**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.

City leaders have limited resources and must make decisions about how best to allocate them to improve the health and well-being of their constituents. We compare the health burden associated with a lack of urban greenspace to that of air pollution from particulate matter, ozone, and nitrogen dioxide to add context to the relative importance of greenspace as an environmental health risk factor. Our analysis quantifies changes in urban greenspace over time across a global set of cities. The results of this study can be used to compare greenspace across cities and over time as well as to make health-centered decisions about how to allocate resources to mitigate urban environmental hazards.

**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 peak 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 (JRC)’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.

*Health Impact Assessment*

We estimated the annual change in premature deaths (either excess or avoided) associated with changes (decreases or increases) in urban greenspace using a linear health impact function:

Equation 1: ,

where represents the annual change in mortality for a given city. We estimated the change in mortality using country-level baseline mortality (), pixel-level population ( the inverse of the hazard ratio (HR) of the protective association between increased NDVI and all-cause mortality (), and grid cell-level changes in NDVI ().

We used country-level baseline mortality estimates from the Global Burden of Disease (GBD) 2021 study 19. We used the 2015 estimates for 2015 and the 2020 estimates for 2020 and 2023. We used 100m pixel-level population estimates from JRC, which we accessed through GEE20. While the Lancet Countdown has previously used 1km estimates from the Global Population of the World, we opted to use a dataset whose resolution more closely aligned with our exposure estimates. Our estimate of the hazard ratio came from a 2019 meta-analysis of longitudinal studies of the association between NDVI and all-cause mortality derived by Rojas-Rueda and colleagues.9 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. Finally, we used the difference in population-weighted peak NDVI values between 2015 and 2020 and 2015 and 2023 to define changes in urban greenspace. This exposure definition most closely aligned with meta-analysis we used for the HR. Several of the large cohort studies included in this study defined greenspace using the average NDVI value in the greenest season.15–17 The population weighted peak-season NDVI was calculated for each city according to the following equation:

Equation 2: .

The average peak-season NDVI value in pixel i (NDVIi)was multiplied by the population in the corresponding pixel for that year (populationi). These values were summed across all pixels within the urban boundaries and divided by the total city population for that year.

Depending on what groupings use introduce:

Development Index, Köppen Climate Classification System, Lancet Countdown groupings, country groupings, and or WHO regions

*Relative Contribution of Health Impact Assessment Inputs*

Description of how we apportioned changes in mortality to changes in pop, changes in NDVI, and changes in baseline mortality--- not included would be changes to distribution of greenspace/population, and changes to age structure (par to changes in baseline mortality

AND/OR

*The Health Burden of Urban Environmental Risk Factors*

Compare lack of urban greenspace as risk factor relative to PM2.5 and ozone from 2015-2020?

* Some weirdness b/c air pollutants have a counterfactual while NDVI can only be compared to itself so comparison might need to be 2015 v. 2020 how have they changed as risk factors over time or .1 increase in NDVI v. x ppb decrease in air pollutant
* Pm2.5 is a 6 different outcome combined mortality, ozone chronic resp mortality, and ndvi all-cause (possibly ok if only pathways to mortality for pm2.5 and ozone are those included?)
* Possible to figure out deaths per some decrease in air pollutant from info provided?

**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.*

*A map of the world

Description automatically generated*

***Figure 1.*** *2023 population-weighted peak NDVI.*

* I think this should be a multi-panel figure with either: a panel below showing green area. Possibly a pie chart by LCD region or level of urban greenness? Or it could show pop-weighted NDVI over time. Maybe 2015 in this scale and then 2020 and 2023 are %diff shown in red for decreasing and green for increasing?

***Figure 2.*** *Green and blue area. Can’t get data to appear yet, but was thinking something like the below (or like restriction graphs from HIA paper but summing to 100%) showing green, blue, and urban/non-vegetated area probably for each region or could do multipanel by region with each city.*A graph showing the number of people in the market

Description automatically generated with medium confidence

***Figure 3.*** *Annual all-cause change in mortality associated with changes in NDVI.*

Either per 100,000 shown on map colored by certain ranges and show 2020-2015 difference and 2020-2023 difference or if just pick one comparison time-frame then maybe per 100,000 and absolute shown

**Figure 4.** compare greenspace as environmental hazard to PM2.5 and ozone

Possibly 2 panels: 1 showing just 2020 values. Side by side or stacked bar of annual deaths from three sources by region or by HDI level (for air pollutants from recommended to observed levels for NDVI per .1 increase)

Second panel showing relative change 2015 v 2020 in deaths from that cause i.e. is it a worsening or improving risk factor

**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. 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

6. 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

7. 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

8. 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

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. 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

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

17. 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

18. 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

19. 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

20. 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

21. 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

**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/).