Estimating Reduced Heat-Attributable Mortality for an Urban Revegetation Project

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ABSTRACT

This paper presents estimates of reductions in heat-attributable excess mortality in Philadelphia, Pennsylvania (USA) that could result under different levels of implementation for urban afforestation, urban green space, and green roof projects. These excess mortality reductions are quantified by integrating results from literature evaluating the possible thermal benefits of various urban heat island (UHI) mitigation measures with results from heat-mortality studies in Philadelphia. These estimates are developed for future periods using regionally downscaled climate change data that reflects one possible future climate in Philadelphia. The estimated time series of mortality reductions is then monetized using a premature mortality value from the health economics and regulatory impact analysis literature. Our results suggest that across the range of implementation currently under consideration, future excessive heat event (EHE) mortality could be reduced by roughly 135 to 315 deaths over the period 2020 through 2049. The equivalent monetized value for this health benefit would be between $0.74 billion and $1.69 billion dollars ($2006). These results highlight the importance of accounting for potential health benefits of UHI mitigation in benefit-cost assessments, especially as reductions in heat-attributable mortality represents only a portion of the anticipated health benefits from the program (health benefits from air quality improvements would also be anticipated). These results also highlight the need to look for opportunities where multiple policy objectives can be achieved with a single action. In this case, the afforestation and urban vegetation options were initially identified as a possible approach for achieving compliance with mandates associated with reducing combined sewer overflows. As detailed here, these actions also provide substantial benefits for reducing excess mortality associated with EHEs through mitigation of UHI effects.

Introduction

Like many older urban areas, Philadelphia faces a challenge in managing its stormwater runoff. Specifically, the city's wastewater and sewage collection and treatment system incorporate a combined sewer overflow (CSO) feature. This means sudden surges in wastewater volumes, for example after a significant rainstorm, can overwhelm the system's wastewater storage and treatment capacity. At that point, some sewage and untreated wastewater may be discharged directly to local receiving waters through the CSO system. These discharges can result in violations of water quality standards that are enforced by the U.S. Environmental Protection Agency (EPA). As a result, EPA is requiring the City of Philadelphia Water Department (PWD) to develop options that will limit pollutant loadings from CSOs in order to help assure that the receiving waters adhere to the applicable water quality standards.

Traditionally, the remedy for CSO problems has involved large infrastructure projects that develop additional wastewater storage capacity that can hold excess volumes until there is capacity available at treatment facilities. In a break from this tradition, the PWD is developing low impact development (LID) options that would focus on achieving the water quality improvements by restoring a more natural balance between stormwater runoff and infiltration, largely by increasing the vegetated acreage in local watersheds, developing vegetated parks, swales, and green roofs, planting trees, and restoring riparian corridors in local watersheds. These efforts are expected to help reduce the volume of stormwater received by the wastewater system so that the number and severity of anticipated future CSO events would still achieve compliance with the relevant water quality standards.

These LID options are of interest to those focused on UHI mitigation because the measures are conceptually equivalent to proposals that could be developed with the goal of mitigating Philadelphia's urban heat island (UHI). Thus, Stratus Consulting's assessment of the benefits of these LID options identifies benefit categories that could also be associated with implementing a vegetation-based UHI mitigation program.

Our assessment identified the following benefit categories for the LID options:

1. Human health improvements: from reductions in urban heat and improved air quality
2. Improved water quality and aquatic habitat: from reduced pollutant and thermal loading
3. Increased outdoor recreation: from the increase in vegetated urban acreage
4. Reduced electrical demand and fuel consumption for electrical generation: from the combined cooling with the shading of trees and lower albedo of vegetated surfaces
5. Creation of local "green collar" jobs: from the labor required to install and maintain the urban vegetation

This paper's main goal is to show how information from different research areas can be combined to produce quantitative and monetized benefit estimates for one component of the human health benefits likely to be generated by UHI mitigation: the expected reduction in mortality associated with reducing the frequency and severity of future excessive heat events (EHEs). The associated discussion of results then explores the relative strengths and weaknesses of this approach along with other options for quantifying this subset of human health benefits from UHI mitigation.

Background: Health Impacts of Excessive Heat Events

Excessive heat events (EHEs) present life-threatening conditions that have a tragically recurrent history of generating adverse public health impacts. As a result, there has been considerable research into defining when conditions change from being merely hot to becoming deadly and to quantifying the heat-health impact relationship during these events. We provide a brief review of this topic to provide basic background information relevant for the rest of the paper.

Identifying EHEs

Part of the historic issue with EHEs is that individuals have failed to recognize that EHE conditions represent more than hot weather. This distinction is revealed in the following quote from a local emergency official involved with the 1995 EHE in the Midwestern United States:

> We knew it was going to be hot…but we had no idea it could be that deadly (NOAA, 1995).

Embedded in this quote is the concept of establishing EHE criteria that can help public officials and private citizens recognize when conditions could be life-threatening. This challenge in establishing EHE criteria was recently recognized in a summary of the World Meteorological Organization's failure to establish a definition for EHEs beyond being a "prolonged period with an unusually high heat load" (WHO, 2009, p. 9).

