Green Stormwater Infrastructure (GSI)

COOLING ANALYSIS

Nighttime Heat Mitigation Co-benefits of Vegetated GSI

September 2023

THE CITY OF PHILADELPHIA OFFICE OF SUSTAINABILITY
PHILADELPHIA WATER DEPARTMENT
Jefferson Thomas Jefferson University HOME OF SIDNEY KIMMEL MEDICAL COLLEGE
WCU WEST CHESTER UNIVERSITY
WILLIAM PENN FOUNDATION

EXECUTIVE SUMMARY

Climate change presents ever expanding risks for Philadelphians. Among these risks, rising temperatures combined with the urban built environment create increasing exposure to extreme heat. Climate projections published for Philadelphia (Useful Climate Science for Philadelphia: Past and Future, 2014; All-Hazard Mitigation Plan, 2022) indicate that the exposure to extremely hot days – when the daily maximum temperature is about 95 degrees Fahrenheit (°F) – are poised to rise both in frequency and severity. Further, local climate projections indicate that the city could experience as many as 28 days at 95°F or above per year by the end of the century under a moderate future warming scenario (RCP4.5).[1] Under a high future warming scenario (RCP8.5), this number could increase to as many as 67 days per year. Additionally, nighttime temperatures are rapidly warming, with cause for concern due to impacts ranging from sleep disruption to immune function, to heat-related mortality.

In light of these risks, the City of Philadelphia ("The City") has prioritized achieving the broadest range of benefits from innovative, multi-use infrastructure programs. While infrastructure planning at large has traditionally focused on assets that perform a single function, the City addresses the intersection of multiple needs by leveraging integrated approaches to resource management. Philadelphia's combined sewer overflow long-term control plan, Green City, Clean Waters, has served as a steadfast example of this policy shift. Green City, Clean Waters is a 25-year plan to reduce the volume of stormwater pollution entering the City's combined sewer system in part through the use of green stormwater infrastructure (GSI). Green infrastructure at scale provides a wide array of additional benefits to many city functions, including air pollution alleviation, carbon emission reduction, and urban heat mitigation. The varied impact of a changing climate thus requires the attention of all departments working at the nexus of climate resilience, public health, and environmental management.

Following an earlier pilot launched in 2019, Philadelphia's Office of Sustainability, in collaboration with the Philadelphia Water Department and academic partners at Thomas Jefferson University and West Chester University, developed this subsequent study to further explore the capacity of GSI to mitigate the impacts of excessive heat. The City believes that this study, titled Analysis of Nighttime Heat Mitigation Co-Benefits of Vegetated GSI, will highlight additional benefits of cooling from various green stormwater practices in both magnitude of impact and geographic distance. In order to ensure the success of this heat-capacity analysis, the project team, with funding from the William Penn Foundation, conducted this preliminary study to build on successful methodology implemented within local, neighborhood contexts. This summary report outlines the key findings and modifications needed for the research design to support continued, larger-scale studies on heat resilience.

1 RCP, or Representative Concentration Pathway, refers to the trajectory of greenhouse gas concentrations in the atmosphere by 2100.

HEAT VULNERABILITY IN PHILADELPHIA

Excessive heat is an invisible hazard and therefore it is easy to underestimate its danger compared to the destruction seen from other weather events like a flood or hurricane. However, excessive heat is the leading cause of weather-related deaths in Philadelphia. Due to climate change, excessive heat events (occurring from a combination of high temperatures and high humidity) in Philadelphia are expected to increase in frequency, intensity, and duration.[2] Residents are experiencing increased and prolonged exposure to elevated heat both during the day and—perhaps of even greater concern—throughout the night. Nighttime heat has been shown to give rise to health risks through sleep disruption, as well as exacerbate existing health conditions; when there is no break from the heat it increases physiological stress to the body. The City of Philadelphia's Heat Vulnerability Index (HVI) reveals that some neighborhoods are more vulnerable to heat than others, based on factors linked to sociodemographic and health status data. Moreover, the energy costs and inaccessibility of air conditioning experienced by low-income communities during high heat events can magnify the heat risk. Philadelphia has several neighborhoods that have been identified as bearing significantly higher energy burdens during peak temperatures[3]—many of which are Black and Latinx communities. These communities are and will continue to be disproportionately affected by extreme heat events, creating an emerging hazard with compounding effects.

