Assessment of Key Ecosystem Services Provided by the Haizhu National Wetland Park in Guangzhou, China

Prepared by: Chris Nootenboom, Eric Lonsdorf, Roy Remme, Rob Griffin, Baolong Han, Tong Wu, and Anne Guerry

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

ESMAP
Energy Sector Management Assistance Program

1818 H Street NW
Washington, DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

Citation
Please cite the report as follows: World Bank. 2022. Assessment of Key Ecosystem Services Provided by the Haizhu National Wetland Park in Guangzhou, China. Washington, DC: World Bank.

Acknowledgments
This technical report was coordinated by Xueman Wang at the World Bank, and prepared by Chris Nootenboom, Eric Lonsdorf, Roy Remme, Rob Griffin, Baolong Han, Tong Wu, and Anne Guerry. Valuable contributions were received from Guangzhou Urban Planning & Design Survey Research Institute, Guangzhou Urban Planning Association, Guangzhou Climate and Agrometeorology Center, Sun Yat-Sen University and South China University of Technology.

Cover photo: Guangzhou Municipal Planning and Natural Resources Bureau. Back cover: © Weiming Lin | Dreamstime.com
Design: Ultra Designs, Inc.

Table of Contents

Photo: HelloRF Zcool

Executive Summary

As humanity charts a path into the urban century, our lives increasingly depend on the built environment. However, human wellbeing is also intimately connected to the natural world and the diverse benefits that nature provides to people. Understanding the linkages between urban nature and human wellbeing will foster the development of the sustainable, livable, equitable cities of the future.

Mapping, measuring, and modeling "ecosystem services" (or the benefits that flow to people from nature) are useful ways to quantify just how much nature promotes human wellbeing. This report details novel approaches to such modeling in urban environments through a case study of the Haizhu National Wetland Park in Guangzhou, Guangdong, China. It addresses:

- The difficulties of spatial data processing in urban environments, where ecosystem services accrue at finer spatial scales than typically modeled;
- Replicable methods for modeling five important urban ecosystem services--climate change mitigation (through carbon storage and sequestration), urban cooling, improvements in mental health, improvements in physical health, and access to recreation;
- Linkages between each service and various health and economic indicators (e.g., climate change impacts, risk of heat death, workplace productivity, thermal energy use, avoided healthcare treatment costs);
- The health and economic value of the Haizhu wetland when compared to a residential housing development in its place.

Urban Ecosystem Services

Urban green spaces provide myriad benefits to cities. They reduce the risk of flooding; attenuate water, noise, and air pollution; mitigate the urban heat island effect; furnish attractive spaces that promote physical and mental health; and provide many other intangible benefits to urban residents and visitors. However, many of these benefits are invisible to those who plan and develop urban spaces and remain poorly articulated for actionable decision-making. For example, predicting air temperature is relatively simple, yet translating urban heat islands into health impacts and economic terms is more difficult. This report provides a critical methodological bridge between the worlds of ecological modeling and economic reporting for urban planners.

Haizhu National Wetland Park

The Haizhu National Wetland Park (the Haizhu Wetland, for short) is an 11km^2 green space in the heart of the Chinese megacity of Guangzhou, in the Province of Guangdong. The wetland supports local biodiversity and provides essential ecosystem services to the city's 7.2 million residents. While the wetland is home to hundreds more insect and avian species than the surrounding city and received more than 60 million visitors over the last decade, many of its additional benefits remain unquantified. Articulating a diverse suite of benefits provided to people by the wetland can help bolster arguments for its continued protection and inform ecological planning in the city.

Urban Ecosystem Services and Human Value

Understanding the ecosystem services provided by the Haizhu Wetland enables city officials and urban planners to make ecologically-informed decisions about urban development in Guangzhou. Ecosystem services can be measured in different metrics. In some cases, "biophysical" metrics, such as degrees of cooling, are useful. In others, monetary metrics resonate. In still others, different types of value metrics (like mortality risk) are most germane. Here, we report ecosystem service values in a range of metrics to maximize the utility of our results for urban planners (Table ES1).

Table ES1 // OVERVIEW OF MODELED ECOSYSTEM SERVICES, WAYS OF ASSESSING VALUE FOR EACH SERVICE, AND SUMMARY RESULTS SHOWING THE VALUE OF THE WETLAND COMPARED TO A RESIDENTIAL DEVELOPMENT OVER THE NEXT 30 YEARS.

Ecosystem Service	Supply Metric	Value Metric(s)	Valuation Modeling Approach	Value of the Wetland (30 year horizon)
Urban cooling*	Air Temperature	Productivity	Loss of workplace productivity as a result of temperature and humidity	Up to 16.1% in avoided productivity losses for nearby districts
		Private cost of cooling	Cost of cooling (and heating) as a function of temperature	$1.9 million USD
		Mortality risk	Relative risk of mortality or morbidity as a function of temperature and region	Up to 1.27% in avoided mortality risks for nearby districts
Climate change mitigation*	Carbon Stored or Sequestered	Social cost of carbon	Net present value of change in damages from carbon emissions	$77.8 million USD (7.4 million tons of avoided emissions)
Recreation*	Access (distance to parks)	Willingness-to-pay	Entry or use-fees; willingness-to-pay	$67.8 million USD
Physical health	Access to urban nature (e.g., distance to parks, tree-lined streets, urban gardens, trails etc.)	Avoided cost of treatment	Change in costs associated with treatment to restore original physical health level	$4.2 million USD
Mental health	Access to urban nature (e.g., views of greenery, distance to parks, amount of trees in neighborhood)	Avoided cost of treatment	Change in costs associated with treatment to restore original mental health level	$70.1 million USD

This report relies on a combination of existing and prototype InVEST models to map and model the value of services provided by the wetland. InVEST is a free and open-source software suite that has been used in over 185 countries globally; it leverages geospatial data inputs alongside known ecological processes to predict the provision of ecosystem services from land and seascapes. This is one of the first applications of the new urban suite of tools in this software.

The usefulness of any ecosystem service model depends on having a realistic alternative to which we can compare. To that end, we created a composite landscape image of a hypothetical residential development and compared its ecosystem service value to that of the wetland, enabling us to quantify the marginal value of the wetland.

Climate Change Mitigation

Cities are critical sources of climate emissions, with a significant amount of global carbon emissions spent on manufacturing and constructing built infrastructure. We amended typical landscape carbon modeling in InVEST with a more lifecycle assessment approach that acknowledges embedded and annual emissions in city infrastructure, ensuring a more comprehensive carbon accounting. We linked changes in carbon stocks and emissions to global climate impacts and resulting economic damages through the Social Cost of Carbon.

- ***Replacing the wetland with residential development would increase net carbon emissions by 7.4 million metric tons and cause a minimum of $77.8 million USD in climate-related damages over the next thirty years.***

Urban Cooling

Green spaces help cool air temperatures by providing shade and evaporative cooling (from plant evapotranspiration) amidst a landscape of heat-retaining pavement and concrete. We applied the InVEST Urban Cooling model to the region to assess the local urban heat island using local geographic and climate datasets. To make the model decision-relevant to urban planners, we converted changes in temperature into changes in the energy expenditures on building temperature control, workplace productivity, and the mortality risk of heat-induced death.

- ***The wetland reduces local energy expenditures for cooling by $1.9 million USD, lowers mortality risk by up to 1.27% in the surrounding area, and prevents up to 16.1% of heat-related reductions in workplace productivity as compared to a residential development.***

Mental Health

Exposure to nature, especially in cities, can promote mental health. We used a prototype InVEST model (adapted from mental health modeling techniques in the scientific literature) to determine the impact the wetland has on human wellbeing. We used methods from the World Health Organization to connect wellbeing to reduced mental health expenditures.

- ***Replacing the wetland with residential housing would cause an additional $70.1 million USD in mental health treatment costs.***

Physical Health

Green spaces in cities bolster citizen's physical health by providing inviting spaces in which to spend time. We used a prototype InVEST model and existing approaches to quantify how much additional physical activity the wetland encourages in the nearby population and related that to the economic costs of physical inactivity in China.

- ***The wetland currently prevents $4.2 million USD in economic damages from physical inactivity.***

Recreational Access

Green space provides unique recreational opportunities that have demonstrable value to urban residents. We used a willingness-to-pay approach to valuing access to green space for recreation, relating the reported values residents place on green space access to rates of access with and without the wetland.

- ***The wetland currently provides $67.8 million USD in recreational activities to local residents.***

The Value of the Haizhu Wetland

We conservatively estimate that the marginal value provided to Guangzhou by the Haizhu Wetland via these five ecosystem services is at least $221.8 million USD over the next 30 years, in addition to reduced mortality risk and increased workplace productivity in the surrounding landscape. Including additional ecosystem services that were beyond the scope of this analysis, such as water purification and flood mitigation, would likely add to this reported value as the ecosystem services displayed here are by no means a comprehensive accounting of the value of the Haizhu wetland.

Beyond the scope of our case study, this report demonstrates a globally generalizable approach to urban ecosystem service valuation. The approaches we developed will make it easier and more efficient to understand the services provided by urban nature and to use that understanding to inform urban planning decisions across China and throughout the world.

Photo: Huang Shengyun

Introduction

Green space can provide a broad range of benefits to people in cities, i.e. ecosystem services—sometimes referred to as nature's contributions to people. It can help reduce the risk of flooding; attenuate water, noise, and air pollution; mitigate the urban heat island effect; and provide attractive spaces that promote physical and mental health (Depietri and McPhearson, 2017; Haase et al., 2014; Keeler et al., 2019; van den Bosch and Ode Sang, 2017). However, green spaces in cities face development pressure from increased urbanization in many areas around the world, including China. Because they offer space for building, it is important to more fully value the benefits green spaces provide to make more informed planning decisions about the costs and benefits development could have on people in urban areas. Information about how much, where, and for whom investments in natural infrastructure yield benefits can improve urban planning and decision-making and direct limited budgets to projects most likely to provide critical benefits to people (Cortinovis and Geneletti, 2020; Hamel et al., 2021; Keeler et al., 2019; Lafortezza et al., 2018). Ultimately, understanding the link between urban nature and human wellbeing can guide the design and re-design of more sustainable, livable, equitable cities.

Urbanization and pressure to develop green space is particularly relevant in China. Guangzhou, China—the focus of this case study—is part of one of the world's largest metro areas: the Guangdong-Hong Kong-Macao Greater Bay Area, with a population of 72 million as of 2019. Within Guangzhou sits the Haizhu National Wetland Park (the Haizhu Wetland, for short), known locally as the "Green Heart" of the city, which at 11km^2 remains the largest wetland in the downtown core of any Chinese megacity and provides many services to residents (Fig. 1). It is highly accessible from the Central Business District and other densely populated areas, making it a key component of greenspace access for locals (Fig. 2); from 2012-2020, the wetland received over 60M visitors. the number of bird species has increased from from 72 to 180; fish species from 36 to 60; and insect species from 66 to 539. With development pressures increasing, what value would be lost if the wetland were urbanized?

Figure 1 // THE LOCATION OF THE HAIZHU WETLAND RELATIVE TO GUANGDONG PROVINCE.

According to the local planners in Guangzhou, the Haizhu Wetland would most likely be replaced by residential housing should it lose its protected status. To determine the value of the wetland, we can simply compare the ecosystem service values provided by the wetland to those provided by a residential development across the same area. This is known as a marginal value approach and is often used to quantify the human values nature can provide (Ricketts and Lonsdorf 2013; Lonsdorf et al. 2021).

The flow of services and value that ecosystems provide to people is often called the 'ecosystem service cascade' (Haines-Young and Potschin-Young, 2010; Tallis et al., 2012). The cascade integrates two key components: a biophysical model that describes how a landscape or seascape supplies a specific ecosystem service and a valuation function that translates how the service contributes to human wellbeing. This integration allows decision-makers and stakeholders to evaluate how potential changes in land cover affect the amount of the service being provided. Urban development in green spaces will be most detrimental in places that have: a) a high density of people using services combined with b) a supply of ecosystem services that are sensitive to changes in land cover. The fine-scale biophysical and socio-economic heterogeneity in urban landscapes makes mapping and assessing the equitable distribution of services under alternate scenarios a more challenging endeavor than in more expansive, "simpler" rural landscapes.

This case study addresses a specific example of development risk on a wetland in a Chinese megacity. However, the data and tools that are the foundation of our analysis are globally available. As much as this report is an examination of the value of the Haizhu Wetland, it also stands as a recipe for conducting similar work elsewhere in the world using free and open-source data and technology. The value of urban nature should not be discounted by any city government or development agency, and these tools give scientists, policy advocates, and the general public an instrument to better understand the contribution of urban nature to the wellbeing of city-dwellers.