However, EHEs have a number of characteristics that can be used to help establish identification criteria, including:

1. EHEs are, by definition, relatively rare meteorological events that, consistent with being rare, represent a significant departure from normal conditions in a location

2. EHEs typically trigger an increase in the incidence of adverse health outcomes.

These characteristics have been used to develop two basic methods for identifying EHE conditions. First, threshold values for a meteorological variable (e.g., daily maximum temperature) are used. When the threshold criterion is satisfied, for example exceeding a maximum temperature value, the day becomes an EHE day. In a number of multi-location studies (e.g., Medina-Ramon and Schwartz, 2007; Anderson and Bell, 2009) this threshold approach is tailored to local conditions by establishing the threshold based on a relative value in the historical distribution of a meteorological variable. For example, EHE days may be defined by having a daily maximum temperature equal to or greater than the 98th percentile value from a 10-year time series of daily data. This approach is consistent with the concept that EHE conditions can and should vary by location (e.g., U.S. EPA, 2006; Matthies et al., 2008; WHO, 2009).

The second method attempts to identify EHE days by categorizing weather conditions and then evaluating the relationship between the weather categories and changes in the incidence of adverse health outcomes. This approach, generally referred to as the spatial synoptic classification (SSC) method, has been used to identify EHE days and estimate the excess mortality impact of EHEs in a number of locations (e.g., Kalkstein and Greene, 1997). Further, a number of cities (e.g., Philadelphia, Chicago, Rome, Toronto) use SSC-based models to evaluate weather data and estimate either the probability of heat-attributable excess deaths or the number of potential heat-attributable excess deaths for given conditions. Public health officials then use this information to determine if and how EHE notification and response plans will be activated.

Health Impacts of EHEs

The human body is a temperature-sensitive machine that begins to fail when core temperatures move outside a narrow range. The combination of heat, humidity, and wind conditions during an EHE force the body to try and cool itself in order to maintain this optimal temperature range. Internal body temperatures begin to rise when natural cooling responses, such as sweating, are overwhelmed. At this point, the individual is at risk of experiencing a heat-attributable adverse health outcome.

Figure 1 presents a summary of the types and severity of adverse health outcomes that can be attributed to excessive heat exposure and a loss of control over core temperatures and the relative expected increases in the incidence of the various outcomes.

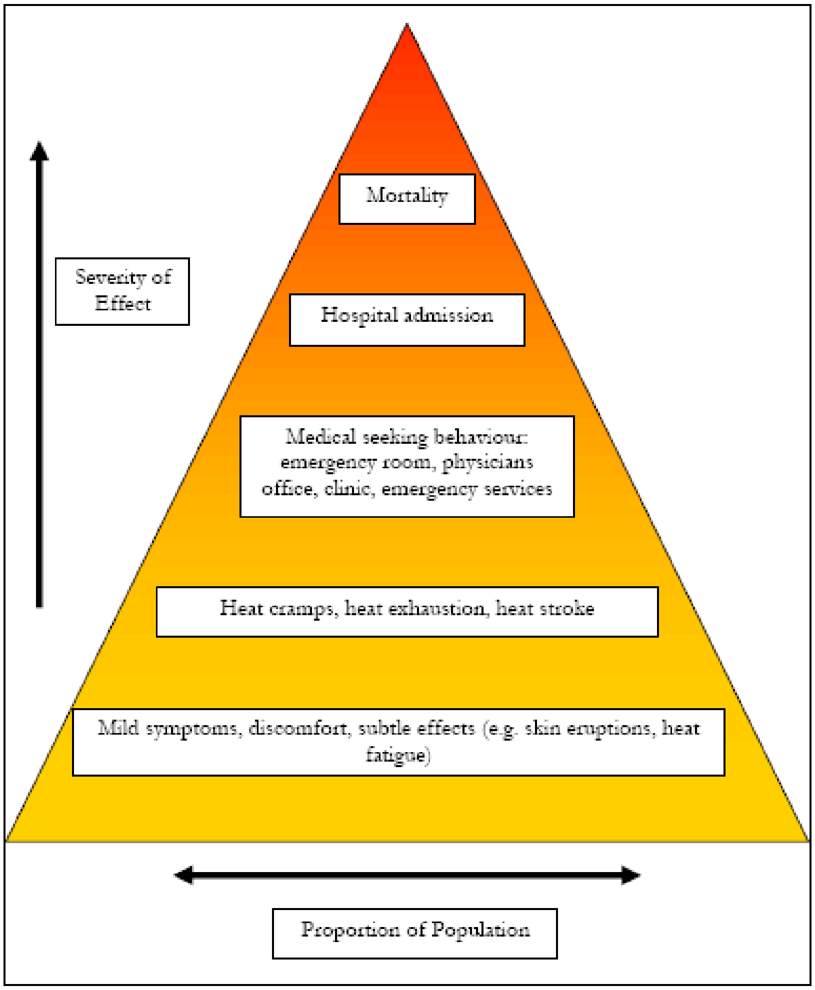


Figure 1. Heat-related illness pyramid.

Source: Bassil et al., 2007, Figure 1.

Despite the wide range of potential adverse health outcomes that are associated with excessive heat exposure, it is the sudden and sharp increases in daily mortality associated with EHEs that typically capture the attention of the public, media, politicians, and researchers. Relatively recent demonstrations of the potential adverse impacts from EHE conditions include the loss of roughly 15,000 lives in France during the 2003 European EHE (Koppe et al., 2004) and over 700 deaths in Chicago, Illinois, in a July 1995 EHE (Kaiser et al., 2007). In addition to increasing mortality, EHEs have also been observed affecting the incidence of a number of morbidity outcomes including increased emergency room use (NOAA, 1995) and hospitalizations (Semenza et al., 1999).

