URBAN ENVIRONMENT & SOCIAL INCLUSION INDEX

METRICS FOR SUSTAINABLE AND INCLUSIVE CITIES

The Urban Environmental and Social Inclusion tracks city performance at the intersection of environment and social inclusion

Data-Driven Yale, a joint research initiative between Yale School of Forestry and Environmental Studies and Yale-NUS College

In collaboration with SAMUEL CENTRE FOR SOCIAL CONNECTEDNESS

About Data-Driven Yale

Data-Driven Yale seeks to address critical environmental challenges using cutting edge data analytics and other innovative methods. Launched in 2015, the research group is an interdisciplinary collaboration of policy experts, data scientists, visual designers, and interactive programmers at the Yale School of Forestry and Environmental Studies and Yale-NUS College, Singapore.

About the Samuel Centre for Social Connectedness

The Samuel Centre for Social Connectedness (SCSC), founded by Kim Samuel, works to catalyze innovative strategies to build connectedness within and between communities. Through interdisciplinary and cross-sectoral partnerships, the Centre conducts research, supports programming, convenes learning initiatives, and advocates for inclusive policy change. Its approach is grounded in listening, awareness, and solidarity, with the objective of fostering belonging and a shared sense of humanity.

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METRICS FOR SUSTAINABLE URBAN DEVELOPMENT

The Urban Environment and Social Inclusion Index is a project by Data-Driven Yale, in collaboration with the Samuel Center for Social Connectedness.

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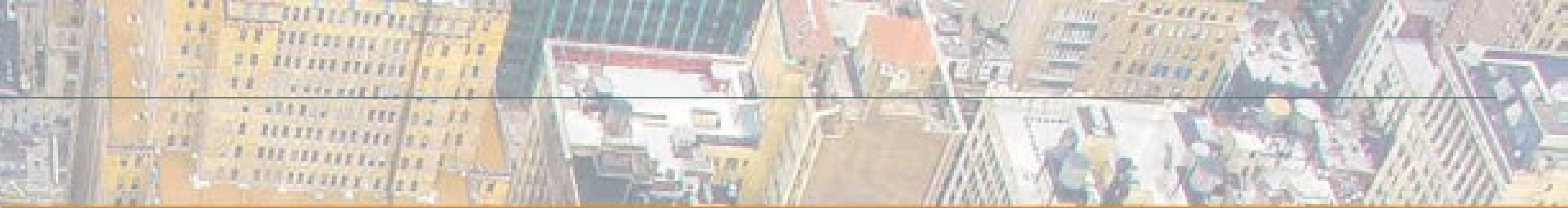


ABBREVIATIONS AND ACRONYMS

$\mu g/m^3$	micrograms per cubic meter
AQI	Air Quality Index
CBPR	Community-based Participatory Research Method
CDC	Center for Disease Control
CIESIN	Center for International Earth Science Information Network
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
COP21	21st Conference of the Parties
CSO	Combined sewer overflows
CSS	Combined sewer systems
ECI	Environmental Concentration Index
EJSM	Environmental Justice Screening Method
EPA	Environmental Performance Agency
EEA	European Environment Agency
ERE	Environmental Risk Exposure
EU	European Union
FAO	Food and Agriculture Organization
FSC	Forest Stewardship Council
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GFW	Global Forest Watch
GHGs	Greenhouse gases
GNI	Gross National Income
GRUMP	Global Rural-Urban Mapping Project
Gt	Gigatonnes
GTFS	General Transit Feed Specification
ICT	Information Communication Technologies
IEA	International Energy Agency
IHME	Institute for Health Metrics and Evaluation
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IPE	Institute of Public and Environmental Affairs
IUCN	International Union for Conservation of Nature
JMP	Joint Monitoring Programme
kWh	Kilowatt Hours
LDCs	Least Developed Countries
LST	Land Surface Temperature
LUSH	Landscaping for Urban Spaces and High-Rises Program
m^2	Square meters
MDGs	Millennium Development Goals
M&E	Monitoring and evaluation
MEP	China's Ministry of Environment Protection
MODIS	Moderate Resolution Imaging Spectroradiometer
MOHURD	China's Ministry of Housing & Urban-Rural Development
NASA	National Aeronautics and Space Administration
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NUA	New Urban Agenda
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
OSM	Open Street Map
PCA	Principal Component Analysis
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter that is 2.5 microns and smaller
ppm	Parts per million
PPP	Purchasing Power Parity
PPT	Proximity to Public Transit
PTC	Public Transportation Coverage
REDD	Reducing Emissions from Deforestation and Forest Degradation
SDI	Socio-demographic Index
SIDS	Small Island Developing States
SDGs	Sustainable Development Goals
SPT	Sustainable Public Transportation
SSO	Sanitary system overflows
SUB	Simplified urban-boundary
USEI	Urban Environment and Social Inclusion Index
UHI	Urban Heat Island
UN	United Nations
UNDP	United Nations Development Programme
UNICEF	United Nations Children's Fund
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNStats	United Nations Statistical Division
URA	Urban Redevelopment Authority of Singapore
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WMO	World Meteorological Organization
WWF	World Wildlife Fund

INTRODUCTION

Cities are civilization's main stage. More than half the world's people now live in urban areas, and, like never before, cities are the arenas for addressing the most pressing environmental problems and tackling challenges of sustainable development.

URBAN ENVIRONMENT & SOCIAL INCLUSION INDEX

With the Sustainable Development Goals and the Paris Agreement on climate change, national leaders formally recognized cities' central importance to a coalescing global development agenda. The Habitat III conference held in Quito, Ecuador in October 2016 aimed to define a "new urban agenda" with a broad scope, that includes human settlements of all sizes and integrates social equity considerations into urban and national development planning. Habitat III's new urban agenda also strives to determine pathways for sustainable urbanization – growing our cities in ways that promote human well-being and enhance environmental health. Urban sustainability's new prominence and prioritization at the top of the global development agenda represents a moment with critical implications for global environmental health and societal harmony. Researchers, policymakers, and citizens must build a broad base of knowledge on the forces that shape urban lives in order to seize the moment and help shape cities' development trajectories.

>50%

of the world's population live in urban areas today.

There are many groups and indices that examine urban sustainability, yet these efforts are often sector-specific, regionally-focused, and one-dimensional in scope.[1] Standardized metrics and definitions are also lacking, making it difficult to compare urban sustainability initiatives from one city to the next. If we cannot agree on what "urban" and "sustainable" mean, forging a path towards a sustainable urban future is a non-starter. As city governments experiment with sustainability initiatives, their efforts must be measured, assessed, compared with one another, and improved upon, or else we risk missing the results and losing the benefits that these programs can bring to everyone. The global community of urban researchers needs to create a standardized framework of novel urban sustainability metrics in order to realize the potential that cities hold.

Measuring the urban environment in a manner that is both accurate and meaningful to city-dwellers is very challenging. And assessing the relative successes and failures of urban environmental policy is even more difficult. In most urban areas, policies lag behind environmental hazards as cities' dynamism outpaces governments' capacity to manage them. Cities are in continuous flux – those in the developing world have expanded at such a breakneck pace in recent decades that their growth has been difficult to manage and their environmental change tough to measure. We observe this phenomenon even in centrally planned cities like Beijing, where rapid industrial and urban growth has led to extreme levels of air pollution. The Chinese government has vowed to clean up the air, pledging blue skies over Beijing within a decade, yet pollution in the country's second-tier cities is worsening, following a similar trajectory to Beijing's. Nearly one in five deaths in China can be attributed to foul air.[2] Cities all over the world, from Indianapolis to Cairo, face similar challenges: more than 95 percent of people living in urban areas that monitor air pollution are exposed to air quality levels that exceed World Health Organization limits.[3]

Sustainable Development Goal 11 and Inclusive Urban Communities

To address environmental sustainability challenges in cities, **Sustainable Development Goal 11** (SDG 11) establishes a goal for urban areas to be both sustainable and inclusive. Three out of the 10 indicators for SDG Goal 11 feature provisions to "ensure" or "provide" access (Indicators 11.1, 11.2, 11.6, 11.7; see Table 1) to environmental goods and services, including basic housing, sustainable transport, and urban green spaces, "in particular for women and children, older persons and persons with disabilities" (Indicator 11.7); or to "substantially increase" cities' policies towards inclusive development" or, more generally, "inclusion" (Indicator 11.3).

As with the terminology describing "sustainable cities," "environmental justice" and "environmental equity" are conceptual hot buttons of debate. Environmental equity is often assessed both through the experience of environmental harms (e.g., exposure to pollutants) and access to environmental benefits (e.g., urban green spaces) that support a higher quality of life.[4] Most assessments of environmental equity strive to capture levels of fairness as the notion arises in environmental management and describe how environmental management can foster and protect fairness for individuals. They fail to evaluate, however, questions such as which communities gain from improved environmental benefits and which are disproportionately impacted by environmental hazards.[5,6] Few research efforts also attempt to quantify the ways sustainability assessments measure equity or the ways in which environmental disparities disproportionately affect some populations over others.[7]

Table 1. Targets and Indicators for SDG-11 related to environmental goals evaluated in the UESI.

Target	Indicator
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	**11.1.1** Proportion of urban population living in slums, informal settlements or inadequate housing
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	**11.2.1** Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	**11.3.1** Ratio of land consumption rate to population growth rate
	11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	**11.6.2** Annual mean levels of fine particulate matter (e.g. $PM_{2.5}$ and PM_{10}) in cities (population weighted)
11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	**11.7.1** Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities

Source: UN Sustainable Development Knowledge Platform.[8]

Towards Measuring Social Inclusion

The difficulty of defining and assessing the equity considerations of urban sustainability helps explain the shortcomings in existing urban sustainability indicator systems and research. What does equity mean for urban inhabitants who are all confronting severe air pollution, even if that pollution is evenly distributed among residents? Does equity entail redistributing access to environmental goods and amenities from wealthier populations to those with lower incomes? In setting a goal for sustainable and inclusive communities, SDG-11 falls short of defining what is meant by these complex, context-specific terms of inclusivity and community.

We therefore define social inclusion as the process of ensuring all members of society have both representation and agency in shaping the decisions that determine their social, political, economic, and cultural lives. Social inclusion can enhance and may reflect the strength of social connectedness, the degree to which individuals and communities are working together to overcome isolation and to foster belonging and solidarity. This definition draws on discussions of inclusive and sustainable development,[9,10] distributive justice,[11,12,13] social exclusion,[14,15,16] well-being,[17] and social cohesion.[18,19,20]

In this context, social inclusion means more than having a seat at the table – it encompasses facilitating inclusion by removing obstacles to participation[21,22] and ensuring that representation in these decision-making forums has real weight.

There are clear links between social inclusion and the urban environment. Mounting evidence shows that environmental health is increasingly viewed as a commodity for urban citizens who can afford it, a paradigm that leads to environmental injustices and exclusion.[23] Studies in political ecology, environmental planning, and gentrification have shown that social exclusion undermines environmental goals and erodes a city's ability to provide for its citizens, combat climate change, and compete in the global economy.[24,25] Cities are inherently social places and the success of urban governance needs to be gauged according to the needs of city residents.

A New Approach to Understanding Social Inclusion and the Urban Environment

To better understand the links between the urban environment and social inclusion, it is our aim to institute a data-driven approach. Robust metrics allow cities to identify urban sustainability priorities, set goals, and benchmark their progress over time. Hurdles to accessing and interpreting data can often reduce citizens' ability to participate in discussions around environmental management. Information is a means of providing people with agency and of removing obstacles to engaging in social, political, economic, and cultural discussions and decision-making. Social inclusion and social connectedness occur – and can be measured – at various and overlapping scales, from households to neighborhoods to entire societies. Monitoring efforts may observe and collect both qualitative and quantitative data as they seek to: (1) create a complete assessment of a neighborhood or city's demographics (e.g., ensure marginalized populations or neighborhoods are included in the definition of a city's population); (2) track how representation and agency vary according to these demographics; (3) measure the ways social, economic, and environmental benefits and burdens are distributed across these demographics; and (4) assess levels of resilience and community-driven actions across these demographics.

The Urban Environment and Social Inclusion Index (UESI) is a tool and research project that helps city leaders track progress towards Sustainable Development Goal (SDG) Goal 11 – to make cities inclusive, safe, resilient and sustainable. The UESI provides a new, spatially-explicit approach to evaluate how different neighborhoods within cities vary in terms of environmental performance and social inclusion. By making neighborhood-level environmental and socio-economic data easily accessible, we hope to increase opportunities for social inclusion by connecting urban residents with information about their environments.

The Index seeks to empower urban residents, providing tools that enable them to track their neighborhood's access to environmental benefits and burdens relative to other city districts. An open snapshot of a city's environmental performance provides a shared starting point and frame of reference for residents and policymakers as they identify environmental management priorities and develop management strategies to meet these goals. The world's cities are diverse, like its people, and this variety – in geography, development stage, and governance, among other issues – creates challenging complexity for standardization efforts. A measure that reports a city's impact on the marine environment, for instance, would be less applicable to Denver than it would be to New York City. And sustainability initiatives in rapidly expanding cities may be very different from those in urban areas with only modest growth. Yet even disparate cities are

able to teach and learn lessons from one another. Lagos, Nigeria could learn from Singapore's water recycling initiatives; Houston, Texas could learn from Bogota's bus-rapid transit system. In these interactions, standardized sustainability metrics would give nations and cities a common language to communicate their initiatives' successes and failures.

The pilot UESI includes over 30 cities across a range of geographies and levels of economic development (Figure 1). We include at least one city from each continent, excluding Antarctica, and these selections reflect a range of capital and non-capital cities (see the Technical Appendix for more details on the city selection process). Cities in the United States are more represented than other countries, with a total of 6 cities, largely due to expert input in the early pilot city selection process that suggested we should include more non-capital and transitional cities in the UESI analysis. Due to data availability, we decided to start with a few U.S. cities (e.g., Atlanta and Detroit) with the ultimate goal to grow the UESI to include more cities around the world. Data availability was the strongest determinant for whether a city was included, particularly within the global South, where the lack of neighborhood-level income and population data made it difficult to evaluate the full suite of UESI indicators.

Figure 1. Map of the pilot cities included in the UESI.

Box 1. Characteristics of Neighborhoods within UESI Cities

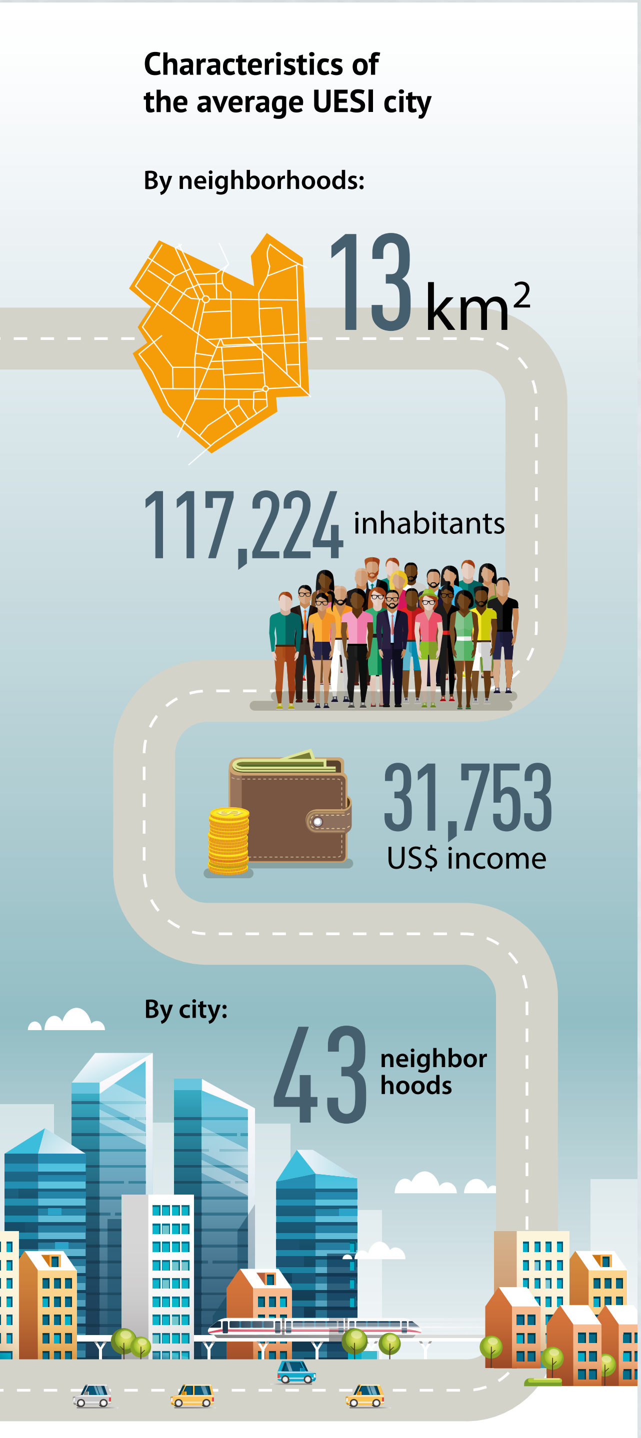
One of the most crucial questions in assessing a city's performance is the scale of the analysis. There are four key scales when examining urban areas: **parcel** (data at the census or city block level), **neighborhood** (groups of parcels), **regional** (which can defined according to political, economic, or geographic boundaries), and **macro systems** (defined according to the national, ecosystem, and global factors shaping urban areas). Table 2 below provides examples of these scales.

Although each city defines what a "neighborhood" is differently, according to their own standards, the UESI adopts the neighborhood as the primary unit of analysis for several reasons. First, we aim to provide a detailed evaluation of environmental performance and social inclusion in a spatially-explicit way that allows citizens and urban managers to understand how these phenomena vary across a city and affect different populations. Adopting a scale coarser than the neighborhood level (i.e., regional or macro-system) would not provide the resolution to allow for an investigation of this variation. Second, although some cities' analysis may warrant a scale even finer than the neighborhood scale, not every city in our sample has data at that level (e.g., at the census or block level). We therefore had to strike a balance between granularity and data availability to allow for comparison across cities.

Table 2. Examples of various urban scales and examples of data for each particular scale.

Scale	Example data
Parcel-level	Data at a fine scale, e.g., at the level of census tracts or city block(s). In addition to census-level data (such as information about a parcel's demographics), data at this scale can include detailed data such as the locations of businesses, geolocated tweets, the location of intersections, and air quality monitors.
Neighborhood	Data aggregated or available at resolutions of 1-50 square km. Examples of neighborhood-level data include the average income of urban districts, urban tree canopy at 30m resolution, and population density.
Regional	Regional data related to the urban system, which could be defined by political boundaries, regional economic systems, contiguously built-up areas, and natural areas such as watersheds and commute sheds. This data can focus on the urban agglomeration by itself, or include surrounding rural areas.
Macro system	Broader circumstances of urban areas may put pressure on the built environment. For example, is the city a port city? Is the city in a desert or a rainforest? Are global labor markets undercutting the manufacturing industry in this city? These questions and others will help contextualize the findings of environmental performance assessment at more detailed scales.

Source: Adapted from Sipus, 2017[26]; Buchanan, 2001[27]; and Golsby-Smith, 1996.[28]



Organization of this Report

The report contains an overview of how each UESI indicator was calculated and the rationale behind its inclusion. Further information about each indicator's data sources, transformations, and other details are accessible through our Technical Appendix (bit.ly/uesi-tech-appendix), online portal (www.datadriven.yale.edu/urban) and in forthcoming academic literature. All UESI data and results are available for free download and use under a Creative Commons license.

The UESI report is organized as follows:

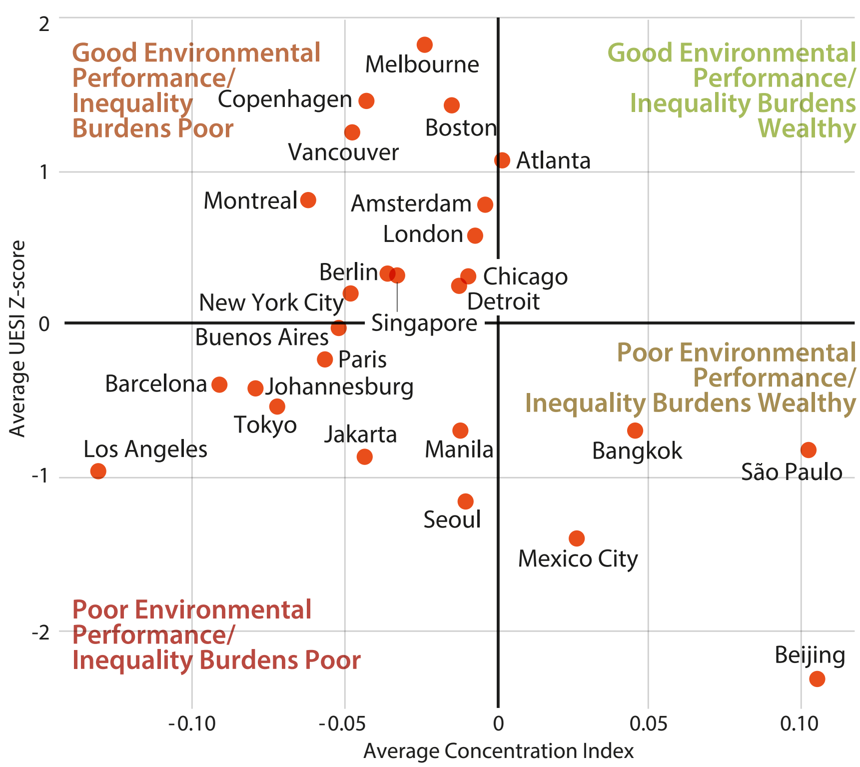
- → The **Key Findings** section provides an overview of some of the main findings for the 30+ pilot cities included in the UESI.
- → A brief **Methods chapter** provides a general overview of how we determined the UESI framework and calculate the proximity-to-target indicators, although more methodological details are provided in each chapter.
- → A chapter on **Equity and Social Inclusion** details our new approach to evaluating how cities are meeting the challenge of achieving environmental performance in an equitable and inclusive way.
- → **Five issue profiles** explain the methods used to calculate the UESI's urban environment and social inclusion indicators. These sections frame each environmental problem included in the UESI, and examine the complexities involved in developing spatially-explicit measures of urban environmental performance and social inclusion at the neighborhood scale.
- → A **Results section** provides an overview of how different cities compare on the environmental indicators selected, and explores overall trends in environmental performance and social inclusion.
- → A **Conclusions section** describes areas of uncertainty and points to future areas of research.

KEY FINDINGS

1 Cities' environmental performance tends to reflect their geography and development. Cities located in similar climates or regions show similarities across environmental indicators. Broadly speaking, a city's environmental quality aligns with its economic development - cities with higher levels of GDP per capita tend to score more highly on the UESI's range of environmental indicators, although the relationship is weak.

2 While many cities perform well or above average on the UESI indicators, most cities are failing to achieve these environmental results in an equitable way, disproportionately burdening poorer populations. As Figure 1 illustrates, most cities are located in the left-hand quadrants, which correspond to environmental burdens on average being concentrated on less wealthy neighborhoods within the UESI cities. This pattern indicates that performance and equity are not necessarily concurrent - better performance does not involve a more equitable environment and vice versa - highlighting the need for cities and local governments to actively address issues of distributional equity as part of their environmental and development interventions.

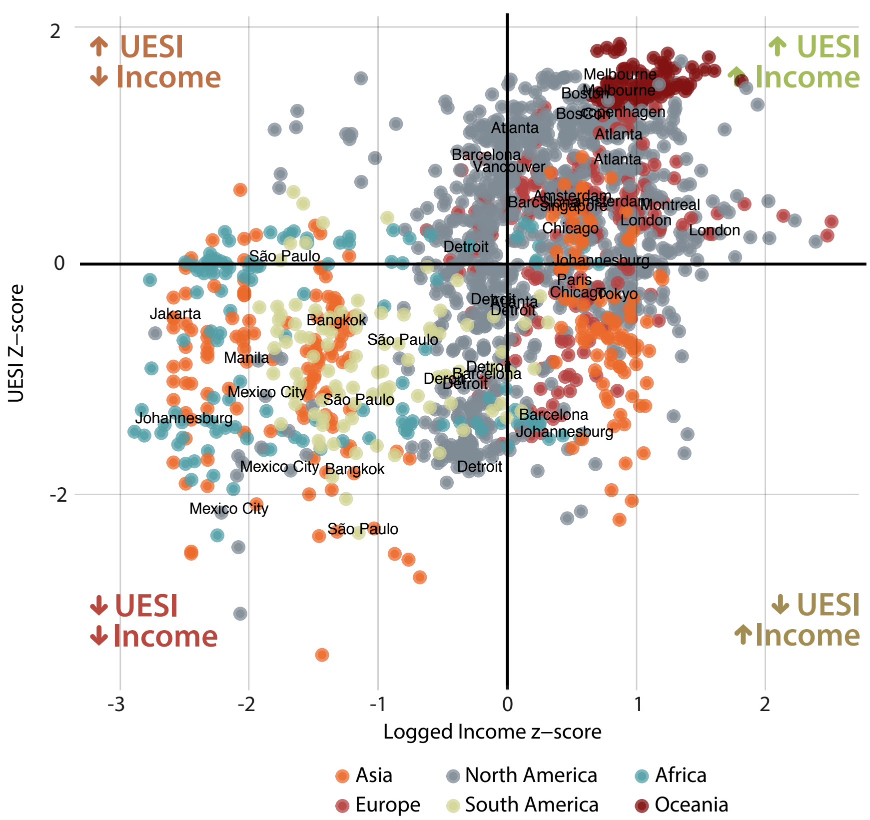
Figure 1. Relationship between environmental performance and equity.



A four-quadrant plot examining relationship between environmental performance (in terms of z-score for a city's average performance on the UESI indicators) and equity (in terms of average concentration index, see *Equity and Social Inclusion* issue profile for more details). Only 25 UESI cities are included in this plot because some cities, including Bangalore, Tel Aviv, Istanbul, Ho Chi Minh City, Casablanca and Lima, do not have neighborhood-level income data.

3 Wealthier neighborhoods tend to have high on average environmental performance compared to lower-income neighborhoods. The positive relationship between environmental performance and income becomes clear when examining the UESI at a neighborhood scale. When comparing income by neighborhood with z-scores of average performance on UESI indicators, disparities between environmental outcomes and income are apparent. There is a high density of neighborhoods located in the upper right-hand quadrant of Figure 2, where neighborhoods perform on average better on UESI indicators and also have better than average levels of income. Many neighborhoods located in developing country cities such as Jakarta, Beijing, and Bangkok are located in the lower left-hand quadrant, where UESI scores and income levels are on average lower. This plots gives further evidence on the positive relation between income levels and environmental performance - a relationship frequently explored at national scale - but that is also present at a local level, suggesting that the achievement of better environmental performance has a predominant - explicit or implicit - bias towards wealthier citizens or neighborhoods.

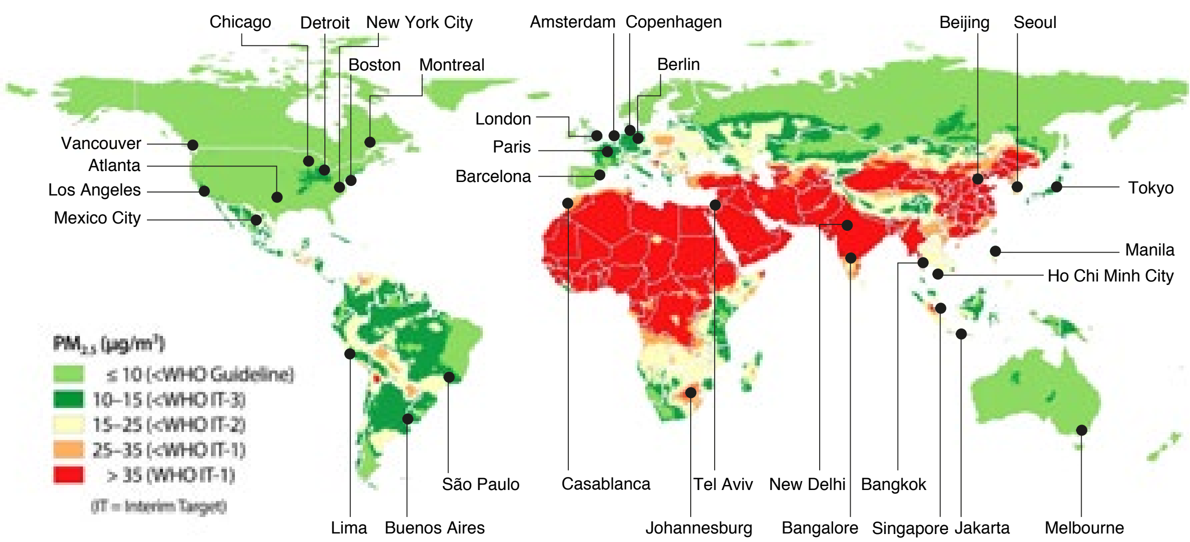
Figure 2. Relationship between income and UESI scores for all neighborhoods.



A four-quadrant plot examining relationship between environmental performance (in terms of z-score for a neighborhood's average performance on the UESI indicators) and z-score of logged income. Only 25 UESI cities are included in this plot because some cities, including Bangalore, Tel Aviv, Istanbul, Ho Chi Minh City, Casablanca and Lima, do not have neighborhood-level income data.

4 Air pollution is one of the biggest urban environmental threats to human health. 96 percent of people living in the UESI's pilot cities are breathing unsafe air that does not meet the World Health Organization's guideline (10 micrograms per cubic meter) for safe exposure to fine particulate pollution - one of the most dangerous threats to human health in cities. Only Amsterdam, Atlanta, Barcelona, Boston, Copenhagen, Melbourne, Montreal, New York City, Tel Aviv, and Vancouver have neighborhoods with $PM_{2.5}$ levels below this threshold.

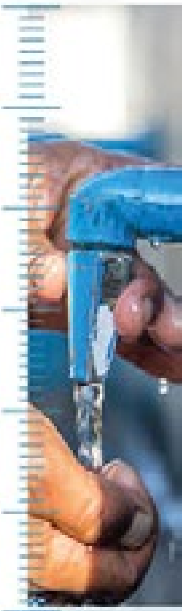
Figure 3. Global map of $PM_{2.5}$ exceedances according to the World Health Organization (WHO) targets.



Data Source: 2018 State of the Global Air Report

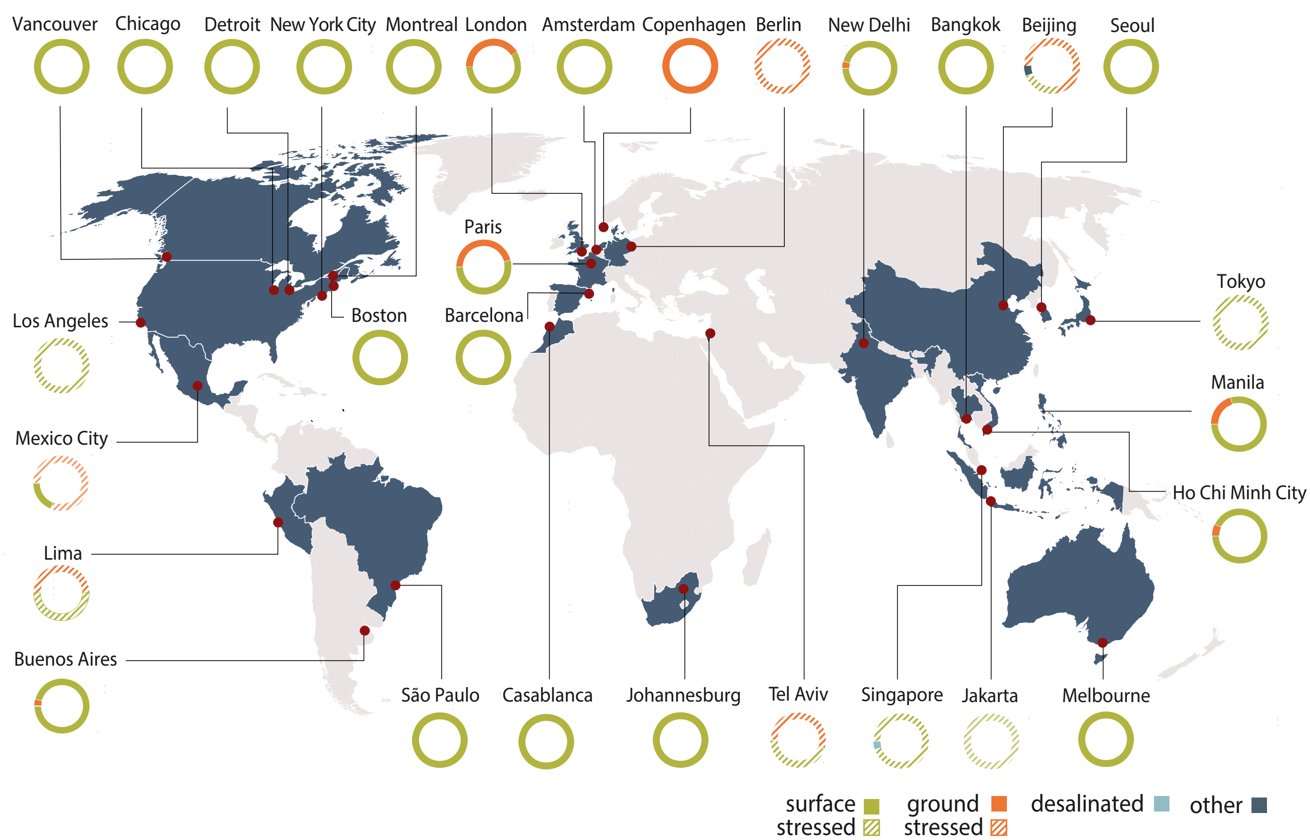
95 %

of the world's population lives in nations with unsafe air quality.



5 One-third of cities rely on water-stressed surface or groundwater sources. Seven of the 25 cities that rely on surface water to meet most (at least 50 percent) of their needs draw on water-stressed sources, while 3 of the 4 cities dependent on groundwater for most of their water needs rely on stressed groundwater resources. Levels of water stress often vary alongside cities' geographic and financial circumstances. Large, wealthy cities can often import water, while lower-income cities often must rely on water sources within closer proximity. However, increasing pressure on and competition for water resources from cities, agriculture and industry will make efficient water use an increasingly urgent priority for most cities.

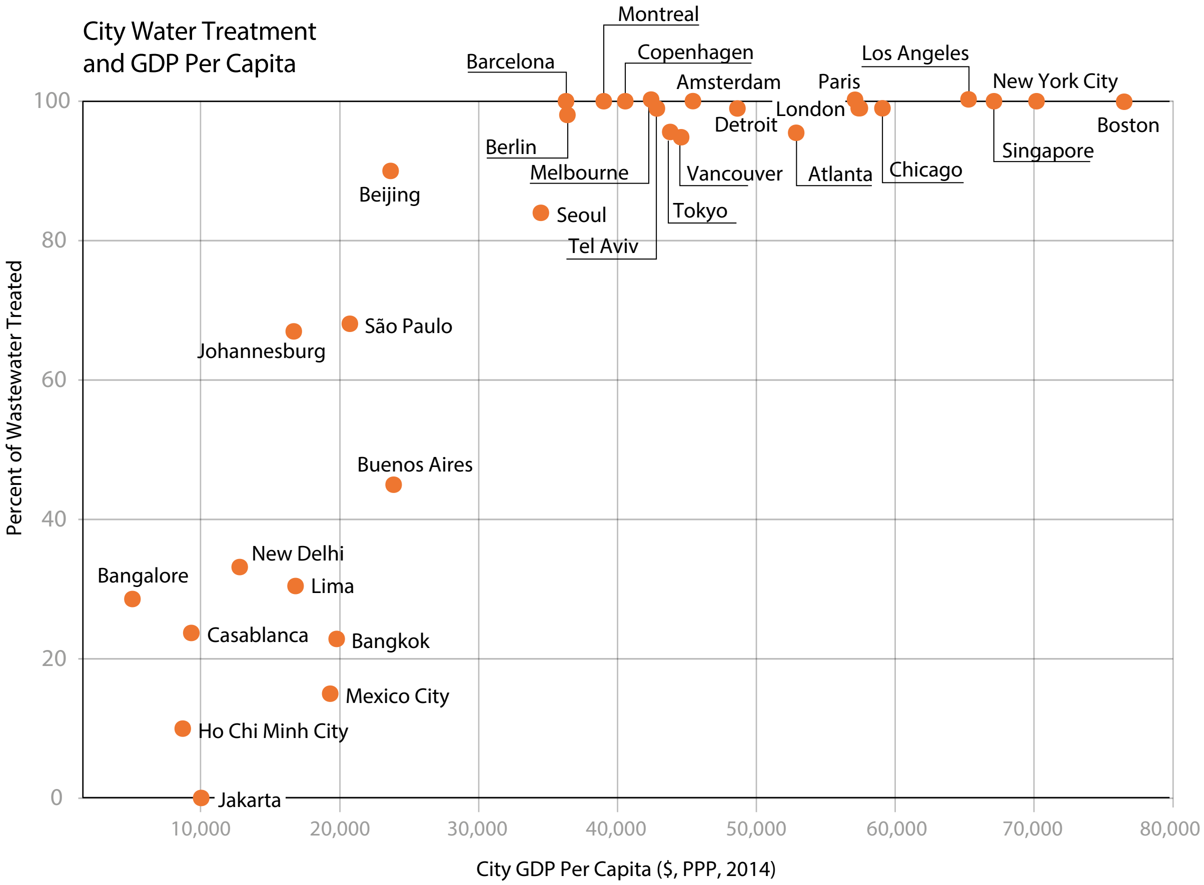
Figure 4. Cities' water supply sources (percent of city water supply from surface freshwater, groundwater, desalinated water, or other sources) and the stress level of surface and groundwater.



Data source: data on the distribution of urban water sources and surface water stress comes from The Nature Conservancy's City Water Map (McDonald & TNC, 2016), utilizing the Water Gap Model (Alcamo et al., 2003); data for groundwater stress comes from McDonald et al. (2014) [1,2,3]

6 Available data suggests that wastewater treatment levels are highest, for the most part, in high-income cities, and lowest in low-income areas. Efforts to more effectively treat and reuse wastewater could protect public health and the environment, while also addressing concerns about water scarcity and water stress.

Figure 5. Relationship between city-wide GDP per capita (in 2014 USD) and percentage of wastewater treated.

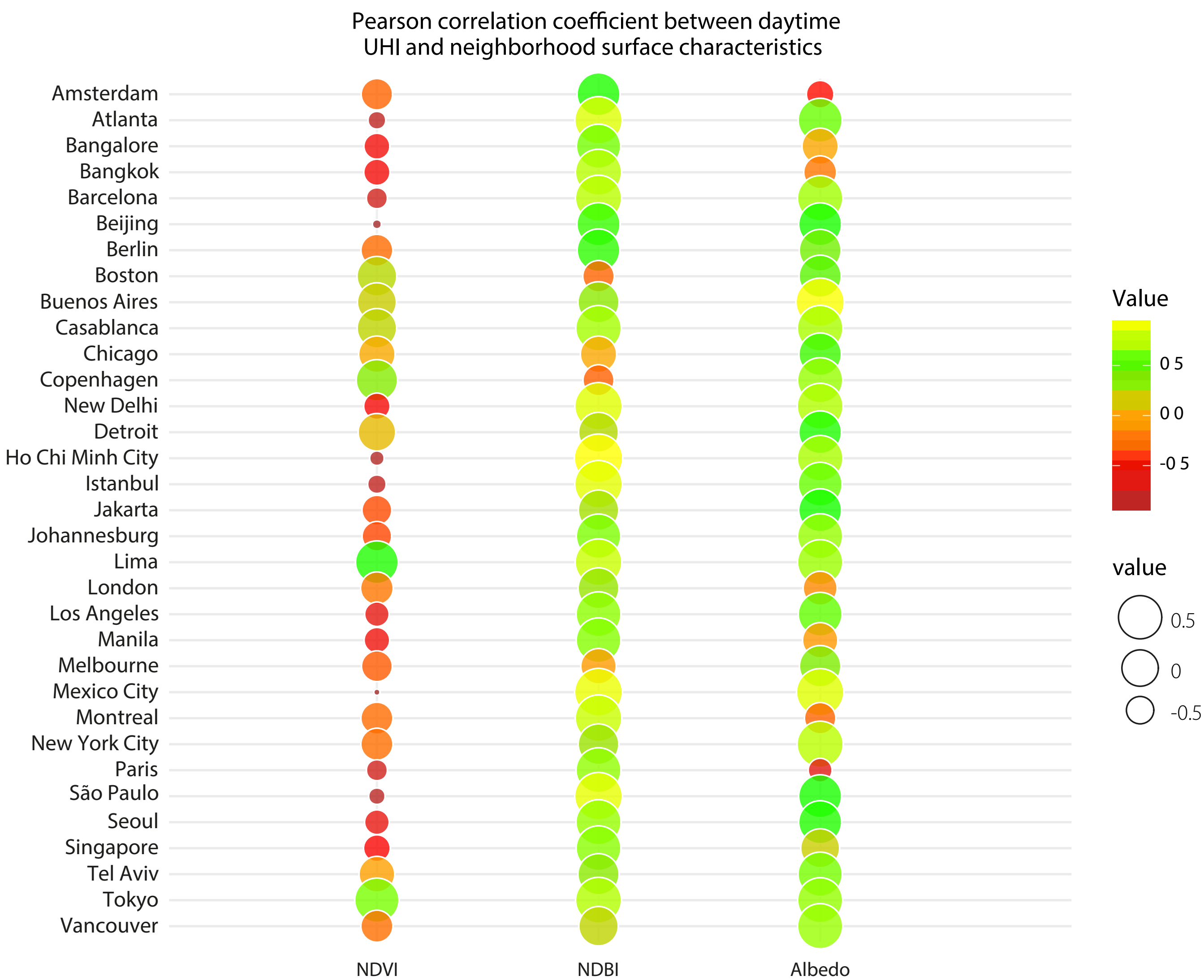


20%

of the urban population still lacked access to improved sanitation in 2012

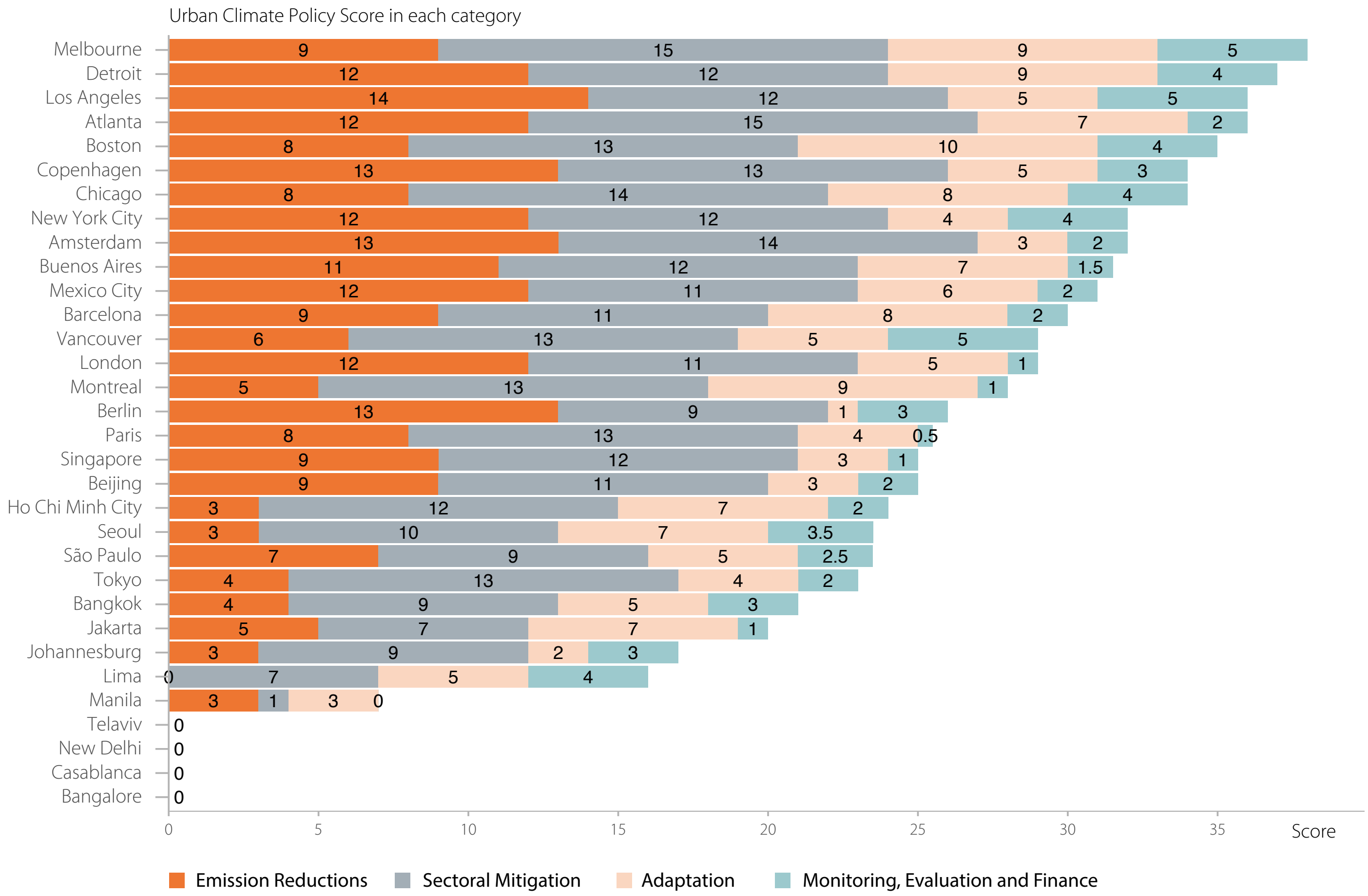
7 The urban heat island effect is exacerbated in cities that have low tree cover or significant built-up areas. Increasing vegetation at the neighborhood scale can help offset urban heat, while the addition of built-up structures enhances the UHI intensity by storing and trapping heat, and replacing vegetation that could provide evaporative cooling. There are some cities that seem to be exceptions to this rule (e.g., Tokyo, Boston, Casablanca, Copenhagen), although they tend to be coastal cities where neighborhoods nearer to the coast have a lower UHI regardless of the vegetation cover of the neighborhood. These exceptions suggest that it is possible for cities to adopt urban heat mitigation measures, although it is critical for cities to consider their own specific contexts when deciding on measures to mitigate the urban heat island effect.

