**Target Journal: Environmental Research Letters**

**Single or double anonymous (author choice)**

**Title**

A quantitative health impact assessment of urban greenspace and all-cause mortality across 1,042 global cities

*The title should be concise, informative and meaningful to the whole readership of the journal. It should include key terms, to help make it more discoverable when people search online. Please avoid the use of long systemic names and non-standard or obscure abbreviations, acronyms or symbols.*

**Authors**

Greta K. Martin1, Patrick L. Kinney2, Jennifer D. Stowell2, Susan C. Anenberg1

1The George Washington University Milken Institute of Public Health, Washington, DC

2Boston University School of Public Health, Boston, MA

*Check the*[*peer review model*](https://publishingsupport.iopscience.iop.org/questions/peer-review-models-on-iop-journals/)*for the journal you are submitting to when preparing the PDF version of your manuscript. If****double-anonymous****then you will need to [anonymise your manuscript](https://publishingsupport.iopscience.iop.org/questions/checklist-for-anonymising-your-manuscript/). If****single-anonymous****then you need to list all authors’ full names and institutions. During the submission process, we recommend you supply*[*ORCID*](https://publishingsupport.iopscience.iop.org/questions/structure-and-format-of-your-journal-article/publishingsupport.iopscience.iop.org/orcid/)*identifiers for all authors to avoid ambiguity. We encourage authors to make specific attributions of contribution and responsibility in the acknowledgements of the article, otherwise all co-authors will be taken to share full responsibility for all of the paper. Authors may wish to use a taxonomy such as [CRediT](http://credit.niso.org/) to describe the contributions of each author. More guidance on authorship, including the responsibilities of the corresponding author, can be found*[*here*](https://publishingsupport.iopscience.iop.org/questions/ethics-of-authorship/)*.*

**Keywords**

Health impact assessment, greenspace, blue space, Normalized Difference Vegetation Index, NDVI, urban nature

*When you submit an article, you will be asked to supply some keywords relevant to your work. If your article is accepted for publication, we will display these keywords on the published article, and they will be used to index your article, helping to make it more discoverable. When choosing keywords, think about the kinds of terms you would use when searching online for related articles.*

**Abstract**

Your abstract should give readers a brief summary of your article. It should concisely describe the contents of your article, and include key terms (especially in the first two sentences, to increase search engine discoverability). It should be informative, accessible and not only indicate the general aims and scope of the article, but also state the methodology used, main results obtained and conclusions drawn. The abstract should be complete in itself; it should not contain undefined acronyms/abbreviations and no table numbers, figure numbers, references or equations should be referred to. Articles relying on clinical trials should quote the trial registration number at the end of the abstract. The abstract should be suitable for direct inclusion in abstracting services and should not normally be more than 300 words. If you submit an article with an abstract longer than 300 words, we may rescind the manuscript and ask you to re-write it. Some journals ask for abstracts to follow a particular structure. Check the [instructions for specific journals](https://publishingsupport.iopscience.iop.org/journals/) to see if you need to submit a structured abstract.

**Introduction**

*This should be concise and describe the nature of the problem under investigation and its background. It should also set your work in the context of previous research, citing relevant references. Introductions should expand on highly specialised terms and abbreviations used in the article to make it accessible for readers.*

Over half of the world’s population lives in cities and this share is predicted to grow to two-thirds by 2050 1.Urbanization has been accompanied by the pollution of natural resources and destruction of natural environments. It is estimated that cities are responsible for over 80% of global greenhouse gas emissions 2. Although cities are the biggest contributors to climate change, they can also be effective entities of change. Cities can provide a large enough scale to create meaningful change while remaining small enough to test policies that might not be feasible at a national scale. City-level interventions to increase urban nature offer a climate adaptation strategy with health advantages.

