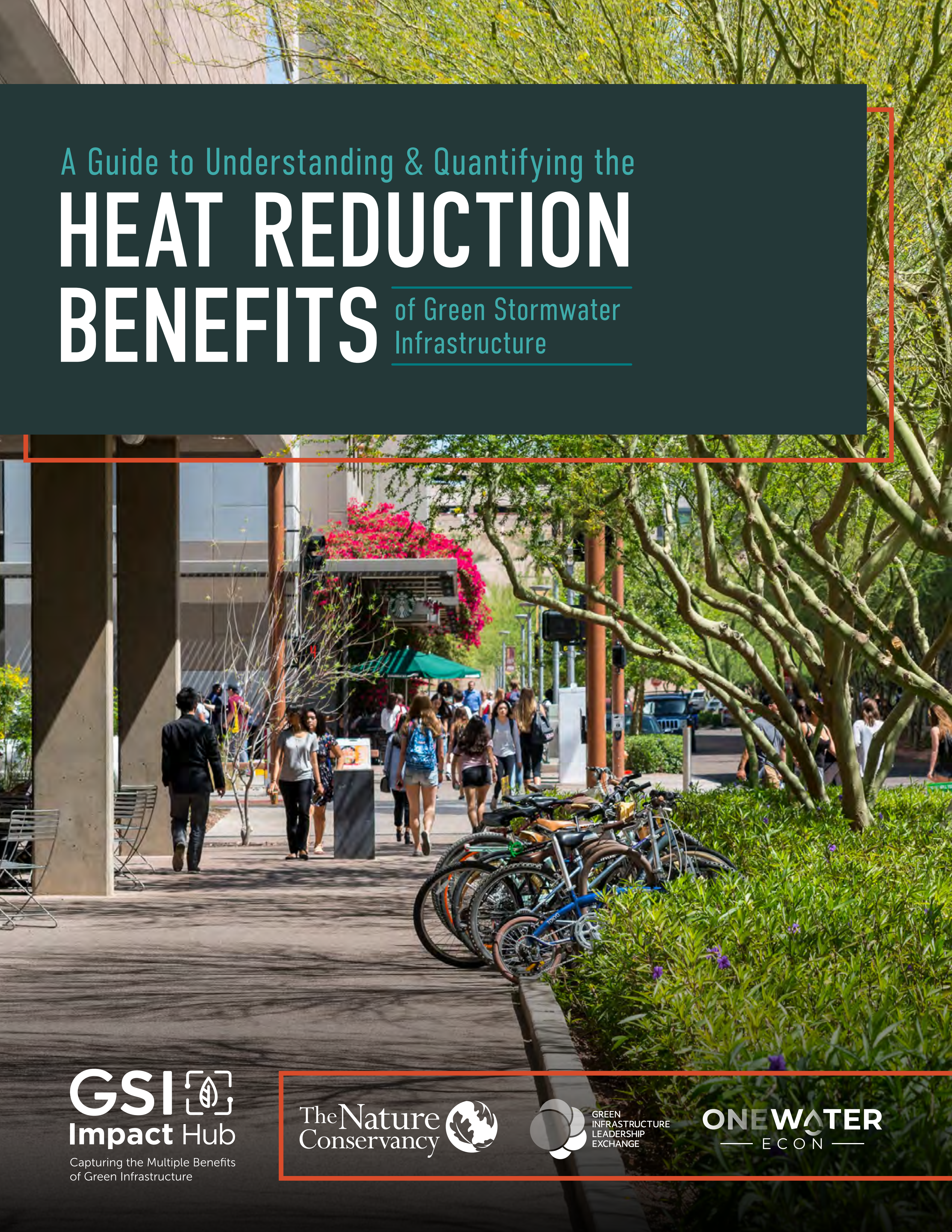
A Guide to Understanding & Quantifying the

HEAT REDUCTION BENEFITS of Green Stormwater Infrastructure



GSI Impact Hub

Capturing the Multiple Benefits of Green Infrastructure

The Nature Conservancy

Green Infrastructure Leadership Exchange

One Water Econ

Credit: Hourigan Group/Green Infrastructure Leadership Exchange

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Credit: Diane Cook and Len Jenshel

INTRODUCTION

Green stormwater infrastructure (GSI) can play an important role in reducing elevated temperatures in urban areas caused by the urban heat island effect (UHI). This guide highlights findings from existing studies and reported on data to help practitioners better understand the impacts of GSI on heat-related outcomes.

Known as the urban heat island (UHI) effect, cities often experience much warmer temperatures than nearby rural areas. The difference in temperature is in large part due to how surfaces in each environment absorb and hold heat. Structures such as buildings, roads, and other infrastructure reflect less solar energy, and absorb and re-emit more of the sun's heat compared to trees, vegetation, and other natural landscapes. Increased temperatures also result from concentrated human activities that generate heat in urban environments, including air conditioning, vehicles, and industrial processes.[1]

> GSI practices such as trees, green roofs, and bioretention areas create shade, reduce the amount of heat absorbing materials, and emit water vapor, all of which cool hot air.

The Environmental Protection Agency (EPA) reports that in the United States, the heat island effect can increase urban daytime temperatures by 1 to 7°F relative to outlying areas. Increased temperatures associated with UHIs can result in adverse environmental and public health effects, particularly during heat waves. The UHI effect is expected to increase in the future as the structure, spatial extent, and population density of urban areas continues to change and grow.[2] Climate change will also exacerbate the impacts associated with UHIs.[3]

Permeable pavement can also provide cooling benefits by increasing the albedo (i.e., surface reflectivity) of urban surfaces and/or releasing more water back into the air compared to traditional pavement.[4] Several GSI practices are among the top cooling strategies recommended by EPA in its *Compendium of Strategies for Reducing Urban Heat Islands*.[5]

GSI Impact Hub

This guide is a component of the GSI Impact Hub, a larger project that provides resources and support related to specific GSI co-benefits. Please visit the GSI Impact Hub website to explore additional resources including:

- Compendium of GSI Co-benefits Valuation Resources
- GSI Impact Calculator, a block-level tool for quantifying and monetizing co-benefits
- Benefit guides related to flood risk reduction, habitat and biodiversity, heat risk reduction, and transportation.

The GSI Impact Hub is a collaboration between The Nature Conservancy, Green Infrastructure Leadership Exchange, One Water Econ, government agencies and technical partners.

While stormwater practitioners recognize the potential for GSI to provide heat reduction benefits, questions remain on how to optimize and plan for UHI benefits, as well as to demonstrate, quantify, and achieve these benefits within their local context. The purpose of this guide is to help municipal staff optimize the implementation of GSI for this purpose by providing information and resources that address these questions (see text box below). It is organized as follows:

- **Section 2** describes the heat reduction benefits of GSI, summarizing findings from the literature on the value of these benefits by region and GSI practice type, as applicable.
- **Section 3** provides guidance and resources to assist municipal staff in identifying high priority areas for siting GSI to reduce urban temperatures and protect vulnerable populations. It also summarizes key design elements for best achieving heat stress reduction benefits.
- **Section 4** provides guidance for quantifying and monetizing the UHI reduction benefits of GSI.
- **Section 5** highlights funding, financing, and partnership opportunities tied to heat stress reduction benefits, as well as partnership opportunities.
- **Section 6** summarizes key findings and identifies key research gaps.

This guide is accompanied by a block-level tool designed to help practitioners quantify the multiple benefits associated with GSI, including some heat stress reduction benefits. It also contains brief case studies highlighting how different municipalities have used GSI to address heat stress.

Key Questions Addressed in This Guide

- What is an urban heat island (UHI)?
- Are elevated temperatures a problem in my community?
  What parts of my service area are most vulnerable to UHI effects?
- How can GSI be used to reduce urban temperatures?
- How can I quantify and monetize the cooling benefits of GSI?
  Is there a way to do this early in the planning process?
- What key GSI design elements or other considerations should I know about to realize UHI reduction benefits?
- Can GSI projects that address urban heat leverage additional funding and/or partnerships?
- What gaps in research exist with respect to this co-benefit?

Credit: Jason Whalen/ Fauna Creative

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The Cooling Benefits of GSI

Credit: Rick Triana

THE COOLING BENEFITS OF GSI

Elevated temperatures can result in increased energy consumption, air pollution, adverse public health effects, and water quality impairments. Properly sited and installed GSI can help cool densely built-up urban environments and play a central role in long-term strategies for reducing these negative effects.

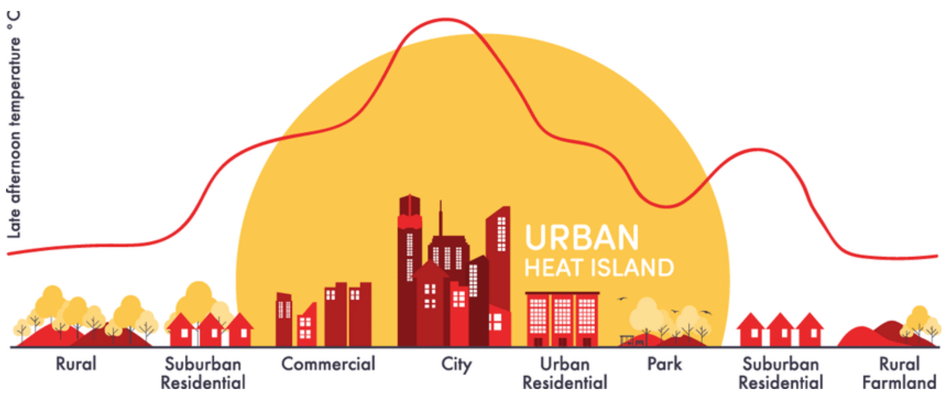
Generally, a range of academic studies indicate that large scale "greening" projects (i.e., parkway tree plantings, conversion of impervious areas to tree canopy, expansion of parks, etc.) are more likely to result in a meaningful decrease in ambient temperatures; when implemented at scale, smaller distributed GSI projects also can make meaningful contributions to larger, citywide cooling efforts.[6]

Estimates of the direct cooling benefits associated with distributed GSI vary significantly by practice type, local climate, measurement technique (e.g., whether a study is examining changes in ambient air temperatures or surface temperatures or comparing directly shaded areas to non-shaded areas), and other community-specific factors. Studies documenting the effects of GSI-related improvements on temperatures have found cooling benefits from converting 6% to 31% of the study area (e.g., city block or entire city) to vegetation or more reflective surfaces. Overall, most studies show that distributed GSI related practices can decrease ambient temperatures between 0.5 and 1.8°F, while trees and canopy cover can offer much higher temperature reductions in directly shaded areas. While these reductions may seem small, when read within the context of climate-related impacts, they can have a meaningful on-the-ground effect. For example, researchers have shown that even small decreases in urban temperatures (e.g., by 0.5 degrees Fahrenheit) can significantly reduce heat-related illnesses and deaths during extreme heat events.[7]

Distributed GSI can decrease ambient temperatures between 0.5 to 1.8°F, while trees and canopy cover can offer much higher temperature reductions in directly shaded areas. Even seemingly small reductions in temperature can have a meaningful on-the-ground effect.

The literature affirms that installing trees and other vegetation can reduce ground level temperatures along streets and parking lots. As droughts, aridification and water supply concerns deepen across much of the country, there may be concerns about investing potable or reclaimed water to irrigate these plantings. Incorporating them into a GSI strategy can be an effective way of supporting vegetation with rainwater and providing social benefits without exacerbating pressure or costs associated with treated water supplies.

Figure 1. The Urban Heat Island Effect



What is an Urban Heat Island?

Urban heat islands (UHIs) refer to the elevated temperatures in developed areas compared to more rural surroundings. UHIs occur for several reasons[1]:

- On average, more than half of urban landscapes have been converted to dark, impermeable surfaces that become hotter in the sunlight than natural and more reflective landscapes.
- Cities have less vegetation than rural areas. Vegetation keeps temperatures lower by providing evaporative cooling and shade.
- The geometry of high-density urban environments - for example tall buildings can trap solar radiation and slow the rate at which cities cool off at night.
- Urban areas serve as concentrated hubs of human activity, many of which generate heat (e.g., air conditioning exhaust, vehicles, industrial processes).

Heat islands can form under a variety of conditions, including during the day or night, in small or large cities, in suburban areas, in northern or southern climates, and in any season. The U.S. EPA reports that in the U.S., the heat island effect results in daytime temperatures in urban areas that are 1 to 7°F higher relative to outlying areas, while nighttime temperatures range from 2 to 5°F above the rural baseline. Humid regions and cities with larger and denser populations experience the greatest temperature differences.[2] As depicted below, temperatures can vary across an urban area. Some areas experience higher temperatures than others due to the uneven distribution of heat-absorbing buildings and pavements, while other spaces remain cooler because they contain more trees and greenery.

Sources: World Meteorological Organization (n.d.)


Credit: Diane Cook and Len Jenshel

Table 1 summarizes results from representative studies that have quantified the effect of GSI-related strategies on urban temperatures in different contexts. As depicted in Figure 2, the direct cooling effect of GSI can translate into significant environmental and economic benefits for communities. The following sections describe the multiple UHI reduction benefits associated with GSI and present results from studies that have evaluated and quantified these benefits based on complex modeling and/or field studies.

2.1 Reduced building energy consumption

Building heating and cooling accounts for almost half of total building energy consumption in the U.S. and is primarily driven by ambient temperatures.[8] A review of available studies reports that for every 1°C increase in temperature, a single building's peak electricity load increases by up to 4.6%.[9] A similar review found that building electricity demands increase by 0.5% to 8.5% per 1°C increase in ambient temperatures, with the highest values calculated for countries that have high rates of air conditioning, like the United States.[10] Evidence from other studies suggest that overall, UHIs cause building cooling energy consumption to increase by a median of 19% globally (ranging from 10%-120%).[11]

> Residential buildings with surrounding trees report average energy savings between 3-25%.

GSI practices, including trees and green roofs, can reduce the need to turn up the air conditioning. Trees offset building energy demands by providing shade and evaporative cooling. A review of empirical studies reports that residential buildings with surrounding trees use 2.3% to 90% less energy for cooling compared to buildings without trees,[12] although most studies reviewed for this guide report savings between 3% and 25%. The impact of trees depends on local climate conditions, building characteristics, and specific design parameters (e.g., the orientation, size, and distance from a building). For example, large trees planted close to the west side of a building will generally provide greater cooling energy savings.

Researchers from the U.S. Forest Service have conducted extensive modeling to better understand and quantify the energy savings associated with trees in different contexts (e.g., across species, regions, planting locations). This research has been incorporated into the agency's well-known i-Tree model, which monetizes the multiple benefits associated with trees in urban settings.