Figure 6. Relationship between daytime Urban Heat Island (UHI) and surface characteristics (e.g., greenness (NDVI), built environment (NDBI), and surface reflectance (albedo)) within the UESI cities.



8 Cities are tackling climate change with myriad policies that represent a broad spectrum of ambition and topic area. Some cities, however, including Tel Aviv, New Delhi, Casablanca, and Bangalore, have no city-level climate policy that details what specific actions it is taking to address climate change mitigation and adaptation and receive a score of 0. No city receives a full score for monitoring and evaluation, indicating cities can do more to bolster tracking and transparency of their efforts. Some cities that are performing particularly well on climate change policy include the city of Melbourne, which covers both mitigation and adaptation policies in its climate action plan and publishes data for monitoring and evaluation.

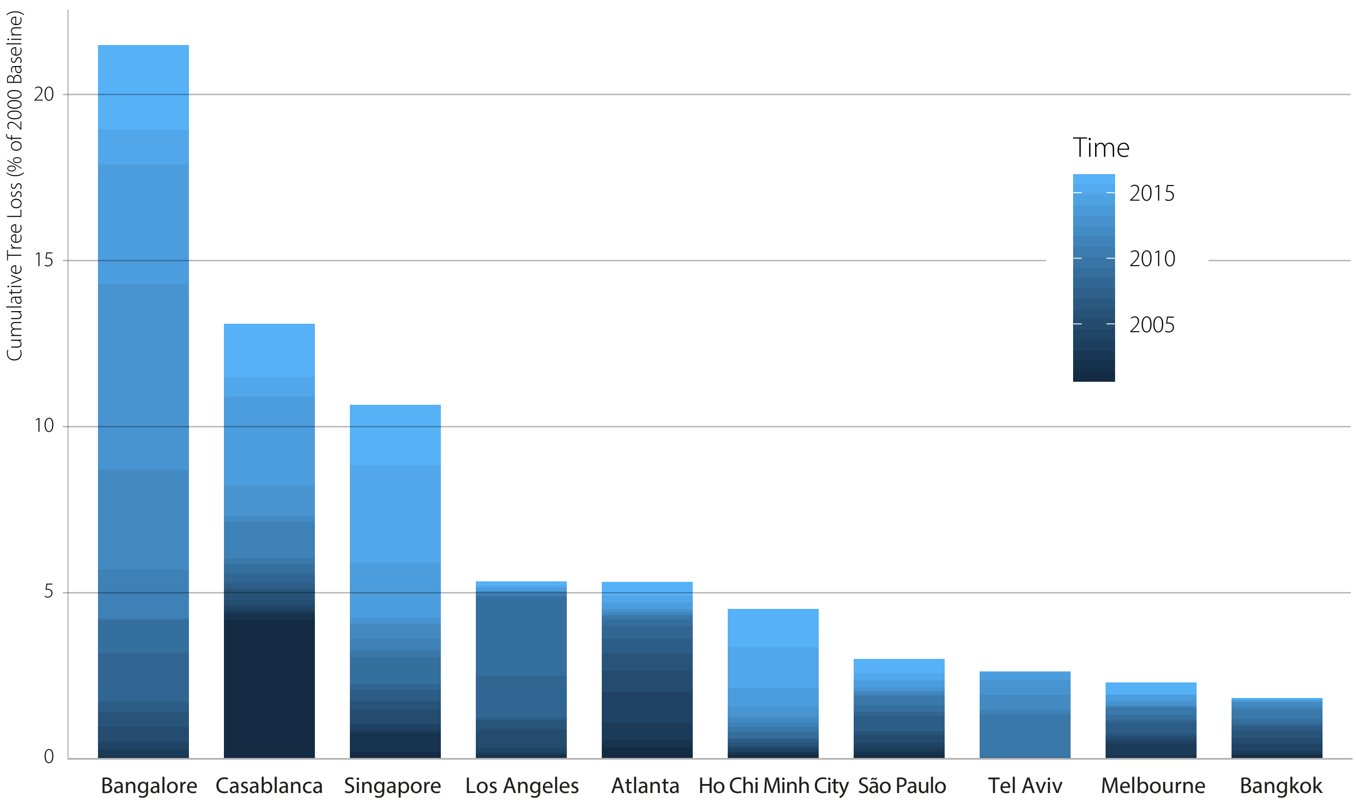
Figure 7. Cities' performance on the UESI Climate Policy indicator.



Cities announce their climate action plans at different points in time and do not always update them regularly. Late-adopters of citywide climate action plans in more recent years may therefore receive a higher score than a city that has not updated its existing climate action plan.

9 The pilot UESI cities have experienced a total loss in urban tree cover of 206 square kilometers from 2001 to 2015. This loss in tree cover covers an area roughly twice the size of Barcelona. Using the 2000 baseline, the cities that have experienced the greatest loss in urban tree cover from 2001 to 2016 include Bangalore, Casablanca, Singapore, Los Angeles, and Atlanta. These cities experienced urban tree cover loss in different time periods, with the majority of Casablanca's and Atlanta's loss occurring in the early 2000s, and Bangalore's, Singapore's and Ho Chi Minh's urban tree cover loss occurring more recently. These findings are relevant to understand a city's dynamics and its development over time, as vegetated space tends to be removed to make space for new developments and city infrastructure.

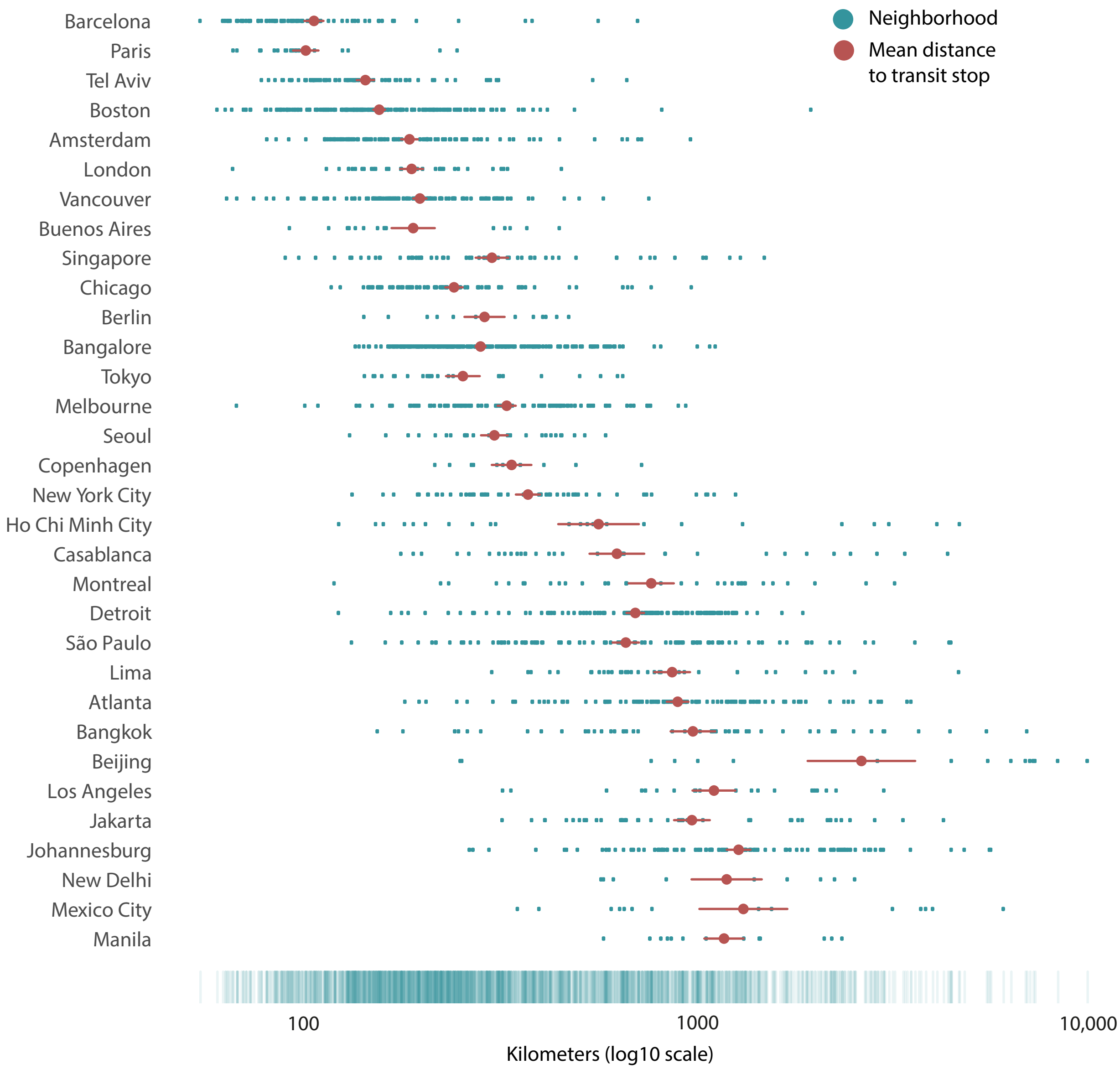
Figure 8. Top 10 UESI cities with the highest proportion of tree loss from 2000 to 2016.



Darker shades correspond to tree loss proportion, based on a year 2000 baseline, that occurred in earlier time periods versus lighter shades, which highlights more recent tree loss.

10 On average, UESI cities are providing sustainable public transit to half of their residents. Access ranges from near universal coverage in cities like Barcelona, London, Tel Aviv, Paris, and Boston to as low as 30 percent in Manila. Where public transit is available, it is often targeted where population density is greatest and people need it the most. The two exceptions are Montreal and Detroit, where there is some public transit in less dense areas at the expense of more densely populated areas. Barcelona and Paris are top ranked when it comes to providing access to public transit on average less than 100 meters within each neighborhood.

Figure 9. Mean distance to transit stops among the UESI cities.



The "rug" along the bottom of the figure shows the range where most of the neighborhoods lie.

AMSTERDAM

ATLANTA

BANGALORE

BANGKOK

BARCELONA

BEIJING

BERLIN

BOSTON

BUENOS AIRES

CASABLANCA

CHICAGO

COPENHAGEN

DETROIT

HO CHI MINH CITY

JAKARTA

JOHANNESBURG

LIMA

LONDON

LOS ANGELES

MANILA

MELBOURNE

MEXICO CITY

MONTREAL

NEW DELHI

NEW YORK CITY

PARIS

SÃO PAULO

SEOUL

SINGAPORE

TEL AVIV

TOKYO

VANCOUVER

METHODS

This section provides an overview of the general process and methods used to develop the UESI framework and selection of indicators. Specific details regarding the calculation of indicators are included in each individual issue chapter and more information is also provided in the Methodological Appendix (www.bit.ly/uesi-tech-appendix).

The UESI Framework

The Index includes five categories of environmental concerns: Air Quality, Climate Change, Water and Sanitation, Urban Ecosystem, and Transportation (Figure 1). Each city is gauged on environmental performance indicators within these issues as well as how different demographic group (e.g., by income and sensitive populations) are affected. For instance, neighborhoods within each city receive scores for the amount of urban tree cover canopy as well as how equitable the access to the green space is. All data are made open and available through an online portal (www.datadriven.yale.edu/urban), which provides an interactive dashboard for citizens, policymakers, and urban managers to explore in more detail where they perform well and which areas may require greater attention. Cities not included in the pilot round will also have access to data and code that will allow them to calculate their own UESI indicators.

Data Sources

The UESI uses primary and secondary data primarily from large-scale remote sensing datasets and open-source geospatial data, such as OpenStreetMap. We also collect census neighborhood and block-level data on population and income. Secondary datasets used in the UESI are restricted to the climate mitigation and adaptation policy action indicator, which draw on city-specific climate action plans, and the water indicators, which draw on a range of wastewater treatment data sources, and use the Nature Conservancy's Urban Water Blueprint data to assess surface water stress (see *Water Resource Management issue profile* and *Metadata* for more details). The UESI applies a set of criteria to determine which datasets to select for inclusion (see Box 1: *Guiding Principles for Indicator Selection in the UESI*).

All sources of data are publicly available and include:

- Satellite data from remote sensing;
- Geospatial datasets,[1] such as gridded global population[2] and location of public transit stops;
- Official statistics measured and formally reported by governments through a census or other data collection effort.

Figure 1. Categories of environmental issues and indicators assessed in the Urban Environment and Social Inclusion Index (UESI).

Box 1. Guiding Principles for Indicator Selection in the UESI

The UESI Framework

1) Spatially-explicit

The index incorporates spatially-explicit indicators as much as possible given data availability.

Because people do not experience cities uni-dimensionally, the UESI aims to incorporate spatial data as much as possible to examine patterns, trends, and differences in environmental performance throughout and between urban areas. Spatially-explicit indicators also expose variation within and between cities. For example, land surface temperature has been connected to population density,[3] although this relationship is varied between cities.[4] Identifying these differences can help urban environmental managers identify distributional impacts of various environmental policies. By combining spatially-explicit environmental and socioeconomic data, the UESI features indicators that allow us to assess how different communities are affected by environmental hazards and benefits.

2) Incorporate equity

We adopt equity and social justice as applicable end goals for our measurement framework and indicators, meaning we strive for our tools and analysis to shed light on socioeconomic drivers, patterns, and differences that can lead to disproportionate levels of environmental quality and performance. Exposing these differences requires detailed spatial data and we will continue seeking data and examples to determine how each city fares in terms of equity. In this sense, the commitment to equity echoes point 1 above.

3) Build on and support SDG 11 and other global goals

SDG 11 sets a goal to make cities "inclusive, safe, resilient, and sustainable," which informs the design of our indicator framework as well as the selection of indicators. Because we aim for this tool to be useful for policymakers to track progress towards SDG 11 and other international policy goals, we have aligned our indicators and framework as much as possible.

4) Focus on outcome, not process, indicators

Targeting policymakers, we designed our framework and indicators to measure outcomes where possible, allowing local managers to address areas of needed improvement in locally-sensitive ways. With the exception of the Climate Policy indicator, UESI indicators do not measure policy responses such as public expenditure on roads.

5) Reproducibility and transparency

We provide a clear and detailed report on the chosen datasets, methodology, framework, and indicators. Access to data in easily accessible formats will be important in ensuring transparency, reproducibility, and relationship building. Ensuring the data is accessible allows individuals and institutions to access the aggregated data to investigate their own research questions. All data are available on our portal: www.datadriven.yale.edu/urban.

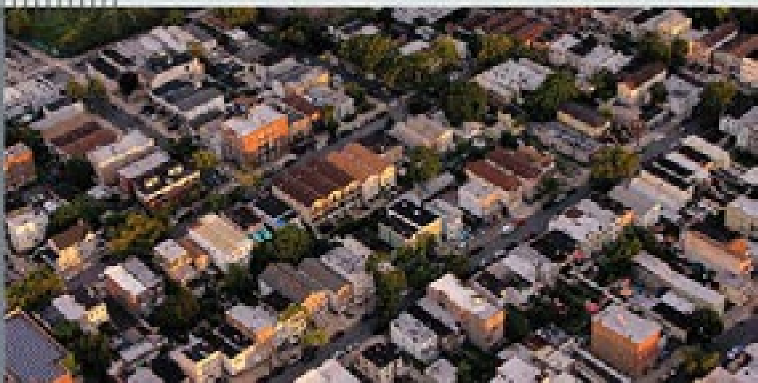
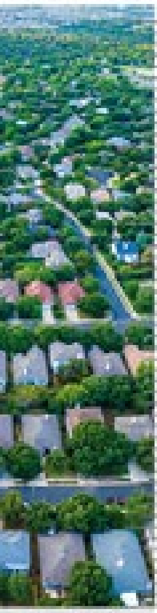


Table 1. Sustainable Development Goal indicators related to the environmental metrics included in the UESI.

	Sustainable Development Goal Indicators	UESI Metric
1 NO POVERTY	**SDG 1: End poverty in all its forms everywhere** ➔ 1.1.1 Proportion of population below the international poverty line, by sex, age, employment status and geographical location (urban/rural)	• Equity indicators
3 GOOD HEALTH AND WELL-BEING	**SDG 3: Ensure healthy lives and promote well-being for all at all ages** ➔ 3.9.1 Mortality rate attributed to household and ambient air pollution	• Average Exposure to $PM_{2.5}$ (µg/m^3) • Average Exposure to Nitrogen Dioxide (NO_2) (ppm) • $PM_{2.5}$ Exceedance (average percentage of the population exposed to $PM_{2.5}$ levels at 10 µg/m^3, 15 µg/m^3, 25 µg/m^3, and 35 µg/m^3)
6 CLEAN WATER AND SANITATION	**SDG 6: Ensure availability and sustainable management of water and sanitation for all** ➔ 6.3.1 Proportion of wastewater safely treated ➔ 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	• Water stress; • Wastewater treatment
11 SUSTAINABLE CITIES AND COMMUNITIES	**SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable** ➔ 11.2 Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities ➔ 11.6.2 Annual mean levels of fine particulate matter (e.g. $PM_{2.5}$ and PM_{10}) in cities (population weighted) ➔ 11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities ➔ 11.A.1 Proportion of population living in cities that implement urban and regional development plans integrating population projections and resource needs, by size of city	• Proximity to Public Transit (PPT); • Public Transportation Coverage (PTC); • Urban Heat Island Intensity; • Tree Canopy Cover Loss; • Tree Cover Per Capita; • Climate Policy; • Equity indicators
13 CLIMATE ACTION	**SDG-13: Take urgent action to combat climate change and its impacts** ➔ 13.1.3 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies	• Climate Policy • Urban Heat Island Intensity

Source: UN Sustainable Development Knowledge Platform.[5]

SUSTAINABLE DEVELOPMENT GOALS



Constructing the UESI

The UESI framework was developed through a multi-step stakeholder engagement process that involved input from academic researchers, urban planners, practitioners, and city representatives. The starting point for the environmental issues we selected was drawn from the Environmental Performance Index,[6] which is a biennial ranking that evaluates national environmental performance in 9 high-priority issue areas (e.g., Air and Water Quality, Biodiversity and Habitat Protection, Forests, Fisheries, Agriculture, Climate Change and Energy, Environmental Health). We then conducted a comprehensive literature review[7] of existing urban environmental sustainability metrics to evaluate prior work and where we could add value. This process also involved reviewing the environmental justice and social equity literature from a multi-disciplinary angle (see the *Equity and Social Inclusion* issue profile). Expert practitioners and academic researchers were involved in the entire framework design and indicator selection process. In the end, the resulting UESI framework and indicators represent a trade-off between a scientific underpinning and available data, as we require all cities[8] to have neighborhood-scale data available for all of the indicators (excluding the Climate Policy and Water indicators that are not applicable at the neighborhood scale) to be included in the pilot UESI.

We present the UESI data in multiple formats recognizing that not all users experience information in the same way. Raw values in native units provide a largely unadulterated view of how neighborhoods and cities perform. Transformed values using a "proximity to target" (see Box 2: *Measuring Environmental Performance: Proximity-to-Target*) method assess how close or far neighborhoods and cities are to achieving an identified policy target.

The targets are high performance benchmarks defined primarily by international or national policy goals or established scientific thresholds. The benchmark for exposure to fine particulate pollution, for instance is 10 µg/m^3, a threshold set by the World Health Organization as safe exposure.[9] A high-performance benchmark can also be determined through an analysis of the best-performing countries. Some of our indicators set benchmarks, for example, at the 95th percentile of the range of data. Scores are then converted to a scale of 0 to 100 by simple arithmetic calculation, with 0 being the farthest from the target and 100 being the closest (Box 2). In this way, scores convey analogous meaning across indicators, policy issues, and throughout the UESI.

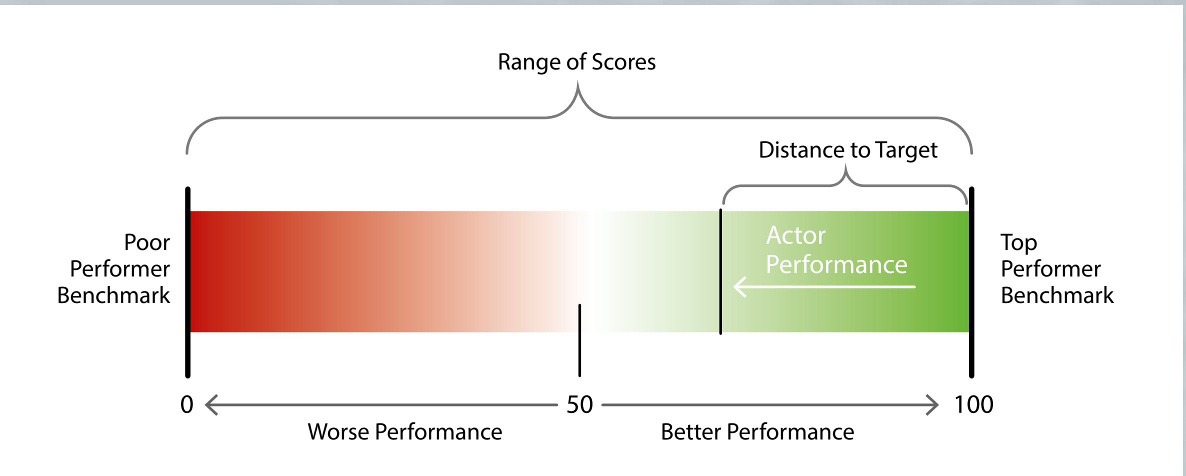
Although the EPI aggregates the proximity-to-target scores into a single, weighted index that applies a series of statistical weights to each indicator and policy issue, the UESI does not combine all of the metrics into a single score. We keep the UESI scores disaggregated and sorted by issue based on the diversity of environmental performance observed at the neighborhood scale (see the *Results* chapter) and because the cities in our pilot effort represent a range of cities at different levels of development. Our aim in selecting these cities was to illustrate the range of urban sustainability solutions and challenges, not to "name and shame" or score cities. Future iterations of the UESI may provide an aggregate ranking, but the pilot version is intended to open a conversation to explore more in-depth variation in environmental performance and social inclusion throughout cities, which all stand to improve in each of the UESI's categories.

People do not experience cities uni-dimensionally, so the UESI strives to incorporate spatially-explicit data wherever possible.

Box 2. Measuring Environmental Performance: Proximity-to-Target

There are many ways to summarize and transform raw data to make it comparable. Targets are set by policy goals (e.g., in the case of the Tree Cover per capita target that uses a UN SDG goal of 15 meters per capita), established scientific thresholds (e.g., in the case of the $PM_{2.5}$ indicator that uses the World Health Organization's 10 microgram/m^3 limit for exposure), or an analysis of the top performers (e.g., the top 5th percentile of the distribution of scores). Each indicator is transformed and given a score from a scale of 0 (worst performer or those at the low performance benchmark) to 100 (best performer or those at the top performance benchmark).

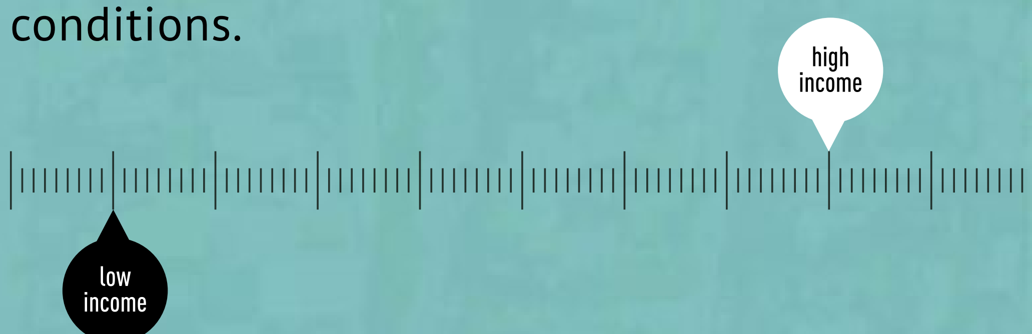
Figure 2. Illustration of the proximity to target methodology



Source: adapted from Hsu et al., 2013)[10].

EQUITY AND SOCIAL INCLUSION

A resident's neighborhood and income level can shape the ways they experience their city's environmental hazards and benefits. The UESI's equity and social inclusion approach evaluates how environmental benefits and burdens vary across a city, and how this distribution relates to socioeconomic conditions.



What it measures

The UESI's approach to equity and social inclusion measures the distribution of environmental harms and goods within a city and assesses the relation between environmental performance and income distribution.

We developed graphic and numeric representations of the distributive equity of selected environmental outcomes (EO) for each city. A city's performance is displayed through a series of curves that illustrate the distribution of both income and environmental burdens throughout a city's neighborhoods. To quantify the relation between the two distributions, we provide a metric - the Environmental Concentration Index (ECI) - that numerically represents the distribution of the environmental outcome in relation to a scenario of perfect equity. In other words, this metric reveals the distribution of the environmental outcome and whether it is unequally allocated to the poorest or richest segments of the population. We have developed a typology that classifies cities based on (1) their overall income inequality and (2) the distribution of environmental outcomes

One caveat to our analysis is that primary demographic and economic data are reported at the neighborhood level. We therefore calculate measures of these characteristics' distribution across neighborhoods, weighted by population, rather than across individuals per se. This approach is equivalent to assuming that all individuals within a neighborhood are identical in terms of both environmental and economic characteristics. We recognize, however, that administrative boundaries often encompass highly heterogeneous populations; some of the wealthiest live juxtaposed to the poorest (see www.unequalscenes.com). Given the granularity of the data, our approach should be interpreted as a first attempt to quantify this issue in several global cities.

Why we include it

The built and natural environment shapes how citizens choose to live their lives to achieve their full potential, and can both enable and hinder their efforts to reach this goal. As described in following chapters, the presence – or absence – of certain environmental conditions have tangible effects in people's health, social capacity, economic opportunities and overall well-being. Unfortunately, unlike other factors – such as income, access to education, health and other public services – the distribution of environmental conditions have been largely left out of many traditional economic and social tools, such as censuses and household surveys, commonly used by governments at every level to inform policies and interventions.

Over the last two decades, there has been an important increase in academic analyses of how environmental benefits and burdens are distributed across different populations. However, there are two important gaps in this research. There are scant consistent, global analyses of environmental distributional equity – while there are important and very relevant tools used for this purpose, they are constrained to specific geographic regions or countries. Additionally, the potential interactions between the distribution of economic and social conditions and the distribution of environmental characteristics has not been extensively explored in global cities.

The UESI aims to address these gaps in the academic literature, complementing local datasets with a broader view of global performance across a range of different cities.

Where the data come from

This analysis draws on population and mean income data from a wide range of national and municipal registries and censuses across the UESI cities (see Metadata). Some cities (e.g., Bangalore, Casablanca, Ho Chi Minh City, New Delhi, Lima and Tel Aviv) do not publish income information at the neighborhood level and were not considered in this calculation. Similarly, equity indicators were only calculated for indicators with spatially-explicit, neighborhood-level data: air pollution, urban heat island, tree cover, and transportation access indicators (see these Issue Profiles and the Metadata for more information about these indicators' data sources). The water and climate change policy indicators are calculated at the city-wide scale; therefore equity indicators were not calculated for these issues.

URBAN ENVIRONMENT & SOCIAL INCLUSION INDEX

DESCRIPTION

The Sustainable Development Goals (SDGs) and social and environmental equity

The United Nations' Sustainable Development Goal 11 (SDG 11) articulates aspirations to make cities inclusive, resilient and sustainable. Specifically, it aims to ensure that people have access to 'adequate, safe and affordable' housing and basic services (Target 11.1) and to 'accessible and sustainable transport systems' (Target 11.2), while reducing adverse environmental impacts (Target 11.6). It also seeks to foster inclusion by enhancing citizens' capacity to participate in urban planning and governance (Target 11.3).[1] Other goals, such as SDGs 5 and 10, seek to promote gender equality, and reduce inequalities among and within countries. While the definition of these goals might not explicitly refer to urban areas, cities have a great part to play in achieving them, due to their prominent political and economic role as well as the fact that over 50% of the global population now lives in cities. The SDG 17 and the SDG 11 Monitoring Frameworks emphasize the need to disaggregate the SDG indicators (e.g., the proportion of people living in slums and the percentage of people with access to public transport) by income, sex, race, ethnicity, disability status and age, to help ensure overall progress does not leave particular groups behind.[2]

TARGETS

What are the targets?

This method develops a descriptive typology for cities' performance, rather than setting specific targets.

Box 1. The landscape of environmental equity tools

By drawing upon concepts from the environmental justice literature, the UESI framework aims to assist cities in tracking progress towards greater inclusion in SDG 11. Environmental justice is an overarching concept that applies social justice considerations in relation to environmental decision-making.[3] Recent literature has identified three primary dimensions of environmental justice: distributive equity, procedural justice, and justice as recognition.[4] Distributive equity emphasizes the distribution of social, economic and political goods, costs, and privileges between members of different genders, social groups, and districts.[5] Procedural justice generally emphasizes the fair access to and democratic participation in environmental policy-making.[6,7] The final dimension, justice as recognition, emphasizes that a key condition for justice is the recognition of diversity and the ways it shapes experiences in the social, political and cultural spheres, which then significantly determines the distribution of goods and harms.[8] See the UESI online portal for a detailed overview of different elements and definitions around environmental justice.

To inform the development of the UESI's environmental equity indicator, we reviewed 33 studies and tools attempting to measure social or environmental equity. These include environmental equity screening tools developed in the United States, social deprivation indices applied across Europe, as well as environmental justice and pollution assessments in relation to socioeconomic inequalities in Korea, Hong Kong, and Brazil.

These 33 analyses predominantly emphasize the distributive dimension of environmental equity. They allow stakeholders to identify the distribution of environmental hazards and exposures in relation to demographic considerations, which generally span income, minority/ethnicity status, employment status, age group, and education levels.

These tools seek to analyze specific measures of environmental inequalities, such as the level of access to green space and transportation infrastructure; identify key areas for improvement in public health; or more broadly survey a spectrum of environmental justice issues. Some of the broad spectrum analysis tools surveyed within the United States, such as EJSCREEN and CalEnviroScreen, primarily rely on environmental and sociodemographic indicators to quickly identify communities with potential environmental concerns. This approach also helps locate especially vulnerable populations, such as schools or hospitals.[9,10]

Across these tools, data unavailability, as well as uncertainty within accessible data, create persistent challenges. Environmental equity tools can only offer information that is as detailed as the primary sources they draw on to gather data about demographic indicators and environmental benefits and hazards. These data are often unavailable at finer scales, or over a wide geographic range. New York City, for instance, has income data at the census tract and block group scales, which are both much smaller than a district, while other cities have similar data only aggregated to the city level. There are critical challenges when establishing a computational approach to balancing data quality, consistency, scale and coverage.[11] There are also serious considerations around identifying vulnerable populations at granular scales that could be used[12] either by political parties or special interest groups.

Even where data are available, these data may themselves be proxies, estimates of actual values, or projections that have inherent uncertainties. Some tools assume that levels of environmental hazards at places of residence are appropriate proxies for actual exposure. Data on the time spent at home or at work, however, are often unavailable. In addition, indices may use data sources that themselves aggregate multiple data sources when measuring exposures, toxicities or emissions.[13] As a result, tools such as EJSCREEN and the EJSM can only serve as screening tools to identify potential environmental justice communities, and not as formal assessment tools.[14,15]

Finally, the tools surveyed differ in their notions of equity, and thus select different indicators to represent socio-economic status. The US-based EJSCREEN, for instance, includes low-income and minority populations in their calculations, while California-based Environmental Justice Screening Method (EJSM) prioritizes "sensitive land uses" of areas with high concentrations of elderly citizens, children and populations with illnesses.[16] This diversity reflects the importance of environmental equity, as well as the challenges of measuring such an expansive and far-reaching topic.

Environmental equity in the UESI

The UESI framework focuses on distributive equity, a key component of environmental justice. While procedural representation and recognition are important conceptual components for the environmental justice principle, data that measures or approximates these pillars of equity is scarce across all UESI cities. By focusing on a set of core issue areas – exposure to air pollution, urban heat island effect, distance to public transportation, and tree cover per capita – we show how environmental burdens vary across neighborhoods of different income levels within cities. This approach is in line with current environmental justice and equity assessment tools such as EJSCREEN[17] and the Environmental Justice Screening Method (EJSM), enabling stakeholders to identify the distributions of environmental hazards and exposures in relation to demographic considerations (see Box 1, *The Landscape of Environmental Equity Tools*).[18] While such demographic considerations may include multiple socioeconomic variables to highlight cumulative social vulnerabilities and intersectionalities from education levels, minority/ethnicity statuses, or age compositions, data on these variables at the desired neighborhood scale is only available and complete for a few cities (See Box 2, *Bringing an intersectional analysis to the UESI*). Balancing data quality, availability and coverage, the UESI focuses primarily on understanding how urban residents with varying income levels may be affected by environmental conditions.

To ensure a consistent analysis across all cities, we utilize income (both household and average individual income), which is largely available at the neighborhood scale, as the primary socioeconomic indicator. Income data for each city comes in different currencies, years and units (e.g. household vs. individual income, monthly vs. yearly income, number of people within an income bracket vs. mean/median income within a neighborhood). We standardize the income data to represent the per capita income for each district maintaining the national currency of each city. In addition, it is worth mentioning that some neighborhoods had no data available due to statistical confidentiality and thus were excluded from the analysis.

The UESI shows how environmental burdens vary across neighborhoods of different income levels within cities.

Calculating equity and social inclusion in the UESI

Building on the rich literature and tools for analyzing distributions of environmental outcomes,[34,35,36,37,38,39] the UESI has developed an approach for analyzing environmental and socioeconomic conditions. The UESI approach draws heavily on the use of graphical representations, such as concentration and Lorenz Curves, to capture the distribution of environmental outcomes and income across a city. In addition, the UESI approach includes a numerical representation of the distribution of income and environmental outcomes. Together, these representations shed light on the relationship between the distribution of environmental outcomes and income within cities.

Graphical representations of income and environmental outcomes

We use Lorenz and concentration curves to analyze the distribution of income and environmental outcomes (Air Pollution, as measured through Average Exposure to $PM_{2.5}$ and NO_2; Urban Heat Island Intensity; Distance to Public Transit; and Tree Cover per capita) respectively, and for each city. Both the Income Lorenz Curve and Environmental Concentration Curve are ordered by per capita income. In the plots, the x-axis refers to the cumulative proportion of a city's population - ranked by income - and the y-axis is the cumulative proportion of income or environmental outcome distributed throughout the city for the Income Lorenz Curve and the Environmental Concentration Curve respectively. A 45-degree line that represents perfect distributive equity is also included as a frame of reference. If income and environmental burdens were distributed equally across each fraction of a city's total population, the Lorenz and concentration curves would look like the 45-degree line.

Due to its definition, the Lorenz income curve will never be above the 45 degree line (i.e., the line of perfect equity). The distance between the income Lorenz curve and the 45 degree line of perfect equity indicates the degree of income distribution inequality: a greater distance between the two lines indicates a more unequal distribution. Environmental Concentration Curves can be either above or below the line of perfect equity, and positions suggest different interpretations. If the curve is fully located above the line of perfect equity it indicates that the environmental outcome is more heavily allocated to those with less income. On the contrary, if the curve is fully located below the line of perfect equity it indicates that the environmental outcome is more heavily allocated to those with more income.[40,41] However, it's important to note that Environmental Concentration curves can have sections located at both sides of the 45 degree line; in this case the interpretation will not be as straightforward as mentioned before, and the interpretation relies on additional metrics, that we will explore in the following sections. Figure 1 provides a graphical representation of the Environmental Concentration Curves and their interpretation.

Box 2. Bringing an intersectional analysis to the UESI

Intersectionality explores how different structures of oppression can reinforce one another to make certain identities more vulnerable than they often appear to be when we view structures of oppression in isolation.[19,20] Legal scholar Kimberlé Crenshaw, who first coined the term intersectionality, points out that Black women face a set of challenges that include both sexism and racism and, therefore, that a feminist movement that confronts sexism without confronting racism fails to empower all women. Structures of oppression, such as racism and sexism, are societally pervasive structures of supremacy that accord privileges to certain identities by discriminating against others through ideological domination, institutional control, and targeted abuse.[21] An intersectional framework highlights how it is insufficient to merely address systems of oppression in isolated ways. They must be dealt with simultaneously, as these systems operate in ways that are larger than the sum of their parts.[22]

Similarly, it is well established that socioeconomic status is not the only determinant of vulnerability. An economic analysis of inequity, one that relies only on income as a variable, can fail to fully capture the complexity of the people impacted by distributional differences in environmental amenities and burdens. As indicated previously in this report, income level is used as the primary socioeconomic indicator because the data is available for standardization across all of the UESI's cities. However, policymakers who rely solely on income as a way of understanding equity may miss several aspects of people's lived experiences and thus risk developing incomplete policy solutions. "The urban poor" do not all look the same, nor do they experience environmental pollution or lack of environmental amenities in the same way.[23]

A study conducted across the United States found that households of similar economic statuses have dissimilar exposures to environmental hazards based on their racial composition.[24] As mentioned in the Air Pollution Issue Profile's *Environmental Injustice and Exposure to Air Pollution* box, the national U.S. rate of exposure to particulate matter is higher for Black populations even once income level and geographic scale has been accounted for.[25] Women are systematically paid less than men (in the United States, a reality even more pronounced for women of color),[26] and thus their reliance on environmental services like public transport can be more acute. At the same time, as highlighted in the Transportation Issue Profile, women experience harassment on public transportation at disproportionally higher rates than men.[27,28,29] Similarly, in water-stressed areas, due to gendered divisions of labor, the onus to find water for their households often falls on women.[30] These are a few examples that highlight how environmental inequities operate in ways that are linked to, but more complex than, income situations. Policy solutions should be sensitive to these inequities. For instance, bringing more public transit options to a low income area may be beneficial to some, but could still exclude women or people living with disabilities if specific measures to include them are not put in place.

It is essential to remember that systems of oppression manifest differently depending on the context. In

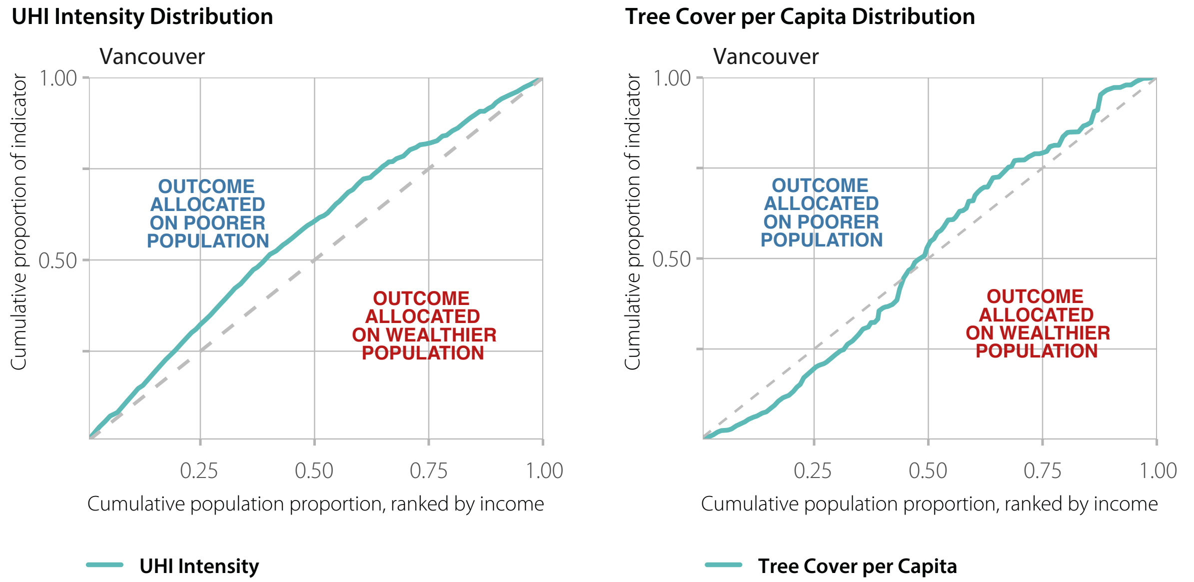
the United States, for example, white men have historically led the environmental movement, perpetuating systems that value heterosexuality, whiteness, and maleness at the expense of those who do not fit those categories.[31] The consequence of this is the development of environmental "solutions" that disproportionately reflect the value sets of this limited group of policymakers and advocates. This can be seen, for instance, in the creation of national parks that conceptualize nature as a commodity and indigenous communities as lesser beings responsible for threatening the United States' "pristine" landscapes.[32] However, understanding this array of social dynamics may do nothing to clarify the social dynamics in a different country. Intersectionality requires high-degrees of local contextualization, which is another reason the UESI, as a global index, relies on income to provide a first assessment of environmental equity. Generally speaking, communities who don't have access to systems of power and policy decision-making are also those who experience poverty the most acutely.

Finally, understanding the connection between income and environmental amenity provisioning is essential to the development of equitable environmental improvement policies. In general, proximity to amenities like green spaces and subway station increases housing property values, which may threaten low-income renters.[33] Infrastructural upgrades, including improving water resources, sustainable transportation, and green spaces, often rely on these property value increases to fund their installation. Ensuring that a neighborhood improvement will not result in the displacement of these communities, or other unforeseen consequences, is a crucial element in interpreting UESI data in a way that will truly lead to equitable and sustainable urban development.

Socioeconomic status is not the only determinant of vulnerability.

The urban poor do not all experience environmental pollution in the same way.

Figure 1. Examples of Environmental Concentration Curves and their interpretation.



