**Chapter 1: Introduction**

* Short, to the point
* Whats the gap
* How does this research contribute to field
* Synthesis across chapters not paper 1 this paper 2 that etc.
* What does my work contribute?
* What gap does it fill?

*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, which meant a source of 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. Study participants have shown consistent preference for natural scenes (Stephen Kaplan & Rachel Kaplan, 1989). When 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. While many observational studies have found that natural spaces mediate health through their role in climatic processes and human activities, the results of these studies show that there is a direct health benefit to viewing nature.

*Population exposure to urban nature*

There has been rapid industrialization and urbanization over the past century; less than a third of the world’s population lived in cities in 1950 a share that is predicted to be 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, which are all lessened by increasing 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, as well as the fall in nature contact as humans have moved to cities, there has been growing interest in polices to expand urban nature.

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 network, a group of approximately 100 cities committed to reducing greenhouse gas emissions, signed an Urban Nature Declaration, setting two 2030 targets 2030: (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 vegetation 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 use 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). Despite NDVI being the most popular measure to define greenspace, studies where green and blue spaces have been combined tend to use land cover datasets to define their exposure (de Keijzer et al., 2019; Gascon et al., 2018; Kabisch et al., 2019; Nieuwenhuijsen et al., 2018). This approach loses information on finer scale green and blue spaces in urban areas.

*The association between greenspace and all-cause mortality*

Epidemiologic observational studies have found that exposure to greenspace is associated with a range of health benefits. A 2018 systematic review and meta-analysis of exposure to greenspace and health outlined the four main pathways that are hypothesized to link greenspace with health: increased physical activity, increased social interaction, exposure to sunlight, and exposure to microorganisms (Twohig-Bennett & Jones, 2018). The authors also note mitigation of harmful environmental effects, such as the urban heat island effect as well as air and noise pollution. The authors found that increased greenspace was associated with decreased salivary cortisol, heart rate, diastolic blood pressure, and HDL cholesterol, decreased risk of preterm birth, type II diabetes, and cardiovascular mortality, as well as increased incidence of good self-reported health (Twohig-Bennett & Jones, 2018). They also found that greenspace was protective of all-cause mortality (risk ratio: 0.69, 95% CI: 0.55, 0.87) (Twohig-Bennett & Jones, 2018). 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 (Rojas-Rueda et al., 2019). This study had the benefit of using solely longitudinal cohort studies with a common exposure definition. One additional meta-analysis of greenspace and all-cause mortality has been published since the Rojas-Rueda et. al study, however it looked specifically at elderly individuals (Yuan et al., 2021).

*Health impact assessments of urban greenspace policies*

*Gaps in the urban greenspace literature*

*Motivation and objectives*

Exposure to urban blue space parallels greenspace in its hypothesized health benefits and mechanisms of action. While urban blue space has been less studied, a few recent systematic reviews highlight the health benefits of blue space. A 2021 review and meta-analysis delineates four casual pathways: social interaction, restoration (e.g. a reduction in stress, anxiety, depression, etc.), environmental factors, and physical activity (Georgiou et al., 2021). This meta-analysis found that living closer to blue space was associated with increased physical activity, living near large bodies of water was associated with higher levels of physical activity and restoration, visiting blue space more often was associated with increased restoration, and the presence of blue space was associated with beneficial environmental factors (Georgiou et al., 2021). Because they tested each exposure metric (e.g. distance to blue space, quantity of blue space) and hypothesized causal pathway (e.g. physical activity, social interaction) combination separately, they were limited in their statistical power. This reflects the fact that there is still no clear consensus in how blue space should be measured. Seventeen different exposure metrics were used in the 50 included studies of this meta-analysis (Georgiou et al., 2021). Another 2021 systematic review and meta-analysis focused specifically on urban blue spaces and human health. It 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 of which defined blue space with different metrics.

The epidemiologic literature describing the effect of exposure to blue space, and to a lesser extent greenspace, on all-cause mortality suffers from a lack of comparability in exposure definitions. Still, these studies show a consistent positive association between natural space and health. While evidence for greenspace is more robust than that of blue space, both exposures are hypothesized to benefit health through similar mechanisms. In addition to studies quantifying the exposure-response function between greenspace and health, a few recent studies have applied these findings to conduct health impact assessments. A 2021 health impact assessment estimated the number of deaths associated with insufficient exposure to greenspace across 978 cities in 31 European countries (Barboza et al., 2021). The authors found that if these cities met 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 similar health impact assessment of greenness in American cities found that 38,000 deaths (95% CI: 28,640-57,281) among those 65 and older could have been avoided in 2019 across the 35 most populous metropolitan areas of the United States if NDVI was increased by 0.1 (Brochu et al., 2022). To the best of my knowledge, there are no such studies quantifying the avoidable deaths from insufficient exposure to blue space.

These cities provide just a few examples of the myriad ways that cities have expressed urban nature policies in terms of scope, timeline, and measures of progress. Part of the reason for this diversity of policies and metrics is that health studies have not identified a level of exposure to greenspace or natural space that is optimal for human health.

Although cities are the biggest contributors to climate change, they can also be effective entities of change. Hoornweg et al. argue that cities are the ideal players in climate change mitigation and adaptation policy because they are well funded compared to rural areas and can act more swiftly than nations, respond to local needs, and facilitate direct communication between the public and decision makers. They suggest that cities provide a large enough scale to create substantial change while remaining small enough to test policies that might not be feasible at a national scale (Hoornweg et al., 2020). Furthermore, though cities are big consumers broadly, there is large variation across cities as well as within them. Cities have the potential to reduce emissions while maintaining a high standard of living, as urban residents account for less greenhouse gas emissions per capita than their suburban and rural counterparts of similar socioeconomic status (Hoornweg et al., 2020). As the world grapples with addressing climate change without sacrificing quality of life, cities will be an important scale for action and intervention. The C40 network provides an example effective climate policy at the city level. C40 consists of approximately 100 mayors from around the world who have committed to halving their cities’ greenhouse gas emissions within a decade.

