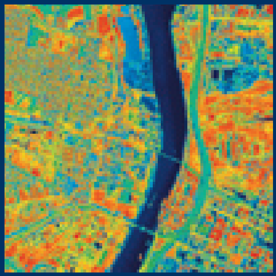
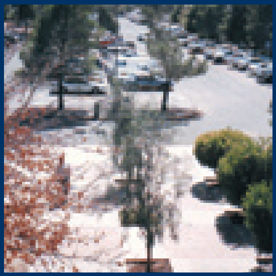
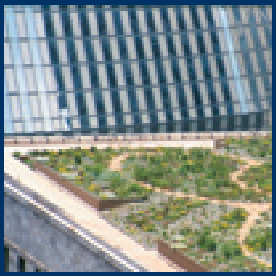
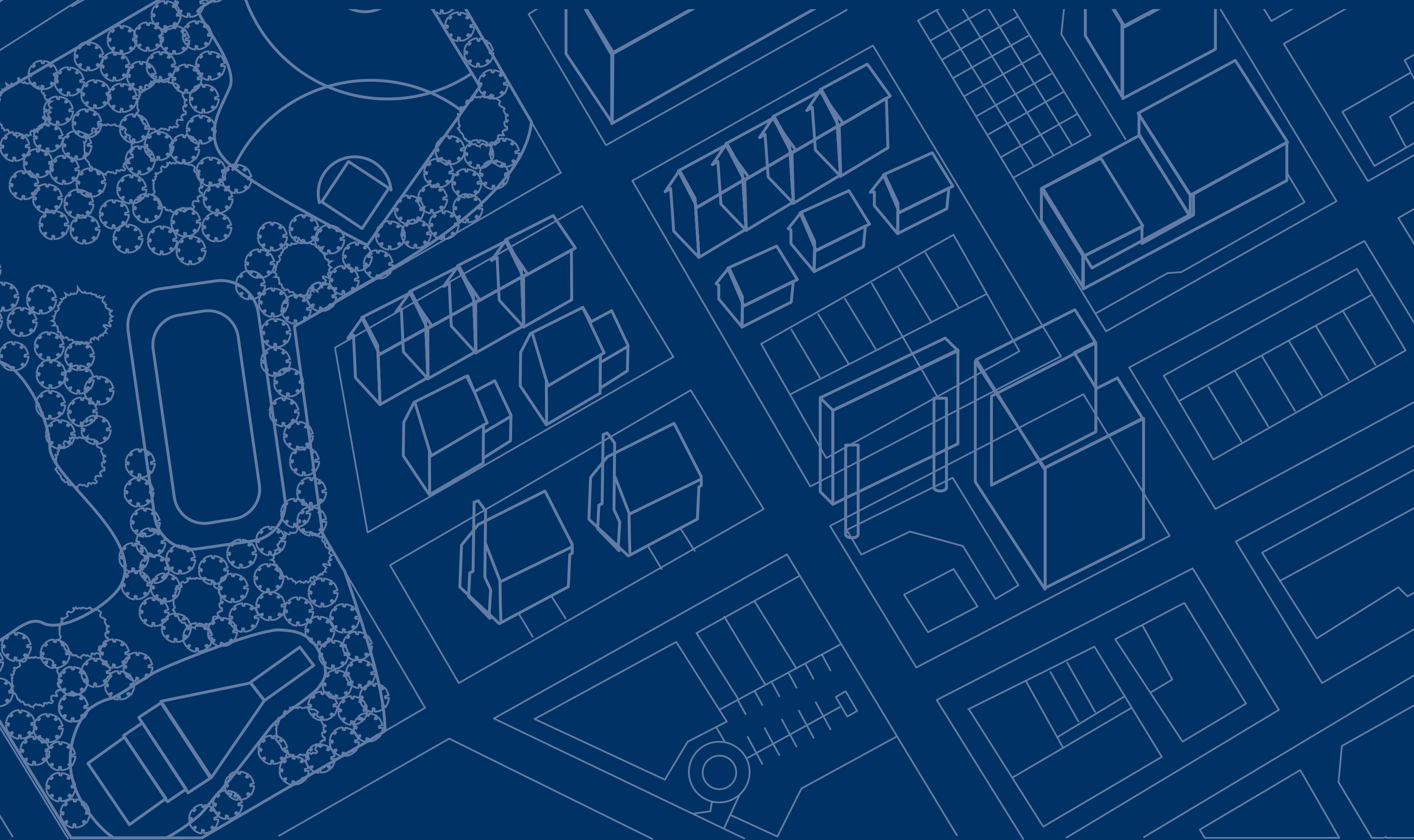
    

Reducing Urban Heat Islands: Compendium of Strategies

Urban Heat Island Basics



Acknowledgements

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Experts who helped shape this chapter include:

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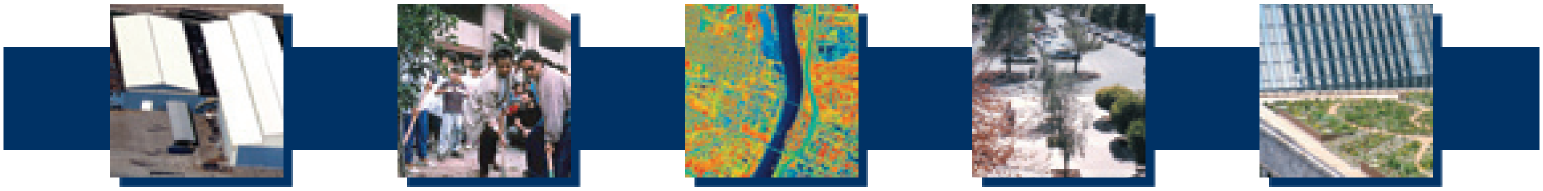


Urban Heat Island Basics

As urban areas develop, changes occur in the landscape. Buildings, roads, and other infrastructure replace open land and vegetation. Surfaces that were once permeable and moist generally become impermeable and dry.* This development leads to the formation of urban heat islands—the phenomenon whereby urban regions experience warmer temperatures than their rural surroundings.

This chapter provides an overview of different types of urban heat islands, methods for identifying them, and factors that contribute to their development. It introduces key concepts that are important to understanding and mitigating this phenomenon, as well as additional sources of information. It discusses:

- General features of urban heat islands
- Surface versus atmospheric heat islands
- Causes of urban heat island formation
- Urban heat island impacts on energy consumption, environmental quality, and human health
- Resources for further information.

1. What Are Urban Heat Islands?

Many urban and suburban areas experience elevated temperatures compared to their outlying rural surroundings; this difference in temperature is what constitutes an urban heat island. The annual mean air temperature of a city with one million or more people can be 1.8 to 5.4°F (1 to 3°C) warmer than its surroundings,[1] and on a clear, calm night, this temperature difference can be as much as 22°F (12°C).[2] Even smaller cities and towns will produce heat islands, though the effect often decreases as city size decreases.[3]

This chapter focuses on *surface* and *atmospheric* urban heat islands. These two heat island types differ in the ways they are formed, the techniques used to identify and measure them, their impacts, and to some degree, the methods available to mitigate them. Table 1 summarizes the basic characteristics of each type of heat island. These features are described in more detail in the following sections of this chapter.

* This change in landscape may differ in regions such as deserts, where moisture may increase in urban areas if development introduces grass lawns and other irrigated vegetation.

Table 1: Basic Characteristics of Surface and Atmospheric Urban Heat Islands (UHIs)[4]

Feature	Surface UHI	Atmospheric UHI
Temporal Development	• Present at all times of the day and night • Most intense during the day and in the summer	• May be small or non-existent during the day • Most intense at night or predawn and in the winter
Peak Intensity (Most intense UHI conditions)	• More spatial and temporal variation: ▪ Day: 18 to 27°F (10 to 15°C) ▪ Night: 9 to 18°F (5 to 10°C)	• Less variation: ▪ Day: -1.8 to 5.4°F (-1 to 3°C) ▪ Night: 12.6 to 21.6°F (7 to 12°C)
Typical Identification Method	• Indirect measurement: ▪ Remote sensing	• Direct measurement: ▪ Fixed weather stations ▪ Mobile traverses
Typical Depiction	• Thermal image	• Isotherm map • Temperature graph

1.1 Surface Urban Heat Islands

On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, like roofs and pavement, to temperatures 50 to 90°F (27 to 50°C) hotter than the air,[5] while shaded or moist surfaces—often in more rural surroundings—remain close to air temperatures. Surface urban heat islands are typically present day and night, but tend to be strongest during the day when the sun is shining.