Urban nature, including green (e.g. parks, tree-lined streets) and blue (e.g. coasts, rivers) space, has been linked to both improvements in health and climate resilience. Greenspace is associated with improved mental and physical health, including reduced all-cause mortality 3. While less studied, blue space has also been linked to improved health4. Urban nature is also associated with beneficial environmental outcomes such as better storm water management and heat regulation, increased biodiversity, and reductions in air pollution and ultraviolet radiation 5–8. Greenspace has generally been the focus of urban nature policies and interventions, as it is more feasible to add than blue space.

The most common metric used to quantify greenspace in the health literature is the normalized difference vegetation index (NDVI)9. NDVI is a satellite-derived measure that uses visible and near infrared light to quantify the density of vegetation. NDVI ranges from -1 to 1, with negative values indicating water, snow, and ice, values near zero representing limited vegetation (e.g. urban areas, barren land), and positive values signifying vegetation.10 Two large-scale health impact assessments have estimated the number of deaths associated with hypothetical changes in greenspace. A 2021 study of 978 cities in 31 European countries found that if cities were to increase their NDVI to a level equivalent with the World Health Organization’s recommendation of universal access to greenspace, 42,968 natural deaths could be avoided annually (95% CI: 32,296, 64,177) among adults 11. A 2022 study of the 35 most populous American cities found that if NDVI was increased by 0.1, 38,000 deaths (95% CI: 28,640-57,281) could have been avoided in 2019 among those 65 and older 12. These studies provide a useful quantification of the potential health benefits of increasing urban nature but are limited to European and American contexts.

In 2020, The Lancet Countdown began tracking urban greenspace across a global set of cities. The Lancet Countdown is an annual publication dedicated to tracking progress towards the goals of the Paris Agreement and documenting the health implications of climate change.13 We use the Lancet Countdown’s estimates of urban greenspace to conduct a health impact assessment of the excess or avoided deaths associated with changes in greenspace over time across 1,042 global cities. While the climate resiliency benefits of increasing urban greenspace are dependent on extreme weather event, the health benefits of such policies are more fixed. Quantifying the health benefits can therefore serve as an impetus to increase greenspace, as these advantages have a more immediate and certain pay-off.

**Methods**

*This section should provide sufficient details of the experiment, simulation, statistical test or analysis carried out to generate the results such that the method can be repeated by another researcher and the results reproduced.*

We estimated urban greenspace in terms of NDVI and the percentage of green and green or blue space in 1,042 cities across 174 countries. We then conducted a quantitative health impact assessment of the change in mortality in each of these cities associated with changes in NDVI from 2015 to 2020 and 2015 to 2023. We used the Global Human Settlement Urban Centre Database (GHS-UCDB) to define urban extents. These spatial bounds are determined using a consistent methodology based on population and remote sensing data.14 Cities were included if they were the most populous in their country or had over 500,000 inhabitants. Due to missing data in the GHS-UCDB or NDVI datasets, 22 countries were not represented in the analysis.

*Greenspace Exposure*

The 2023 Lancet Countdown reported four greenspace exposure metrics for 2015 and each subsequent year since 2020. These metrics included: the maximum seasonal NDVI value (peak NDVI), the four-season average NDVI value, the population-weighted maximum seasonal NDVI value, and the population-weighted four-season average NDVI. Additionally, we estimated the percent greenspace and percent green or blue space in 2015 and 2020 for each of the included cities.

NDVI estimates were derived from Landsat 8 satellite imagery, which we accessed through Google Earth Engine (GEE). Landsat is a joint mission of the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) and is available at the 30m resolution with new images approximately every 16 days. We first removed cloudy images using the “Landsat.simpleComposite” algorithm from GEE. In an update to the Lancet Countdown’s methodology, we then used the Joint Research Commission’s dataset to mask pixels that were classified as permanent water. This dataset aligns spatially with our urban greenspace estimates, as it is a Landsat-derived product. We used the 2015 dataset to mask water pixels in our 2015 greenspace estimates and the 2020 dataset to mask water pixels in our 2020 and 2023 estimates. Previously, all NDVI pixels with negative values had been set to 0, which affected in a mix of water and urban areas. We then calculated seasonal-NDVI averages for the following time periods (with labels based on the northern hemisphere):

* Winter- December 1 of the previous year through February 28
* Spring- March 1 through May 31
* Summer- June 1 through August 31
* Fall- September 1 through November 30.

