3	408	32·35	66·85	43 (0–85)	9 (0–18)	0·96% (0–1·91)	82 (0–163)
Bratislava (Slovakia)	3	435	32·87	63·34	28 (0–56)	11 (0–21)	0·75% (0–1·49)	83 (0–165)
Zagreb (Croatia)	3	485	53·77	46·94	58 (0–116)	10 (0–19)	0·71% (0–1·42)	79 (0–158)
Dublin (Ireland; greater city)	3	514	43·54	64·33	63 (0–125)	9 (0–18)	0·81% (0–1·61)	64 (0–127)
Vilnius (Lithuania)	4	585	49·54	48·25	32 (0–64)	8 (0–16)	0·61% (0–1·22)	74 (0–148)
Ljubljana (Slovenia)	4	590	48·43	52·42	16 (0–31)	7 (0–14)	0·75% (0–1·49)	68 (0–135)
Stockholm (Sweden; greater city)	5	707	37·67	57·72	72 (0–144)	6 (0–12)	0·64% (0–1·27)	52 (0–103)
Luxembourg (Luxembourg)	5	720	35·62	53·92	4 (0–8)	6 (0–12)	0·62% (0–1·23)	52 (0–104)
Prague (Czech Republic)	5	768	39·91	47·12	60 (0–120)	6 (0–12)	0·49% (0–0·98)	50 (0–100)
Helsinki (Finland; greater city)	5	816	43·14	45·19	31 (0–62)	4 (0–8)	0·42% (0–0·85)	37 (0–74)

Table 3: **Preventable mortality burden due to the increase in percentage of green area (GA) in the 31 European capitals, from highest (top) to lowest (bottom) burden**

For the %GA, the use of city-level average %GA also resulted in the greatest change in estimated overall mortality burden estimations (–93%), suggesting that accounting for the geographical distribution of the %GA and population within the cities is important. The use of CLC (n=927 cities) data instead of Urban Atlas data caused an increase of 54% in the mortality burden estimations and the use of UK LCM (n=135 cities) caused a 41% increase. The use of 30%GA as alternative counterfactual exposure resulted in an increase of 36% in the mortality estimations (ie, 24 378 preventable deaths; table 1; appendix 2 pp 31–35).

Discussion

This is the first large study to estimate the annual number of deaths that could be prevented if European cities and greater cities achieved the WHO recommendation for exposure to green space. The distribution of NDVI and %GA varied between and is not equally distributed within cities, and the total estimated mortality burden varied from 0% to 5·5% of all natural-cause deaths for NDVI and from 0% to 2·0% of all natural-cause deaths for %GA. Based on our sensitivity analyses, an even larger number of deaths could be prevented by providing more green space than the WHO recommendations. Among the European capital cities, Athens, Brussels, Budapest, Copenhagen, and Riga showed some of the highest mortality burden attributable to the lack of green space.

Results of other studies using a similar health impact assessment methodology are comparable to our estimates for the %GA proxy and were conducted in the European cities of Vienna,[23] Barcelona,[22,24] Bradford,[25] and Madrid.[24] Moreover, Mitsakou and colleagues[39] reported preventable mortality rates slightly higher than ours for Athens, Barcelona, and Lisbon, while slightly lower for London, Stockholm, and Turin. The differences in the values by Mitsakou and colleagues and ours might partially be due to the difference in the spatial unit, from a fine scale (ie, grid cell in our study) to a medium scale (ie, city or district level in their study).

In the USA, Kondo and colleagues[26] estimated that nearly 400 deaths annually could be prevented by applying a policy to increase the tree canopy cover from around 20% to 30% of the land surface in Philadelphia, and showed that poorer neighborhoods would benefit more.[26] In Spain, Mueller and colleagues[21] estimated that around 60 deaths annually could be prevented in one neighbourhood of Barcelona by implementing the Superblocks Program and increasing the percentage of green space from 6·5% to 19·6% GA.[21] Furthermore, a large study examined the impact of land use or cover and mortality in 233 cities from 24 European countries and found a reduction in mortality in areas with more green spaces (ie, in cities in eastern and western Europe).[40]

Open and public green spaces in cities (best represented by the %GA proxy) have been associated with increased physical activity levels, social interaction and social cohesion, psychological restoration (ie, stress reduction and attention restoration), and better general health and wellbeing.[1] Additionally, parks and larger green spaces provide ecosystem services by mitigating detrimental exposures, such as air pollution, noise, and the urban heat island effect.[1] General greenness in cities (best represented by the NDVI proxy), might not reflect accessibility to perform physical activity and social interaction, but still reflects the provision of ecosystems services, promotes psychological restoration, and increases general health and well-being.[1] Besides, general greenness might be more widespread in the city than public green spaces, and hence have a larger impact.