On average, the difference in daytime surface temperatures between developed and rural areas is 18 to 27°F (10 to 15°C); the difference in nighttime surface temperatures is typically smaller, at 9 to 18°F (5 to 10°C).[6]

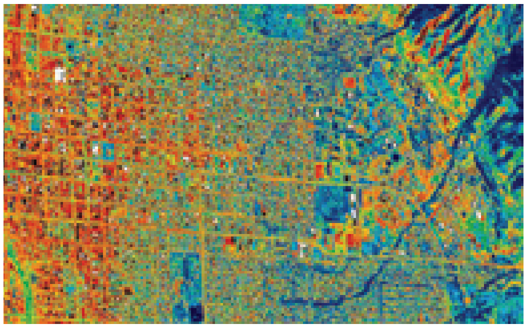
The magnitude of surface urban heat islands varies with seasons, due to changes in the sun's intensity as well as ground cover and weather. As a result of such variation, surface urban heat islands are typically largest in the summer.[7]

How Weather Influences Urban Heat Islands

Summertime urban heat islands are most intense when the sky is clear and winds are calm. Heavy cloud cover blocks solar radiation, reducing daytime warming in cities. Strong winds increase atmospheric mixing, lowering the urban-rural temperature difference. This document, *Reducing Urban Heat Islands: Compendium of Strategies,* focuses on mitigating summertime heat islands through strategies that have maximum impact under clear, calm conditions.

To identify urban heat islands, scientists use direct and indirect methods, numerical modeling, and estimates based on empirical models. Researchers often use remote sensing, an indirect measurement technique, to estimate surface temperatures. They use the data collected to produce thermal images, such as that shown in Figure 1.

Figure 1: Thermal Image Depicting a Surface Urban Heat Island



NASA/Marshall Space Flight Center

This image, taken from an aircraft, depicts a midday surface urban heat island in Salt Lake City, Utah, on July 13, 1998. White areas are around 160°F (70°C), while dark blue areas are near 85°F (30°C). Note the warmer urban surface temperatures (left side of image) and cooler surfaces in the neighboring foothills (on the right).

1.2 Atmospheric Urban Heat Islands

Warmer air in urban areas compared to cooler air in nearby rural surroundings defines atmospheric urban heat islands. Experts often divide these heat islands into two different types:

- **Canopy layer urban heat islands** exist in the layer of air where people live, from the ground to below the tops of trees and roofs.
- **Boundary layer urban heat islands** start from the rooftop and treetop level and extend up to the point where urban landscapes no longer influence the atmosphere. This region typically extends no more than one mile (1.5 km) from the surface.[8]

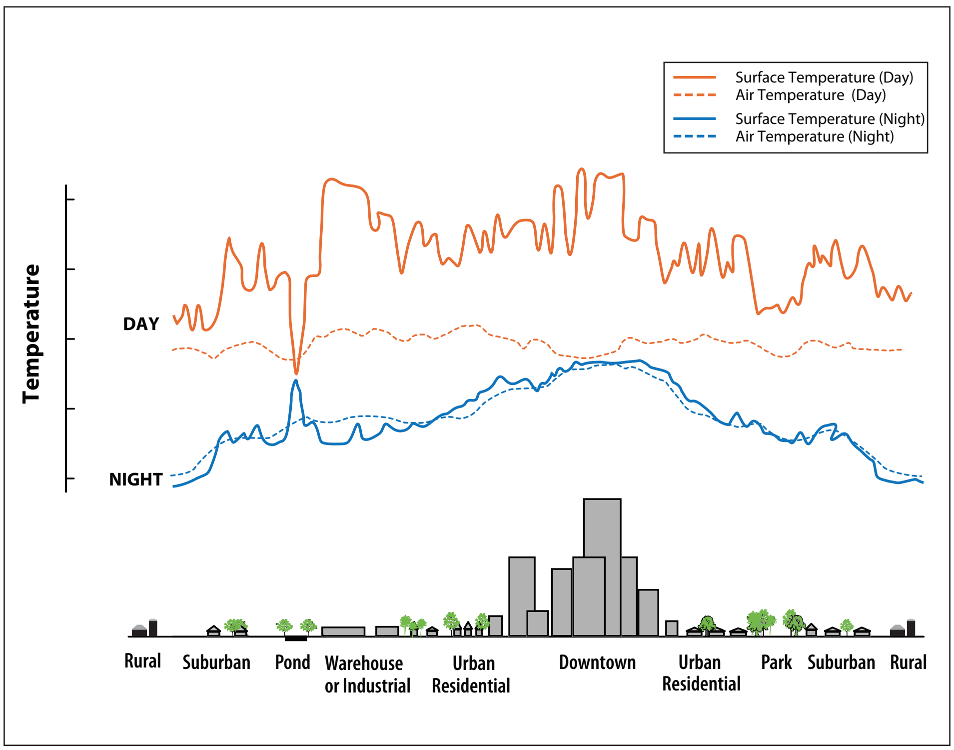
Canopy layer urban heat islands are the most commonly observed of the two types and are often the ones referred to in discussions of urban heat islands. For this reason, this chapter and compendium use the more general term *atmospheric urban heat islands* to refer to canopy layer urban heat islands.

Atmospheric urban heat islands are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructure. The timing of this peak, however, depends on the properties of urban and rural surfaces, the season, and prevailing weather conditions.

Surface and Air Temperatures: How Are They Related?

Surface temperatures have an indirect, but significant, influence on air temperatures, especially in the canopy layer, which is closest to the surface. For example, parks and vegetated areas, which typically have cooler surface temperatures, contribute to cooler air temperatures. Dense, built-up areas, on the other hand, typically lead to warmer air temperatures. Because air mixes within the atmosphere, though, the relationship between surface and air temperatures is not constant, and air temperatures typically vary less than surface temperatures across an area (see Figure 2).

Figure 2: Variations of Surface and Atmospheric Temperatures



Modified from Voogt, 2000

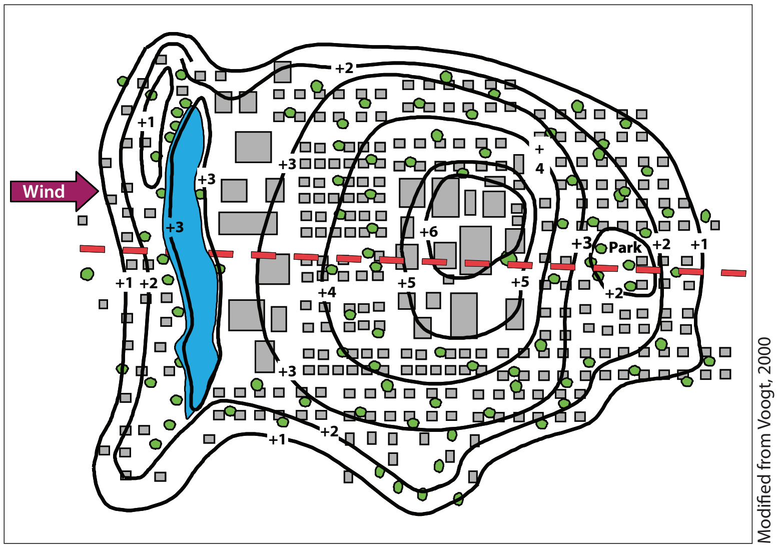
Surface and atmospheric temperatures vary over different land use areas. Surface temperatures vary more than air temperatures during the day, but they both are fairly similar at night. The dip and spike in surface temperatures over the pond show how water maintains a fairly constant temperature day and night, due to its high heat capacity.

* Note: The temperatures displayed above do not represent absolute temperature values or any one particular measured heat island. Temperatures will fluctuate based on factors such as seasons, weather conditions, sun intensity, and ground cover.