Philadelphia and EHEs

Philadelphia has its own tragic history of adverse public health impacts from EHEs. Notably, in 1991 and 1993, the county coroner determined EHE conditions were responsible for over 20 and 100 deaths, respectively (CDC, 1994; U.S. EPA, 2006). These findings drew significant attention to the heat-health relationship in Philadelphia and resulted in a number of formal responses including:

1. The establishment of Philadelphia's Heat Task Force to help develop and implement EHE notification and response plans

2. Development of the city's SSC-based Heat Watch Warning System, which predicts daily mortality increases based on forecasted weather conditions (Kalkstein et al., 1996).

Philadelphia's Vegetation Program and UHI mitigation

As previously mentioned, the LID options being developed by the PWD closely resemble the type of urban vegetation program that could be developed and implemented to mitigate Philadelphia's UHI. This section provides information on how the UHI benefits of these LID options were determined.

LID program details

The critical elements of interest to UHI mitigation in Philadelphia's LID options are the proposed increases in vegetated acreage in the four watersheds that define the study area: Tacony/Frankford, Cobbs, Schuykill, and the Delaware. Table 1 provides background information on these watersheds along with information and interpretation of the anticipated range in the increase of vegetated acreage associated with the LID options.

Table 1 indicates that by almost any relevant measure the PWD's potential vegetation increases would significantly changes the urban landscape in the watersheds under consideration.

An important element of the LID options concerns the timing for various elements of the program, specifically the timeline for planting new trees and the timeline for implementing green roofs. In our analysis, we assume 2010 would be the first year of implementation for green roof and tree planting projects. New trees would be planted over

Table 1. Details of the Vegetation Acreage Increases in the LID Options

Acreage Category	Units (measure)
Area covered by the CSO system	41,024 (acres)
Impervious area within the area covered by the CSO system	27,666 (acres)
Pervious area within the area covered by the CSO system	13,258 (acres)
Increase in vegetated acreage	1,574 (acres – low option) 8,626 (acres – high option)
Increase in vegetated acres as a percentage of originally impervious acres in CSO system	6% - low option 31% - high option
Increase in vegetated acres as a percentage of originally pervious acres in CSO system	8% - low option 43% - high option
Increase in vegetated acres as a percentage of the area covered by the CSO system	4% - low option 21% - high option

a 35-year period with 10% of the trees planted over the first 6 years of the program, 35% planted over the following 14 years, and 55% planted over the final 15 years. As a result, while tree planting would begin in 2010, it would not be completed until 2045.

In addition, the newly planted trees will take time to reach maturity. We assume planted trees will take 20 years to reach maturity in terms of reaching their maximum UHI mitigation potential. We further assume the trees' benefits increase in a linear fashion over the 20-year growth period (i.e., 5% of benefits per year) and that benefits remain constant once maturity is reached. Collectively, the 35-year planting schedule and the 20-year maturity assumption result in the full benefits for the tree planting not being realized until 55 years after the planting begins. In contrast, the green roofs program is expected to be fully implemented by 2044, which would be its 35th year. Green roofs are assumed to provide their full UHI mitigation benefits in the year the roof is installed. However, progress in implementation over this period is nonlinear.

The assumed effective schedules for both tree planting and green roofs is presented with the results for the avoided EHE deaths.

Temperature impacts of the LID options

Increasing the vegetated acreage in an urban area provides an opportunity to reduce ambient temperatures as a result of increased shading and evapotranspiration. In prior studies, the cooling benefit from increasing urban vegetation has been calculated using complex spatial models that calculate how changes in urban vegetation levels affect solar energy absorption and ultimately local meteorological values such as temperature and humidity.

In general, these studies first divide an area into grid cells. Each grid cell is then assigned to a land category class that has its own unique combination of attribute values (e.g., solar reflectivity/absorption, moisture, roughness). The impact of a program that increases urban vegetation is then accounted for by recalculating and reassigning attribute values in cells where the policy would be implemented. For example, in the simplest approach, each grid cell would be assigned to one of two land categories, nonvegetated or vegetated. A policy to increase urban vegetation would then describe a percentage increase in vegetation across the study area. To simulate the effects of this policy, a new set of attribute values would be calculated for all cells initially assigned to the nonvegetated category. These new attribute values would reflect a weighted average of the nonvegetated and vegetated attribute values. For example, if there was a 10% increase in vegetation across the study area, the new attribute value in previously nonvegetated cells would now be equal to 90% of the original nonvegetated attribute value plus 10% of the vegetated attribute. Values for cells originally categorized as vegetated would remain unchanged in this example. The policy's impact on urban meteorology is then calculated by running a meteorological model for the base case and the policy case and calculating the difference between meteorological values of interest (e.g., average daily temperature).

This approach has previously been used to estimate the impact of a 10% increase in urban vegetated acreage for a number of U.S. cities, including Philadelphia, in simulations that consider a limited number of days (e.g., Hudischewskyj et al., 2001; Sailor, 2003). In the Hudischewskyj et al. (2001) study, the modeling was limited to considering the period July 14–15, 1995. Sailor (2003) modeled a number of multi-day events from June through August 1991–2001.

Table 2 presents the results of both studies with respect to changes in various air temperature measures in Philadelphia associated with the increased urban vegetation.