Green roofs can also reduce the demand for air conditioning by providing better insulation than conventional roofs, reducing the transfer of heat from a building's exterior to its interior through the roof, and lowering roof surface temperatures through evaporative cooling.[13] A systematic review of studies found that building energy use associated with green roofs ranges from an increase of 7% to a decrease of 90% compared to traditional roofs.[14] Some studies document significant monetary savings associated with green roofs; for example, early reports indicated that the 113,000 square foot green roof on the Target Center Arena in Minneapolis decreased annual building energy costs by $300,000 (2020 US$), although some percentage of this was likely due to reduced heating needs in the winter.[15]

Across studies, the effect of green roofs varies significantly based on local climate conditions and building and roof characteristics. Buildings with poor insulation garner much larger savings, as do intensive green roofs, which have greater soil depth and leaf area for evaporative cooling. The U.S. EPA and other researchers have modeled the effects of green roofs on building cooling needs, accounting for these different factors (Figure 3).

Figure 2. Adverse impacts of UHIs and associated costs/outcomes.

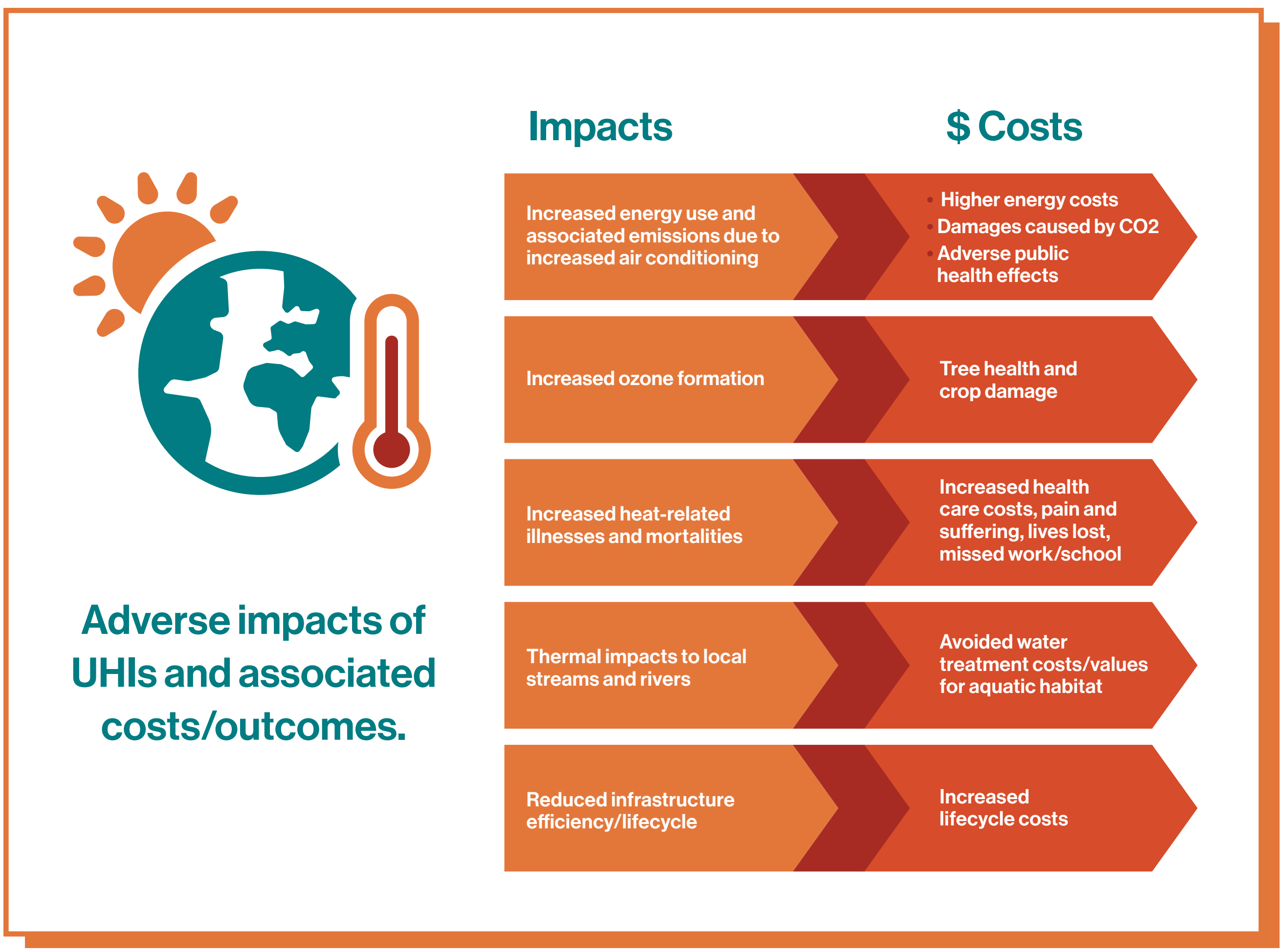


Table 1. Selected research on direct cooling benefits of GSI

GSI Practice type	Region	Description
Studies analyzing change in temperatures associated with a city-scale implementation of vegetative cover, tree canopy, and/or surface reflectivity in urban landscapes		
Albedo, vegetative area	20 major US cities	Modeled decrease in temp based on increase in either albedo or vegetation
Albedo, tree canopy cover, green roofs	Review of 146 studies	Review of numerical modelling literature, 1987-2017
Green roofs	Chicago, IL	Modeled changes in roof temperature associated with installation of green roofs
Tree cover	Multi-regional 29 cities on 5 continents	Reviewed 55 scenarios from existing literature to summarize the impact of increase of urban tree cover on ambient temps
Trees and vegetated areas	601 cities across Europe	Modeled temperature difference between baseline, no vegetation, and urban green infrastructure scenarios to estimate cooling impacts
Green roofs	Xiamen Island, China	Large-scale city-wide green roof installation
Street trees, green roofs	New York City	Temperature effects of converting impervious area to vegetation during heat wave
Vegetated areas	Washington, D.C., Baton Rouge, New Orleans, Atlanta, Charlotte, Detroit, Grand Rapids, Baltimore, Philadelphia	Direct cooling benefits associated with an increase in vegetated areas
Studies analyzing change in temperatures associated with small scale implementation of GSI		
Trees	US average	Peak air temps compared to open terrain
Green roof & urban forests	Toronto, Canada	Field study of GSI impact on average minimum daily temps July – Aug
Trees, shrubs, grasses, green roofs, green walls, parks	International, representation of every continent	Review of literature on GSI from 2009-2020

	Results (temperature results relate to measured air temperature)	Author/year
	10% increase in albedo = 0.48 °C decrease in temp 10% increase in vegetation = 0.33 °C decrease in temp	Sailor and Dietsch 2007[16]
	10% increase in albedo = 0.2-0.6°C decrease in temp 10% increase in canopy cover = 0.3 °C decrease in temp	Krayenhoff et al. 2021[17]
	100% green roof coverage = 5 °C decrease in roof surface temp A 25% decrease in green roof coverage = 1.25 °C increase in temp	Sharma et al. 2018[18]
	100% implementation of GSI = 1.8°C max decrease in daily peak temp 20% increase in GSI = 0.3°C decrease in temp Urban trees surrounded by impervious surfaces have lower cooling potential	Santamouris 2020[19]
	Minimum 16% tree cover required for 1°C decrease in urban temp City-wide greening = 1.07°C average and up to 2.9°C decrease in temp	Marando et al. 2022[20]
	Decreased surface temperature of 0.91 °C Every 1,000 m2 of green roof decreased average surface temp of roof 0.4 °C	Dong et al. 2020[21]
	3%-4.2% temp decrease converting impervious area to vegetation	CCSR 2006[22]
	10% increase in vegetation = 0.13 – 0.5°F (0.07 – 0.28 °C) decrease in average temp 10% increase in vegetation = 0.16 – 0.72°F (0.09 – 0.4 °C) decrease in maximum temp	Sailor 2003[23]
	Tree groves decrease air temps by 9 °F	U.S. EPA[24]
	Urban forest: 0.93 °C decrease in temp Green roof: 0.75 - 1.96 °C decrease in temp	Anderson and Gough 2021[25]
	Median decrease in temp by trees in urban area = 1 °C	Balany 2020[26]

2.2 Air quality improvements

Energy savings from reduced cooling demand decrease related emissions of pollutants and greenhouse gases (GHGs). Key pollutants associated with energy production include sulfur dioxide (SO2), nitrous oxides (NOx), and particulate matter 2.5 ($PM_{2.5}$). The U.S. EPA tracks pollutant and GHG emission rates for all power generation in the United States, by region. Published emissions rates and tools such as EPA's Emissions & Generation Resource Integrated Database (eGRID) and Avoided Emissions and Generation Tool (AVERT) allow users to estimate pollution reductions from decreased energy.

Reducing emissions results in important public health and environmental benefits. NO_2 and SO_2 are both linked to respiratory illness, while NOx and sulfur oxides (SOx) contribute to an array of adverse respiratory and cardiovascular effects. PM is linked to premature deaths, chronic bronchitis, asthma, respiratory infections, and other illnesses. The benefit of reducing these pollutants can be valued based on associated reductions in health care costs and/or willingness-to-pay (WTP) to avoid specific health outcomes.

> By reducing the cooling demand of buildings, GSI and trees can result in energy savings and improved public health benefits.

The U.S. EPA's Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) currently serves as the most comprehensive source of information on air quality changes and related public health improvements, including avoided health care costs (see Section 4.3 for more information). This model allows users to value emission reductions based on characteristics of the local population (e.g., age mix, density), geography, existing ambient air pollution levels, and power generation mix (for emissions reduction), among other factors. To value GHG emission reductions, economists typically use the "social cost of carbon" (SCC), which represents the aggregate net economic value of damages from climate change across the globe, including the impact on agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.

Elevated temperatures can also increase the rate of ground-level ozone formation (i.e., smog).[27] Ozone pollution is not directly emitted to the air but occurs when NOx (precursor emissions from automobiles and smokestacks) and volatile compounds react in the presence of sunlight and hot weather. Ground-level ozone can adversely affect human respiratory and cardiovascular health and damages plant tissues, which affect crop yields and forest growth. Climate change is expected to increase summertime surface ozone in polluted regions, as well as the number of days on which exceedances occur.[29]

Determining ozone reductions associated with decreases in temperature is complex. Surface ozone pollution levels are dependent on nonlinear correlations with temperature, precursor emissions, local meteorological conditions, and chemical reaction rates.[30] However, clear relationships have been identified – one study found that for every 1.8°F the temperature in Los Angeles rises above 71.6°F, smog increases by 5%.[31] At extreme temperatures, the relationship between temperature and ozone can diminish due to meteorological processes known as "ozone suppression."[32] However, U.S. EPA reports that overall, UHI mitigation strategies that increase albedo and/or vegetation generally reduce ozone concentrations.[33] In a 2016 webinar, the agency cites four modeling studies that support this finding, while acknowledging that benefits vary by weather, city size, topography, population density, and other factors.

UHI mitigation measures are most effective for ozone reduction if implemented on a large scale in a city or region. EPA encourages the incorporation of UHI mitigation strategies into Statewide Implementation Plans (SIPs) for meeting federal air quality standards for ozone, citing examples from Washington DC, Sacramento, and Maryland, which have all adopted tree canopy goals as part of overall compliance plans.[34]

Researchers have established values for the avoided health care costs associated with ozone reduction. A study by the U.S. Forest Service (USFS) reports an average value for avoided health care costs, including mortalities, acute respiratory symptoms, hospital admissions, emergency room visits, and lost school days, of $3,748 per ton (2020 US$) of ozone reduction in urban areas. This varies significantly with population density (e.g., in Philadelphia, which has a population density of 12,060 per square mile, the USFS model results in a value of more than $16,000 per ton of ozone reduction).[35]

> Extreme heat events (EHEs) pose a significant public health risk to urban communities.

Figure 3. Quantifying Energy Savings and Air Quality Benefits of Green Roofs

EPA Case Study on the Energy Savings and Air Quality Benefits of Green Roofs

In 2018, the U.S. EPA partnered with local agencies and researchers in Kansas City, Missouri to quantify the environmental and health benefits associated with wide-scale green roof implementation. Kansas City has been installing green roofs on public buildings since 1999.[28] With an annual growth rate of 10%, city officials at the time estimated that more than 730,000 square feet of green roof would be operational by 2020. The authors used the National Green Roof Energy Calculator and tools developed by U.S. EPA to estimate the annual benefits associated with this level of implementation. In addition to stormwater management benefits, results indicate that green roofs in Kansas City reduce roof temperatures by more than 60% during summer months, save $41,600 annually in building energy costs, and reduce air pollutants across the metro area. The reduction in air pollutants also reduces adverse health outcomes, with associated economic benefits (e.g., avoided health care costs) ranging from $35,500 to $80,500 in 2020.

2.3 **Avoided heat-related illnesses and fatalities**

Extreme heat events (EHEs) pose a significant public health risk to urban communities. According to the Center for Disease Control and Prevention (CDC), heat is the leading weather-related killer in the U.S. Over the past decade, extreme heat days have resulted in more than 1,500 premature fatalities per year, on average.[36] In addition to causing premature fatalities, EHEs are also associated with a range of heat-related illnesses, including general discomfort, respiratory difficulties, heat cramps and exhaustion, cardiovascular stress, kidney or liver failure, and blood clots. The CDC reports that heat is responsible for more than 67,500 emergency department visits and 9,200 hospitalizations each year. This likely underestimates the full impact of exposure to periods of high temperatures, as heat-related illnesses are often unrecognized or misclassified as another underlying cause.

The relationship between heat and adverse public health effects varies based on local demographics, economic well-being, underlying disease risk, the presence of vulnerable subpopulations, weather variability, physiologic acclimatization, and locally available adaptations. For example, several studies have shown that heat waves take a disproportionate toll on people of color and low-income urban populations who often live in neighborhoods that have older, lower quality building stock, less tree cover, and fewer buildings with air conditioning.[37] Historical patterns of discrimination and disinvestment in marginalized communities have contributed to higher average temperatures for poor and minority residents.[38 39]

Several key studies have helped shed light on the number of deaths caused by extreme heat by developing statistically significant relationships between extreme heat days and mortalities in different cities. As part of the Fourth National Climate Assessment, EPA's Climate Change Impacts and Risk Analysis (CIRA) estimated the number of deaths attributable to extreme temperatures in 49 U.S. cities under various future climate scenarios.[40] This study defined extremely hot days as those with a daily minimum temperature that is warmer than 99% of the days in the historical reference period and is at least 20°C (68°F). Results indicated that by 2090, changes in extreme temperatures will result in an additional 5,000 to 9,300 premature deaths per year in the 49 cities under the "high- and low-end emission scenarios," respectively. Another study[41] estimated increased mortality risk during heat waves in 43 U.S. cities, defining heat waves as days with mean temperatures greater than the 95th percentile temperature for more than two days. Results indicated that nationally, mortality increased 3.74% during heat wave days compared to non-heat wave days. This translates to a heat wave mortality risk increase of 2.49% for every 1°F increase in heat wave intensity, indicating that even small increases in temperature can result in significant public health effects.

> In many areas, the cooling effect associated with GSI can be enough to reduce heat stress-related fatalities and illnesses during extreme heat events.