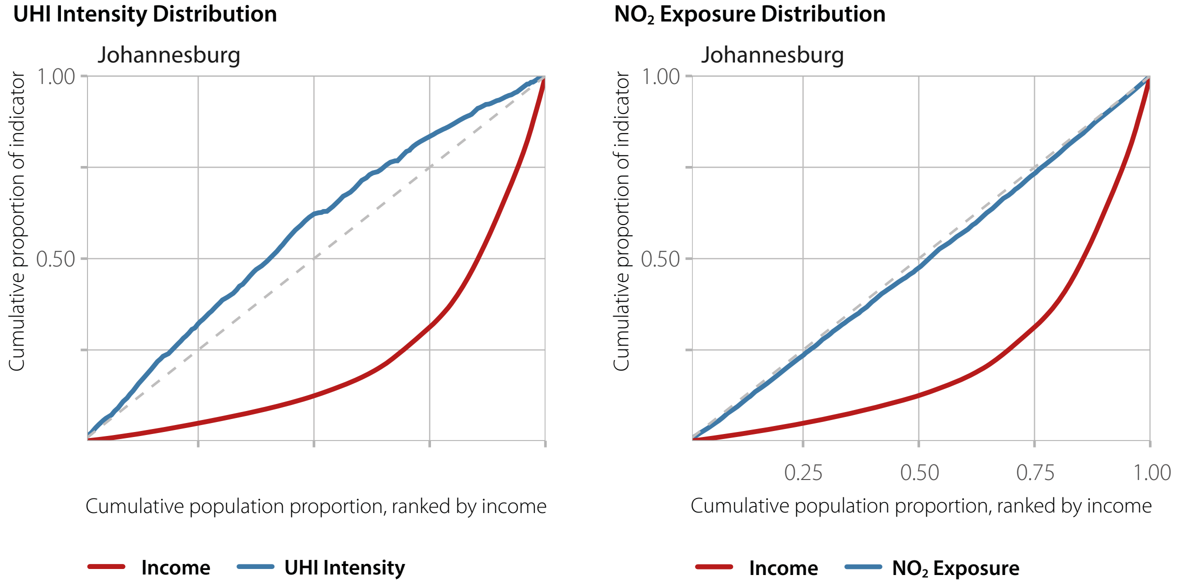
The left panel shows an Environmental Concentration Curve that falls above the line of perfect equity, indicating the environmental allocation is placed more heavily on the poorer population. The right panel shows a concentration curve that falls simultaneously on both sides of the line of equity, making it difficult to obtain a conclusion about the burden allocation based exclusively on the curve, which we address in the next section using a numeric representation.

The specific interpretations of the concentration curves for different indicators follow below:

- **$PM_{2.5}$ Equity:** Cumulative proportion of total exposure to $PM_{2.5}$ concentration for the entire population (Negative Environmental Outcome)
- **NO_2 Equity:** Cumulative proportion of total exposure to NO_2 concentration for the entire population (Negative Environmental Outcome)
- **UHI Equity:** Cumulative proportion of total exposure to UHI Intensity for the entire population (Negative Environmental Outcome)
- **Tree Cover Equity:** Cumulative proportion of the total Tree Cover per capita for the entire population (Positive Environmental Outcome)
- **Distance to Public Transit Equity:** Cumulative proportion of total distance to nearest public transportation station for the entire population (Negative Environmental Outcome)

An example of two sample Environmental Concentration Curves and the Income Lorenz Curves for Johannesburg can be seen in Figure 2. It is important to note that the concentration curves do not indicate whether the cumulative exposure to air pollutants, UHI intensity, tree cover per capita, or distance to public transportation for a given city

Figure 2. Distribution of Income Lorenz Curve (Red), UHI Intensity (Blue) and NO_2 Exposure Concentration Curves (Blue) for the city of Johannesburg.



is large or small. They simply indicate whether the distribution of these environmental burdens is more or less equally distributed relatively to income.

The Environmental Concentration Curve results indicate that UHI Intensity is concentrated in the low-income populations in the city. By contrast the NO_2 exposure is only slightly more concentrated in high-income populations, and still within a marginal distance from the line of perfect equity. Finally, the Income Curve indicates that there is an important inequality in the distribution of income, due to the distance of the curve to the 45 degree line of equity.

Numeric representations of inequality of income and environmental outcomes

While numeric metrics have been developed to analyze distributive equity in different fields, their use has not been as extensive as graphical representations in assessing environmental outcomes. Existing examples of the use of numeric metrics to environmental assessments include Padilla and Serrano's (2006) use of the Kakwani Index,[42] and inequality indices such as the Atkinson and Kolm-Pollack, as detailed by Maguire and Sheriff (2011).[43] Although methodologically robust, the construction and interpretation of these indices can be challenging from a decision-maker's perspective, particularly due to the complex mathematical definition of the indices. Therefore, building on the literature around the use of concentration indices as an accepted measure of inequalities, particularly around health-related outcomes,[44,45,46,47] we use this approach to to explore the relationship between income and environmental outcome distributions.

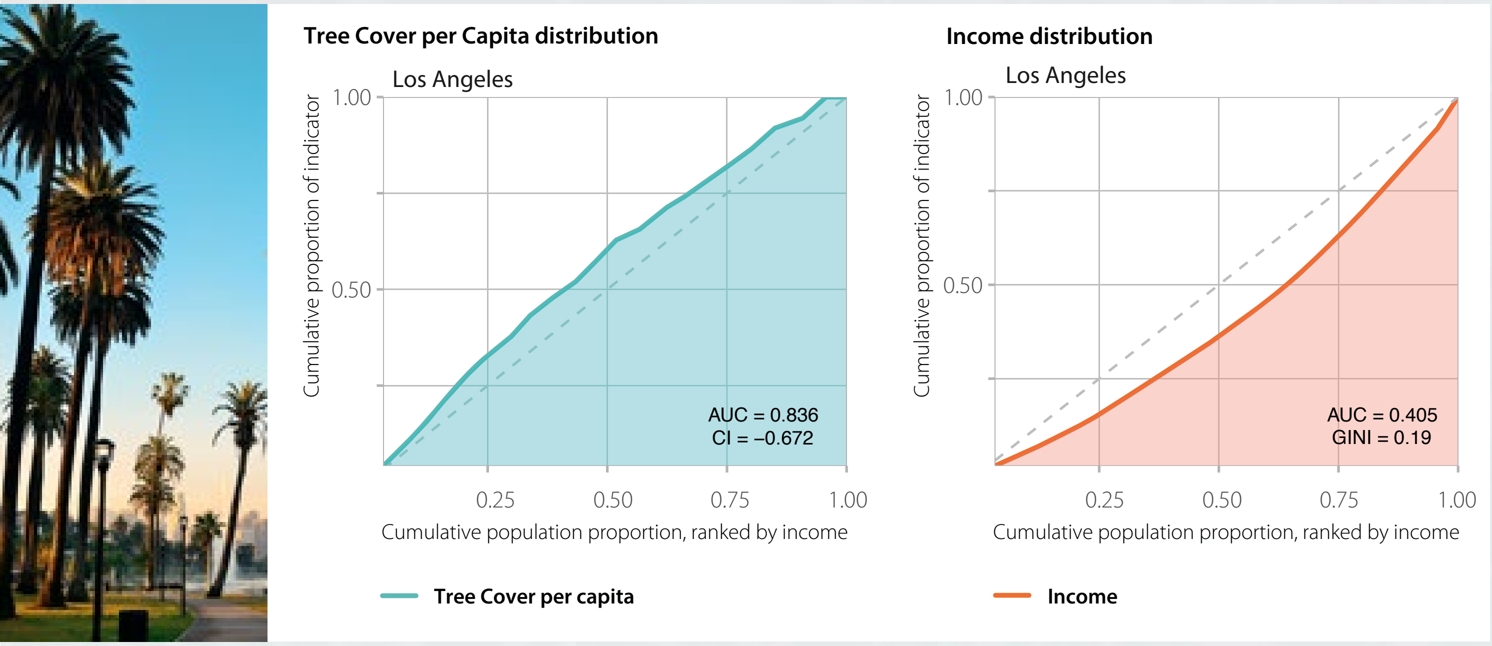
The UESI's approach to numerically quantifying inequality uses the concentration curves presented in the previous section, and calculates a summary measure called the Environmental Concentration Index (ECI) using the following formula:

$$ECI = 1 - 2*AUCenv$$

Where ECI is the concentration index for the environmental outcome (env) and AUC is the area under its corresponding curve.[48] A concentration index value can range from –1 (i.e, the environmental burden is allocated to the poorest individual) to 1 (i.e., the environmental burden is allocated to the wealthiest person).[49] The ECI serves a summarizing feature, providing a numeric value of inequality in a city, which is particularly useful for when conclusions are difficult to obtain from the graphical representations alone. Given its definition,[50] however, the absolute value of the ECI is the net inequality of a city, while the sign, positive or negative, indicates where that net inequality is allocated, whether to richer or poorer populations. As a result, while useful by themselves, the ECI values should be analyzed in conjunction with the curves to have a more accurate interpretation of the results around the presence of different pockets of inequality.

Complementary to the ECI, the UESI also calculates the Gini Coefficient for each city – a commonly used metric of income inequality – using the already defined Lorenz Curve for income. This calculation is done using the same formula as the ECI, as both of them are based on the area under the curve (AUC) value. A graphic example of these calculations is shown in Figure 3.

Figure 3. Example of Environmental Concentration for Tree Cover per Capita and the Lorenz Income Curve for the city of Los Angeles.



Typology of relationships between income and environmental outcomes

Even though the ECI provides an important metric to describe the relationship between income and the environmental outcome, the picture is still incomplete because each city's income inequality is a relevant factor to consider. To contextualize these results in a more meaningful way and to understand the interplay between environmental and socioeconomic inequalities, we developed a typology to categorize where cities fall in relation to each other using both the ECI and the Gini coefficients.

The typology's four quadrants are defined based on two axes. The x-axis denotes the Environmental Concentration Index of a variable and the y-axis denotes the income inequality, as expressed through the Gini coefficient. The UESI uses a Gini coefficient value of 0.36[51] and an ECI value of 0 to separate the quadrants.

To better understand the potential interaction between both distributions, it is important to consider that the income distribution of a city – represented in the Gini value – reflects the level of homogeneity in the allocation of economic resources obtained by a household, resources that are used to provide an adequate standard of living for its inhabitants. On the other hand, the distribution of environmental outcomes – represented by the ECI values – reflects the inequality in the allocation of positive or negative environmental conditions that affects a sector of the population, which can impact their economic conditions, positively or negatively, relative to other segments of the population.

For example, a group of people disproportionately burdened by air pollution (a negative environmental outcome), such as $PM_{2.5}$, may be further economically disadvantaged through additional healthcare costs resulting from air pollution-related respiratory problems. In another example, a segment of the population that has less access to Tree Cover (a positive environmental outcome) would have to spend resources, such as time and money, to travel to another area with higher tree cover if they expect to enjoy the same benefits tree cover affords.

This impact of the environmental allocation on the income distribution, which we call *environmental pressure*, is then a potential source of inequality – unaccounted by most traditional analysis. When the environmental pressure is placed on the poorer segments of the population - either though an unequal allocation of negative environmental outcomes to the poorest, or positive environmental outcomes to the richest – it can exacerbate the inequalities between the poorer and richer residents of a city to different degrees, by increasing the resources that the poorest need to invest to compensate for the negative impacts, or for gaining access to the positive ones. These degrees to which environmental burdens exacerbate income inequality are described by the scenarios detailed in the quadrants in Figure 4. The interpretation of the ECI values related to the quadrants will depend on the type of environmental outcome (EO) analyzed, positive or negative.

Environmental pressure: how environmental burdens and benefits interact with income distribution.

Before exploring the results of this novel approach for analyzing environmental and income distribution among our cities, there are a few considerations that are relevant for discussion. The most significant difference is in the UESI's use of neighborhood-level information to make comparisons, unlike more traditional uses of the Lorenz and concentration curves whose data points are generally at the individual level. While making our equity calculations on the neighborhood level may disregard heterogeneity within neighborhoods, the UESI reflects a more conservative reflection of inequalities than those that happen at the micro or individual scale.

Figure 4. The four-quadrant typology of the UESI.

Positive EO	Positive Concentration Index (> 0)	Negative Concentration Index (< 0)
Negative EO	Negative Concentration Index (< 0)	Positive Concentration Index (> 0)
Low Gini (< 0.36)	**Cities where the environmental outcome is allocated to the lowest income earners (Low ECI) and there is low income inequality (Low Gini).** In this quadrant, although there is low income inequality, the environmental pressure potentially exacerbates the gap between poorer and richer citizens. 1	**Cities where the environmental outcome is allocated to the highest income earners (High ECI) and there is low income inequality (Low Gini).** In this quadrant the allocation of environmental outcomes is placed among the highest earners of the city, potentially avoiding environmental pressure on lowest earners. 2
High Gini (> 0.36)	**Cities where environmental outcome is allocated to the lowest income earners (Low ECI) and there is high income inequality (High Gini).** The existing income inequality is prominently exacerbated by the environmental pressure, significantly increasing the gap between poorer and richer citizens. 3	**Cities where the environmental outcome is allocated to the highest income earners (High ECI) and there is high income inequality (High Gini).** The existing income inequality is not exacerbated by the environmental pressure, as it is allocated to the highest income earners. 4

RESULTS

The results of this analysis have highlighted important aspects of inequality and its relation to environmental burdens. The overall results suggest that while some cities in the global South, such as Johannesburg, are remarkably unequal in their income distribution, income inequality occurs in both developing and developed world cities. For instance, cities in the U.S., such as Boston and Atlanta, have relatively high income inequality, while cities in the global South, like Jakarta, demonstrate lower income inequality.

In general, most cities included in the analysis are located in the low-income inequality quadrants (top right and left quadrants) of the typology, while Johannesburg is the only city of our sample located in the high income inequality quadrants (bottom right and left). The remaining cities are variable in terms of how environmental outcomes affect different populations. This variability demonstrates that in every population, regardless of average income, there is a sector that is in some way disproportionately burdened with negative environmental outcomes or benefiting from positive environmental outcomes.

For detailed analyses, results and interpretations of equity calculations, please refer to the corresponding chapters.

Income inequality occurs in both developed and developing world cities.

AIR POLLUTION

Air Pollution has become a hallmark of urban life, with more than more than 96 percent of the population living in the UESI cities breathing unsafe air.[1]

96%

URBAN ENVIRONMENT & SOCIAL INCLUSION INDEX

6th leading
cause of death worldwide

4.2 million
deaths worldwide from $PM_{2.5}$ exposure in 2016.

What it measures

This issue category includes three indicators: Average Exposure to $PM_{2.5}$ (fine particulate matter in micrograms per cubic meter (µg/m^3); Average Exposure to Nitrogen Dioxide (NO_2) (ppm); and $PM_{2.5}$ Exceedance (average percentage of the population exposed to $PM_{2.5}$ levels at 10 µg/m^3, 15 µg/m3, 25 µg/m^3, and 35 µg/m^3, which represent the World Health Organization's (WHO) interim I, II, and III targets, respectively according to its air quality guidelines).[2]

Why we include it

Air pollution is a growing, worldwide problem that afflicts urban areas in both developed and developing countries. Although rural air pollution is a concern, particularly in households that still combust solid fuels indoors for cooking and heating, nearly every urban area in the world experiences unsafe air quality, whether episodically or on a continuous basis. Suspended air particles contribute to cardiovascular disease, stroke, acute lower respiratory infections and other diseases such as cancer. They can penetrate human lung and blood tissue, leading to higher incidences of cardiovascular and lung disease. Fine particulates, or $PM_{2.5}$ (2.5 microns and smaller), lodge deep in blood and lung tissue and are particularly injurious to human health.

Nitrogen dioxide (NO_2) is also harmful to humans both directly, and and when it reacts with other compounds like sunlight and volatile organic compounds (VOCs) to produce ozone or secondary particulate pollution.[3] Strong associations between NO_2 and mortality have been identified in multi-city studies around the world.[4] According to the U.S. Environmental Protection Agency, direct exposure to NO_2, ranging from 30 minutes to 24 hours, can cause airway inflammation and negative respiratory effects for people with asthma.[5] Direct inhalation of both ozone and NO_2 can aggravate the human respiratory system, especially in people who have respiratory illnesses such as asthma. Prolonged exposure to elevated concentrations of NO_2 can also lead to asthma development and leave people more susceptible to respiratory infections.[6] NO_2 can also serve as a robust indicator of many traffic- and combustion-related pollutants that are not always monitored routinely.[7]

Where the data come from

- Dalhousie University's Atmospheric Composition Analysis Group provides the satellite-derived $PM_{2.5}$ and NO_2 data.
- Population data to measure the proportion of the population above various $PM_{2.5}$ concentration thresholds are obtained from the Global Rural Urban Mapping Project, v.4[8] at the NASA Socioeconomic Data and Applications Center, hosted by the Center for International Earth Science Information Network (CIESIN) at Columbia University.

For more information, see Metadata.

DESCRIPTION

Risks and sources of air pollution

Air pollution is the leading environmental risk factor for death worldwide and the fifth leading cause of death overall.[9] It claims around 4.2 million lives a year, and more than 92 percent of the global population breathes unsafe air.[10] The primary culprit for air-pollution-related deaths is fine particulate pollution, made up of particles smaller than 2.5 microns in diameter ($PM_{2.5}$), which are fine enough to lodge deep into human lung and blood tissue. A complex mixture of toxic particles, particulate matter places exposed populations at risk of cardiovascular and lung disease, ranging from stroke to chronic obstructive pulmonary disease, asthma, and lung cancer.[11] Elderly populations and young children are particularly vulnerable to health effects of $PM_{2.5}$. The leading cause of mortality for children between the ages of one to five is pneumonia, and half of these cases are due to air pollution.[12]

Airborne particulates originate from a variety of natural and anthropogenic sources. $PM_{2.5}$ is primarily the product of combustion, whether from human activity, such as burning coal or car emissions, or through forest fires and volcanoes. In parts of Asia, where coal combustion is the primary source of electricity generation, $PM_{2.5}$ pollution has led some cities, like Beijing, to eliminate coal-fired power plants

TARGETS

What are the targets

10 μg/m³ for Average Exposure to $PM_{2.5}$ (fine particulate matter)

0 for $PM_{2.5}$ Exceedance

1st percentile for Average Concentration of NO_2.

as part of their air pollution control plans.[13] In other parts of the world, wildfires, such as those that have plagued Western U.S. states like California, are a major source of PM.[14] $PM_{2.5}$ can also be generated through secondary formation, when other precursor gases, such as sulfates from power plants and industrial facilities and nitrates from mobile sources and power plants, react in the atmosphere. During winter months, secondary PM formation can be particularly acute due to temperature inversions that trap warm air – and pollutants – below a layer of cold air. Temperature inversions and the secondary formation of $PM_{2.5}$ during cold winter months are the primary cause of high levels of air pollution observed in cities like New Delhi. India's capital city experienced air pollution levels 30 times higher than WHO recommended levels in November 2017. Its Chief Minister equated the city to a gas chamber.[15]

Nitrogen dioxide (NO_2) is derived from combustion processes similar to particulate matter formation. It forms from road traffic and power plants, and is a precursor to particulate matter and ozone, which also have significant human health effects. Ground-level ozone at high concentrations, particularly during summer months, is a major component of urban smog. It can have acute respiratory health effects and has been responsible for a million premature deaths each year.[16]

NO_2 pollution has increased in many European countries where diesel fuel is subsidized, in some cases by as much as 15 percent more than other less-polluting fuels.[17] Diesel cars are also not subject to the same strict emissions testing as other vehicles, such as heavy trucks and buses, meaning that modern diesel cars produce 10 times more air pollution than other kinds of vehicles.[18] This problem came under international scrutiny when "Dieselgate" revealed that Volkswagen had been circumventing NOx emissions controls on its vehicles, resulting in higher emissions than lab tests suggested.[19] A European Environment Agency report found that Italy had the highest number of NO_2-related deaths in 2013, at 20,000, and London hosted the continent's worst NO_2 hotspot, at double the allowable EU limit.[20]

Urbanization and air quality

Now that more than half of the global population lives in cities, air pollution has become a hallmark of urban life. Industrialization has concentrated economic activity in cities, which are responsible for some 80 percent of global gross domestic product (GDP).[21] This aggregation has increased population density in urban areas relative to rural surroundings, creating larger demands on energy and natural resources while generating pollution and waste. The growth of personal car usage, building stock, and energy demand has led to severe air pollution crises in many cities around the world. London, for instance, was reported to have air pollution levels worse than Beijing in January 2017, reaching 197 on the Air Quality Index (AQI) (see the UESI online portal for a box on *Communicating Air Quality*).[22] Paris became so polluted in 2015 that the city government enacted emergency measures, such as restricting vehicles and subsidizing public transportation

A global risk

92%

of the global population breathes unsafe air

use.[23] Los Angeles has notoriously struggled with air pollution for decades, with smog levels persisting despite decreasing emissions in recent years.[24] Globally, about 95 percent of the world's population breathes outdoor particulate matter concentrations in excess of the WHO's Air Quality guideline (annual mean concentration less than 10 µg/m^3). Nearly 60 percent of people live in areas where fine particulate matter exceeds the acute WHO air quality target (35 µg/m3)[25]. The WHO notes that there is no threshold concentration for particulate matter below which no damage to health is observed, indicating that the vast majority of the global population is being exposed to air pollution with deleterious health effects.[26]

With worsening air pollution in urban areas, city managers have implemented a range of policies to address it. These efforts include tackling emissions sources, such as coal-fired power plants, to encouraging efficiency and cleaner fuel standards for motor vehicles. Since transportation is the number one contributor to air pollution in many urban areas around the world, many cities have made reducing transit-related emissions a top priority. For nearly two decades, New Delhi, for instance, has mandated that all public transportation use compressed natural gas (CNG), which is lower in emissions than diesel, to lower the transport-related emissions that drive its pollution. Now that the number of private vehicles have far outpaced other transportation modes in the capital city, the government is looking to expand public transit options to address its growing air pollution problem.[27] Other cities, like Singapore, are planning to restrict the total number of vehicles altogether, by outlawing future increases in private vehicle ownership.[28]

Globally, growing policy attention has focused on air quality as an urban issue, with air pollution inserted as a target in Sustainable Development Goal (SDG) 11 for cities. Goal 11, to "Make cities inclusive, safe, resilient and sustainable," sets a target to "reduce the adverse per capita environmental impact of cities" with particular attention to air quality."[29] Air is also included in the opening text of the Sustainable Development Goals (SDGs), cementing the issue as central to both sustainable development and human health.

Towards improved monitoring

Despite its known health impacts, global monitoring of air pollution is lagging, usually because of lack of capacity, resources, technology, or public demand. Monitoring gaps primarily occur in developing countries outside of North America and Western Europe, where air pollution is more severe and the number of air-pollution related deaths has increased dramatically over the last 15 years (see Figure 1).[30] Given the sparseness of ground-based monitors, satellite-derived estimates have been utilized for global comparability and applied in epidemiological studies.[31] Satellites develop "wall to wall" measures of aerosols and pollutants in the earth's atmosphere, enabling consistent side-by-side comparisons between entities. While a potent proxy, these satellite data fail to measure ambient air conditions directly at the ground where people breathe. They can also miss short-term spikes in air pollution that can occur episodically, particularly if the sensor fails to pass through an area during these acute events. Satellite estimates are also averaged over long periods of time, tending to smooth out and present lower pollution concentration values than a city might experience on an hourly basis.

Haze over eastern China, NASA Goddard, 12/8/2017

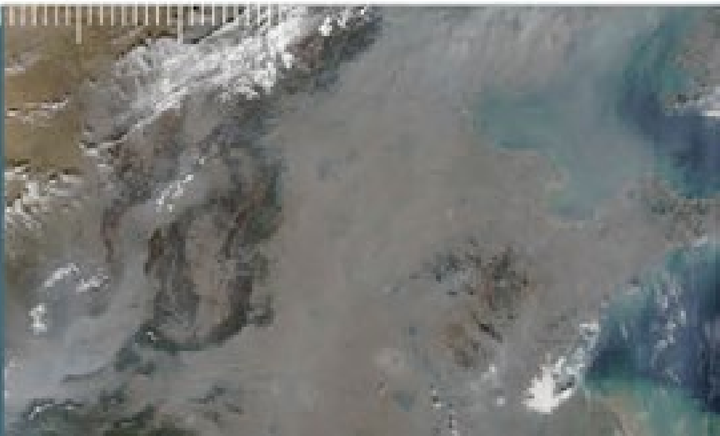
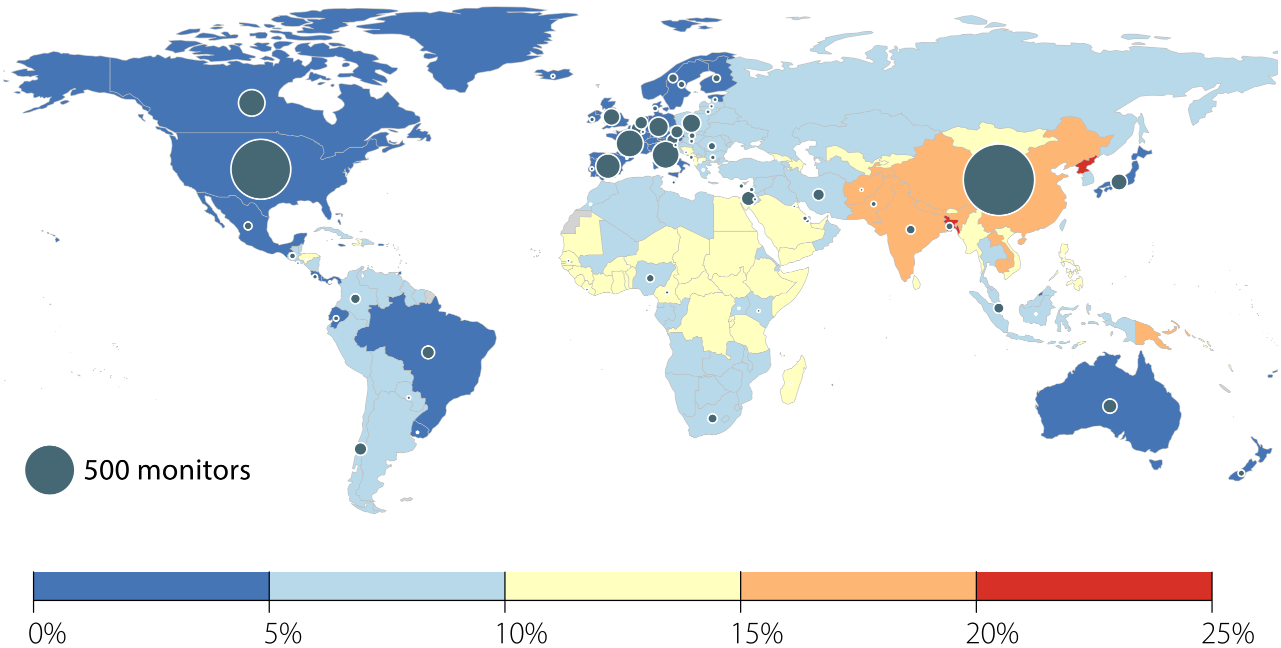


Figure 1. Percentage of air-pollution related deaths in 2016 compared to availability of ground-based monitoring data.



A map juxtaposes the number of ground-based $PM_{2.5}$ monitoring stations with the proportion of air pollution-related deaths within each country. Purple points represent the number of monitoring stations within each country (larger sizes indicate a higher number of monitors); the point size for 500 monitors is included in the legend for reference. The percentage of air-pollution related deaths relative to all causes of death in a country is shaded from blue to red. A shortage of ground-based monitoring sites are found in countries where air-pollution related deaths are highest.

Data sources: IHME, 2017 and WHO, 2016.[32]

A growing number of bottom-up, citizen-driven and private efforts show promise to improve the landscape of global air quality monitoring (see the UESI online portal for a discussion of how *Air Quality Data are Getting Bigger*). Improvements in technology, including low-cost air sensors, are critical in helping to fill air quality gaps and allow for the real time monitoring of health risks. These new data are helping citizens and governments understand new sources of air pollution, identify personal health exposure risks, and forecast future air pollution events.

Combined with other sources of near real-time data, citizen-generated information is providing new, previously unexplored insights into the economic and social costs of air pollution (see *Hacking Data for Climate Action: Data Philanthropy Provides Real-Time Data* on the UESI portal).

RESULTS

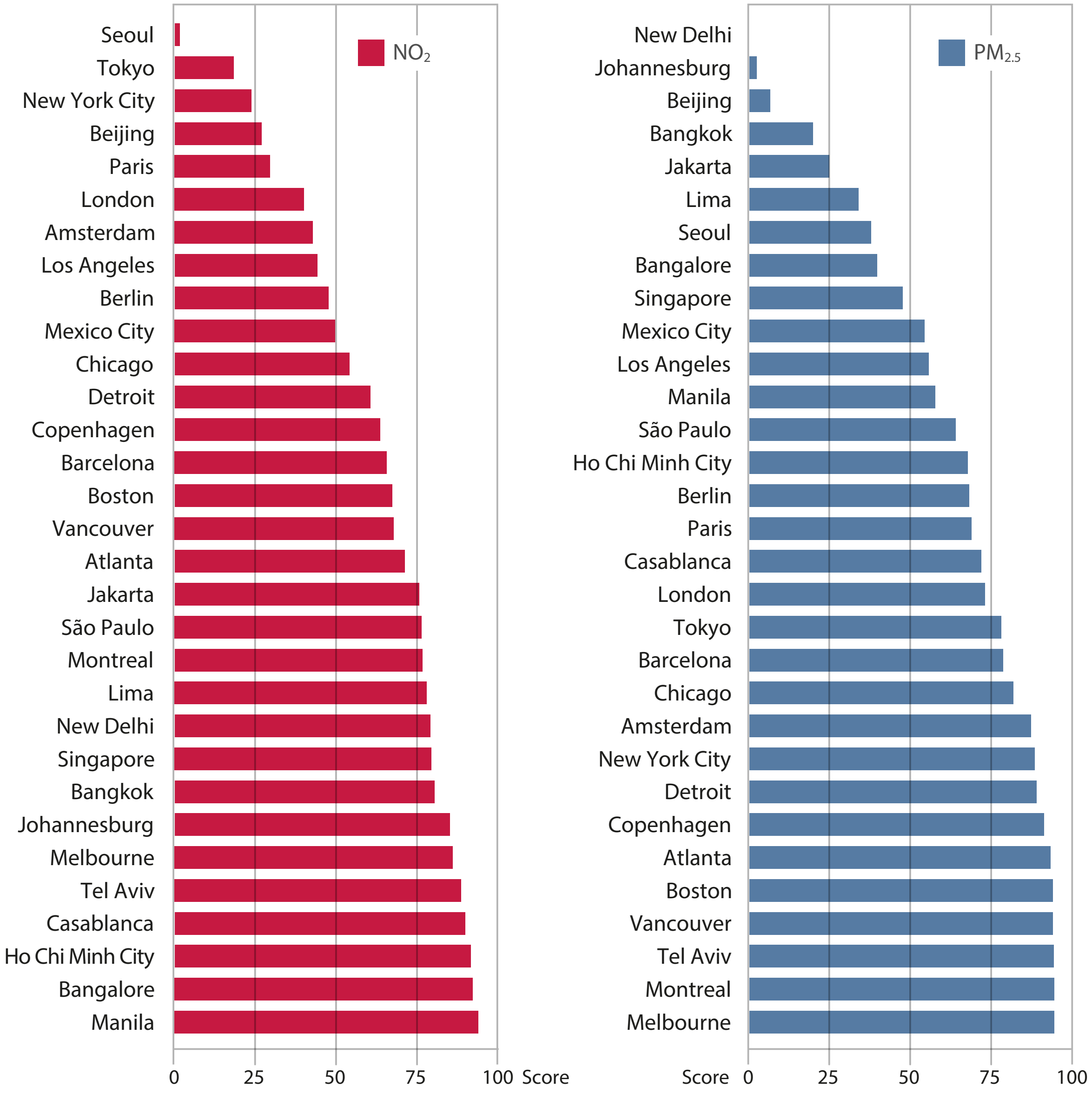
Cities in the UESI show a range of results for air pollution (Figure 2). A high score indicates better performance on that air pollution metric, while a low score indicates comparatively worse performance. Delhi, which includes India's capital city New Delhi, scores the lowest on average exposure to $PM_{2.5}$ pollution with a score of 0, reflecting the highest average annual concentrations of $PM_{2.5}$. The average summer-time concentration of $PM_{2.5}$ in Delhi is approximately 300 µg/m3, compared to the acceptable level of 60 µg/m3 set by Delhi's Department of the Environment. The Department attributes these pollution levels primarily to airborne road dust, soil and ash as well as combustion-related carbons from energy generation, automobiles, and the burning of municipal waste.[33] Climatic conditions exacerbate the air pollution problems experienced in India. In general, cities in more developing countries perform poorly when it comes to $PM_{2.5}$ pollution. Los Angeles and Singapore are notable exceptions to this trend, both having scores less than 75. $PM_{2.5}$ production in these cities is primarily due to combustion, such as from burning coal, car emissions, and forest fires. The National Environmental Agency of Singapore attributes its air pollution levels to the same factors that affect most major cities, including industrial and motor vehicle emissions. However, the Agency notes that "Singapore enjoys an air quality better than many cities in Asia and is comparable with the air quality of US and European cities."[34]

New Delhi scores worst in $PM_{2.5}$ exposure; Seoul performs poorest in NO_2.

In contrast to $PM_{2.5}$, NO_2 performance appears worse in more developed countries. Primarily developed country cities like Seoul, Tokyo, New York City, Paris, London, and Amsterdam all have scores below 50, while Los Angeles and Berlin score only moderately higher. These low scores likely reflect the use of diesel fuel in motorized vehicles as described above.

Although regulations against polluting vehicles have strengthened in many of these cities over the past decades, pollution levels have continued to rise. Following the Volkswagen emissions scandal, studies by the German, French and British governments found that vehicle manufacturers routinely take advantage of loopholes in European Union regulations in order to produce vehicles that do not meet emissions standards.[35] These revelations have led many cities to propose new regulations regarding diesel-burning vehicles. In London, where approximately 40 percent of the city's air pollution is due to diesel vehicles, a new regulation applies a daily monetary fine to vehicles that do not meet European Union emissions standards.[36] The UESI results demonstrate the importance of tighter and more effective NO_2 regulations.

Figure 2. Comparison of NO_2 (red) and $PM_{2.5}$ (blue) proximity-to-target scores across cities.



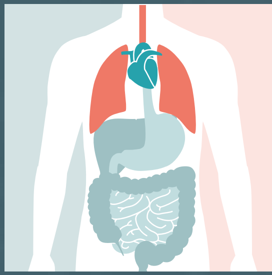
A score of 100 means a city has achieved the target, while 0 represents the low performance benchmark.

INEQUITY IN AIR POLLUTION EXPOSURE

Recent policy attention has also focused on the unequal distribution of air pollution within an urban area. Clark et al. (2014) found major differences in different demographic groups' exposure to NO_2 pollution within the United States (see the UESI online portal for a discussion of *Environmental Injustice and Exposure to Air Pollution*). Nationally, non-white racial groups are exposed to NO_2 concentrations 38 percent higher than white racial groups; in urban areas, NO_2 pollution is higher for low-income groups than for high income groups.[37] In some North American cities, however, opposite trends have been observed. Hajat et al. (2015) reviewed 37 studies from around the world (22 in North America, 10 in Europe, and 5 studies from Africa and the Asia Pacific) investigating air pollution exposure and socioeconomic status. This review found that larger cities, including New York City, Toronto and Montreal, had opposite associations – areas with higher socioeconomic status had higher concentrations of ambient air pollution.[38] The authors suggested that these surprising findings could be the result of high socioeconomic status individuals clustering around busy roadways that may have better access to urban amenities.

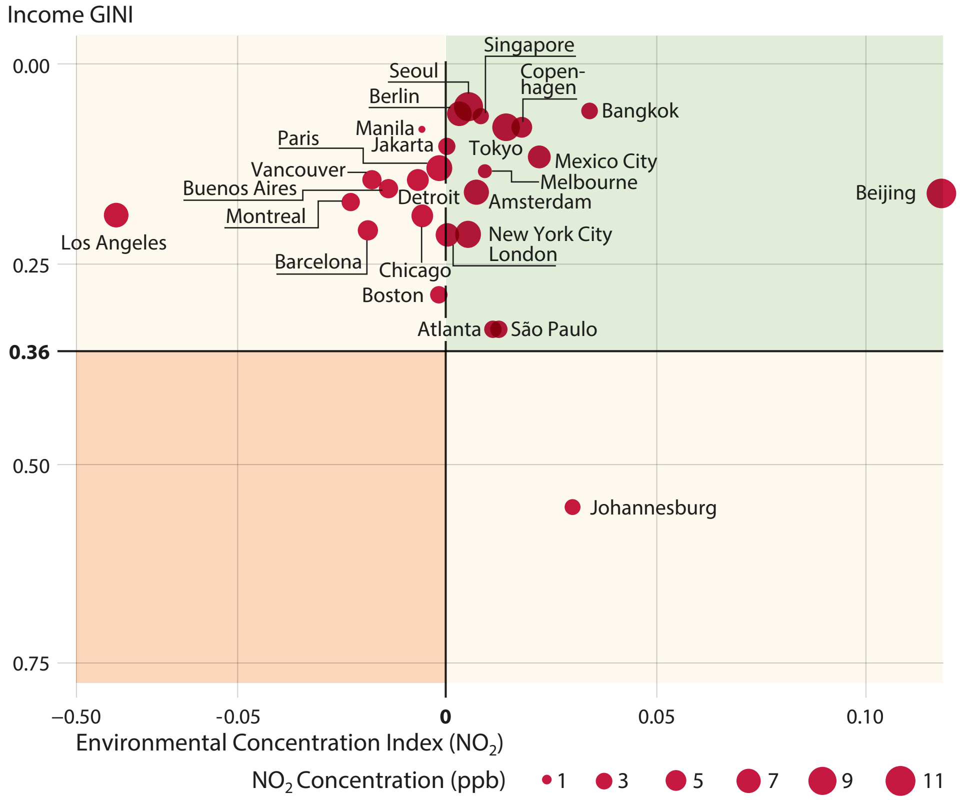
Governments are calling attention to environmental inequities through visual mapping tools. The U.S. Environmental Protection Agency (EPA) has developed an environmental justice mapping tool (EJ Mapper)[39] to highlight which census blocks are more or less unequal with respect to the distribution of ozone, particulate pollution, and proximity to hazardous waste in major American cities, including Chicago, Boston and New York City (see the *Equity and Social Inclusion* issue profile).[40] The state of California has developed a more granular tool, CalEnviroScreen,[41] to reveal which communities are disproportionately burdened by environmental pollution, including their exposure to pollution sources such as traffic, diesel exhaust and toxic releases.

The UESI's pilot cities show fairly similar distributions with respect to socioeconomic status, as measured by average income and exposure to air pollution ($PM_{2.5}$ and NO_2) (Figures 4 – 6). This result, however, is likely due to the nature of the satellite-derived air pollution data, which lacks the spatial resolution to distinguish small-scale differences between neighborhoods. In most cases, as illustrated in Figures 5 and 6, the air pollution



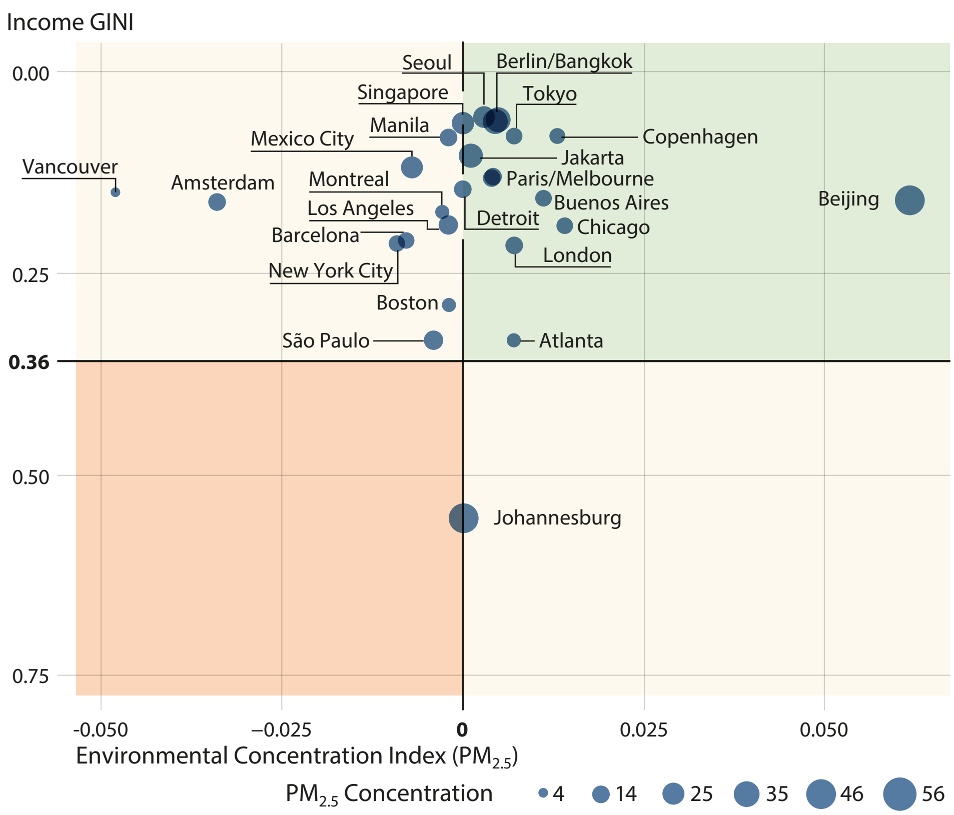
Scientific studies show relationships between air pollution exposure and socioeconomic status. In some cases, different racial groups have been found to be more exposed; in others, wealthier populations are.

Figure 3. NO_2 Concentration Plot.



The plot considers the Income Gini and NO_2 Concentration Index to define four quadrants. The Income Gini Values represent the distribution of wealth across the population and range in value from 0 to 1. A Gini value of zero indicates a perfectly equal distribution of income across the population, while a high Gini value (out of a maximum of 1) suggests a highly unequal distribution of wealth. The Environmental Concentration Index (ECI) measures the variation of NO_2 in response to income. Positive ECI values indicate that the environmental burden is allocated on the poorest citizens, while a negative ECI indicates that the environmental burden is allocated on the wealthier citizens. The size of the dots represents the extent of a city's NO_2 concentration (in ppb) (See the *Equity and Social Inclusion* issue profile for a more detailed description of this plot).

Figure 4. $PM_{2.5}$ Concentration Plot.



These plots show the concentration distributions of $PM_{2.5}$ (e.g., the concentration curve) and income (e.g., the Lorenz curve) throughout neighborhoods in cities.

