### **Abstract of Dissertation**

Quantifying urban nature and the associated health benefits across global cities using high-resolution satellite imagery

**Background:** Epidemiologic literature links urban green (e.g. parks, tree-lined streets) and blue (e.g. coasts, rivers) space to improved mental and physical health. Increasingly, cities are expanding urban nature for its health and climate resiliency benefits. Despite interest in urban nature interventions, gaps remain in measuring nature exposure and linking policy goals to expected health benefits.

**Methods:** We used high-resolution satellite imagery from the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), accessed through Google Earth Engine, to quantify urban nature across a global set of cities. We first addressed the incompatibility between scientific measures and real-world policies by quantifying the 2020 urban nature extent and distribution across the 96 C40 Climate Leadership Cities and their 2030 urban nature targets in terms of the Normalized Difference Vegetation Index (NDVI). Next, we estimated the associated health benefits of incremental progress towards these targets across the 96 cities, by combining our exposure metrics with baseline mortality data from the Global Burden of Disease study and gridded population data. Finally, we assessed urban nature levels across 1,041 global cities from 2014 to 2023, and estimated changes in mortality associated with changes in NDVI over time.

**Results**: We found that global cities vary greatly in their extent, distribution, and type of urban nature. We estimated a mean greenest pixel NDVI across the 96 C40 cities of 0.538 (range: 0.148, 0.739). After converting the C40 2030 urban nature targets to the NDVI scale, we found that approximately 80% of C40 cities already meet at least one target, and almost 50% meet both. We quantified the potential reductions in mortality associated with incremental progress towards the two C40 targets. We found that if cities were to increase greenspace uniformly across their urban extents by 1%, in accordance with the first C40 target, a median of 1.74 (range: 0.63, 3.44) annual premature deaths per 100,000 could be averted. Increasing the population percentage with nearby green or blue space by 1%, mirroring the second target, was associated with a median of 0.55 (range: 0.11, 1.66) fewer annual deaths per 100,000. Adding greenspace in areas with the least amount of nature and the greatest density of population provide 1.4-1.7 times (depending on the target) and 2.7 times the health gains, respectively, compared to uniform increases. We observed large variation in greenest-season NDVI across cities (mean: 0.270, range: 0.072, 0.580), related to region and climate classification. While city greenspace has remained relatively constant from 2014-18 to 2019-23, it has changed by over 20% in individual cities. We estimated that on average, across 1,041 global cities, changes in NDVI over these two periods were associated with 5.04 (95% CI: 4.64, 5.19) additional deaths per 100,000 annually, ranging from 569.84 fewer to 521.82 more deaths per 100,000 across cities.

**Discussion:** This work addresses the lack of interoperability between the health literature and urban nature policies by providing a framework for measuring urban nature targets on the NDVI scale. We use these translations to quantify the health benefits of expanding urban greenspace across a global set of cities. We find that where urban greenspace is added has important implications for the magnitude of the associated health benefits. Adding greenspace near population centers provides the greatest health impact. We found substantial inter-annual variation in greenest-season NDVI which would suggest that efforts to increase urban nature may be partially masked or exaggerated by climate patterns. Our work supports existing literature in finding that increasing urban greenspace can be beneficial to climate mitigation and human health and highlights the limitations of NDVI as a measure for capturing the effect of urban greenspace interventions.

**Chapter 1: Introduction**

*Nature and health*

Psychological theory, experimental evidence, and observational studies support a relationship between exposure to nature and improved human health. Edward O. Wilson’s biophilia hypothesis states that humans have an instinctive affinity for natural environments and other living organisms. He suggests that humans have strong biological responses to nature that are based in evolution, including phobias towards poisonous animals and attraction to green and blue spaces, representing food, water, and shelter (E. O. Wilson, 1984). The attention restoration theory states that nature provides therapeutic effects against mental fatigue and stress (Kaplan & Kaplan 1989). Experimental evidence back these theories. Participants have shown consistent preference for natural scenes (Stephen Kaplan & Rachel Kaplan, 1989). In studies where participants were randomized to view images of nature or with human influence, those shown images of water and vegetation had improved emotional states, decreased heart rates, and decreased blood pressure (Ulrich, 1981).Even a window view of nature showed improved productivity and well-being among workers (Kaplan, 1993) and faster recovery post-surgery among patients (Ulrich, 1984).The results of these experimental studies are important because they demonstrate that there are beneficial properties of nature beyond its functionality.