Atmospheric heat islands vary much less in intensity than surface heat islands. On an annual mean basis, air temperatures in large cities might be 1.8 to 5.4°F (1 to 3°C) warmer than those of their rural surroundings.[9]

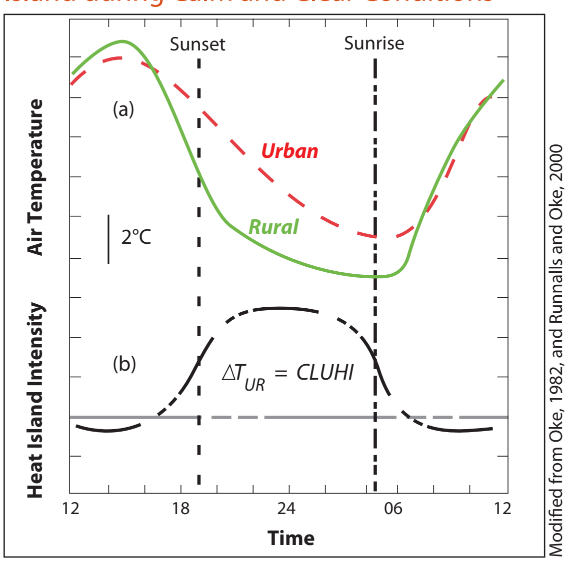
Researchers typically measure air temperatures through a dense network of sampling points from fixed stations or mobile traverses, which are both direct measurement methods. Figure 3 illustrates a conceptual isotherm map that depicts an atmospheric urban heat island. The center of the figure, which is the hottest area, is the urban core. A simple graph of temperature differences, as shown in Figure 4, is another way to show the results.

Figure 3: Isotherm Map Depicting an Atmospheric Nighttime Urban Heat Island



This conceptual map with overlaid isotherms (lines of equal air temperature) exhibits a fully developed nighttime atmospheric urban heat island. The dotted red line indicates a traverse along which measurements are taken.

Figure 4: Conceptual Drawing of the Diurnal Evolution of the Urban Heat Island during Calm and Clear Conditions



Atmospheric urban heat islands primarily result from different cooling rates between urban areas and their surrounding rural or non-urban surroundings (section (a) of Figure 5). The differential cooling rates are most pronounced on clear and calm nights and days when rural areas can cool more quickly than urban areas. The heat island intensity (section (b)) typically grows from mid- to late afternoon to a maximum a few hours after sunset. In some cases, a heat island might not reach peak intensity until after sunrise.

Urban Heat Islands, Climate Change, and Global Warming

Urban heat islands refer to the elevated temperatures in developed areas compared to more rural surroundings. Urban heat islands are caused by development and the changes in radiative and thermal properties of urban infrastructure as well as the impacts buildings can have on the local micro-climate—for example tall buildings can slow the rate at which cities cool off at night. Heat islands are influenced by a city's geographic location and by local weather patterns, and their intensity changes on a daily and seasonal basis.

The warming that results from urban heat islands over small areas such as cities is an example of local climate change. Local climate changes resulting from urban heat islands fundamentally differ from global climate changes in that their effects are limited to the local scale and decrease with distance from their source. Global climate changes, such as those caused by increases in the sun's intensity or greenhouse gas concentrations, are not locally or regionally confined.

Climate change, broadly speaking, refers to any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer). Climate change may result from:

- Natural factors, such as changes in the sun's intensity or slow changes in the Earth's orbit around the sun
- Natural processes within the climate system (e.g. changes in ocean circulation)
- Human activities that change the atmosphere's composition (e.g. burning fossil fuels) and the land surface (e.g. deforestation, reforestation, or urbanization).

The term climate change is often used interchangeably with the term global warming, but according to the National Academy of Sciences, "the phrase 'climate change' is growing in preferred use to 'global warming' because it helps convey that there are [other] changes in addition to rising temperatures."

Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the lowest layer of the atmosphere, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, "global warming" often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities. Global warming can be considered part of global climate change along with changes in precipitation, sea level, etc.

The impacts from urban heat islands and global climate change (or global warming) are often similar. For example, some communities may experience longer growing seasons due to either or both phenomena. Urban heat islands and global climate change can both also increase energy demand, particularly summertime air conditioning demand, and associated air pollution and greenhouse gas emissions, depending on the electric system power fuel mix.

Strategies to reduce urban heat islands—the focus of this document, *Reducing Urban Heat Islands: Compendium of Strategies*—produce multiple benefits including lowering surface and air temperatures, energy demand, air pollution and greenhouse gas emissions. Thus, advancing measures to mitigate urban heat islands also helps to address global climate change.

For more information on global warming see EPA's Climate Change website, <www.epa.gov/climatechange>.

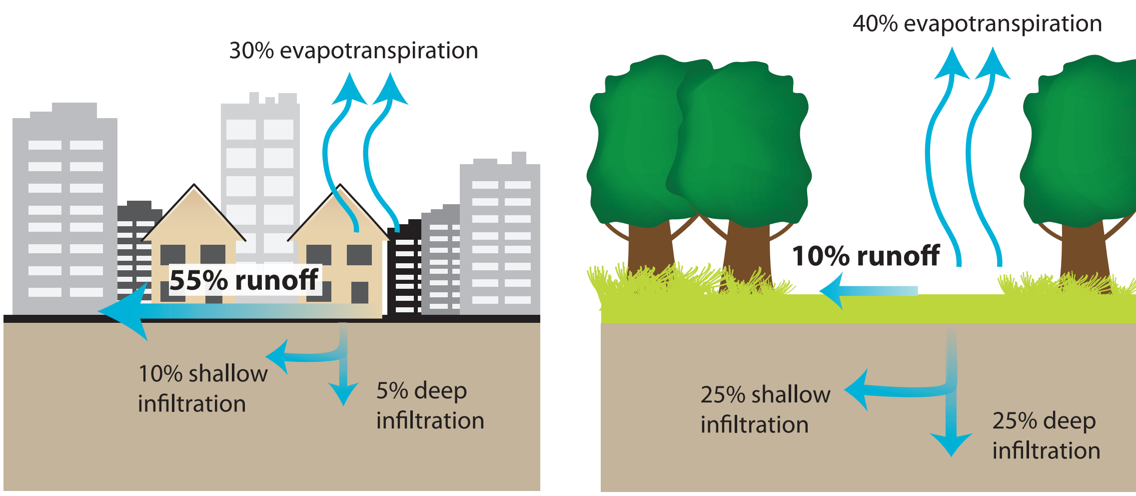
2. How Do Urban Heat Islands Form?

While many factors contribute to urban heat island formation (see Table 2), this chapter focuses on vegetative cover and surface properties because communities can directly address these factors with available technologies. See the "Trees and Vegetation," "Green Roofs," "Cool Roofs," and "Cool Pavement" chapters for detailed information on these strategies.

2.1 Reduced Vegetation in Urban Areas

In rural areas, vegetation and open land typically dominate the landscape. Trees and vegetation provide shade, which helps lower surface temperatures. They also help reduce air temperatures through a process called evapotranspiration, in which plants release water to the surrounding air, dissipating ambient heat. In contrast, urban areas are characterized by dry, impervious surfaces, such as conventional roofs, sidewalks, roads, and parking lots. As cities develop, more vegetation is lost, and more surfaces are paved or covered with buildings. The change in ground cover results in less shade and moisture to keep urban areas cool. Built up areas evaporate less water (see Figure 5), which contributes to elevated surface and air temperatures.

Figure 5: Impervious Surfaces and Reduced Evapotranspiration



Modified from the Federal Interagency Stream Restoration Working Group (FISRWG)

Highly developed urban areas (right), which are characterized by 75%-100% impervious surfaces, have less surface moisture available for evapotranspiration than natural ground cover, which has less than 10% impervious cover (left). This characteristic contributes to higher surface and air temperatures in urban areas.

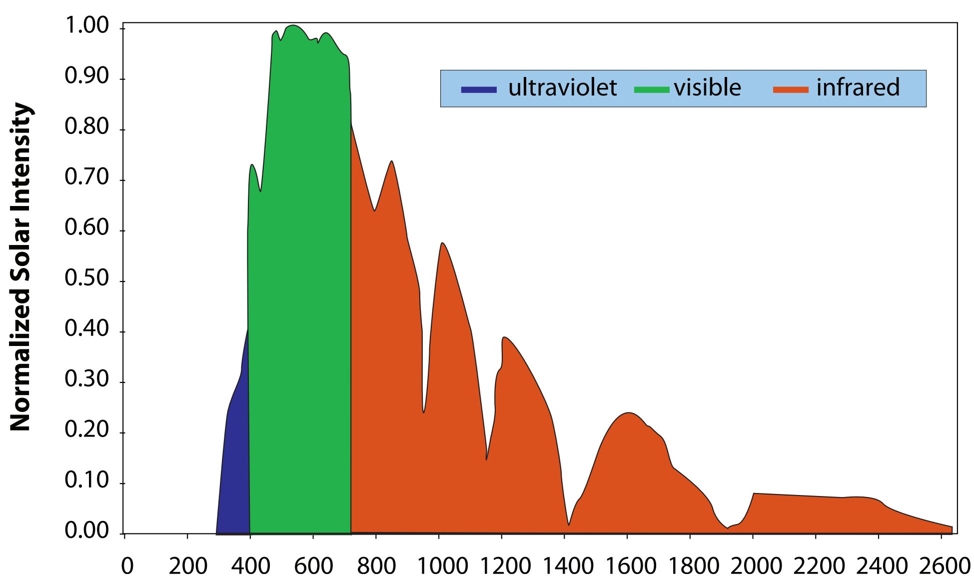
2.2 Properties of Urban Materials

Properties of urban materials, in particular solar reflectance, thermal emissivity, and heat capacity, also influence urban heat island development, as they determine how the sun's energy is reflected, emitted, and absorbed.