Table 2. Summary of predicted urban temperature reduction from increasing urban vegetation in Philadelphia

Study	**Vegetation scenario**	**Calculated temperature reduction in °F (temperature measure considered)**	**Notes**
Sailor (2003)	10% increase in urban vegetation from increased deciduous broadleaf tree cover	0.39 (average temperature)	Average temperature change calculated as the average of estimated hourly temperature differences calculated from 8 a.m. to 7 p.m.
		0.49 (maximum temperature)	Maximum temperature is the difference between the maximum daily temperatures in the control and policy cases
Hudischewskyj et al. (2001)	10% increase in urban vegetation (type of vegetation not specified)	0.70 (maximum temperature 7/14)	Difference in maximum surface temperatures in base and policy case
		0.40 (maximum temperature 7/15)	

The results in Table 2 suggest that a 10% increase in urban vegetation, might reduce urban temperatures in Philadelphia by between 0.40°F and 0.70°F depending on the temperature measure (i.e., maximum vs. average temperature).

A similar study (Columbia University Center for Climate Systems Research et al., 2006) evaluated a number of potential changes to the urban landscape in New York City. The study estimated that there would be a 0.40°F reduction in temperature at 3 p.m. in New York City if 6.7% of the total city area were to receive shading by adding trees along streets. The study also estimated a potential 1.10°F reduction at 3 p.m. if 31% of the city area were converted from its current mix of grass areas, streets without trees, and impervious roofs to areas with trees and living (i.e., vegetated) roofs.

We used the results of these studies to define a range of plausible changes in Philadelphia's urban meteorology taking into account similarity and differences in the changes in acreage in these studies with those anticipated under the low and high LID options. Our results are presented in Table 3.

Table 3. Alternative heat and relative humidity impact scenarios for Philadelphia LID options

Scenario	**Reduction in daily maximum temperature (° F)**	**Increase in daytime dew point temperature (° F)**
1. Temperature only: minimum	0.25	0.00
2. Temperature only: maximum	1.75	0.00
3. Temperature and relative humidity: minimum	0.75	0.25
4. Temperature and relative humidity: maximum	1.25	0.50

Scenarios 1 and 2 only define changes in the daily maximum temperature. The range of these changes effectively bound the changes from the earlier studies in an effort to provide a conservative range of plausible impacts. In contrast, Scenarios 3 and 4 incorporate defined changes in both temperature and dewpoint. Dewpoint changes were incorporated in these scenarios in order to increase the realism of the meteorological impacts because increasing vegetated acres would also be expected to increase humidity.

Estimating mortality reductions from increased vegetation in Philadelphia

Estimating how the LID options might affect EHE-attributable mortality in Philadelphia presents a number of challenges. First, the effective timeline for the tree planting and green roof components of the options requires an evaluation of impact over multiple years in the future. As a result, the evaluation would ideally account for anticipated changes in climate. With a future climate defined, an approach is needed to quantify the health benefits for the potential meteorological changes the LID options could provide as defined in Table 3. This section addresses both of these challenges and provides the resulting estimates of potential reductions in future EHE-attributable mortality in Philadelphia across the range of LID options under consideration.

Defining the future climate in Philadelphia

Because some of the benefits from the LID options will not be fully achieved until 2065, the meteorological data used for the evaluation was provided by regionally downscaled General Circulation Model (GCM) results from a compilation of the A1 family of climate change emissions scenarios. Regionally downscaled results are used in this evaluation to provide a more locally appropriate approximation of the future climate. The downscaled meteorological results are produced for each day, from April 1 through August 31, in a representative year using a deterministic method that incorporates linear monthly regressions to help adjust the GCM results and ensure the probability distributions for the values for a baseline period in the 1990s are generally consistent with observed values during this time. Among the key meteorological variable data provided from this downscaling are daily estimates of temperature at 4am, 10am, 4pm, and 10pm. This regional downscaling approach for GCM data has been used for similar assessments of potential future heat impacts (e.g., Hayhoe et al., 2004).

To capture inter-annual variability and provide results at different points in the LID project lifecycle, downscaled results were calculated for two future decades: 2020–2030 and 2045–2055. To help provide a point of reference similar calculations were made for the 1990–2000 period.

Mortality Impact of EHEs in Philadelphia

We considered two information sources to quantify the EHE-attributable mortality impact of the LID options:

1. The Philadelphia-specific results from the Medina-Ramon and Schwartz (2007) study
2. The SSC-based EHE evaluation model incorporated in Philadelphia's heat watch warning system

Both sources of information are appropriate as they have reasonable criteria for identifying EHE days and provide an EHE-mortality relationship where estimates of EHE-attributable deaths would be affected by incorporating the potential meteorological changes associated with the LID options. In this context, we decided to use the SSC-based evaluation model mainly because it is already incorporated as a decision-making tool that helps guide Philadelphia's public health officials in deciding if and how to activate their EHE notification and response program by providing estimates of the potential excess mortality for given conditions. In addition, this model was used in a similar assessment of the health benefits of UHI mitigation in Philadelphia (Kalkstein and Sheridan, 2003).

The estimates of the potential reductions in EHE-attributable mortality that could be produced by implementing the range of LID options in future years are developed in a five-step process.

First, each day in the downscaled GCM data was assigned to a SSC air mass category based on the available meteorological data. Air mass categories characterize weather conditions based on the values for a set of meteorological variables including temperature, dew point, wind speed, and cloud cover. Specific air mass categories include:

- Dry moderate (DM): A warm, comfortable air mass that occurs in Philadelphia frequently in summer.
- Dry polar (DP): Cooler than DM, but still quite warm in the summertime. Usually occurs immediately after the passage of a cold front.