Figure 2 // THE HAIZHU WETLAND AND NEARBY GUANGZHOU CENTRAL BUSINESS DISTRICT.

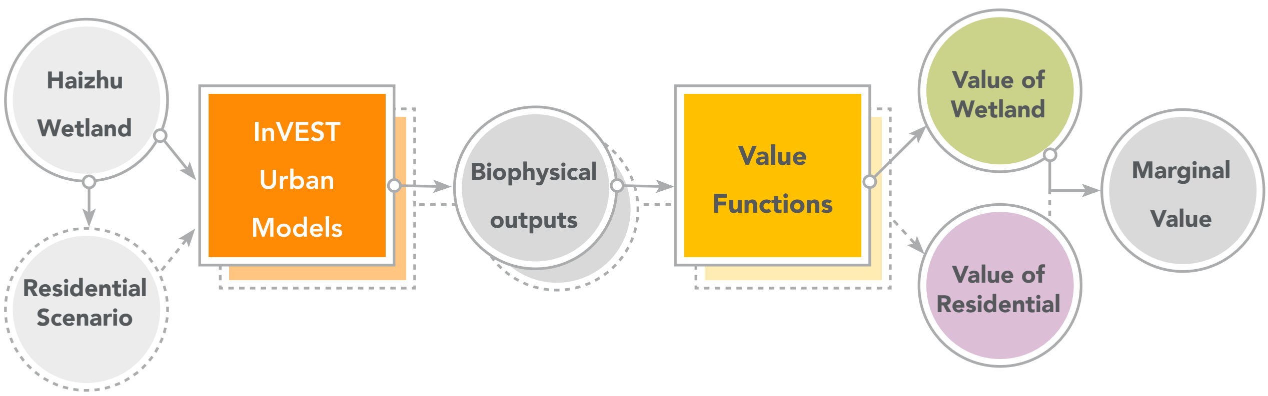
Photo: Guangzhou Haizhu District Wetland Protection and Management Office

Methods

We used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software suite (Hamel et al., 2021; Sharp et al., 2021) to implement the ecosystem service cascade for a number of urban services. This free and open-source software has been used in over 185 countries worldwide to map, measure, and value the benefits provided by nature to people. InVEST takes data on land use and land cover, alongside other climatological and biological data inputs, and applies ecological production functions to calculate the ways in which the landscape provides a specific ecosystem service. To assess the services provided by the Haizhu Wetland, we used a combination of existing and prototype InVEST models to quantify the value the wetland provides for five services (Table 1): climate change mitigation (carbon storage and sequestration), urban cooling, improvements in health (via physical activity's impact on both mental health and physical health), and recreational access. We then calculated the provision of these services in a future without the wetland to determine the marginal values of each service (Fig. 3). We selected these services because they capture a broad range of nature's value to urban residents and because we could link changes in the biophysical nature of these services to discrete human values (e.g., monetary valuation, mortality rates, workplace productivity).

Figure 3 // CONCEPTUAL MODEL ILLUSTRATING HOW THE INVEST MODELING SUITE IS USED TO QUANTIFY THE VALUE THE HAIZHU WETLAND PROVIDES TO PEOPLE.

The process involves modeling the ecosystem services provided by the Haizhu Wetland (solid lines) and comparing those values to those that would be provided if the wetland were converted to a residential development (dashed lines).



Source: Assessment of key ecosystem services provided by the Haizhu National Wetland Park in Guangzhou, China (World Bank, 2022)

Table 1 // MODELLED URBAN ECOSYSTEM SERVICES AND THEIR SUPPLY OF BENEFITS TO PEOPLE LIVING IN CITIES, ALONG WITH SELECTED METRICS WE USED TO VALUE THESE SERVICES AND METHODS FOR QUANTIFYING THOSE VALUES.

Those with * are currently addressed in the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software suite (Hamel et al., 2021; Sharp et al., 2021), though not all models provide the full suite of valuation modeling approaches taken below.

Ecosystem Service	Supply Metric	Value Metric(s)	Valuation Modeling Approach
Urban cooling*	Air Temperature	Productivity	Loss of workplace productivity as a result of temperature and humidity
		Private cost of cooling	Cost of cooling (and heating) as a function of temperature
		Mortality risk	Relative risk of mortality or morbidity as a function of temperature and region
Climate change mitigation*	Carbon Stored or Sequestered	Social cost of carbon	Net present value of change in damages from carbon emissions
Recreation*	Access (distance to parks)	Willingness-to-pay	Entry or use-fees; willingness-to-pay
Physical health	Access to urban nature (e.g., distance to parks, tree-lined streets, urban gardens, trails etc.)	Avoided cost of treatment	Change in costs associated with treatment to restore original physical health level
Mental health	Access to urban nature (e.g., views of greenery, distance to parks, amount of trees in neighborhood)	Avoided cost of treatment	Change in costs associated with treatment to restore original mental health level

Input data

In urban areas, all ecosystem services are influenced by the interaction of land cover and land use, while some services are also affected by soil and air properties. Land cover describes what the surface is, while land use provides information how that cover is being used and thus how it might be managed. For example, turf grass is a common land cover type in urban areas. However, it is used differently and managed differently depending on its use as a residential lawn, recreation area, golf course, cemetery etc. A residential lawn is likely mowed more frequently and fertilized more heavily than grass cover in city parks. These differences in land use within the same land cover type could affect biodiversity, nutrient runoff and retention, and carbon storage and sequestration. If one only used land cover, these differences would not be captured. Thus, it is critical that assessments of urban ecosystem services include both land cover and land use to accurately capture the ways in which urban green spaces support biodiversity and generate ecosystem services. Unfortunately, single land use-land cover (LULC) data sets that can account for this degree of heterogeneity are often unavailable, requiring creation by combining information from two or more data sources (Lonsdorf et al., 2021).

For Guangzhou, we generated a new LULC dataset for the Haizhu Wetland by combining land cover from GlobeLand30 (Chen et al., 2017) with land use from OpenStreetMaps (OSM) (OpenStreetMap contributors, 2021), overlaying a Normalized Difference Vegetation Index (NDVI) dataset for 2019, derived from Copernicus Sentinel-2 using Google Earth Engine, to further classify types of urban green space. We extracted six data layers from OSM for the study area that described land use, places of interest, places of worship, water features, buildings, and roads which we buffered to varying widths based on classification (e.g., primary road vs secondary road). Because OSM data are crowd-sourced and lack a standard classification system, we simplified many categories to fit our analytical scope (Table 2). We then sequentially overlaid each OSM dataset on top of the GlobeLand30 land cover data in the following order: (1) land use, (2) places of interest and/or worship, (3) water features, (4) buildings, and (5) roads. To account for the presence of water features within parks, such as the Haizhu Wetland itself, we reclassified any overlapping water and park features as 'Park (Waterbody)'. Finally, to identify urban green spaces unaccounted for at the scale of OSM and GlobeLand30, we overlaid NDVI data on all non-vegetative LULC classes—we classified areas exceeding 0.2 NDVI as 'Urban Green Space', with the exception of those in park features, which we labeled as 'Park (Green Space)'. See Fig. 4A for the resulting map.

Table 2 // RECLASSIFICATION SCHEME TO SIMPLIFY OPENSTREETMAPS DATA FOR MODELING PURPOSES.

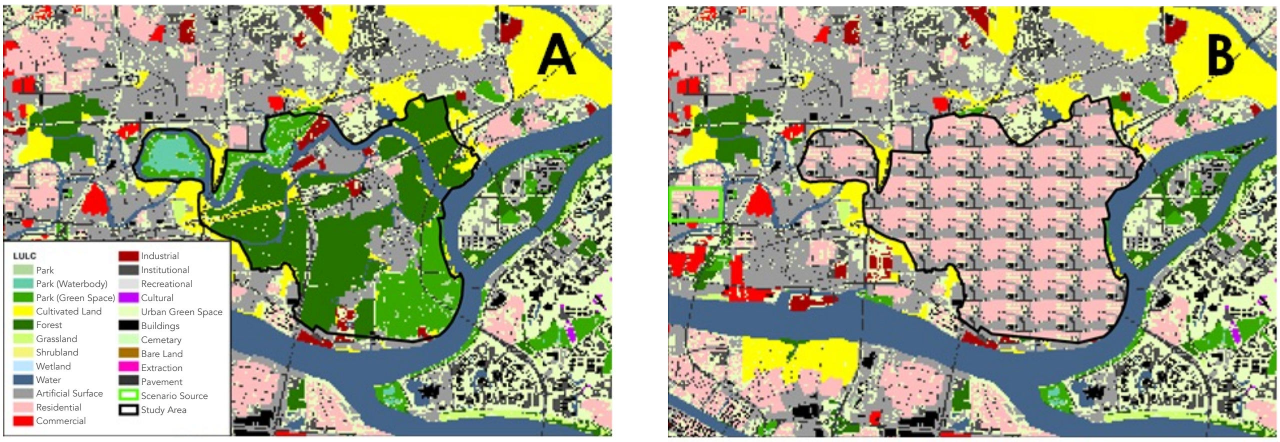
LULC Classification	OSM Source Layer	OSM Classifications (fclass)
Agriculture	Land Use	allotments; farmland; farmyard
Forest	Land Use	forest; nature_reserve; orchard
Shrub/scrub	Land Use	scrub
Grassland	Land Use	grass; meadow
Water	Water	reservoir; river; riverbank; water
Wetland	Water	wetland
Park	Land Use	park
	Places of Interest	park
Cemetery	Land Use	cemetery
	Places of Interest	graveyard
Residential	Land Use	residential
	Places of Interest	guesthouse
Commercial	Land Use	commercial; retail
	Places of Interest	bank; bookshop; cafe; car_dealership; cinema; clothes; comms_tower; community_centre; computer_shop; convenience; department_store; doityourself; fast_food; florist; food_court; furniture_shop; hostel; hotel; mall; newsagent; observation_tower; restaurant; shelter; sports_shop; supermarket; theatre; theme_park; toilet; tourist_info; tower
Cultural	Places of Interest	arts_centre; artwork; attraction; castle; fountain; memorial; monument; museum; ruins; sports_centre; stadium
Recreational	Land Use	recreation_ground
	Places of Interest	camp_site; golf_course; pitch; playground; swimming_pool; track; viewpoint; zoo
	Water	dock
Institutional	Land Use	heath; military
	Places of Interest	college; courthouse; doctors; fire_station; hospital; kindergarten; library; police; post_office; prison; public_building; school; town_hall; university
	Places of Worship	buddhist; christian; christian_catholic; muslim; muslim_sunni; taoist
Industrial	Land Use	industrial
	Places of Interest	recycling; wastewater_plant; water_tower; water_works
Pavement	Roads	**2m buffer**: bridleway; cycleway; footway; path; pedestrian; service; steps; track; track_grade1; unclassified; unknown **4m buffer**: living_street; residential **5m buffer**: motorway; motorway_link; primary; primary_link; secondary; secondary_link; tertiary; tertiary_link; trunk; trunk_link
Building	Buildings	building
Extraction	Land Use	quarry

Residential Scenario Development

To understand the value of the wetland using a marginal value approach, we needed a "without the wetland" scenario with which to compare the services provided by the wetland today. In consultation with the local planners in Guangzhou, we chose a dense residential scenario to represent the most likely conceivable future without protection of the wetland. We used the 'wallpapering' method (Lonsdorf et al., 2021) to create a residential scenario that reflects a pattern and configuration consistent with that of existing residential developments found in the study area. We identified and sampled the LULC pattern of a residential development near the wetland and replicated it until it covered the selected portion of the study area. The resulting residential scenario (Fig. 4B) forms the basis for our marginal value calculations for each of the ecosystem services we modeled. We repeated this process for NDVI using the same sample location as for LULC.

Figure 4 // LAND COVER AND LAND USE IN AND SURROUNDING THE HAIZHU WETLAND IN GUANGZHOU, CHINA:

(A) current landscape patterns, (B) residential land use scenario (see the green box "Scenario Source" in (B) for the area sampled to generate the new scenario.



Current Landscape ***Residential Scenario***

Ecosystem Service Models

Climate Change Mitigation (Carbon Storage, Sequestration, and Avoided Emissions):

Climate change mitigation is an important goal for communities and decision-makers in urban areas. Two key mitigation pathways are the reduction of emissions and the sequestering of carbon on the landscape, via natural lands and green infrastructure. Traditional methods of estimating landscape carbon storage and sequestration often focus on land cover and center on four pools of carbon: aboveground biomass, belowground biomass, soil carbon, and organic matter (Sharp et al., 2021). These pools have analogues in the built environment—soil carbon still persists underneath buildings and pavement (Edmondson et al., 2012), urban green spaces have abundant vegetative carbon stocks above and belowground, and we can even account for organic matter stored in the built environment (e.g. building materials, furniture, books) (Churkina et al., 2010). However, carbon accounting in urban areas must be expanded to include human impacts on the carbon cycle: *flux carbon*, in the form of annual emissions from energy use and land management, and *embedded emissions*, the CO2 generated during the manufacture and construction of built infrastructure (Kuittinen et al., 2016). Embedded emissions are an acknowledgement of the carbon cost of development, as producing building materials and constructing the built environment generates carbon emissions that are unaccounted for in either landscape carbon or annual emissions. Increases in embedded emissions therefore represent increases in the landscape's climate impact.