Figure 6 shows the typical solar energy that reaches the Earth's surface on a clear summer day. Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: five percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat. Energy in all of these wavelengths contributes to urban heat island formation.

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Much of the sun's energy is found in the visible wavelengths (see Figure 6); thus, solar reflectance is correlated with a material's color. Darker surfaces tend to have lower solar reflectance values than lighter surfaces. Researchers are studying and developing cool colored materials, though, that use specially engineered pigments that reflect well in the infrared wavelengths. These products can be dark in color but have a solar reflectance close to that of a white or light-colored material. (See the "Cool Roofs" chapter for further discussion of cool colored roof products.)

Figure 6: Solar Energy versus Wavelength Reaching Earth's Surface



Solar energy intensity varies over wavelengths from about 250 to 2500 nanometers.

Urban areas typically have surface materials, such as roofing and paving, which have a lower albedo than those in rural settings. As a result, built up communities generally reflect less and absorb more of the sun's energy. This absorbed heat increases surface temperatures and contributes to the formation of surface and atmospheric urban heat islands.

Although solar reflectance is the main determinant of a material's surface temperature, thermal emittance, or emissivity, also plays a role. Thermal emittance is a measure of a surface's ability to shed heat, or emit long-wave (infrared) radiation. All things equal, surfaces with high emittance values will stay cooler, because they will release heat more readily. Most construction materials, with the exception of metal, have high thermal emittance values. Thus, this property is mainly of interest to those installing cool roofs, which can be metallic. See the "Cool Roofs" chapter of the compendium for more information.

Another important property that influences heat island development is a material's heat capacity, which refers to its ability to store heat. Many building materials, such as steel and stone, have higher heat capacities than rural materials, such as dry soil and sand. As a result, cities are typically more effective at storing the sun's energy as heat within their infrastructure. Downtown metropolitan areas can absorb and store twice the amount of heat compared to their rural surroundings during the daytime.[10]

Radiative and Thermal Properties—Cool Roofs and Cool Pavements

Albedo and emissivity are considered "radiative properties." Heat capacity, on the other hand, is one of several "thermal properties" a material can possess. For thin materials like roofing, which is typically placed over insulation, reflectance and emittance are the main properties to consider, as the heat capacity of a well insulated roof is low. For pavements, which are thicker than roofing products and are placed on top of the ground, which has its own set of thermal characteristics, designers and researchers need to consider a more complex set of factors that include radiative and thermal properties—such as heat capacity, thermal conductivity, and density.

2.3 Urban Geometry

An additional factor that influences urban heat island development, particularly at night, is urban geometry, which refers to the dimensions and spacing of buildings within a city. Urban geometry influences wind flow, energy absorption, and a given surface's ability to emit long-wave radiation back to space. In developed areas, surfaces and structures are often at least partially obstructed by objects, such as neighboring buildings, and become large thermal masses that cannot release their heat very readily because of these obstructions. Especially at night, the air above urban centers is typically warmer than air over rural areas. Nighttime atmospheric heat islands can have serious health implications for urban residents during heat waves (see textbox in Section 3.3, "Factors in Heat-Related Illnesses and Death.")

Researchers often focus on an aspect of urban geometry called urban canyons, which can be illustrated by a relatively narrow street lined by tall buildings. During the day, urban canyons can have competing effects. On the one hand, tall buildings can create shade, reducing surface and air temperatures. On the other, when sunlight reaches surfaces in the canyon, the sun's energy is reflected and absorbed by building walls, which further lowers the city's overall albedo—the net reflectance from surface albedo plus urban geometry—and can increase temperatures.[11] At night, urban canyons generally impede cooling, as buildings and structures can obstruct the heat that is being released from urban infrastructure.

Table 2: Factors that Create Urban Heat Islands

Factors Communities are Focusing On
• Reduced vegetation in urban regions: Reduces the natural cooling effect from shade and evapotranspiration. • Properties of urban materials: Contribute to absorption of solar energy, causing surfaces, and the air above them, to be warmer in urban areas than those in rural surroundings.
Future Factors to Consider
• Urban geometry: The height and spacing of buildings affects the amount of radiation received and emitted by urban infrastructure. • Anthropogenic heat emissions: Contribute additional warmth to the air.*
Additional Factors
• Weather: Certain conditions, such as clear skies and calm winds, can foster urban heat island formation. • Geographic location: Proximity to large water bodies and mountainous terrain can influence local wind patterns and urban heat island formation.

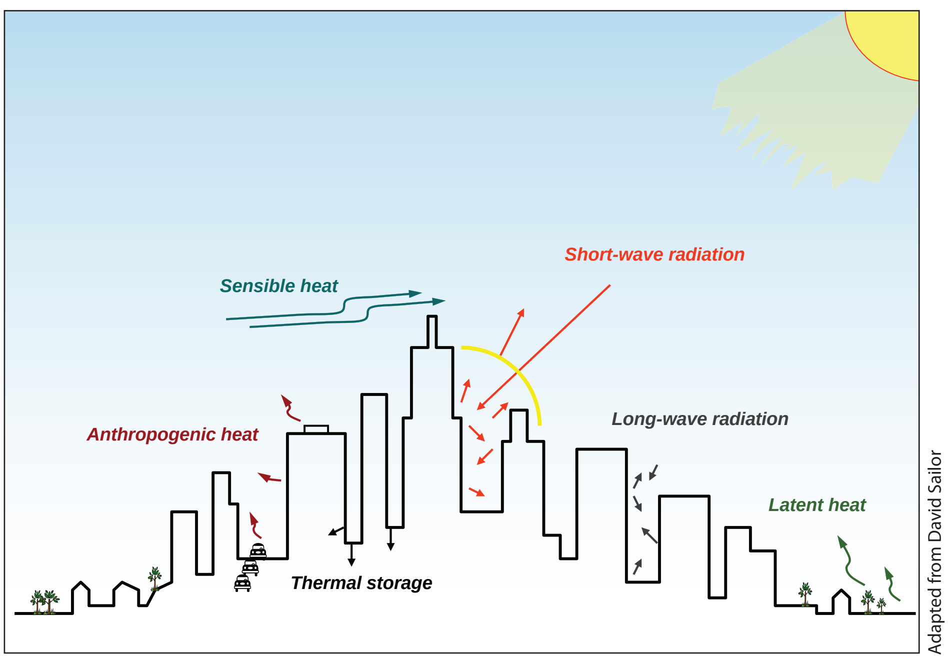
* Although communities currently can lower anthropogenic heat emissions through energy efficiency technologies in the building and vehicle sectors, this compendium focuses on modifying vegetative cover and surface properties of urban materials, as they have long been regarded as urban heat island reduction strategies. An emerging body of literature on the role waste heat plays in urban heat island formation, though, may lead communities to focus on anthropogenic heat in the near future.

The Urban Surface Energy Budget

An energy budget provides an equation that quantifies the balance of incoming and outgoing energy flows, or fluxes (see Figure 7). The surface energy budgets of urban areas and their more rural surroundings will differ because of differences in land cover, surface characteristics, and level of human activity. Such differences can affect the generation and transfer of heat, which can lead to different surface and air temperatures in urban versus rural areas. Various elements of the budget include:

- **Short-wave radiation** is ultraviolet, visible light, and near-infrared radiation from the sun that reaches the Earth (see Figure 6). This energy is a key driver of urban heat islands. Urban surfaces, compared to vegetation and other natural ground cover, reflect less radiation back to the atmosphere. They instead absorb and store more of it, which raises the area's temperature.
- **Thermal storage** increases in cities in part due to the lower solar reflectance of urban surfaces, but it is also influenced by the thermal properties of construction materials and urban geometry. Urban geometry can cause some short-wave radiation—particularly within an urban canyon—to be reflected on nearby surfaces, such as building walls, where it is absorbed rather than escaping into the atmosphere.