- Dry tropical (DT): The hottest air mass in the summer, with temperatures usually exceeding 95 degrees and sometimes topping 100. Little cloud cover and low humidity lead to potentially rapid dehydration.
- Moist moderate (MM): A cloudy, mild air mass that may sometimes be associated with fog and light rain.
- Moist polar (MP): Usually a winter, rather than summer, air mass, this situation is often associated with storms moving up the East Coast.
- Moist tropical (MT): Very warm and humid air mass, sometimes associated with summer thunderstorms. Sticky and uncomfortable, and quite common in summer.
- Moist tropical plus (MT+) and Moist tropical plus plus (MT++): These are particularly hot and humid subsets of the MT air mass. Dewpoint temperatures are very high, temperatures are in the 90s, and overnight temperatures are the warmest of any air masses. These hot, humid conditions have historically led to increased mortality in Philadelphia.
- Transition (T): Associated with a frontal passage, when temperature, dewpoint, and other meteorological factors are changing rapidly.

In the second step, offensive air masses are identified. In short, those air masses that have a historical record of daily mortality values that are consistently larger than longer-term averages are labeled offensive. In Philadelphia, the offensive air mass categories include: DT, MT+, and MT++.

In the third step, the heat-attributable mortality for each offensive air mass day is calculated using the downscaled GCM data. These calculations are completed using mortality algorithms developed using stepwise regression process that produces the model providing the best explanation of the observed difference in mortality from the longer term trends (i.e., the heat-attributable mortality) from a pool of explanatory variables. The potential explanatory variables include meteorological variables such as different temperature measures and humidity as well as indicator variables that account for the timing of the offensive air mass day within the summer season, and the persistence of the EHE.

This mortality algorithm that underlies the estimates of EHE-attributable excess mortality on offensive air mass days in Philadelphia is:

Equation 1. Daily heat-attributable mortality

Daily heat attributable mortality =

$$[-22.904+(1.79 \times \text{DIS})+(1.198 \times \text{Tmax}) - (0.054 \times \text{Julian})] / 4.722$$

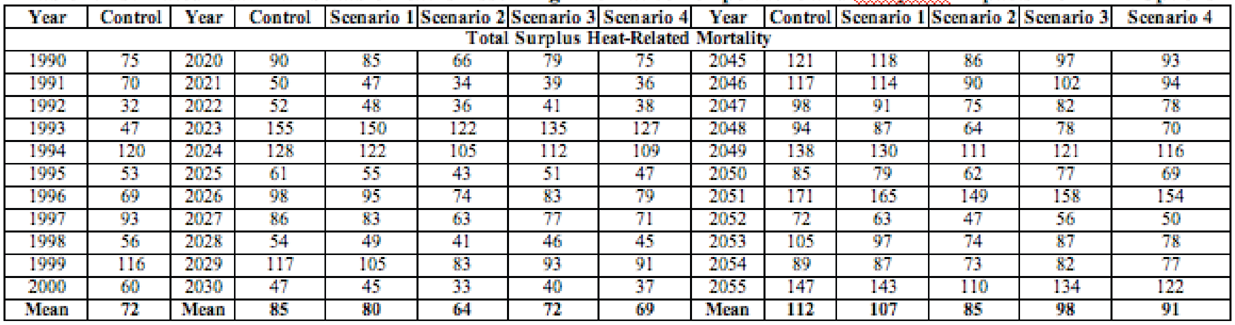
where:

DIS = day in sequence value, 1 is the first day of an offensive air mass, 2 is the second consecutive day, etc
Tmax = daily maximum temperature in °C
Julian = Julian is the time of year variable, with April 1 =1, April 2 = 2 … August 31 = 153
4.722 = this is an adjustment value used so that the GCM 1990 control scenario mortality estimates match actual heat attributable mortality estimates for the decade.

The fourth step repeats the process for evaluating each study day after adjusting the predicted meteorological values by the values in the Table 3 scenarios to account for the UHI mitigation from the tree planting and green roof programs.

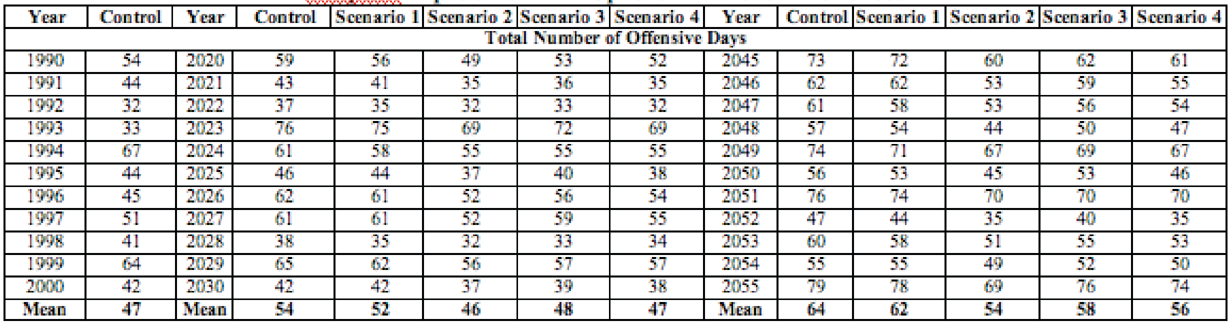
Tables 4 and 5 present the results of evaluating the GCM data for the control case and the different scenarios in terms of the number of EHE-attributable deaths and EHE days in each year with data for each of the defined LID UHI impact scenarios.