Climate change mitigation supply: We reviewed the relevant literature linking our LULC classifications to landscape **carbon stocks** (Bae and Ryu, 2015; Chaparro and Terradas, 2010; Churkina et al., 2010; Davies et al., 2011; Edmondson et al., 2012; Escobedo et al., 2010; Golubiewski, 2006; Hutyra et al., 2011; Jo, 2002; Kaye et al., 2005; Kellett et al., 2013; Luo et al., 2014; McPherson et al., 2013; Nero et al., 2017; Nowak, 1993; Nowak et al., 2013; Nowak and Crane, 2002; Pouyat et al., 2006; Raciti et al., 2012b, 2012a; Strohbach and Haase, 2012; Tang et al., 2016; Vodyanitskii, 2015; Yoon et al., 2016; Ziter and Turner, 2018), **embedded emissions** (Arıoğlu Akan et al., 2017; Boyle and Lavkulich, 1997; Churkina et al., 2010; Kuittinen et al., 2016; Norman et al., 2006), **and flux carbon** (Fissore et al., 2011; Goldstein et al., 2020; Golubiewski, 2006; Kellett et al., 2013; Kuittinen et al., 2016; Norman et al., 2006; Tidåker et al., 2017) to distill a parameter table that reclassifies LULC into estimates of carbon pools and fluxes (Table 3). Using carbon storage and emissions estimates for equivalent LULC classifications from the literature, we performed a weighted average calculation to condense that literature into the individual values presented below. We then reclassified LULC into each carbon pool (Mg C/ha), flux (Mg C/ha/year), and embedded emissions (Mg C/ha) under the wetland and residential scenarios (see Fig. 4).

Climate change mitigation value: We translated the carbon storage and sequestration results into monetary value using the Social Cost of Carbon (Nordhaus, 2017) as it is a standard valuation method; in cases where local government regulations (or carbon markets) mandate a price or cost to carbon, such a price would replace the Social Cost of Carbon. To provide a conservative estimate of value, we selected the average price of the Social Cost of Carbon (US$ 14 per metric ton in 2020, with a 5% discount rate) currently in use by the US government (Interagency Working Group on Social Cost of Greenhouse Gasses, 2021). For annual emissions, we used a net present value approach over a 30-year time horizon with a 5% discount rate to make future emissions relevant to a present-day decision.

Table 3 // CARBON STORED IN VARIOUS POOLS (MG C/HA) AND EMBEDDED IN BUILT INFRASTRUCTURE (MG C/HA), ALONGSIDE EXPECTED ANNUAL EMISSIONS (MG C/HA/YR), BY LULC DESIGNATION.

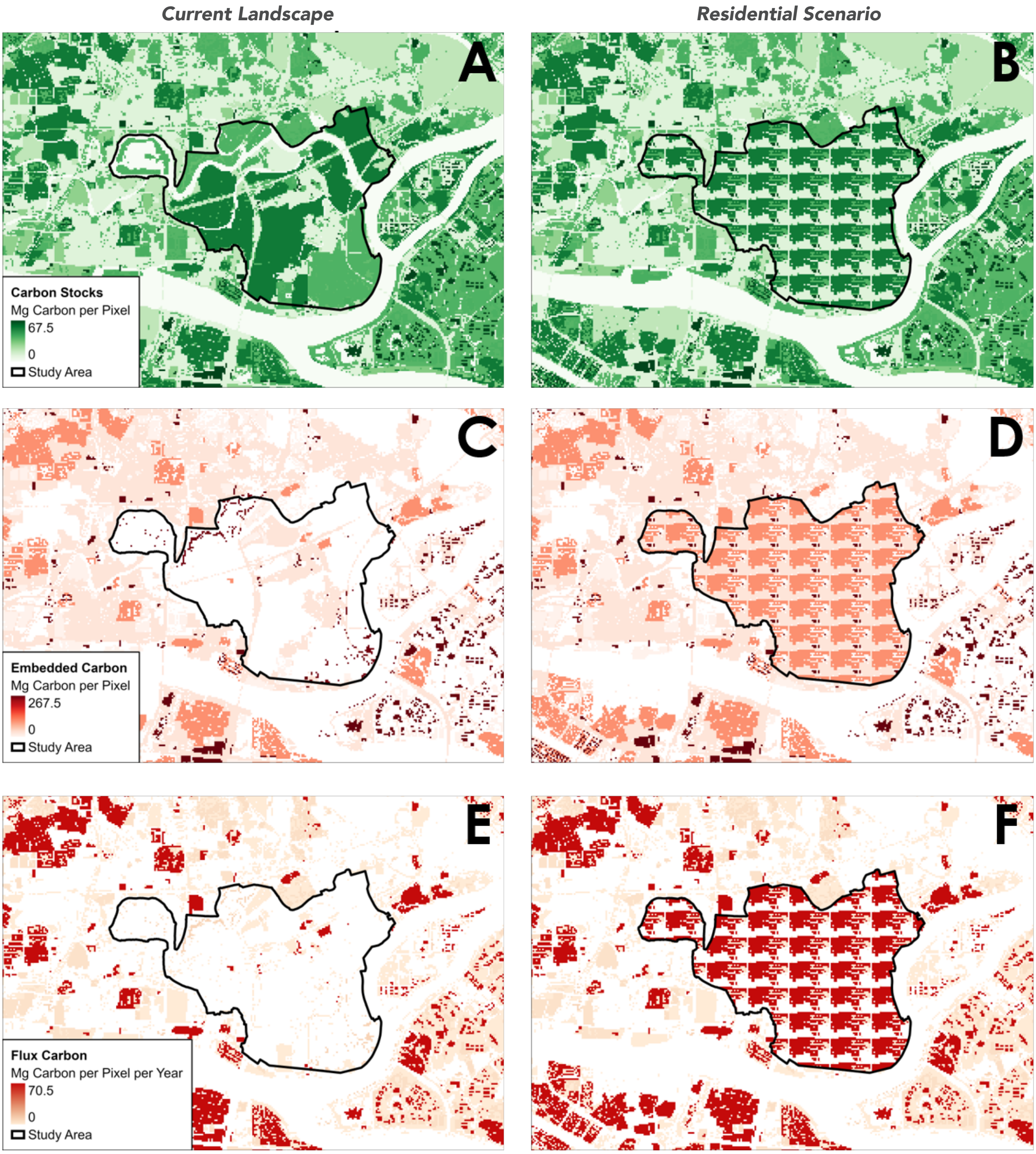
LULC Classification	Aboveground Carbon (Mg/ha)	Belowground Carbon (Mg/ha)	Soil Carbon (Mg/ha)	Dead Carbon (Mg/ha)	Embedded Carbon (Mg/ha)	Flux Carbon (Mg/ha/yr)
Park	111.6	-	26.9	-	1254.8	52.0
Park, water	-	-	-	-	-	-
Park, green	49.0	1.9	97.9	2.6	-	-
Cultivated Land	4.8	-	65.8	-	-	-
Forest	94.4	-	103.8	10.7	-	-
Grassland	10.1	8.0	98.8	-	-	-
Shrubland	47.9	-	68.2	-	-	-
Wetland	33.5	-	716.9	-	-	-
Water Body	-	-	-	-	-	-
Tundra	-	-	-	-	-	-
Artificial Surfaces	-	-	38.6	-	792.2	-
Residential	125.5	2.2	68.1	13.0	941.1	365.8
Commercial	48.1	1.4	58.6	0.5	752.9	25.1
Industrial	94.6	1.4	58.5	0.5	752.9	6.4

Table 3 // CARBON STORED IN VARIOUS POOLS (MG C/HA) AND EMBEDDED IN BUILT INFRASTRUCTURE (MG C/HA), ALONGSIDE EXPECTED ANNUAL EMISSIONS (MG C/HA/YR), BY LULC DESIGNATION.

LULC Classification	Aboveground Carbon (Mg/ha)	Belowground Carbon (Mg/ha)	Soil Carbon (Mg/ha)	Dead Carbon (Mg/ha)	Embedded Carbon (Mg/ha)	Flux Carbon (Mg/ha/yr)
Institutional / Recreational / Cultural	97.6	1.4	54.1	0.5	752.9	31.2
Urban green space	52.3	2.7	90.3	1.3	-	0.4
Buildings	328.0	-	16.5	24.7	2972.1	783.2
Cemetery	52.3	2.7	90.3	1.3	-	0.4
Bare Land	6.8	-	25.5	-	-	-
Extraction	6.8	-	25.5	-	-	-
Pavement	-	-	38.6	-	792.2	-
Permanent snow and ice	-	-	-	-	-	-

Climate change mitigation results: Replacing the wetland with dense residential development would sequester an additional 3.7 kMg (3.2 Mg/ha) of carbon in landscape pools, primarily from carbon stored in wood and other building materials (Fig. 5A,B). This is equivalent to $52,500 USD ($45 per hectare) in sequestration value. However, the residential development scenario generated significant embedded emissions from manufacturing concrete, steel, and other components of the built environment, increasing embedded emissions by 763 kMg (659 Mg/ha) (Fig. 5C,D), at a societal cost of $10.7 million USD ($9,200 per hectare). Annual emissions similarly increased with transition to the residential scenario by 213 kMg CO2-e/yr (184 Mg/ha/yr) (Fig. 5E,F) at a societal cost of $3.0 million USD per year ($2,600 per hectare per year). Using a net present value approach with a discount rate of 5% and a 30-year time frame, we found the residential scenario causes $67.2 million USD in damages from annual emissions. Combined, the residential scenario will cause a net total of 7.4 million metric tons (7,300 kMg) of carbon emissions from landscape carbon storage, embedded emissions, and annualized emissions, accounting for $77.8 million USD in climate-related damages.

Figure 5 // CARBON SEQUESTERED IN LANDSCAPE STORAGE WITH (A) AND WITHOUT (B) THE WETLAND; CARBON ASSOCIATED WITH EMBEDDED EMISSIONS (CO2GENERATED FROM THE MANUFACTURE AND CONSTRUCTION OF BUILT INFRASTRUCTURE) WITH (C) AND WITHOUT (D) THE WETLAND; AND FLUX CARBON (ANNUAL CARBON EMISSIONS FROM ENERGY USE AND LAND MANAGEMENT) WITH (E) AND WITHOUT (F) THE WETLAND.



Urban Cooling

The urban heat island (Deilami et al., 2018; Oke, 1973; Rizwan et al., 2008) arises in cities due to a combination of heat capture and radiation by the built environment. Buildings and pavement capture solar radiation as excess heat, releasing that stored heat slowly and, if arranged in a dense enough urban fabric, raise the city's baseline ambient air temperature. This process can exacerbate extreme heat waves and increase the risk of mortality and morbidity among vulnerable populations, a pattern likely to worsen under human-induced climate change (Santamouris, 2020).

Urban cooling supply*:* We used the InVEST Urban Cooling model to calculate the effect of the residential land use scenario on the local urban heat island (Sharp et al., 2021). In addition to LULC maps, this model requires data for reference evaporation (Trabucco and Zomer, 2019), reference air temperature for each month (Kenji and Willmott, 2018), the maximum urban heat island magnitude (2.07 °C, from https://yceo.users.earthengine.app/view/uhimap) (Chakraborty and Lee, 2019), the air temperature blending distance (600m) (Lonsdorf et al., 2021; Oke, 2006; Schatz and Kucharik, 2014), and the maximum distance from which large contiguous green areas (>2 ha) contribute additional cooling (100m, as per InVEST recommendations). In addition, the model relies on a parameter table linking each LULC category with five primary drivers of the urban heat island: shade, evapotranspiration potential, albedo, green area inclusion, and building intensity (Table 4).

Table 4 // INVEST URBAN COOLING MODEL PARAMETERS USED IN THIS STUDY, BY LULC DESIGNATION.