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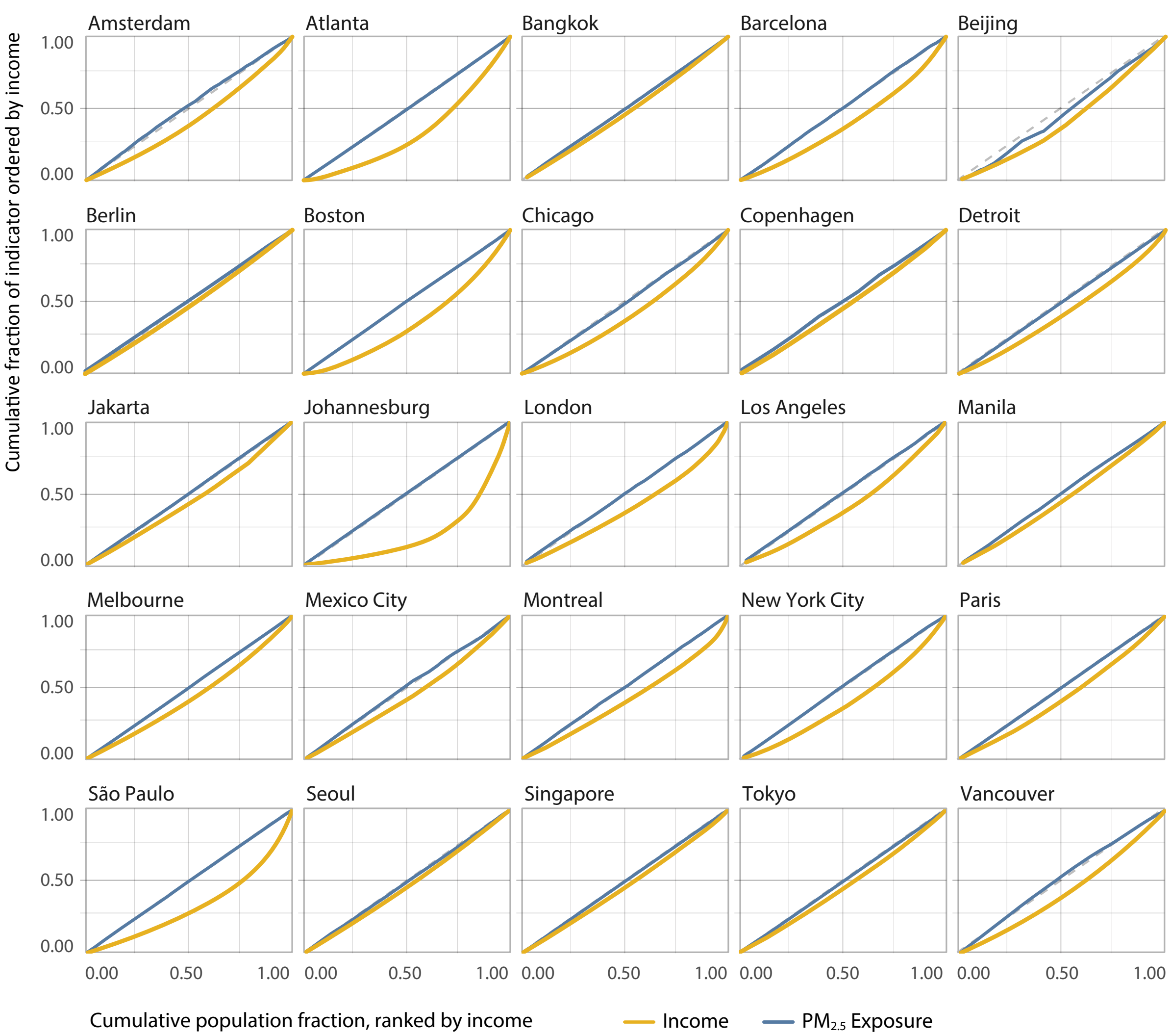
curves appear to be more equitably distributed (i.e., closer to the 45-degree diagonal line representing perfectly equitable distribution) than income. Bangkok, Berlin, and Copenhagen are all examples where the air pollution and income distribution curves are nearly identical and on top of the line of perfect equity – suggesting that the distribution of income is likely not exacerbating air pollution exposure. In other cities, such as Johannesburg, income is much more unequally distributed than air pollution.

To better distinguish subtle differences in air pollution and income distribution in the UESI cities, the equity typology quadrant plots (Figures 3 and 4) provide a way of mathematically summarizing the relationship between air pollution and income distribution. In the top left quadrant (e.g., low Gini and negative Environmental Concentration Index or ECI), Los Angeles is located the furthest left for greatest inequality in NO_2 exposure for the lowest income earners, while Vancouver has the most negative ECI

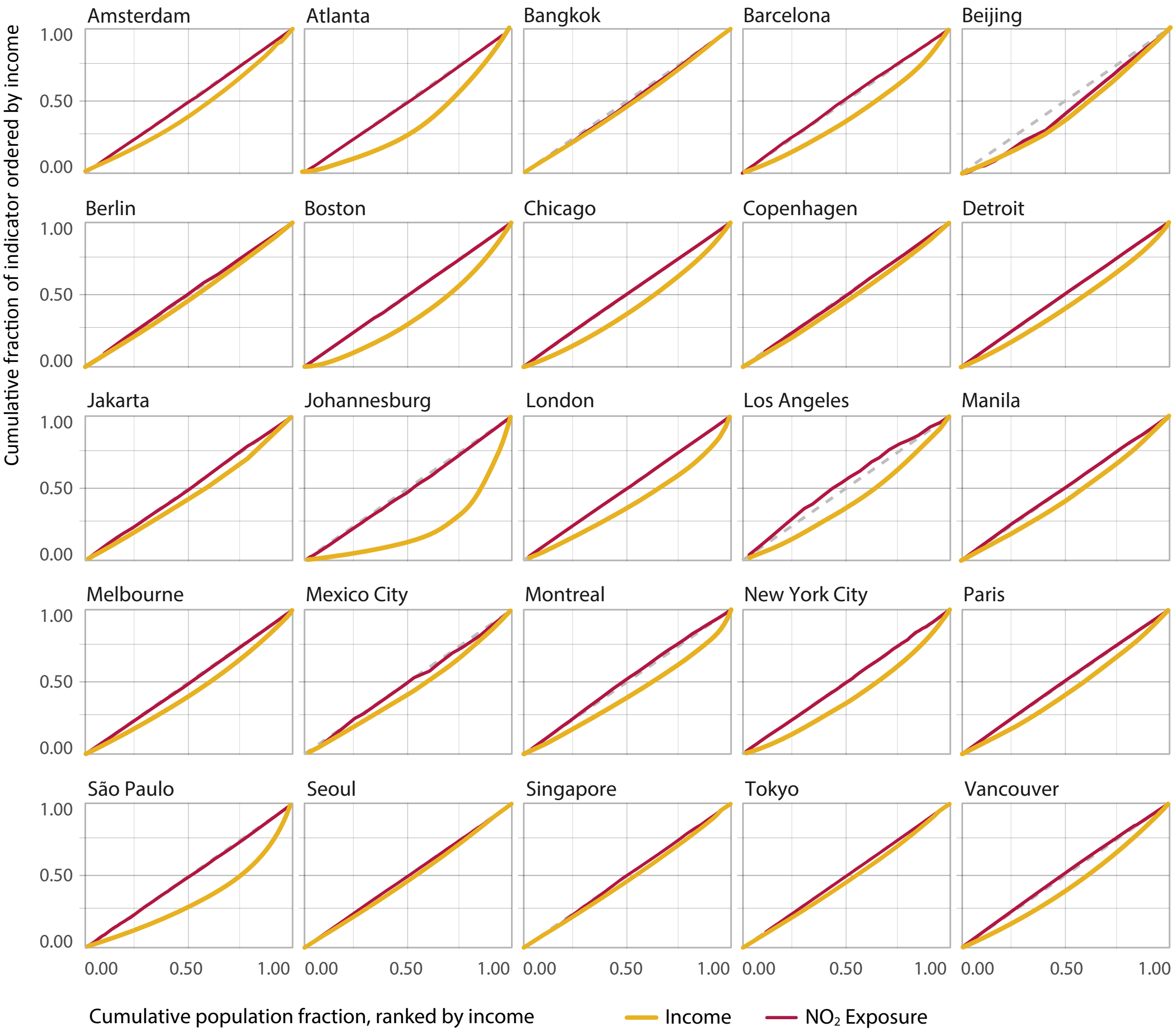
Figure 5. $PM_{2.5}$ Exposure Distribution



These plots show the concentration distributions of $PM_{2.5}$ pollution (e.g., concentration curve) and income (e.g., Lorenz curve) throughout neighborhoods in cities. Deviations from the dotted line (e.g., the line of perfect equity) illustrate cities that are less equitable in their distribution of $PM_{2.5}$ pollution.

for $PM_{2.5}$ distribution. For both air pollutants, Beijing appears the right-most in the upper right-hand quadrant (low Gini, positive ECI), which suggests low income inequality has not aggravated the distribution of air pollution. Beijing, however, has among the highest in terms of absolute exposure to air pollution, suggesting that although the distribution may not be inequitable or burdening the poor more than wealthier populations, everyone regardless of income is exposed to poor air quality.

Figure 6. NO_2 Exposure Distribution



These plots show the concentration distributions of NO_2 pollution (e.g., concentration curve) and income (e.g., Lorenz curve) throughout neighborhoods in cities. Deviations from the dotted line (e.g., the line of perfect equity) illustrate cities that are less equitable in their distribution of NO_2 pollution.

CLIMATE CHANGE

Cities are contributing to global warming as well as developing policies to lessen their climate impact. The Climate Change category tracks cities' Urban Heat Island intensity and their mitigation and adaptation strategies.

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UHI

Urban Heat Island Index

UCPS

Urban Climate Policy Score

What it measures

The Climate Change category includes two indicators: Urban Heat Island (UHI) intensity and Urban Climate Policy Score. UHI intensity measures the 15-year (2003-2017) mean difference in daytime and nighttime surface temperatures between urban land cover and non-urban land cover within the city, in degrees Celsius (°C). The Urban Climate Policy Score assesses cities' efforts to reduce their contribution to climate change as well as to adapt to a changing climate.

Why we include it

Urban Heat Island

Urban Heat Island intensity has both public health and economic consequences. As the world warms, heat waves are expected to become more frequent, and UHI amplifies this effect in urban areas, exacerbating heat stress and accounting[1] for a large proportion of deaths during heat waves.[2] Hot and arid communities are frequently water-stressed, and higher temperatures in these regions can aggravate water scarcity by spurring residents' increased water consumption.[3] By enhancing chemical reaction rates, urban heat can also increase production of secondary pollutants,[4] such as ground-level ozone, worsening local air quality.[5] Since ground-level ozone is a precursor to photochemical smog, UHI can have a particularly detrimental impact in cities already struggling with this issue. However, warmer surfaces can also increase convective mixing, which can reduce the concentration of primary pollutants; put another way, UHI can help prevent temperature inversions, which trap warm air – and pollutants – beneath a layer of cold air.[6]

The UHI effect also has a wide range of economic impacts. Urban heat increases cooling and reduces heating requirements, which, in turn, may increase or decrease electricity use.[7] A large number of studies have investigated the possible effects of UHI on power demand.[8] In London, urban heat increases cooling load by 25 percent and reduces heating load by 22 percent on an annual basis.[9] In Greek cities, UHI doubled the cooling load, while lowering the heating load by 30 percent.[10] A literature review of similar studies shows the UHI effect increases cities' average energy load by 11 percent, accounting for both the decreased heating and increased cooling loads.[11] Higher urban temperatures can also reduce the efficiency and life span of devices, such as cooling systems, automobile engines, and electronic appliances, creating costs of hundreds of million dollars for some cities.[12] Additionally, UHI can exacerbate the contributions of heat stress to work absenteeism and productivity loss.[13,14] In short, UHI can dramatically shape the lives of its urban residents, but these impacts are heavily dependent on the city in question and can vary substantially across urban areas.

Climate Policy

Cities' climate mitigation and adaptation actions impact the urban environment and beyond. Cities host more than half of the global population and roughly 80 percent of the world's GDP.[15] As a result, they also shape the world's energy use, driving two-thirds of global primary energy demand.[16] As cities continue to grow, to accommodate the estimated 2.5 to 3 billion people expected to live in urban areas by 2050, decisions about urban infrastructure, density, and land use will play a key role in influencing global energy use and greenhouse gas emissions.[17] Cities' ability to respond to the impacts of climate change – from heat stress to changing precipitation patterns to sea level rise – will also be critical in protecting the well-being and livelihoods of a growing percentage of the world's population, and the infrastructure that serves them.

Where the data come from

Urban Heat Island

For the UHI intensity indicator, measurements of Land Surface Temperature (LST) and land use are both derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the Aqua satellite.[18,19] This satellite gathers daytime values at 1:30 pm local time, and nighttime values at 1:30 am local time. For the UESI, we only consider the cloud-free MODIS pixels with an uncertainty of less than 3 °C from 2003 to 2017. For each city, the reference LST is defined as the mean of the non-urban, non-water pixels. This reference value is subtracted from the mean LST of all the pixels in each neighborhood to get the UHI of the neighborhoods of a city. In other words, we compare each neighborhood's UHI intensity to the overall intensity of UHI across the entire city. The method used in the UESI is a modified version of the simplified urban-extent (SUE) algorithm adjusted for neighborhood-level UHI detection.[20]

Climate Policy

Data for the Urban Climate Policy indicator was derived from publicly-available climate action plans that had not ended or expired in 2017. We created a checklist that covers different dimensions of a city's climate mitigation and adaptation policies, as shown in Table 1 below. Cities' climate policies and actions are scored based on the rubric, and each category is scored only once.[21] For example, if a city has five different climate actions in the Electricity or Energy sector, we only record one action, choosing the one with the highest value in our scoring system.

TARGETS

What are the targets

There are currently no standardized targets for the UHI effect since its consequences vary on a city-by-city basis. For instance, public health consequences, like increased heat stress, depend on the background climate of the city and the physiological adaptation of the people living in that area. But, for most locations, the goal is to reduce and, if possible, completely negate the UHI. In addition, the change in the UHI intensity over time and the variation of the UHI intensity within neighborhoods is important to quantify, since they represent how the urban heat stress has worsened or improved over time, and how it disproportionately affects populations within the same city.

For Urban Climate Policy Score, the target is a maximum possible score of 47 points.

DESCRIPTION

Urban Heat Island

The UHI effect is one of the oldest known consequences of urbanization. The phenomenon was observed for the first time over a century ago, and is currently one of the major research themes in urban climatology.[22] The act of urbanization replaces natural surfaces with built-up structures. This conversion changes the radiative, thermal, and aerodynamic properties of the surface, which modifies the energy balance over urban surfaces.[23] Urbanization involves the replacement of vegetated land surface with built-up structures, which are predominantly composed of asphalt (for highways) and concrete (for buildings). Concrete is slightly lighter in color (has a higher albedo) than vegetation, while asphalt is darker and has a lower albedo than vegetation. Thus, concrete reflects a higher percentage of solar radiation than vegetation, while asphalt absorbs more radiation than natural surfaces. Depending on the percentage of concrete and asphalt in an urban area, it might absorb less or more radiation than it would in its natural state. Urbanization also leads to the replacement of vegetation with built-up structures. This shift reduces the evaporative cooling vegetation provides, further increasing heat build-up in urban areas. There are other city-specific factors that modulate UHI intensity, including: the higher thermal mass of built-up structures; the ability of urban canyons and urban haze to trap outgoing longwave radiation; and the difference in surface roughness between the city and its surroundings, illustrated in Figure 1.[24,25,26]

Table 1. Scoring Rubric for Climate Actions.

Emission reduction	Sectoral mitigation	Adaptation	Transparency and finance
Timeline Pre-2020/short-(3 points), 2020-2030/medium-(2 points) and post 2030/long-term (1 point)	Presence (1 point) and articulation (2 points) of goals in each of the following sectors: • Building and Construction; Industrial; Residential; • Waste; • Transport; Electricity/Energy; Others	Presence (1 point) and articulation (2 points) of adaptation goals under each of the following themes: • Infrastructure; • Institution; • Social; • Others	Emissions inventory and data transparency (1 point for presence; 2 points for open access)
Ambitious goal (1 point)			Measuring and Evaluating mitigation actions (1 point; 2 points for evidence of actual M&E)
Boundary (only government operations vs. city-wide) (2 points)	Implementation status of mitigation goals (1 point)	Implementation status of adaptation goals (1 point)	Measuring and Evaluating adaptation actions (1 point; 2 points for evidence of actual M&E)
			Financing climate actions (1 point)
Max points: 15	Max points: 15	Max points: 10	Max points: 7

Figure 1. Factors causing UHI:

1. Greater absorption of solar radiation due to low reflectivity of some building materials, as well as radiation trapping due to multiple reflection between buildings.
2. Air pollutants trap longwave radiation in the urban environment.
3. The urban canyon effect intercepts emitted longwave radiation, eventually trapping excess heat.
4. Anthropogenic heat generated by humans and human activity, including heating and cooling loads, combustion, industrial processes, and traffic.
5. Cities' higher thermal mass, due to surface area and higher specific heat capacity, enables them to store more heat.
6. Reduction of evaporative cooling due to the replacement of vegetated land surfaces with impermeable built-up structures.
7. Lower turbulent heat transport due to wind speed reduction; this can be offset by higher convective mixing during the day, due to the greater surface roughness of urban areas in arid zones, or exacerbated in humid regions where buildings are aerodynamically smoother than surrounding vegetation.

Adapted from (Kleerekoper et al., 2012).[27]

There are two primary approaches to measuring UHI intensity. The canopy UHI measures the difference in air temperature between the urban region and its surrounding "background" or non-urban region. The surface UHI measures the difference in the surface temperature between the urban and "background" regions, often using satellite data. Our UHI indicator focuses on the surface UHI – the difference in daytime and nighttime mean surface temperatures – since air temperature measurements are usually not available for cities (see the UESI online portal's box on *The Rural Reference: Defining the Urban Heat Island Magnitude,* and Box 1, *Canopy versus Surface Urban Heat Islands: Heat Stress Implications*, for additional discussion of the implications of different approaches to measuring UHI).

Box 1. Canopy versus surface urban heat islands: Heat stress implications

While urban heat island (UHI) is a standard term in urban studies, the UHI can have two distinct meanings. Traditionally, researchers observed higher air temperatures in urban areas, which were based on measurements collected at a standard height (between 1.5 to 2 m above ground).[28] Since this height is within the urban canopy, it is termed the canopy UHI. Later, with the advent of satellite data, the difference in the surface temperature between the urban core and its surroundings could be observed – this is known as the surface UHI.[29]

The surface and air temperatures show similar annual values. However, there are significant differences at the diurnal and seasonal scales due to how fast the surface and air respond to the incoming solar radiation.[30] The canopy air temperature maxima lags behind the surface temperature maxima by a couple of hours every day – in other words, the surface responds first to the incoming radiation. Similarly, the maximum and minimum air temperatures lag behind the corresponding surface temperatures at the seasonal scale. Furthermore, these lags can be influenced by land cover. The response of the surface to incoming radiation depends on the specific heat capacity of the surface material; this is higher for built-up structures, meaning that urban areas heat up and cool down slower than vegetated landscapes. Additionally, the response of the canopy air depends on how the surface dissipates the heat, and whether this is predominantly through evaporation or convection. Evaporation leads to an increase in the moisture content (but not temperature) of the air above the surface, while convection leads to a transfer of heat from the surface to the air near the surface. This causes dissimilarities between the canopy and surface UHI, as seen in a few recent studies.[31,32] Finally, the horizontal movement of air across the land surface disperses warmer air, helping to mix the canopy and surface UHI intensities.[33] For cities in maritime climates, cooling by sea breezes may reduce the canopy UHI further than the surface UHI.

A major consequence of the UHI is the additional heat stress in urban areas affecting a rapidly increasing urban population. This problem can translate into higher incidence of heat strokes, loss of productivity due to absenteeism from work, and even heat related mortality.[34] It is important to note that the human response to heat stress is due to higher air temperatures, and thus the canopy UHI.[35] On the other hand, the surface UHI has an effect on the local urban climate, including changes in precipitation patterns.[36]

A number of challenges make it difficult to assess canopy UHI at the neighborhood scale. Unfortunately, the World Meteorological Organization (WMO) standards do not typically result in routine measurements of air temperature within urban areas, since these measurements are carried out at airports.[37] Temperature sensors used in different cities may not have comparable accuracy, which adds uncertainty to inter-city comparisons. Moreover, it is difficult to set up a dense enough network of sensors to investigate the spatial variation in the canopy UHI, which prevents comparisons at the neighborhood scale.

Thus, the UESI uses surface UHI measurements, since they are based on data from a single sensor (MODIS) and the dataset is available at a fine spatial resolution (1 kilometer x 1 kilometer) for the whole globe. While the surface UHI magnitude may be slightly higher or lower than the corresponding canopy UHI, comparing its value between neighborhoods for the same city can be a useful proxy for the heat stress and other consequences of the UHI.

The future of UHI studies requires dense networks of air temperature sensors within urban areas to quantify the spatial variation of the canopy UHI. While steps have been taken in this regard for select cities,[38] they should become routine measurements for cities that want to use these data to inform city planning and policymaking.

The urban heat island effect and urban policy

The UHI effect, and by extension, its consequences, all stem from urban-scale changes. These effects can be prevented through more-informed policymaking and city planning. There are various ways to geoengineer urban areas to lessen the magnitude of the UHI. For instance, urban temperatures can be reduced by increasing the reflectivity of the city or by increasing evaporative cooling over urban surfaces. Four main methods are normally used to mitigate the UHI:

- **White roofs**: White roofs can increase the surface albedo, reflecting more of the sun's radiation back to space.
- **Green spaces**: Green spaces can increase evaporative cooling over land, thus reducing the average temperature over cities.
- **Green roofs:** Green roofs are similar to green spaces, but can directly reduce the temperature over built-up structures.
- **Reflective pavements:** Like white roofs, reflective pavements also increase the surface albedo, and thus, reduce the absorption of radiation by urban areas.

Previous studies have quantified the impact of these methods on the UHI magnitude for individual cities.[39] A recent large-scale study on UHI mitigation strategies over 57 cities in Canada and the U.S. showed that the combination of white roofs, reflective pavements, and green roofs can negate the effect of both global warming and the UHI for many cities.[40] These mitigation strategies involve changing the surface cover, and can be implemented for existing cities. Rapidly expanding cities can also opt for large-scale engineering of the urban structure to reduce the UHI intensity. For instance, zoning policies can increase the horizontal dissipation of heat by staggering building heights against the prevailing winds.[41]

While solving climate change requires global effort and cooperation between different countries, it is possible to temporarily shield urban residents from some of the consequences of climate change by enacting policies designed to curb the UHI. With around 66 percent of the global population expected to live in urban areas by 2050, mitigating urban heat can provide large benefits for both human health and the economic growth of cities. In this regard, city-level policies, enacted in tandem with multi-scale adaptation strategies, will become important to ensuring the sustainable growth of urban areas in a rapidly warming world.

Socioeconomic disparities in urban heat

The UESI pilot cities show a large range of daytime UHI values, from approximately 0 °C to above 7 °C (see Figure 2). Most of the cities show higher UHI values in the city core. Some of the neighborhoods, including several Johannesburg neighborhoods and some of Beijing and Vancouver's outer neighborhoods, have negative daytime UHI, meaning parts of the city are cooler than their reference non-urban areas. For instance, some of Beijing's neighborhoods, especially those near the edges of the city, tend to have more green space, and more rural or suburban land use, than the city as a whole, so are cooler than the average city neighborhood. São Paulo shows the highest mean daytime UHI, followed closely by Mexico City and Manila. Johannesburg shows no significant UHI during the day.

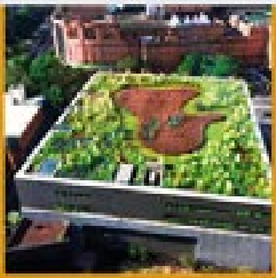
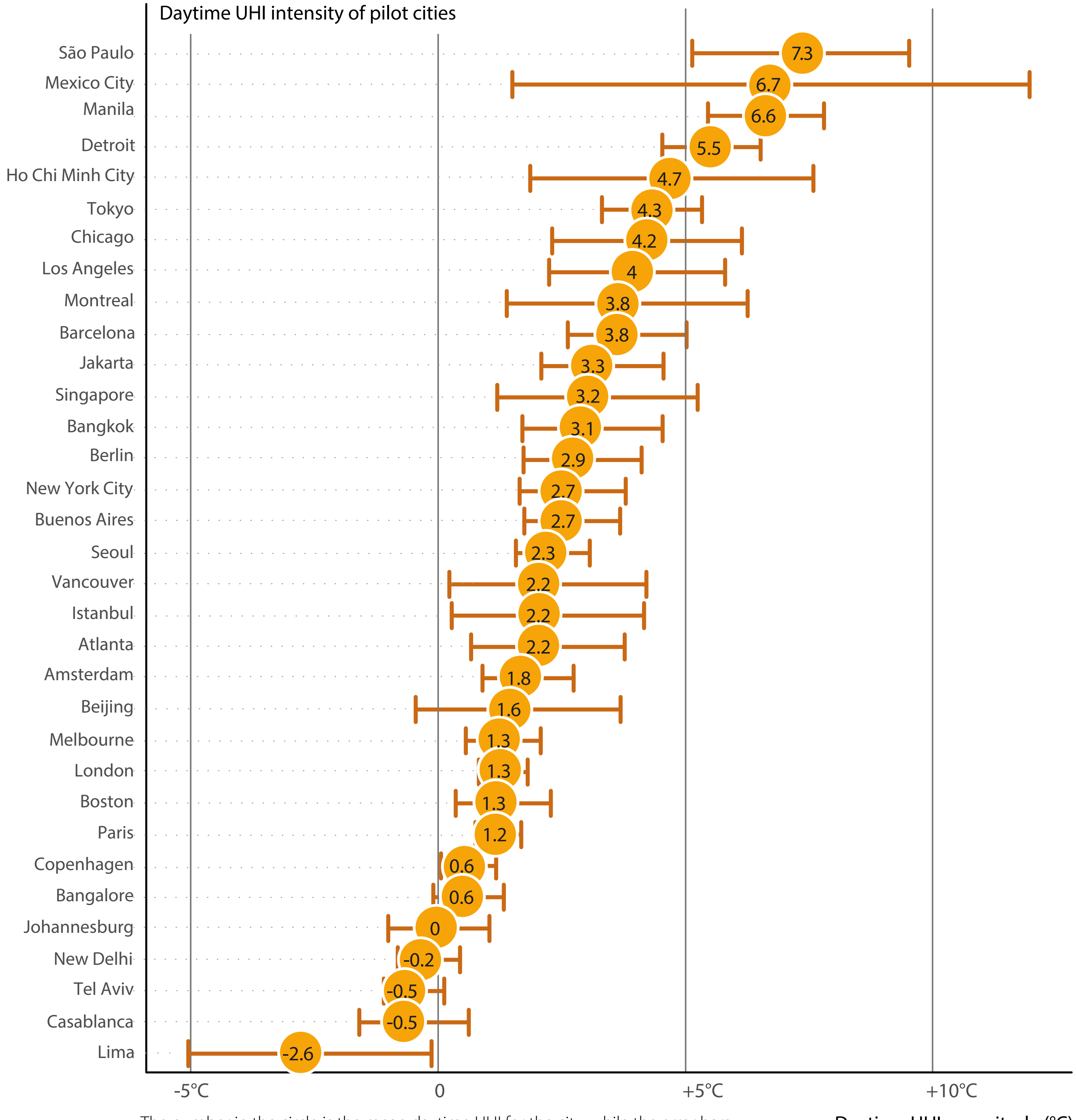


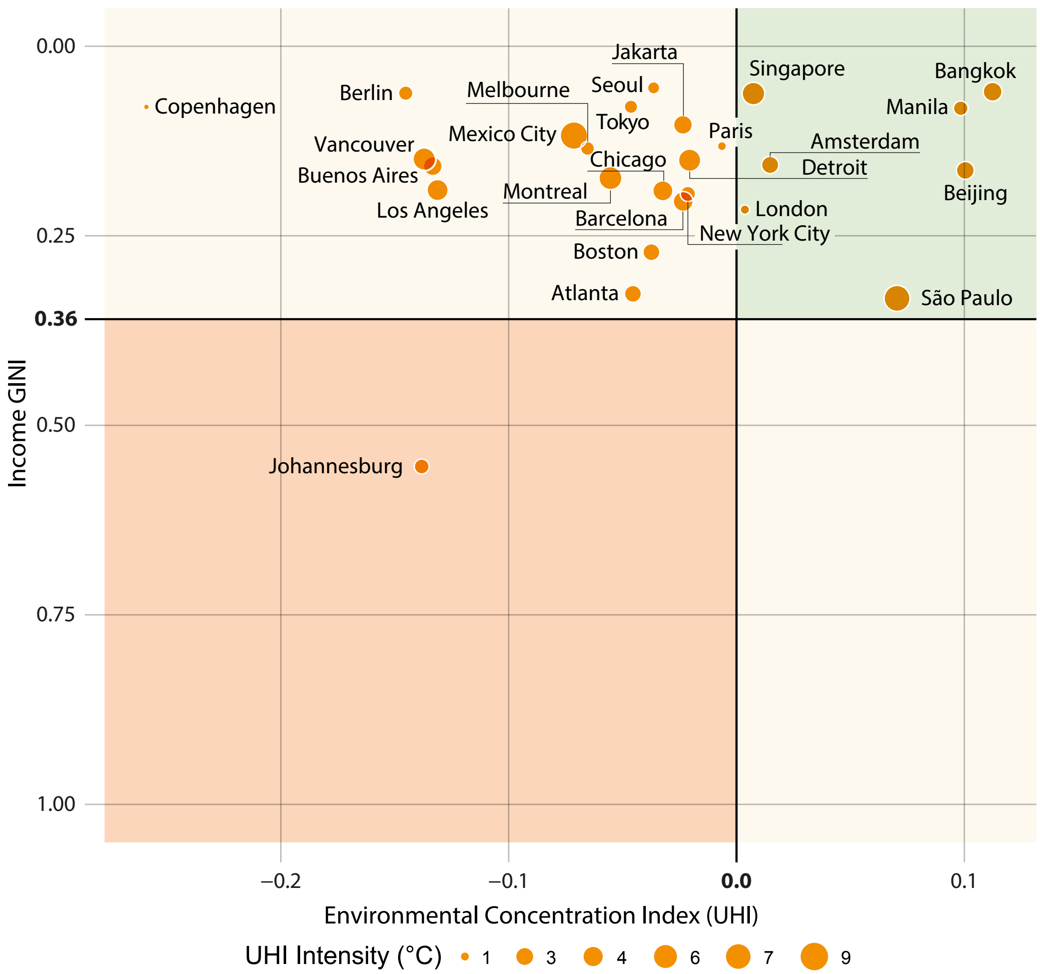
Figure 2. Daytime UHI intensity of pilot cities as calculated in the UESI using the modified SUE algorithm.



The number in the circle is the mean daytime UHI for the city, while the error bars represent the standard deviation of UHI values across different neighborhoods of the city.

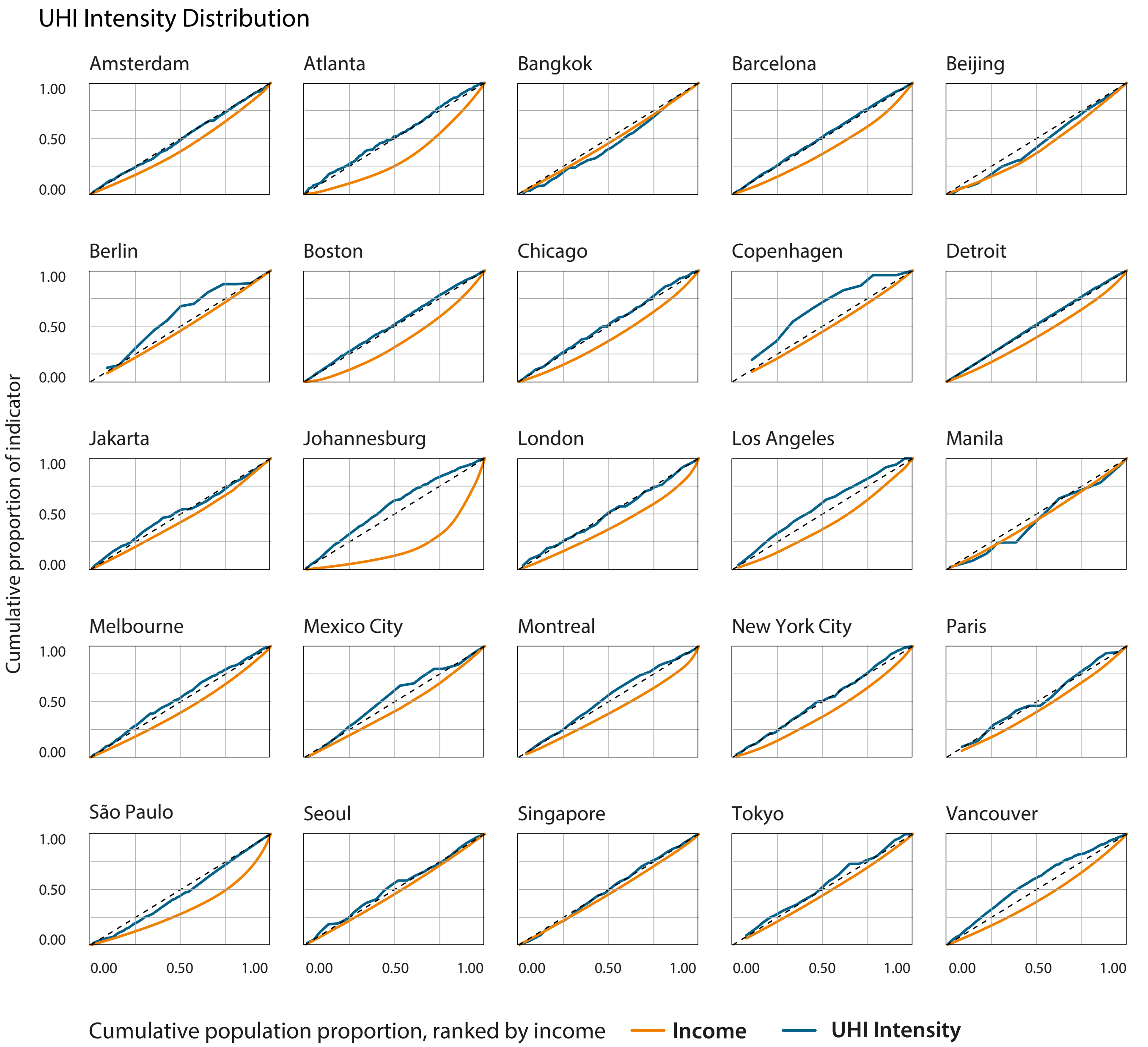
Figures 3 and 4 capture the income inequality within the UESI pilot cities using the income GINI coefficient, as well as the degree to which neighborhoods' UHI intensity is sensitive to income, using a concentration index. Cities like Los Angeles, Vancouver, Detroit and Atlanta fall into the second quadrant in the UESI's typology comparing relationships between income and environmental outcomes across cities. These cities have low income inequality, but a greater UHI burden falls on the poorer sections of society. For cities like Bangkok, São Paulo, Beijing and Singapore, the rich are affected more by the UHI, possibly because the city core, with high UHI values, is populated by a wealthy section of society. In Johannesburg, there is high income inequality, which is further compounded by a disproportionate heat island burden for the lower-income group.

Figure 3. UHI typology quadrant plot.



The plot considers the Income Gini and UHI Concentration Index to define four quadrants. The Income Gini Values represent the distribution of wealth across the population and range in value from 0 to 1. A Gini value of 0 indicates a perfectly equal distribution of income across the population, while a high Gini value (out of a maximum of 1) suggests a highly unequal distribution of wealth. The Environmental Concentration Index (ECI) measures the variation in UHI in response to income. Positive ECI values indicate that the environmental burden is allocated to the wealthiest citizens, while a negative ECI indicates that the environmental burden is allocated to the poorest citizens. The size of the dots represents the extent of UHI intensity (in °C). (See the *Equity and Social Inclusion* issue profile for a more detailed description of this plot).

Figure 4. Environmental and Income Distribution Curves for selected cities.



These plots show the concentration distributions of UHI intensity (e.g., the concentration curve) and income (e.g., the Lorenz curve) throughout neighborhoods in cities. Deviations from the dotted line (e.g., the line of perfect equity) illustrate cities that are less equitable in their distribution of UHI intensity. Concentration curves above the line of equity indicate the environmental burden is more heavily allocated to those with less income; concentration curves below the line of equity indicate that the environmental burden is more heavily allocated to those with greater income. (See the *Equity and Social Inclusion* issue profile for a more detailed description of this plot).

A range of city climate policies

Municipal actors play an increasingly important role in climate change mitigation. Nation-states have, until recently, been the focal points of global climate action, reporting, and target-setting. This paradigm has shifted, however, and multinational frameworks, like the UN Framework Convention on Climate Change (UNFCCC), have begun to recognize a sea change: countries are no longer the sole actors in global climate governance. Cities, regions, and states, along with businesses, investors, and civil society organizations play an increasingly prominent role in climate mitigation, adaptation and finance. The UNFCCC's 21st Conference of Parties (COP21) negotiations, held in Paris in December 2015, codified this shift in the Paris Agreement's text.[42] And more than 400 mayors, civic leaders, and CEOs participated in the concurrent Climate Summit for Local Leaders in Paris's City Hall.[43]

A special chapter on non-state (e.g., business) and subnational (e.g., cities and states) actors in the 2018 UN Emissions Gap Report projects that by 2030, these new climate actors could narrow the emissions gap by 0.2-0.7 gigatons (Gt) CO_2 equivalent per year, compared to the full implementation of Nationally Determined Contributions, or 1.5-2.2 Gt CO_2 equivalent per year compared to current policy scenarios in 2030.[44] In countries like the United States, where political events have weakened national level climate action, actors at the state, city, and businesses levels have taken up the responsibility to stay on track to meeting Paris Agreement goals.[45] Cities are also at the frontline of climate adaptation policies and actions, and can develop, pilot and implement targeted action plans to meet context-specific mitigation challenges.

Networks like the C40 Cities Climate Leadership Group, which includes over 90 global cities from New York City to Johannesburg, and the Global Covenant of Mayors for Climate and Energy, which includes more than 8,000 cities, are connecting cities to share best practices for addressing climate change at the urban scale. In recent years, these groups have attracted more participants from a wider geographic range, while new networks and alliances continue to spring up, promoting the exchange and sharing of goals and best practices among cities. Many networks and initiatives publish their members' emission data and detailed climate plans. A large portion of city climate action data used in this project are downloaded from climate action registries and networks like the Global Covenant of Mayors for Climate and Energy and ICLEI's carbon*n* Climate Registry.

Table 2 summarizes the Climate Policy scores of UESI cities. Overall, Melbourne, Detroit, Atlanta, Los Angeles and Boston are the top scorers, while Manila scores lowest. Bangalore, Casablanca, New Delhi, and Tel Aviv are not included in the table because no publicly available climate action plan could be found. These cities receive a score of 0, although there are some indications that climate plans are in development for Tel Aviv, which joined C-40 Cities for Climate Leadership Group in December 2017[46] and is in the process of working with the group to develop its city-level climate action plan.

Table 2. Climate Policy Score Breakdown.

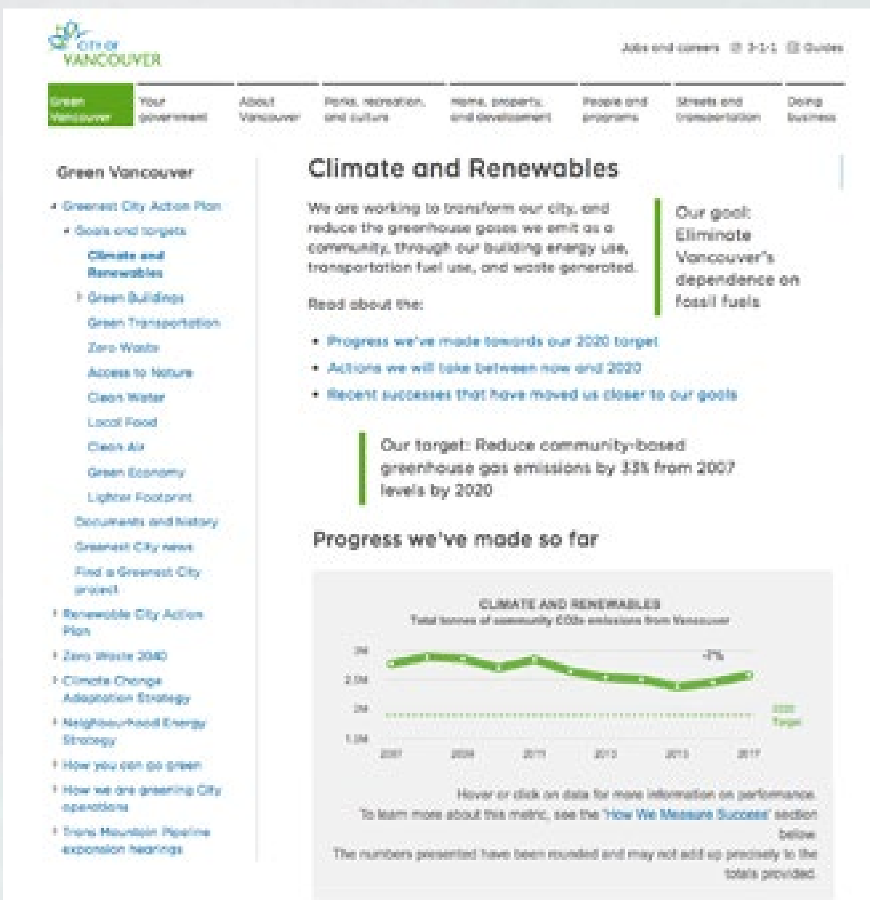
City	Emission reductions	Sectoral mitigation	Adaptation	M&E and finance	Total score
Amsterdam	13	14	3	2	32
Atlanta	12	15	7	2	36
Bangkok	4	9	5	3	21
Barcelona	9	11	8	2	30
Beijing	9	11	3	2	25
Berlin	13	9	1	3	26
Boston	8	13	9	5	35
Buenos Aires	11	12	7	1.5	31.5
Chicago	8	14	8	4	34
Copenhagen	13	13	5	3	34
Detroit	12	12	9	4	37
Ho Chi Minh City	3	12	7	2	24
Jakarta	5	7	6	2	20
Johannesburg	3	9	2	3	17
Lima	0	7	5	4	16
London	12	11	5	1	29
Los Angeles	14	12	5	5	36
Manila	3	1	3	0	7
Melbourne	9	15	9	5	38
Mexico City	12	11	6	2	31
Montreal	5	13	8	2	28
New York City	12	12	4	4	32
Paris	8	14	4	0.5	26.5
São Paulo	7	9	4	3.5	23.5
Seoul	3	10	7	3.5	23.5
Singapore	9	12	3	1	25
Tokyo	4	13	3	3	23
Vancouver	6	13	4	6	29

Amsterdam, Atlanta, Berlin, Copenhagen, Detroit, Los Angeles, London, Mexico City and New York City have mitigation targets that cover pre-2020, 2020-2030 and post-2030 timeframes. Amsterdam, Beijing, Berlin, Melbourne, Jakarta, Johannesburg, Seoul and Vancouver have emission reduction targets that exceed the country's climate action plans, or (Intended) Nationally Determined Contributions ((I)NDCs).

Most UESI cities have included detailed mitigation plans and targets to improve energy efficiency and reduce emissions across different sectors. The presence and level of details of adaptation policies show greater variance and are not as well documented as mitigation efforts. Notably, Seoul, Melbourne, Mexico City and Jakarta have introduced adaptation policies and detailed climate adaptation projects in their urban climate policies, therefore receiving higher scores in this category.

Vancouver has the most comprehensive monitoring and evaluation (M&E) information about its climate policies, and scored the highest under the "M&E and Finance" category. Vancouver documents its annual progress towards its climate targets, through a yearly report, and through a user-friendly online interface that tracks and quantifies the city's progress, as shown in Figure 4. Other M&E practices adopted by UESI cities include progress reports, annual updates and iterations of existing policies.

Figure 4. Screenshot of Vancouver's Greenest City Action Plan portal.



Source: http://vancouver.ca/green-vancouver/climate-and-renewables.aspx.[47]

Box 2. Challenges of scoring cities' climate policies on a global scale

To collect climate action policies of the UESI cities, we conducted extensive searches on the cities' official government and environment websites in English and languages commonly-spoken in the city, and drew from global climate action databases, such as ICLEI's carbon*n* Carbon Registry, the Global Covenant of Mayors for Climate and Energy, and the Under2 Coalition. While every effort was made to ensure that all climate actions and policies were recorded, we cannot guarantee that the policies collected are exhaustive. The level of transparency and ease of data access differ across cities, and we have incorporated this aspect into the scoring methodology. The Vancouver example highlighted stands out as the only city with an accessible and real-time M&E interface.

The climate policy score allocation is skewed towards emissions reduction and sectoral mitigation. These two categories each account for 15 out of 47 points in the total score. On the other hand, adaptation and M&E and Finance categories have a relatively low share of the overall score. This discrepancy is due to theoretical and practical reasons. Compared to climate change mitigation targets, which are often iterated as discrete reductions of carbon emissions from different emission sources, adaptation is much harder to define. The term "adaptation" does not always have a clear and consistent usage,[48] and operationalizing and measuring adaptation policy is still largely a work in progress in the academic field.[49] Empirically, adaptation policies and action plans of the pilot UESI cities do not have the same level of breadth and depth as mitigation policies which are covered in much greater detail. Another area that is critical for cities in addressing climate change is capacity - institutional, financial, and human-capital related. Capacity is much more difficult to measure, although there are some efforts that are tackling this challenge, including Notre Dame's Global Adaptation Index (ND-GAIN).[50] The ND-GAIN measures countries on an 'adaptive capacity' dimension that evaluates multiple dimensions of capacity for each issue in the index, from agriculture and food security to government readiness.