Table 4. Estimated Heat-Attributable Deaths Assuming Alternative Temperature and Dewpoint Impacts from LID Options



Year	Control	Year	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Year	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Surplus Heat-Related Mortality													
1990	75	2020	90	85	66	79	75	2045	121	118	86	97	93
1991	70	2021	50	47	34	39	36	2046	117	114	90	102	94
1992	32	2022	52	48	36	41	38	2047	98	91	75	82	78
1993	47	2023	155	150	122	135	127	2048	94	87	64	78	70
1994	120	2024	128	122	105	112	109	2049	138	130	111	121	116
1995	53	2025	61	55	43	51	47	2050	85	79	62	77	69
1996	69	2026	98	95	74	83	79	2051	171	165	149	158	154
1997	93	2027	86	83	63	77	71	2052	72	63	47	56	50
1998	56	2028	54	49	41	46	45	2053	105	97	74	87	78
1999	116	2029	117	105	83	93	91	2054	89	87	73	82	77
2000	60	2030	47	45	33	40	37	2055	147	143	110	134	122
Mean	**72**	**Mean**	**85**	**80**	**64**	**72**	**69**	**Mean**	**112**	**107**	**85**	**98**	**91**

Table 5. Estimated Offensive Air Mass Days Assuming Alternative Temperature and Dewpoint Impacts from LID Options in Various Time Periods



Year	Control	Year	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Year	Control	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Number of Offensive Days													
1990	54	2020	59	56	49	53	52	2045	73	72	60	62	61
1991	44	2021	43	41	35	36	35	2046	62	62	53	59	55
1992	32	2022	37	35	32	33	32	2047	61	58	53	56	54
1993	33	2023	76	75	69	72	69	2048	57	54	44	50	47
1994	67	2024	61	58	55	55	55	2049	74	71	67	69	67
1995	44	2025	46	44	37	40	38	2050	56	53	45	53	46
1996	45	2026	62	61	52	56	54	2051	76	74	70	70	70
1997	51	2027	61	61	52	59	55	2052	47	44	35	40	35
1998	41	2028	38	35	32	33	34	2053	60	58	51	55	53
1999	64	2029	65	62	56	57	57	2054	55	55	49	52	50
2000	42	2030	42	42	37	39	38	2055	79	78	69	76	74
Mean	**47**	**Mean**	**54**	**52**	**46**	**48**	**47**	**Mean**	**64**	**62**	**54**	**58**	**56**

Initial impact of LID programs on EHE-attributable mortality

Based on the results shown above, a number of general conclusions can be drawn:

1. Any measurable cooling provided by implementing a LID option is likely to reduce EHE-attributable mortality
2. EHE-attributable mortality reductions across options are roughly proportional to the relative magnitude of the assumed temperature change
3. The health benefits of the LID options are relatively constant across the different decades, except for the 1.75°F temperature reduction scenario which has a noticeable increase in lives saved comparing the 2045–2055 period to the 2020 period.
4. EHEs are likely to become an increasing risk to public health in Philadelphia without continued adaptation.

A review of the EHE mortality algorithm shows that the results are generally proportional to the assumed temperature changes in the scenarios because Tmax is the only meteorological variable in the equation. However, this emphasis on the maximum temperature in the mortality algorithm overlooks that the assumed changes in dewpoint temperature do play an important role in the results as they influence the air mass categories a day is assigned to and thus, in some cases, whether it falls into an offensive or non-offensive category.

Perhaps the most important feature of both the mortality and EHE day estimates in Tables 4 and 5 is the significant variability within the year-by-year results for a scenario and across scenarios. Expressed as a percentage of the mean values for estimated EHE-attributable deaths, the standard deviation of the decadal results is roughly 45% in the 2020–2030 estimates and roughly 30% in the period 2045–2055. Within years, results for scenarios can be roughly 2–3 times as large when comparing the largest estimates to the smallest. In short, while the results show the benefits of pursuing a LID program in terms of reducing EHE-attributable mortality in Philadelphia, predicting the exact nature of benefits in any given time period is complicated and becomes increasingly uncertain if narrower time windows are considered.

Converting EHE-attributable mortality estimates into a time series of UHI mitigation benefits

The fifth step requires converting the information in Table 4 into a time series of benefits for the EHE-attributable mortality reductions from the LID program options with the goal of defining benefits through the year 2049 to represent 40 years where the green roof and tree planting projects are being implemented (i.e., 2010-2049). This step is accomplished by calculating the average number of lives saved in each decade evaluated for Scenario 1 and 2 (these are the focus as they provide the endpoints on the range of benefit estimates). This value represents the difference in the estimate of EHE-attributable mortality in the control scenario for each decade with the corresponding estimate for each scenario. This value for the 2020-2030 period will be the anchor value for the years 2020-2029 in each scenario. Similarly, the value for the 2045-2055 will provide the anchor value for the years 2040-2049. The anchor value for the period 2030-2039 is calculated as the average of the anchor value for the two surrounding decades.

Given the nature of our data and to reflect some lag in realizing benefits, we assume EHE-attributable mortality reductions are not realized until 2020. The effective reduction in EHE- attributable mortality in each year for each scenario is then calculated as the product of the anchor value and the weighted average program effectiveness value based on the level of implementation in the green roof program combined with the level of implementation and maturity of the planted trees.

These mortality reductions are in turn monetized using a base value of $7 million per avoided death, measured in 2006 dollars with 2010 income. This value is consistent with the values used to support the monetization of premature mortality in EPA's air quality benefits assessment model (U.S. EPA, 2008a). For purposes of comparison and summary, monetary values are expressed in their present value equivalents using 2008 as a base year while inflating the value per avoided mortality at 4% per year and discounting future benefits at 4.875%, rates that are consistent with ranges used in other assessments and that were selected for comparison with the costs in the Philadelphia LID assessment.