Markevych and colleagues define three domains linking greenspace and health: reducing environmental harm (i.e. less heat, noise, and air pollution), restoring capacities (i.e. improved restoration and reduced stress), and building capacities (i.e. increased physical activity and social gathering) (Markevych et al., 2017). Exposure to urban blue space parallels greenspace in its hypothesized mechanisms of action, including increased social interaction, restoration (e.g. a reduction in stress, anxiety, depression, etc.), environmental factors, and physical activity (Georgiou et al., 2021). A few studies have tested these causal pathways and found evidence that greenspace is associated with health through better air quality, increased physical activity, and reduced stress (Zhang et al., 2021) and that the relationship between green and blue spaces and health is mediated through increased physical activity and social contact (Elliott et al., 2023). Observational studies have found that nature exposure mediates health through its role in climatic processes and human activities and supports experimental evidence that there is a direct health benefit to viewing nature through restoration.

*Population exposure to urban nature*

Rapid industrialization and urbanization over the past century has raised the share of the world’s population living in cities from less than a third in 1950 to more than half in present day, and this proportion that is predicted to increase to two-thirds by 2050 (Alex Baeumler et al., 2021; Leon, 2008). This demographic shift has resulted in less contact with nature. The switch from natural to manmade environments has increased other environmental hazards, including air pollution, the urban heat island effect, flooding, and species loss, hazards mitigated by urban nature (Ampatzidis et al., 2023; Brückner et al., 2022; Hunter et al., 2019; Wolf et al., 2020). Due to nature’s beneficial effects on health and role in mitigating other environmental exposures, urban policies to expand nature have become more commonplace.

In 2017, the World Health Organization recommended a minimum of 0.5 hectares (5,000 square meters) of public greenspace be available within 300m of a person’s home (Urban Green Spaces: A Brief for Action, 2017). In 2021, 31 mayors from the C40 Climate Leadership network, a group of approximately 100 cities committed to reducing greenhouse gas emissions, signed an Urban Nature Declaration, setting two 2030 targets: (1) “30-40% of urban built-up area will be greenspace or other permeable surface”, and (2) “70% of residents will have access to public green or blue space within a 15-minute walk or bike” (C40 cities, 2021). In addition to these larger entities, numerous individual cities have made commitments to expanding urban nature. For example, Philadelphia has set a goal of achieving 30% tree canopy cover by 2025 (Kondo et al., 2020), London has pledged to become the first “national park city”, with half of its area designated as greenspace (*London Environment Strategy*, 2018), and Medellín undertook a Green Corridors project, planting trees along 20km of roads and waterways to reduce pollution and the urban heat island effect (C40 Cities Climate Leadership Group, Nordic Sustainability, 2019).

*Measuring urban nature*

A growth in observational studies of urban nature and population health has paralleled interest in urban nature policies. Broadly, the literature has focused on greenspace and to a lesser extent, blue space. The most common metrics used to quantify greenspace in the epidemiologic literature are the satellite-derived normalized difference vegetation index (NDVI) and land cover maps. Because chlorophyl, a green pigment found in plant leaves, absorbs visible light (VIS) for photosynthesis and plant cell structures reflect near-infrared (NIR) light, the combination of these wave lengths can be used to differentiate not only greenspaces from other surfaces but also the health and density of vegetation using satellite imagery (“NASA Earth Observatory,” 2000). NDVI is calculated as (NIR-VIS)/(NIR +VIS) and ranges from -1 to 1. Values near zero represent no vegetation (e.g. urban areas, dirt), while negative values are usually clouds, water, snow, or ice. Higher values indicate healthier, denser vegetation.

Generally, studies have used the average greenest-season NDVI within a geographical or administrative boundary or within a certain buffer of the target population. The advantage of NDVI as a measure of greenspace is that there is global coverage on a fine spatial and temporal scale. The main limitation of NDVI is that it does not provide information on the type of greenspace, nor its accessibility or quality. Land cover datasets, on the other hand, classify pixels by type, such as forest, crop land, or urban. However, because they provide a discrete classification, they can miss smaller scale urban greenspaces such as tree-lined streets or small parks. Additionally, they are updated less frequently. Studies using land cover maps to define greenspace generally calculate the percentage of green area within a geographic or administrative area.

The literature on blue space is less established. Epidemiologic studies of blue space exposure have employed a wide range of metrics. In a systematic review of 50 studies on the relationship between blue space and health, 17 different measures of blue space were used (Georgiou et al., 2021). Some of these exposure metrics included the presence of blue space within in various buffers of a person’s home, residential proximity to a coastline, the percentage of blue space in a certain geographic or administrative area, measures of activity near water from personal monitors or self-report, self-reported accessibility, frequency of visitation, or proximity to water, and satellite-derived measures such as the normalized difference water index (NDWI). Studies exploring combined exposure to green and blue spaces tend to use land cover datasets (de Keijzer et al., 2019; Gascon et al., 2018; Kabisch et al., 2019; Nieuwenhuijsen et al., 2018).