LULC Classification	Shade (0 to 1)	Kc	Albedo	Green Area	Building Intensity
Park	0	0.10	0.15	0	0.25
Park, water	0	1.00	0.06	0	0
Park, green	0.5	0.97	0.17	1	0
Cultivated Land	0	0.72	0.16	0	0
Forest	1.0	1.00	0.14	1	0
Grassland	0	0.93	0.19	1	0
Shrubland	0	0.97	0.19	1	0
Wetland	0	1.10	0.14	1	0
Water Body	0	1.00	0.06	0	0
Tundra	0	0	0.80	0	0
Artificial Surfaces	0	0.10	0.20	0	0.75
Residential	0	0.10	0.20	0	0.75
Commercial	0	0.10	0.20	0	0.75
Industrial	0	0.10	0.20	0	0.75
Institutional	0	0.10	0.20	0	0.75
Recreational	0	0.10	0.20	0	0.75
Cultural	0	0.10	0.20	0	0.75
Urban green space	0.5	0.88	0.16	1	0
Buildings	0	0.10	0.23	0	1.00
Cemetery	0.2	0.86	0.18	1	0.05
Bare Land	0	0.61	0.23	0	0
Extraction	0	0.61	0.23	0	0
Pavement	0	0.10	0.12	0	0
Permanent snow and ice	0	0	0.80	0	0

Shade: We treated shade as an index of expected tree cover, with forested LULC classes receiving a full value of 1. We assumed cemeteries, urban green space, and the green space within parks to be forested to some extent, and assigned them values of 0.2, 0.5, and 0.5 accordingly. We assumed all other categories to have no tree cover and thus assigned them a value of 0.

Crop Evapotranspiration (Kc): We based our Kc parameterization on work by Hamel et al. (2021), matching similar classes from the parameter tables therein with corresponding classes in our LULC dataset (forest, grassland, shrubland, water, cultivated land, barren land). For the 'building' and 'pavement' LULC categories, we used the recommended value from the InVEST Users Guide (Sharp et al., 2021). For the remaining LULC categories, we used a series of assumptions regarding the composition of land covers within a land use type to create a weighted average parameter value that reflected how much pavement, building, tree, and grass cover comprise a given land use (Table 5).

Table 5 // LAND COVER ASSUMPTIONS USED IN PARAMETERIZING MORE COMPLEX LAND USE CATEGORIES.

LULC Classification	Tree cover (%)	Grass cover (%)	Pavement (%)	Buildings (%)
Park	-	-	75	25
Park, green	50	50	-	-
Artificial Surfaces	-	-	25	75
Residential	-	-	25	75
Commercial	-	-	25	75
Industrial	-	-	25	75
Institutional	-	-	25	75
Recreational	-	-	25	75
Cultural	-	-	25	75
Urban green space	45	45	10	-
Cemetery	20	70	5	5

Albedo: Similar to Kc, we based our initial albedo parameterization on work by Hamel et al. (2021) by matching LULC categories. For the 'building' LULC category we reviewed existing literature and took the average value of a typical roof (Ban-Weiss et al., 2015; Berardi and Graham, 2020; Li et al., 2014; Ma et al., 2017; Masson et al., 2014; Oleson et al., 2010; Razzaghmanesh et al., 2016; Santamouris, 2013; Silva et al., 2010; Susca et al., 2011; Yang et al., 2015); we used the albedo value from Santamouris (2013) for the 'pavement' category. We used the weighted average method described above for Kc parameterization to assign values to the remaining LULC categories.

Green Area: We treated green area as a binary variable, with all primarily vegetated LULC classes (including 'urban green space' and 'cemetery') assigned a value of 1.

Building Intensity: We based this parameter on the assumed percentage of buildings per LULC (Table 5), with the 'buildings' category receiving the full value of 1.

Urban cooling value: We assessed the monetary value of the wetland using a marginal value approach, calculating the projected loss of workplace productivity and increased energy cost of cooling buildings in the surrounding areas. We used the Wet Bulb Global Index to inform changes in workplace productivity (Kjellstrom et al., 2009), using an average relative humidity of 71.1% (Ou et al., 2014). As data on workplace location and intensity of work (e.g., outdoor labor vs indoor office work) were unavailable for the study area, we assumed that commercial and institutional areas were 'light work' and industrial areas were 'heavy work' as per the InVEST guidelines (Sharp et al., 2021).

We translated the increased air temperature from the residential scenario into the increased energy consumption necessary to cool residential and commercial buildings. Documented relationships between air temperature, heating and cooling degree days (a common method of assessing thermal energy needs in the built environment) and building energy use (Roxon et al., 2020) allowed us to convert InVEST-derived maps of air temperature into expected changes in energy load for heating and cooling buildings surrounding the wetland, which we then converted into monetary value using the typical costs of energy per building type in Guangzhou (He et al., 2013; Li, 2020) LI Yehong, HUANG Tao, JIANG Xiangyang, YANG Jiankun(2020). Calculation of Total Amount and Intensity of Building Energy Consumption in Guangzhou(11),116-123.

In addition to monetary value, we also estimate the avoided mortality provided by the wetland. Epidemiological literature reports that relative risk of heat-induced mortality increases above a 'minimum-mortality' threshold temperature, which varies regionally due to the acclimatization of local populations but generally hovers around the 75th percentile of a region's temperature range (Guo et al., 2014). This relationship between relative risk and temperature is non-linear and changes in risk are only presented at certain thresholds (i.e. 90th and 99th temperature percentiles). However, our results are presented as continuous changes in temperature and, lacking an explicitly continuous relationship between temperature and risk, we assumed a linear relationship to convert temperature maps into risk maps.

Urban cooling results: Average air temperatures surrounding the wetland vary between 30.7 and 31.5 °C (Fig. 6A). Should the wetland be redeveloped into extensive residential housing, the surrounding 600m buffer would experience an average 0.25 °C increase in air temperature on a typical day, a figure that increases to more than 1 °C within the wetland area itself (Fig. 6B). This represents the typical summer urban heat island effect—during an extreme heat wave, we can expect the loss of the wetland to further exacerbate temperature rise.

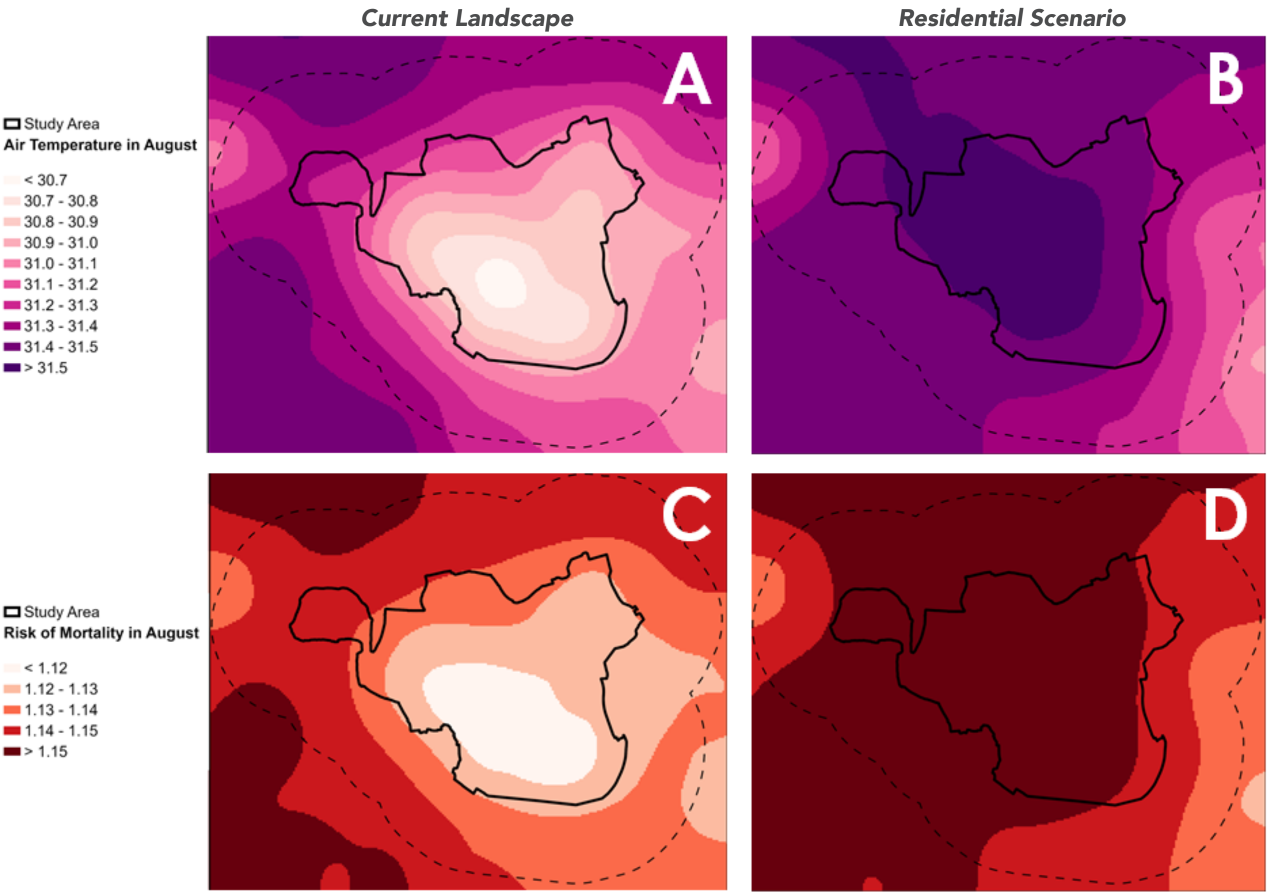
Converting the wetland into a residential development caused increased loss of workplace productivity between May and October. For heavy work environments, the pre-existing summertime decline in productivity extended to May and October (2.5% and 16.1% losses in productivity, respectively). Light work environments see no change in productivity.

The increase in air temperature under the residential scenario increased cooling energy demand during the summer months but decreased demand for heating energy during the winter months. However, as Guangzhou sits in a generally tropical climate, the cooling demand outstrips heating demand over the course of a year: increased cooling demand raised annual energy consumption by buildings within 600m of the wetland by 1.5 million kWh at a cost of $167,600, while reduced heating demand lowered energy consumption by 0.45 million kWh at a savings of $47,900. Using a net present value approach with a discount rate of 5% and a 30-year time frame, this represents $1.9 million USD in additional energy use.

For Guangzhou, the 75th, 90th, and 99th temperature percentiles are 28, 30.1, and 32°C, respectively; the relative risk of mortality at each of those thresholds are 1, 1.08, and 1.18 (Guo et al., 2014). Linear interpolation between these points allows us to convert temperature to relative risk, which we use to compute the difference in relative risk of mortality between our two scenarios (Fig. 6C,D). The surrounding 600m buffer will experience between 1.23% and 1.27% increase in mortality risk each month between June and September, a pattern likely to worsen during extreme heat events.

Figure 6 // MODELED AIR TEMPERATURE IN AUGUST UNDER THE (A) CURRENT LANDSCAPE AND (B) RESIDENTIAL SCENARIO AND THE ASSOCIATED RELATIVE RISKS OF MORTALITY (C, D).

Under the residential scenario, temperatures increased by an average of 0.25 °C within the 600m buffer surrounding the wetland (dotted line), corresponding with a 1.23% increase in mortality risk.



Recreation

We modeled urban green space supply and use as a proxy for recreation. The approach applied was similar to the approach presented in Liu et al. (2020), assessing the availability of greenspace for inhabitants of Guangzhou. Liu et al. (2020) based their assessment on the percentage greenspace within a set distance from people's homes. Greenspace availability per capita was calculated based on the amount of greenspace and population density.

We extended the approach applied by Liu et al. (2020) to calculate both greenspace supply and demand by using the *two-step floating catchment approach* (2SFCA) (Liu et al., n.d.). The 2SFCA approach assesses supply from both the urban green space perspective and the perspective of inhabited pixels. The model enables calculations that visualize which areas have sufficient urban green space and which areas have deficits.

Recreational supply: The 2SFCA method applies two steps to calculate green space supply (Liu et al., n.d.). In the first step, for each green space pixel *j*, the algorithm computes the ratio between green space and population (R_j) by dividing the green space area in pixel *j* (S_j) by population (*pk*) within the search radius. The search radius is defined here as the distance a person is willing to travel from home for recreation. A decay function $f(d_{kj})$ is applied to population values to correct for the decline in visitation over distance from residential areas.

$$R_j = \frac{s_j}{\sum_{k\in\left[d_{kj}\le d_0\right]} p_{k\times f(d_{kj})}}$$ *(Equation 1)*

where Rj is the green space-population ratio of green space pixel j; Sj is the green space area in pixel j (m^2); pk is the population in pixel k; d_{kj} is the Euclidean distance between pixel k and d_0 is the applied travel distance. $f(d_{kj})$ is the decline of service against distance, in this case using a Gaussian function.