The results of these calculations are presented in Table 6.

Table 6. Estimates of Lives Saved and Monetary Value for Implementing LID Program Options

	Project Year	Green Roof Effectiveness Timeline	New Trees Effectiveness Timeline	Weighted Average Effectiveness Timeline	Estimated Reduction in EHE-Attributable Mortality: Scenario 2 (1.75° F temp reduction)	Estimated Reduction in EHE-Attributable Mortality: Scenario 1 (0.25 ° F temp reduction)	Monetized Present Value Benefits of Lives Saved in Scenario 2: ($2006 millions, rounded for presentation)	Monetized Present Value Benefits of Lives Saved in Scenario 1: ($2006 millions, rounded for presentation)
2008	0	0.0%	0.0%	0.0%				
2009	1	0.0%	0.0%	0.0%				
2010	2	1.8%	0.1%	0.9%				
2011	3	3.5%	0.2%	1.9%				
2012	4	5.3%	0.3%	2.8%				
2013	5	7.1%	0.4%	3.8%				
2014	6	8.9%	0.6%	4.7%				
2015	7	10.6%	0.8%	5.7%				
2016	8	13.1%	1.0%	7.1%				
2017	9	15.6%	1.3%	8.5%				
2018	10	18.1%	1.6%	9.9%				
2019	11	20.6%	2.0%	11.3%				
2020	12	23.1%	2.5%	12.8%	2.4	1.1	$15.4	$7.2
2021	13	25.6%	3.0%	14.3%	2.7	1.3	$17.1	$8.0
2022	14	28.1%	3.6%	15.9%	3.0	1.4	$18.8	$8.8
2023	15	30.6%	4.3%	17.5%	3.3	1.6	$20.5	$9.6
2024	16	33.1%	5.2%	19.1%	3.6	1.7	$22.3	$10.4
2025	17	35.6%	6.1%	20.9%	4.0	1.9	$24.1	$11.3
2026	18	38.1%	7.2%	22.7%	4.3	2.0	$25.9	$12.1
2027	19	40.6%	8.5%	24.6%	4.7	2.2	$27.9	$13.0
2028	20	43.1%	10.0%	26.6%	5.1	2.4	$29.9	$14.0
2029	21	45.6%	11.8%	28.7%	5.5	2.5	$32.0	$15.0
2030	22	49.2%	13.9%	31.6%	6.8	3.0	$39.6	$17.5
2031	23	52.9%	16.0%	34.4%	7.4	3.3	$42.8	$19.0
2032	24	56.5%	18.2%	37.4%	8.0	3.6	$46.1	$20.4
2033	25	60.1%	20.5%	40.3%	8.7	3.9	$49.3	$21.9

	Project Year	**Green Roof Effectiveness Timeline**	**New Trees Effectiveness Timeline**	**Weighted Average Effectiveness Timeline**	**Estimated Reduction in EHE-Attributable Mortality: Scenario 2 (1.75°F temp reduction)**	**Estimated Reduction in EHE-Attributable Mortality: Scenario 1 (0.25 °F temp reduction)**	**Monetized Present Value Benefits of Lives Saved in Scenario 2: ($2006 millions, rounded for presentation)**	**Monetized Present Value Benefits of Lives Saved in Scenario 1: ($2006 millions, rounded for presentation)**
2034	26	63.7%	22.9%	43.3%	9.3	4.1	$52.6	$23.3
2035	27	67.4%	25.4%	46.4%	10.0	4.4	$55.8	$24.7
2036	28	71.0%	28.1%	49.5%	10.7	4.7	$59.1	$26.2
2037	29	74.6%	30.7%	52.7%	11.3	5.0	$62.3	$27.6
2038	30	78.2%	33.4%	55.8%	12.0	5.3	$65.5	$29.0
2039	31	81.9%	36.1%	59.0%	12.7	5.6	$68.6	$30.4
2040	32	85.5%	38.9%	62.2%	15.0	6.4	$80.2	$34.0
2041	33	89.1%	41.7%	65.4%	15.7	6.7	$83.6	$35.5
2042	34	92.7%	44.5%	68.6%	16.5	7.0	$87.0	$36.9
2043	35	96.4%	47.4%	71.9%	17.3	7.3	$90.4	$38.4
2044	36	100.0%	50.4%	75.2%	18.1	7.7	$93.7	$39.8
2045	37	100.0%	53.3%	76.6%	18.4	7.8	$94.7	$40.2
2046	38	100.0%	56.2%	78.1%	18.8	8.0	$95.7	$40.6
2047	39	100.0%	59.2%	79.6%	19.2	8.1	$96.7	$41.1
2048	40	100.0%	62.2%	81.1%	19.5	8.3	$97.8	$41.5
2049	41	100.0%	65.4%	82.7%	19.9	8.5	$98.8	$42.0
				Total	**314.1**	**136.8**	**1,694.1**	**739.4**

Table 6 shows our estimates that implementing the vegetative element of the LID options in the four Philadelphia area watersheds could reduce EHE-attributable mortality by between 137 and 314 deaths during the 30-year period 2020-2049 based on assumed average daily reductions in summertime temperatures of 0.25°F and 1.75°F respectively. The monetized present value equivalent for this range of time-series of impacts is estimated to be $0.74 billion to $1.69 billion ($2006) for the 0.25°F and 1.75°F temperature reduction scenarios respectively

These results, while treated as a co-benefit estimate in the CSO compliance study, also reflect a plausible estimate of the scale of one aspect of the potential human health benefits that could be assigned to such a vegetation program had it been proposed primarily as a UHI mitigation effort.