Figure 7: Urban Surface Energy Budget



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The Urban Surface Energy Budget (continued)

- Similarly, urban geometry can impede the release of **long-wave, or infrared, radiation** into the atmosphere. When buildings or other objects absorb incoming short-wave radiation, they can re-radiate that energy as long-wave energy, or heat. However, at night, due to the dense infrastructure in some developed areas that have low sky view factors (see section 2.3), urban areas cannot easily release long-wave radiation to the cooler, open sky, and this trapped heat contributes to the urban heat island.
- Evapotranspiration describes the transfer of **latent heat,** what we feel as humidity, from the Earth's surface to the air via evaporating water. Urban areas tend to have less evapotranspiration relative to natural landscapes, because cities retain little moisture. This reduced moisture in built up areas leads to dry, impervious urban infrastructure reaching very high surface temperatures, which contribute to higher air temperatures.*
- Convection describes the transfer of **sensible heat,** what we feel as temperature, between the surface and air when there is a difference in temperature between them. High urban surface temperatures warm the air above, which then circulates upwards via convection.
- **Anthropogenic heat** refers to the heat generated by cars, air conditioners, industrial facilities, and a variety of other manmade sources, which contributes to the urban energy budget, particularly in the winter.

* This change in landscape may differ in regions such as deserts, where moisture may increase in urban areas if development introduces grass lawns and other irrigated vegetation.

The effects of urban geometry on urban heat islands are often described through the "sky view factor" (SVF), which is the visible area of the sky from a given point on a surface. For example, an open parking lot or field that has few obstructions would have a large SVF value (closer to 1). Conversely, an urban canyon in a downtown area that is surrounded by closely spaced, tall buildings, would have a low SVF value (closer to zero), as there would only be a small visible area of the sky.

2.4 Anthropogenic Heat

Anthropogenic heat contributes to atmospheric heat islands and refers to heat produced by human activities. It can come from a variety of sources and is estimated by totaling all the energy used for heating and cooling, running appliances, transportation, and industrial processes. Anthropogenic heat varies by urban activity and infrastructure, with more energy-intensive buildings and transportation producing more heat.[12] Anthropogenic heat typically is not a concern in rural areas and during the summer. In the winter, though, and year round in dense, urban areas, anthropogenic heat can significantly contribute to heat island formation.

2.5 Additional Factors

Weather and location strongly influence urban heat island formation. While communities have little control over these factors, residents can benefit from understanding the role they play.

- **Weather.** Two primary weather characteristics affect urban heat island development: wind and cloud cover. In general, urban heat islands form during periods of calm winds and clear skies, because these conditions maximize the amount of solar energy reaching urban surfaces and minimize the amount of heat that can be convected away. Conversely, strong winds and cloud cover suppress urban heat islands.
- **Geographic location.** Climate and topography, which are in part determined by a city's geographic location, influence urban heat island formation. For example, large bodies of water moderate temperatures and can generate winds that convect heat away from cities. Nearby mountain ranges can either block wind from reaching a city, or create wind patterns that pass through a city. Local terrain has a greater significance for heat island formation when larger-scale effects, such as prevailing wind patterns, are relatively weak.

3. Why Do We Care about Urban Heat Islands?

Elevated temperatures from urban heat islands, particularly during the summer, can affect a community's environment and quality of life. While some heat island impacts seem positive, such as lengthening the plant-growing season, most impacts are negative and include:

- Increased energy consumption
- Elevated emissions of air pollutants and greenhouse gases
- Compromised human health and comfort
- Impaired water quality.

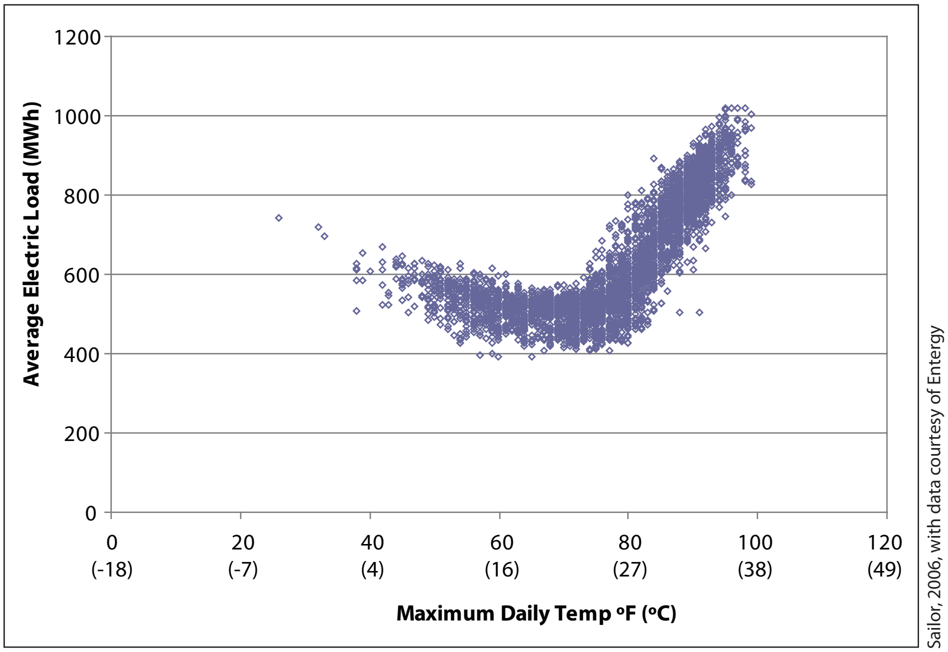
Wintertime Benefits of Urban Heat Islands

Communities may benefit from the wintertime warming effect of urban heat islands. Warmer temperatures can reduce heating energy needs and help to melt snow and ice on roads. Fortunately, urban heat island mitigation strategies—for example, trees and vegetation and green roofs—generally provide year-round benefits, or their winter penalty, such as that from cool roofs, is much smaller than their summertime benefits.

3.1 Energy Consumption

Elevated summertime temperatures in cities increase energy demand for cooling and add pressure to the electricity grid during peak periods of demand, which generally occur on hot, summer weekday afternoons, when offices and homes are running cooling systems, lights, and appliances (see Figure 8). This peak urban electric demand increases 1.5 to 2 percent for every 1°F (0.6°C) increase in summertime temperature. Steadily increasing downtown temperatures over the last several decades mean that 5 to 10 percent of community-wide demand for electricity is used to compensate for the heat island effect.[13] During extreme heat events, which are exacerbated by urban heat islands, the resulting demand for cooling can overload systems and require a utility to institute controlled, rolling brownouts or blackouts to avoid power outages.

Figure 8: Increasing Power Loads with Temperature Increases[14]



As shown in this example from New Orleans, electrical load can increase steadily once temperatures begin to exceed about 68 to 77°F (20 to 25°C). Other areas of the country show similar demand curves as temperature increases.

3.2 Air Quality and Greenhouse Gases

As discussed in Section 3.1, higher temperatures can increases energy demand, which generally causes higher levels of air pollution and greenhouse gas emissions. Currently, most electricity in the United States is produced from combusting fossil fuel. Thus, pollutants from most power plants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and mercury (Hg). These pollutants are harmful to human health and contribute to complex air quality problems such as acid rain. Further, fossil-fuel-powered plants emit greenhouse gases, particularly carbon dioxide (CO_2), which contribute to global climate change.

In addition to increases in air emissions, elevated air temperatures increase the rate of ground-level ozone formation, which is produced when NO_x and volatile organic compounds (VOCs) react in the presence of sunlight. If all other variables are equal—such as the level of precursor emissions or wind speed and direction—ground-level ozone emissions will be higher in sunnier and hotter weather.

3.3 Human Health and Comfort

Increased daytime surface temperatures, reduced nighttime cooling, and higher air pollution levels associated with urban heat islands can affect human health by contributing to general discomfort, respiratory difficulties, heat cramps and exhaustion, non-fatal heat stroke, and heat-related mortality.