In many areas, the cooling effect associated with GSI can be enough to reduce heat stress-related fatalities and illnesses during extreme heat events. In general, wide-scale implementation of GSI is required to make a noticeable impact (e.g., a 10-percentage point increase in vegetated area). However, avoided heat-related health impacts can be accounted for when assessing the benefits and costs of site-level projects that are part of a larger, long-term GSI plan. Table 2 summarizes results from representative studies that have estimated reductions in heat-related deaths and/or illnesses as a result of increased vegetative cover, reflective surface, and/or tree canopy.

Table 2. Representative studies linking GSI-based cooling strategies to positive public health outcomes

Health Indicator	Region	Description	Results	Author/ year
Mortality	Baltimore, MD, Los Angeles, CA, and New York City, NY	Estimated reductions in heat-related mortality associated with increasing surface vegetation by 0.10 and reflectance by 0.10	Lives saved over 10-years: Baltimore: 12 New York City: 197 Los Angeles: 2	Vanoes et al. 2016[42]
Mortality	Washington D.C.	Evaluated reduction in heat-related mortalities associated with 10-percentage point increase in vegetative cover	6% decrease in heat-related deaths, approximately 20 lives per decade.	Kalkstein et al. 2013[43]
Mortality	Multi-regional 29 cities on 5 continents	Compared 13 case studies of GSI and tree cover contributing to decreased heat-related mortality	Increasing tree cover and GI by 20% decreases peak temperatures by an average of 0.3°C, and a 1°C reduction in max daily temperature reduces heat-related mortality by 30.5%	Santa-mouris 2020[44]
Mortality	Atlanta, GA, Philadelphia, PA, and Phoenix, AZ	Paired global and regional climate models with human health effects models to estimate change in heat-related deaths in 2050 resulting from modifications to vegetative cover and surface albedo	Combinations of vegetation and albedo enhancement would offset projected increases in heat-related mortality due to climate change by 40% to 99% across the three cities, with an average reduction of 57%. w/ aggressive green scenarios.	Stone et al. 2014[45]
Heat-related emergency calls	Toronto, ON	Used regression models to examine the effect of increased trees and vegetation on the number of heat-related ambulance calls from different neighborhoods.	Increased trees/vegetation result in 40 - 50% reduction in heat-related ambulance calls.	Graham 2012[46]
Heat-related emergency calls	Phoenix, AZ	Modeled UHI mitigation strategies (emissivity, vegetation, thermal conductivity and albedo) against emergency service data	Increasing GSI between 5% - 20% leads to decrease in emergency calls from 17% - 70%.	Silva et al. 2010[47]
Hospital admissions	Darwin, Australia	Simulated increase in tree cover from 19% to 39%	Decrease of average peak daily temperature by 0.5°C reduced annual hospital admissions by 31%	Yenneti et al. 2020[48]

2.4 Water quality improvements

Urban impervious areas with high surface temperatures increase the temperature of stormwater runoff discharged into local waterways. Increases in ambient air temperatures also increase the temperature of local rivers and streams. Warmer water has wide-reaching implications for drinking water quality and aquatic habitat.

A review of available literature examined the effect of heat on lakes, rivers, and streams in relation to drinking water production,[49] reporting increases in acidity, lower dissolved oxygen concentration, increased mineralization from soil organic matter, increased rate of pollutant uptake, and development of cyanobacteria blooms. The U.S. EPA notes that higher water temperatures and the associated impacts increase pathogens and invasive species that thrive in warmer, more contaminated waters, while decreasing aquatic species whose survival and breeding are temperature dependent.[50] Urban stream aquatic communities show higher indications of thermal stress as a result of stormwater runoff from low albedo, paved surfaces that have absorbed solar radiation.[51] Increasing temperatures also ramps up the rate of evapotranspiration, shrinking waterbodies and increasing pollutant concentrations, altering fragile aquatic habitats.

GSI, and especially tree planting, has the potential to play a significant role in temperature reduction in urban streams. Several states in the Pacific Northwest have established plans to address temperature TMDLs (Total Maximum Daily Loads) for rivers and streams. Several cities and suburban locations have planted streamside forests to reduce water temperatures at wastewater treatment plants on the stream. The streamside forest plantings are estimated to cost significantly less than the chillers and to provide significant co-benefits. Tree plantings by Clean Water Services (CWS), a wastewater and surface-water utility in suburban Portland, Oregon were designed to average 45 feet wide for a distance totaling 17 miles. The modeling by the water agency showed that the trees would block 18.8 million kcal/mile/day of solar energy. The project cost $18.3 million (2022 dollars) and was estimated to save $74.7 million (2022 dollars) over the alternative to install chillers. The city of Portland OR also investigated the impact of establishing streamside forests on Johnson Creek, an urban stream in the southeast quarter of the city, before it empties into the Willamette River. Reduced water temperatures were in turn expected to increase fish populations and avoid costs of complying with the Clean Water Act and the Endangered Species Act.[52]

> GSI, and especially tree planting, has the potential to play a significant role in temperature reduction in urban streams.

GSI is typically designed to manage stormwater volume and/or quality, with less consideration given to reducing the thermal pollution of stormwater runoff. A review of literature found that GSI can apply the processes of water retention or attenuation of runoff volume to help reduce effects of stormflow, slow drainage rates, and reduce pollutant loads where water is contained. Adding trees to GSI practices also cools impervious surfaces using shade, thereby reducing the heat transfer to stormwater runoff. Interestingly, deeper bioretention cells are more likely to prevent elevated runoff temperatures than shallow wet ponds or stormwater basins that can be more easily influenced by solar radiation.[53] A recent study modeled the impact of thermal mitigation practices of bioretention, cool surfaces and increased forest canopy on downstream heat loads affecting trout in Stroubles Creek watershed in Virginia.[54] The authors found that the combined practices reduced total heat load by 62% and the percentage of time the creek was heated above toxic levels decreased by 12% over the entire summer, and the heat loads from storm events were nearly eliminated.[55]

Credit: Jen Guyton

2.5 Increased lifecycle/ efficiency of infrastructure

In a guide for municipal management of extreme heat, the Delaware Valley Regional Planning Commission outlined the ways in which rising temperatures can impact public infrastructure.[56] Dark paving surfaces like asphalt soften and expand after prolonged heat exposure, making them more vulnerable to potholes and ruts. Heat can also warp railroad tracks and cause overhead powerlines to sag. The increased cooling demands associated with UHIs put additional strain on utility infrastructure. In addition, extreme heat causes metal power lines to expand and impedes the efficiency with which transformers shed heat, lowering the overall efficiency of the system. Water demands also tend to increase with increasing temperatures; as periods of extreme heat lengthen, water delivery systems may become stressed as well.[57] Across these systems, increased temperatures means that more money must be spent to maintain and repair electric, transportation, and water infrastructure.

When located in a manner that provides the most benefit, GSI practices can help to mitigate some of these issues, resulting in avoided infrastructure maintenance and replacement costs. For example, tree shade on asphalt reduces the impacts of heat and thus the need to repave as frequently. In a study of shaded and unshaded streets in California, large trees providing at least 20% shade on streets saved $1 per square foot and reduced repaving costs by 58% over a 30-year lifecycle (updated to 2022 US$).[58] Alternatives to asphalt, such as porous pavement and permeable pavers, can mitigate heat by decreasing surface albedo and increasing evapotranspiration; permeable or porous surfaces develop fewer cracks and potholes due to resilience to freeze/thaw cycles and have been shown to have a lifecycle 15 years longer than traditional asphalt parking lots.[59] Reducing ambient air temperatures around air conditioner intakes and units can improve air conditioner efficiency, further reducing building energy requirements. This benefit has been documented in several studies of the benefits of green roofs in relation to roof top air conditioners.[60 61]

3

Planning and Designing GSI for UHI Reduction Benefits

Credit: Kevin Arnold

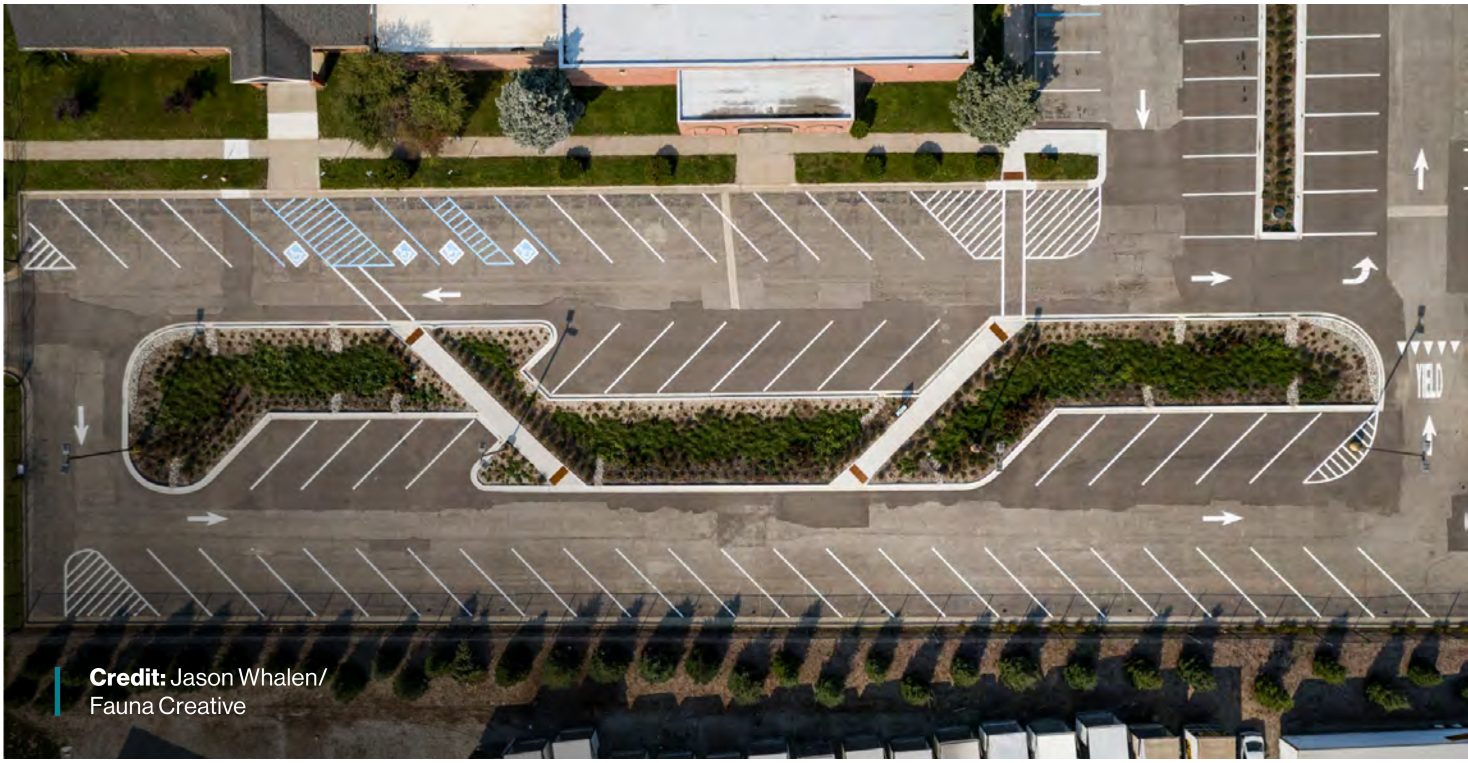
PLANNING AND DESIGNING GSI FOR UHI REDUCTION BENEFITS

At a municipal planning and implementation level, it is important to identify locations, GSI practices, and design elements that can effectively reduce the effects of elevated temperatures in urban areas.

Publicly available data, mapping tools, and information on key design elements can assist municipal staff with this task. The following sections describe ways for identifying locations within a city where GSI-related interventions will result in the greatest benefits, describe factors that affect the provision of these benefits, and provide guidance from the literature on effective GSI design for achieving this co-benefit.

3.1 Identifying "Intra-Urban" Heat Islands

The UHI effect can vary significantly across an urban area - neighborhoods in highly-developed parts of town can experience peak temperatures that are 15 to 20°F hotter than neighborhoods with more trees and less pavement.[62] Socioeconomic characteristics that make certain



Credit: Jason Whalen/ Fauna Creative populations more vulnerable to heat also vary throughout an urban area. Temperature data, combined with land use and socioeconomic data at the neighborhood scale, can be used to identify a range of values that are important for understanding local heat stress benefits of GSI implementation. This data can also be used to correlate heat impacts with other GSI-related priorities, such as flooding and water quality impacts (for further information, see other guides in this series).

The first step to identifying areas within a community where GSI is likely to have the greatest effect is to obtain temperature data at relevant scales. Air temperature data (e.g., mean and/or average maximum temperatures for summer months) are reflective of conditions in the urban canopy, from ground level to the tops of trees and buildings. They are most useful for studies attempting to measure public health risks since they are the best indicators of conditions experienced by people. Air temperature data can be obtained from standard weather stations (e.g., through NOAA and/or the NWS, local networks); however, this data is typically only readily available for limited locations within a city.

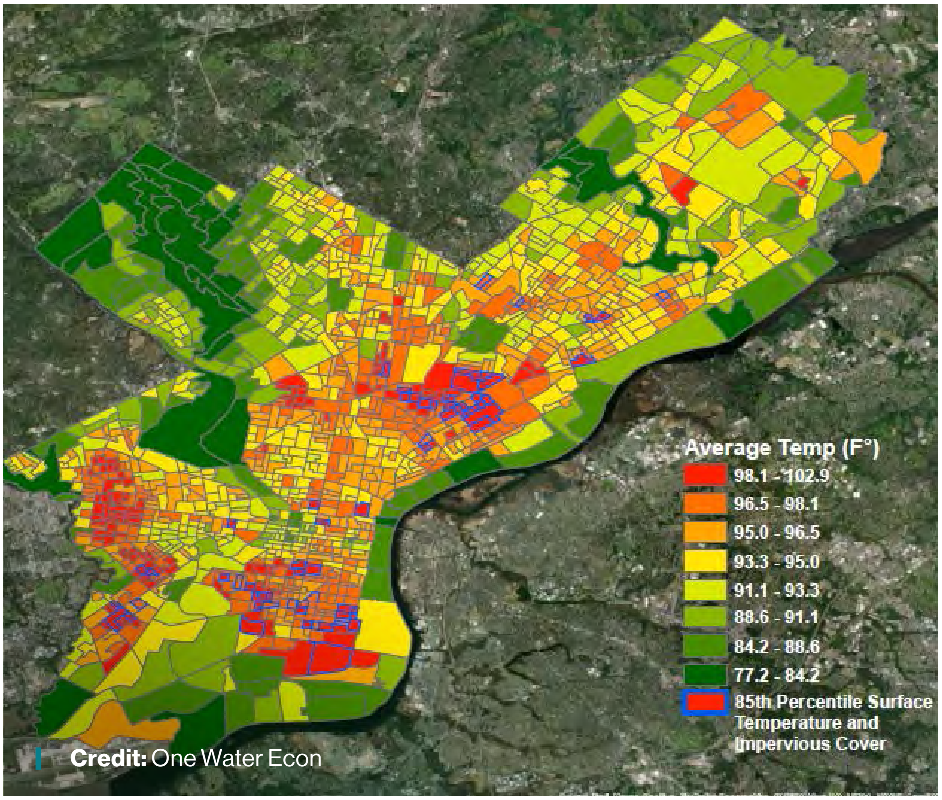
For this reason, many municipalities and public health researchers have relied on surface temperature data to identify areas of high heat. Surface temperatures represent heat energy given off by land, buildings, and other surfaces. Technologies that measure surface temperatures (i.e., satellites) can provide better geographic coverage than those used for recording air temperatures and can reveal temperature differences at relatively fine scales.[63] Although not a perfect proxy, surface temperature is highly correlated to air temperature; when paired with data on vegetative cover within an area, correlations between surface temperature and air temperature have been found to exceed 90%.[64] Surface temperatures may be especially relevant for identifying areas where GSI might be most beneficial in reducing building cooling demand, decreasing stormwater runoff temperatures, and/or protecting municipal infrastructure assets from heat-related exposure.