Climate actions with co-benefits, or advantages beyond greenhouse gas reductions, are often the most politically salient. Air pollution and a lack of nature are compelling urban issues because they influence both climate change and human health. While the climate benefits of policies aimed at climate change mitigation are geographically dispersed, the health benefits of such policies are often concentrated locally. Because of this, climate mitigation and adaptation policies with health co-benefits tend to be an easier sell. Quantifying these co-benefits can therefore serve as an impetus to climate action, as they provide a more immediate pay-off in terms of health gains and healthcare dollars saved. While the health co-benefits of reducing air pollution have been widely recognized and studied (Thompson et al., 2014; Thurston, 2013; West et al., 2013), there is less information on co-benefits from policies that increase urban green and blue spaces, or natural space.

Urban natural spaces have direct and indirect impacts on human health (Fig. A). Natural spaces have implications for the climate, including reducing the urban heat island effect as well as air, noise, and light pollution, which in turn helps to mitigate related morbidity and mortality (Twohig-Bennett & Jones, 2018). Furthermore, natural spaces provide a physical space for recreational activities, including physical and social activities that benefit health directly through increased exercise and social interaction (Yang et al., 2021). Additionally, such spaces increase the population’s exposure to microorganisms which help to boost the immune system (Yang et al., 2021). Finally, there is an inherent health benefit of viewing and being immersed in natural spaces that protects against psychiatric morbidity, including stress, anxiety, and depression (Stephen Kaplan & Rachel Kaplan, 1989).

There is a growing interest in expanding green and blue (“natural”) spaces in urban areas to enhance climate resiliency by mitigating the effects of extreme weather such as heatwaves and flooding. To date, health impact assessments of urban nature on health have largely focused on American and European cities and been limited to analyses of greenspace. We aim to address the current literature gaps by characterizing both green and blues spaces within the global C40 network of cities and by linking health gains to stated urban policy goals. We will achieve this research objective through three analyses. First, we describe the current state of natural space across C40 cities and convert C40 policy targets into the metric most used in health literature. Second, we conduct a health impact assessment to estimate the reductions in all-cause mortality from reaching C40 urban nature goals. Lastly, we quantify the racial and socioeconomic equity gaps in health outcomes due to differential access to natural space in American C40 cities.

**Aim 1:**

Describe the extent, composition, and distribution of natural space in C40 cities by comparing current natural space to C40’s 2030 Urban Nature Declaration targets. These targets are: 1) Quality Total Cover: “30-40% of total built-up city surface area will consist of green spaces… or permeable spaces”, and 2) Equitable Spatial Distribution: “70% of city population has access to green or blue public spaces within a 15-minute walk or bike ride.”

*Significance and innovation:*

Epidemiologic studies of urban natural space and health have largely remained removed from real-world policy goals and focused solely on greenspace. This study will expand on the existing knowledge base by providing a link from C40 policy targets to the exposure-response function between NDVI and all-cause mortality. Furthermore, it will characterize urban natural space not only in terms of greenspace, but also through a combined measure of green and blue space.

Expected results:

The outcome of this analysis will be city-level mean observed NDVI and modified NDVI (to include blue space) as well as two city-level NDVI targets that are equivalent to meeting each of the C40 targets. These results will demonstrate the large range in urban natural space across our study population, with many cities already in compliance with C40 targets and others far from achieving adequate levels of urban nature. The results will help to motivate cities not in compliance with one or both targets to increase urban nature.

**Aim 2:**

Quantitatively estimate the health benefits, in terms of reductions in annual all-cause mortality, of expanding natural spaces to C40 2030 targets in each of the ninety-six member cities of the C40 network.

*Significance and innovation:*

Health impact assessments quantifying reductions in all-cause mortality from expanding greenspace exist for many American and European cities. This analysis will build on such studies by using natural space targets set by the cities themselves as the counterfactual to increase political buy-in. Furthermore, it will include 96 cities from all global regions rather than focusing on American and European cities, which tend to have some of the highest concentrations of urban natural space globally. Lastly, this research will use the combined metric of blue and greenspace, created in the first paper, to assess the health benefits of expanding access to a broader range of natural spaces. Understanding local health benefits from policies to expand urban nature is important because it provides convincing political leverage. While C40 cities are united in their commitment to reduce greenhouse gas emissions, the environmental benefits of expanding natural space in urban areas are more long term and diffuse than the health benefits of such actions.

Expected results:

The results of this study will be the estimated city-level reductions in annual all-cause mortality from achieving each of the two C40 urban nature targets. These results will stress the substantial health gains that many cities could experience by enacting policies to meet the C40 targets.

While theoretical and observation evidence link nature exposure to health, gaps remain in measuring urban nature. First, water has largely remained apart from studies of urban greenspace, despite many shared mechanisms of action. Second, while NDVI is largely accepted as a measure of urban greenspace due to its fine temporal and spatial resolution, global availability, and ability to capture small scale urban greenspaces, it is limited in its ability to differentiate between many characteristics of greenspace that are important for health. Lastly, there is no consensus on an ideal level of greenspace for human health. This has important consequences for the relevance of urban policy goals as well as the ability to estimate the health benefits of such policies or observed changes in greenspace.