Urban heat islands can also exacerbate the impact of heat waves, which are periods of abnormally hot, and often humid, weather. Sensitive populations, such as children, older adults, and those with existing health conditions, are at particular risk from these events. For example, in 1995, a mid-July heat wave in the Midwest caused more than 1,000 deaths.[15] While it is rare for a

Factors in Heat-Related Illnesses and Death

Low income elderly people who live in row homes are at a particular risk for heat-related health incidents. Living on the upper floor of a typical row home, with a dark roof, brick construction, and windows on only two sides, could contribute to the risk of heat-related illness or death during heat waves, as temperatures in these homes can be extreme.[16] These homes often lack air conditioning, especially in areas unaccustomed to high temperatures. Further, even when air conditioning is available, residents may not use it for fear of high utility bills.

Social isolation and physical health also contribute to one's vulnerability. Elderly people, especially, may not have family or friends nearby, may not report to work regularly, and may lack neighbors who can check on them, leaving them stranded during extreme heat events. The elderly may also fail to hear news or other warnings of impending heat waves and recommendations on how to cope. Finally, their bodies may be less able to handle heat stress.

The lack of nighttime relief in air temperatures is strongly correlated with increased mortality during heat waves. Some studies suggest that these oppressive nighttime temperatures may be more significant than high maximum daytime temperatures.[17]

For more information on heat-related health incidents and ways to respond, see the EPA Excessive Heat Events Guidebook <www.epa.gov/hiri/about/pdf/EHEguide_final.pdf>

heat wave to be so destructive, heat-related mortality is not uncommon. The Centers for Disease Control estimates that from 1979 to 1999, excessive heat exposure contributed to more than 8,000 premature deaths in the United States.[18] This figure exceeds the number of mortalities resulting from hurricanes, lightning, tornadoes, floods, and earthquakes combined.

3.4 Water Quality

Surface urban heat islands degrade water quality, mainly by thermal pollution. Pavement and rooftop surfaces that reach temperatures 50 to 90°F (27 to 50°C) higher than air temperatures transfer this excess heat to stormwater. Field measurements from one study showed that runoff from urban areas was about 20-30°F (11-17°C) hotter than runoff from a nearby rural area on summer days when pavement temperatures at midday were 20-35°F (11-19°C) above air temperature. When the rain came before the pavement had a chance to heat up, runoff temperatures from the rural and urban areas differed by less than 4°F (2°C).[19] This heated stormwater generally drains into storm sewers (see Figure 5) and raises water temperatures as it is released into streams, rivers, ponds, and lakes. A study in Arlington, Virginia, recorded temperature increases in surface waters as high as 8°F (4°C) in 40 minutes after heavy summer rains.[20]

Water temperature affects all aspects of aquatic life, especially the metabolism and reproduction of many aquatic species. Rapid temperature changes in aquatic ecosystems resulting from warm stormwater runoff can be particularly stressful. Brook trout, for example, experience thermal stress and shock when the water temperature changes more than 2 to 4ºF (1-2°C) in 24 hours.[21]

4. Strategies to Reduce Urban Heat Islands

Although urban climatologists have been studying urban heat islands for decades, community interest and concern regarding them has been more recent. This increased attention to heat-related environment and health issues has helped to advance the development of heat island reduction strategies, mainly trees and vegetation, green roofs, and cool roofs. Interest in cool pavements has been growing, and an emerging body of research and pilot projects are helping scientists, engineers, and practitioners to better understand the interactions between pavements and the urban climate.

This compendium *Reducing Urban Heat Islands: Compendium of Strategies* provides details about how these strategies work, their benefits and costs, factors to consider when selecting them, and additional resources for communities to further explore. It presents the multiple benefits—beyond temperature reduction—that a community can accrue from advancing heat island reduction strategies. It also gives examples of how communities have implemented these strategies through voluntary and policy efforts in the "Heat Island Reduction Activities" chapter. Communities can use this compendium as a foundation and starting point for understanding the nuts and bolts of existing urban heat island reduction strategies that communities are currently advancing.

Future policy efforts may focus on encouraging strategies to modify urban geometry and anthropogenic heat in communities to reduce urban heat islands. Research in this area is on-going, and there is a growing awareness of the importance of these factors.

5. Additional Resources

The table on the next page provides additional resources on urban heat island formation, measurement, and impacts.

Table 3: Urban Heat Island Resources

Name	Description	Web Link
General Information		
EPA's Heat Island Website	Through this website, EPA provides background information, publications, reports, access to national webcasts, a database of urban heat island activities, and links to other resources to help communities reduce urban heat islands.	<www.epa.gov/heatislands>
International Association for Urban Climate (IAUC)	This international website is the main forum in which urban climatologists communicate. Urban climate resources, including a bimonthly newsletter, and information on upcoming meetings can be found here.	<www.urban-climate.org>
Lawrence Berkeley National Laboratory (LBNL) Heat Island Group	LBNL provides background information on urban heat islands and their impacts through this website. It also presents some of the impacts heat island reduction strategies can have on temperature, energy consumption, and air quality.	<http://eetd.lbl.gov/HeatIsland>
National Center of Excellence - SMART Innovations for Urban Climate and Energy	Arizona State University's National Center of Excellence collaborates with industry and government to research and develop technologies to reduce urban heat islands, especially in desert climates. Its website provides background information on urban heat islands.	<www.asusmart.com/urbanclimate.php>
Urban Heat Islands: Hotter Cities	This article explains urban heat islands and presents solutions to mitigate them.	<www.actionbioscience.org/environment/voogt.html>
Measuring Heat Islands and Their Impacts		
National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey Landsat Program	The Landsat program is a series of Earth-observing satellites used to acquire images of the Earth's land surface and surrounding coastal regions. These images provide information from which researchers can derive surface temperatures and evaluate urban heat islands.	<http://landsat.gsfc.nasa.gov/>
National Weather Service	The National Weather Service is a source for air temperature measurements, climate and weather models, and past and future climate predictions. The site also has links to excessive heat outlooks, fatality statistics, historic data on major heat waves, drought information, and advice on how to minimize the health risks of heat waves.	<www.nws.noaa.gov/>
EPA's Excessive Heat Events Guidebook	This document is designed to help community officials, emergency managers, meteorologists, and others plan for and respond to excessive heat events by highlighting best practices that have been employed to save lives during excessive heat events in different urban areas. It provides a menu of options that officials can use to respond to these events in their communities.	<www.epa.gov/hiri/about/heatguidebook.html>

Endnotes

1 Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287.

2 Oke. T.R. 1987. Boundary Layer Climates. New York, Routledge.

3 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24. The threshold city population for heat islands of the size 2-5°F may be closer to 100,000 inhabitants in some cases. See also Aniello, C., K. Morgan, A. Busbey, and L. Newland. 1995. Mapping Micro-Urban Heat Islands Using Landsat TM and a GIS. Computers and Geosciences 21(8):965-69.

4 From: 1) Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287. 2) Oke. T.R. 1987. Boundary Layer Climates. New York, Routledge. 3) Voogt, J.A. and T.R. Oke. 2003. Thermal Remote Sensing of Urban Areas. Remote Sensing of Environment. 86. (Special issue on Urban Areas): 370-384. 4) Roth, M., T. R. Oke, and W. J. Emery. 1989. Satellite-derived Urban Heat Islands from Three Coastal Cities and the Utilization of Such Data in Urban Climatology. Int. J. Remote Sensing. 10:1699-1720.

5 Berdahl P. and S. Bretz. 1997. Preliminary Survey of the Solar Reflectance of Cool Roofing Materials. Energy and Buildings 25:149-158.

6 Numbers from Voogt, J.A. and T.R. Oke. 2003. Thermal Remote Sensing of Urban Areas. Remote Sensing of Environment. 86. (Special issue on Urban Areas): 370-384. Roth, M., T. R. Oke, and W. J. Emery. 1989. Satellite-derived Urban Heat Islands from Three Coastal Cities and the Utilization of Such Data in Urban Climatology. Int. J. Remote Sensing. 10:1699-1720.

7 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24.

8 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24.

9 Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287.

10 Christen, A. and R. Vogt. 2004. Energy and Radiation Balance of a Central European City. International Journal of Climatology. 24(11):1395-1421.

11 Sailor, D.J., and H. Fan. 2002. Modeling the Diurnal Variability of Effective Albedo for Cities. Atmospheric Environment. 36(4): 713-725.