> **Understanding local temperature data and identifying heat vulnerable populations are critical to siting GSI for the greatest heat reduction benefits.**

Surface temperature data is available globally from the United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) LandSat Collection-2 Level-2 or the Collection-2 Analysis Ready Data datasets. Landsat data is based on continuous satellite images of the earth's land surface and can be downloaded from the USGS EarthExplorer tool. Use of this data requires a relatively basic level of expertise with Geographic Information Systems (GIS) and some (relatively limited) post-processing analysis. Landsat serves as a useful resource for evaluating differences in the UHI across an urban area. However, U.S. EPA notes that satellite surface temperature data has some limitations. It does not always capture the finer details of hot spots within neighborhoods. Trees or tall buildings may prevent satellites from accurately capturing the temperatures of surfaces at ground level. In addition, data are collected only during the times when a satellite passes over a city and are available only for clear weather conditions.

Figure 4 shows the application of Landsat surface temperature data by Census block group to identify UHI hotspots within Philadelphia, as well as data related to impervious cover from the National Land Cover Database (NLCD). Together these two variables explain much of the variation in temperatures across a city and point to areas of the city where the UHI effect is likely to be greatest. These areas are often referred to as "intra-urban" heat islands.[65]

Figure 4. Average land surface temperatures and highly impervious Census block groups, Philadelphia



Credit: One Water Econ

Characterizing Heat Islands Across Philadelphia Using Surface Temperature and Impervious Cover Data

The map above shows Landsat surface temperature grid data by Census block group (CBG). CBGs with blue boundaries fall within the 85th percentile for surface temperatures and impervious cover. Averaging the Landsat and NLCD grid data by CBG or Census tract allows for a direct comparison of socioeconomic variables from the U.S. Census that have been found to be correlated to increased heat vulnerability (see Figure 5).

3.2 Areas with High Vulnerability to UHI Effects

Another key component for identifying high priority areas at the intersection of GSI and urban heat stress is to identify those areas where populations are most vulnerable to the impacts of increased temperatures. A review of research on this topic reveals several key socioeconomic variables that have been directly (positively) correlated to heat-related impacts, including number of children under the age of five, number of elderly households, income, and poverty rates. In addition, EPA reports that communities of color are disproportionately exposed to heat islands; specifically, neighborhoods with higher numbers of African American residents tend to experience more intense heat island effects than other areas (see Heat Equity text box).[66] Finally, population and density have been found to be the most statistically significant variables in predicting changes in temperature associated with incremental changes in impervious cover. This means that GSI projects provide greater benefit when they are sited in areas with higher populations and greater density. Figure 5 presents a simple demonstration of using Census data to identify communities most at risk.

As an important note, the analyses and data summarized above provide a relatively simple approach to characterizing the effects of UHIs within an urban area and identifying potentially vulnerable communities. Public health and other researchers have developed much more complex methods – for example, developing heat indices that better characterize "human thermal comfort" based on comprehensive meteorological data and modeling. The above analyses provide a sound methodology for understanding how and where to maximize cooling benefits associated with GSI-based stormwater management strategies, and can be overlaid with data on water quality, localized flooding, sewer system capacity, or other stormwater management variables to identify areas where these objectives overlap.

3.3 GSI Design Elements and Other Considerations for Achieving Heat Stress Reduction Benefits

Having identified locations within a community where GSI can contribute meaningfully to heat stress reduction, the next step is to identify appropriate GSI practices that will deliver the economic and human health benefits associated with reduced heat. This section provides a summary of findings from existing research that documents key design elements and other considerations for GSI installations that impact urban temperatures.

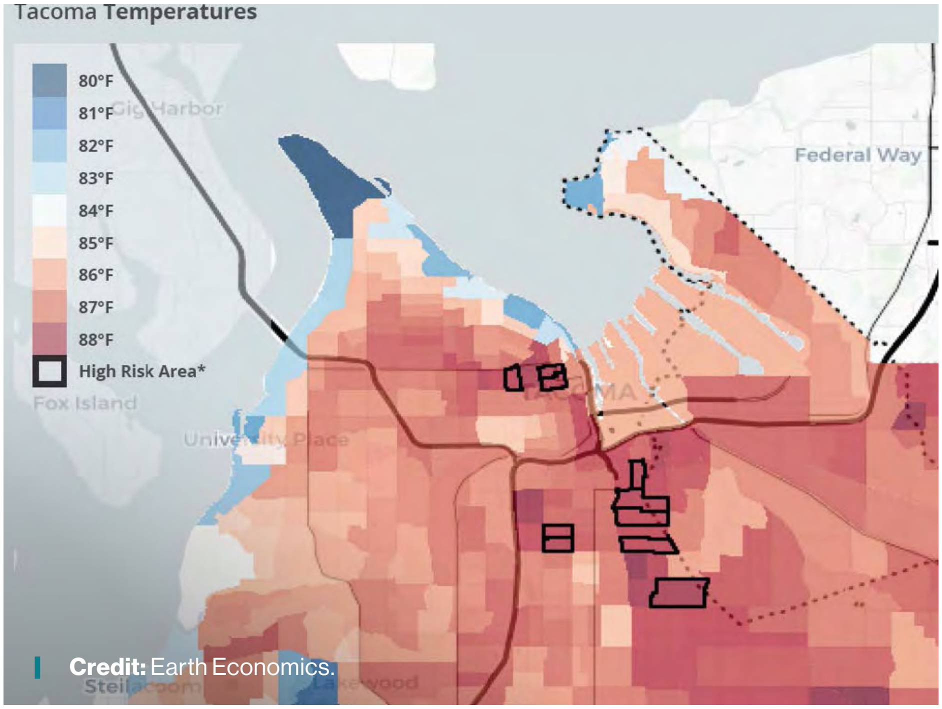
3.3.1 General considerations informing GSI design to reduce heat stress

The scale of temperature measurements matters in the assessment of urban heat reduction: temperature reductions at the block or neighborhood scale are more easily achieved than city-wide cooling. It is important to note that the differences of modeling techniques, modeling scales, study location, and practice types often make studies on urban cooling difficult to compare, as cooling magnitudes vary widely between studies.[71]

The heat reduction benefits of GSI depend on several factors:

- **Baseline conditions** of a city, neighborhood, or site will affect the degree of heat stress reduction that can be achieved. The amount of dark and impermeable surfaces, existing levels of vegetation, local climate, building inventory characteristics, and other physical locational attributes impact the level of potential benefits provided by GSI projects.[72] For example, cities that have a long history with extreme heat events may be more likely to have adapted over time and often experience fewer relative adverse health effects, although increasing temperatures associated with climate change may raise new concerns. GSI-related heat reduction strategies are likely to be less effective

Figure 5. High risk Census tracts for urban heat, Tacoma, WA



Credit: Earth Economics.

Identifying "At Risk Census Tracts" in Tacoma, WA

An analysis by Earth Economics (EE) demonstrates a relatively simple approach to identifying high risk Census tracts with respect to human health and urban heat.[67] For this analysis, the EE team used proprietary data (Carto Maps) to map average maximum temperatures in July by Census tract and overlaid this data with socioeconomic variables from the U.S. Census. This analysis indicated that neighborhoods in Central and South Tacoma can be as much as 14°F hotter than neighborhoods in North Tacoma. In the above graphic, Census tracts where average per capita incomes are less than 200% of the federal poverty level are outlined in black – EE reports that 11,980 people live in these "high risk" neighborhoods.

EE's review of temperature data also found that that Tacoma experiences 30 days above 82°F per year, on average – temperatures above this level have been found to significantly increase the risk of cardiovascular diseases, respiratory illnesses, and heat stroke.[68] Further, the number of days above the 82°F threshold has increased by more than 50% since 1980. EE also found that the burden of urban heat islands is disproportionately levied on the lowest income households. In Tacoma there is a strong correlation between household income and urban heat islands.

(at the margin) in areas with a high level of existing vegetation.

- **Scale of implementation within study area.** Studies documenting the effects of GSI-related improvements on temperatures have found benefits associated with converting 6% to 31% of the study area (e.g., city block or entire city) to vegetation or more reflective surfaces.[73] As a general rule, greater impacts are associated with larger conversion areas.
- **The type of GSI installation and other design elements** may matter as well. One study found that increasing the albedo of urban surfaces resulted in an approximately 44% greater temperature reduction compared to increasing vegetative cover by the same amount.[74] This indicates there may be the potential for achieving greater benefits with permeable pavement practices when they can increase surface reflectivity relative to baseline conditions. Trees and green roofs also have been found to result in greater cooling benefits relative to other ground-level vegetated practices. Table 3 contains more information on GSI design elements that affect heat stress reduction benefits.

The effect of GSI on urban heat stress vary by the city's geographic and climatic attributes, as well as by GSI siting within a city. For example, GSI can provide meaningful heat reductions in urban environments located in hot, dry climates; however, these benefits are diminished if urban vegetation used in GSI installations is not adequately irrigated, particularly during the plant palette establishment period.[75] However, inclusion of native vegetation in GSI can be instrumental in ensuring the functionality of these practices across a range of climatic conditions.[76] Among city-specific variables such as population, area, density, latitude and climate, one study found population to be the most statistically significant determinant of changes in temperature associated with incremental changes in vegetative cover: cities with higher population experience a larger decrease in temperatures when vegetative cover is increased.[77]

To maximize heat stress benefits within a city, the siting of GSI in relation to other attributes becomes an important factor. A recent modeling study found that adding vegetation in urban districts or industrial areas with little to no greening will be more effective at mitigating heat than adding trees in canopied neighborhoods, where temperatures are already lowered by other vegetation.[78] Also, locating GSI between tall buildings on narrow streets has been found to be less effective at reducing surface temperatures because buildings provide shading and reduce solar exposure. Conversely, wide street canyons with high solar exposure or narrow street canyons with low buildings should be prioritized for street trees and vegetation because the cooling benefits are higher in urban environments.[79]

3.3.2 Design Considerations for GSI Practice Types

The choice of GSI practice is an important consideration when aiming to reduce heat stress. The practice type chosen will often be influenced or determined by the available space for GSI: alleyways and parking lots may have room for permeable pavement and rain gardens, whereas areas of high-density building may only have space for green roofs. The width of rights of way along street corridors can determine the selection of tree and vegetation species. While green roofs can improve building cooling, they have been found to have limited impacts on direct ambient temperature reduction.[80] [81] In contrast, large tree-covered areas and urban agriculture systems are highly effective cooling agents.[82] Table 3 presents research on design elements of some practices that could improve the performance of GSI in reducing urban heat. reducing urban heat.

Heat Equity Considerations

Heat equity refers to policies and practices that address the inequitable distribution of heat risks across different populations in urban areas through heat island mitigation and extreme heat adaptations.[69]

Often heat islands are most pronounced in "intra-urban" areas due to uneven distribution of heat absorbing buildings and pavement and cooler greened spaces. U.S. EPA reports that people of color and community members with low incomes are more likely than other groups to live in intra-urban heat islands, citing historic redlining as a contributing factor. The physical risks associated with heat stress are compounded on social and health risk factors, resulting in disproportionate public health impacts on vulnerable residents.

Equity can be at the center of consideration when planning to use green infrastructure to reduce urban heat stress. One example of a heat equity program is Cool Neighborhoods NYC. The NYC Department of Health and Mental Hygiene, in partnership with Columbia University, developed a Heat Vulnerability Index that helped to identify New York City's most heat vulnerable neighborhoods. This project informed Cool Neighborhoods NYC, a citywide strategy to reduce extreme heat and target adaptation strategies in high risk areas.[70] This program dedicated funding to street tree planting and tree planting in parks, in partnership with the NYC Department of Parks and Recreation, which committed to tree maintenance.

For more information on the equity aspects of GSI planning and implementation, see the Green Infrastructure Leadership Exchange GSI Equity Guide, which was published in March 2022.

Table 3. Design elements and considerations for heat stress reduction performance, by practice

GSI Practice Type	Key Design Considerations
Trees	Trees are the most effective GSI practice for heat stress reduction.[83] The ability of trees to reduce heat is highly dependent on canopy cover providing shade, indicating that the species of vegetation also has implications for effectiveness.[84] On a micro-scale, placement of trees on the south side of a building will increase the cooling effects on that building.[85] For ambient temperatures, planting trees on east-west oriented streets has a greater cooling effect than trees planted along north-south oriented streets.[86] Trees planted for shade should have a dense, moderate sized crown and be prioritized by species placement within regional hardiness zones. Deciduous trees over coniferous will provide shading in the summer but allow sunlight to hit buildings in the winter, reducing heating costs.[87] Trees can reduce building energy consumption by shading walls and roofs, providing evaporative cooling and blocking winter winds. Energy savings are higher for trees that are closer to buildings, located adjacent to south, east and west facing walls where they can provide meaningful shade and wind break effects.[88] Roadside trees can cool land surface temperatures in transit-oriented spaces. This cools neighborhoods and can improve the longevity of transportation assets like streets and sidewalks.[89] Careful consideration must be given to tree species selection, installation, and maintenance in these settings to ensure sight lines and traffic safety needs are met.[90]
Bioretention, green space, and parks	Ground-level vegetation is positively correlated with cooling ambient temperatures, although parks are more efficient at reducing heat when combined with trees.[91] Some studies have shown that parks with dense tree canopy provide better heat reduction during the peak daytime temperatures, but more open parks (<30% canopy) allow higher wind speeds and increased evapotranspiration for nighttime cooling.[92] Additionally, when parks are implemented at higher elevations within a city, it is possible for the cool air to sink to lower elevation areas.[93]
Green roofs and green walls	Green roofs and walls have the benefit of being most suitable for urban areas where large spaces for GSI are limited. For lower buildings with only one or two stories, green roofs can effectively contribute to building cooling, while green walls provide better cooling benefits on multistory buildings.[94] Cooling benefits of green roofs are enhanced when soil moisture increases, suggesting that intensive green roofs with deep planting mediums, more irrigation, and larger biomass enhance cooling benefits.[95] Simulated models indicate moderate ambient temperature decreases with 30% or greater of total roof area converted to green roofs.[96] Because of these effects, green roofs and walls can also reduce building energy consumption due to the increased insulation and reduced heat transfer that they provide. These savings will vary depending on location and the medium/plant palette used but can be significant.[97]
Permeable pavement	Replacing existing asphalt and other dark pavements with reflective pavements (i.e. pavements with high albedo) that absorb less solar energy will reduce ambient temperatures.[98] Water infiltration though permeable pavements can aid heat loss through these surfaces. The water held in these pavements can provide post-rain event evapotranspiration, with a greater degree of cooling benefit with more accumulated moisture. Because permeable pavement materials do not absorb as much heat, these surfaces cool off a night more readily.[99]