In the second step, for each pixel in the study area, the algorithm sums up R_j values from green space pixels within the search radius.

$$Sup_i = \sum_{j\in\{d_{ij}\le d_0\}} R_j * f(d_{ij})$$ *(Equation 2)*

where $Supi$ is the supplied green space per capita (m^2/cap) in pixel i, R_j is the green space-population ratio of a greenspace pixel j, d_{ij} is the Euclidean distance between pixel i and j, and d_0 is the travel distance.

The demand for greenspace is determined by policy targets or local preferences in the model (Liu et al., n.d.). A balance between supply and demand is then calculated for each pixel to determine whether areas have sufficient green space available for recreation.

To calculate recreational supply we used two data sources: an urban green space raster and a population raster. The urban green space raster is just a subset of the LULC map (Fig. 4), selecting all classes deemed urban green space: parks, forest, grassland, urban green space, and cultivated land (mainly orchards). For population, we used the population raster developed by Liu et al. (2020) for the central Guangzhou districts.

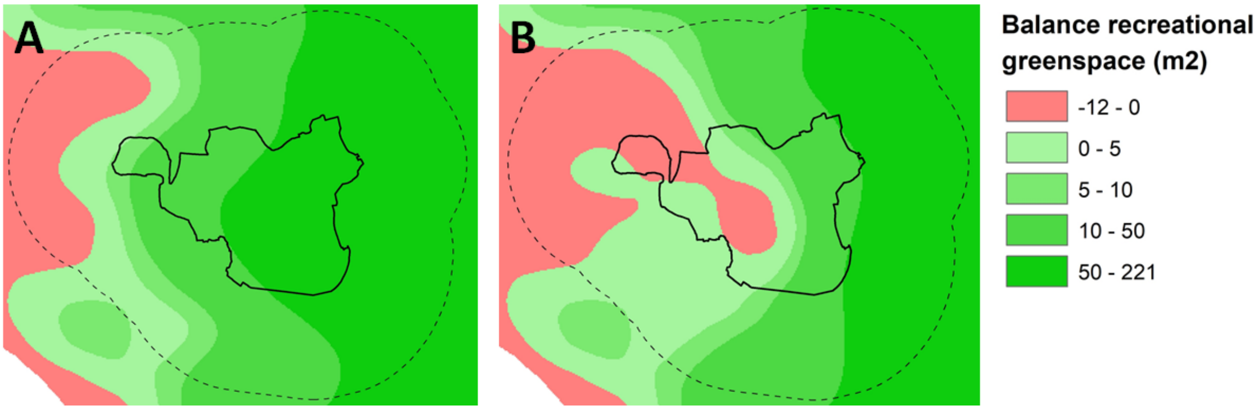
The urban green space model also requires estimates of the demand for urban green spaces and the distance that local residents are likely to travel to access green space. We used estimates for both of these parameters from Liu et al. (2020), who used local survey results to estimate a demand of 16.7 m^2 of urban green space per person in central Guangzhou and a maximum travel distance of 2230m for recreational access. The model was run for both the current landscape and the residential scenario.

Recreational value: A willingness-to-pay study by Jim and Chen (2006) found that Guangzhou residents valued urban green space at 17.14 RMB/month, or approximately 300 RMB per person per year in 2021. To calculate the marginal value of the Haizhu Wetland for recreation of local residents we allocated this value to every resident that would have a green space deficit if the wetland was replaced by a residential area (i.e., the difference between the current situation and the scenario). In addition to a calculation of the current annual value, we applied a net present value (NPV) approach using a 30 year period and a discount rate of 5%.

Recreation results: The mean urban green space balance per inhabitant decreased by 16 m2 in the residential scenario compared to the current situation, although the overall balance remained positive. In the current situation 145,700 residents have an urban green space deficit (23% of the local population). In the residential scenario 240,500 residents have an urban green space deficit (37% of the local population). The areas with the most deficit are located to the west and in the central part of the Haizhu Wetland, in the most densely populated area (Fig. 7). The largest decrease in available urban green space per person occurs within the wetland boundary.

In total, the Haizhu Wetland ensures that 95,000 local inhabitants have sufficient urban green space for recreation. The coupled monetary value is US$ 4.4 million annually, with an NPV of US$ 67.8 million over 30 years.

Figure 7 // URBAN GREEN SPACE SUPPLY-DEMAND BALANCE FOR THE HAIZHU WETLAND AND SURROUNDINGS IN THE CURRENT SITUATION (A) AND THE RESIDENTIAL SCENARIO (B). RED INDICATES AN URBAN GREEN SPACE DEFICIT.



Physical Health

Urban nature and green spaces affect people's physical health in multiple ways. An important pathway is through the provision of space for physical activity, which leads to multiple positive health outcomes (Remme et al., 2021; Warburton, 2006). We adapted an approach from Vivid Economics (2017), where the value of greenspace for physical health is a function of the "catchment area" of greenspace for physical activity (the area from which a local green space draws visitors), the contribution of greenspace to physical activity provision, population, and the costs of physical inactivity.

Physical activity supply: Liu et al. (2020) determined that the catchment area was 2230m from a park boundary for Guangzhou. To incorporate the effect of other parks just outside the Haizhu Wetland catchment on the population in the catchment, we doubled this buffer size in the calculations. We included parks of >2ha in size on the LULC map within this buffer in our calculations determining green space accessibility. Of course, other factors can contribute to people's total physical activity so it is important to scale the potential contribution appropriately. Unfortunately, specific data on this contribution was lacking for Guangzhou (and even for China), so we applied a conservative estimate of the contribution from literature. We assumed that green space could contribute up to 11% of an individual's total physical activity, as found in Seattle, USA (Stewart et al., 2018); this rate is conservatively comparable to studies of physical activity across the globe (Schipperijn et al. 2017). We used the population dataset developed by Liu et al. (2020) to scale the benefit of activity by each person.

We assumed that the contribution of greenspace to total physical activity declines with increasing distance from greenspace throughout the catchment. We assumed the contribution of greenspace to physical activity to be 11% over the first 300m, the shortest commonly used distance in many physical activity and greenspace studies (Labib et al., 2020), followed by a linear decay towards 0% at 2230m from a park, leading to the following relationship:

$$PA\_Contrib_{0\text{-}300} = 11$$

$$PA\_Contrib_{300\text{-}2230} = 11 - 0.005699*D \qquad \text{(Equation 3)}$$

$$PA\_Contrib_{>2230} = 0$$

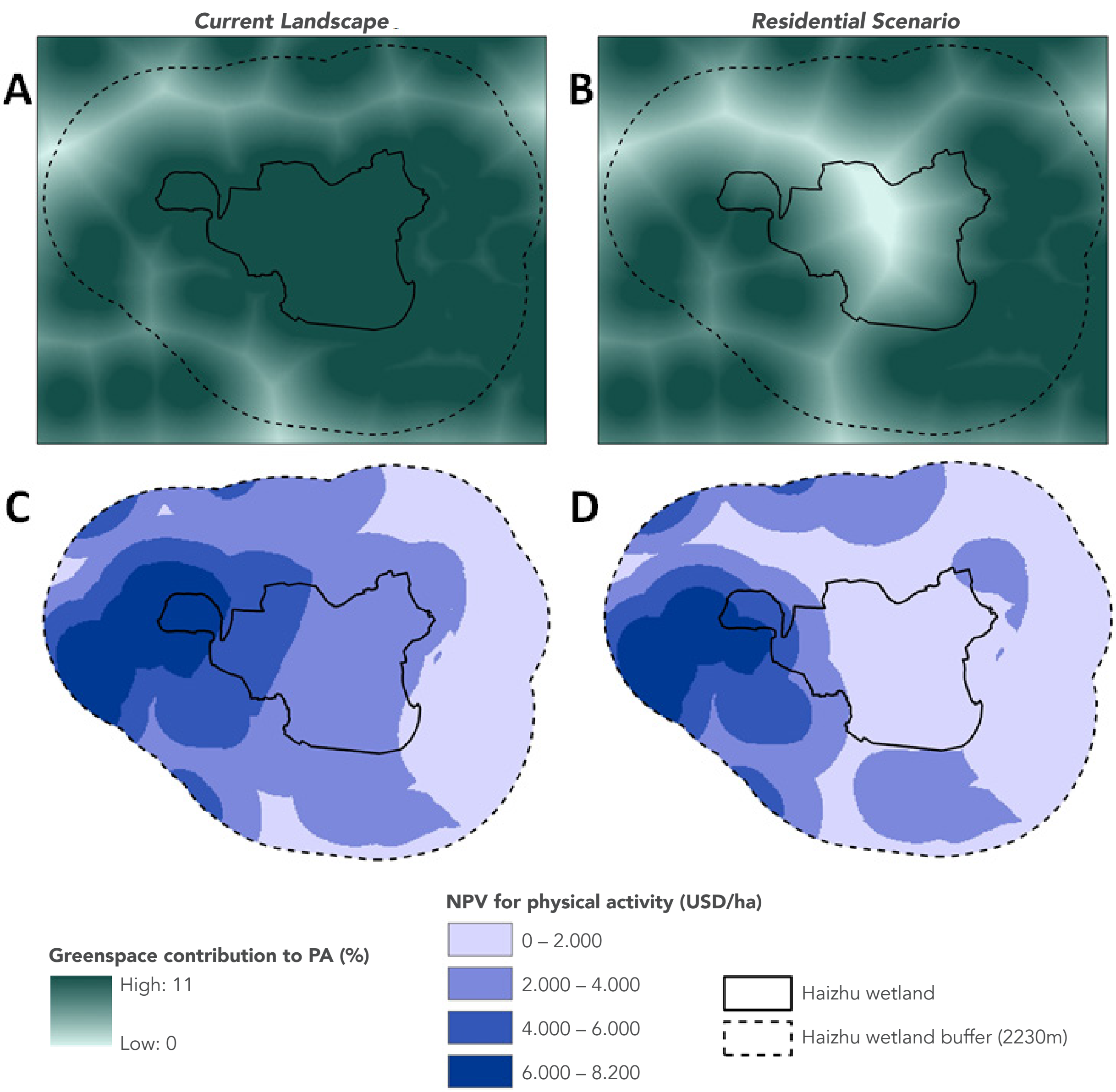
where *PA_Contrib* is the percent contribution of greenspace to physical activity and *D* is the distance from a park.

Physical activity value: To estimate the avoided health care costs due to physical activity in greenspaces, we calculated the costs of physical inactivity, based on the valuation done by (Zhang and Chaaban, 2013) for China: US $44.2 billion in 2007. We extrapolated these costs to 2017 based on health expenditure figures for China (The World Bank, 2021) and corrected those to 2020 US dollars: US $215.6 billion. With a population of 1.386 billion in 2017 this results in physical inactivity costs of US$23.58 per capita. We applied a net present value approach with a 30-year time period and a discount rate of 5% to calculate the difference in value between the current and residential scenarios.

Physical activity results: If the Haizhu Wetland were developed into a residential area the average contribution of greenspace to physical activity would drop from 9.3% to 7.0% in the 2230m buffer zone (Fig. 8). The Haizhu Wetland is of particular importance for the population living in and to the northwest of the wetland where there are few alternative sizable urban green spaces that could sufficiently support physical activity (Fig. 8). The Haizhu Wetland buffer zone is currently valued at $1.3 million/yr for avoided health expenditures related to physical activity with a net present value of $20.7 million over 30 years. This would drop to $1.0 million/yr with a net present value of $16.5 million over 30 years if the wetland were replaced by a residential area, conservatively leading to a net present value loss of $4.2 million over 30 years.

Figure 8 // THE PERCENT CONTRIBUTION OF GREENSPACE TO PHYSICAL ACTIVITY (PA) FOR (A) THE CURRENT LANDSCAPE AND (B) THE RESIDENTIAL SCENARIO, AND THE NET PRESENT VALUE (NPV) OF GREENSPACE FOR PHYSICAL ACTIVITY IN THE HAIZHU WETLAND AND SURROUNDINGS FOR (C) THE CURRENT SITUATION AND (D) THE RESIDENTIAL SCENARIO.

In the 2230m buffer zone, the net present value loss is US $4.2 million under the residential scenario compared to the current situation.



Mental Health

Mental health has been linked to access to green space in urban areas (Bratman et al., 2019; Gascon et al., 2015; Houlden et al., 2018). Here we use a dose-response relationship where mental health outcomes and changes in expenditures on those outcomes at the population level are derived as a function of natural area within a given distance from urban populations.