We found a similar percentage of European city dwellers who lacked exposure to surrounding greenness (62% expressed as NDVI) and of those who lacked exposure to green areas (65% expressed as %GA), and results for %GA analysis followed a similar pattern to those for NDVI. However, in general the number of attributable deaths and related outcome indicators were half of that of the NDVI and the %GA results were not significant. This difference might be largely due to the different strength and magnitude of the association of each proxy with mortality in the meta-analyses and the quality of the studies included. Indeed, considering that the association between green space and mortality might be stronger in urban than rural areas[41] and that both meta-analyses include studies from different populations, it is possible that the real impact of green spaces on mortality in the European urban population is even stronger than our estimations.

We based our counterfactual exposure for %GA on analyses conducted in previous studies.[22,23,25] We then estimated a city-specific counterfactual exposure level for NDVI that could be observed in areas in the city complying with the %GA target. We followed a similar approach used in the prospective health impact assessment study for the city of Philadelphia, in which Kondo and colleagues[26] calibrated tree canopy cover with corresponding NDVI levels, to estimate the reduction in the attributable mortality burden related to tree coverage increase. In our approach, we considered geographical, climatic, and biological variations in vegetation when determining each city's NDVI levels (ie, cities in Southern Europe having naturally different NDVI levels than cities in Northern Europe). This approach generally worked well. However, for those cities with low GAM adjusted R^2 (40 cities with adjusted $R^2<0·4$; appendix 1 p 1), the city-NDVI target and, consequently, the mortality burdens estimations must be interpreted with caution.

Among the European capital cities, Athens, Brussels, Budapest, Copenhagen, and Riga showed some of the highest mortality burden due the lack of green space. All of these cities have an unequal distribution of green spaces in the territory, with parks concentrated in specific areas or in the outskirts, and with a shortage of tree coverage outside those green spaces. In the past few years, most of the European capitals have been defining strategic local plans to improve urban quality and climate change resilience that considers the increase of green areas and greenness, which can improve the amount of green space in the near future.

Most European cities have a consolidated historic built environment with little vacant parcels of land; however, green interventions can target the recovery of urban areas (eg, turning former industrial areas into urban parks), the increase of nature-based solutions in the actual urban fabric (eg, green roofs and vertical gardens), reconfigurations of traffic and reallocation of road and parking space to green and natural environments (eg, green belt and corridors of Vitoria-Gasteiz[42] and Barcelona superblocks[43]), and providing general greening of the city with increasing street trees, green corridors, and pocket parks.

A considerable number of cities with high attributable mortality burden estimates are located at coastlines, or contain lakes and rivers (eg, blue spaces in the capital cities mentioned earlier). Previous research suggests that exposure to blue spaces also benefits health and reduces the risk for mortality.[5,44–46] Therefore, the mortality burden caused by a lack of natural outdoor environments (green and blue spaces) estimated might be overestimated given that exposure to blue spaces can offset the negative impacts of lack of green space, which were not considered in this study.

In the uncertainty analyses, we demonstrated that not propagating all possible sources of error through the health impact assessment leads to an overestimation of the precision in the results. In the NDVI analysis, the age structures of the population and the baseline mortality rates were the most important sources of uncertainty, while for %GA, these sources of uncertainty were the exposure response functions and age structures of the population.

In the sensitivity analyses, we observed the greatest difference in the total preventable mortality burden estimation with the analyses using city average levels of NDVI and %GA, suggesting that modelling green space exposure at the grid-cell level better captures the geographical differences in the access to residential green space than modelling at the city level, which is coherent with the different level of data aggregation. Additionally, the city-level green space estimates might not sufficiently consider the residential distance of green space such as recommended by WHO.

This is the first study that compares exposure to green space among a large number of European cities and greater cities. We used the grid-cell level with a spatial resolution of 250 m×250 m as our unit of analysis, and applied city-specific mortality rates, which allowed the comparison of estimated impacts within and between the cities, and contributes to the design of evidence-based policies for green interventions in urban environments.[47] Additionally, the use of two green space exposure proxies (NDVI and %GA) allowed the comparison of the distribution and impact of green spaces. Finally, several sensitivity and uncertainty analyses were conducted to evaluate the robustness of our results.