2 National Weather Service (NWS) Glossary: Excessive Heat. Retrieved 8 June 2023.

3 Philadelphia Department of Public Health. (2019). Philadelphia Heat Vulnerability Index. https://phl.maps.arcgis.com/apps/webappviewer/index.html?id=9ef74cdc0c83455c9df031c868083efd

GREEN SOLUTIONS

Urban heat island (UHI) impacts have been well-documented in Philadelphia, such that some neighborhoods experience heat disparities upwards of 20°F during peak midday summer heat.[4] Importantly, neighborhoods with increased canopy cover have reduced heat vulnerability: urban greenspace reduces the UHI effect by increasing shade cover and the amount of sunlight reflected, and through evaporative cooling. Impacts of these processes can be measured by their magnitude (cooling intensity) and geographic reach (cooling distance). Magnitude is measured by comparing surface temperature differences between the vegetated area and the surrounding area, while geographic reach evaluates the distance beyond vegetation at which temperature is influenced.

One way the City currently increases urban greenspace is through innovative "green" stormwater management programs like Green City, Clean Waters (GCCW). Typical, or "gray," stormwater infrastructure is designed to manage water inputs through a combination of channels, pipes, and drains that ultimately feed into a larger body of water. Green stormwater infrastructure (GSI) is designed to manage water where it falls, mimicking natural processes, e.g., permeable pavements. Vegetated GSI includes rain catchment systems that incorporate plants such as trees, shrubs, and other wet area-tolerant plant assemblages. Examples seen across Philadelphia are rain gardens, stormwater tree trenches, planters, and bumpouts.

Though this 25-year program is intended to reduce combined sewer overflows, GCCW also considers integrated heat mitigation opportunities. GCCW vegetation could have considerable influence on cooling in urban areas: a 2019 pilot study on GSI cooling suggested correlations between proximity to GSI and reduced daytime surface temperature and relative humidity. As the City grapples with more frequent high heat days—and perhaps of greater concern, more high heat nights—integrated solutions that combine stormwater management with heat reduction are a critical consideration.

4 Philadelphia Office of Sustainability. (2015). Growing Stronger: Toward A Climate-Ready Philadelphia.

ANALYSIS OBJECTIVES

The Green Stormwater Infrastructure (GSI) Cooling Analysis aimed to answer the following questions:

- **What are the geographic disparities in nighttime heat at various locations?**
- **To what extent does vegetated GSI mitigate nighttime warming?**

To better understand how the City's infrastructure can support multipurpose solutions, this analysis aims to evaluate the magnitude and geographic reach of nighttime surface temperature cooling generated by vegetated GSI. With funding from the William Penn Foundation, the Philadelphia Office of Sustainability, in collaboration with Philadelphia Water Department and academic partners at Thomas Jefferson University and West Chester University, designed this follow-up study to further highlight the additive value of integrating heat mitigation into stormwater infrastructure planning.

METHODOLOGY

Site selection

When choosing locations for this study, the project team prioritized sites with low tree canopy cover in neighborhoods with high heat vulnerability (Figure 1). The two GSI sites in Upper North Philadelphia included the Panati Playground ("Panati") and the Cecil B. Moore Recreation Center ("CBM"), both of which had less than 10% canopy cover within a 500-square foot radius.