Mental health supply: We linked the WHO-5 index value, a commonly used survey-based index measuring psychological wellbeing (Topp et al., 2015) to natural areas in Guangzhou based on Liu et al. (2019). Liu et al. (2019) used multiple regression methods to relate WHO-5 scores in Guangzhou to a variety of neighborhood characteristics, including demographic variables and importantly an indicator of green space—the mean Normalized Difference Vegetation Index (NDVI) within a 1km buffer around the neighborhood. The mean observed WHO-5 score (out of 25) was 12.081 in Guangzhou, and the WHO-5 goes up by one point for every 0.136 increase in mean neighborhood NDVI (baseline 0.097), all else being equal, i.e.

$$W = 12.081+((NDVI-0.097)/0.136) \qquad \textit{(Equation 4)}$$

Unfortunately, we did not have the required data to apply this as a functional value transfer approach, where we adjust neighborhood estimates based on variation in other covariates besides NDVI, so we use this unit value approach. While unit value transfer approaches generally perform poorly compared to function transfer (Kaul et al., 2013), in this case the value estimates were derived in the Guangzhou case study area and are more likely to be representative of the population than if they were transferred from elsewhere.

Mental health value: We linked changes in population-level expenditures on mental health in the Haizhu Wetland area in Guangzhou to natural areas using the following equation adapted from Vivid Economics (2017):

$$\text{Change in expenditures}_i = Pop_i * Exp_i * ((-1)*(W_i^R - W_i^C)/W_i^C) \qquad \textit{(Equation 5)}$$

Where:

Pop_i = Population in raster cell ("neighborhood") *i*

Exp^i = Per capita mental health expenditures in neighborhood *i*

W_i^j = Score (index value) on the World Health Organization five question wellbeing survey in neighborhood *i* for scenario *j*, where *j* ∈ *{Current, Residential}*. WHO-5 scores range from 0 to 25, with larger values indicating greater quality of life. The (-1) establishes an inverse relationship between expenditures and WHO-5 score.

The linkage between change in WHO-5 survey score and change in per capita mental health expenditures is assumed to be 1:1. The actual relationship is likely to be more nuanced than this ratio suggests (Buckley et al., 2019), though there is insufficient data to parameterize it in Guangzhou.

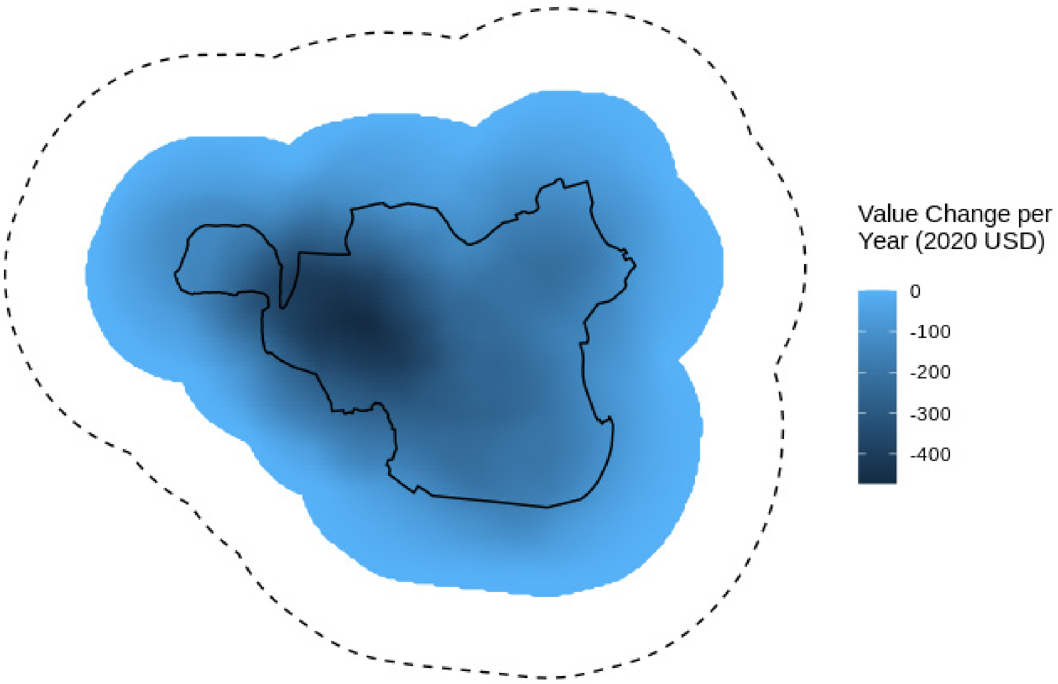
We treated per-capita neighborhood expenditures on mental health as constant across neighborhoods. We derived this value from Xu et al (2016), who estimated an annual burden in China (total social expense) of $88.1 billion (2013) for those that elect for treatment, and $484.1 billion if all who suffered mental health issues were treated. This latter figure is more appropriate as a social welfare metric. The population of China was 1.357 billion in 2013, so this comes out to $356.74 per person per year, or $389.54 in U.S. 2020 dollars.

We calculated the expected change in expenditures for a given neighborhood between scenarios *Current* and *Residential* by substituting equation (5) into equation (4) for WHO-5 values calculated at {*Current, Residential*}. Total change in expenditures is equal to the sum of the change in neighborhood expenditures, for neighborhoods within 1km of Haizhu Wetland. Neighborhoods for this analysis are defined as population cells (30m^2) from the population dataset developed by Liu et al. (2020).

We reflected the difference between the *Current* and *Residential* scenarios through a change in NDVI within the Haizhu Wetland boundaries, holding all else equal. We extracted the mean NDVI within a 1km buffer for all neighborhoods from the baseline NDVI map, derived from Copernicus Sentinel 2/Google Earth Engine at 10m resolution. For the *Current* scenario, we calculated a neighborhood's mean NDVI and then used a NDVI "wallpapering" approach consistent with the land cover wallpapering (Fig. 4) to calculate the NDVI for the *Residential* scenario. The analysis does not account for the wellbeing of any new residents that accompany a developed Haizhu Wetland.

Mental health results: Residential development leads to decreases in the value of the Haizhu Wetland for mental health (Fig. 9). Aggregate population in affected neighborhoods inside or within 1km of the Haizhu Wetland equals 310,725 people. Mean NDVI across neighborhoods in the *Current* scenario is 0.22; in the *Residential* scenario it is 0.14. This loss in natural areas leads to an annual increase in mental health expenditures of $4.56 million, with a net present value of $70.1 million over 30 years at a 5% discount rate.

Figure 9 // ANNUAL CHANGE IN VALUE TO NEIGHBORHOODS FROM SCENARIO CHANGE, BASED ON MENTAL HEALTH TREATMENT EXPENDITURES.



Overall results and discussion

W*e estimate that the marginal value provided to Guangzhou from the Haizhu Wetland from five ecosystem services is at least $221.8 million USD over the next 30 years* (Table 6), in addition to reduced mortality risk and increased workplace productivity in the surrounding landscape. This is by no means an assessment of total economic value—there are many additional ecosystem services and market benefits that remain unarticulated in this analysis. Rather, this is a conservative estimate with some key sources of uncertainty as to how much higher the total value could be. First, past work has shown that mental health, recreation, and physical health are all interrelated and thus there may be some overlap or double counting between their respective valuations, potentially reducing the wetland's composite value. For instance, additional work is needed to understand how much of a person's willingness-to-pay for recreation is based on avoided healthcare expenditures from increased physical and mental health. Second, there are additional ecosystem services provided by the wetland that were beyond the scope of this analysis. For example, wetlands are generally known to provide water purification services by capturing runoff and to mitigate flood risk by storing water (Maltby and Acreman, 2011; Keeler et al. 2019). While their nutrient purification impact is more limited in urban areas with developed wastewater treatment networks (Griffin et al. 2020), the value of flood prevention is likely quite high due to the proximity of dense, high-value residential development (Brody et al. 2017). Wetlands also support biodiversity by providing habitat for local flora and fauna, which provide non-market value.

Critically, our analysis does not analyze the economic opportunity cost of the wetland. While the real estate value of the wetland is likely more than the $221.8 million USD ecosystem service marginal value, the loss of the wetland would likely reduce the value of adjacent real estate (Du and Huang 2018). Articulating these conflicting values would require an intensive hedonic analysis and highlights the need for holistic assessments of land value: the private price of land does not necessarily endogenize that land's effect on its surroundings (either in ecological or in economic terms).

Table 6 // THE MARGINAL VALUE OF FIVE ECOSYSTEM SERVICES GENERATED BY THE HAIZHU WETLAND WHEN COMPARED TO A RESIDENTIAL DEVELOPMENT SCENARIO.

All monetary metrics reflect their net present value in $USD millions over the next 30 years, using a 5% discount rate. Note that the value metrics and ecosystem services presented are not exhaustive, and thus this is an underestimate of the marginal value of the wetland.

Ecosystem Service	Value Metric(s)	Current Landscape	Residential Scenario	Marginal value of the Haizhu Wetland	
				Subtotal	Total
Urban cooling	Private cost of cooling	$90.9	$93.5	$2.6	$1.9
	Private cost of heating	$9.3	$8.5	-$0.7	
	Productivity			2.5% to 16.1% increased workplace productivity within 600m (May and October)	
	Mortality risk			1.23% to 1.27% decreased risk of monthly mortality within 600m (June through September)	
Climate change mitigation	Sequestered Carbon (SCC)	$2.16	$2.21	-$0.05	$77.8
	Embedded Emissions (SCC)	$2.9	$13.6	$10.7	
	Annual Emissions (SCC)	$1.9	$69.0	$67.2	
Recreation	Willingness-to-pay	$365.0	$288.2	$67.8	
Physical health	Health Expenditures	$212.5	$216.7	$4.2	
Mental health	Health Expenditures	$1,634	$1,704	$70.1	

Limitations

It is critical to acknowledge the limitations and potential sources of uncertainty made in our assessment. These limitations arise from each step in the ecosystem service cascade and potentially for each service modeled. Here, we lay out the potential limitations in estimating supply, valuing the services, and challenges related to fine-scale heterogeneity.

Estimating supply: The supply assessments used in this study are done using process-based models rather than empirically-driven statistical models. Empirical statistical models built from city-specific data may provide more robust results if a city has high quality data, but are not transferable from region to region. Process-based models are a useful tool for generating ecosystem service estimates when data are sparse, but we acknowledge that empirical models can provide better predictions—although they often require significant quantities of data. For example, the recreation and physical activity models are based on a supply-demand calculation, and are not based on empirical data of visitor numbers to parks in Guangzhou. Future assessments could use observed data to improve confidence in the models. We also wish to acknowledge that including explicit geospatial data on tree canopy cover in future studies could improve these models; data on this are now available globally (Potapov et al. 2021) at 30m resolution and would improve estimates of green space in urban areas.

Valuation: To estimate the value provided by each service, the research team had to identify the best available source of data to use in calculations of value, with data desirability increasing with decreasing distance to Guangzhou in space and time. In a perfect world, a valuation study would have been done recently in Guangzhou for each of the examined services; those values could then be used to parametrize each model. This was obviously not the case. The carbon sequestration model relies on global literature for estimates of carbon storage and emissions. For recreation, Guangzhou is a rapidly urbanizing city, so the willingness-to-pay results from Jim and Chen (2006) may not reflect the current situation. For our assessment of physical activity, the monetary valuation approach was based on national scale health data, and local deviations from national averages could not be incorporated, and given the highly urban context, a deviation from the national average is likely.

Heterogeneity in supply and value: While this case study articulates the overall ecosystem service supply and value provided by the Haizhu Wetland, it does not explicitly identify how the value of those services may vary depending on the location or socio-economic status of the beneficiary. Socio-economic status can intersect with ecosystem services to ameliorate—or exacerbate—existing vulnerabilities (Keeler et al., 2019). For instance, the urban cooling benefit of the Haizhu Wetland will be of greatest benefit to households lacking air conditioning or individuals at greater risk of complications due to excessive heat exposure. Also, in our recreation assessment, all urban green space was assumed to be relevant for recreation, actual accessibility and suitability of these sites for recreation was not considered in this model.

Advances and applicability to additional cities

Beyond the specific results of this case study, we find the methodological advances set forth here to be compelling for urban ecosystem research more broadly. Harmonizing typical landscape carbon stock modeling with a more lifecycle assessment approach that acknowledges embedded and annual emissions helps better identify tradeoffs between built infrastructure and green space in terms of climate change. Linking changes in air temperature to myriad forms of value (energy costs from additional cooling, lost workplace productivity, increased mortality risk) provides decision-makers a more nuanced understanding of the externalities of the built environment. Furthermore, this work improves upon the current InVEST Urban Cooling model by performing the analysis at an annual scale—the urban heat island may negatively impact wellbeing during summer months while reducing heating costs during winter months. We also present novel approaches to modeling recreation, physical activity, and mental health, which are critically important to the lives of city residents.