Varying timeframes for when city-wide climate plans and policies were initiated also affect the Climate Policy scores. Tokyo was an early adopter of city-level climate action and announced Tokyo Climate Change Strategy in 2007[51] – an ambitious plan outlining policies and targets for "a Carbon-Minus Tokyo" by 2017.[52] The plan, however, has not been updated, nor has a progress report been made since 2011. The Agenda set a number of 2012 targets, which had already expired. On the other hand, a high-scoring city like Detroit released its first climate action plan in 2017 and has the advantage of being a late adopter, synthesizing lessons learned and best practices from other cities and propose more comprehensive climate action plans. Lastly, some cities have iterative climate policies that are regularly updated. For example, Vancouver's Greenest City Action Plan, originally announced in 2011, has two phases of priority actions and involves public consultations to keep its contents relevant.

URBAN TREE COVER

Tree cover and green space help cool cities and creates habitat that supports biodiversity. Access to green space also enhances the social, physical, and economic health of a community.

What it measures

The Urban Tree Cover indicator measures the presence of tree cover within a city. This indicator also acts as a proxy for a city's green space – the physical presence of vegetation – within city neighborhoods. The Urban Tree Cover issue category includes two indicators: Tree Canopy Cover Loss and Tree Cover Per Capita.

The Tree Canopy Cover Loss indicator describes the total area (in square kilometers) of urban tree loss from 2001 to 2016, benchmarked against the tree cover baseline extent in 2000. As defined by Hansen et al. (2013),[1] *tree cover loss* is a stand-replacement disturbance, or a change from a forest to non-forest state, such as the removal or death of trees, regardless of the cause and inclusive of all types of tree cover, including the deforestation of primary forests and harvesting of tree plantations.

The second indicator, Tree Cover Per Capita, assesses a population's access to its urban forest, measuring the tree cover extent per person living in the defined area of analysis. A variation of this indicator, Tree Cover per Capita Deficit, is also calculated, and defined as the additional square meters of tree cover needed to reach the UN-Habitat's suggested 15 square meters (m^2) of tree cover per capita.

Why we include it

Green spaces and tree cover, as part of open public spaces, are a critical component of a thriving urban environment, with the potential to provide economic, social and environmental benefits to a city, and improve the livelihoods of its citizens. These benefits are well-documented in the academic literature (see, for instance, Escobedo et. al. 2011,[2] Dobbs et.al. 2011[3]) and include:

- Regulation and reduction of air pollution[4, 5]
- Improvement of stormwater infiltration[6] and reduction of surface water runoff[7]
- Regulation of the urban heat island effect,[8] resulting in a decrease in energy used for cooling purposes[9]
- Conservation of wildlife refuge and habitat[10]
- Increased physical and mental health[11]
- Potential economic development[12] and increased property values[13] in areas with improved streetscapes and proximity to urban forests
- Community empowerment and social cohesion, both actively, through the process of greening the community, and passively, from the use of the green spaces[14]

15 m^2
of tree cover per capita are recommended

As a result of the increasing understanding of the benefits of urban green spaces, many cities have included green space as a component for the evaluation and management of sustainable urban centers. These initiatives use several methods to evaluate of green space – ranging from remote sensing imagery to administrative data of parks and tree inventories – that allow decision makers to evaluate trends over time. This data can also track the general population's access to urban green spaces, which can inform both citywide and very local strategies.

Access to green space is key aspect of urban sustainability. A disproportionate lack of access to green spaces in relation to social factors, such as income and ethnicity, has also been highlighted as a particularly relevant aspect of environmental equity.[15,16] Providing public services and access to infrastructure can reduce income inequality, and has a stronger redistributive effect among specific groups at higher risk of poverty,[17] particularly because the poor have less access to private substitutes for these services.[18] Given the links between environmental health risks and poverty,[19] and the economic and social benefits associated with green space, access to inclusive and safe green spaces is one way to reduce inequalities within urban areas. Sustainable Development Goal (SDG) 11 includes a target (11.7) that aims to provide universal access to safe, inclusive, and accessible green and open spaces, as measured through the proportion of open space – including green space – for public use in cities' built-up areas.

Where the data come from

The data for both indicators is derived from the Global Forest Change 2001–2016 (Hansen et al. 2013) dataset.[20] Three main layers of the dataset – Baseline, Loss and Gain – were used for the extraction of the tree cover values, and additional socioeconomic and spatial information was used for the calculation of the indicators. Although the Hansen et al. (2013) satellite-derived gain numbers have been criticized for their inaccuracy at higher latitudes[21] and the authors themselves caution against developing a net number by subtracting gain numbers from tree cover loss, we utilize the gain data to correct for issues – such as negative tree cover presence – in the time series for some urban areas at a very small scale, a problem that is not usually found when the data is used exclusively for the analysis of forests.

TARGETS

What are the targets

The target for urban Tree Canopy Cover Loss is zero, indicating that the city has not lost any tree canopy cover between 2001 and 2016. While this target might be suitable for established cities, many growing cities – particularly in the developing world – might have some tree cover loss due to the conversion of vegetated, undeveloped land to a built environment. This shift is not necessarily a reflection of inadequate management or a disregard for green spaces, but a result of the city's growth.

The target for Tree Cover Per Capita is 15 square meters (m^2) of tree cover per capita, which we adopt from the UN-Habitat's calculation of their City Prosperity Index.

DESCRIPTION

History of identifying and monitoring urban green space

Green spaces and parks have been a feature of cities since ancient times. Beginning in the late 19th century, many urban planning schools and approaches sought to capture their role and relevance for cities. The Garden City Movement, founded in 1898 by Ebenezer Howard in the United Kingdom, proposed the development of limited-size cities, with proportionate areas for housing, industry, and agriculture, surrounded by rural green belts. The City Beautiful Movement, developed in the US since 1893, promotes the beautification of cities using, among other features, parks and green spaces.[24] The New Urbanism movement gained prominence in the 1990s. Its main components include the strong need for public space, of which public green space is a key element.[25] The Sustainable Communities Movement has also grown since it founding in the mid-1990's – it aims to bring the concept of sustainability to the urban context, and highlights the use of green spaces to address many urban challenges.[26]

All of these movements, with their respective approaches and limitations, aim to improve citizens' quality of life, often in response to poor conditions in urban centers, and include green space as an important tool to achieve this goal. Most recently, the adoption of the Sustainable Development Goals (SDGs), particularly SDG 11, and the New Urban Agenda (NUA) – which includes the explicit objective of achieving equitable access to green spaces for all citizens – demonstrate the increasing recognition of urban green spaces' importance in making urban centers more sustainable.

Given the benefits it provides, the identification and monitoring of urban vegetation has been explored through different techniques, primarily through remote sensing imagery or survey-based data.[27] Remotely sensed imagery has been used extensively in studies that aim to relate land use patterns with other spatial features, such as land temperature or air pollution. Survey-derived data, such as administrative inventories of green spaces, have been used in studies exploring issues around access to green spaces and the equitable distribution of green spaces in a city. Recently, new approaches have leveraged additional datasets to measure green space. The Treepedia project,[28] for instance, uses street-photographs to measure the greenness of a city (see the UESI online portal for additional details about the Treepedia project). Box 1, *Complementary measures of greenness in urban spaces,* highlights the relationship between satellite-derived measures of urban tree canopy and additional sources of information, such as administrative data about parks and street trees within a city.

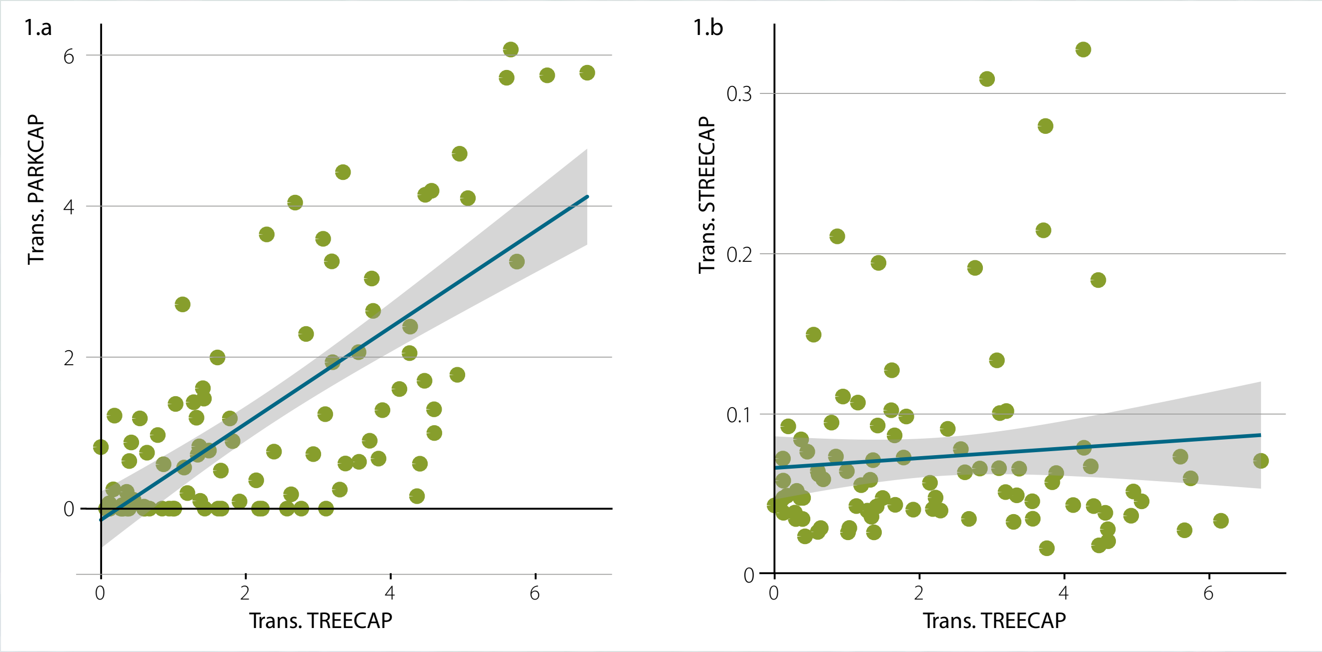
Box 1. Complementary measures of greenness in urban spaces

The most common approaches to analyzing urban vegetation involve either remote sensing, data derived from field surveys, or a combination of both. While these approaches aim to measure a city's greenness, due to limitations in their nature and methods, none can completely measure all its elements, and the results of different indicators for the same city could be significantly different.

To explore these differences, the following graphs compare three different indicators that measure the green space for the city of São Paulo, using different approaches. The first indicator, TREECAP, represents the total amount of tree cover per person, measured from the Global Forest Change Dataset (Hansen et. al. 2013), and is an example of a satellite-derived indicator. The other two indicators examine the green space of a city using primarily survey-based data. The PARKCAP indicator represents the total amount of official park area per person, measured using the city of São Paulo, official public park repository. The STREECAP indicator measures the number of street trees per person, according to the city's street database.

A visualization of the relationship between these three indicators illustrates their complementary nature. Figure 1 shows scatterplots of the three transformed indicators, compared in a pairwise form, including a trend line of their relationships. Figure 1.a shows that the TREECAP and PARKCAP indicators are positively associated. In other words, the provision of tree canopy cover per person is positively associated with the provision of urban parks in city of São Paulo. While this might seem like a very logical relation, its important to consider that the presence of tree cover is not exclusive to urban parks, and in fact some urban parks, like plazas or monumental spaces, might not provide tree cover at all.

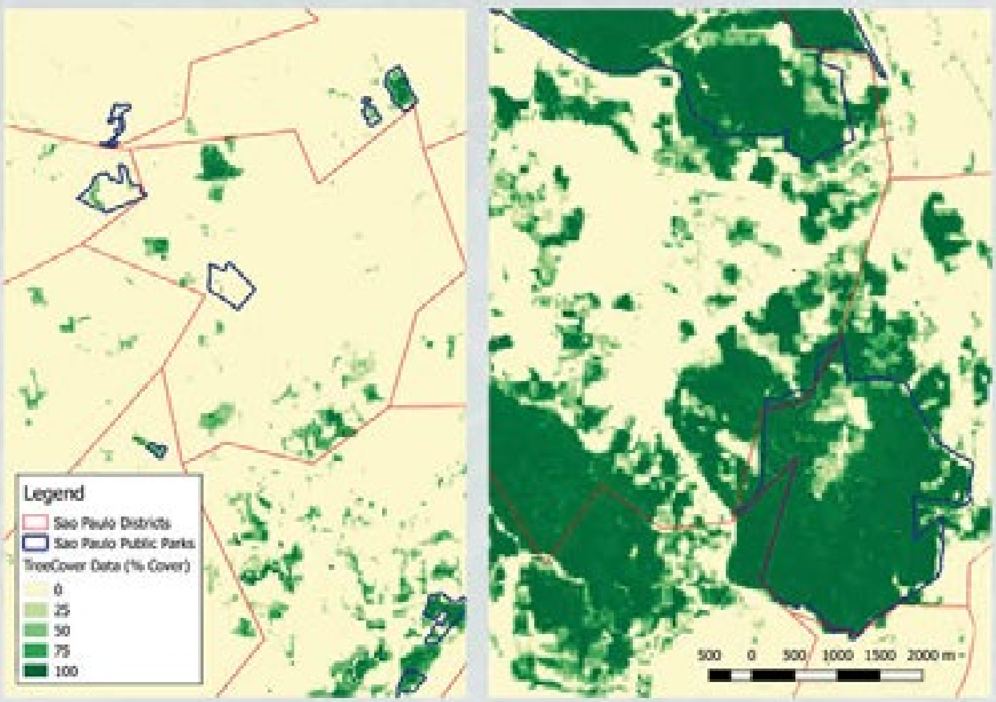
Figure 1. Graphical association of indicators of Green Space for the city of São Paulo.

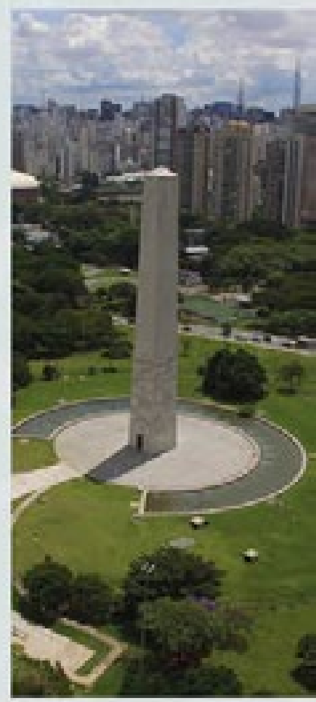


Another potential source of difference between the TREECAP and PARKCAP indicators is related to specific elements that they are able to measure. For instance, while the tree cover indicator provides a broad indication of the presence of areas with accumulated tree canopy in cities, it cannot distinguish between the public and private spaces where this vegetation is located, a key aspect when access and equity is considered. Figure 2 exemplifies this issue, illustrating that much of the city's tree cover occurs outside official parks, in what could be private areas, or vegetated undeveloped land.

In other cases, indicators are less closely aligned. In Figure 1.b, which compares the TREECAP and the STREECAP indicators, the association between the two is almost non-existent, suggesting that the indicators measure very different aspects of the urban vegetation, due to the nature of their methods. Whereas TREECAP is able to identify and measure areas of tree cover as small as 90m^2, STREECAP is able to measure individual trees and linear green spaces at a much more granular level. This difference highlights the need of fully understand the nature of the indicators that are being used and which component of a city's greenness is being measured.

Figure 2. Map of tree cover as it relates to public parks in São Paulo.





In summary, even though the UESI uses a remote sensing approach to measure green spaces, a more comprehensive analysis of urban vegetation should involve the use of multiple complementary measures. The use of large-scale remote sensing datasets should be complemented with administrative records of the managed parks and vegetation, in order to provide complete information about the state of a city's vegetation. Unfortunately, this integration faces several barriers, especially in developing countries, where access to remote sensing imagery and the construction of local repositories both entail additional costs and human capacity. Attention to new methods and databases that can generate these indicators – such as the Global Forest Change Dataset,[29] or the Treepedia project from MIT-Senseable Lab (see the UESI online portal's box on *The Treepedia Project* for more details on this initiative) – could help overcome some of the existing barriers for obtaining quality and policy relevant data.

In addition to exploring methods to identify and quantify urban green spaces, researchers have attempted to analyze how different forms of urban green space impact the city environment and urban citizens. Ekkel and Vries suggest that it is quite common for health-related studies to only consider green spaces above a minimum size.[30] Positive associations between green space and residents' well-being have been found in studies that focus on green spaces of at least 500 square meters (m^2).[31] However, the role of small and consistent green spaces – such as street trees – cannot be discarded, as other studies have also found positive associations between these streetscapes and health indicators.[32]

Recent papers have also explored the relationship between different types of green spaces and urban heat island (UHI) mitigation. Xi and Ratti (2008) applied innovative techniques using Google street-view images as a way to measure the shade and cooling benefits of urban street trees in Boston.[33] Park et al. found that linear green spaces – lines of vegetation planted in one or two rows – appear to have no significant relationship on UHI reduction, while polygonal green spaces of at least 300 square meters, with 2300 cubic meters of vegetation cover volume, could reduce UHI by 1ºC in their study area.[34] Yang et al. also found that the composition and configuration of green spaces affected the distribution of land surface temperature, though this effect varied across different seasons, and with the size and shape of urban green spaces, among other factors.[35]

Other studies analyze the role different types of vegetation configurations play in providing the benefits of green space. A study by Shashua-Bar et al. suggests that tree shade reduces thermal stress more than grass alone.[36] Considering the water needed to maintain different types of vegetation – grass has a greater demand of water than trees, for instance – shade trees reduced thermal stress more efficiently than the combination of trees and grass, or grass alone. Similarly, a study of green spaces on roofs (or green roofs) by Yang et al. found that trees remove more air pollutants than short grass or tall herbaceous plants.[37]

The UESI draws its Tree Cover indicators from the Global Forest Change 2001–2016 dataset.[38] While originally developed as a tool for large landscape observation, this dataset provides a meaningful and refined analysis of green spaces. It measures the presence of trees at least 5 meters tall, in line with some studies that suggest that trees provide more additional benefits than other forms of vegetation, such as grass or shrubbery. Other studies[39, 40] have also utilized large-scale data – in these examples, Landsat data – to measure urban tree cover. The specific indicators calculated for this issue area aim to represent both the evolution in the presence of tree cover in a city over the last 15 years (Tree Canopy Cover Loss), as well as the physical existence of these green spaces in relation to the population living in specific neighborhoods (Tree Cover Per Capita). The Tree Cover Deficit indicator, defined as the amount of tree cover required to reach the minimum target of 15 square meters of tree cover per capita, is used to assess equitable access to tree cover by income group in each city.

RESULTS

The results of the green space indicators suggest that there is an uneven distribution of tree cover throughout the analyzed districts of the UESI cities, with most districts falling into the lower end of the range. An analysis of the Tree Canopy Cover Loss indicator across all the districts of the UESI cities reveals a mean district Tree Canopy Cover Loss of 3.4 percent, and a median loss of 0.2 percent. This indicates a heavily skewed distribution, where most districts have a very small proportion of Tree Cover Loss, while a handful of other districts have very high values of Tree Cover Loss. Only 1.1 percent of the districts had lost 100 percent of their tree cover, while more than 50 percent of the districts had not experienced any tree cover loss. This distribution can be also seen when the data is aggregated at the city level. Bangalore had the highest average Tree Canopy Cover Loss of all evaluated cities, at 17.27 percent, followed by Casablanca and Singapore with 16.58 percent and 12.95 percent losses, respectively. The other cities have average values of Tree Canopy Cover Loss below 7 percent, with a minimum of 0.04 percent in Lima.

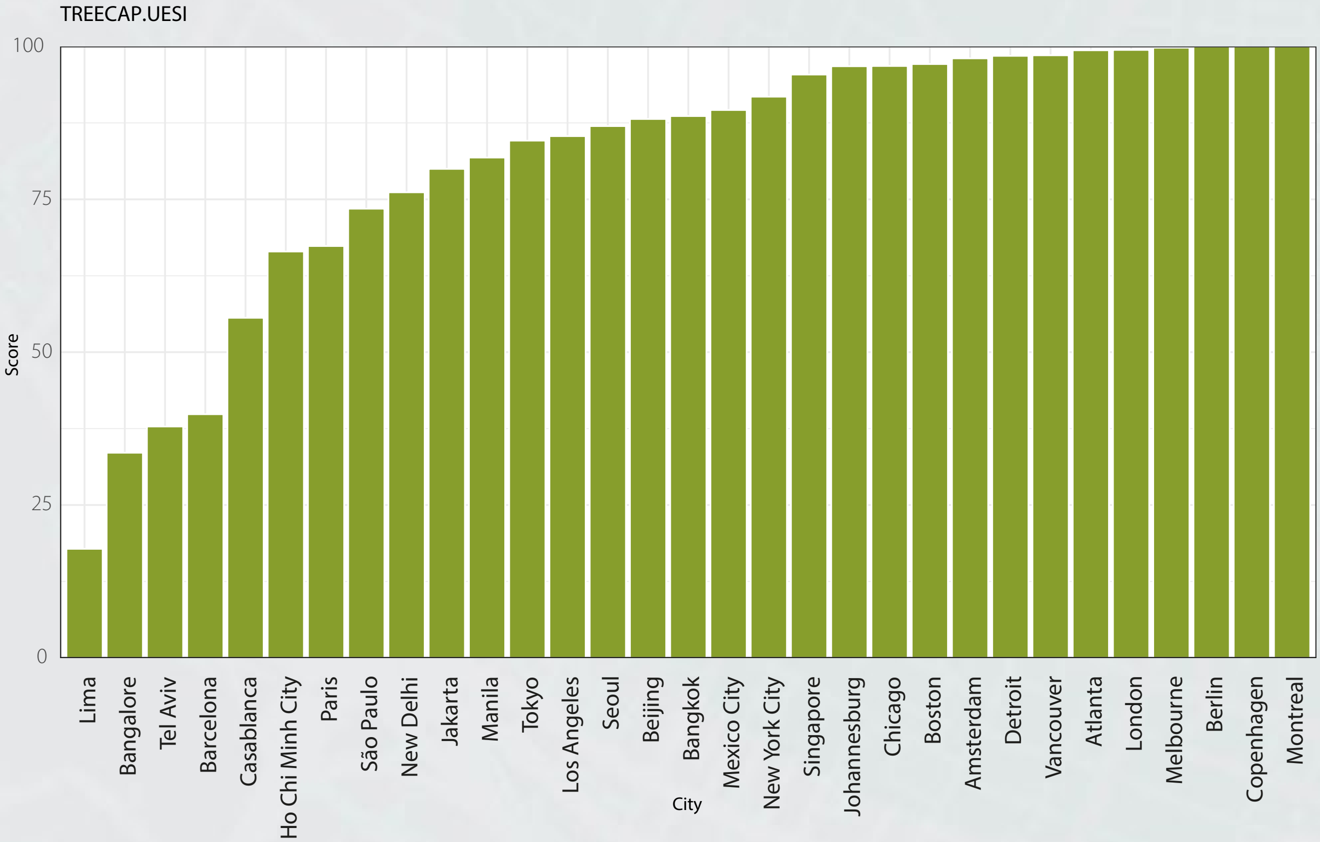
The Tree Cover Per Capita indicator has a very similar distribution, with a mean value of 1341.8 m^2 and a median value of 41.17 m^2. In fact, about 61.8 percent of all districts within the UESI cities have amounts of tree cover per capita greater than the 15 m^2 per capita target, with most cities having at least one neighborhood that has 0 m^2 of tree cover per person. An analysis at the city level provides a complementary perspective: only 9 cities have an average tree cover per capita values below the defined target, with Lima as the city with the lowest average tree cover area per capita, 0.29 m^2. The other cities are Tel Aviv (1.82 m^2), Bangalore (3.16 m^2), Manila (6.1 m^2), Tokyo (8.54 m^2), Paris (8.55 m^2), Jakarta (9.41 m^2), New Delhi (11.5 m^2), and Casablanca (12.5 m^2).

Another way to look at the Tree Cover Per Capita indicator is through its inverse, Tree Cover Deficit, the average amount that citizens in each neighborhood are lacking to reach the 15 m^2 per capita target. This analysis provides interesting insights and a different perspective on the distribution of tree cover for the UESI cities mentioned before. The results indicate that only 3 of the cities, Montreal, Berlin and Copenhagen, have an average deficit of 0 m^2 per capita target, meaning that all their districts have at least 15 m^2 per person. The other cities have positive values of Tree Cover Deficit, starting with Melbourne with an average deficit of 0.13 m^2 per capita, and finishing with Lima, with an average deficit of 14.7 m^2 per person. Figure 3 shows a ranking of the UESI cities based on their proximity to achieving the 15 m^2 per capita target.

-17.3%

of tree canopy cover loss in Bangalore.

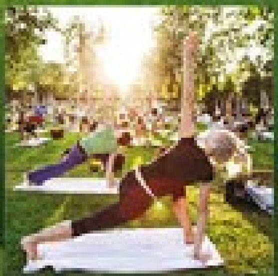
Figure 3. Proximity to Target Scores for Tree Cover per Capita.



Higher performing cities are those that are near or at 100, while lower performing cities are closer to 0.

As with any indicator and dataset, there are some caveats and limitations to be considered. The first and probably most relevant limitation is associated with the 30 x 30 meters per pixel (or 900 m^2) spatial resolution of the dataset. This resolution may limit the detection of small green spaces or areas with trees below 5 meters of height, which could be providing some meaningful benefit to citizens. Finer-resolution data are now becoming available and could enable more detailed analyses; for instance, the US Department of Agriculture's urban forest dataset covers 17 cities across the U.S. at a 3-meter spatial resolution.[41] Similarly, this indicator will not include most streetscape components, such as street trees and linear gardens; while these elements might have a more limited provision of benefits than trees, their impact should

Trees reduce air pollution and thermal stress, and provide shade. They also provide other social and psychological benefits.



not be fully discarded. On the UESI online portal, the box *High-rise greenery in Singapore* describes how this city, for instance, has leveraged linear gardens to add more green space to the city.

Another element that affects the results of the Tree Cover Per Capita indicator is the population distribution, and the selected boundaries of the analysis. While the analysis aims to analyze the tree cover distribution around urban areas, the physical boundaries and disaggregation have been defined according to the administrative boundaries of the city. This selection, while necessary in order to combine socioeconomic and environmental datasets, does not distinguish between the strictly urban areas, peri-urban areas, and rural areas located in the periphery or in the middle of the city itself. As a result, some of the districts might incorporate areas with heavy tree cover and very low population density, something that is reflected in some of the very high Tree Cover Per Capita results for some districts.

Tree cover and equity

Using the approach detailed in the Equity and Social Inclusion Issue Profile, we performed an analysis comparing distributional equity of both income and Tree Cover per Capita.[42] The results of this analysis are summarized in Figures 4 and 5.

Figure 4 provides a graphical representation of Tree Cover per Capita in each of the UESI cities, based in the construction of Environmental Concentration and Income Lorenz curves. The position of the curves relative to a 45 degree line, which represent a scenario of perfect equity, provides information about the segments of the population in which the environmental outcome – Tree Cover per Capita – is unequally allocated. For example, the position of the Concentration curve below the 45 degree line for cities such as Johannesburg and Singapore, indicates that there is more tree cover per capita allocated to those with more income. To the contrary, the position of the curve above the 45 degree line in cities like São Paulo, indicates that there is more tree cover per capita available for those with lower income.

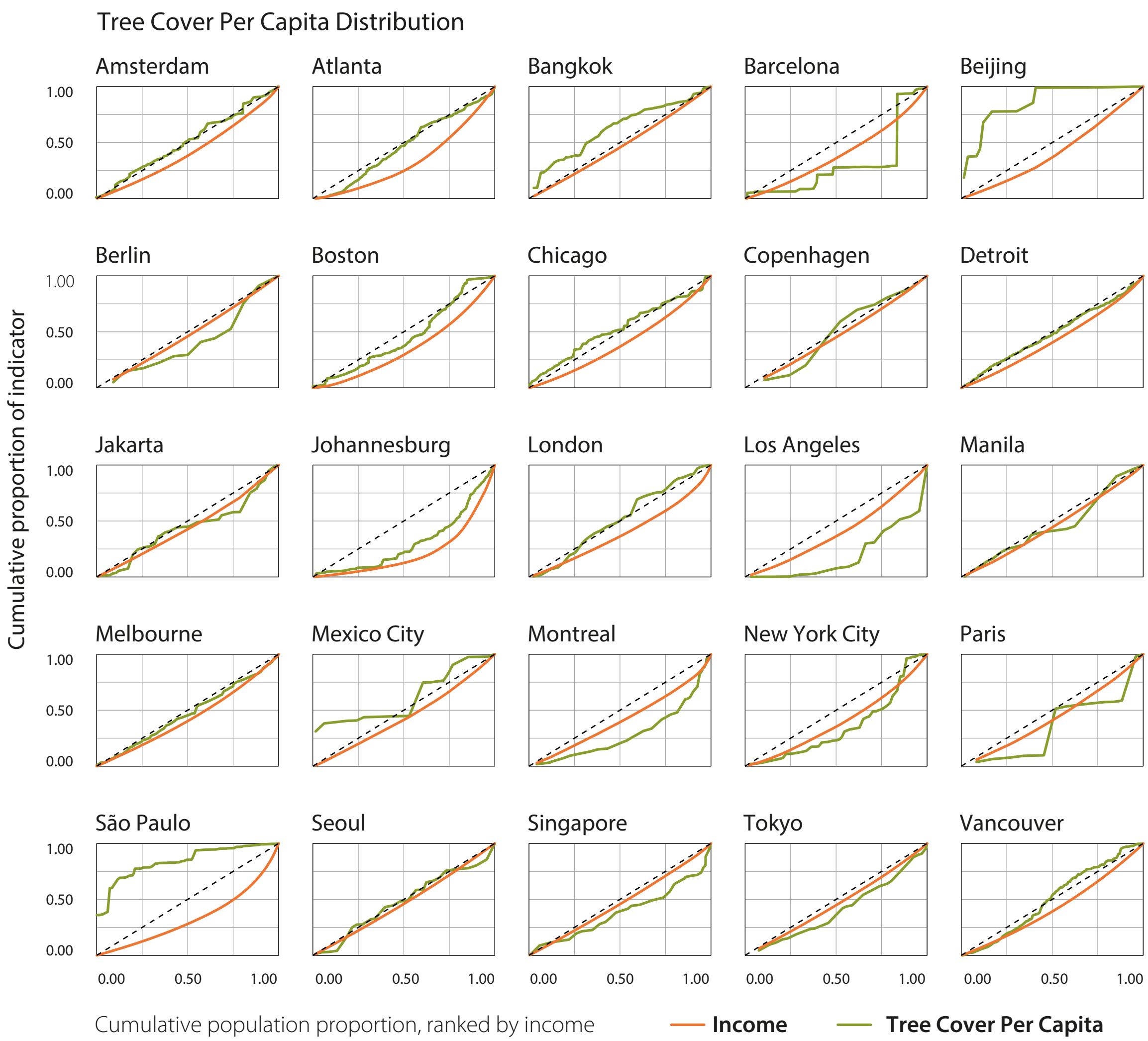
For many cities the concentration curve crosses the 45 degree line of perfect equity. This case suggests that within a city, sectors of the population with different levels of income might experience different relationships with Tree Cover per Capita allocation. For example, in Copenhagen, the Tree Cover per Capita concentration curve presents two pockets of inequity, one located below the equity line, affecting the poorest citizens, and one above below the equity line, benefiting a segment of wealthier citizens. These changes in the relationship between and environmental burden and different sectors of the population can help identify especially vulnerable sectors of the population and help policymakers respond to their particular situation.

A numeric quantification of the inequality in distributions of Tree Cover Deficit and Income, derived from the curves in Figure 4, is summarized in Figure 5. The quadrant plot presents the UESI's proposed typology that categorizes the relation between the environmental inequality and the income inequality, using the Environmental Concentration Index (ECI) and the Gini Coefficients respectively (see the *Equity and Social Inclusion Profile* for a more detailed description of this plot). The results indicate that most of the cities have low Income Inequality (low Gini coefficient), with

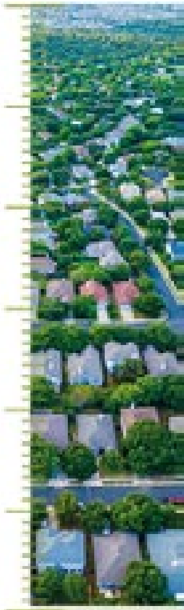
the exception of Johannesburg, which has the highest level of income inequality among the UESI cities.

The top left quadrant (Low Gini and positive ECI) includes cities such as Melbourne, Los Angeles, Atlanta, Barcelona, and Seoul, where the Tree Cover per Capita is more heavily allocated to the richest income earners in those cities. While these cities have low income inequality, the environmental pressure falls hardest on low-income populations – who are negated the benefits of access to green space at the same level as other citizens – potentially creating an additional economic pressure on the lowest-earners of the city and increasing the gap between poorer and richer citizens. In the top right quadrant (low Gini and negative CI) includes cities such as London, Mexico City and São Paulo, where the Tree Cover per Capita is more heavily allocated to the lowest-income earners of city. In these cities, the inequality of the Tree Cover per Capita does not actively aggravate the relatively low income inequality throughout the city, because the poorer citizens don't need to spend economic resources to gain access to tree cover or green spaces.

Figure 4. Environmental and income distribution curves for selected UESI cities.



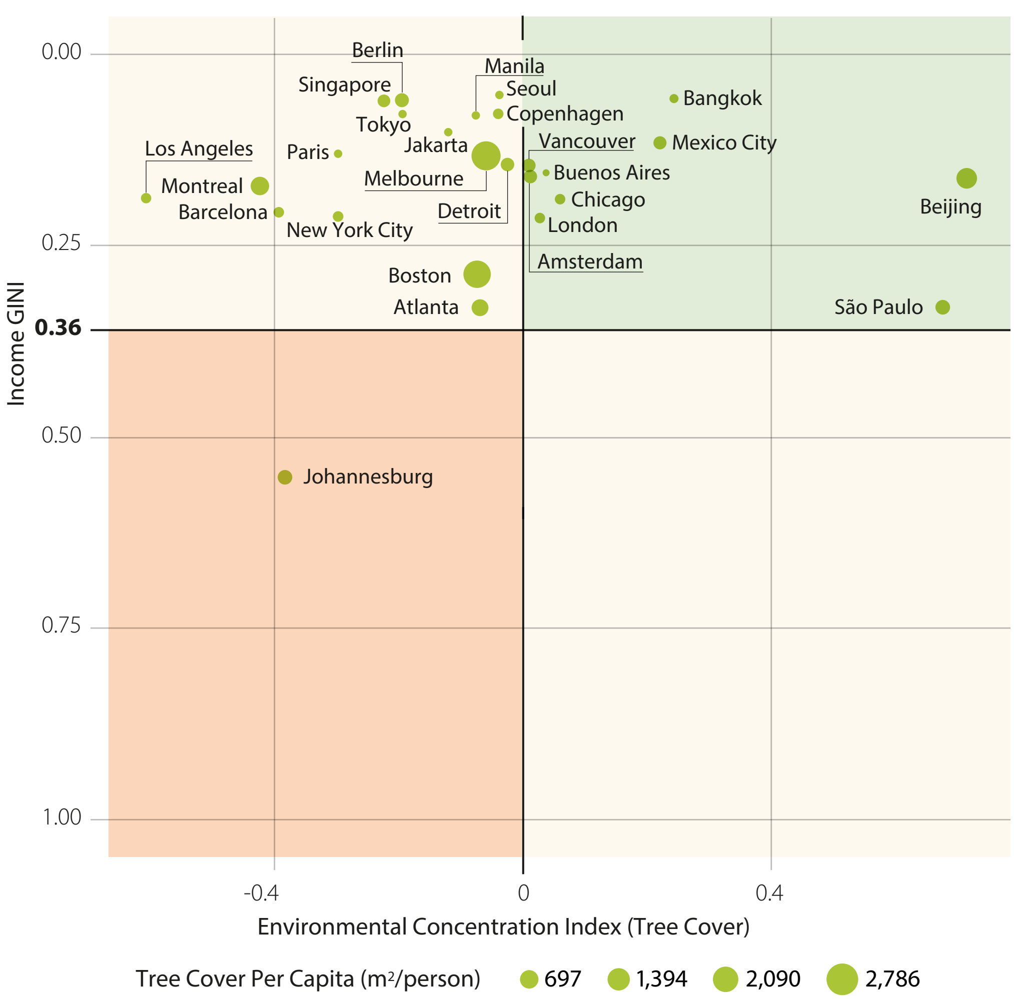
These plots show the distributions of Tree Cover per Capita (e.g., the concentration curve in blue) and income (e.g., the Lorenz curve in red) throughout city neighborhoods. Deviations from the dotted line (e.g., the line of perfect equity) illustrate cities that are less equitable in their distribution of Tree Cover per Capita. Concentration curves above the line of equity indicate the environmental benefit is more heavily allocated to those with less income; concentration curves below the line of equity indicate that the environmental benefit is more heavily allocated to those with greater income.



The only city in the lower left quadrant (high Gini and negative ECI) is Johannesburg, a city with both high income inequality and high environmental inequality. In other words, the unequal allocation of tree cover could compound the city's income inequality, exacerbating the situation of the lowest income-earners and increasing the gap between poorer and richer citizens.

Finally, it is worth mentioning that while the ECI and Gini values are relevant summary indices to evaluate inequality in the distribution of an environmental outcome, there are some limitations to be considered (see the *Equity and Social Inclusion Profile* for a more details). The interpretation of the ECI needs to be complemented with an analysis of the Environmental Concentration curves themselves and the data used for their construction. This process will allow the decisionmakers to have a more comprehensive picture of the specifics of their cities, both in terms of the allocation and the intensity of the environmental outcomes, as well as its relation with income to craft potential useful interventions to address these issues.

Figure 5. Tree Cover per Capita Equity typology plot.



The plot considers the Income Gini and Tree Cover Per Capita Concentration Index to define four quadrants. The Income Gini Values represent the distribution of wealth across the population and range from 0 to 1. A Gini value of zero indicates a perfectly equal distribution of income across the population, while a high Gini value (out of a maximum of 1) suggests a highly unequal distribution of wealth. The Environmental Concentration Index (ECI) measures the variation of Tree Cover per Capita in response to income. Positive ECI values indicate that the environmental benefit is allocated on the poorest citizens, while a negative ECI indicates that the environmental benefit is allocated on the wealthier citizens. The size of the dots represents the extent of a city's Tree Cover per Capita (in square meters/person). See the *Equity and Social Inclusion* issue profile for a more detailed description of this plot.

SUSTAINABLE PUBLIC TRANSPORTATION

Public transportation infrastructure (e.g., rail, mass transit, and bus) enable people to move across a landscape, connects residential areas with work and recreational opportunities, and is a central aspect of urban and regional planning.

420m

(0.25 miles) is the PTC ratio for a bus stop.

What it measures

We score cities on two indicators for Sustainable Public Transportation:

1. Proximity to Public Transit (PPT): the proximity of a public transportation stop to where people live in an urban neighborhood. This indicator is represented as the median distance required for residents to reach a public transit stop. The mean distance required for residents to reach a public transit stop is weighted by the neighborhood's residential population density.[1]

2. Public Transportation Coverage (PTC): the ratio of area within walking distance to a public transportation stop for each neighborhood. PTC measures the ratio of neighborhood area within walking distance to a transit stop. Transportation planning guidelines frequently define walking distance in quarter-mile or 400-meter increments[2,3,4] and assume that people will walk farther to access transit of higher speeds and greater reliability, regardless of the mode. However, we use mode here as a proxy for more general qualities of urban transportation.[5] The PTC ratio is based on buffers with a radius of 420 meters (approximately 0.25 miles) for bus stops and 1.2 kilometers (approximately 0.75 miles) for train stops, to reflect this difference.[6]

Additionally, we provide a City-wide Proximity to Public Transit (CPPT) measure (Table 2 on page 95) to summarize whether a city-wide average measure of proximity to public transit takes into consideration more densely populated neighborhoods that have greater access to public transit than less densely populated areas.

For a discussion of alternative methods we explored to calculate Sustainable Public Transit, see the boxes on *Limitations of the data and indicators, Alternative Method: Disaggregating Population* and *Alternative Method: Transit Accessibility (Applied to Singapore)* on the UESI online portal.

Why we include it

The Sustainable Development Goals (SDGs) identify the improvement of public transit as key to address climate change and development. Sustainable Development Target 11.2 calls for "safe, affordable, accessible and sustainable" public transit to help deliver resilient and inclusive cities. The US transportation sector, for example, has historically been one of the largest carbon-emitters due to personal automobile use. In 2015, the U.S. transportation sector contributed 27 percent of the country's greenhouse gas emissions.[7] In conjunction with policies, such as congestion pricing, that directly disincentivize driving personal automobiles, urban administrations can provide convenient public transportation options to encourage alternatives to personal automobiles.

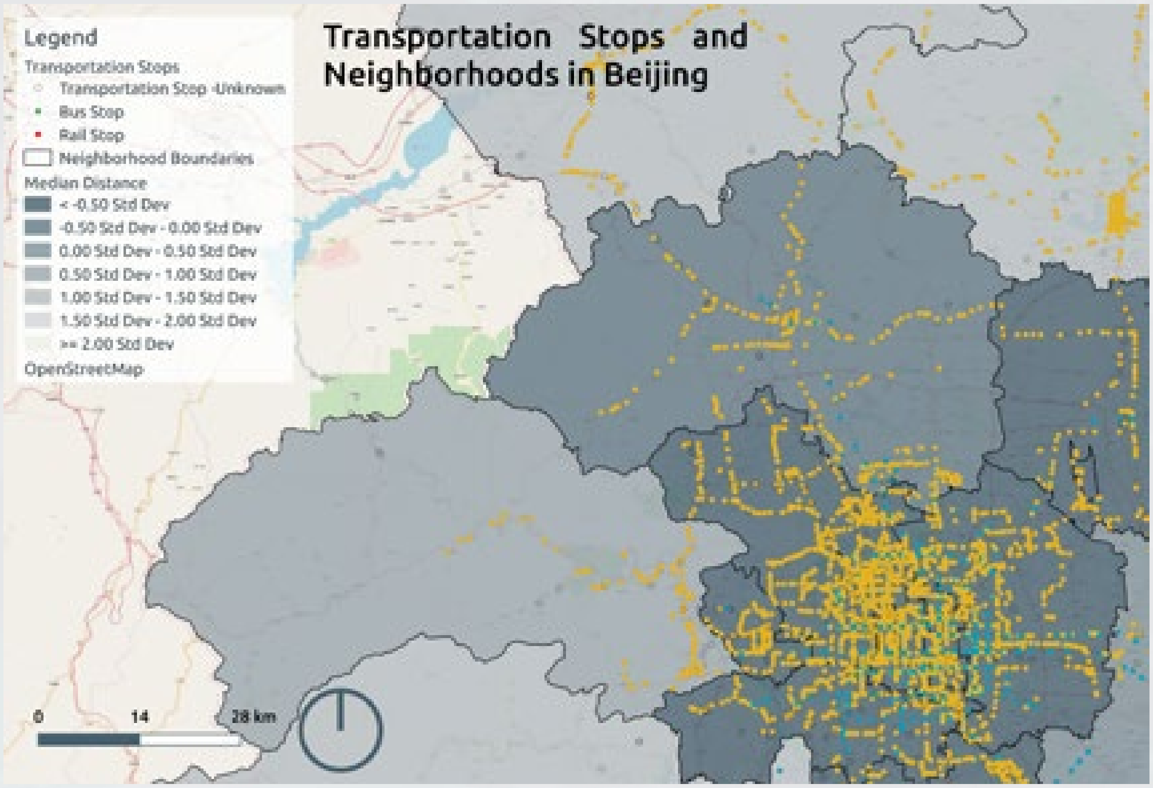
Public transport also contributes to social inclusion in communities.[8] Transportation connects populations within a city, providing access to essential services, such as schools, grocery stores, and health facilities, job sites, and recreational facilities. Recognizing the importance of public transportation for both environmental and social inclusion goals, many city governments have set goals for public transportation availability.