Study Sites Compared to Philadelphia Heat Variation

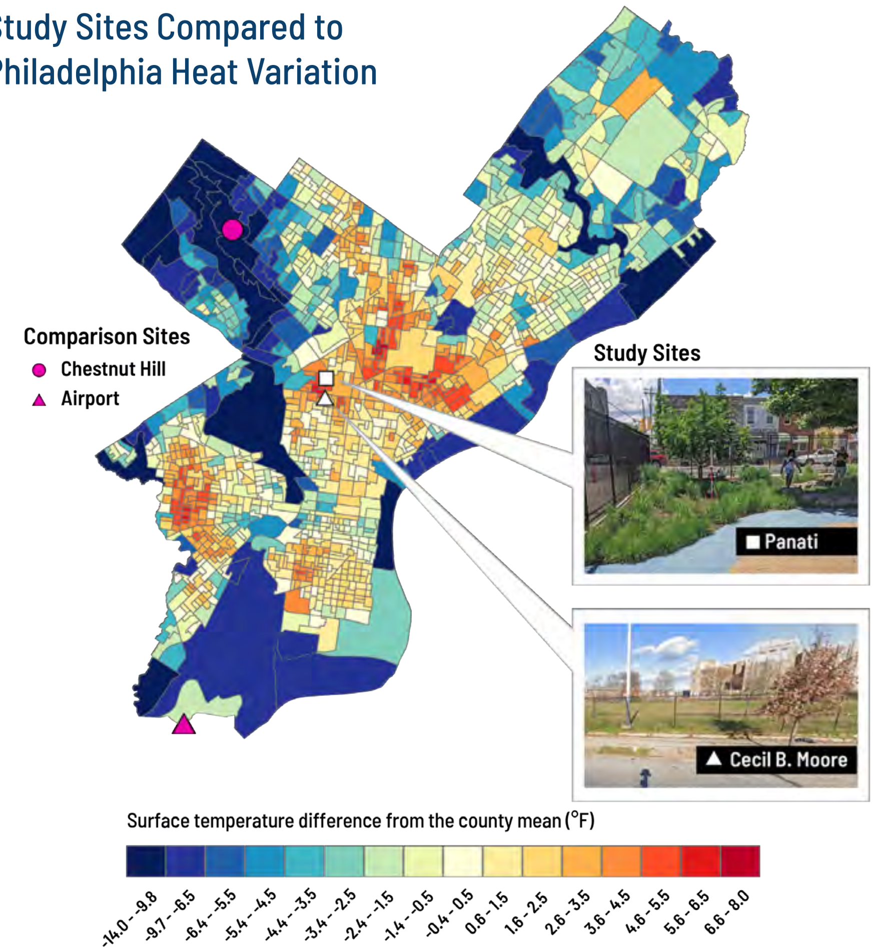

Figure 1. A heat map of Philadelphia showing average temperature differences from the county mean for the hottest 7 cloud-free days taken by satellite (2013-2015), relative to study sites. Data courtesy of David Hondula, Arizona State University.

Figure 2. Panati Playground (top-left and top-right) and Cecil B. Moore Recreation Center (bottom)

The type of vegetated GSI varied between sites: the Panati Playground has a rain garden with trees, whereas the Cecil B. Moore Recreation Center has tree trenches incorporated into the sidewalk (Figure 2).

Temperature and Albedo Recordings

Surface temperature recordings were taken using low-cost sensors with air temperature and relative humidity measurement and logging capability. Sensors were placed at ground-level; recorded temperatures represent surface temperatures. These sensors also had comparable precision and accuracy to high-end sensors at Philadelphia Health Department's Air Management Services Laboratory. August 25 and 26, 2021 were chosen for sampling because they fell during a series of days of elevated temperatures in the 90s with no rain or cloud cover, thus considered "extreme heat" days. Temperature measurements were taken hourly and averaged 'overnight' (8:00pm-7:00am) for each day and site.

Albedo, a measure of reflectivity, was characterized for all surface types at each site. Mean brightness of matte white cardstock was compared to mean brightness of surfaces next to each sensor.

To assess the magnitude and geographic reach of GSI cooling, sensors were spaced at optimized distances ranging on average 8 feet apart (range 2.5-16 feet) at Panati, and on average 6 feet apart (range 2-12 feet) at CBM. Magnitude assessment compared sensor readings from GSI locations to adjacent sidewalk, using sidewalk without GSI as a control. Geographic reach was evaluated through spatial analysis that interpolated surface temperature for each time frame from sensor and albedo data.