In addition to these methodological improvements, we made further advances in applying these models that will make valuing ecosystem services in additional cities—in China and elsewhere—easier in the future. While we evaluated the value of one wetland in Guangzhou in this case, the process we used to quantify its value can be applied to any natural area in other cities for three reasons: (1) we developed a novel land use data set using globally available data, a process which can be replicated in additional cities; (2) we used the wallpaper approach to develop scenarios, an approach that is also generalizable to any other city; and (3) we parameterized ecosystem service models and valuation techniques from models that are either in the InVEST software (or soon will be) that can be applied to any city. Together, this means that existing infrastructure and workflows enable the evaluation of urban planning decisions in China and across the world.

As the case of the Haizhu Wetland illustrates, analyzing the supply and consequent value of urban ecosystem services allows decision-makers to more fully understand the externalities of development decisions. As cities continue to grow into megacities and beyond, a more complete understanding of urban ecosystem services and their connections to the wellbeing of urban residents can lead to decisions with better outcomes for both people and nature.

Photo: Weiming Lin | Dreamstime.com

References

Arıoğlu Akan, M.Ö., Dhavale, D.G., Sarkis, J., 2017. Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain. J. Clean. Prod. 167, 1195–1207. https://doi.org/10.1016/j.jclepro.2017.07.225

Bae, J., Ryu, Y., 2015. Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. Landsc. Urban Plan. 136, 57–67. https://doi.org/10.1016/j.landurbplan.2014.11.015

Ban-Weiss, G.A., Woods, J., Millstein, D., Levinson, R., 2015. Using remote sensing to quantify albedo of roofs in seven California cities, Part 2: Results and application to climate modeling. Sol. Energy 115, 791–805. https://doi.org/10.1016/j.solener.2014.10.041

Berardi, U., Graham, J., 2020. Investigation of the impacts of microclimate on PV energy efficiency and outdoor thermal comfort. Sustain. Cities Soc. 62, 102402. https://doi.org/10.1016/j.scs.2020.102402

Bondarenko, M., Kerr, D., Sorichetta, A., Tatem, A.J., 2020. Census/projection-disaggregated gridded population datasets, adjusted to match the corresponding UNPD 2020 estimates, for 183 countries in 2020 using Built-Settlement Growth Model (BSGM) outputs. WorldPop.

Boyle, C.A., Lavkulich, L., 1997. Carbon Pool Dynamics in the Lower Fraser Basin from 1827 to 1990. Environ. Manage. 21, 443–455. https://doi.org/10.1007/s002679900041

Bratman, G.N., Anderson, C.B., Berman, M.G., Cochran, B., de Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J.J., Hartig, T., Kahn, P.H., Kuo, M., Lawler, J.J., Levin, P.S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J., Scarlett, L., Smith, J.R., van den Bosch, M., Wheeler, B.W., White, M.P., Zheng, H., Daily, G.C., 2019. Nature and mental health: An ecosystem service perspective. Sci. Adv. 5, eaax0903. https://doi.org/10.1126/sciadv.aax0903

Brody, S.D., Highfield, W.E., Blessing, R., Makino, T. and Shepard, C.C., 2017. Evaluating the effects of open space configurations in reducing flood damage along the Gulf of Mexico coast. Landscape and Urban Planning, 167, pp.225-231.

Buckley, R., Brough, P., Hague, L., Chauvenet, A., Fleming, C., Roche, E., Sofija, E., Harris, N., 2019. Economic value of protected areas via visitor mental health. Nat. Commun. 10, 5005. https://doi.org/10.1038/s41467-019-12631-6

Chakraborty, T., Lee, X., 2019. A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability. Int. J. Appl. Earth Obs. Geoinformation 74, 269–280. https://doi.org/10.1016/j.jag.2018.09.015

Chaparro, L., Terradas, J., 2010. Ecosystem services of urban forest. https://doi.org/10.13140/RG.2.1.4013.9604

Chen, J., Cao, X., Peng, S., Ren, H., 2017. Analysis and Applications of GlobeLand30: A Review. ISPRS Int. J. Geo-Inf. 6, 230. https://doi.org/10.3390/ijgi6080230

Churkina, G., Brown, D., KEOLEIAN, G., 2010. Carbon stored in human settlements: The conterminous United States. Glob. Change Biol. 16, 135–143. https://doi.org/10.1111/j.1365-2486.2009.02002.x

Cortinovis, C., Geneletti, D., 2020. A performance-based planning approach integrating supply and demand of urban ecosystem services. Landsc. Urban Plan. 201, 103842. https://doi.org/10.1016/j.landurbplan.2020.103842

Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R., Gaston, K.J., 2011. Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale: Urban above-ground carbon storage. J. Appl. Ecol. 48, 1125–1134. https://doi.org/10.1111/j.1365-2664.2011.02021.x

Deilami, K., Kamruzzaman, Md., Liu, Y., 2018. Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. Int. J. Appl. Earth Obs. Geoinformation 67, 30–42. https://doi.org/10.1016/j.jag.2017.12.009

Depietri, Y., McPhearson, T., 2017. Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction, in: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Springer International Publishing, Cham, pp. 91–109. https://doi.org/10.1007/978-3-319-56091-5_6

Du, X. and Huang, Z., 2018. Spatial and temporal effects of urban wetlands on housing prices: Evidence from Hangzhou, China. Land use policy, 73, pp.290-298. https://doi.org/10.1016/j.landusepol.2018.02.011

Edmondson, J.L., Davies, Z.G., McHugh, N., Gaston, K.J., Leake, J.R., 2012. Organic carbon hidden in urban ecosystems. Sci. Rep. 2, 963. https://doi.org/10.1038/srep00963

Escobedo, F., Varela, S., Zhao, M., Wagner, J.E., Zipperer, W., 2010. Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. Environ. Sci. Policy 13, 362–372. https://doi.org/10.1016/j.envsci.2010.03.009

Fissore, C., Baker, L.A., Hobbie, S.E., King, J.Y., McFadden, J.P., Nelson, K.C., Jakobsdottir, I., 2011. Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region. Ecol. Appl. 21, 619–639. https://doi.org/10.1890/10-0386.1

Gascon, M., Triguero-Mas, M., Martínez, D., Dadvand, P., Forns, J., Plasència, A., Nieuwenhuijsen, M., 2015. Mental Health Benefits of Long-Term Exposure to Residential Green and Blue Spaces: A Systematic Review. Int. J. Environ. Res. Public. Health 12, 4354–4379. https://doi.org/10.3390/ijerph120404354

Goldstein, B., Gounaridis, D., Newell, J.P., 2020. The carbon footprint of household energy use in the United States. Proc. Natl. Acad. Sci. 117, 19122–19130. https://doi.org/10.1073/pnas.1922205117

Golubiewski, N.E., 2006. Urbanization Increases Grassland Carbon Pools: Effects Of Landscaping In Colorado's Front Range. Ecol. Appl. 16, 555–571. https://doi.org/10.1890/1051-0761(2006)016[0555:UIGCPE]2.0.CO;2

Griffin, R., Vogl, A., Wolny, S., Covino, S., Monroy, E., Ricci, H., Sharp, R., Schmidt, C. and Uchida, E., 2020. Including additional pollutants into an integrated assessment model for estimating nonmarket benefits from water quality. Land Economics, 96(4), pp.457-477.

Guo, Y., Gasparrini, A., Armstrong, B., Li, S., Tawatsupa, B., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Leone, M., Pan, X., Tong, S., Tian, L., Kim, H., Hashizume, M., Honda, Y., Guo, Y.-L.L., Wu, C.-F., Punnasiri, K., Yi, S.-M., Michelozzi, P., Saldiva, P.H.N., Williams, G., 2014. Global Variation in the Effects of Ambient Temperature on Mortality: A Systematic Evaluation. Epidemiology 25, 781–789. https://doi.org/10.1097/EDE.0000000000000165

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez-Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Rall, E.L., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., Wurster, D., Elmqvist, T., 2014. A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. AMBIO 43, 413–433. https://doi.org/10.1007/s13280-014-0504-0

Haines-Young, R., Potschin-Young, M., 2010. The links between biodiversity, ecosystem service and human well-being, in: Ecosystem Ecology: A New Synthesis. pp. 110–139. https://doi.org/10.1017/CBO9780511750458.007

Hamel, P., Guerry, A.D., Polasky, S., Han, B., Douglass, J.A., Hamann, M., Janke, B., Kuiper, Jan J, Levrel, H, Liu, H, Lonsdorf, E, McDonald, Robert I, Nootenboom, C, Ouyang, Z, Remme, RP, Sharp, R, Tardieu, L, Viguie, V, Xu, D, Zheng, H, Daily, Gretchen C, 2021. Mapping the benefits of nature in cities with the InVEST software. Urban Sustain. https://doi.org/10.1038/s42949-021-00027-9

He, Ding, Xu, 2013. The Energy Consumption Status and Analysis of Energy-saving Measures on Residential Building in Guangzhou Urban Area.

Houlden, V., Weich, S., Porto de Albuquerque, J., Jarvis, S., Rees, K., 2018. The relationship between greenspace and the mental wellbeing of adults: A systematic review. PLOS ONE 13, e0203000. https://doi.org/10.1371/journal.pone.0203000

Hutyra, L.R., Yoon, B., Alberti, M., 2011. Terrestrial carbon stocks across a gradient of urbanization: a study of the Seattle, WA region: URBAN TERRESTRIAL CARBON STOCKS. Glob. Change Biol. 17, 783–797. https://doi.org/10.1111/j.1365-2486.2010.02238.x

Interagency Working Group on Social Cost of Greenhouse Gasses, 2021. Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990 (Technical Support Document). United States Government.

Jim, C.Y., Chen, W.Y., 2006. Recreation–amenity use and contingent valuation of urban greenspaces in Guangzhou, China. Landsc. Urban Plan. 75, 81–96. https://doi.org/10.1016/j.landurbplan.2004.08.008

Jo, H., 2002. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. J. Environ. Manage. 64, 115–126. https://doi.org/10.1006/jema.2001.0491

Kaul, S., Boyle, K.J., Kuminoff, N.V., Parmeter, C.F., Pope, J.C., 2013. What can we learn from benefit transfer errors? Evidence from 20 years of research on convergent validity. J. Environ. Econ. Manag. 66, 90–104. https://doi.org/10.1016/j.jeem.2013.03.001

Kaye, J.P., McCulley, R.L., Burke, I.C., 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Glob. Change Biol. 11, 575–587. https://doi.org/10.1111/j.1365-2486.2005.00921.x

Keeler, B.L., Hamel, Perrine, McPhearson, Timon, Hamann, Maike H, Donahue, Marie L, Meza Prado, Kelly A, Arkema, Katie K, Bratman, Gregory N, Brauman, Kate A, Finlay, Jacques C, Guerry, Anne D, Hobbie, Sarah E, Johnson, Justin A, MacDonald, Graham K, McDonald, Robert I, Neverisky, Nick, Wood, Spencer A, 2019. Social-ecological and technological factors moderate the value of urban nature. Nat. Sustain. 2, 29–38. https://doi.org/10.1038/s41893-018-0202-1

Kellett, R., Christen, A., Coops, N.C., van der Laan, M., Crawford, B., Tooke, T.R., Olchovski, I., 2013. A systems approach to carbon cycling and emissions modeling at an urban neighborhood scale. Landsc. Urban Plan. 110, 48–58. https://doi.org/10.1016/j.landurbplan.2012.10.002

Kenji, M., Willmott, C.J., 2018. Terrestrial Air Temperature: 1900-2017 Gridded Monthly Time Series.

Kjellstrom, T., Holmer, I., Lemke, B., 2009. Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. Glob. Health Action 2, 2047. https://doi.org/10.3402/gha.v2i0.2047

Kuittinen, M., Moinel, C., Adalgeirsdottir, K., 2016. Carbon sequestration through urban ecosystem services: A case study from Finland. Sci. Total Environ. 563–564, 623–632. https://doi.org/10.1016/j.scitotenv.2016.03.168

Labib, S.M., Lindley, S., Huck, J.J., 2020. Spatial dimensions of the influence of urban green-blue spaces on human health: A systematic review. Environ. Res. 180, 108869. https://doi.org/10.1016/j.envres.2019.108869

Lafortezza, R., Chen, J., van den Bosch, C.K., Randrup, T.B., 2018. Nature-based solutions for resilient landscapes and cities. Environ. Res. 165, 431–441. https://doi.org/10.1016/j.envres.2017.11.038

Li, 2020. Calculation of Total Amount and Intensity of Building Energy Consumption in Guangzhou Guangzhou Electricity Price.

Li, D., Bou-Zeid, E., Oppenheimer, M., 2014. The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ. Res. Lett. 9, 055002. https://doi.org/10.1088/1748-9326/9/5/055002

Liu, H., Hamel, P., Tardieu, L., Remme, R., Han, B., Ren, H., n.d. A geospatial model of nature-based recreation for urban planning: Case study of Paris, France. Land Use Policy.