Where the data come from

The locations of bus and train stops and of green spaces are the only data needed to compute the Sustainable Public Transit indicators. For all selected cities, transit stop locations were downloaded from OpenStreetMap (OSM), queried using the OpenStreetMap OverPassAPI (see Table 1 for the specific OpenStreetMap "tags" considered to be relevant). OSM is a crowdsourced map of the world that has grown in coverage and quality since its inception in 2006,[9, 10, 11] with some researchers predicting that some OSM data will be available on every square kilometer of the Earth's surface by 2020.[12] Still, the quality of OSM data depends on volunteer mappers, and the Sustainable Public Transit indicator's accuracy is limited by the quality of OSM data.

To calculate the Proximity to Public Transit (PPT) indicator, the median distance to a transit stop within each neighborhood was computed. The locations of green spaces, also gathered from OSM, were masked out of the neighborhoods to more accurately

Figure 1. Distance to public transit in Beijing's municipal subdivisions, with density of subdivisions shown in gray scale (lighter colors are more dense).

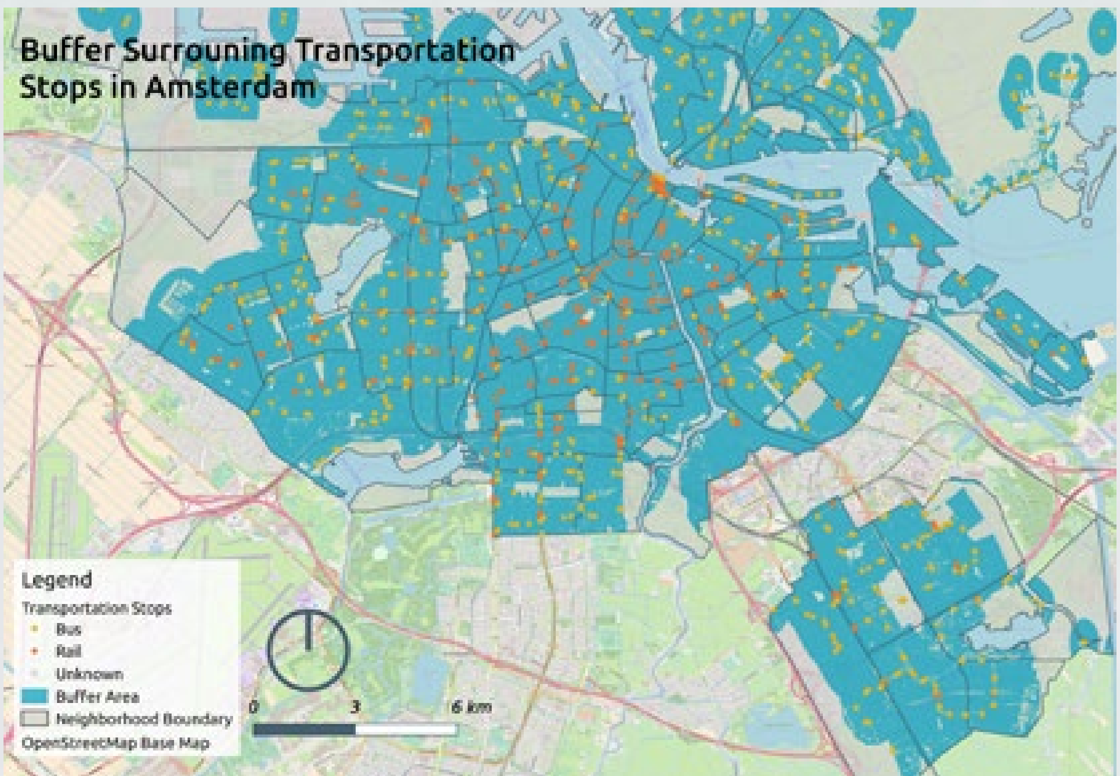


Data source: OpenStreet-Map.

represent where residences may be located. The distances represent the shortest distance from randomly located points in each neighborhood to the nearest public transportation stop in any neighborhood. Figure 1 shows an example of this in Beijing.

To calculate the Public Transportation Coverage (PTC) indicator, we placed a buffer of 420 meters around each bus stop and 1.2 kilometers around each intra-city rail stop. We then dissolved these buffers to create a GIS layer designating the area proximate to a transit stop. The proximate area was compared to the neighborhood's area to calculate the percentage of a neighborhood covered by public transit. Figure 2 below shows the locations of transit stops as points on a map of Amsterdam. The blue shading indicates areas within the walkshed of transit stops, and the grey shading indicates the neighborhood boundaries. Gaps in neighborhoods represent waterways and areas outside the city limits.

Figure 2. An illustration of the Public Transit Coverage layer in Amsterdam.
We excluded park areas from the area calculation for both the buffer and the total neighborhood calculation.



PPT
Proximity to Public Transit

PTC
Public Transportation Coverage

Table 1. Definitions of Transit Queried from OpenStreetMap[13]

Transit type	OpenStreetMap definition
Bus	A form of public transport that operates mainly on the road network
Train (rail/mainline)	Full sized passenger or freight trains in the standard gauge for the country or state
Subway	A city passenger rail service running mostly grade-separated (defined as a method of aligning a junction of two or more surface transport axes at different heights so that they will not disrupt the traffic flow on other transit routes when they cross each other)
Tram	City-based rail systems with one/two carriage vehicles, which often share roads with cars
Metro	A rapid transit train system
Light Rail	A higher-standard tram system, normally in its own right-of-way

TARGETS

What are the targets

For Proximity to Public Transit (PPT), the target median distance to a public transportation stop is 1.2 kilometers.[6] While most urban planning literature cites a "catchment zone" (i.e., a geographic area encompassing all possible riders for a mode of public transit) of 0.25 to 0.5 miles (0.4 to 0.8 km), Durand et al. (2016) found in a survey that riders express willingness to travel further. We therefore adopted a target of 1.2 km. The target for Percent Transit Coverage indicator is 80 percent, which is the 50th percentile of the PTC for UESI cities. There is a lack of clarity in the literature on the appropriate coverage for cities, so we chose this as a relative target for this indicator. While 100 percent coverage would allow all inhabitants to engage with public transit, some low density areas of the city may not be viable for public transportation service because of the cost per person. Rather, we focused on determining whether public transit evenly covers income groups (described further in the *Key Equity Indicators section)*. While some cities contain low-density neighborhoods, most neighborhoods in the sample cities belong to the central municipality of the city, rather than peri-urban or rural areas.

Three notable exceptions include Beijing, where the peripheral neighborhoods contain large areas spanning primarily rural and non-urban extent; São Paulo, which contains densely forested areas that may not be viable for public transportation; and Mexico City, whose city boundaries, like Beijing's, extend beyond the densely-populated urbanized area. Including less-populated peri-urban areas in more cities' boundaries, and including smaller cities, may result in further lowering the target, since low density areas are not economical for public transit. For a further discussion of these limitations and possible strategies to address them, see the online portal's box on *Limitations of the Data and Indicators* and the *Discussion*.

Transportation in the Sustainable Development Goals

Transportation is a cross-cutting issue that relates to seven[14] Sustainable Development Goals (SDGs), each suggesting transportation-relevant indicators. SDG 11 Target 11.2 calls for sustainable urban development for all, particularly for "vulnerable situations, women, children, persons with disabilities and older persons" (see Box 1, *Why Isn't Public Transit Gender Neutral?*, for a discussion of barriers to public transit access according to gender). The single indicator for Target 11.2, SDG Indicator 11.2.1, refers to the "proportion of population that has convenient access to public transport, by sex, age and persons with disabilities."[15]

As mentioned above, transportation is one of the largest contributors to urban greenhouse gas emissions (GHGs) globally (see the online portal for a box on *Transportation and the New Economy*). Increasing the share of trips taken by public transportation, instead of through individual automobile travel, can lower GHG emissions per passenger mile. For example, the average single occupancy vehicle in the United States emits 0.964 pounds of carbon dioxide per passenger mile, whereas light rail and buses emit 0.365 and 0.643 pounds, respectively.[16] To address transportation's large share of urban emissions, dense mixed-use developments surrounding public transit are a goal for urban planning and development. SDG 12 also suggests ending fossil fuel subsidies used to lower the price of gasoline and other fossil fuels in some countries, which would greatly increase the price of car travel and likely lead to changes in urban development patterns. Seto et al. (2011) showed that fuel prices are a strong indicator of the rate of urban expansion globally, hinting at the systemic nature of the relationship between transportation and urbanization.[17] Other SDGs (SDG 7 on sustainable energy generation and provision, SDG 8 on decent work opportunities[18] and economic growth, SDG 9 on resilient infrastructure) rely on changes in transportation infrastructure and patterns of use, though the transportation sector is not specifically mentioned in the targets or indicators.

The transportation sector is one of the largest contributors to greenhouse gas emissions globally.

Box 1. Why isn't transport gender neutral?

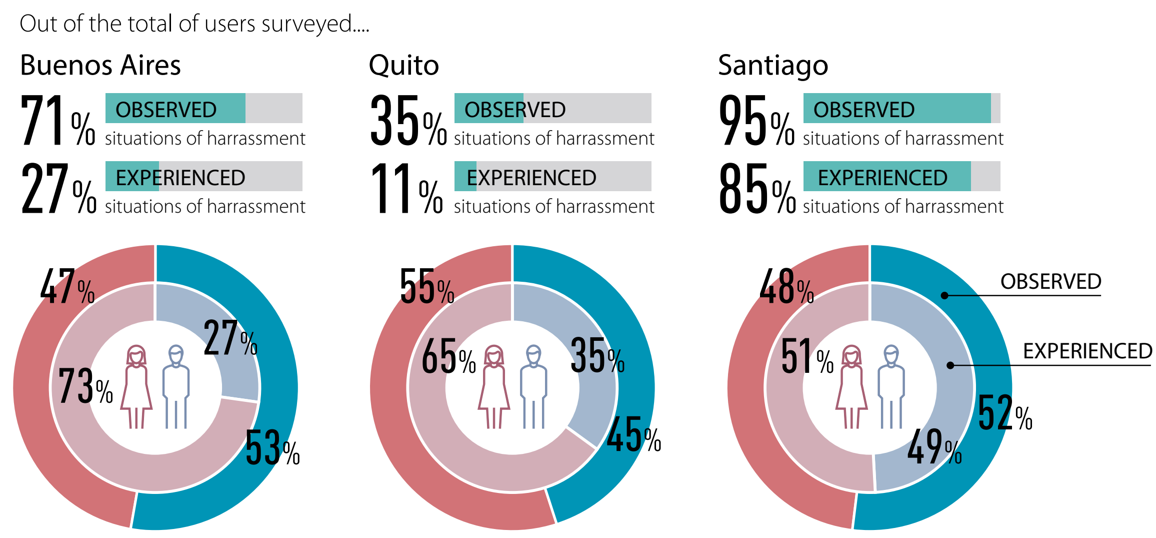
Our analysis of public transit access equity assumes urban dwellers will take advantage of public transportation within walksheds. In reality, this scenario is seldom the case; many factors, such as safety on public transit, can lower transit use. In particular, women face more barriers to public transport access.

This problem has huge social development and civil rights implications as limited access to public transport restricts women from jobs and learning opportunities, and prevents them from actively participating in social activities.

Sexual Harassment and Access to Public Transport

Both women and men experience sexual harassment on public transport, though harassment survivors are primarily women. Sexual harassment can take a variety of different forms, that can range from verbal and physical contact.[19] The FIA Foundation and CAF Latin American Development Bank report "Ella Se Mueve Segura- She Moves Safely," examines women's security on public transport in three Latin American cities (see Figure 6). The report finds that 72 percent of Buenos Aires female respondents and 58 percent of male respondents feel insecure on public transport due to harassment.[20]

Figure 3. Summaries of experienced and observed harassment in Buenos Aires, Quito, and Santiago, as reported by men (in blue) and women (in red)



Across all three cities, women experienced and witnessed higher levels of harassment. The highest disparity between harassment between men and women was found in Buenos Aires (FIA Foundation & CAF Latin American Development Bank, 2017).

In China, a report on the state of public harassment in Shenzhen's public transport shows 42 percent of women have experienced sexual harassment. The probability of experiencing harassment is 10 percent higher among students and young people.[21] Their higher risk demonstrates that the phenomena of sexual harassment depends on a combination of different factors, including gender, age and class. These reported figures, however, may underestimate the true values, as most survivors choose to remain silent.[22]

The experience of sexual harassment can affect physical and mental health. The insecurity of public transport has caused women riders to abandon public transport, thereby restricting their job and learning opportunities, and preventing them from actively participating in social activities. Losing the ability to use public spaces as a result of sexual harassment is a civil rights violation, and sexual harassment represents a threat to social development.

Professional Participation and Decision Making Power

Women are less represented in transportation occupations such as bus, train, or truck drivers and construction workers. This underrepresentation is partially linked to the gender stereotypes that exist in many cultures and to gender discrimination in hiring and working environments. In addition, the transportation sector has long been a male-dominated sector. There are fewer women employed compared to men, and women seldom serve as high-level decision-makers. Transportation policies have long neglected the needs of women, due to their absence from the planning and decision-making processes.[23]

Addressing Transport Gender Inequity with Data

Data collection can support a shift towards greater gender equity in public transit access and use. There is a huge data gap in addressing gender inequity in transportation. Without data, we cannot formulate transportation policies that take into account the needs of women. For starters, we do not know where and how women use public transportation. Research shows that in Buenos Aires, women's travel needs are different from men's, including traveling more frequently and for different purposes (such as picking up their children).[24] Cities should collect more gender-specific data to help develop more gender-inclusive transportation policies and create safer public spaces. Crowdsourcing is one option for gathering such data. The Safecity project (http://safecity.in) in India allows survivors to locate and share their stories through mobile phones.[25] This valuable data can not only increase public awareness of sexual harassment, but also advance the formulation and legislation of anti-sexual harassment policies.

RESULTS

Sustainable Public Transit in the UESI

Public Transit Coverage in the UESI cities ranges from near universal coverage[26] in neighborhoods of Paris, Barcelona and Boston to about 30 percent in Detroit, Beijing, New Delhi and Manila. The top ten cities in the sample (top half) provide transit to well over half of their residents, while the bottom ten cities (bottom half) provide transit to between 46 percent (Montreal) and 27 percent (Detroit and Beijing). A relatively large gap separates the 17th and 18th ranking ciites (Singapore at 77 percent and Ho Chi Minh City at 56 percent, respectively) making two natural clusters of higher and lower ranking cities. The top five cities are situated in developed countries, some of which are well-known for their transit systems. Part of the gap between developed and developing countries (Table 2) may be due to poor data coverage or a reliance on informal bus and taxi services in developing countries.

On the Public Transportation Coverage indicator, the difference between the average city-level access and the average neighborhood-level access suggests that transit stops are located in more densely populated neighborhoods. Figure 4 below shows the distribution of all neighborhood and city mean distances. Just under half of the population represented in the sample is not within proximity to public transit. Neighborhoods in the UESI cities have populations ranging from a minimum of 10 in Singapore to a maximum of nearly 3.95 million in Beijing. The median population for all neighborhoods is 95,370. In sum, the population of the sample cities together represent more than 147.1 million people.

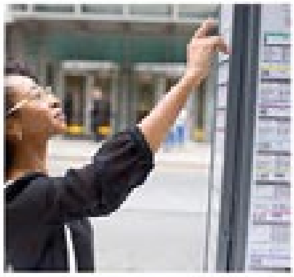
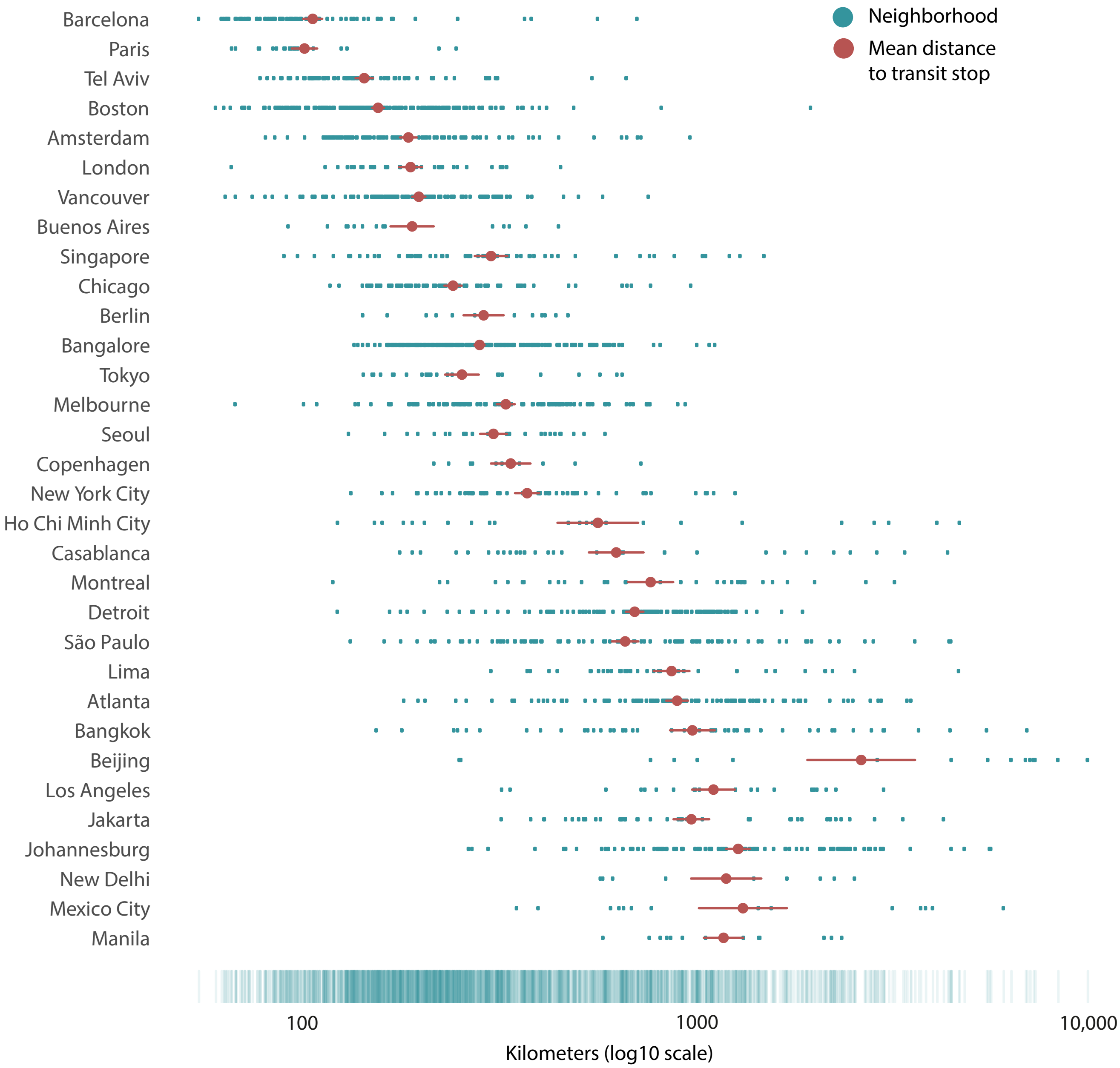


Table 2. Cities' distance to public transit, both weighted and unweighted by population density.

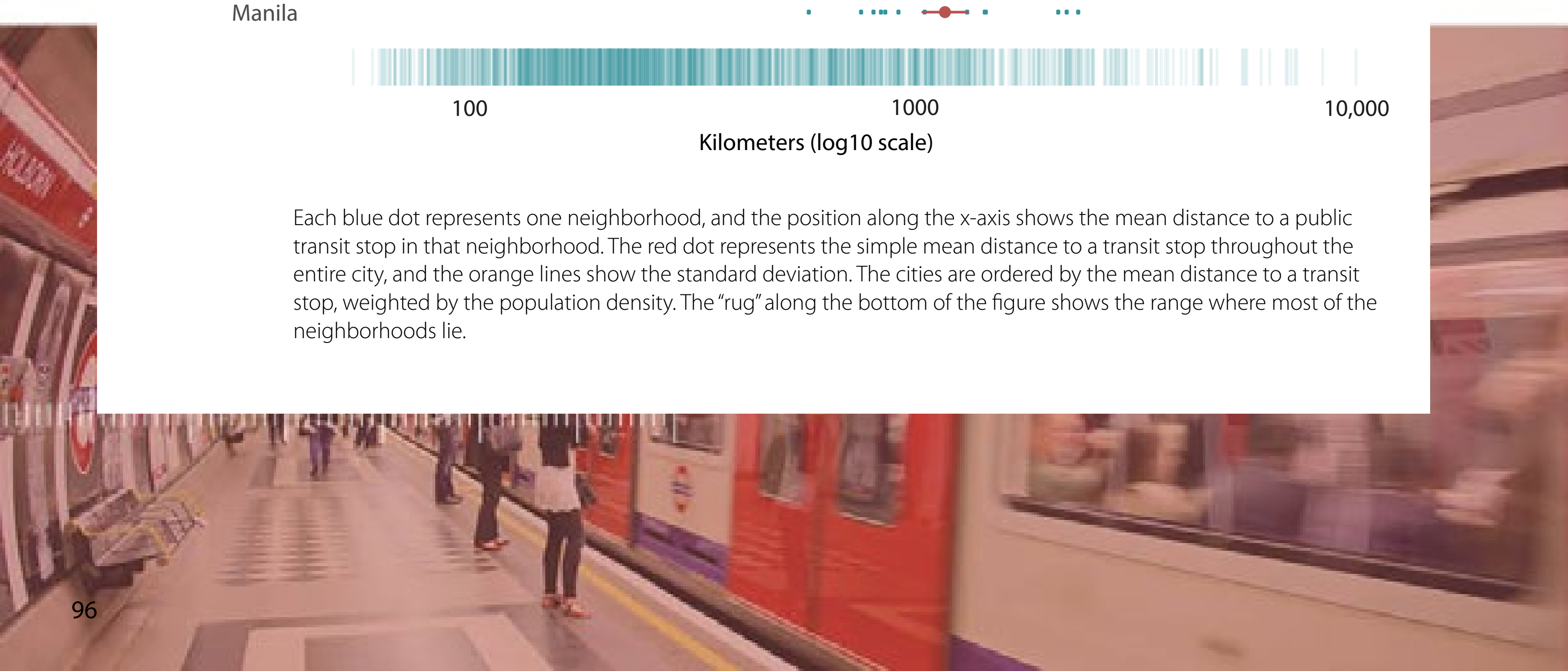
City		City-wide Proximity to Public Transit (meters) (CPPT)	Proximity to Public Transit (PPT) (meters)	Coverage (PTC)
1	Paris	119	107	0.98
2	Barcelona	102	123	0.97
3	Boston	157	177	0.96
4	Tel Aviv	134	159	0.94
5	Amsterdam	182	213	0.92
6	Tokyo	334	284	0.92
7	London	205	200	0.90
8	Buenos Aires	217	212	0.90
9	Chicago	249	268	0.89
10	Bangalore	347	308	0.88
11	Vancouver	210	214	0.87
12	Seoul	330	325	0.85
13	Melbourne	341	369	0.84
14	New York City	430	427	0.83
15	Berlin	305	307	0.80
16	Copenhagen	363	358	0.80
17	Singapore	242	389	0.77
18	Ho Chi Minh City	1045	1074	0.56
19	São Paulo	1032	884	0.55
20	Atlanta	1147	1073	0.54
21	Casablanca	1002	970	0.54
22	Mexico City	1825	1986	0.51
23	Montreal	721	983	0.46
24	Bangkok	1701	1434	0.41
25	Johannesburg	1747	1565	0.38
26	Jakarta	1468	1225	0.37
27	Lima	1204	1066	0.35
28	Los Angeles	1271	1282	0.34
29	New Delhi	1772	1391	0.30
30	Manila	1390	1277	0.30
31	Detroit	765	779	0.27
32	Beijing	2808	4387	0.27

Cells highlighted in green represent cities where the average distance to a transit stop is 420 meters or less (the distance the average resident is willing to walk to a bus stop), while cells highlighted in yellow represent cities where the average distance to a transit stop is greater than 1.2 kilometers (the distance the average resident is willing to walk to a metro stop).

Figure 4. Mean distance to transit stops among the UESI cities.



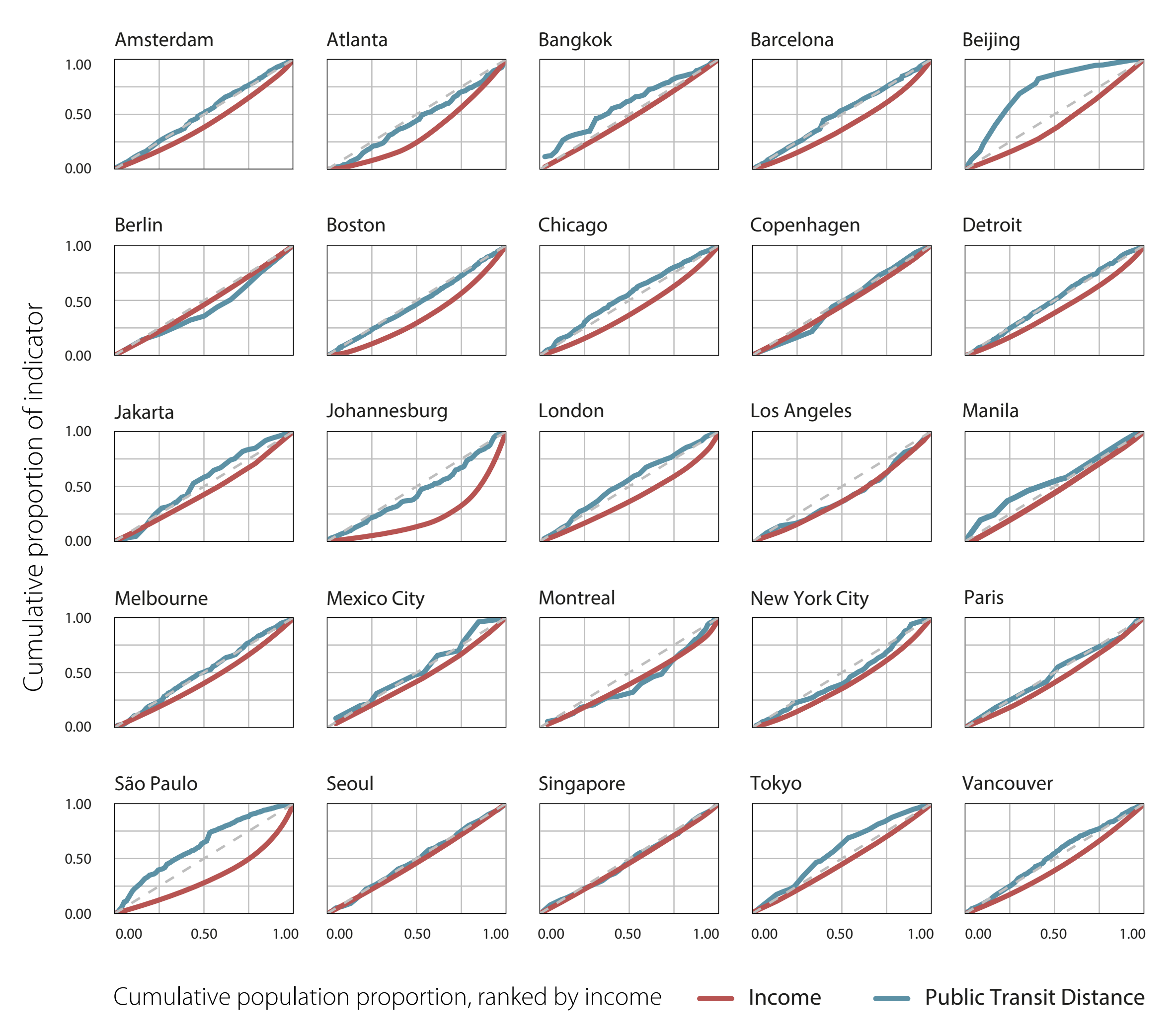
Each blue dot represents one neighborhood, and the position along the x-axis shows the mean distance to a public transit stop in that neighborhood. The red dot represents the simple mean distance to a transit stop throughout the entire city, and the orange lines show the standard deviation. The cities are ordered by the mean distance to a transit stop, weighted by the population density. The "rug" along the bottom of the figure shows the range where most of the neighborhoods lie.



Key equity considerations

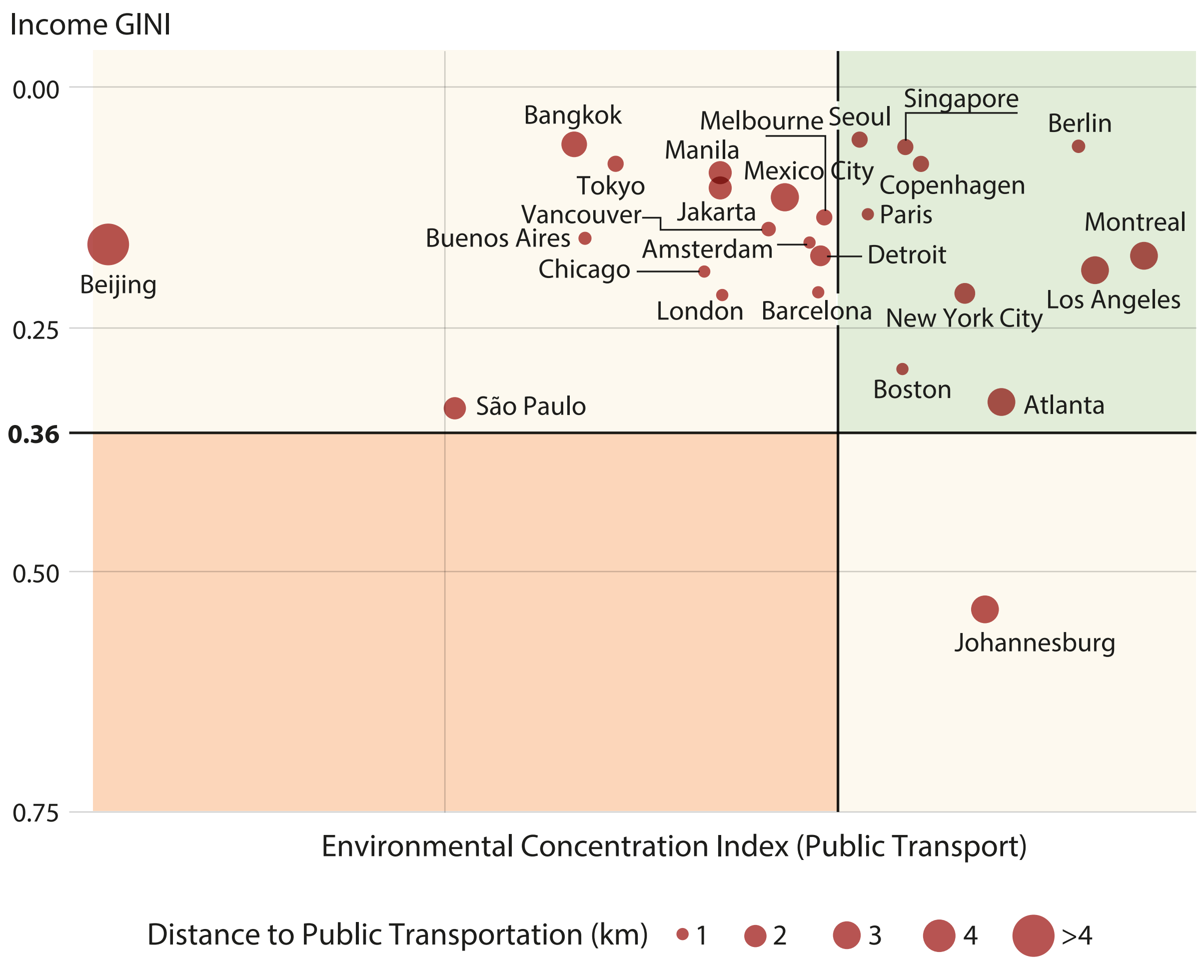
Using the approach described in the *Equity and Social Inclusion Indicator Profile*, we analyzed the distributional equity of income and distance to public transit. The results show that the majority of the pilot cities have low income inequality (i.e. low Gini values), except for Johannesburg (see Figure 5). In Bangkok Beijing, Jakarta, São Paulo, Tokyo and to a lesser extent Manila and London, the burden of lack of proximity to public transit is falling more heavily on lower income populations. The inequities are most severe in Beijing, Bangkok and São Paulo, as determined in their position in the upper left-hand quadrant of the equity typology plot (Figure 6). Some cities, however, have managed to achieve near perfect equality with respect to distance to public transit - Barcelona for instance, has an Environmental Concentration Index (ECI) value of nearly 0, although it does have less equitable income distribution than other cities, such as Boston. Several cities are located in the upper right-hand quadrant (low Gini, positive ECI), which suggests that cities like Los Angeles, Montreal and New York City are burdening wealthier populations with greater distances to public transit. This result may also reflect a preference for wealthier populations living in these cities for choosing to live farther away from public transit stops.[27]

Figure 5. Environmental and income distribution curves for selected UESI cities.



These plots show the concentration distributions of distance to public transit (e.g., the concentration curve in blue) and income (e.g., the Lorenz curve in red) throughout neighborhoods in cities. Deviations from the dotted line (e.g., the line of perfect equity) illustrate cities that are less equitable in their distribution of distance to public transit. Concentration curves above the line of equity indicate the environmental burden is more heavily allocated to those with less income; concentration curves below the line of equity indicate that the environmental burden is more heavily allocated to those with greater income (see the *Equity and Social Inclusion Indicator Profile* for a more detailed description of this plot).

Figure 6. Distance to Public Transit Equity typology quadrant plot.



The plot considers the Income Gini and Distance to Public Transit Concentration Index to define four quadrants. The Income Gini Values represent the distribution of wealth across the population and range in value from 0 to 1. A Gini value of zero indicates a perfectly equal distribution of income across the population, while a high Gini value (out of a maximum of 1) suggests a highly unequal distribution of wealth. The Environmental Concentration Index (ECI) measures the variation of Distance to Public Transit in response to income. Positive ECI values indicate that the environmental burden is allocated on the poorest citizens, while a negative ECI indicates that the environmental burden is allocated on the wealthier citizens. The size of the dots represents the extent of a city's distance to public transit (in km). See the *Equity and Social Inclusion* indicator profile for a more detailed description of this plot.

The equity curves shown in Figure 5 provide further insights into the distribution of Proximity to Public Transit and Income in the UESI cities. Cities exhibiting nearly equitable distributions of the distance to public transit can be identified as those with a blue line that follows the dotted diagonal line (the line of perfect equity). These include: Amsterdam, Boston, Seoul, Barcelona, Melbourne, and Johannesburg. The transportation curves of the following cities suggest that the environmental burden is allocated more heavily to lower-income earners: Bangkok, Beijing, Jakarta, London, São Paulo, Tokyo, and Vancouver. The transportation curves for Berlin, Los Angeles, Montreal, New York City, and Paris suggest the opposite; i.e., that the burden of greater distance to public transit is more heavily allocated to higher-income earners. It is important to note that these curves do not indicate whether the Distance to Public Transportation for a given city is large or small. They simply indicate whether the Distance to Public Transportation remains relatively constant across the population.

It is noteworthy that the transportation curves for several cities cross the diagonal line of perfect equity, such as in the case of Barcelona, Copenhagen, Jakarta, and Mexico City. This result may suggest that certain segments of the population are taking on a disproportionate burden as compared to the rest of the population. For example, Jakarta's equity curve suggests that the middle-income earners, as illustrated by the slight bulge in the curve above the line of perfect equity between the 25th and 75th income percentiles bear a disproportionate amount of the environmental burden associated with distance to public transportation stops.

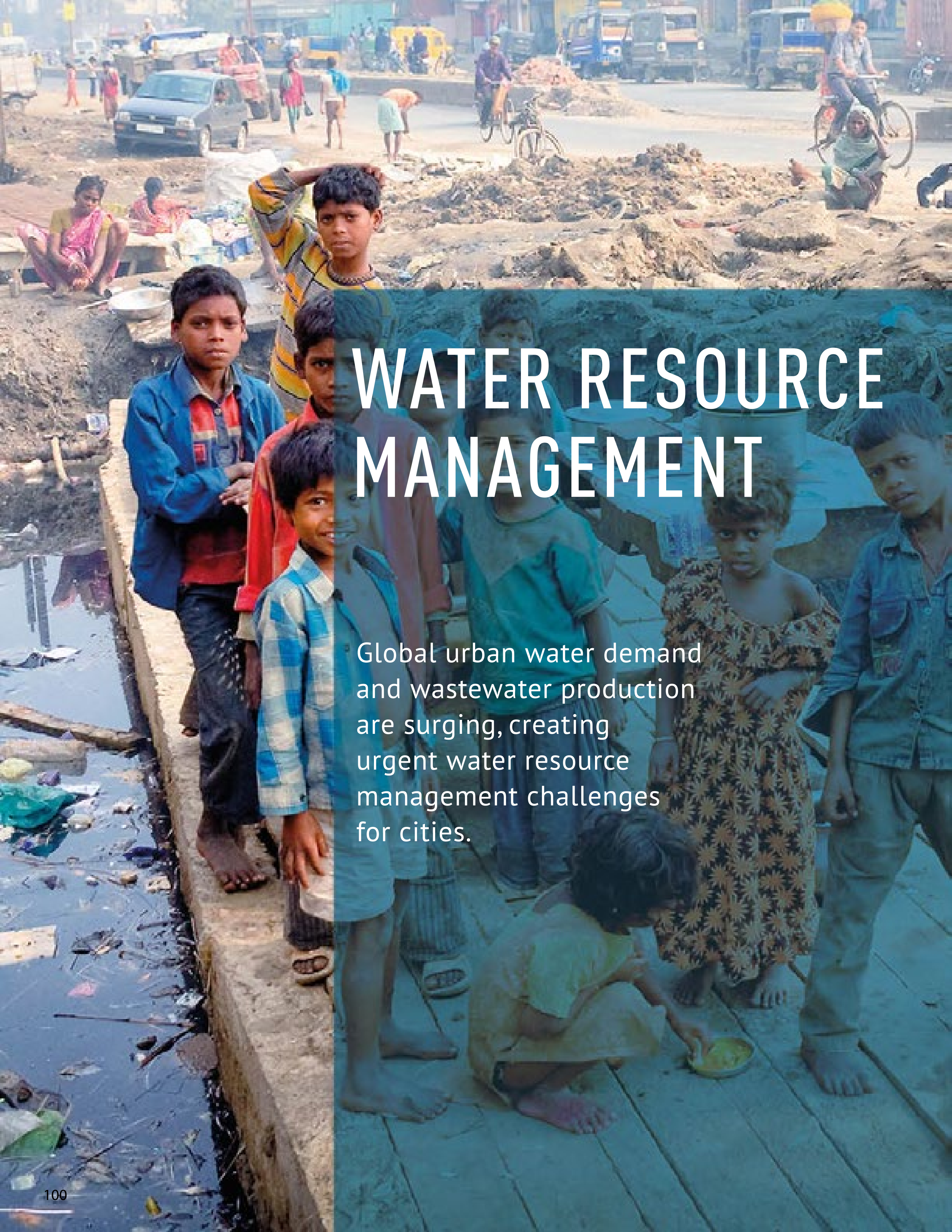
DISCUSSION

Access to public transit is a critical measure of urban environmental sustainability, although it is a challenging indicator to assess consistently across cities. The UESI's two sustainable public transit indicators, Proximity to Public Transport and Public Transportation Coverage, provide a first step for comparing how cities perform. When interpreting these indicators, however, it is important to note that they likely overestimate the real distance of a neighborhood to transit stops, since we expect population density to be higher closer to transit stops but have no way to account for this variability in the indicators. As well, the relationship between population density and the viability of public transit, while commonly used, varies between rapidly-urbanizing and developed cities, and it is not clear whether transit stops are a leading or lagging indicator for population density.[28] Despite these limitations, the spatial access explored by the Sustainable Public Transit indicators remains a crucial element of equitable access to public transportation in the UESI cities.

As previously mentioned, a key assumption underpinning the Sustainable Public Transit indicators is urban residents' use of these options. Simple proximity to public transit does not translate into use. Contributing to public transit's use is the quality of service - an indicator that we currently do not evaluate in the UESI but could be incorporated into future iterations. Service levels are often not homogeneous across different populations; for example, middle and low-income residents who live in more affordable suburban and peri-urban areas often have lengthy commutes, regardless of the distance to the nearest transit stop. The desirability of access to public transportation inflates the monetary value of residential units within transit walksheds, raising prices and leading to gentrification.

The UESI's public transit indicators may also not adequately reflect the story of city-specific transit trends, such as the popularity of bike commuting in Amsterdam or the prevalence of informal bus systems in New Delhi, which provides an opportunity for future research and case studies. Lastly, the above-mentioned aspects of travel (e.g., safety, pollution levels, commuting time) are not included in the indicator of access, though they are important for quality of life and sustainability issues in urban areas and may be prioritized in future iterations of the UESI.

Future work could further explore intersections between transit and pollution. Higher density areas may have higher levels of air pollution due to traffic congestion – leading to a negative externality associated with a possible urban sustainability solution. This aspect may complicate the basic premise that walking to public transportation is a net health benefit. While effective public transit should reduce congestion and improve the capacity and efficiency of the overall transit system, cars and trucks do commonly use the same areas as pedestrians accessing public transit.



WATER RESOURCE MANAGEMENT

Global urban water demand and wastewater production are surging, creating urgent water resource management challenges for cities.

What it measures

The water resource management issue category includes two indicators. **Water stress** measures the ratio of surface water withdrawn, relative to the total annual natural availability of surface water available, in key sub-basins of interest. **Wastewater** treatment measures the percentage of the urban population connected to sanitation networks, and the proportion of wastewater that is treated before it is released back into the environment. When this data is not available, we measure the percentage of wastewater that is treated, relative to the percentage of wastewater generated by an urban area.

Why we include it

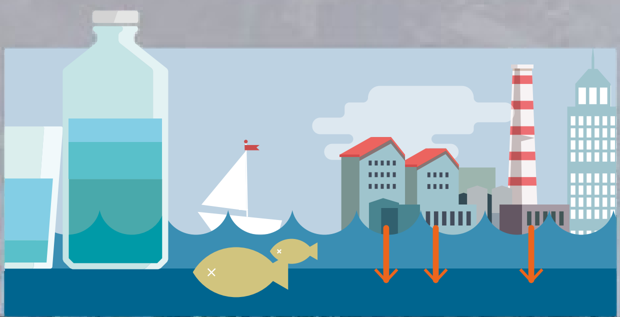
Water stress: Water stress measures a city's vulnerability to drought, pollution, and other shocks or threats to water availability, as well as an urban area's environmental impact on the lakes, rivers, and streams it draws water from. As urban populations grow, it will be increasingly vital for cities to use water efficiently, to prevent degrading the upstream ecosystems they rely on; ensure they can meet the needs of their growing populations and economies; and reduce conflicts between competing water needs from agriculture, industry, and other communities.

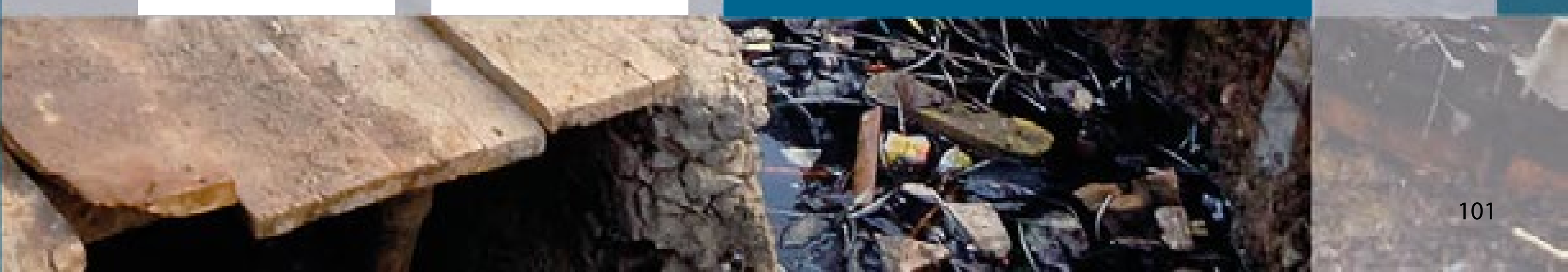
Wastewater Treatment: Wastewater includes any water degraded by anthropogenic influences. It is often a mix of domestic gray water, discharged from home sinks, baths, or washing machines; blackwater, such as water discharged from toilets; and industrial wastewater, which often carries chemical contaminants. Wastewater can also include surface water and stormwater runoff, which occurs when rain gathers pollutants and speed as it travel over a city's sidewalks, roads, and other surfaces.