The percent green and green or blue space metrics were calculated from NASA’s Modis satellite, which we also accessed through GEE. This dataset is available yearly and provides various landcover classifications for each 500m pixel. We used the Annual University of Maryland (UMD) classification. We first created binary indicators of greenspace, which included pixels classifies as forests, shrublands, savannas, grasslands, and croplands, and green or blue space, which included these categories as well as waterbodies and permanent wetlands. We then took the average over the urban boundary to arrive at a city-level estimate of percent greenspace and green or blue space.

For the health impact assessment, we use the population-weighted greenest season NDVI value, in line with several large epidemiologic cohort studies.15–17

*Health Impact Assessment*

*Relative Contribution of Health Impact Assessment Inputs*

average NDVI; population-weighted peak NDVI; and population-weighted mean NDVI. The population weighted NDVI was computed for each city by multiplying each NDVI value (peak and four-season average) by the population size of the corresponding year within the same 1x1 km raster, summing up over the weighted values within the urban extent, and dividing by the sum of the weights, as shown by the equation below:

Additional analyses include subsetting the data by levels of the Human Development Index (HDI, see Figure 1), climate regions as defined by the Köppen Climate Classification System (see Figure 2), Lancet Countdown regional country groupings, and WHO region (see Figure 3).(5) Google Earth Engine was used to generate the raw data for analysis. The R Statistical Software was used for data analysis and management and to compute the four metrics described above. We defined ‘Level of Greenness’ according to the table below (Table 1):

Following a similar approach to Brochu et. al 18, we estimated the avoided premature deaths associated with increases in greenspace using a linear health impact function:

Equation 1: ,

where represents the annual change in mortality, for a given city, associated with each incremental change in greenspace. Key inputs include national (or subnational where available) baseline mortality for a given age category i (), grid cell-level population in age category i ( the inverse of the hazard ratio (HR) of the protective association between increased NDVI and all-cause mortality (), and the grid cell-level increase in NDVI ().

We used baseline mortality rates for each five-year age category from 20-24 to 80+ years from the Global Burden of Disease (GBD) 2021 study 19. These data are generally available at the country level, with sub-national estimates for some countries. Population estimates are from WorldPop for five year age categories at the 100m x 100m grid-cell level 20.

For our estimate of the hazard ratio, we first reviewed published multi-national meta-analyses of epidemiological studies examining associations between greenspace and all-cause mortality in urban areas (appendix, p. 2). We identified four meta-analyses and used the pooled hazard ratio derived by Rojas-Rueda and colleagues (32) because it most closely matched our analysis. In particular, this meta-analysis included only low-bias longitudinal studies with consistent definitions of greenspace exposure (NDVI) and included adult populations from seven countries. This study found a pooled hazard ratio of 0.96 (95% confidence interval (CI): 0.94, 0.97) for each 0.1 increase in NDVI within 500m of a person’s home.

While there is one meta-analysis providing a quantitative estimate of the relationship of urban blue space on mortality, it is limited to three studies using different exposure definitions 4 (appendix, p. 3). While evidence suggests that blue space provides similar health benefits as greenspace 21 only a few epidemiological studies explore the relationship between blue space and all-cause mortality. For this reason, we assumed that any increase in NDVI was the result of additional greenspace. This assumption reflects most urban nature policies, which generally aim to increase vegetation as it is often more practical than creating new water bodies.

We assumed a linear health impact function, in line with the meta-analysis from which we derived the hazard ratio and the epidemiological studies included in the meta-analysis. However, some evidence suggests that the exposure-response curve could be non-linear at NDVI values below and above 0.2-0.5, with more uncertain associations outside this range 22. We explored the impact of restricting the health benefits to increases in NDVI within this range in a sensitivity analysis, by separately estimating avoided mortality for different ranges of NDVI. This analysis provides more conservative estimates of expected health benefits from greenspace interventions, as it may be more feasible to increase NDVI within this range, where there is not already dense vegetation or built-up area.