Liu, H., Remme, R.P., Hamel, P., Nong, H., Ren, H., 2020. Supply and demand assessment of urban recreation service and its implication for greenspace planning-A case study on Guangzhou. Landsc. Urban Plan. 203, 103898. https://doi.org/10.1016/j.landurbplan.2020.103898

Liu, Ye, Wang, R., Grekousis, G., Liu, Yuqi, Yuan, Y., Li, Z., 2019. Neighbourhood greenness and mental wellbeing in Guangzhou, China: What are the pathways? Landsc. Urban Plan. 190, 103602. https://doi.org/10.1016/j.landurbplan.2019.103602

Lonsdorf, E.V., Nootenboom, C., Janke, B., Horgan, B.P., 2021. Assessing urban ecosystem services provided by green infrastructure: Golf courses in the Minneapolis-St. Paul metro area. Landsc. Urban Plan. 208, 104022. https://doi.org/10.1016/j.landurbplan.2020.104022

Luo, S.H., Mao, Q.Z., Ma, K.M., Wu, J., 2014. Spatial distribution of soil carbon and nitrogen in urban greenspace of Beijing. Shengtai Xuebao Acta Ecol. Sin. 34, 6011–6019. https://doi.org/10.5846/stxb201301220132

Ma, S., Goldstein, M., Pitman, A.J., Haghdadi, N., MacGill, I., 2017. Pricing the urban cooling benefits of solar panel deployment in Sydney, Australia. Sci. Rep. 7, 43938. https://doi.org/10.1038/srep43938

Maltby, E., Acreman, M.C., 2011. Ecosystem services of wetlands: pathfinder for a new paradigm. Hydrol. Sci. J. 56, 1341–1359. https://doi.org/10.1080/02626667.2011.631014

Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X., Lemonsu, A., 2014. Solar panels reduce both global warming and urban heat island. Front. Environ. Sci. 2. https://doi.org/10.3389/fenvs.2014.00014

McPherson, E.G., Xiao, Q., Aguaron, E., 2013. A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests. Landsc. Urban Plan. 120, 70–84. https://doi.org/10.1016/j.landurbplan.2013.08.005

Nero, B.F., Callo-Concha, D., Anning, A., Denich, M., 2017. Urban Green Spaces Enhance Climate Change Mitigation in Cities of the Global South: The Case of Kumasi, Ghana. Procedia Eng. 198, 69–83. https://doi.org/10.1016/j.proeng.2017.07.074

Nordhaus, W.D., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. 114, 1518–1523. https://doi.org/10.1073/pnas.1609244114

Norman, J., MacLean, H.L., Kennedy, C.A., 2006. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. J. Urban Plan. Dev. 132, 10–21. https://doi.org/10.1061/(ASCE)0733-9488(2006)132:1(10)

Nowak, D.J., 1993. Atmospheric Carbon Reduction by Urban Trees. J. Environ. Manage. 37, 207–217. https://doi.org/10.1006/jema.1993.1017

Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA. Environ. Pollut. 116, 381–389. https://doi.org/10.1016/S0269-7491(01)00214-7

Nowak, D.J., Greenfield, E.J., Hoehn, R.E., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. Environ. Pollut. 178, 229–236. https://doi.org/10.1016/j.envpol.2013.03.019

Oke, T.R., 2006. Initial guidance to obtain representative meteorological observations at urban sites (No. 81), WMO Instruments and Observing Methods. WMO/TD 1250.

Oke, T.R., 1973. City size and the urban heat island. Atmospheric Environ. 1967 7, 769–779. https://doi.org/10.1016/0004-6981(73)90140-6

Oleson, K.W., Bonan, G.B., Feddema, J., 2010. Effects of white roofs on urban temperature in a global climate model: EFFECTS OF WHITE ROOFS ON TEMPERATURE. Geophys. Res. Lett. 37, n/a-n/a. https://doi.org/10.1029/2009GL042194

OpenStreetMap contributors, 2021. Planet dump retrieved from https://planet.osm.org

Ou, C.Q., Yang, J., Ou, Q.Q., Liu, H.Z., Lin, G.Z., Chen, P.Y., Qian, J., Guo, Y.M., 2014. The Impact of Relative Humidity and Atmospheric Pressure on Mortality in Guangzhou, China. Biomed. Environ. Sci. 27, 917–925. https://doi.org/10.3967/bes2014.132

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon Storage by Urban Soils in the United States. J. Environ. Qual. 35, 1566–1575. https://doi.org/10.2134/jeq2005.0215

Potapov, P., Li, X., Hernandez-Serna, A., Tyukavina, A., Hansen, M.C., Kommareddy, A., Pickens, A., Turubanova, S., Tang, H., Silva, C.E. and Armston, J., 2021. Mapping global forest canopy height through integration of GEDI and Landsat data. Remote Sensing of Environment, 253, p.112165.

Raciti, S.M., Hutyra, L.R., Finzi, A.C., 2012a. Depleted soil carbon and nitrogen pools beneath impervious surfaces. Environ. Pollut. 164, 248–251. https://doi.org/10.1016/j.envpol.2012.01.046

Raciti, S.M., Hutyra, L.R., Rao, P., Finzi, A.C., 2012b. Inconsistent definitions of "urban" result in different conclusions about the size of urban carbon and nitrogen stocks. Ecol. Appl. 22, 1015–1035. https://doi.org/10.1890/11-1250.1

Razzaghmanesh, M., Beecham, S., Salemi, T., 2016. The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. Urban For. Urban Green. 15, 89–102. https://doi.org/10.1016/j.ufug.2015.11.013

Remme, R.P., Frumkin, H., Guerry, A.D., King, A.C., Mandle, L., Sarabu, C., Bratman, G.N., Giles-Corti, B., Hamel, P., Han, B., Hicks, J.L., James, P., Lawler, J.J., Lindahl, T., Liu, H., Lu, Y., Oosterbroek, B., Paudel, B., Sallis, J.F., Schipperijn, J., Sosič, R., de Vries, S., Wheeler, B.W., Wood, S.A., Wu, T., Daily, G.C., 2021. An ecosystem service perspective on urban nature, physical activity, and health. PNAS. https://doi.org/10.1073/pnas.2018472118

Ricketts, T.H. and Lonsdorf, E., 2013. Mapping the margin: comparing marginal values of tropical forest remnants for pollination services. Ecological Applications, 23(5), pp.1113-1123. https://doi.org/10.1890/12-1600.1

Rizwan, A.M., Dennis, L.Y.C., Liu, C., 2008. A review on the generation, determination and mitigation of Urban Heat Island. J. Environ. Sci. 20, 120–128. https://doi.org/10.1016/S1001-0742(08)60019-4

Roxon, J., Ulm, F.-J., Pellenq, R.J.-M., 2020. Urban heat island impact on state residential energy cost and CO2 emissions in the United States. Urban Clim. 31, 100546. https://doi.org/10.1016/j.uclim.2019.100546

Santamouris, M., 2020. Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. Energy Build. 207, 109482. https://doi.org/10.1016/j.enbuild.2019.109482

Santamouris, M., 2013. Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. Renew. Sustain. Energy Rev. 26, 224–240. https://doi.org/10.1016/j.rser.2013.05.047

Schipperijn, J., Cerin, E., Adams, M.A., Reis, R., Smith, G., Cain, K., Christiansen, L.B., Van Dyck, D., Gidlow, C., Frank, L.D. and Mitáš, J., 2017. Access to parks and physical activity: An eight country comparison. Urban forestry & urban greening, 27, pp.253-263. https://doi.org/10.1016/j.ufug.2017.08.010

Schatz, J., Kucharik, C.J., 2014. Seasonality of the Urban Heat Island Effect in Madison, Wisconsin. J. Appl. Meteorol. Climatol. 53, 2371–2386. https://doi.org/10.1175/JAMC-D-14-0107.1

Sharp, R., Douglass, J., Wolny, S., Arkema, K.K., Bernhardt, J.R., Bierbower, W., Chaumont, N., Denu, D., Fisher, D., Glowinski, K., Griffin, R., Guannel, G., Guerry, A.D., Johnson, J., Hamel, P., Kennedy, C., Kim, C.K., Lacayo, M., Lonsdorf, E., Mandle, L., Rogers, L., Silver, J.M., Toft, J., Verutes, G., Vogl, A.L., Wood, S.A., Wyatt, K., 2021. InVEST 3.9.0 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Silva, H.R., Phelan, P.E., Golden, J.S., 2010. Modeling effects of urban heat island mitigation strategies on heat-related morbidity: a case study for Phoenix, Arizona, USA. Int. J. Biometeorol. 54, 13–22. https://doi.org/10.1007/s00484-009-0247-y

Stewart, O.T., Moudon, A.V., Littman, A.J., Seto, E., Saelens, B.E., 2018. Why neighborhood park proximity is not associated with total physical activity. Health Place 52, 163–169. https://doi.org/10.1016/j.healthplace.2018.05.011

Strohbach, M.W., Haase, D., 2012. Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. Landsc. Urban Plan. 104, 95–104. https://doi.org/10.1016/j.landurbplan.2011.10.001

Susca, T., Gaffin, S.R., Dell'Osso, G.R., 2011. Positive effects of vegetation: Urban heat island and green roofs. Environ. Pollut. 159, 2119–2126. https://doi.org/10.1016/j.envpol.2011.03.007

Tallis, H., Mooney, H., Andelman, S., Balvanera, P., Cramer, W., Karp, D., Polasky, S., Reyers, B., Ricketts, T., Running, S., Thonicke, K., Tietjen, B., Walz, A., 2012. A Global System for Monitoring Ecosystem Service Change. BioScience 62, 977–986. https://doi.org/10.1525/bio.2012.62.11.7

Tang, Y., Chen, A., Zhao, S., 2016. Carbon Storage and Sequestration of Urban Street Trees in Beijing, China. Front. Ecol. Evol. 4. https://doi.org/10.3389/fevo.2016.00053

The World Bank, 2021. Current health expenditure per capita (current US$) - China [WWW Document]. URL https://data.worldbank.org/indicator/SH.XPD.CHEX.PC.CD?locations=CN

Tidåker, P., Wesström, T., Kätterer, T., 2017. Energy use and greenhouse gas emissions from turf management of two Swedish golf courses. Urban For. Urban Green. 21, 80–87. https://doi.org/10.1016/j.ufug.2016.11.009

Topp, C.W., Østergaard, S.D., Søndergaard, S., Bech, P., 2015. The WHO-5 Well-Being Index: A Systematic Review of the Literature. Psychother. Psychosom. 84, 167–176. https://doi.org/10.1159/000376585

Trabucco, A., Zomer, R., 2019. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. https://doi.org/10.6084/M9.FIGSHARE.7504448.V3

van den Bosch, M., Ode Sang, Å., 2017. Urban natural environments as nature-based solutions for improved public health - A systematic review of reviews. Environ. Res. 158, 373–384. https://doi.org/10.1016/j.envres.2017.05.040

Vivid Economics, 2017. Natural capital accounts for public green space in London - Methodology document. London, UK.

Vodyanitskii, Yu.N., 2015. Organic matter of urban soils: A review. Eurasian Soil Sci. 48, 802–811. https://doi.org/10.1134/S1064229315080116

Warburton, D.E.R., 2006. Health benefits of physical activity: the evidence. Can. Med. Assoc. J. 174, 801–809. https://doi.org/10.1503/cmaj.051351

Xu, J., Wang, J., Wimo, A., Qiu, C., 2016. The economic burden of mental disorders in China, 2005–2013: implications for health policy. BMC Psychiatry 16, 137. https://doi.org/10.1186/s12888-016-0839-0

Yang, J., Wang, Z.-H., Chen, F., Miao, S., Tewari, M., Voogt, J.A., Myint, S., 2015. Enhancing Hydrologic Modelling in the Coupled Weather Research and Forecasting–Urban Modelling System. Bound.-Layer Meteorol. 155, 87–109. https://doi.org/10.1007/s10546-014-9991-6

Yoon, T., Seo, K., Park, G., Son, Yeong, Son, Yowhan, 2016. Surface Soil Carbon Storage in Urban Green Spaces in Three Major South Korean Cities. Forests 7, 115. https://doi.org/10.3390/f7060115

Zhang, J., Chaaban, J., 2013. The economic cost of physical inactivity in China. Prev. Med. 56, 75–78. https://doi.org/10.1016/j.ypmed.2012.11.010

Ziter, C., Turner, M.G., 2018. Current and historical land use influence soil-based ecosystem services in an urban landscape. Ecol. Appl. 28, 643–654. https://doi.org/10.1002/eap.1689

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

ESMAP
Energy Sector Management Assistance Program