4

Quantifying and Monetizing UHI Reduction Benefits

Credit: Karine Aigner

QUANTIFYING AND MONETIZING UHI REDUCTION BENEFITS

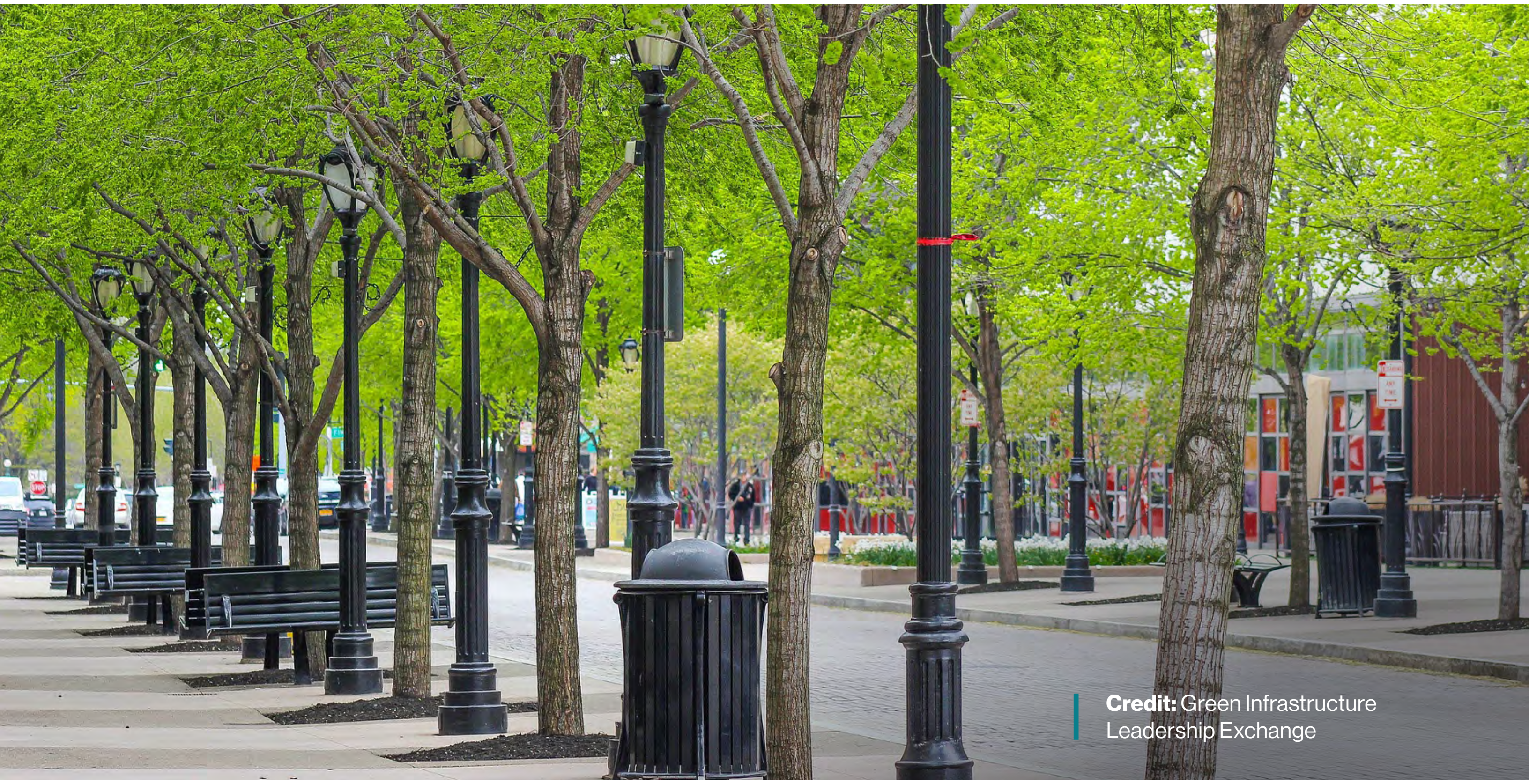
Through this research, stormwater utilities identified a need for simple approaches and tools that would allow them to quantify and monetize co-benefits early in the planning stages of GSI projects. This section describes the methodology, key assumptions, and factors to consider for quantifying and monetizing GSI co-benefits related to urban heat.

To address this need, the project team developed a simplified co-benefits tool that allows for the quantification of GSI co-benefits at the block level and across various practices. The block-level tool builds on benefit valuation methods developed by the authors of this guide for the Water Research Foundation's (WRF's) more complex and customizable GSI Triple Bottom Line (TBL) Tool by integrating common assumptions related to GSI design to determine the level of benefits achieved in different locations. This section describes the methodology, key assumptions, and factors to consider for quantifying and monetizing GSI co-benefits related to urban heat.

4.1 Building energy savings from street trees

As noted in a previous section, USFS has conducted extensive modeling to estimate the energy savings benefits of trees in different settings, including "yard" trees (planted directly next to buildings), public trees or street trees, and urban forests. This research has been integrated into the agency's suite of i-Tree tools, which estimates the monetary value of the ecosystem services that trees provide. Based on extensive field sampling and simulation modeling, i-Tree represents the most comprehensive and peer-reviewed source of information and data on the benefits of urban trees.

Based on information from i-Tree and the USFS Urban Tree Database, Table 4 shows the average reduction in cooling demand, and associated monetary savings, that can be attributed to street trees in urban areas across U.S. climate zones (Figure 6). To monetize energy savings, we relied on 2022 data from the Energy Information Administration (EIA) on average electricity costs per kWh by state, for residential and commercial customers. These savings represent benefits at (nearly) full tree maturity (30 years). However, the energy saving benefits of trees will scale over time as trees grow and mature, with much lower benefits in early years. The block-level tool includes a tree growth model that accounts for this growth in benefits over time.



Credit: Green Infrastructure Leadership Exchange

Table 4. Average Annual Electricity savings from Reduced Building Cooling Demand Associated with Street Trees in Urban Areas, by Climate Region.

Climate Region	kwH/tree (year 30)	$/tree (year 30)
Central Florida	97	$12.66
Coastal Plain	158	$19.43
Inland Empire	122	$30.96
Inland Valleys	164	$41.62
Interior West	112	$14.49
Lower Midwest	72	$9.27
Midwest	267	$39.84
North	125	$14.53
Northern California Coast	132	$33.50
Northeast	85	$19.83
Pacific Northwest	68	$7.00
South	154	$20.64
Southern California Coast	60	$15.23
Southwest Desert	182	$22.42
Temperate Interior West	205	$23.82
Tropical	82	$36.35

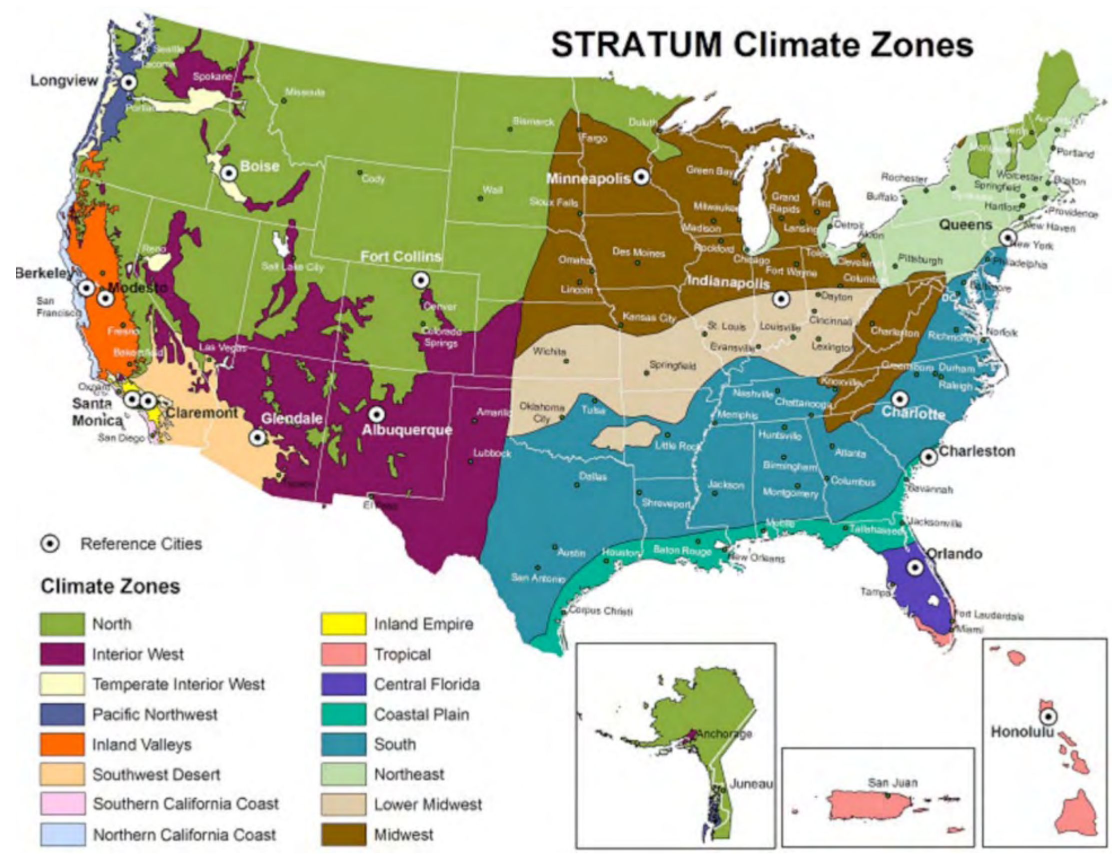
Source: Developed by the project team based on information from i-Tree and USFS Urban Tree Database.

4.2 Building energy savings from green roofs

As described previously, the energy savings benefits of green roofs depend on several factors, including local climate, building characteristics, and green roof design parameters. The [National Green Roof Energy Calculator]() is the most comprehensive tool available for quantifying reduced cooling demands associated with green roofs based on these different factors. The Calculator is based on more than 8,000 modeling simulations for 100 cities (and their corresponding weather and precipitation files), two building vintages ("old" and "new"), two building categories (office and multi-family residential), and 20 roof types (including traditional roofs, white roofs, and different green roof configurations that vary based on soil depth, leaf area index, and irrigation status).[100] Table 5 shows the various inputs the Calculator uses to estimate energy savings for different types of green roofs.

Based on the data behind the National Green Roof Energy Calculator, Table 6 shows the average energy savings per square foot of green roof (relative to black roofs) by climate region. To calculate associated monetary savings, the project team integrated data from the Energy Information Administration (2022 on average electricity costs per kWh by state for commercial customers. Users also have the option of entering local energy costs. The block-level tool that accompanies this guide contains this data for 100 cities.

Figure 6. i-Tree Climate Zones.



Source: i-Tree

Table 5. Green Roof Input Variables, National Green Roof Energy Calculator.

Variable category	Input range
Leaf area index[a]	0.5, 2, 5
Soil depth (cm)	5, 15, 30
Building type[b]	Multi-family residential; Office building
Building vintage[c]	Old, New
Irrigation status	Yes, No

4.3 Reductions in energy-related emissions

Reduced energy use for cooling in turn decreases pollutant emissions (e.g., SO_2, NO_x, $PM_{2.5}$) and GHGs associated with electricity generation. The U.S. EPA tracks emission rates for different pollutants (i.e., lbs of pollutant emitted per MWh) for almost all electric power generation in the United States through its Emissions & Generation Resource Integrated Database (eGRID). eGrid includes emission rates (i.e., pounds of pollutant emitted per MWh or MMBtu generated) for three GHGs - carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O); as well as for NO_x and SO_2. EPA's AVoided Emissions and geneRation Tool (AVERT) publishes avoided (direct) $PM_{2.5}$ emissions associated with energy efficiency projects for 10 U.S. sub-regions (for electricity generation only). Regional emission rates from eGrid and AVERT can be applied to GSI-related energy savings to estimate the associated reduction in emissions/pollutants.

Reductions in emission-related pollutants can directly reduce the risk of adverse human health effects, including premature mortality and a broad array of respiratory and cardiovascular illnesses.[101] The benefit of reducing these pollutants can therefore be valued based on associated reductions in health-related costs and/or willingness-to-pay (WTP) to avoid specific health outcomes.

The U.S. EPA's Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) currently serves as the most comprehensive source of information on air quality changes and related public health improvements. BenMAP-CE is a software package and database that allows users to estimate the health-related benefits of air quality improvements based on established health impact function (HIFs). The HIFs are derived from epidemiology studies that relate pollutant concentrations to specific health endpoints.

a. Leaf area index (LAI) is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, ranging from 0 (which represents bare ground) to 6 (which represents a dense forest).

b. Calculator relies on the U.S. Department of Energy "benchmark building" input files for a medium office building and a midrise apartment. The building types published by DOE are further divided into 16 distinct input files, each representing a U.S. climate zone. The input files account for internal and environmental loads on the building, mechanical/HVAC equipment schedules/efficiencies, and models any building system for each of the 8760 hours in a "typical" year.

c. "NEW" building vintage corresponds to building characteristics as specified in ASHRAE 90.1-2004. The "OLD" category of buildings generally represents building characteristics typical of 1980s vintage construction.