Unfortunately, the data for %GA was only available for 2012 (Urban Atlas and Corine) and 2015 (UK Land Cover). However, considering that the %GA is linked with land use that is modified through the medium or long-term interventions, we believe that %GA exposure has not changed substantially during the studied period and represents well the official current public green spaces in cities. Also, we did sensitivity analyses to estimate differences in outcomes by data source to verify the comparability of the final results.

We made a first attempt to translate the WHO recommendation for European cities by using the estimated %GA counterfactual from previous studies and running the GAM to define the NDVI counterfactual for each city. These approaches are innovative but are open for improvement. The 25%GA counterfactual exposure was estimated for cities from different countries, urban traditions, and landscapes (ie, Barcelona, Bradford, and Vienna);[22,23,25] nonetheless, there is a risk of 25%GA not being a good counterfactual exposure in all European cities. Furthermore, the relationship between %GA and NDVI varied between cities. This variation could be partly explained by the issue that NDVI and %GA account for different types of green space, and other local characteristics. The city-target NDVI estimations for cities with low GAM adjusted R^2 must be interpreted with caution, and, consequentially, their estimated mortality burdens.

A further limitation is that both proxies (%GA and NDVI) do not reflect quality or use of green spaces. Urban green spaces have different components that affect their quality and, consequently, the type of use, time spent, and level of interaction with a green space by different population sub-groups, which can affect the health mediators and outcomes associated with the exposure to a green space.[48,49] Moreover, visiting green space might be better associated with health than proximity to green space or surrounding greenness.[50] However, we did not have good data on quality, visits, and exposure-response functions to conduct such analyses.

We could only obtain mortality and age-structure data at the city level, which is insensitive to within-city variability, and only for 2015. Despite not accounting for within-city variability in mortality and age, the analysis at the 250 m scale allowed us to consider the variability in residential green space exposure within-city, and results were comparable to those from previous studies.[22–25] Additionally, more in-depth geographical health impact assessment analyses could be performed when within-city mortality and age-structure data become available.

Finally, we used two different exposure-response functions, depending on the green space proxy applied. The exposure response function used for the NDVI proxy from Rojas-Rueda and colleagues[9] is more robust and the studies included in it were more consistent, and therefore we have more confidence in the risk estimates from the NDVI analysis, even though the exposure response function from Rojas-Rueda and colleagues showed some heterogeneity.[9] The exposure response function used for the %GA proxy from Gascon and colleagues[5] has two main limitations: it included different types of epidemiological studies with different metrics of green spaces, and the confidence interval includes a null value.[5] However, in the same study, an additional analysis of high versus low exposures to green and mortality was statistically significant, showing that high exposure to green spaces was associated with reducing the mortality risk.[5] Therefore, we decided to use both exposure response functions to compare the two different green space proxies. Only studies published before November, 2014, were included in the meta-analysis from Gascon and colleagues;[5] however, new evidence has strengthened the role of green space as a protective factor for mortality.[51–53] Therefore, we assumed zero as the lower value for %GA impact estimates. Finally, these exposure-response functions did not provide stratified estimates by age, sex, ethnicity, or any socioeconomic indicators. Therefore, we were unable to address potential differential effects of green spaces on mortality for different subgroups within the populations, which might exist.[51,54–59]

To conclude, our study shows the importance of increasing green space in European cities to reduce natural-cause mortality, while contributing to the development of sustainable, livable, and healthy cities.

Contributors

MN conceptualised the study. EPB and MC worked on the study design and data collection. EPB and SK did the data analysis. EPB, MC, SK, TI, NM, and MN contributed to data interpretation. NM, DR-R, and MK provided input on the health impact assessment methods. JB-G provided help with all statistical analyses and wrote the R script for the uncertainty analyses. EPB, MC, SK, and TI accessed and verified the data. EPB wrote the manuscript. All authors reviewed and edited the manuscript, and provided feedback on the study design, data analysis, and interpretation of results. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All the data collected is routinely collected data with no information on specific people. All the data is available upon request to the corresponding author (mark.nieuwenhuijsen@isglobal.org) and with agreement of the steering group.

Acknowledgments

We acknowledge support from the Spanish Ministry of Science and Innovation through the Centro de Excelencia Severo Ochoa 2019–23 Programme, GoGreenRoutes through the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 869764, the Generalitat de Catalunya through the Centres de Recerca de Catalunya Programme, unnamed funding from the United States Department of Agriculture (USDA) Forest Service. The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the USDA Forest Service.

Editorial note: the *Lancet* Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

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