Analysis changes:

* Changed seasonal dates to non-overlapping (i.e. December 1 to Feb 28 instead of Mar 1)
* Changed data set for 1km population from GPW population density to GPW population count
* Changed shape file upload. Old file had two cities (Sao Tome and Male actually pointing to Port Moresby, PNG)
* In old version Sao Tome not in final results file but included in the shapefile upload (renamed Sio TomA in old data for some reason?)
* Landcover- did not mask water in calculation of green area

A 2019 meta-analysis using longitudinal studies of the association between NDVI and all-cause mortality, reported a pooled hazard ratio of 0.96 (95% CI: 0.94-0.97) per 0.1 increase in NDVI within a 500m buffer of a person’s residence 9. This study had the benefit of using solely longitudinal cohort studies with a common exposure definition.

**Results**

The results section should detail the main findings and outcomes of your study. You should use tables only to improve conciseness or where the information cannot be given satisfactorily in other ways such as histograms or graphs. Colour should not be used in tables, if you need to denote different things in a table then you can use bold or italics etc. providing no coloured text or shading is included. Tables should be numbered serially and referred to in the text by number (table 1, etc.). Each table should have an explanatory caption which should be as concise as possible.

1. Map with pop-weighted NDVI
   1. Side panel with %green/blue/urban maybe by region

**Discussion**

*This should discuss the significance of the results and compare them with previous work using relevant references.*

* RR for 20+ adults but all pop included here
* Limits of NDVI and satellite data

**Conclusion**

*This section should be used to highlight the novelty and significance of the work, and any plans for future relevant work.*

**Acknowledgements**

*Check the*[***peer review model***](https://publishingsupport.iopscience.iop.org/questions/peer-review-models-on-iop-journals/)*for the journal you are submitting to when preparing the PDF version of your manuscript. If****double-anonymous****then do not include any author names or institution information in the Acknowledgements section of your manuscript. Author names and Funding information should be removed and can be re-added later in the peer review process. For****single-anonymous****please include an acknowledgements section before the References section in your PDF manuscript.*

*During the submission process all authors and co-authors are required to disclose any potential conflict(s) of interest when submitting an article (e.g. employment, consulting fees, research contracts, stock ownership, patent licences, honoraria, advisory affiliations, etc). This information should be included in an acknowledgements section at the end of the manuscript (before the references section). All sources of financial support for the project****must****also be disclosed in the acknowledgements section. The name of the funding agency and the grant number should be given, for example: This work was partially funded by the National Institutes of Health (NIH) through a National Cancer Institute grant R21CA141833. When completing the online submission form, we also ask you to select funders and provide grant numbers in order to help you meet your funder requirements. We encourage authors to use the acknowledgements section of the article to make specific attributions of author contribution and responsibility, otherwise all co-authors will be taken to share full responsibility for all of the paper.*

**References**

*This section should be used to list all relevant work.*[***More information on referencing***](https://publishingsupport.iopscience.iop.org/questions/references/)*. However, check the*[***peer review model***](https://publishingsupport.iopscience.iop.org/questions/peer-review-models-on-iop-journals/)*for the journal you are submitting to. If****double-anonymous****then when referring to thesis/unpublished work, please avoid identifying information. You should include non-identifiable information e.g. journal name, year etc...*

*If you need more information or guidance about any of the above then please*[***contact the journal***](https://publishingsupport.iopscience.iop.org/journals/)*to which you are submitting.*

1. Alex Baeumler, Olivia D’Aoust, Maitreyi Das, et al. *Demographic Trends and Urbanization*. World Bank; 2021.

2. Hoornweg D, Sugar L, Gomez CLT. Cities and Greenhouse Gas Emissions: Moving Forward. *Urbanisation*. 2020;5(1):43-62. doi:10.1177/2455747120923557