Table 6. Range of Average Annual Electricity Savings per Square Foot of Green Roof in Urban Areas, by Climate Region

Source: National Green Roof Energy Calculator

Climate Zone	Electricity Savings: High (kwH)	Electricity Savings: Low (kwH)	$ Saved per sq. ft.: High	$ Saved per sq. ft.: Low
Central Florida	11.82	-0.14	$1.54	-$0.02
Coastal Plain	12.30	1.27	$1.51	$0.16
Inland Empire	7.13	0.21	$1.81	$0.05
Inland Valleys	11.13	1.32	$2.83	$0.34
Interior West	8.91	2.00	$1.15	$0.26
Lower Midwest	7.86	2.04	$1.01	$0.26
Midwest	6.30	1.48	$0.94	$0.22
North	5.77	1.53	$0.67	$0.18
Northeast	5.17	1.32	$1.21	$0.31
Pacific Northwest	4.47	1.09	$0.46	$0.11
South	10.53	1.69	$1.41	$0.23
Southern California Coast	6.25	0.39	$1.59	$0.10
Southwest Desert	14.54	1.19	$1.79	$0.15
Temperate Interior West	5.89	1.70	$0.68	$0.20
Tropical	9.72	-1.10	$4.31	-$0.49

BenMAP-CE applies that relationship to the location and population experiencing the change in pollution exposure to calculate health impacts. Using values from the literature, BenMAP-CE also applies WTP and avoided cost estimates to calculate benefits in monetary terms. Detailed information and sources of all values used in BenMAP-CE are available in the BenMAP documentation and its technical appendices.[102]

In 2018, EPA used BenMAP-CE to calculate the benefit-per-ton of reducing $PM_{2.5}$ and $PM_{2.5}$ precursor emissions (i.e., NOx, SO_2) nationally in 17 industry sectors. Table 7 shows the resulting benefit-per-ton values for the electricity generating sector in terms of the monetary value of avoided mortality and morbidity risk. While these values can be used to estimate the value of emissions reductions at a screening level, health outcomes (and associated monetary values) will range based on the local population (e.g., density and age mix), geography, and power generation mix, among other factors.[103]

Table 7. Health-related benefits (mortality and morbidity) per ton of pollutant reduction, electricity generating sector. (2018 US$)

NO_x	SO_2	Directly emitted $PM_{2.5}$
$10,600	$69,900	$249,000

Source: U.S. EPA 2018

Several approaches have been developed to estimate the value of reducing GHG emissions. The standard (or most widely accepted) estimate is known as the "social cost of carbon" (SCC), which was developed by the U.S. Government Interagency Working Group (IWG) on Social Cost of Greenhouse Gases based on models that estimate the global impacts from climate change. The SCC estimates current and future monetary damages associated with an incremental increase in carbon emissions emitted now. These damages "include but are not limited to the impact on agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change."[104] The current estimate for the SCC is $51 per ton of avoided carbon dioxide equivalent ($CO2_e$, 2020 US $, last updated in February 2021).[105]

4.4 Heat-related health benefits

As outlined in Section 2, several studies have quantified the effect of GSI-related changes in the urban landscape for reducing adverse health outcomes associated with extreme heat, including premature fatalities and heat-related illnesses. The following sections summarize the general structure of these studies and describe a simplified approach for estimating these benefits that has been incorporated into the block-level tool developed as part of this research effort.

4.4.1 Existing studies that quantify heat-related health benefits

Quantifying and monetizing reductions in heat-related deaths, and to some extent heat-related illnesses, associated with GSI generally require the following general steps/components.

Step 1: Understanding the baseline relationship between extreme heat days and heat-related mortalities and illnesses. Researchers have developed statistically significant relationships between extreme heat days and premature fatalities in different cities. These models allow us to understand the number of deaths on extremely hot days that can be attributed to heat based on the percentage increase in baseline mortalities on those days, while controlling for other factors. Extreme heat days are typically defined based on mean or maximum temperatures, air mass category (which accounts for temperature, humidity, windspeed),[106] or days when nighttime temperatures do not fall below a minimum threshold. Several studies have applied these models to examine heat-related impacts across a large number of cities, helping to paint a national picture of heat-related impacts, including differences across regions.[107] Because the models are based on historical climate and mortality data, they inherently capture the extent to which communities have adapted to hot weather (e.g., cities with high rates of air conditioning or that are more used to higher temperatures typically experience less adverse effects). The relationship between extremely hot days and heat-related illnesses has been less studied on a national scale.

Step 2: Determining how GSI affects local temperatures/climatic conditions that in turn affect human health outcomes. The next step is to understand the extent to which increased vegetation or changes in surface reflectivity reduce urban temperatures (or improve climatic conditions) associated with EHEs. While several city-specific studies exist on this topic, there is limited literature at the national scale. Professor Sailor estimated the effect of a 10 percentage-point increase in vegetative cover in nine different U.S. cities (Table 8), reporting changes in both mean and average maximum temperatures during the summer months.[108] While temperature changes may seem small, as reported in Section 2.3 (e.g., Table 2) meaningful reductions in heat-related deaths and illnesses are achieved with changes in temperature of less than 1°F. To understand temperature differential, some researchers have directly compared temperatures/climate conditions in neighborhoods with varying levels of vegetative cover, reflective surfaces, and/or tree canopy and examined differences in health-related outcomes.

Step 3: Estimating the reduction in mortality and/or illnesses associated with GSI cooling effect. The last step is to determine the reduction in heat-related deaths and/or illnesses associated with the estimated temperature/climatic changes determined in Step 2. This has been done in different ways, for example, some studies have used estimated temperature reductions/climate changes (e.g., temperature combined with humidity, air mass days) to determine the annual change in the number of days classified as "heat wave days" or "extreme heat days," quantifying health outcomes by assuming heat-related mortalities do not occur on days that no longer meet this classification. Others have used results from existing studies to correlate reductions in fatalities and illnesses to reductions in temperature. For example, to estimate heat related mortalities in Tacoma (see

Figure 5), Earth Economics seemingly applied findings from a study that found a 2.05% increase in mortality for each 1°C increase in temperature above 28 °C (82°F) – this assumption was applied at the Census tract level to better capture impacts within intra-urban heat islands (see Table 2). For heat-related illnesses, several studies have compared emergency room visits, hospitalizations, and/ or emergency calls from neighborhoods with varying levels of vegetation and/or reflective surfaces.

Step 4: Monetizing avoided health outcomes. According to economic theory, the best measure of the value of reducing the risk of an adverse health effect is the average that individuals are willing-to-pay to reduce the risk by a small amount. For example, when evaluating environmental policies, the U.S. EPA applies estimates of how much people are willing to pay for small reductions in their risks of dying from adverse health conditions that may be caused by environmental pollution. These estimates of willingness to pay (WTP) for small reductions in mortality risks are often referred to as the "value of a statistical life" (VSL). This is because these values are typically reported in units that match the aggregate dollar amount that a large group of people would be willing to pay for a reduction in their individual risks of dying in a year, such that we would expect one fewer death among the group during that year on average.[109] The current VSL is equal to $10.7 million per avoided death (2022 US $).

For non-mortality health related health outcomes, reliable WTP studies are not always available. Alternative methods for valuing health outcomes include avoided medical costs and/or estimates of lost productivity. These methods result in relatively conservative estimates of value because they only consider a portion of the total demand for avoiding a health risk. For example, BenMAP-CE values hospital admissions based on the medical costs incurred during the stay in the hospital; this ignores the pain and suffering components of value that would be included in WTP. Table 9 presents monetary values included in BenMAP-CE (per incident) for hospital admissions and emergency room visits.

4.4.2 Applying these studies to estimate GSI-related urban cooling benefits

Overall, quantifying and monetizing the effects of GSI (and other UHI interventions) on heat-related deaths and illnesses is complicated, and depends on several location-specific factors. However, as evidenced throughout this guide, significant health benefits can be achieved. To estimate the value

Table 8. Direct Cooling Benefits Associated with 10-Percentage Point Increase in Vegetated Area in Nine U.S. Cities

City	Average Temperature Reduction in temperature (°F)	Maximum Temperature Reduction in temperature (°F)
Washington D.C.	0.31	0.32
Baton Rouge	0.22	0.18
New Orleans	0.13	0.27
Atlanta	0.5	0.58
Charlotte	0.04	0.16
Detroit	0.5	0.72
Grand Rapids	0.25	0.27
Baltimore	0.4	0.23
Philadelphia	0.38	0.49

Source: Sailor, D.J. 2003. Streamlined Mesoscale Modeling of Air Temperature Impacts of Heat Island Mitigation Strategies. May 12. Final Project Report. US EPA Assistance ID No. 82806701.

of these benefits, the block-level tool relies on data from the U.S. EPA CIRA and other studies to estimate baseline heat-related mortalities in 60 cities. For each city, we estimate reductions in temperatures based on findings reported in Tables 10a and 10b below, extrapolating findings for specific cities to develop regional estimates. We then correlate temperature reductions and/or reductions in extreme heat days to estimate associated changes in heat-related deaths. This yields an estimate of the citywide change in premature fatalities associated with a 10% increase in urban greening.

Obviously no individual GSI project will result in a 10% change in urban surfaces within an individual city. However, block-level greening efforts may provide this benefit and/or individual projects may contribute to larger GSI or urban greening efforts, thus offering a "contributory benefit." We therefore developed downscaled results for each city to estimate the average per unit benefits of GSI for different practices (e.g., benefits that each square foot of green roof or per tree contributes). Because it is based on citywide data, this method likely underestimates the benefits of GSI cooling interventions located in "intra-urban" heat islands (i.e., Census areas where UHI effects are particularly pronounced). However, given the uncertainty associated with the overall estimates, this method provides reasonable screening level estimates for characterizing the heat-related health benefits associated with GSI. Within a given city, more detailed analysis could be performed to better capture the benefits in high priority areas for urban heat.

To estimate reductions in heat-related illnesses, the tool relies on data from CDC's National Environmental Health Tracking Network (NEHTN), which tracks heat-related mortalities, emergency room visits, and hospitalizations for participating states. Specifically, it applies the ratio of heat-related mortalities to heat-related emergency room visits and hospitalizations using data in each participating state (average regional values are applied to non-participating states) to the number of avoided deaths determined in the previous analysis. It is worth noting that there is great uncertainty related to the morbidity effects of extreme heat events. Heat-related illnesses are historically underreported and are often misclassified or not identified as being related to extreme temperatures. Because of this, the number of heat-related illnesses reflected in the CDC data likely underestimate the full impact of exposure to periods of high temperatures.

Finally, the tool applies EPA's VSL and the values reported in Table 10a to estimate the monetary value of avoided heat-related health effects. Table 10b shows per unit values developed for three representative cities based on the methodology described herein. In addition to benefits associated with avoided heat-health effects, the table also shows per unit energy saving values for each city.

4.5 Additional benefits

Section 2 provided a summary of additional potential benefits associated with the cooling effect of GSI, including reduced ozone formation, water quality improvements, and reduced wear and tear on infrastructure. Due to the site-specific nature of these benefits, and lack of available (widely zapplicable) studies, quantitative values for these benefits were not developed as part of this research. However, consideration of qualitative values should be incorporated into GSI-related decision-making.

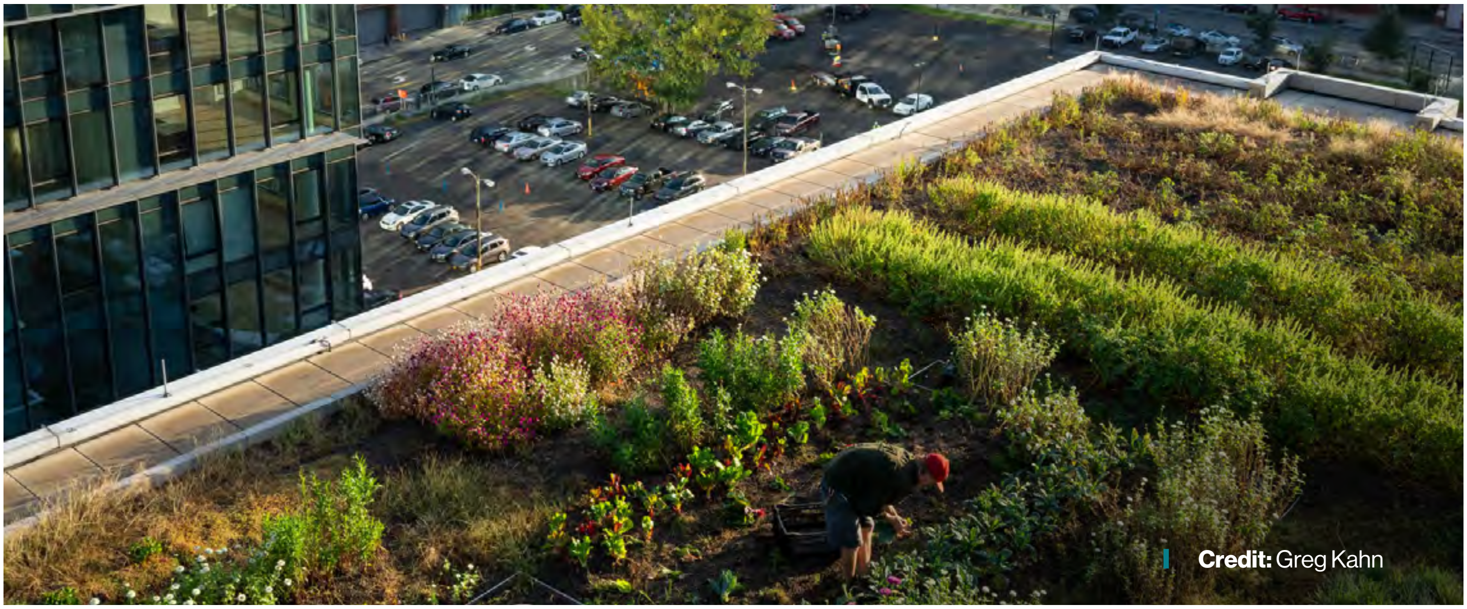
Table 9. EPA Values Hospitalizations and ER Visits

Health Effect	Value per Case (2018 US$)
Hospital admission	$18,195 to $49,128 (varies by age and cause of hospitalization)
Emergency room visit	$474 - $566

Source: U.S. EPA 2018

Table 10a. Sample estimates of values associated with conversion of ten percent of impervious area to vegetated cover or light reflective permeable pavement, by region and practice type (Dollar values in 2022 US$)

Region & Practice	Temp. Reduction (°F)	Decrease in days over MMT* [110]	Decrease in Heatrelated Deaths	Decrease in ER visits	Decrease in hospitalizations	Value of avoided death ($M)	Value of decreased ER visits ($M)	Value of reduced hospitalization ($M)	Total Public Health value ($M)	Public Health Value per sq.ft or tree
Philadelphia										
Green Roof	0.38	6.40	16.76	50.6	130.7	$157.22	$0.03	$4.48	$161.72	$0.41
Permeable Pavement	0.55	8.65	22.69	72.7	177.0	$212.85	$0.04	$6.07	$218.96	$0.55
Rain Garden/ Bioretention	0.38	6.40	16.76	50.6	130.7	$157.22	$0.03	$4.48	$161.72	$0.41
Trees	0.38	6.40	16.76	50.6	130.7	$157.22	$0.03	$4.48	$161.72	$290.92
Tucson										
Green Roof	0.30	4.88	3.01	21.4	6.0	$28.22	$0.04	$0.21	$28.44	$0.04
Permeable Pavement	0.44	6.20	3.82	27.1	7.6	$35.79	$0.01	$0.26	$36.06	$0.06
Rain Garden/ Bioretention	0.30	4.88	3.01	21.4	6.0	$28.22	$0.01	$0.21	$28.44	$0.04
Trees	0.30	4.88	3.01	21.4	6.0	$28.22	$0.01	$0.21	$28.44	$43.61
Atlanta										
Green Roof	0.50	8.20	3.63	530.2	99.8	$34.04	$0.28	$3.42	$37.74	$0.10
Permeable Pavement	0.72	12.40	5.52	806.7	151.9	$51.79	$0.43	$5.20	$57.43	$0.15
Rain Garden/ Bioretention	0.50	8.20	3.63	530.2	99.8	$34.04	$0.28	$3.42	$37.74	$0.10
Trees	0.50	8.20	3.63	530.2	99.8	$34.04	$0.28	$3.42	$37.74	$130.35



Credit: Greg Kahn

Table 10b. Sample estimates of energy savings associated with reduced need for building climate control by region and practice type

Region & Practice	Electricity Savings (kW.h/sq.ft)	Annual electricity savings ($M)	Annual Natural Gas Savings ($M)	Annual natural gas savings ($M)	Total Annual Energy Savings ($M)	Energy Savings per sq.ft or tree	Air Emission Savings from energy use Reduction per sq.ft. or tree
Philadelphia							
Green Roof	0.5	$16.48	0.0	$27.29	$43.77	$0.11	$10.77
Trees	84.6	$5.33	30.2	$25.08	$30.41	$54.70	$2.63
Tucson							
Green Roof	0.7	$45.26	0.0	$15.48	$60.74	$0.10	$7.29
Trees	182.1	$14.11	1.2	$0.95	$15.06	$23.10	$2.82
Atlanta							
Green Roof	0.6	$21.42	0.0	$14.14	$35.56	$0.09	$7.39
Trees	153.5	$4.90	5.1	$2.67	$7.57	$26.15	$1.47

5 Funding, Financing, and Partnerships

Credit: Paul Joseph Brown


Harrison St 300

FUNDING, FINANCING, AND PARTNERSHIPS

Funding has been identified as a major barrier to implementing GSI. Additionally, extreme heat has not historically been prioritized as a major public health risk or environmental hazard.