To place these assessments in a broader context, nighttime temperature disparities were evaluated between neighborhoods across the city. Measurements from Panati and CBM were compared to those reported from Chestnut Hill, which represents one of the coolest neighborhoods, Philadelphia International Airport (PHL), which is the official thermometer of record in Philadelphia. The 30-year historic average (1992-2021) daytime maximum and minimum temperatures at PHL were referenced from National Oceanic and Atmospheric Administration (NOAA) Automated Surface Observation System (ASOS) records.[5]

FINDINGS

Local Temperature Disparities

Temperature recordings across various locations in Philadelphia, including PHL, Chestnut Hill, and sites used for this study, revealed geographic disparities in UHI effect (Figure 3). In the study sites, averaged overnight temperatures were nearly as high as historic daytime highs at PHL. Furthermore, overnight temperatures were notably higher—by about 6-8 °F—at study sites compared to Chestnut Hill, one of the coolest neighborhoods in the city.

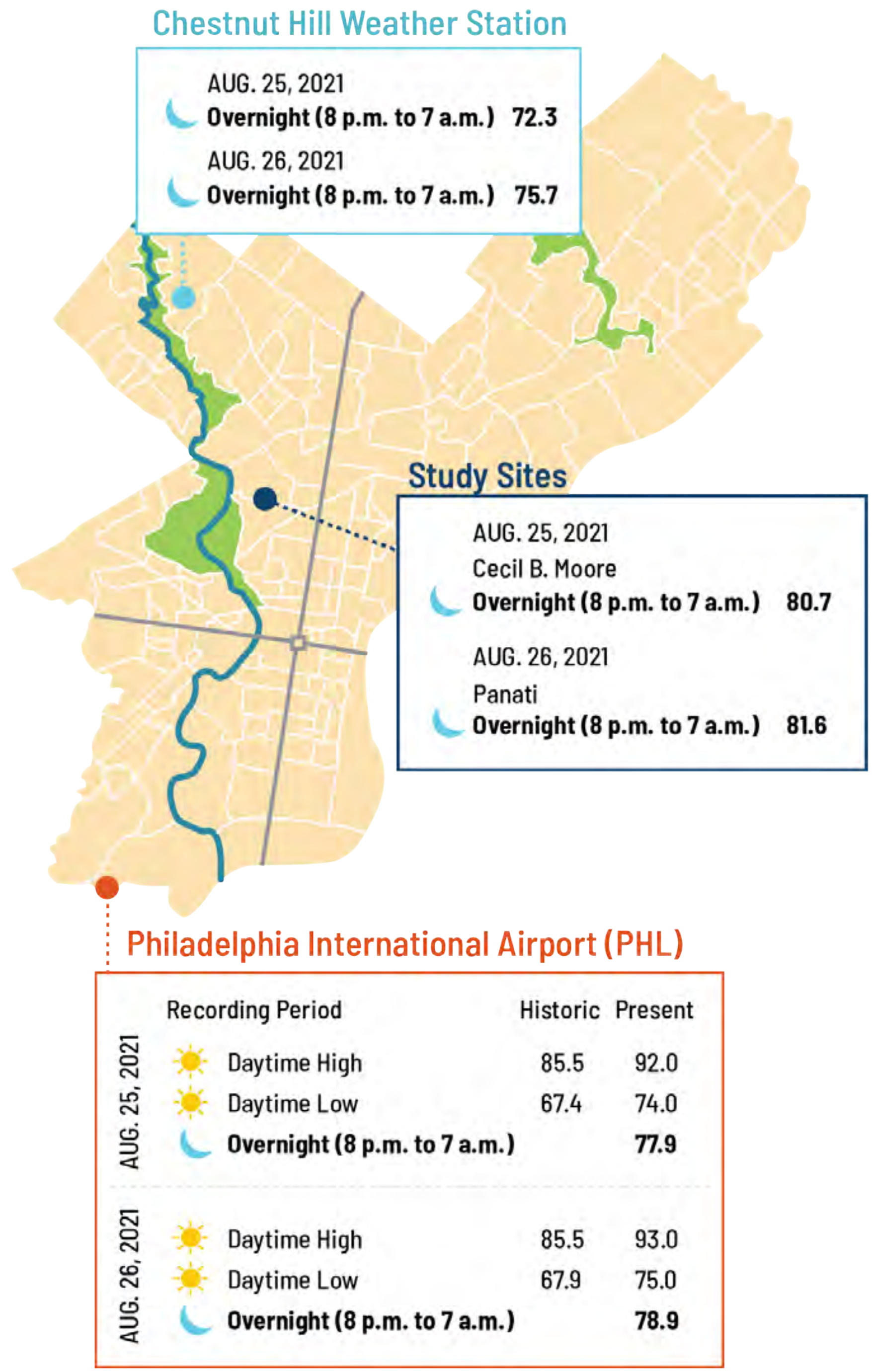

Figure 3. Averaged overnight temperatures at various locations across Philadelphia