*Quantifying association between urban nature and all-cause mortality*

There are four quantitative meta-analyses of the association between urban greenspace and all-cause mortality. Two such studies from 2017 and 2018 use a mix of greenspace exposure metrics, including landcover datasets and NDVI. Gascon et al. include 11 studies (from North America (N=5), Europe (N=5), and Oceania (N=1)) and report a risk ratio of 0.92 (95% confidence interval (CI): 0.87, 0.97) between areas with greenspace in the high compared to low end of the interquartile range of greenspace (Gascon et al., 2017). Twohig-Bennett & Jones estimated a pooled all-cause mortality hazard ratio of 0.69 (95% CI: 0.55, 0.87) between people living in the top and bottom quintile of greenspace (Twohig-Bennett & Jones, 2018). This meta-analysis included 143 studies from 20 different countries, mainly from Europe (~50%) and Japan ~17%). More recent meta-analyses have used NDVI to quantify urban greenspace. Rojas-Rueda et al. (2019) included only longitudinal studies of the association between NDVI and all-cause mortality, reporting 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 (Rojas-Rueda et al., 2019). The studies in this meta-analysis were similarly skewed towards North America (N=4) and Europe (N=3), with one study each from Australia and China. Finally, Yuan et al. conducted a meta-analysis of all-cause mortality among older adults (mean age of 60) and estimated a poled hazard ratio of 0.99 (0.97, 1.00) per 0.1 increase in NDVI (Yuan et al., 2021). This analysis was based on eight cohort studies from North America (N=3), Europe (N=2), Japan, Australia, and China. We use the risk estimate from Rojas-Rueda et al. because it uses a consistent exposure definition, includes only low-bias longitudinal studies, and has a more inclusive population definition than that of Yuan et al.

Only one meta-analysis reported a quantitative estimate of the association between urban blue space and all-cause mortality. Smith et al. found a protective effect of blue space within 500m of a person’s residence on all-cause mortality, with a pooled hazard ratio of 0.99 (95% CI: 0.97, 1.00) (Smith et al., 2021). This estimate was based on three studies, all using different metrics of blue space. Given the lack of a robust exposure-response function for urban blue space, we have focused on quantifying the health benefits of efforts to expand greenspace.

*Health impact assessments of urban greenspace and all-cause mortality*

There are large, multi-city health impact assessments of urban greenspace and all-cause mortality. A 2021 health impact assessment estimated the number of deaths associated with insufficient exposure to greenspace across 978 European cities (Barboza et al., 2021). The authors found that if these cities were to meet 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 aged 20 and over (Barboza et al., 2021). A 2021 health impact assessment in the 35 most populous American cities found that 38,000 deaths (95% CI: 28,640-57,281) among those 65 and older could have been avoided in 2019 if NDVI was increased by 0.1 (Brochu et al., 2022).

*Motivation and objectives*

Epidemiologic studies of urban natural space and health have largely remained removed from real-world policy goals. The most widely used exposure-response function estimates risk using increases in NDVI, while most urban nature goals do not. Polices and initiatives to expand urban nature tend to frame greenspace in more relatable terms. Many urban nature goals address how people interact with green and blue spaces, for example the availability and accessibility of nearby parks, expanding networks of walking and biking paths, or increasing tree canopy cover for shade. These policies are not easily expressed with NDVI, making it challenging to quantity their associated health benefits. Additionally, epidemiologic studies and health impact assessments of urban nature and health have largely been conducted in American and European settings. Less is known about the health impact of expanding greenspace in other regional contexts, which tend to be less green.

In this work we aim to address key gaps in the greenspace literature by:

1. Providing a framework for converting extent- and access-based urban nature policies into NDVI terms, so that their health benefits may be estimated.
   1. We estimate city-level baseline nature in terms of the C40 Climate Leadership Network’s two Urban Nature Declaration targets.
   2. We then estimate the relationship between these targets and NDVI for each of its 96 member cities, representing 48 countries across all major world regions.
2. Estimating the reduction in all-cause mortality associated with incremental progress towards the C40 Urban Nature Declaration targets.
   1. We explore the effect of three different spatial allocation of greenspace to better inform resource allocation.
3. Quantifying urban nature over the past decade across a global set of 1,041 cities and estimating the change in mortality associated with trends in greenspace over time.
   1. We provide estimates of the health benefits and burdens from changes in NDVI across two time periods and reveal regional and climate group trends.

Increasing urban greenspace has the potential to provide benefits to both the climate and human health. Quantifying the local health benefits of urban actions provides salient political leverage.