3. Yang BY, Zhao T, Hu LX, et al. Greenspace and human health: An umbrella review. *The Innovation*. 2021;2(4):100164. doi:10.1016/j.xinn.2021.100164

4. Smith N, Georgiou M, King AC, Tieges Z, Webb S, Chastin S. Urban blue spaces and human health: A systematic review and meta-analysis of quantitative studies. *Cities*. 2021;119:103413. doi:10.1016/j.cities.2021.103413

5. Brückner A, Falkenberg T, Heinzel C, Kistemann T. The Regeneration of Urban Blue Spaces: A Public Health Intervention? Reviewing the Evidence. *Front Public Health*. 2022;9:782101. doi:10.3389/fpubh.2021.782101

6. Hunter RF, Cleland C, Cleary A, et al. Environmental, health, wellbeing, social and equity effects of urban green space interventions: A meta-narrative evidence synthesis. *Environment International*. 2019;130:104923. doi:10.1016/j.envint.2019.104923

7. Wolf KL, Lam ST, McKeen JK, Richardson GRA, Van Den Bosch M, Bardekjian AC. Urban Trees and Human Health: A Scoping Review. *IJERPH*. 2020;17(12):4371. doi:10.3390/ijerph17124371

8. Ampatzidis P, Cintolesi C, Kershaw T. Impact of Blue Space Geometry on Urban Heat Island Mitigation. *Climate*. 2023;11(2):28. doi:10.3390/cli11020028

9. Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. *Lancet Planet Health*. 2019;3(11):e469-e477. doi:10.1016/S2542-5196(19)30215-3

10. NASA Earth Observatory. Measuring Vegetation: Normalized Difference Vegetation Index (NDVI). August 30, 2000. Accessed October 6, 2022. https://earthobservatory.nasa.gov/features/MeasuringVegetation/measuring\_vegetation\_2.php

11. Barboza EP, Cirach M, Khomenko S, et al. Green space and mortality in European cities: a health impact assessment study. *The Lancet Planetary Health*. 2021;5(10):e718-e730. doi:10.1016/S2542-5196(21)00229-1

12. Brochu P, Jimenez MP, James P, Kinney PL, Lane K. Benefits of Increasing Greenness on All-Cause Mortality in the Largest Metropolitan Areas of the United States Within the Past Two Decades. *Front Public Health*. 2022;10:841936. doi:10.3389/fpubh.2022.841936

13. Romanello M, Napoli C di, Green C, et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *The Lancet*. 2023;402(10419):2346-2394. doi:10.1016/S0140-6736(23)01859-7

14. Freire S, Schiavina M, Corbane C, et al. GHS-UCDB R2019A - GHS Urban Centre Database 2015, multitemporal and multidimensional attributes. Published online January 28, 2019. doi:10.2905/53473144-B88C-44BC-B4A3-4583ED1F547E

15. Nieuwenhuijsen M, Gascon M, Martinez D, et al. Air Pollution, Noise, Blue Space, and Green Space and Premature Mortality in Barcelona: A Mega Cohort. *IJERPH*. 2018;15(11):2405. doi:10.3390/ijerph15112405

16. Crouse DL, Pinault L, Balram A, et al. Urban greenness and mortality in Canada’s largest cities: a national cohort study. *The Lancet Planetary Health*. 2017;1(7):e289-e297. doi:10.1016/S2542-5196(17)30118-3

17. Zijlema WL, Stasinska A, Blake D, et al. The longitudinal association between natural outdoor environments and mortality in 9218 older men from Perth, Western Australia. *Environment International*. 2019;125:430-436. doi:10.1016/j.envint.2019.01.075

18. Brochu P, Jimenez MP, James P, Kinney PL, Lane K. Benefits of Increasing Greenness on All-Cause Mortality in the Largest Metropolitan Areas of the United States Within the Past Two Decades. *Front Public Health*. 2022;10:841936. doi:10.3389/fpubh.2022.841936

19. Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2019 (GBD 2019) Reference Life Table. Published online 2021. doi:10.6069/1D4Y-YQ37

20. WorldPop. Population Counts 2020 UN-Adjusted Constrained 1 Available from: www.worldpop.org/doi/10.5258/SOTON/WP00660.

