**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**

*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 and blue area 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*

We used NDVI derived from Landsat 8 satellite imagery to quantify urban greenspace. Landsat images are publicly available through Google Earth Engine (GEE) at the 30m resolution approximately every 16 days. We first calculated seasonal-NDVI 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

*Health Impact Assessment*

*Relative Contribution of Health Impact Assessment Inputs*

We did this for five different years: 2015, 2020, 2021, 2022, and 2023. Landsat 8 (2015, 2020, 2021) and Landsat 9 (2022, 2023) were used to estimate values for the included years. For each year and city, a total of four exposure metrics were calculated: peak NDVI (maximum NDVI across the four seasons); annual mean NDVI based on the four-season 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 16, 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 17. 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 18.

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 19 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 20. 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 handling of negative NDVI values
  + JRC global surface water data set to mask water pixels (2015 and 2020)
    - Used just permanent water not seasonal water
  + Left remaining negative pixels (urban areas) as is
* 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**

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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/advantages 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**

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