12 Voogt, J. 2002. Urban Heat Island. In Munn, T. (ed.) Encyclopedia of Global Environmental Change, Vol. 3. Chichester: John Wiley and Sons.

13 Akbari, H. 2005. Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation. Retrieved 2 Jul. 2008 from <http://www.osti.gov/bridge/servlets/purl/860475-UlH-WIq/860475.PDF>.

14 Sailor, D. J. 2002. Urban Heat Islands, Opportunities and Challenges for Mitigation and Adaptation. Sample Electric Load Data for New Orleans, LA (NOPSI, 1995). North American Urban Heat Island Summit. Toronto, Canada. 1-4 May 2002. Data courtesy Entergy Corporation.

15 Taha, H. and L.S. Kalkstein, S.C. Sheridan, and E. Wong. 2004. The Potential of Urban Environmental Controls in Alleviating Heat-wave Health Effects in Five US Regions. Presented at the American Meteorological Society Fifth Conference on Urban Environment. 25 August. See also NOAA. 1995. Natural Disaster Survey Report: July 1995 Heat Wave. Retrieved 20 June 2008 from <http://www.nws.noaa.gov/om/assessments/pdfs/heat95.pdf>.

16 Kalkstein, L.S. and S.C. Sheridan. 2003. The Impact of Heat Island Reduction Strategies on Health-Debilitating Oppressive Air Masses in Urban Areas. Prepared for U.S. EPA Heat Island Reduction Initiative.

17 Kalkstein, L.S. 1991. A New Approach to Evaluate the Impact of Climate upon Human Mortality. Environmental Health Perspectives 96: 145-50.

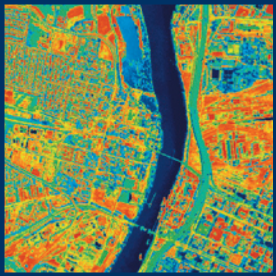
18 CDC. 2004. Extreme Heat: A Prevention Guide to Promote Your Personal Health and Safety. Retrieved 27 July 2007 from <http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp>.

19 Roa-Espinosa, A., T.B. Wilson, J.M. Norman, and Kenneth Johnson. 2003. Predicting the Impact of Urban Development on Stream Temperature Using a Thermal Urban Runoff Model (TURM). National Conference on Urban Stormwater: Enhancing Programs at the Local Level. February 17-20. Chicago, IL. Retrieved 17 Jul. 2008 from <http://www.epa.gov/nps/natlstormwater03/31Roa.pdf>.

20 EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.

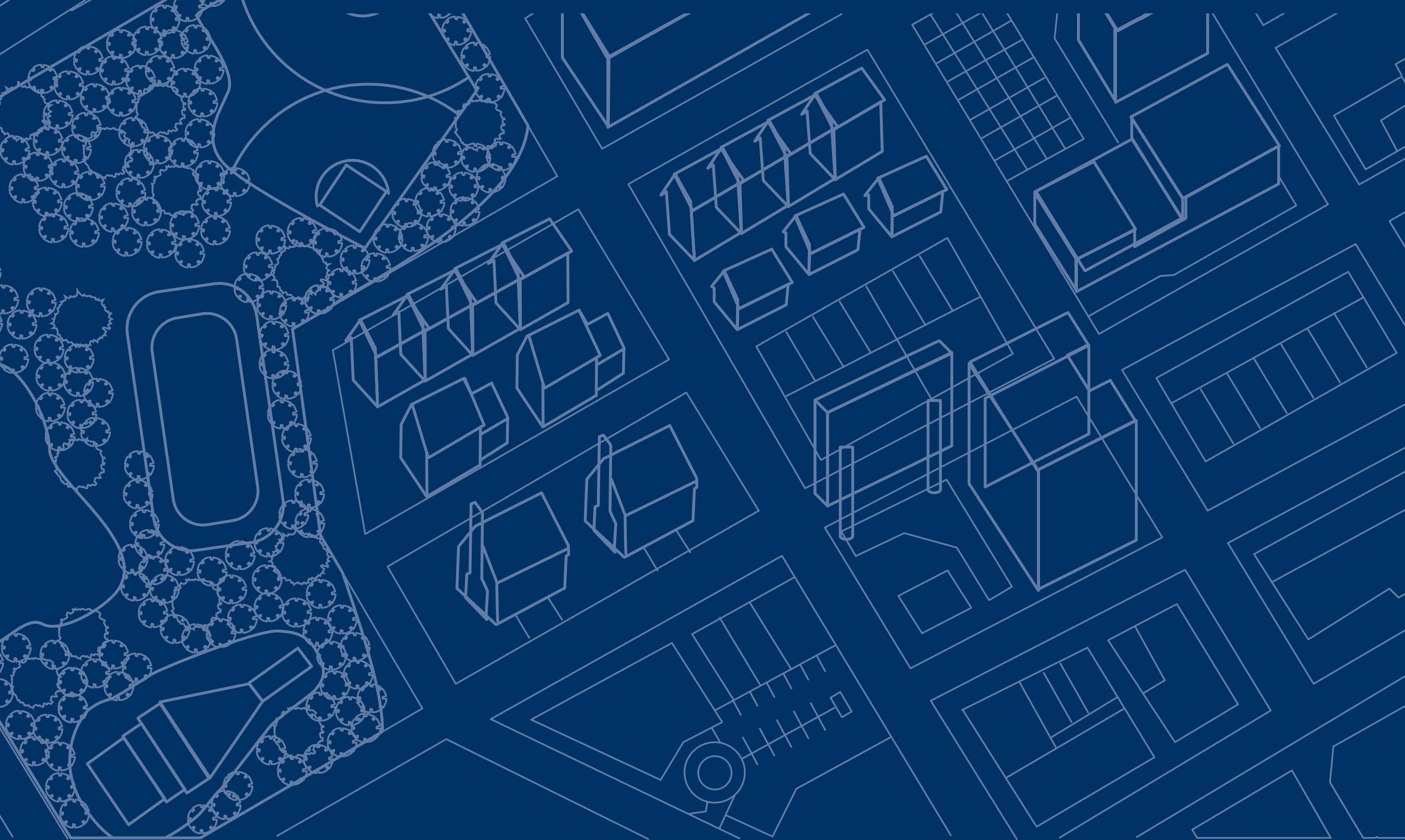
21 EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.





Reducing Urban Heat Islands: Compendium of Strategies

Trees and Vegetation



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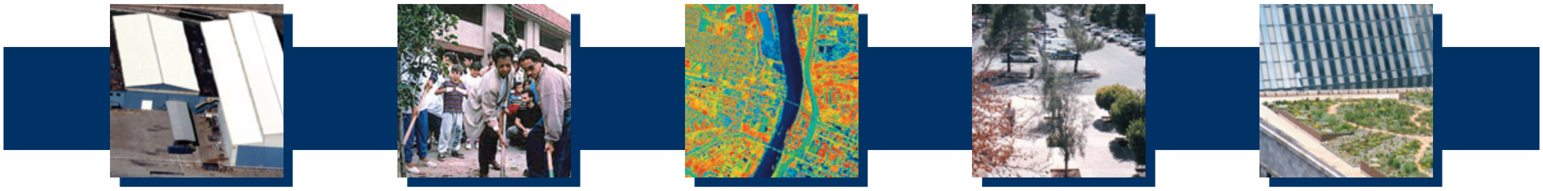


Trees and Vegetation

Shade trees and smaller plants such as shrubs, vines, grasses, and ground cover, help cool the urban environment. Yet, many U.S. communities have lost trees and green space as they have grown. This change is not inevitable. Many communities can take advantage of existing space, such as grassy or barren areas, to increase their vegetative cover and reap multiple benefits.