21. Georgiou M, Morison G, Smith N, Tieges Z, Chastin S. Mechanisms of Impact of Blue Spaces on Human Health: A Systematic Literature Review and Meta-Analysis. *IJERPH*. 2021;18(5):2486. doi:10.3390/ijerph18052486

22. Labib SM, Lindley S, Huck JJ. Nonlinear associations between urban greenness exposures and neighborhood level years of potential life lost: A study in Greater Manchester. *Science Talks*. 2023;6:100218. doi:10.1016/j.sctalk.2023.100218

**Figures**

Carefully chosen and well-prepared figures, such as diagrams and photographs, can greatly enhance your article. You are encouraged to prepare figures that are clear, easy to read and of the best possible quality and resolution.

To make your figures accessible to as many readers as possible, try to avoid using colour as the only means of conveying information. For example, in charts and graphs use different line styles and symbols. Where colours are used try to ensure that:

* there is good contrast between adjacent colours;
* colours are distinguishable if the figure is converted to greyscale;
* different line styles, fill styles, symbols or labels are used in addition to different colours.

We accept that it is not always possible to follow these guidelines, for example with figures that use colour gradient scales to convey information, or for photographic images. As with all figures, it is important to use the figure caption to describe the information conveyed by the figure. See below for further details.

Figures are converted and sized to the journal template as part of the production process for accepted articles, but they are not normally edited further. It is your responsibility to ensure that the figures you supply are legible and technically correct.  
Characters should appear as they would be set in the main body of the article. Aim for text sizes of 8 to 12 pt at the final figure size: typically 8.5cm for a small/single-column figure and 15cm for a large/double-column figure. Micrographs should include a scale bar of appropriate size, e.g. 1 μm. Figures should be numbered in the order in which they are referred to in the text, using sequential numerals (e.g. figure 1, figure 2, etc.).

If there is more than one part to a figure (e.g. figure 1(a), figure 1(b), etc.), the parts should be identified by a lower-case letter in parentheses close to or within the area of the figure.

**File types**

For articles prepared using LaTeX2e, please make sure that your figures are all supplied as vector Encapsulated PostScript (EPS) and linked to your main TeX files using appropriate figure inclusion commands such as \includegraphics. For articles prepared using Word, where possible please also supply all figures as separate graphics files (in addition to being embedded in the text). Our preferred graphics format is EPS. These files can be used directly to give high-quality results, and file sizes are small in comparison with most bitmap forms.  
If you are unable to send us images in EPS, we can also accept:

* TIFF
* JPEG
* PDF (and images embedded within PDF files)
* Images/drawings coded using TeX/LaTeX package
* Images/figures embedded in MS Word, Excel or PowerPoint
* Graphics application source files (Photoshop, Illustrator, CorelDraw).

**Vector formats**

The advantage of vector graphics is that they give the best possible quality at all output resolutions. In order to get the best possible results, please note the following important points:

* Fonts used should be restricted to the standard font families (Times, Helvetica, Courier or Symbol).
* Certain proprietary vector graphics formats such as Origin, Kaleidagraph, Cricket Graph and Gnu Plot should not be sent in their native format. If you use these applications to create your figures, please export them as EPS.

**Figure captions**

Captions should be included in the text and not in the graphics files. Figure captions should contain relevant key terms and be self-contained (avoiding acronyms) so that a reader can understand the figure without having to refer to the text. To make your figures accessible to as many readers as possible, include the main points that the figure demonstrates in the caption. We provide further information and examples on [**this page**](https://publishingsupport.iopscience.iop.org/questions/example-figures/).