**Target Journal: Environmental Research Letters**

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**Title**

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

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**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

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**Keywords**

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

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**Introduction**

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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

*Sensitivity Analysis*

Compare 3-year avg (2014-2016) v. (2019-2021) to 2015 v. 2020 result from main paper

*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

**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.*

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

* 2015 pop, 2020 % diff, 2023 % diff show in opposite colors (color-blind friendly)

***Figure 2.*** *Green and blue area. Organize by pop size w/in region, by HDI see if any trends appear, if not could be multi-panel by region*

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

Multi-panel: per 100,000 results. Panel A: 2020 v 2015 using 2015 for pop and mort

Panel B: 2023 v 2020 using 2020 for pop and mort

**Figure 4.** breakdown contributing factors

Look at Veronica’s PM paper--- avg across cities in each region (line graphs with trend for population,

A graph with different colored squares

Description automatically generated

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
* A few sentences comparing rate of change of NDVI v. pollutants to PM2.5/ozone

**Conclusion**

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

**Acknowledgements**

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