Left untreated, wastewaters' nutrient and chemical loads can disrupt natural water systems, triggering algal blooms, impacting aquatic life, and endangering aquatic ecosystems.[1] Untreated wastewater endangers human health, putting critical drinking water supply systems at risk, and leaving residents vulnerable to exposure to waterborne diseases, heavy metals and pesticides, or illness from consuming contaminated fish or freshwater organisms.[2] It also takes a financial toll, by increasing health care costs and threatening economic activities that use water, such as industrial production, fisheries, aquaculture and tourism.[3]

+50 %
in water demand is expected globally by 2030.

40 %
of the world's population lives in regions where the water demand exeeds water supply.





Where the data come from

The Nature Conservancy's Urban Water Blueprint project[4] provides the water stress data. Wastewater treatment data comes from a combination of sources, including the World Council on City Development, OECD Water Governance in Cities, Food and Agriculture Organization of the United Nations' (FAO) Aquastat database of national municipal wastewater treatment data, city and utility reports, and academic literature. Please see the Metadata for detailed accounting of data sources.

DESCRIPTION

The Growth in Global Water Demand

Urban water resource management faces a critical juncture. The 100 largest global cities occupy less than 1 percent of the earth's land area. However, their drinking water source watersheds span 1.7 billion hectares, roughly 12 percent of global land area, and provide water to nearly one billion people.[5] Cities' water management strategies will have outsize repercussions for their residents' water security and for the health of the world's watersheds.

Rapidly growing urban populations, and the stress of a changing climate, have already led to mounting pressure on the world's watersheds.[6] The World Economic Forum's 2014 Global Risk Report classified water security as one of the greatest threats to global prosperity.[7,8] Already, municipal, industrial, and agricultural sectors compete for freshwater, especially in water-scarce areas.[9] Water demand currently exceeds water supply in regions containing over 40 percent of the world's population,[10] with limited access to freshwater shaping lifestyles and constraining development opportunities in water scarce areas (see Box 1, *Urban Access to Safe Drinking Water and Sanitation*).[11]

TARGETS

What are the targets

The water stress indicator target is a ratio of annual surface freshwater water withdrawal, relative to annual surface freshwater availability, below 0.4:

$$\frac{\textit{Annual surface freshwater withdrawal}}{\textit{Annual surface freshwater availability}} > 0.4$$

The wastewater treatment indicator target is collection and treatment of the wastewater generated by a city.

100%

By 2030, global demand for water is expected to increase by 50 percent, with most of this growth concentrated in cities;[12] by 2050, urban water demand is expected to rise by 80 percent, as climate change alters the distribution and timing and water availability.[13] One analysis of the future of nearly 500 cities by Flörke et al. (2018) found that more than 27 percent of these cities studied, containing 233 million people, will have water demands that exceed surface-water availability in 2050.[14] At the same time, rapidly expanding urban populations, improved living conditions, and economic development are accelerating wastewater generation.[15,16] The combined rise in the urban demand for water and the growth of municipal wastewater generation creates an urgent management challenge for cities.

Fostering improved water management is a core part of the UN's Sustainable Development Goals (SDGs). SDG 6, which aims to ensure the availability and sustainable management of water and sanitation for all, includes targets for halving the proportion of untreated wastewater and substantially increasing safe reuse and recycling of water (Target 6.3), as well as substantially increasing water-use efficiency and ensuring sustainable withdrawals and supplies of freshwater (Target 6.4) by 2030 (UNDP, 2015). These targets are deeply intertwined. Expanding the treatment and safe reuse of water and using water more efficiently (Targets 6.3 and 6.4) would increase water available for drinking (Target 6.1) and other uses.[17] These accomplishments would lessen the pressure on water-related ecosystems, helping to achieve SDG target 6.6, which seeks to protect and restore these habitats by 2020. Strategic wastewater management and reuse could also help deliver other SDGs: incorporating treated wastewater into irrigation systems, for instance, could aid sustainable food production (SDG 2) while reusing wastewater by-products could create opportunities for economic development (SDG 8).[18]

Box 1. Urban Access to Safe Drinking Water and Sanitation

Rapidly growing urban populations, combined with the high cost of building and maintaining infrastructure, have exacerbated drinking water and sanitation challenges in urban areas. Roughly 80 percent of the world's urban residents have access to piped drinking water, and 96 percent have access to improved drinking water sources.[19] However, these aggregate numbers often mask local disparities and gaps in access; informal settlements and slums, for instance, typically face lower levels of access than other areas of a city.[20]

Similarly, though access to improved sanitation has grown most rapidly within cities, approximately 20 percent of the urban population still lacked access to improved sanitation, and some 100 million city residents still practiced open defecation, in 2012.[21] Globally, just 26 percent of urban wastewater services prevent human contact along the entire course of the sanitation chain.[22] Access remains particularly poor in informal settlements, where high population density, combined with a dearth of physical space, infrastructure and resources, creates challenges to traditional strategies for sanitation access.[23]

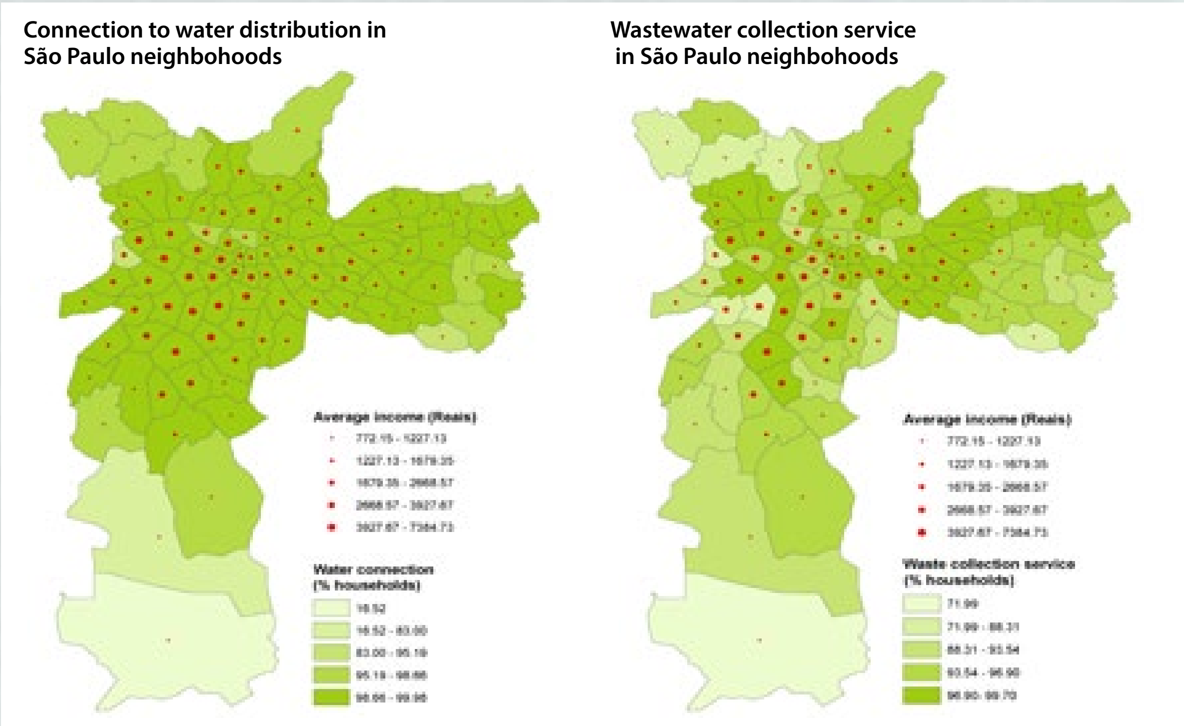
Data that tracks access to improved drinking water and sanitation within urban areas could guide efforts to expand access, update infrastructure, or pilot new kinds of solutions. However, this information is often incomplete, inconsistent, or simply absent.

The data that does exist – collected by cities, utilities, and NGOs – suggests that access to improved water and sanitation often varies in concert with socio-economic indicators. As the maps of São Paulo's household water supply and sanitation coverage illustrate, access often – though not always – varies alongside income (see Figure 1).

Additionally, for many, "improved" water is not always safe, reliable, affordable, or accessible.[25] The U.S. city of Flint, Michigan, for instance, generated headlines for dangerously high levels of lead in its drinking water supply during the summer of 2015. A survey of nearly 50,000 U.S. public water utilities revealed similar threats facing communities across the country: between 2010 and 2015, almost 19,000 public water systems had at least one instance of lead detection above 3.8 parts per billion, the level at which a formula-fed baby is at risk for elevated blood lead levels.[26] Globally, more than 50 percent of urban residents in developing countries are still affected by illnesses related to insufficient access to safe drinking water and improved sanitation.[27]

Even when households are connected to piped sources of improved water, the availability of water can be intermittent, forcing residents to wait at home to capture water, or to purchase water from outside sources. In the words of one expert, the impact of an uncertain water supply "is a huge problem, similar to having no water at all."[28] This uncertainty has particular implications for women and girls, who are often responsible for waiting at home to collect water, missing opportunities to attend school or work.[29] A 2007 survey by the Asian Development Bank and the Urban Development Government of India found that hours of water availability ranged from 0.75 hours (in

Figure 1. Maps compare how average income levels vary alongside the lack of household water supply and sanitation, across neighborhoods in São Paulo, Brazil.



Data Source: Resultados do Universo do Censo Demográfico 2010.[24]

Indore) to 12 (in Chandigarh), and averaged 4.3 hours, across 20 cities.[30] Water availability can also fluctuate widely within cities. Although the average water supply in New Delhi is 157 litres per day, access varies widely across different districts. Residents in Mehrauli and Narela can expect some of the city's lowest levels of water, of 29 and 31 litres per day, respectively, while the wealthy Cantonment district accounts for nearly 70 percent of the city's water supply, drawing 509 litres per day.[31]

A number of innovative solutions are poised to help address these gaps in water and sanitation access. The NextDrop mobile app in India, for instance, connects utilities with customers and private water suppliers, notifying residents of when water will flow through their pipes, and helping utilities better understand and manage their distribution system.[32] Hyderabad's Metropolitan Water Supply and Sewerage Board will soon adopt a similar approach, using a mobile app to help them track service reservoirs, water supply trunk mains, and their distribution network.[33] Similar strategies to identify and communicate challenges in water infrastructure are poised to help utilities prioritize and address gaps in service.

20%
of the urban population still lacked access to improved sanitation in 2012

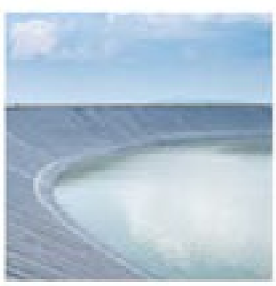
Reducing Water Stress

The UESI's water stress indicator reflects cities' vulnerability to shocks or threats to water availability, as well as their environmental impact on the lakes, rivers, and streams it draws water from. Water stress measures the ratio of total annual surface water withdrawals, relative to the annual natural availability of surface water, in particularly important watersheds.

Adopting the approach of many recent analyses,[34, 35] we classify a city as water stressed if the ratio of annual surface freshwater withdrawal to annual surface freshwater availability is 0.4 or greater – meaning 40 percent or more of the total available surface freshwater is withdrawn. This threshold should be considered a benchmark, rather than the only or final determinant, of a city's water stress. Cities with water stress ratios of 0.3 and 0.5, for instance, may face very similar levels of vulnerability to water shocks or shortages, despite falling on different ends of this 0.4 threshold. It will also be important for future analyses to track water stress over time, to counter the potential impact of droughts, floods, or other events that may influence a city's score in one particular year.

Additionally, water withdrawal can begin to negatively impact aquatic ecosystems well before water scarcity becomes a threat to cities. Thresholds for the level of water withdrawal that negatively affect freshwater aquatic ecosystems vary, depending on geography, stream type, and a number of other factors. In a review of 128 river basins, Smakhtin et al. (2004) found that freshwater-dependent ecosystems required approximately 20 to 50 percent of the mean annual river flow to maintain fair conditions, and suggest that as a universal metric, at least 25 percent of a river's flow should be left in a river or stream to support aquatic flora and fauna.[36] In other words, withdrawal rates well below 40 percent can still threaten these freshwater ecosystems.

In addition to surface freshwater, drawn from lakes, streams, and rivers, cities often also rely on groundwater, desalinated water, or water from other sources, such as recycled water, rainwater harvesting, or private water vendors. Table 1 lists each city's reliance on different water sources. The majority of cities (21/32) rely on surface water for at least 90 percent of their water needs, and 25 cities rely on it for the majority (at least 50 percent) of their water needs. Four cities – Beijing, Berlin, Copenhagen and Mexico City – are mostly dependent on groundwater, while Lima splits its water supply equally between surface and groundwater. While we focus the UESI indicator on surface freshwater stress, to enable consistent comparisons across cities, Table 1 also notes the results of a 2014 analysis by McDonald & Shemie (extending the analysis of Gleeson et al., 2012), assessing whether the abstraction of groundwater, relative to the rate of groundwater recharge, is greater than 1, and therefore stressed.[37,38] Three of the four cities reliant on groundwater for a majority (over 50 percent) of their urban water supply – Beijing, Berlin, and Mexico City – rely on stressed groundwater resources.



3/4 UESI cities

reliant on groundwater for a majority of their water supply depend on stressed groundwater resources

Table 1. Description of cities' water supply sources
(percent surface freshwater, groundwater, desalinated water, or other sources).

City	Source of water supply				Surface water stressed	Groundwater stressed
	Ground water	Surface water	Desalinated water	Other		
Amsterdam	0%	100%	0%	0%	Not stressed	NA
Atlanta	No data	No data	No data	No data	No data	Not stressed
Bangalore	No data	No data	No data	No data	No data	Not stressed
Bangkok	0%	100%	0%	0%	Not stressed	NA
Barcelona	0%	100%	0%	0%	Not stressed	NA
Beijing	72%	22%	0%	7%	Stressed	Stressed
Berlin	100%	0%	0%	0%	NA	Stressed
Boston	0%	100%	0%	0%	Not stressed	NA
Buenos Aires	4%	96%	0%	0%	Not stressed	Not stressed
Chicago	0%	100%	0%	0%	Not stressed	NA
Copenhagen	100%	0%	0%	0%	NA	Not stressed
Casablanca	1%	99%	0%	0%	Not stressed	Not stressed
Detroit	0%	100%	0%	0%	Not stressed	NA
Ho Chi Minh City	7%	93%	0%	0%	Not stressed	Not stressed
Jakarta	0%	100%	0%	0%	Stressed	NA
Johannesburg	0%	100%	0%	0%	Not stressed	NA
Lima	50%	50%	0%	0%	Stressed	Stressed
London	41%	59%	0%	0%	Not stressed	Not stressed
Los Angeles	0%	100%	0%	0%	Stressed	NA
Manila	20%	80%	0%	0%	Not stressed	Not stressed
Melbourne	0%	100%	0%	0%	Not stressed	NA
Mexico City	81%	19%	0%	0%	Not stressed	Stressed
Montreal	0%	100%	0%	0%	Not stressed	NA
New Delhi	4%	96%	0%	0%	Not stressed	Not stressed
New York City	0%	100%	0%	0%	Not stressed	NA
Paris	46%	54%	0%	0%	Not stressed	Not stressed
São Paulo	0%	100%	0%	0%	Not stressed	NA
Seoul	0%	100%	0%	0%	Not stressed	NA
Singapore	0%	95%	5%	0%	Stressed	NA
Tel Aviv	55%	45%	0%	0%	Stressed	Stressed
Tokyo	0%	100%	0%	0%	Stressed	NA
Vancouver	0%	100%	0%	0%	Not stressed	NA

A city's surface water sources are classified as stressed if the annual ratio of surface freshwater water withdrawal, relative to surface freshwater available, is greater than 0.4. A city's groundwater source is classified as stressed if the ratio of annual abstraction of groundwater, relative to the annual recharge of groundwater, is greater than 1. (Sources: Data on the distribution of urban water sources and surface water stress comes from The Nature Conservancy's City Water Map (McDonald & TNC, 2016), utilizing the Water Gap Model (Alcamo et al., 2003); data for groundwater stress comes from McDonald et al. (2014)).[39, 40, 41]

Increasing Wastewater Treatment

Many of the drivers behind growing water demand are also contributing to increased wastewater generation. Wastewater includes any water degraded by anthropogenic influences. Urban wastewater is often a mix of domestic gray water, discharged from home sinks, baths, or washing machines; blackwater, such as water discharged from toilets; commercial wastewater, from sources such as hospitals; and industrial effluent, which often carries chemical contaminants. Cities' wastewater can also include surface water and stormwater runoff, which occurs when rain gathers pollutants and speed as it moves over a city's sidewalks, roads, and other surfaces.[42, 43]

Untreated wastewater carries environmental, economic, and human health risks. High levels of nutrients can trigger algal blooms, eutrophication and dead zones; contaminants and increased water temperatures can also endanger aquatic ecosystems and biodiversity.[44] Uncollected or untreated wastewater can increase the burden of disease by degrading drinking and bathing water sources. People also face exposure to pathogens through the consumption of food irrigated by untreated wastewater, or from working or playing in close proximity to untreated wastewater.[45]

Untreated wastewater also takes a financial toll, through increased health care costs and impacts on economic activities that use water, such as industrial production, fisheries, aquaculture and tourism.[46] Exposure to wastewater can even limit the ability to export certain goods, due to restrictions on contaminated products.[47] Conversely, successful wastewater treatment can enable cities to profit from the reuse of wastewater, as a source of water, energy, fertilizer, and other industrially valuable materials.[48]

The UESI's wastewater treatment metric measures both the coverage of sewerage systems – that is, the ability of the city to collect wastewater – as well as the city's ability to treat it. Collection systems typically take the form of either off-site systems, where waste is transported through a sewage network to a treatment plant or disposal point, or on-site systems, where waste accumulates in a pit or septic tank.[49]

While urban systems typically employ off-site systems, septic tanks remain a prevalent strategy in many cities. Eight-five percent of Manila's population and 64 percent of Jakarta's population rely on septic systems.[50, 51] More than 3,000 houseboats parked along Amsterdam's canals also rely on on-site sanitation, much of which bypassed the city's treatment system until recently.[52] The treatment options for on-site systems vary: they can be periodically emptied, and then transported to sites for additional treatment and/or disposal. Some are linked to small-scale sewerage systems that convey wastewater to nearby treatment plants. Still others are treated through leaching beds that filter and partially treat water as its absorbed into the ground.[53]

Old or overstressed on-site systems can become significant sources of pollution.[54] In many cases, however, large volumes of wastewater captured by an on-site sewerage system may also be untreated, as water is lost through broken or leaking pipes; discharged before being treated when a sewage network is overwhelmed with rainwater; or captured

80%

of the world's waste-water is returned to the environment without adequate treatment

for illegal reuse by residents along the network[55] (see the UESI online portal for a box discussing *The Challenges of Modernizing Urban Sewer Systems*).

Once collected, a mix of physical, chemical and biological processes are combined to reach different levels of wastewater treatment.[56] Primary treatment involves the screening and filtration of suspended solid waste, which reduces wastewater's biochemical oxygen demand; secondary treatment breaks down the dissolved organic matter remaining after primary treatment; and tertiary treatment includes any additional purification processes.[57]

Despite the benefits of wastewater treatment, an estimated 80 percent of the world's wastewater is returned to the environment without adequate treatment.[58, 59, 60] On average, high-income countries treat approximately 70 percent of the wastewater they generate; middle-income countries treat around 38 percent; lower middle-income countries treat 28 percent; and low-income countries treat just 8 percent.[61] Within cities, wastewater collection systems often bypass informal settlements, leaving these residents especially vulnerable to the health risks of untreated wastewater.[62]

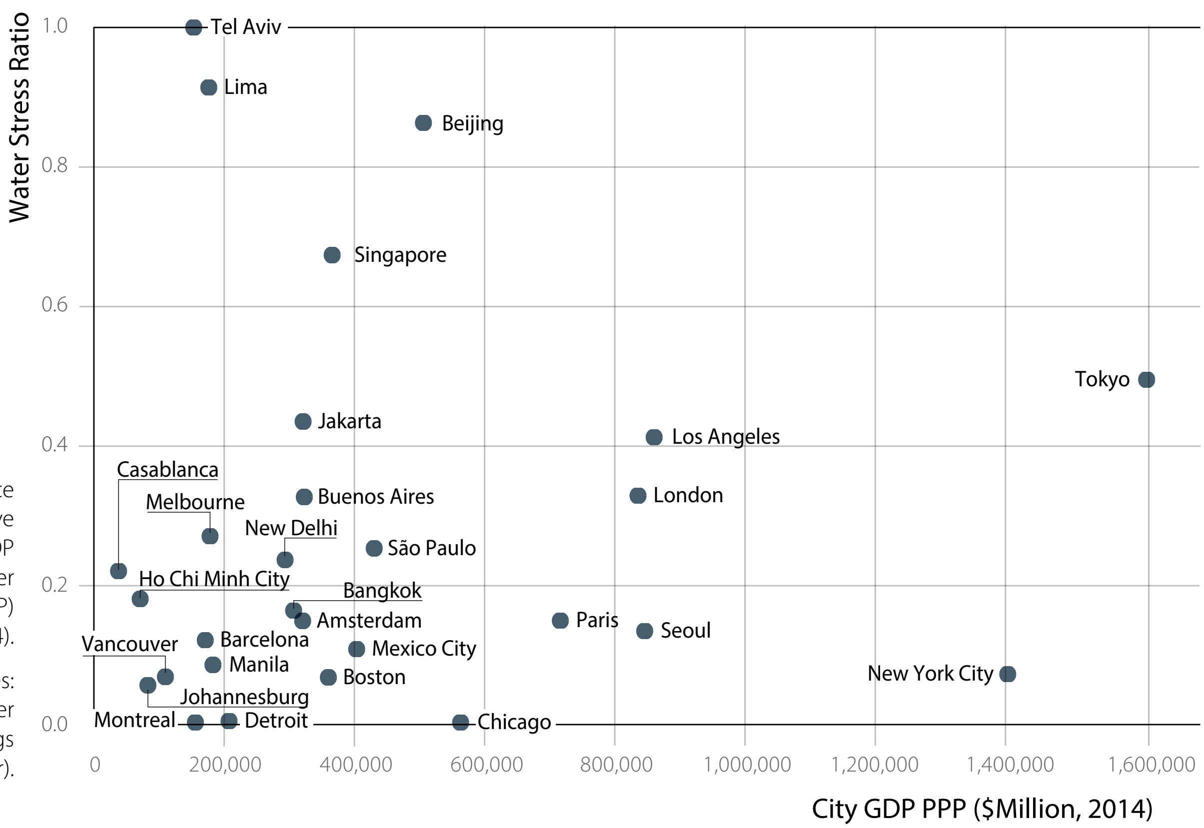
Data tracking cities' performance in collecting and treating wastewater – from their sewerage networks, from on-site sanitation systems, and from informal settlements – would be invaluable in helping city managers strengthen their performance. Unfortunately, like national-level wastewater treatment data,[63, 64] city-level data on wastewater remains sparse and heterogeneous. We used a data ladder to combine information from different sources, using city-specific data whenever possible, but often turned to national urban wastewater statistics when this information was not available. As the pressure on wastewater systems grows, filling these data gaps – with city-specific information on the generation, collection, and treatment of wastewater; the level and performance of wastewater treatment; and the rates and types of wastewater reuse – would aid cities in developing, modernizing, and expanding their approach to wastewater management. On the UESI online portal, a box on *The Black and Smelly Waters Program: Citizen-Generated Environmental Transparency in China* explores some strategies cities are using to begin to fill these data gaps.

WHO IS MOST AFFECTED?

Water stress scores often vary alongside cities' geographic and financial circumstances. The high levels of water stress in arid Los Angeles and tiny Singapore reflect the constraints of their geographic locations. However, some cities are better equipped than others to reach beyond their water-scare circumstances, by funding infrastructure that draws water from more distant sources. Los Angeles, New York City, and Tokyo, for instance, all rely heavily on water drawn from drainage basins far outside these cities' geographic footprints.[65] Wealthy cities, in other words, can often import water, while lower-income cities often must rely on water resources in close proximity to the city. In an analysis of over 100 cities, McDonald et al. (2014) found that cities with higher GDP per capita drew on twice as much imported water than cities with lower GDP per capita.[66] Figure 2 illustrates UESI cities' levels of water stress relative to their GDP. Since the McDonald et al. (2014) study and the UESI focus mainly on large cities, this relationship may not apply to small or medium-sized cities.

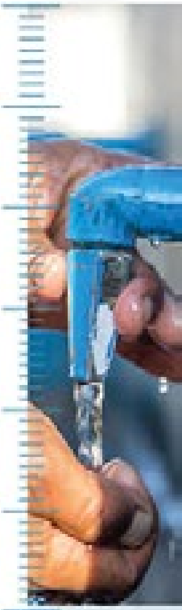
However, the strategy of relying on interbasin transfers may be nearing its limits. Los Angeles, facing regional competition for dwindling and increasingly unpredictable water resources, has moved to foster greater water efficiency.[67] Singapore, wary of its dependence on water imported from Malaysia, has installed some 320 sensors to detect leaks in its water supply pipeline, cutting its total water loss from leaks to less than 5 percent a year.[68, 69] Cities like New York City have worked to proactively protect or purchase their water sources, while other cities, such as Jakarta, are looking at strategies to restore the degraded ecosystems they rely on, to help recharge aquifers and filter water.[70] Globally, implementing strategies to protect water sources – by protecting or restoring forests, implementing agricultural best management practices, restoring riparian habitats, and reducing forest fuel – could save $890 million USD per year on treatment plant operations and management, freeing up capital for infrastructure improvement and development.[71] Reducing vulnerability to water stress may also require working with other stakeholders and water users. Flörke et al.'s survey of nearly 500 cities found that improvements in agricultural water-use efficiency could free up enough water for urban use in 80 percent of future "high-conflict" watersheds, where urban and agricultural sectors would struggle to both meet their projected water demands.[72]

Figure 3. Urban Water Stress and City GDP.



Levels of surface water stress relative to cities' GDP Purchasing Power Parity (PPP) ($ Million, 2014).

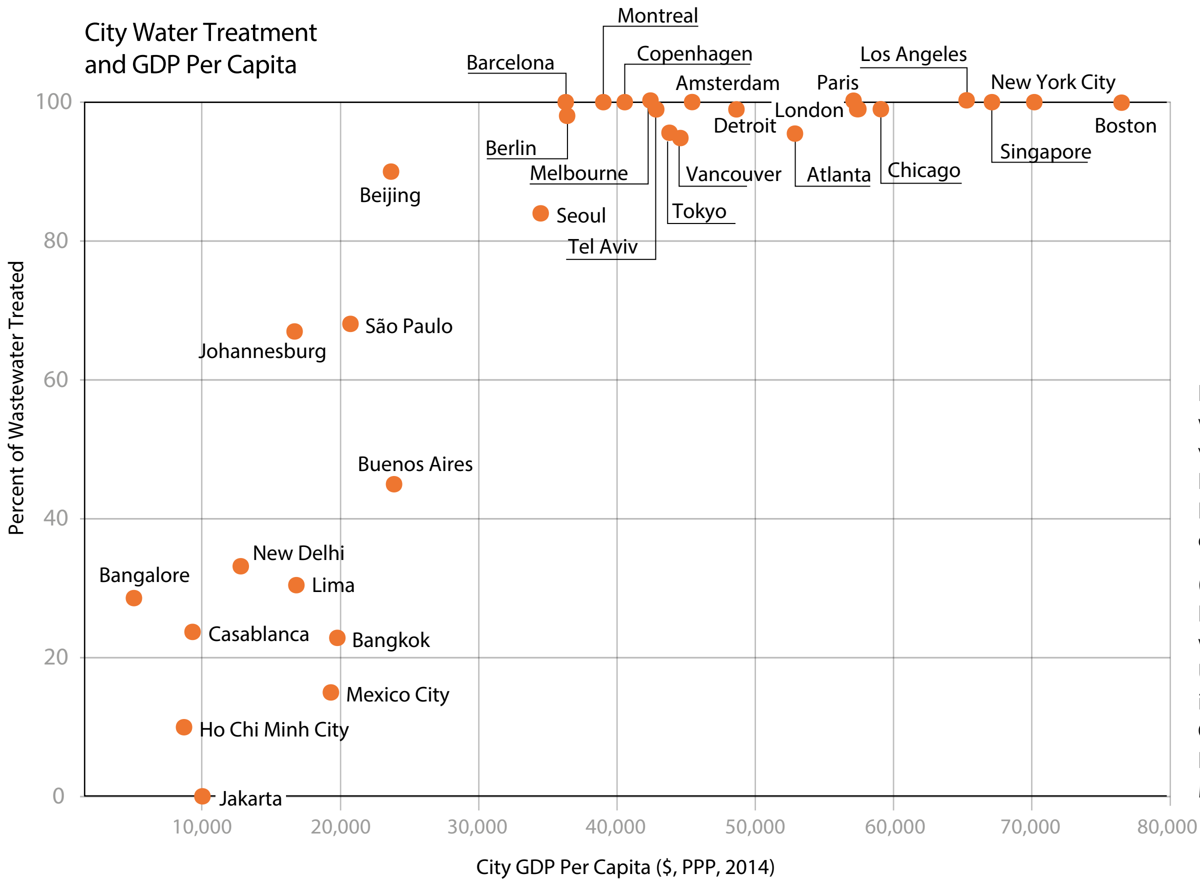
(Data sources: Urban Water Blueprint; Brookings Metro Monitor).



Effective wastewater treatment strategies can also help cities reduce their water stress, by freeing up water for reuse. Singapore, which treats nearly 100 percent of its wastewater, has implemented an aggressive water reuse and recycling program to help offset its limited freshwater resources.[73] Similarly comprehensive wastewater strategies could aid water-stressed cities like Beijing, Jakarta, and Los Angeles address the threat of water scarcity.

Across the cities included in the UESI, wastewater treatment reflects global trends – treatment levels are highest, for the most part, in high-income countries, and lowest in low-income areas (see Figure 3). No city-level data is available for Manila, likely reflecting the difficulty of tracking the treatment of septic systems, but making it difficult to assess the impact of wastewater on the city. Data tracking coverage and treatment within cities is scarce, but globally, sewerage coverage and wastewater treatment remains an especially pressing challenge for informal settlements.

Figure 4. City Water Treatment and GDP Per Capita.



Percent treated wastewater versus cities' GDP Purchasing Power Parity (PPP) per capita ($ in 2014).

(Data sources: Percent treated wastewater from UESI wastewater indicator; city GDP data from Brookings Metro Monitor).

RESULTS –
OVERALL ENVIRONMENTAL PERFORMANCE

The Urban Environment and Social Inclusion Index (UESI) demonstrates a range of insights regarding the pilot cities' performance on environment. Here we take a look at trends and drivers of urban environmental performance.

OVERALL PERFORMANCE

The UESI pilot cities demonstrate a range of variation with respect to overall environmental results. We present several ways of diving into the UESI results within cities and across indicators, although the data and findings are best explored online through our interactive portal (www.datadriven.yale.edu/urban). To compare how cities perform on average in all of the environmental indicators, we transform the raw data to a normalized scale of 0 to 100, with 0 being the worst performer and 100 the best (See Methods: *Box 2: Measuring Environmental Performance - Proximity to Target*). This normalization allows for comparison across both cities and indicators.

Trends across Indicators

As illustrated in Figure 1, cities generally perform well in the public transit access and water stress indicators and perform poorly in measures of wastewater treatment, climate change and air pollution. Scores in Proximity to Public Transit and Tree Cover per Capita are more narrowly distributed between 75 and 100, suggesting that most neighborhoods and cities in the UESI perform well on this indicators. For the Wastewater Treatment, Climate Policy, and $PM_{2.5}$ indicators, the range of performance is much broader – some cities perform well on these indicators while others have much more room to improve. The range for the Water Stress indicator is much narrower due to the lack of neighborhood-scale data available for this indicator, which represents city-wide vulnerability to water availability.

Many aspects of the natural and built environment are inextricably linked, and correlation between some environmental indicators used in the UESI is expected (Figure 2). A strong positive relationship exists between Tree Cover per Capita and Climate Policy, which suggests that cities that have outlined strong plans to tackle climate change mitigation and adaptation have also been successful at achieving goals for providing tree cover for their residents. The two sustainable public transit indicators are also fairly positively correlated with the air pollution metrics, indicating that cities who are performing well in providing public transit options have lower levels of air pollution. This pattern makes sense, as public transit reduces reliance on personal automobiles and reduces congestion that would intensify local urban air pollution.

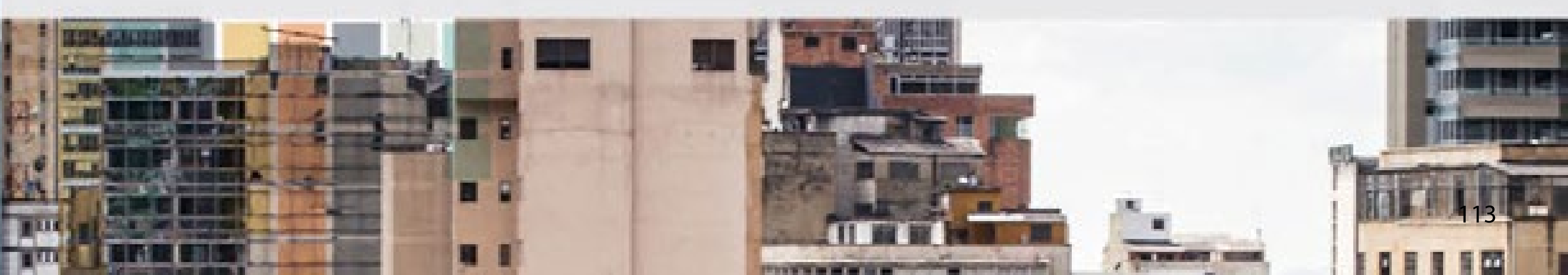
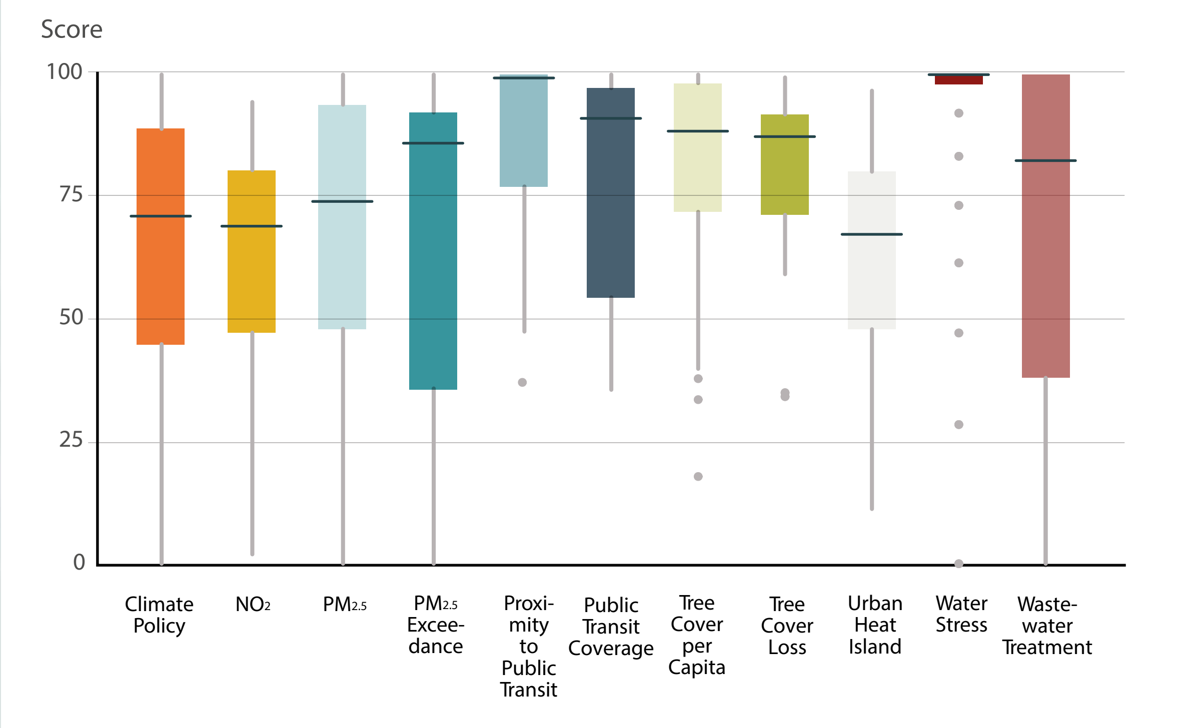


Figure 1. Summary proximity-to-target scores for environmental metrics captured by the UESI.



The range of scores for the water stress indicator are more narrow than the other indicators due to its spatial resolution at the overall city scale rather than the neighborhood level.

Figure 2. Correlation matrix that illustrates relationships between the UESI indicators.

	NO_2	$PM_{2.5}$	$PM_{2.5}$ Exceedance	Proximity to Public Transit	Public Transit Coverage	Tree Cover per Capita	Tree Cover Loss	Urban Heat Island	Water Stress	Wastewater Treatment	Climate Policy
Climate Policy	−0.41	0.41	0.41	0.33	0.3	0.47	0.24	−0.31	0.39	0.46	1
Wastewater Treatment	−0.44	0.48	0.49	0.55	0.51	0.25	0.06	0.16	−0.1	1	0.46
Water Stress	−0.09	0.12	0.16	0.1	0.07	0.5	0	−0.35	1	−0.1	0.39
Urban Heat Island	−0.01	−0.18	−0.11	0.03	0.19	−0.25	−0.01	1	−0.35	0.16	−0.31
Tree Cover Loss	−0.14	0.12	0.17	0.08	0.03	0.1	1	−0.01	0	0.06	0.24
Tree Cover per Capita	−0.27	0.06	0.04	−0.02	−0.01	1	0.1	−0.25	0.5	0.25	0.47
Public Transit Coverage	−0.31	0.63	0.68	0.81	1	−0.01	0.03	0.19	0.07	0.51	0.3
Proximity to Public Transit	−0.15	0.75	0.76	1	0.81	−0.02	0.08	0.03	0.1	0.55	0.33
$PM_{2.5}$ Exceedance	−0.09	0.98	1	0.76	0.68	0.04	0.17	−0.11	0.16	0.49	0.41
$PM_{2.5}$	−0.04	1	0.98	0.75	0.63	0.06	0.12	−0.18	0.12	0.48	0.41
NO_2	1	−0.04	−0.09	−0.15	−0.31	−0.27	−0.14	−0.01	−0.09	−0.44	−0.41

Correlation Coefficient: 1.0, 0.5, 0.0, −0.5, −1.0

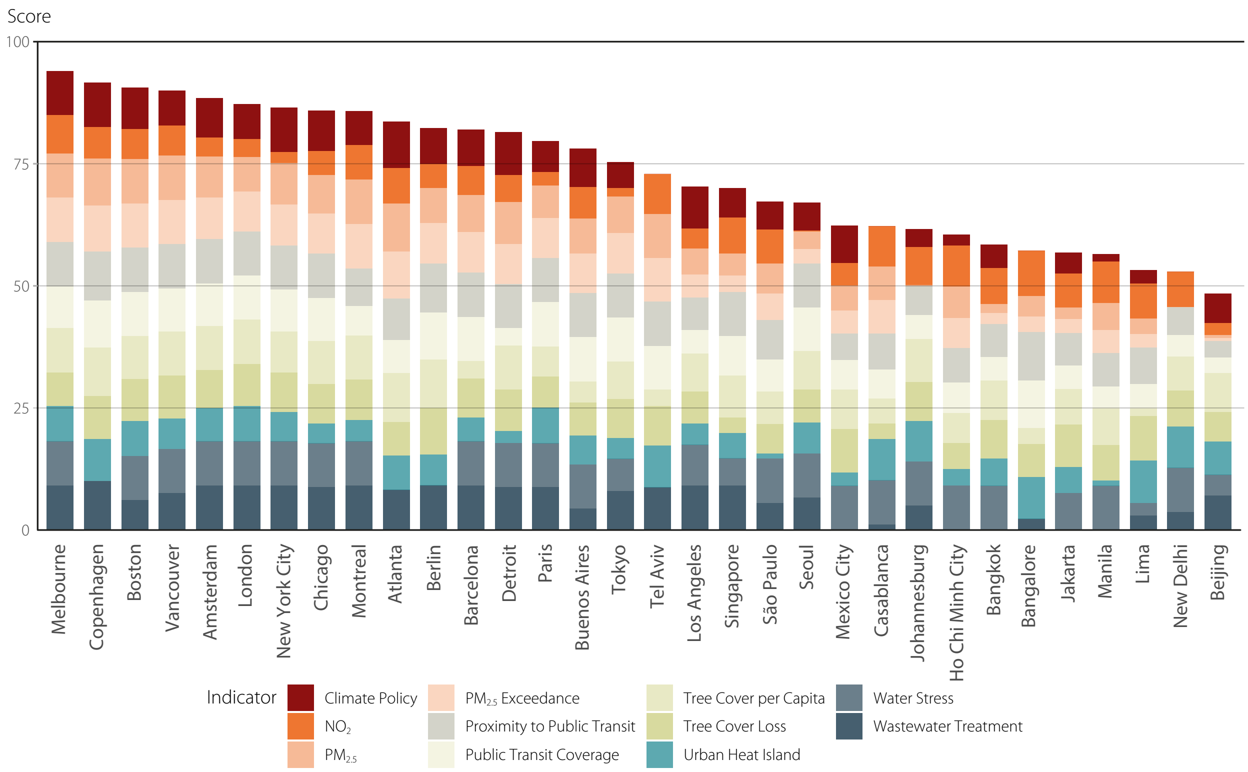
The more strongly positively related indicators (i.e., a high value on one indicator generally corresponds to a high value on the other) have values close to 1 (perfect correlation) and are shaded in blue, while the more negatively correlated indicators (i.e., a high value on one indicator generally corresponds to a low value on the other) are shaded in red and closer to -1 (perfectly negative correlation).

Trends across cities

Although the UESI does not provide an overall ranking of cities' environmental performance due to challenges with respect to varying levels of development for each city, we present Figures 3 and 4 as ways to summarize cities' scores on each of the 11 indicators. This illustration is meant to show which indicators cities perform well in, relative to other indicators. Melbourne, for instance, performs less well on the wastewater treatment and urban heat island indicators, while Copenhagen performs among the best in terms of wastewater treatment. This figure provides a snapshot comparing cities' performance in each category, and provides an indication of their overall performance.