5 Menne, Matthew J., Imke Durre, Bryant Korzeniewski, Shelley McNeill, Kristy Thomas, Xungang Yin, Steven Anthony, Ron Ray, Russell S. Vose, Byron E.Gleason, and Tamara G. Houston (2012): Global Historical Climatology Network - Daily (GHCN-Daily), Version 3. [GHCND:USW00013779]. NOAA National Climatic Data Center. DOI: 10.7289/V5D21VHZ.

Table 1. Average overnight temperature measurements (°F) of various surfaces for both study sites. 'Reference' refers to paved locations adjacent to or across the street from GSI locations that are used to represent the absence of GSI.

	Site	
	Cecil B. Moore	Panati
Vegetated GSI	Tree trench pits	Rain garden
	78.9	79.5
Surrounding Surface	Adjacent, newly installed sidewalk	Adjacent sidewalk
	82.2	83.0
Reference	Original sidewalk	Across street sidewalk
	80.7	90.3

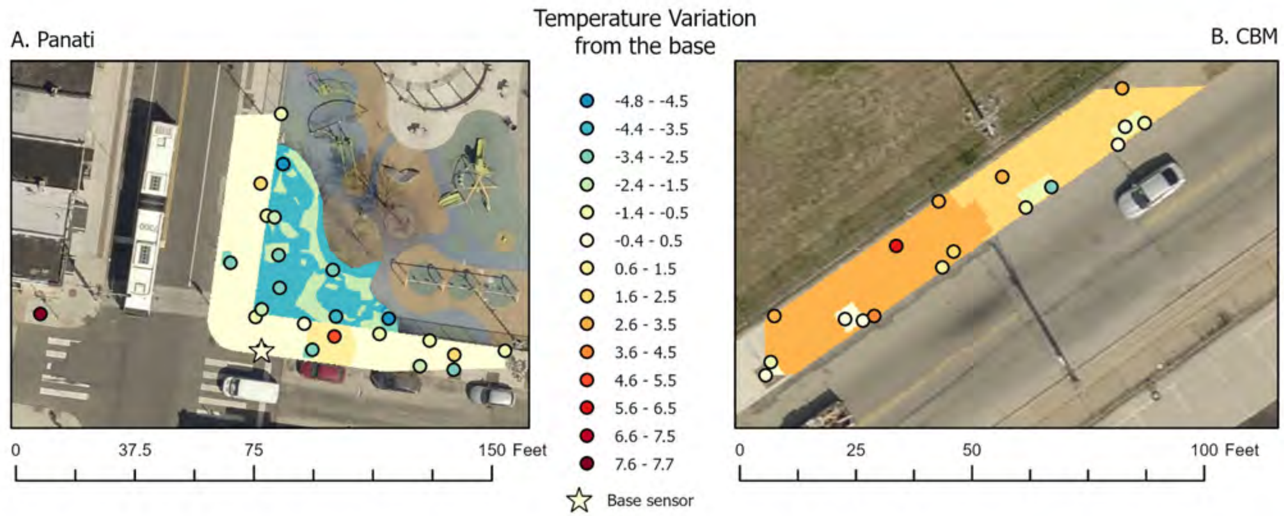

Figure 4. Sensor deployment and overnight surface temperature variation at A. Panati Playground and B. Cecil B. Moore Recreation Center

Magnitude of Cooling

Both study locations showed reduced overnight (8:00pm-7:00am) temperatures in areas with vegetated GSI compared to adjacent sidewalk. At the Cecil B. Moore Recreation Center, tree trench pits were cooler than both sidewalk types; newly installed sidewalks were on average warmer than the originally installed sidewalk. The Panati Playground rain garden experienced cooling by more than 10°F on average when compared to the sidewalk across the street (Table 1, Figure 4).