As such, strategies to mitigate heat stress or increase heat resiliency have lacked an obvious or dedicated source of funding. As demonstrated throughout this guide, intentionally designed GSI can reduce urban heat and improve public health outcomes. This provides a unique opportunity to apply for alternative sources of funding or co-fund or partner with public health agencies on stormwater management projects. This section presents information on example funding opportunities and outlines case studies of successful partnerships for publicly funded GSI heat mitigation projects.

5.1 Federal funding for extreme heat

To create a comprehensive guidance on the array of federal funding for urban heat stress, the Georgetown Climate Center published the Federal Funding Compendium for Urban Heat Adaptation. This compendium lists federal programs that could potentially fund state and local government adaptations to urban heat islands. None of the programs outlined in the compendium are specific to urban heat stress reduction, but the variety of goals allow for

Credit: Diane Cook and Len Jenshel

flexibility of funds to be utilized for urban heat relief while accomplishing other objectives. The programs are broken down into Community Development, Energy, Environment, Public Health, and Transportation sectors. In the decade since the publication of this still-applicable compendium, other federal funding has become available that would be suitable for GSI projects aimed at reducing urban heat. The National Wildlife Federation has recently released the Nature-based Funding Solutions Database, a more up to date and comprehensive guide to federal funding opportunities supported by the Bipartisan Infrastructure Law and Inflation Reduction Act.

Some additional sample programs currently supported by direct or indirect federal funding include:

- **EPA Environmental Justice small grants program** supports communities working on solutions to local environmental and public health issues. Grants can be issued directly to nonprofit organizations or tribal governments for amounts between $75,000 - $100,000. In the most recent grant cycle, a community development corporation in Mesa, AZ was awarded a grant to focus on urban heat interventions including street trees for shade in an underserved neighborhood.
- **NOAA Urban Heat Island mapping program** is part of the Justice40 Initiative, which targets funds towards communities that are marginalized, underserved and overburdened by environmental degradation. The program funds a process to help cities plan and execute a volunteer-based community science field campaign that engages residents in a study to map and understand heat distribution in their communities. Over 40 communities across the United States have participated in this program over the past 5 years.
- **FEMA Building Resilient Infrastructure and Communities (BRIC) grant** funding doubled over the last year to $2.3 billion to help states and local governments, tribes, and territories proactively reduce their vulnerability to heat waves, drought, wildfires, floods, and other hazards. BRIC is one of the few FEMA grants that can be applied pre-disaster mitigation and does not require an emergency declaration. This grant prioritizes climate and clean energy investment in disadvantaged communities.
- **FEMA Safeguarding Tomorrow Revolving Loan Funds** were included in FEMA's appropriations within the Bipartisan Infrastructure Law. This fund supports the states and tribal entities in establishing hazard mitigation loan funds. Projects eligible to access funding from a local revolving loan program include those that address extreme heat, flooding, shoreline erosion, and other impacts associated with GSI responses.
- **Environmental and Climate Justice Block Grants**, authorized by the Inflation Reduction Act, under a $3 billion appropriation to US EPA's Office of Environmental Justice. These three-year grants will be available for community-led projects that reduce extreme heat, monitor air pollution, or increase resilience and adaptation.
- **Urban and Community Forestry Assistance** programs offered through the US Forest Service received $1.5 billion from the Inflation Reduction Act to provide grants for tree-planting and related activities in urban areas.

5.2 State funding and financing opportunities

Several federal funding programs are delegated to state governments which then match and administer these grant and loan programs. Some key examples that could be sources of support for nature-based projects that address heat stress include:

- **Housing and Urban Development Community Block Grants** can provide municipal agencies with support for local community projects that provide a benefit to low-income populations or prevent deterioration in vulnerable neighborhoods. GSI solutions provide a variety of benefits that foster healthier communities. Through collaborative community planning, GSI practices can lead to solutions that address environmental justice challenges.

- **Rebuilding American Infrastructure with Sustainability and Equity (RAISE) Grants,** administered at the federal level by the US Department of Transportation, provide capital and planning funding for surface transportation projects that will have a significant local or regional impact. Under the 2021 Bipartisan Infrastructure Law, this funding prioritizes resilience to climate change impacts, including projects that reduce emissions, promote clean water and air, and increase community resiliency.

GSI projects that incorporate heat mitigation components may be eligible for non-traditional funding sources with a focus on public health and environmental justice.

In addition to these federally sponsored programs, many state governments provide grant funding for municipal projects that reduce urban heat island, particularly through increasing the urban forest canopy. GSI projects that include trees within streetscape or rain-garden practices may be eligible for these grants. Examples include:

- Chesapeake Bay Trust (MD) Urban Trees Grant Program. Created and funded by the Maryland Legislature, this program provides local governments, non-profits, and community- and faith-based organizations with funding for urban tree planting. Offering funding at a range of scales, the primary requirement is that tress must be planted in urban areas with low median household income levels, high unemployment, and neighborhoods with housing projects or that were historically red lined at any time.
- Arizona Dept of Forestry and Fire Management Community Challenge Grants. This program is intended to promote and enhance the quality of Arizona's urban and community forests through more citizen involvement. Funded projects have been designed to improve the long-term health and care of the urban forest, or to initiate new urban forestry projects in Arizona communities. This kind of funding can be particularly valuable for engaging community members in the planning and care of local GSI projects.

Other state funding programs focus more broadly on environmental justice, and projects which reduce the harmful impacts associated with climate change in disadvantaged communities. As UHI effects disproportionately burden these communities, these funding sources may support responsive GSI projects or planning. Examples include:

- California EPA Environmental Justice Small Grants: while eligibility is limited to Tribal governments and non-profit organizations, this funding could support partnership efforts with local municipalities. Among the types of projects supported by this funding are those that improve community resilience through increased green space and tree cover in urban centers, improved water conservation, and increased access to safe biking or walking routes, all of which can be provided through intentionally-designed GSI.
- New York State DEC Environmental Justice Community Impact Grants. In 2022, this program distributed $3.1 million to 32 New York communities for a range of projects and programs that address environmental and public health concerns. Many projects focused on community engagement, and training in environmental issues and community-driven responses. Several highlighted urban agriculture and air quality improvements through monitoring and GSI projects.

Leveraging Partnerships to Build the Urban Tree Canopy in Louisville, KY

A partnership between TreesLouisville, a non-profit in Louisville, KY and that city's Division of Community Forestry and Department of Public Works and the area's Metropolitan Sewer District, has led to the planting of over 16,000 trees. TreesLouisville champions the multiple benefits urban trees provide including managing stormwater, reducing urban heat island, increasing habitat, improving air quality, and increasing public health. The organization galvanizes partnerships with public agencies as well as non-profit organizations and businesses to conserve and increase Louisville's urban tree canopy. Other similar programs include Trees Charlotte, Tree Pittsburgh, Tree Philly, Keep Indianapolis Beautiful, D.C.'s Casey Trees, and the Sacramento Tree Foundation.

This partnership complements the Green Infrastructure Financing Incentive Program created by MSD and the City of Louisville's Office of Sustainability. Since 2015, they have offered a one-time matching funds incentive for GSI projects that reduce stormwater runoff and help the city meet its federal consent decree to reduce sewer overflows while also reducing the city's urban heat island effect. Projects such as rain gardens, green roofs, pervious pavement and other GSI practices could qualify for matching funds through the Office of Sustainability if they kept at least 1" of stormwater out of the city's combined sewer system. The Office of Sustainability provides a $10,000 match for projects that receive $50,000 or less from MSD. The incentive program serves as a model for other cities looking to leverage combined funding opportunities across different agencies.

5.3 Project finance and partnership opportunities

GSI projects that address heat-related impacts while reducing or preventing water pollution are capital investments that can be included in municipal bond offerings or other public debt financing. There is often widespread uncertainty about this topic, but provided certain legal conditions are met, municipalities and public utilities can use revenue bonds to finance a wide variety of capital projects including on:

- Public property that the utility owns
- Public property that the utility does not own; and
- Private property when the project provides a public service

Two organizations, the WaterNow Alliance and Ceres have created guides that provide additional, practical information on this topic.

In addition, some municipalities are exploring pathways to attract outcomes-based finance for public infrastructure projects. Environmental Impact Bonds deployed in Atlanta, Buffalo, Hampton Road, VA and other cities have linked the achievement of locally desired environmental and community benefits to rates of return and risk transfer associated with private investment. Quantified Ventures, an impact investment strategy provider, has pioneered many of these bond issuances and has a history of working with municipalities and local, industry and philanthropic funders to link nature-based infrastructure solutions to public health outcomes.[111]

Private and corporate philanthropy can also provide financial support to projects that increase urban greening and reduce heat island impacts. In California, Pacific Gas and Electric's Corporate Foundation sponsors the Better Together Resilient Communities grant program to build community resilience and capacity to withstand climate-related hazards. The program solicited applications from projects that prioritized responses to past or projected exposure to climate hazards and those that address the needs of disadvantaged and/or vulnerable communities. In Connecticut, the Connecticut Urban Forest Council has supported an Urban Forest Climate Change Grants Program to fund urban forestry projects that combine efforts to respond to the local effects of climate change and that address equity and environmental justice.

5.4 Partnership opportunities

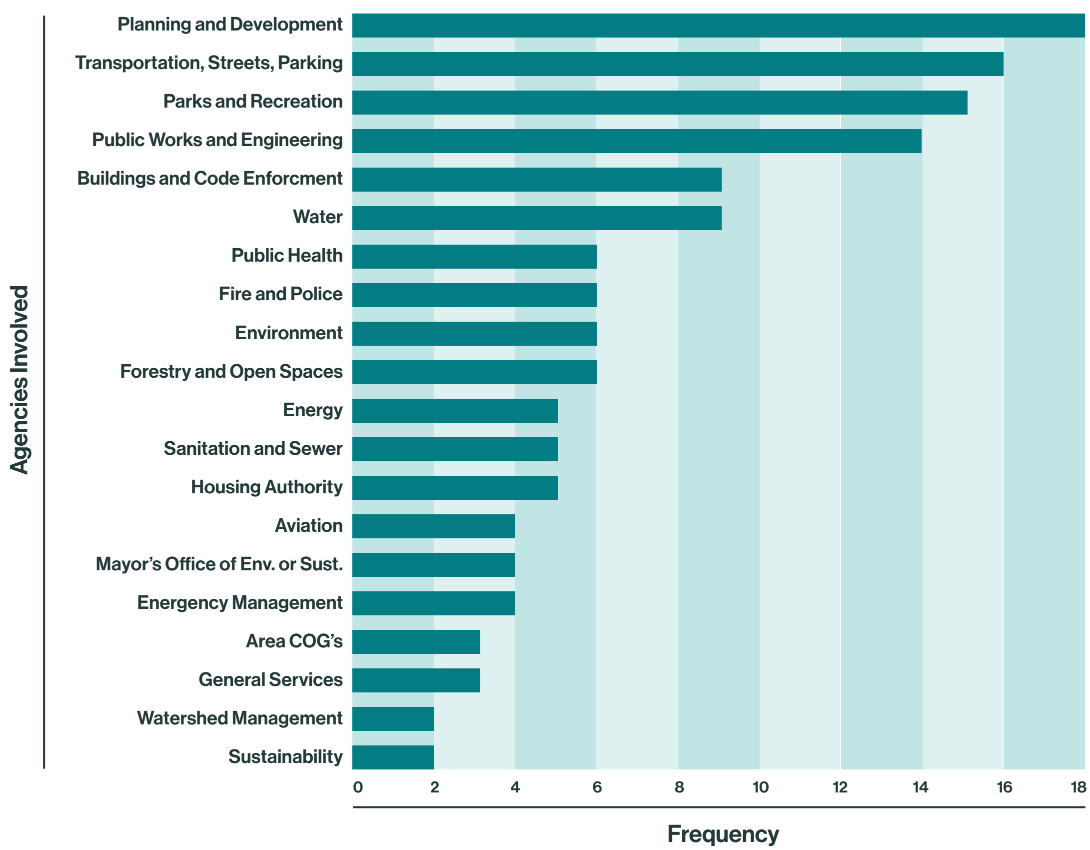
Identifying, quantifying, and monetizing the heat reduction benefits of GSI presents opportunities for partnerships related to innovative design and implementation ideas, knowledge sharing, co-funding, and increasing awareness and engagement. These partnerships can occur between municipal agencies, or with private or non-profit organizations. For example, opportunities may include public health agencies, with goals linked to respiratory, cardiovascular, or mental health outcomes; state agencies and regional partners acting under statewide ozone implementation plans; corporate or philanthropic programs with community, environmental and sustainability goals; and, potentially, participant in markets for carbon offsets or other environmental outcomes.

Intra-Municipal Partnerships for Addressing Urban Heat

In 2014, the American Council for an Energy-Efficient Economy and Global Cool Cities Alliance surveyed 26 North American cities to learn more about efforts to mitigate urban heat and its impacts. The survey found that cities plan and organize UHI mitigation strategies in a variety of ways. Most cities' policies and programs are included in an overarching comprehensive climate action or sustainability plan. Only one city had specifically included heat mitigation in its stormwater management plan. However, most of the cities set quantitative or qualitative heat reduction goals related to increasing urban tree canopy. Many had established goals related to green roofs.

Another interesting finding is that no city relied on a single department to run all UHI programs and implementation (see graph below). Only four cities indicated that a single agency is the lead for UHI plans and strategies. However, administrative burden may ease when one agency has full authority over a program. Further, when one agency coordinates actions among agencies, a larger citizen base may be engaged, departmental expertise can be leveraged, and more co-benefits may be realized.