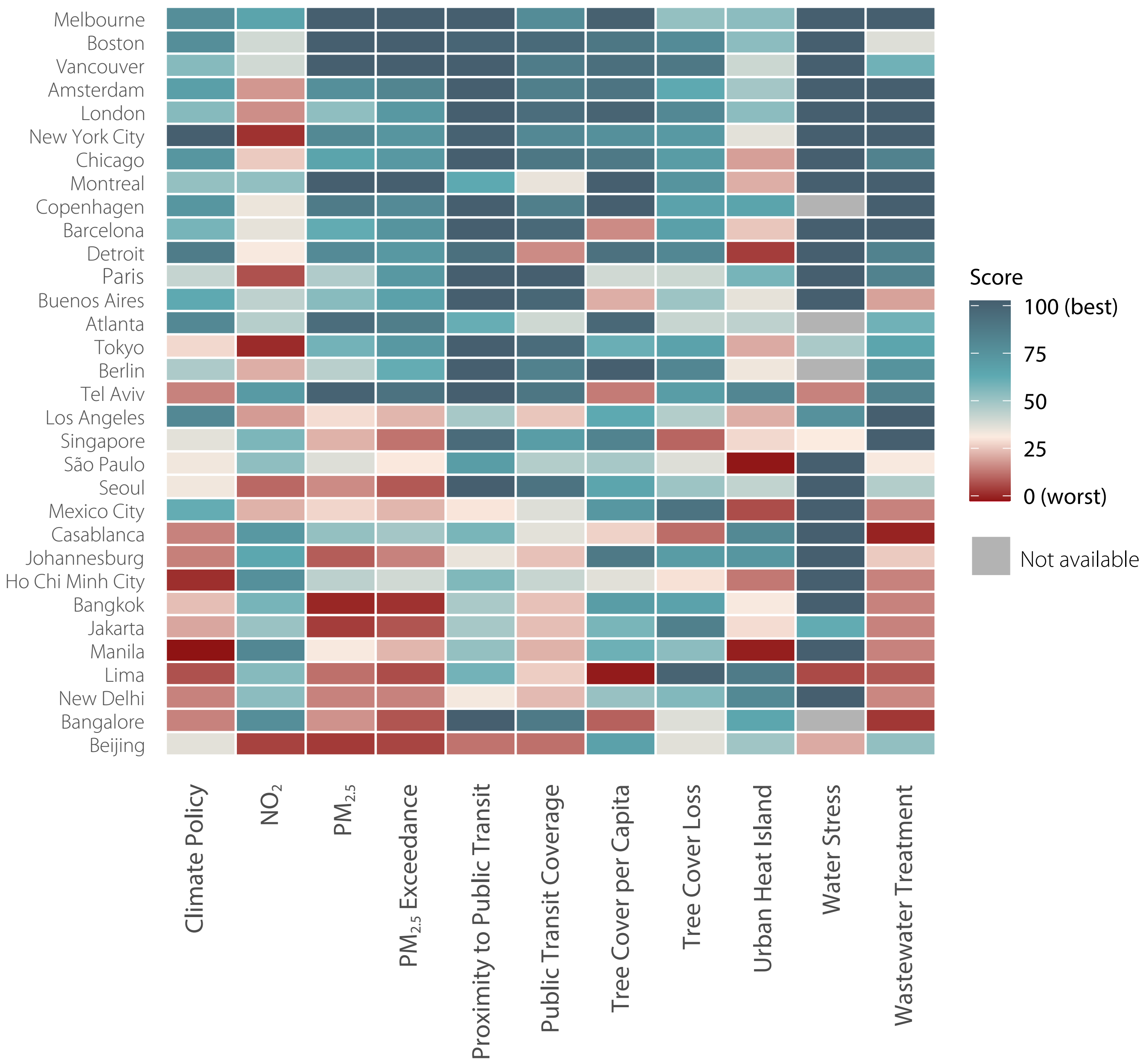
It also brings attention to where there are gaps in data for cities. The data source for water stress lacks data on Atlanta and Bangalore. Tel Aviv, Casablanca, Ho Chi Minh City, New Delhi, Bangalore, and Lima all receive a score of 0 for climate policy because no evidence of a city-level climate mitigation or adaptation policy could be located (See the *Climate Change* issue profile for more details on how we scored cities on this indicator).

Figure 3. UESI Cities ordered by a simple average of their proximity-to-target environmental score on each of the 11 environmental indicators.



A city's overall score is calculated by taking the proximity-to-target score of each metric and dividing by the number of metrics available for a given city.

Figure 4. A heat map of the pilot UESI's proximity-to-target scores by UESI indicator.



Blue indicates higher performance, while red indicates poor performance. Some cities are missing data for the water stress indicator and are shaded as gray.

Box 1. Physical characteristics of cities

The physical characteristics of a city can influence its environmental performance. A city's form and layout, built environment, density and compactness, elevation, and fabric all play a role in determining differences in environmental performance.[1] Some of these measures, such as elevation, are physical features or natural endowments that are not influenced by policy or anthropogenic causes. Our analysis of urban environmental performance includes several variables that evaluate the physical characteristics of cities or other properties, such as population density and standardized income per neighborhood. Data to assess these attributes are derived either from reported census information or from satellite images.

We include these physical attributes to understand potential underlying drivers of urban environmental performance. While there are some characteristics cities have no control over (e.g., elevation), there are others relating to urban form that cities' planning and design decisions can influence. *The Journal of the American Planning Association in 1997* featured a now iconic debate between two camps of planners: those like Peter Gordon and Harry Richardson,[2] who argued that sprawl reflects consumer preferences,[3] and those like Reid Ewing who advocate compact cities as a more desirable alternative. But for urban sustainability, what do these camps say about which is a solution for environmental issues? An active debate has explored whether compactness and density can provide a solution for environmental challenges such as access to urban services and reduction of greenhouse gas emissions.

Both compact and sprawl are loaded terms, but there are characteristics of compactness and sprawl that urban planning literature can agree on. The key attributes of a compact urban form include: 1) dense and proximate development patterns, 2) neighborhoods linked by public transport systems, and 3) accessibility to local services and jobs.[4] On the other hand, the term sprawl usually equates to three prototypes: 1) leapfrog and scattered development patterns, 2) transportation dominated by privately owned vehicles, and 3) spatial segregation for different land uses.[5]

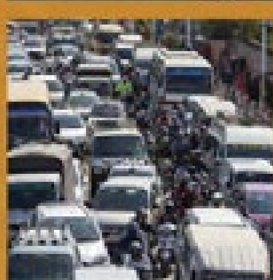
This debate, often situated in a developed country context, like the United States, where the notion of sprawl first emerged, can be generalized as: proponents of sprawl argue there is no clear evidence that high-density development would lead to reduced energy consumption, and technological advancement can mitigate increased emission.[6] On the other hand, some scholars claim that compact urban forms, with increased efficiency in resources usage, do have effects on improving air quality, reducing energy consumption, and mitigating climate change.[7]

Transportation provides one concrete example of this debate between compactness and sprawl. Would a compact city lead to less Vehicle Miles Traveled (VMT), a common metric of a compact city that suggests overall lower energy consumption from commuting, and therefore reduced transportation emissions? There is no short and clear answer to this question, and the evidence is complicated. For instance, in the U.S. context, Ewing and Cervero[8] found that population and job density had the smallest impact on VMT, suggesting a compact form does not necessarily reduce how much people drive. Byproducts of dense urban forms, such as public-transit job accessibility, however, demonstrate an impact on lowering VMT, suggesting that the distance between where people live and work may be the key determinant of this indicator.[9] A recent paper by Stokes and Seto (2018)[10] demonstrated trade-offs between increasing the accessibility of employment opportunities and social equity, finding that most U.S. cities that have increased job accessibility have not accomplished this goal in a way that reduces emissions.

Table 1. Physical Characteristics in the UESI.

Characteristic	Description
INCOME_STD	*Average income, standardized to US dollars*
DENSITY	*Population density in thousands per sq. km*
ALBEDO	*Average surface reflectance. Satellite-derived.* Albedo measures the amount of incoming light that is reflected off the surface, and both weather and development patterns influence it within a city. Sunlight is absorbed by darker colors, so climates with brighter colors tend to have lower albedo. Cloud cover, common construction materials, and soil composition all contribute to the albedo of a given city.
ELEVATION	*Average elevation of neighborhood. Satellite-derived.*
NDVI	*Normalized difference vegetation index. Satellite-derived.* A measure of surface greenness.
NDBI	*Normalized difference built-up index. Satellite-derived.* A measure of how much an urban area is built up.
TREEPROP	*Proportion of an entire city or neighborhood that is covered by tree cover. Satellite-derived.*

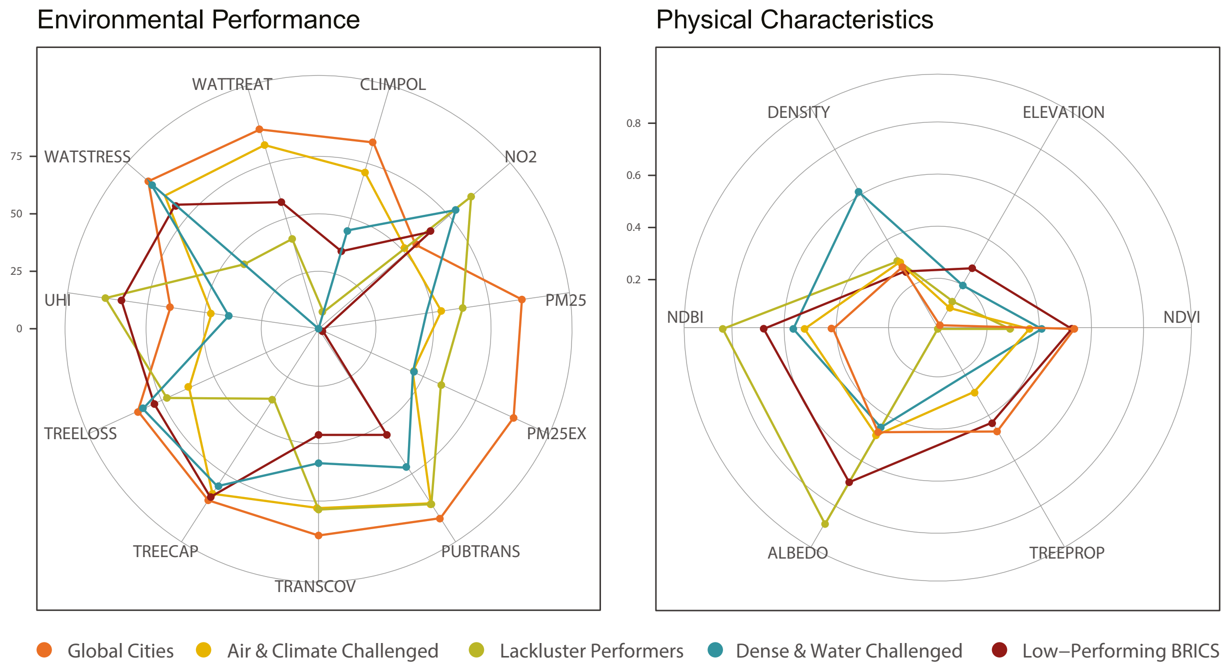
In this chapter, values for physical characteristics have been scaled to have values ranging from 0 (minimum) to 1 (maximum) for analysis. This transformation is done to make it easier to compare relative differences between indicators.



TYPOLOGIES OF URBAN ENVIRONMENTAL PERFORMANCE

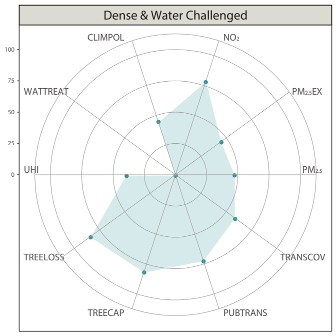
Exploring how cities tend to group together when measured across the UESI indicators can shed light on the similarities or dissimilarities in their environmental performance. We developed a typology to describe how similarly cities perform using a statistical approach called k-means clustering, which identifies groups within data based on how similar data points are to each other with a pre-defined number of "k" clusters. Although there is no exact method for determining the optimal number of clusters, the general technique is to determine the number of clusters that minimizes the distance between the cluster averages and the data points. For the UESI cities, this optimal number was five clusters. Figure 5 and Table 2 describe these 5 clusters in more detail and explore common elements across the cities' environmental performance and physical characteristics.

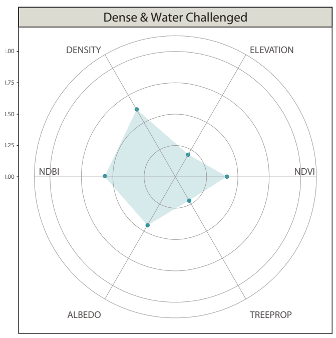
Figure 5. Two plots show the average score of each cluster's performance across the UESI's environmental indicators (left) and physical urban features (right).



Environmental indicators are scaled 0-100, with 100 representing the top performance benchmark. Physical indicators are scaled 0-1. A higher score is not necessarily better for physical features.

Table 2. Five typologies of urban environmental performance.





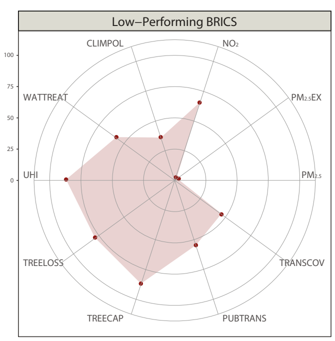
Dense & Water Challenged

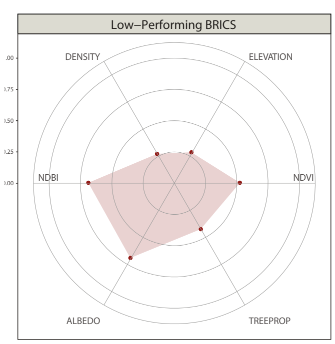
(Mexico City, Bangkok, Ho Chi Minh City, Jakarta, Manila)

This cluster contains large cities with water treatment challenges, most of which are very dense and located in Asia. Along most metrics, these cities perform at close to average levels. They distinguish themselves due to high levels of fine particulate air pollution, as indicated through low performance on the $PM_{2.5}$ (47) and $PM_{2.5}$ Exceedance (45) indicators, and the worst wastewater treatment scores in the UESI sample. These cities also stand out as containing the highest density of all clusters.

These cities have all experienced rapid growth and development in recent history. Rapid urbanization and development have strained existing water infrastructure, which may explain this cluster's low performance on wastewater.

In Bangkok, a series of natural disasters in the early 2010s damaged infrastructure already in need of significant maintenance. To address this challenge, the Thai government has recently come out with a series of development plans aimed at dramatically upgrading water infrastructure by 2026.[11] In Jakarta, long-running debates and lawsuits surrounding the privatization of water resources stall the long-term development of infrastructure. Recent developments suggest a larger role for the state to provide clean water throughout the city, including significant investment into poorer areas that have been chronically underserved.[12]





Low-Performing BRICS

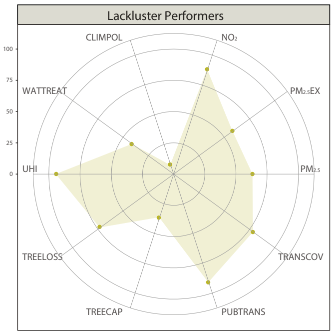
(Beijing, Johannesburg, New Delhi)

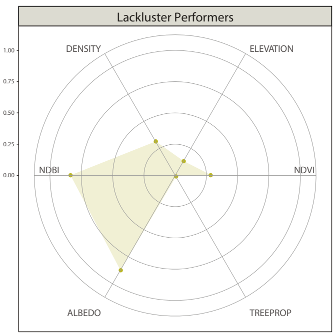
This cluster contains three of the four cities in our dataset from the BRICS (Brazil, Russia, India, China and South Africa) emerging economies. These cities are all major economic hubs in countries that have experienced rapid growth in the past 30 years. Perhaps as a result of this growth and increased economic output, these cities cluster together due to their extremely poor levels of airborne $PM_{2.5}$ or fine particulate matter (3).

Although UESI cities in general perform well on the public transit indicators across the board (see Figure 1), the cities in this cluster have the lowest public transportation access of any cluster. With the early stages of industrialization achieved, the governments of these cities are slowly investing in public transit, with Beijing adding more than 20 lines since 2002 and now boasting the highest ridership of any mass transit system in the world with more than 10 million riders each day.[13] While these investments in public transit are encouraging, the overall extent of Beijing's urban area is the reason it performs poorly on these indicators - some areas completely lack public transportation options due to low density or low built environment.

Despite performing poorly on the climate policy indicator, with New Delhi receiving a score of 0 for failing to have any city-level climate action plan, these cities perform well according to urban heat island and measures of tree cover. This result, however, may be somewhat skewed by certain primarily forested and rural neighborhoods in Beijing, which cover a significant area outside the municipal limits (for more, see Box 3: *Challenges in Evaluating Beijing's Large Urban Extent*).

Table 2. Five typologies of urban environmental performance. (continued)





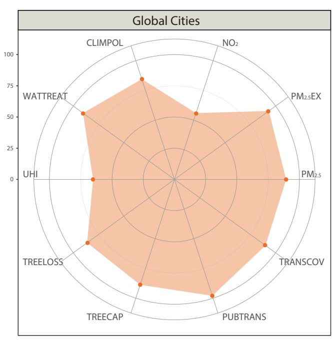
Lackluster Performers

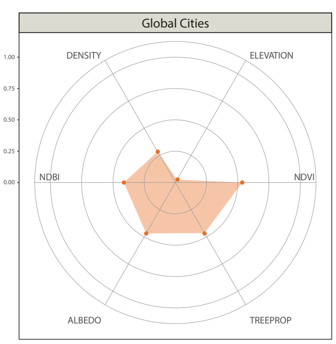
(Lima, Casablanca, Bangalore, Tel Aviv)

The cities in the lackluster performers cluster are diverse in their geography, size, and economic development. They perform well across some measures, including the highest aggregate performance for NO_2 (88) and urban heat island effect (94), despite having low levels of tree cover and being relatively built up (measured via NDBI). Lima is a clear laggard in the cluster across a number of environmental metrics. The city's poor fuel quality, a car and bus fleet over 20 years old, combined with the city's geography between the Andes to the East and the Pacific Ocean to the West, give the city what one World Health Organization study found to be the worst $PM_{2.5}$ levels among Latin American cities.[14, 15]

The environmental performance of cities in this cluster may be due in part to a physical feature of the cities, albedo. This group has the highest albedo levels of any cluster by a large margin, which could explain why cities in this group perform well on urban heat island effect despite low levels of tree cover. These high albedo levels are likely due to this cluster's high built-up area (NBDI: .84), as structures built of concrete tend to have higher reflectance than natural land covers, such as forest or grassland.

Another notable characteristic of this cluster that distinguishes it from others is the lack of urban climate policies in many of these cities. Bangalore is another city, along with New Delhi, that lacks a climate action plan, due to a myriad of reasons that involve both the lack of local authority and capacity to effectively coordinate across departments and ministries to address climate change.[16] While Karnataka, the province within which Bangalore is located, does have a state action plan for climate change, critics have pointed to its failure to appropriately mainstream climate change into development concerns.[17]





Global Cities

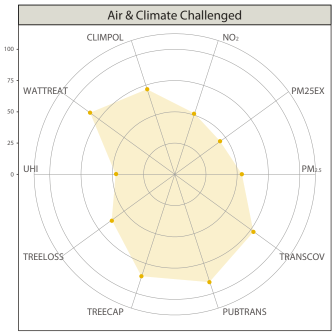
(New York City, Boston, Montreal, Atlanta, Detroit, Berlin, Chicago, Melbourne, Vancouver, Amsterdam, Copenhagen, Buenos Aires, Barcelona, Tokyo, Paris, and London)

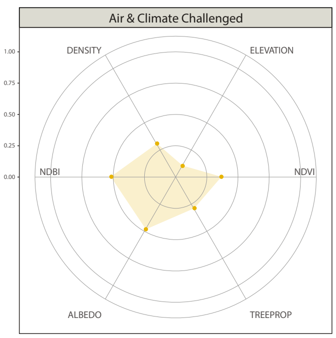
The global cities cluster has the most cities, most of which are are located in countries with high levels of economic development. Many of these cities are capitals in their respective countries, with all frequently identified as "global cities" according to world rankings and lists, such as A.T. Kearney's Global Cities Index, which recognizes these cities for having a favorable mix of business activity, human capital, information exchange and political engagement to thrive.[18] From an environmental perspective, these cities are characterized by high levels of tree cover per person, strong public transit access, and low levels of $PM_{2.5}$.

While most of these cities are in countries that have long-standing federal policies limiting air pollutants, performance is mixed with respect to the air indicators. These cities generally perform well on the particulate matter indicators ($PM_{2.5}$: 89) but display mediocre performance on NO_2. National legislation such as the U.S.'s Clean Air Act in America or Australia's National Clean Air Agreement have likely contributed to these cities' high performance on $PM_{2.5}$. However, performance on the NO_2 indicator is amongst the lowest for this cluster (NO_2: 56). Low scores on NO_2 are likely due to the persistence of diesel vehicles in many developed country cities. Earlier this year, Germany banned older diesel vehicles from their roads and sales of these vehicles have already dropped 25 percent.[19]

Detroit is an auto-oriented city that has low population density and as a result scores low on public transit alongside poor performance on air quality. In recent years, however, Detroit has placed new emphasis on improving existing transit systems within the city, and recently released a strategic plan aimed at making it easier, safer and more affordable to get around the "the Motor City."[20]

Table 2. Five typologies of urban environmental performance. (continued)





Air and Climate-Challenged Cities
(São Paulo, Seoul, Singapore, and Los Angeles)

This cluster contains large, prominent cities that perform fairly poorly on urban heat island (47), climate policy (71), and air quality indicators (NO_2: 51, $PM_{2.5}$: 54, $PM_{2.5}$ Exceedance: 45).

Poor air quality is an issue throughout densely populated South Korea, particularly in its capital city of Seoul, and the country was determined to have the worst air quality of any OECD (Organisation for Economic Co-operation and Development) member state as recently as 2017.[21] The public perceives the real risk of poor air quality, as one study claimed South Koreans fear poor air more than the risk of nuclear weapons being used on the Korean Peninsula.[22] Shifting transportation modes from vehicles to public transit is an effective way to improve air quality, and to try to initiate this shift, Seoul's government has experimented with making public transportation free within the city.[23] Seoul also suffers from regional air pollution problems due to its proximity to China, which has struggled with its own air pollution problems.[24]

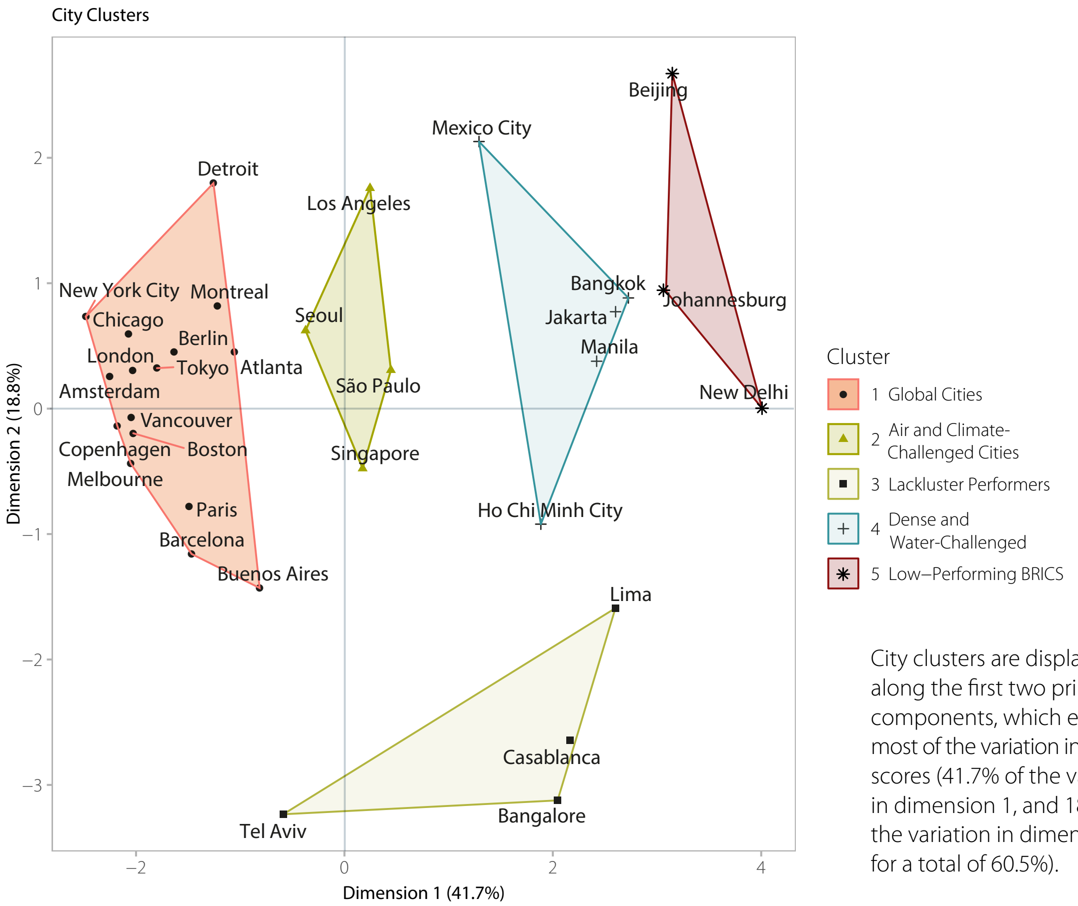
Due to high transit-related air pollution emissions, most of these cities have invested in mass public transit, which is evident through their strong performance on the public transportation indicators (Proximity to Public Transit: 90, Public Transit Coverage: 78). A number of these cities were listed in 2017 for having "the world's best metro systems."[25]

These cities also perform well on tree cover per capita, mostly due to Singapore's extensive tree cover. Singapore, the best performer for tree cover among any city in the UESI pilot cities, shows how policies can lead or aid environmental performance. The Singapore National Parks Board (NParks) has a policy to replace any vegetation that is displaced as a result of construction, which results in preservation of green space throughout the city-state. Vertical gardens and green roofs are also subsidized through Singapore's Skyrise Greenery Incentive Scheme 2.0.[26] These efforts to improve tree cover in Singapore have worked, as the city-state ranks highest in measures of tree cover, despite clearing significant amounts of green space for development, including construction of an airport, over the past 20 years.

EXAMINING VARIATION IN ENVIRONMENTAL PERFORMANCE WITHIN CITIES

One approach to understanding variation in environmental performance is through principal component analysis or PCA, a statistical method that takes many different variables and identifies those that are most critical to explain variation within the original data.[27] Applied to the UESI cities, this technique can help to isolate some drivers explaining differences in environmental performance at both the city and neighborhood scale. Combining both data on physical characteristics of cities and environmental performance on the UESI indicators, we can see what factors contribute most to variation in cities' scores. Figure 6 displays the five city clusters above along the first two principal components, which explain around 60 percent of the variation in environmental performance within the cities. This illustration presents a clear picture of how similar and dissimilar various clusters are: the Global Cities (e.g., New York City, Montreal, Atlanta, etc.) and the Air and Climate-Challenged Cities (e.g., Tokyo, Seoul, and Paris) show some similarities in their performance, with the former cluster more strongly explained by the first principal component.

Figure 6. UESI cities clustered (using k-means clustering algorithm) according to their proximity-to-target scores.



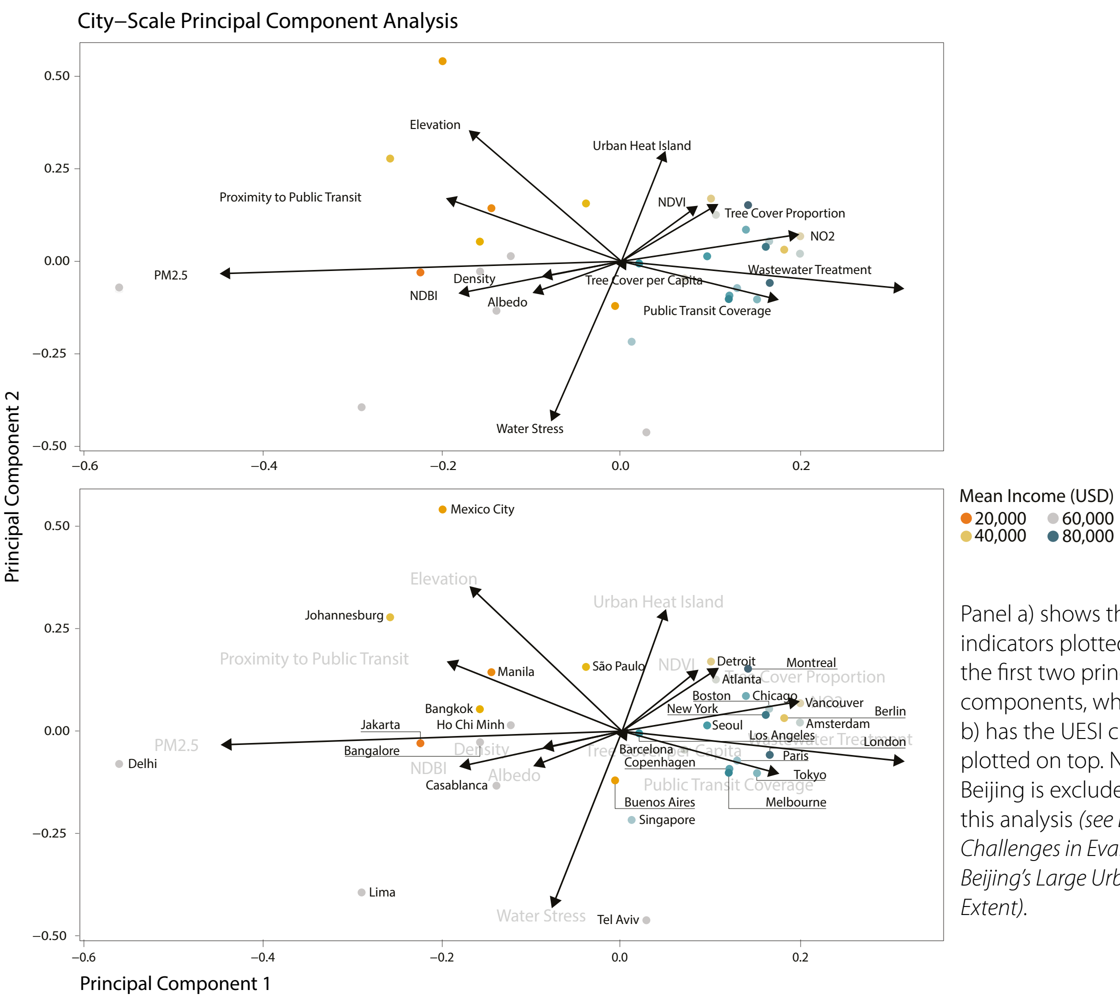
City clusters are displayed along the first two principal components, which explain most of the variation in the city scores (41.7% of the variation in dimension 1, and 18.8% of the variation in dimension 2, for a total of 60.5%).

City-scale analysis of principal components

Figure 7 provides a juxtaposition of two principal component analyses at the city-scale: panel a) highlights the environmental performance and physical characteristic indicators, while panel b) features the UESI cities on top. The first two PCAs explain around 50 percent of the variability within cities, with the first principal component having strong negative associations with $PM_{2.5}$ but strong positive associations with wastewater treatment. New Delhi stands out as a city that has strong negative associations with $PM_{2.5}$, which is unsurprising given the city's last-place performance on this indicator. Developed country cities like Boston, London, Amsterdam, Berlin, Vancouver, Paris are all clustered near the vector for Wastewater Treatment and NO_2, and Transportation Coverage, which all have positive associations within PC1. In general, developed-country and developing country cities are nearly equally split according to PC1: developed-country cities primarily have positive associations with PC1 and developing-country cities are located on the left-hand side of the PC1 axis.

Principal component 2 is negatively associated with Water Stress and positively associated with Elevation, with Mexico City located closest to that vector, given its high elevation compared to other cities in the UESI sample. Tree cover proportion and NDVI, two measures of a city's greenness, are other indicators that have positive associations within PC2.

Figure 7. First two principal components for indicators and city-level performance.



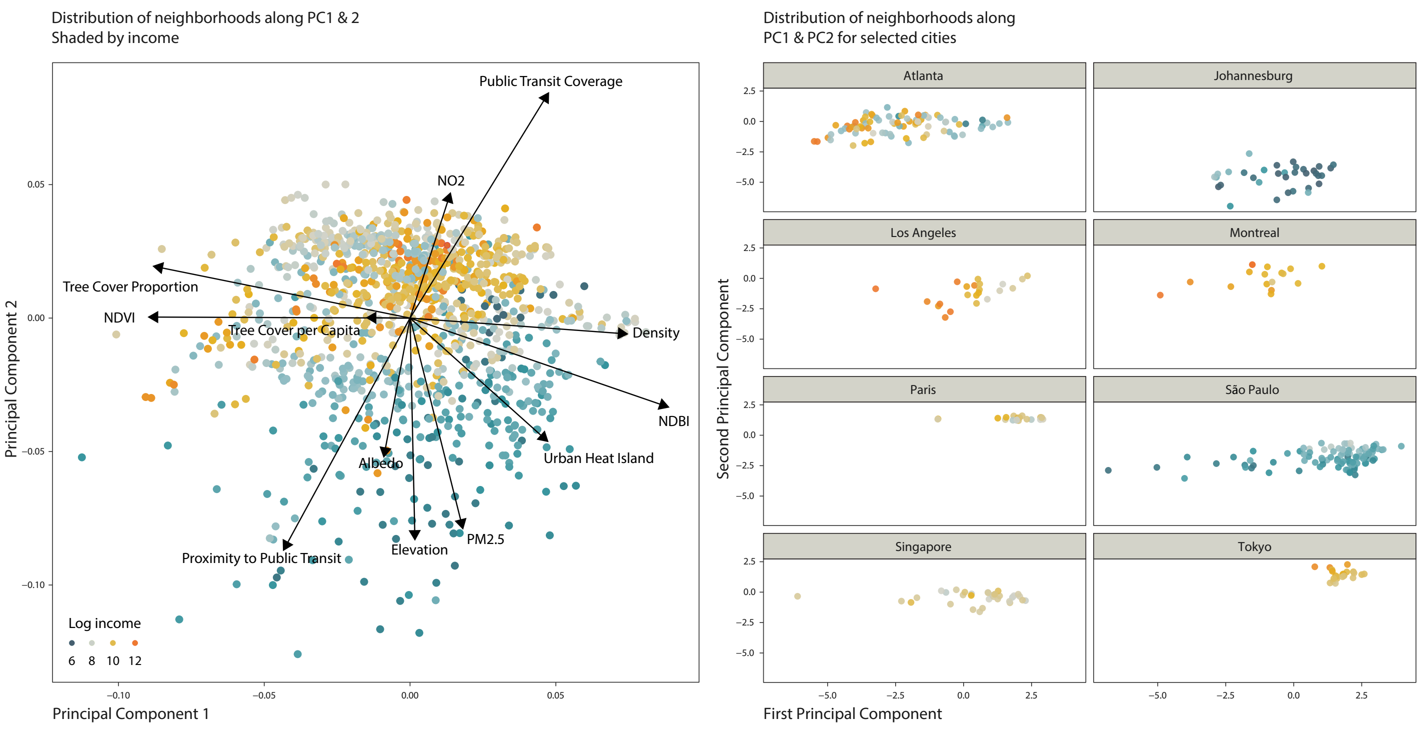
Panel a) shows the UESI indicators plotted along the first two principal components, while panel b) has the UESI cities plotted on top. Note: Beijing is excluded from this analysis *(see Box 2: Challenges in Evaluating Beijing's Large Urban Extent).*

Neighborhood-scale analysis of principal components

Applying a PCA to the neighborhood level (n=1,354) reveals a general division of performance along income levels. Figure 8 illustrates the application of a PCA to neighborhoods with complete environmental performance data, shaded according to income per capita. For higher-income neighborhoods (around $160,000 USD per capita; shaded in red), most of the variation in scores is driven by positive associations with public transportation coverage, greenness (NDVI), and tree cover proportion. Lower income neighborhoods (less than $3,000 USD per capita; shaded in blue-green) tend to fall on the right-hand side of the PCA plot in Figure 7, with negative associations with PM2.5 and built environment (NBDI) explaining most of the variability in those cities' results.

The right-hand panel of Figure 8 provides more detailed views of where cities fall within the overall PCA plot. While neighborhoods within a city tend to cluster together, within city clusters some neighborhoods display varying levels of income, which is particularly evident in São Paulo and Atlanta, although the log transformation has the effect of downplaying some of these differences in income.

Figure 8. Neighborhoods within selected cities plotted along the first 2 principal components shaded by logged income (GDP per capita) levels.



Note: Beijing is excluded from this analysis (see Box 2: *Challenges in Evaluating Beijing's Large Urban Extent*).

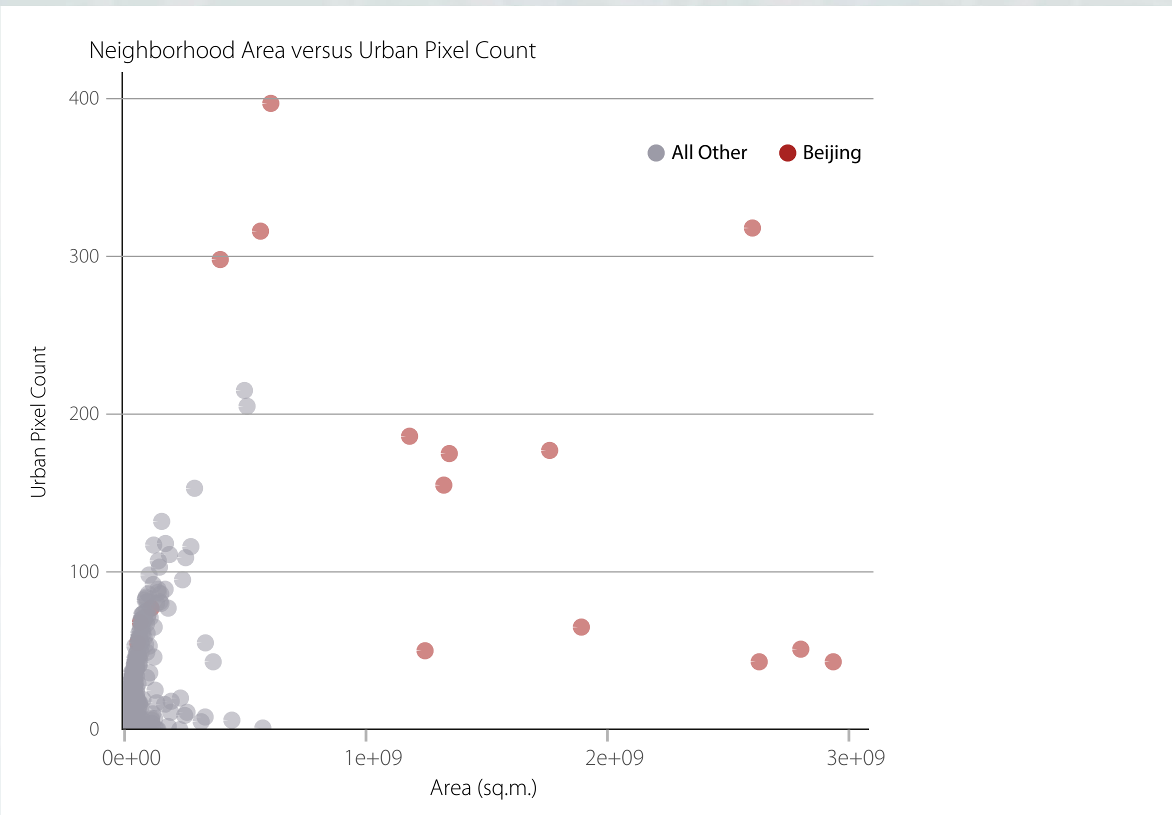
Box 2. Challenges in Evaluating Beijing's Large Urban Extent

What defines a city? While local governments set administrative boundaries to define city limits, distinguishing between urban and non-urban, rural from suburban, and everything in between is so challenging that most scholars simply refer to the "rural-urban continuum" to recognize that these categories are not so clear cut. The UESI also wrestled with this issue (see *Methodological Appendix; www.bit.ly/uesi-tech-appendix*), given the variable definitions and boundaries cities adopt when delineating their urban extents.

While our analysis revealed urban and neighborhood definitions between cities were generally comparable, Beijing stood out for its large urban extent and diverse neighborhoods, with some neighborhoods surrounding Beijing's urban core – the densely-populated area within the capital's sixth ring road and centered around the famous Forbidden city -- primarily forested, rural and with few residents. To illustrate this point, we used satellite analysis of land cover to compare the size of neighborhoods (n=2,107) within the UESI cities and whether they were primarily urban or rural (Figure 8).[28] Compared to other cities, Beijing's neighborhoods are much larger and show a range of variation in terms of the number of urban pixels in each, suggesting that some neighborhoods in the bottom right of the plot are primarily rural and very large in overall area.

While we considered removing neighborhoods from Beijing that contained a low ratio of urban to non-urban pixels, removing certain neighborhoods from Beijing would have required a similar consideration for other neighborhoods in other cities. Determining an appropriate threshold for exclusion would have been challenging. After conducting a sensitivity analysis (see *Methodological Appendix*), we determined Beijing represented an outlier that would have unduly influenced the other results and decided to not include Beijing in the PCA analysis.

Figure 9. Size of neighborhoods within the UESI dataset and the number of urban pixels within them.



CONCLUSION

The global center of gravity is increasingly shifting to cities. Urban areas hold just over half of the world's population,[1] generate roughly 80 percent of global GDP,[2] and drive 70 percent of global energy-related carbon dioxide emissions.[3] 3.9 billion people currently live in cities, a number expected to climb to 6.4 billion – two-thirds of the world's population – by 2050.[4]

The stakes of cities' decisions over the following decades are exceptionally high. Many of the global South cities projected to grow the most have the fewest per capita financial resources.[5] City leaders in these areas often face a difficult balancing act between addressing the urgent and growing need for essential services, and making longer-term decisions and investments that will shape the urban environment – and its residents – for years to come.[6] In more developed cities, officials must grapple with previous land-use and infrastructure decisions that have led to unsustainable levels of resource consumption and set up costly paths for continued development.[7,8,9] Around the world, shared challenges such as air pollution and climate change place millions at risk.

Cities also hold unique opportunities to foster equitable and sustainable growth. Denser, more connected, and more coordinated cities could save $17 trillion USD by 2050.[10] Compact urban areas could increase residents' access to jobs, services and amenities, while reducing infrastructure costs.[11] City policies and practices can help mitigate climate change and build resilience to its impacts.[12,13]

As cities take on increasing leadership in charting a trajectory that navigates these challenges, the goals of fostering inclusive, equitable development and successful environmental management are deeply intertwined. Environmental burdens and risks – such as air pollution, heat waves, extreme weather events, and the risk of floods and droughts – can sharpen inequality,[14,15,16] while access to environmental benefits, such as green space and public transit, can help mitigate it. Building public transit to connect underserved communities to the city center helped Medellin, Colombia transform from the world's murder capital to into a safer and more inclusive city.[17,18] Programs fostering social cohesion can lessen the impacts of urban heat waves and build resilience to extreme weather events and natural disasters.[19,20,21]

Data will be imperative to enabling cities to address these integrated challenges. At the moment, frameworks that compare cities' progress and challenges – and assess how this performance varies across different neighborhoods – remain scarce. The UESI provides a resource that tracks neighborhood-level access to environmental goods and exposure to environmental harms to help city managers and urban residents understand how the environmental quality of life varies across different locations and socioeconomic demographics. This report also provides a starting point and proof of concept for understanding how the application of large-scale and unconventional datasets – from satellite data to OpenStreetMap – can

create a comprehensive, detailed, and timely dataset of urban performance. Over time, the UESI aims to provide a flexible and adaptable framework and data source that new cities can adapt for their own analysis and management purposes.

We find overall that cities are not meeting the charge of sustainable and inclusive environmental policies. Although there are some cities that perform well on the UESI's environmental indicators, nearly all are burdening poorer populations with the consequences of uneven air pollution distribution, access to tree cover, public transit, and exposure to urban heat. We see that income still plays a strong role in determining environmental performance in many cities, with cities tending to cluster on the UESI results with other cities of a similar economic development status. Higher levels of income, however, do not determine equitable outcomes, as the UESI results show wealthy and poor cities alike are placing the greatest environmental inequalities on poorer populations. For instance, urban heat island intensity places a greater burden on poorer populations in Atlanta, Los Angeles, and Mexico City. Johannesburg's high levels of income inequality are compounded by inequitable distributions of urban heat island, urban tree cover, and distance to public transit, which disproportionately burden lower income earners.

Data gaps still remain: vital socioeconomic data proved especially difficult to collect and standardize across different urban contexts, while tools like OpenStreetMap are prone to gaps in volunteers' data collection. Data alone, however, is not a panacea – cities' ability to investigate and respond to data signals depends on technical knowledge, financial resources, and political will. The continued growth of mobile phones and information communication technology and the innovation in new modes of data collection have the potential to help ground and inform cities' growing role in fostering sustainable development. We hope this tool provides a starting point and sparks a discussion about how role of data in support urban sustainability to create a more robust dataset of urban triumphs and challenges, and to mobilize support for efforts to chart safe, inclusive future.

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EQUITY AND SOCIAL INCLUSION

1 See footnote 2.

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41 It is also important to mention that this approach is not intended to compare income versus environmental distributions - in other words, it should not be used to judge whether the distribution of an environmental outcome is more or less equitable than that of income for the same city, or between the same curves for different cities.

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RESULTS

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