Geographic Reach of Cooling

Cooling effects in areas beyond vegetated GSI were mixed for overnight surface temperatures. While there was no evidence of cooling on the sidewalks surrounding tree pits, the sidewalks adjacent to the rain garden were slightly cooler to the northwest of installments. In addition, there may be a cooling effect from vegetation at larger scales such as the level of the entire corner: surface temperatures of paved areas surrounding the rain garden were much cooler overnight than sidewalk across the street (Table 1, Figure 4). Sidewalk materials (newly installed and original cement) also showed varying albedo and nighttime temperature readings, with higher temperatures being recorded from the lighter, newly installed material.

Additional Considerations for Vegetated GSI Cooling Potential

Recent studies suggest that nighttime cooling from vegetation is strongly influenced by humidity, with drier conditions yielding greater cooling effects.[6] As Philadelphia's climate changes, conditions are expected to become wetter and hotter—this is an important consideration, as increased humidity may reduce the magnitude of potential cooling.

In addition to humidity, surrounding pavement materials are important to consider when evaluating cooling co-benefits of vegetated GSI. Sidewalks with higher reflectance seen in this study did not reduce surface temperatures as expected: some materials, despite being lighter in color, emitted absorbed heat at a higher rate than darker materials. Though this relationship is drawn from a limited set of observations, it is important to evaluate thermal emittance of surface materials used in heat reduction efforts. A related study that assessed roofing material showed a similar trend, where relying on albedo alone is not sufficient in determining cooling effects.[7] Therefore, it is critical to consider thermal emittance of intended paving materials in heat reduction efforts.

---

6 Ibsen, P. C., Borowy, D., Dell, T., Greydanus, H., Gupta, N., Hondula, D. M., ... & Jenerette, G. D. (2021). Greater aridity increases the magnitude of urban nighttime vegetation-derived air cooling. *Environmental Research Letters*, 16(3), 034011.

7 Simpson, J. R., & McPherson, E. G. (1997). The effects of roof albedo modification on cooling loads of scale model residences in Tucson, Arizona. *Energy and buildings*, 25(2), 127-137.

SUMMARY OF FINDINGS

- Areas with greater amounts of canopy cover had lower surface temperatures than areas without vegetation at night by 2.7-8.7°F.
- Vegetated GSI appears to have an influence on observed nighttime heat, with notably lower surface temperatures (1.8-10.8°F) recorded at or near GSI installments.
- The reach of cooling is more notable at rain gardens than individual tree trenches.
- Even in overall high heat, relatively small amounts of greening can have a noticeable impact in highly paved neighborhoods.
- Humidity has important implications for cooling effects and may limit magnitude of cooling.
- Surrounding materials may absorb and radiate heat in different ways which may influence the cooling effects of vegetated GSI. More investigation is needed to discern the influence of materials.
- Neighborhoods can experience considerably higher temperatures than Philadelphia International Airport, the City's official thermometer of record.

IMPLICATIONS

- The findings from this preliminary study suggest that GSI has the potential to reduce urban heat island effect during the night. Further study is necessary as this experiment had limited geographic and temporal data from which to draw conclusions.
- Nighttime heat is a further stressor of urban heat island, not addressed by daytime cooling centers.
- Given the disparity of heat impacts between neighborhoods, the City's response to heat health emergencies must work towards neighborhood-specific responses and shape communication and resources to better support the most vulnerable communities.
- Neighborhood-specific responses should also consider the need for a strategy to address high nighttime temperatures to compliment daytime heat mitigation efforts.
- This work supports the need for continued innovation and collaboration across departments to address disproportionate heat stress, and to bridge cooling accessibility gaps at the neighborhood level.

THE CITY OF PHILADELPHIA

OFFICE OF

SUSTAINABILITY

PHILA.GOV/SUSTAINABILITY