Caveats to Results

While the assumptions used to develop our estimates of the reduction in EHE-attributable mortality are based on a reasonable use of available information, they also need to be interpreted recognizing and considering several important sources of uncertainty and potential biases. A number of the most important of these sources are discussed in this section

Accuracy of any scenario defining temperature and/or dewpoints changes

Well-understood basic physical principles underlie the assumption that significantly increasing the vegetated acreage in Philadelphia by implementing one of the proposed LID options should reduce ambient temperatures while increase relative humidity and dewpoint temperatures. However, the magnitude and spatial heterogeneity of this change is uncertain.

Past studies have calculated changes in meteorological variables for UHI mitigation scenarios that incorporate the unrealistic step of an instantaneous change in the nature of a significant portion of an urban area. The more realistic scenario, incorporated in our estimates, is that these changes will occur and their impact will be fully realized over time. What complicates calculating the associated impact of these changes is that they are also likely to be a function of other changes in the urban landscape. This uncertainty prevents assigning a likely direction of bias in the current estimates.

What the SSC-based mortality algorithm for Philadelphia makes clear is that larger temperature reductions will, all else equal, increase the health benefit of LID/UHI mitigation program implementation.

Uncertainty of climate change

Philadelphia has a long history of being adversely affected by EHEs. All else equal, climate change is likely to increase the public risks and impacts associated with future EHEs as shown in the control scenario results of Tables 4 and 5. However, while acceptance of the basic elements of climate change impacts on meteorology continues to grow, there is still considerable uncertainty over what the future climate will look like in Philadelphia or any given location on a daily time scale.

This uncertainty is already reflected in differences in ambient CO_2 concentrations predicted by different SRES emissions scenarios that have been the focus of most GCM efforts. Of note, these differences increase the farther into the future one goes. At the same time, researchers have begun to note how several climate change-related impacts that were anticipated to begin appearing later in the century may have already begun and how the pace of climate change may be more rapid than previously anticipated suggesting existing scenarios may be too conservative to begin with.

In this study, we rely one future climate estimates from one emissions scenario. This limits our ability to directly incorporate uncertainty into our results. Using the SSC-based method increased future warming would, all else equal, increase the number of EHE days in the control scenario. This means future temperature reductions could result in a greater reduction in the number of days that meet EHE criteria and/or that the reduction will be applied to a larger number of EHE days. Either way the result should be an increase in the reduction of EHE-attributable mortality assuming a LID or UHI mitigation program is implemented.

Changing population size, demographics and response to heat

Heat is a well-recognized public health threat in Philadelphia and the city has an active and aggressive EHE education, notification, and response program. Our current estimates of future reductions in EHE-attributable mortality assume the nature of the public health response to future EHE conditions will remain unchanged. To the extent Philadelphia's EHE program becomes more effective or factors that currently increase an individual's vulnerability to EHE conditions become less of an issue (e.g., better access and use of air conditioning), the current heat mortality estimates could be overstated. In contrast, anticipated future increases in urban temperatures as a result of climate change could result in increased incidence of adverse health outcomes if adaptation does not keep pace. Similarly future changes in the size and vulnerability of Philadelphia's residents would likely affect our estimates (e.g., for changes in obesity levels) but the uncertain nature of these changes prevents accounting for these impacts at this time.

The benefits of nonfatal heat stress cases avoided are not included

Our analysis focused on estimating only reductions in EHE-attributable mortality that associated with mitigating Philadelphia's UHI under different LID options. These health improvement results are clearly conservative for two reasons. First, we have not attempted to quantify the reduction in nonfatal adverse health outcomes associated with reducing the number of EHE days and the severity of the conditions in the remaining EHE days.

Second, this summary of our work has omitted consideration of the significant health improvements that could accrue as a result of improvements in ambient air quality, primarily ozone and particulate matter concentrations, as a result of implementing a LID program. As with EHE-attributable mortality a rich literature and modeling options exist that can be used to define plausible changes in ambient air quality that might result from the reductions in ambient urban temperatures because of reduced demand for electrical cooling and reduced rates of photochemical formation of these pollutants.

Conclusions

The scale of our estimated reductions in heat-attributable mortality associated with increasing urban vegetation in Philadelphia highlight the potential benefit of quantifying and monetizing potential reductions in EHE-attributable health outcomes, especially excess mortality, when determining the benefits of UHI mitigation efforts. With plausible estimates of the anticipated changes in future meteorological conditions and a baseline meteorological scenario, a robust epidemiological literature and number of assessment techniques can be applied to develop these estimates. Given that the focus of much of the relevant epidemiological literature has been on developing quantitative relationships for how the incidence of excess mortality in locations responds to the development of or changes in EHE conditions, this quantitative effort will focus on a health outcome that is considered highly relevant in public policy analyses as a result of its severity, equity considerations, and its associated monetary value per avoided outcome.

Finally, this study highlights both how effective UHI mitigation can be achieved by projects not initially developed for this objective and, conversely, how UHI mitigation can potentially generate a wide range of co-benefits not typically addressed in most benefit-cost analyses. For example, explicitly recognizing and quantifying the potential air and water quality benefits of increasing urban vegetation in programs initially promoted for UHI mitigation could increase support for implementing these actions from other sectors that may be working on achieving air and water quality improvements. This observation also highlights the advantage of using a multi-disciplinary team to identify and evaluate the potential benefits of UHI mitigation actions.

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