The survey also collected data on program funding. While city budgets play a role, 19 cities utilized funding from nonprofit groups, local utilities, philanthropic foundations, or local universities. Many cities partner with groups or foundations dedicated to specific environmental causes. For example, Portland partnered with Friends of Trees, Dallas with Texas Trees Foundation, and Los Angeles with CityPlants. Some cities reported funding programs with state financial assistance. For example, Pennsylvania state PENNVEST loans funded a $30 million green streets project in Philadelphia. While a bit dated, the results of this survey highlight the role that partnerships can play in achieving and funding projects that result in UHI benefits.



Source: Global Cool Cities Alliance (2014)

6 Conclusion

Credit: Diane Cook and Len Jenshel

CONCLUSION

Understanding the potential benefits and limitations of GSI on heat-related outcomes is an important first step to planning and designing projects that can most greatly reduce UHIs and inform planning for future projects.

The authors strongly recommend the content in this document be utilized for guidance only. There are important caveats to the findings presented as well as known research gaps that should be considered when accounting for the benefits of green infrastructure in reducing heat stress and the associated public health impacts.

However, even with those caveats, this information and the benefits tool that we have provided can be useful in local efforts to "make the case" for investing in GSI. In our experience, there is considerable value in the ability to bring credible information about co-benefits to conversations with elected officials, local stakeholders, and potential project co-funders. We recommend that readers take the time to understand the nuances of identifying and calculating the heat stress reduction benefits that can be achieved through properly sited, selected and designed GSI practices.

We are particularly committed to the use of geospatial and other data to better understand the current effects of heat stress, particularly on disadvantaged and vulnerable members of our communities. The mapping resources described above can be important tools for identifying these impacts and for informing outreach efforts that engage members of these communities in planning GSI strategies and projects.

As local agency staff move into planning GSI projects (or community-scale plans,) the following overarching considerations may be useful in working with the findings from this guide:

- While it's possible to quantify the heat stress benefits of GSI, that information may be more useful in a qualitative way. The numbers don't speak for themselves; they help to illustrate and illuminate the relative merits of GSI approaches and practice types. In this way, it can be important to think about the quantified information as components of an outreach strategy with key stakeholders and decision-makers.
- Data about the distribution of heat stress impacts can provide valuable guidance in planning the location and type of GSI interventions. Tailoring these interventions to an appropriate scale of impact and effectiveness is an important factor in achieving heat reductions, as well as water quality improvements and other benefits. There is no 'one size fits all' approach.
- Because heat stress reduction is linked to public health, energy conservation and climate health outcomes, GSI programs and projects can be opportunities to create or leverage partnerships with entities that may not typically be invested in stormwater management. Collaboration with partners in these sectors can help stormwater managers optimize project design, secure community support, and secure additional funding.


Credit: Fauna Creative

ENDNOTES

1. U.S. EPA. 2022a. Climate Change Indicators: Heat Related Deaths. Available: https://www.epa.gov/climate-indicators/climatechange-indicators-heat-related-deaths. Also, Kalkstein, L., D. Sailor, K. Shickman, S. Sheridan, and J. Vanos. 2013. *Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia*. Prepared for Global Cool Cities Alliance.
2. U.S. EPA. 2002. Overview of the Human Health and Environmental Effects of Power Generation: Focus on Sulfur Dioxide (SO2), Nitrogen Oxides (NOx) and Mercury (Hg). Available: https://archive.epa.gov/clearskies/web/pdf/overview.pdf.
3. U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001.
4. Kalkstein et al. 2013.
5. U.S. EPA. 2008. Reducing Urban Heat Islands: Compendium of Strategies. Available: http://www.epa.gov/heat-islands/heatisland-compendium.
6. See, e.g., Aram, F., Garcia, E., Solgi, E., and Mansour, S. 2019, Urban green space cooling effect in cities. Heliyon 5 e01339. doi: 10.1016/j.heliyon.2019.e01339.
7. Vanos, J., L. Kalkstein, D. Sailor, K. Shickman, and S. Sheridan. 2016. Assessing the health impacts of urban heat island reduction strategies in the cities of Baltimore, Los Angeles, and New York. Prepared for Global Cool Cities Alliance. Available: https://www.coolrooftoolkit.org/knowledgebase/health-impacts-of-urban-cooling-strategies-in-baltimore-los-angeles-andnew-york-city/.
8. Kyle, P., L. Clarke, F. Rong and S.J. Smith. 2010. Climate policy and the long-term evolution of the U.S. building sector. The Energy Journal 31:2.
9. Santamouris, M., C. Cartalis, A. Synnefa, and D. Kolokotsa. 2015. On the impact of urban heat island and global watrming on the power demand and electricity consumption of buildings – A review. Energy and Buildings 98:119-124.
10. Santamouris and Osmond. 2020.
11. Li, X., Y. Zhou, S. Yo, G. Jia, H. Li, and W. Li. 2019. Urban heat island impacts on building energy consumption: A review of approaches at findings. Energy 174:407-419.
12. Ko, Y. 2018. Trees and vegetation for residential energy conservation: A critical review for evidence-based urban greening in North America. Urban Forestry and Urban Greening.
13. Wise, S., J. Braden, D. Ghalayini, J. Grant, C. Kloss, E. MacMullan, S. Morse, F. Montalto, D. Nees, D. Nowak, S. Peck, S. Shikh, and C. Yu. 2010. Integrating Valuation Methods to Recognize Green Infrastructure's Multiple Benefits. Center for Neighborhood Technology Publication. Available: https://doi.org/10.1061/41099(367)98.
14. Francis, L., F. Møller, and M. Bergen Jensen. 2017. Benefits of green roofs: A systematic review of the evidence for three ecosystem services. Urban Forestry and Urban Greening 28:167–176.
15. American Rivers, American Society of Landscape Architects, Eco Northwest, and Water Environment Federation. 2012. Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-wide.
16. Sailor, D.J. and N. Dietsch. 2007. The urban heat island Mitigation Impact Screening Tool (MIST). Environmental Modeling & Software 22:1529-1541.
17. Krayenhoff, E.S., A.M. Broadbent, L. Zhao, M. Georgescu, A. Middel, J.A. Voogt, A. Martilli, D. Sailor, and E. Erell. 2021. Cooling hot cities: a systematic and critical review of the numerical modelling literature. Environmental Research Letters 15:053007.
18. Sharma, A., S. Woodruff, M. Budhathoki, A.F. Mahlet, F. Chen, and H.J.S. Fernando. 2018. Role of green roofs in reducing heat stress in vulnerable urban communities – a multidisciplinary approach. Environmental Research Letters 13:094011.
19. Santamouris, M. and P. Osmond. 2020. Increasing green infrastructure in cities: Impact on ambient temperature, air quality and heat-related mortality and morbidity. Buildings 10(12):233. Available: https://doi.org/10.3390/buildings10120233.
20. Marando, F., M. Heris, G. Zulian, A. Udías, L. Mentaschi, N. Chrysoulakis, D. Parastatidis, and J. Maes. 2022. Urban heat island mitigation by green infrastructure in European Functional Urban Areas. Sustainable Cities and Society Vol. 77. DOI: 10.1016/j.scs.2021.103564.
21. Dong, J., M. Lin, J. Zui, T. Lin, J. Liu, C. Sun, and J. Luo. 2020. Quantitative study on the cooling effect of green roofs in a highdensity urban area – a case study of Xiamen, China. Journal of Cleaner Production 255.
22. Rosenzweig, C., W. Solecki, and R. Slosberg (PIs). 2006. Mitigating New York City's Heat Island With Urban Forestry, Living Roofs, and Light Surfaces. New York

City Regional Heat Island Initiative Final Report. P. Savio, Project Manager. Prepared for New York State Energy Research and Development Authority. NYSERDA Report 06-06.

23. Sailor, D.J. 2003. Streamlined Mesoscale Modeling of Air Temperature Impacts of Heat Island Mitigation Strategies. Final Project Report. US EPA Assistance ID No. 82806701.

24. U.S. EPA. 2008. Reducing Urban Heat Islands: Compendium of Strategies. Available: http://www.epa.gov/heat-islands/heatisland-compendium.

25. Anderson, V. and W.A. Gough. 2021. Nature-based cooling potential: a multi-type green infrastructure evaluation in Toronto, Ontario, Canada. International Journal of Biometeorology 66:397-410.

26. Balany, F., A. WM Ng, N. Muttil, S. Muthukumaran, and M. Sing Wong. 2020. Green Infrastructure as an Urban Heat Island Mitigation Strategy – A Review. Water 12:3577.

27. U.S. EPA. 2008.

28. U.S. Environmental Protection Agency. 2018. *Estimating the environmental effects of green roofs: A case study in Kansas City, Missouri*. EPA 430-S-18-001. www.epa.gov/heat-islands/using-green-roofs-reduce-heat-islands.

29. Jacob, D.J. and D. A. Winner. 2009. Effect of climate change on air quality. Atmospheric Environment 43(1): 51-63.

30. Porter, W.C. and C.L. Heald. 2019. The mechanisms and meteorological drivers of the summertime ozone–temperature relationship. Atmospheric Chemistry and Physics 19:13367–13381.

31. Akbari, H. 2002. Shade trees reduce building energy use and CO2 emissions from power plants. Environmental Pollution 116:S119-S126.

32. Steiner, A.L., A.J. Davis, S. Sillman, R.C. Owen, A.M. Michalak, and A.M. Fiore. 2010. Observed suppression of ozone formation at extremely high temperatures due to chemical and biophysical feedbacks, Proceedings of the National Academy of Sciences of the U.S.A. 107:46.

33. U.S. EPA. 2008.

34. Ludwig, V. 2016. The Heat Island Effect and Air Quality. EPA Advance Program Webinar Series.

35. Nowak, D.J., S. Hirabayashi, A. Bodine, and E. Greenfield. 2014. Tree and forest effects on air quality and human health in the United States. Environmental Pollution. 193: 119-129.

36. Kalkstein, L., D. Sailor, K. Shickman, S. Sheridan, and J. Vanos. 2013. Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia. Prepared for Global Cool Cities Alliance.

37. Kalkstein et al. Also, U.S. EPA. 2022a.

38. Wilson, B. 2020. Urban Heat Management and the Legacy of Redlining. Journal of the American Planning Association 86(4):443-457. DOI: 10.1080/01944363.2020.1759127.

39. Hoffman, J.S., V. Shandas, and N. Pendleton. 2020. The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas." Climate 8(1):12. https://doi.org/10.3390/cli8010012.

40. U.S. EPA. 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. Available: https://www.epa.gov/cira/multi-model-framework-quantitativesectoral-impacts-analysis.

41. Anderson, B. and M. Bell. 2011. Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 US communities. Environmental Health Perspectives 119(2):210–218.

42. Vanos, J. et al. 2016.

43. Kalkstein, L. et al., 2013.

44. Santamouris and Osmond. 2020.

45. Stone, B. Jr., J. Vargo, P. Liu, D. Habeeb, A. DeLucia, M. Trail, Y. Hu and A. Russel. 2014. Avoided heat-related mortality through climate adaptation strategies in three US Cities. PloS one 9,6. DOI: 10.1371/journal.pone.0100852.

46. Graham, A. 2012. Census Tract-Level Outdoor Human Thermal Comfort Modelling and Heat-Related Morbidity Analysis during Extreme Heat Events in Toronto: The Impact of Design Modifications to the Urban Landscape. A thesis presented to the University of Guelph in partial fulfilment of requirements for the degree of Master of Landscape Architecture. Available: https://atrium.lib.uoguelph.ca/items/9a6bf635-b839-4d9e-ad3f-9ad9f4395d23.

47. Silva, H.R., P.E. Phelan, and J.S. Golden. 2010. Modeling effects of urban heat island mitigation strategies on heat-related morbidity: a case study of Phoenix, AZ. International Journal of Biometeorology 54:13-22.

48. Yenneti, K., L. Ding, D. Prasad, G. Ulpiani, R. Paolini, S. Haddad, and M. Santamouris. 2020. Urban overheating and cooling potential in Australia: An evidence-based review. Climate 8:126.

49. Delpla, I., A.V. Jung, E. Baures, M. Clement, and O. Thomas. 2009. Impacts of climate change on surface water quality in relation to drinking water production. Environmental International 35:1225-1233.

50. U.S. EPA. 2022b. The Effect of Climate Change on Water Resources and Programs. Watershed Academy Web. Available: https://cfpub.epa.gov/watertrain/moduleFrame.cfm?parent_object_id=2407.

51. Timm, A., V. Ouellet, and M. Daniels. 2020. Swimming through the urban heat island: Can thermal mitigation practices reduce the stress? River Research and Applications. DOI: 10.1002/rra.3732.

52. Niemi, E., K. Lee, and T. Raterman. 2006. Net Economic Benefits of Using Ecosystem Restoration to Meet Stream Temperature Requirements. Proceedings of the Water Environment Federation 2007(5). DOI: 10.2175/193864707786619521.

53. Timm et al. 2020.

54. Ketabchy, M., D.J. Sample, T. Wynn-Thompson, and M.N. Yazdi. 2019. Simulation of watershed-scale practices for mitigating stream thermal pollution due to urbanization. Science of the Total Environment: 671:215-231.

55. Ketabchy et al. 2019.

56. Delaware Valley Regional Planning Commission (DVRPC). 2021. Municipal Management of Extreme Heat. Available: https://www.dvrpc.org/Reports/MIT033.pdf.

57. DVRPC. 2021.

58. McPherson, E.G. and J. Muchnick. 2005. Effects of street tree shade on asphalt concrete pavement performance. Journal of Arboriculture 31(6).

59. Kats, G. and K. Glassbrook. 2016. Achieving Urban Resilience: Washington DC actively managing sun and rain to improve District health and livability and slow global warming while saving billions of dollars. Capital-E. Available: https://www.coolrooftoolkit.org/wp-content/uploads/2016/12/Kats-SmartsurfacesDC-FullReport.pdf.

60. Garrison, N., C. Horowitz, and C.A. Lunghino. 2012. Looking Up: How Green Roofs and Cool Roofs Can Reduce Energy Use,

FIGURE CITATIONS

World Meteorological Organization. Urban heat island (webpage). Available: https://community.wmo.int/en/activity-areas/urban/urban-heat-island.

U.S. EPA. 2018. Environmental Benefits Mapping and Analysis Program – Community Edition: User's Manual. Updated for BenMAP-CE Version 1.4.8. Available: https://www.epa.gov/sites/production/files/2015-04/documents/benmapce_user_manual_march_2015.pdf.

i-Tree. i-Tree Streets climate zones. Available: https://static.itreetools.org/media/images/StratumClimateMap_v9_Sep2007.original.jpg

US EPA. 2018. Estimating the Environmental Effects of Green Roofs: A Case Study in Kansas City, Missouri. EPA 430-S-18-001. Available: https://www.epa.gov/heatislands/estimating-environmentaleffects-green-roofs-case-study-kansas-city-missouri.

Flickr. Available: https://c1.staticflickr.com/5/4120/4754624921_6dd1b7b2b6_b.jpg

Global Cool Cities Alliance. 2014. Urban Heat Island Policy Survey. Available: https://globalcoolcities.org/urban-heat-island-policy-survey/

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GSI Impact Hub

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