Opportunities to Expand the Use of Urban Trees and Vegetation

Most U.S. communities have opportunities to increase the use of trees and vegetation. As part of the U.S. Environmental Protection Agency's (EPA's) Urban Heat Island Pilot Project, the Lawrence Berkeley National Laboratory conducted analyses to estimate baseline land use and tree cover information for the pilot program cities.[1] Figure 1 shows the percentage of vegetated and barren land cover in four of these urban areas. The high percentage of grass and barren land cover show the space potentially available for additional tree canopy cover. The statistics do not show the loss of dense vegetated cover as cities expand, however. For example, a 2005 report estimates that Houston lost 10 million trees per year from 1992 to 2000.[2]

Figure 1: Land Cover Statistics for Various U.S. Cities (Above Tree Canopy)

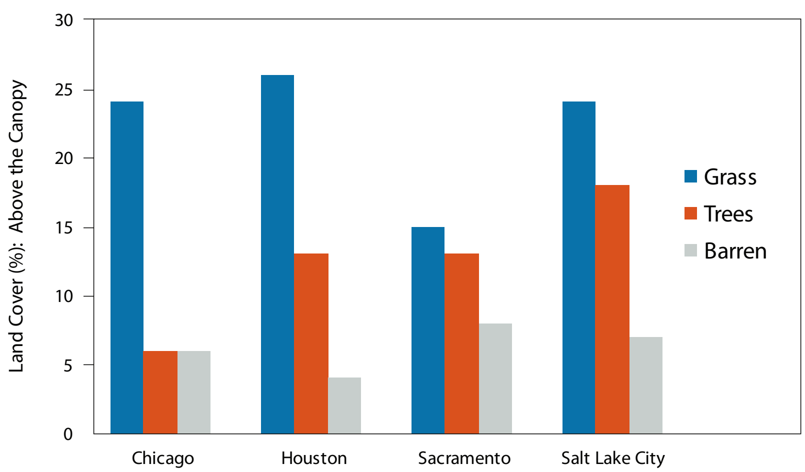
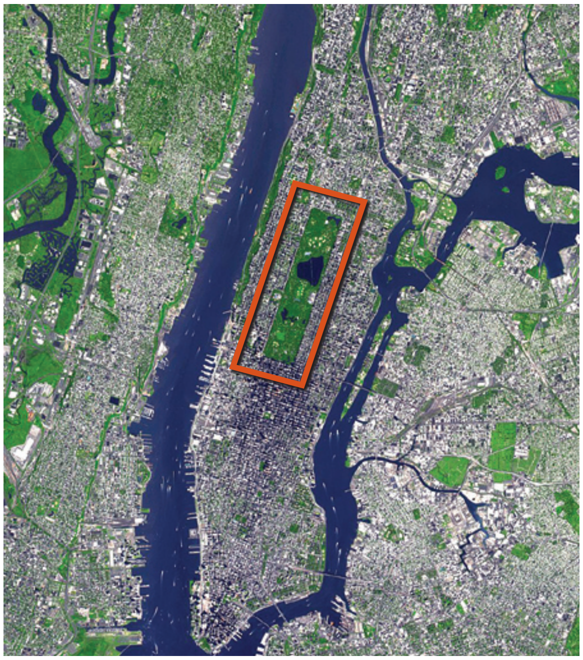


Figure 2: Vegetative Cover in New York City



NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

New York City reveals how developed areas (gray and white in this image) can replace vegetation (green). Central Park is highlighted by the orange rectangle.

This chapter outlines some of the issues communities might consider in determining whether and how to expand the use of trees and vegetation so as to mitigate urban heat island conditions. Among the topics covered in this chapter are:

- How trees and vegetation reduce temperatures
- Some of the benefits and costs associated with trees and vegetation
- Other factors a mitigation program might consider
- Urban forestry initiatives
- Tools and resources for further information.

1. How It Works

Trees and vegetation help cool urban climates through shading and evapotranspiration.

Shading. Leaves and branches reduce the amount of solar radiation that reaches the area below the canopy of a tree or plant. The amount of sunlight transmitted through the canopy varies based on plant species. In the summertime, generally 10 to 30 percent of the sun's energy reaches the area below a tree, with the remainder being absorbed by leaves and used for photosynthesis, and some being reflected back into the atmosphere. In winter, the range of sunlight transmitted through a tree is much wider—10 to 80 percent—because evergreen and deciduous trees have different wintertime foliage, with deciduous trees losing their leaves and allowing more sunlight through.[3]

Figure 3: Trees Shade a Home

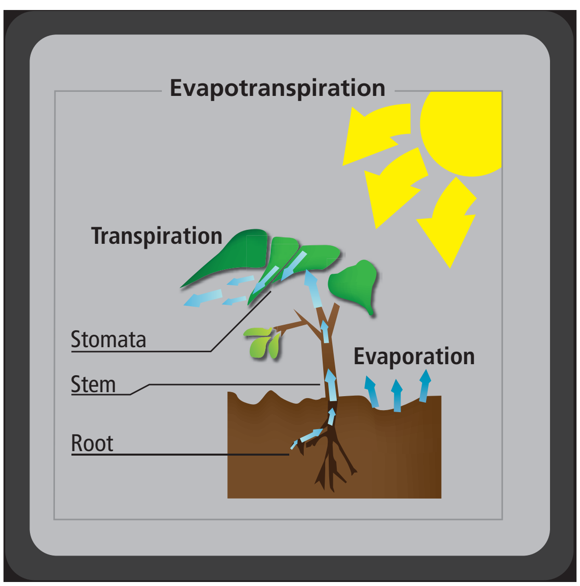
Steve Cundy

Tree canopies, such as the deciduous trees around this home in Virginia, can block much of the sunlight from reaching the ground or the building.

Shading reduces surface temperatures below the tree canopy. These cooler surfaces, in turn, reduce the heat transmitted into buildings and the atmosphere. For example, a multi-month study measured maximum surface temperature reductions ranging from 20 to 45°F (11-25°C) for walls and roofs at two buildings.[4] Another study examined the effects of vines on wall temperatures and found reductions of up to 36°F (20°C).[5] A third study found that tree shading reduces the temperatures inside parked cars by about 45°F (25°C).[6]

Evapotranspiration. Trees and vegetation absorb water through their roots and emit it through their leaves—this movement of water is called "transpiration." A large oak tree, for example, can transpire 40,000 gallons of water per year; an acre of corn can transpire 3,000 to 4,000 gallons a day.[7] Evaporation, the conversion of water from a liquid to a gas, also occurs from the soil around vegetation and from trees and vegetation as they intercept rainfall on leaves and other surfaces. Together, these processes are referred to as evapotranspiration. Evapotranspiration cools the air by using heat from the air to evaporate water.

Figure 4: Evapotranspiration



Plants take water from the ground through their roots and emit it through their leaves, a process known as transpiration. Water can also evaporate from tree surfaces, such as the stalk, or surrounding soil.

Evapotranspiration, alone or in combination with shading, can help reduce peak summer air temperatures. Various studies[8,9] have measured the following reductions:

- Peak air temperatures in tree groves that are 9°F (5°C) cooler than over open terrain.
- Air temperatures over irrigated agricultural fields that are 6°F (3°C) cooler than air over bare ground.
- Suburban areas with mature trees that are 4 to 6°F (2 to 3°C) cooler than new suburbs without trees.
- Temperatures over grass sports fields that are 2 to 4°F (1 to 2°C) cooler than over bordering areas.

Trees and other large vegetation can also serve as windbreaks or wind shields to reduce the wind speed in the vicinity of buildings. In the summertime, the impacts can be positive and negative. In the wintertime, reducing wind speeds, particularly cold north winds, can provide substantial energy benefits.

2. Using Trees and Vegetation in the Urban Landscape

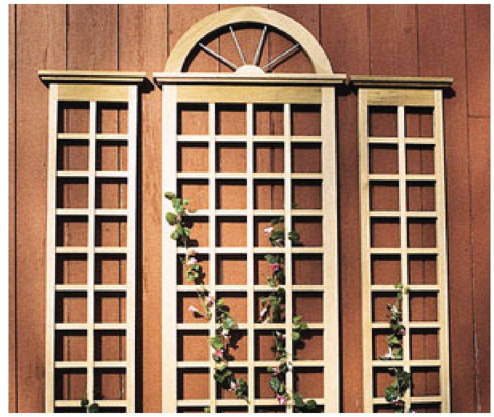
Trees and vegetation are most useful as a mitigation strategy when planted in strategic locations around buildings. Researchers have found that planting deciduous species to the west is typically most effective for cooling a building, especially if these trees shade windows and part of the building's roof. Shading the east side of a structure also reduces air conditioning demand.[10,11]

Planting trees to the south generally lowers summertime energy demand, but must be done carefully. Depending on the trees, the building's height, and the distance between the trees and a building, trees may be detrimental to an energy efficiency strategy if they block useful solar energy in the winter, when the sun is low in the sky, without providing much shade during the summer, when the sun is high in the sky.

Shading pavement in parking lots and on streets can be an effective way to help cool a community. Trees can be planted around perimeters and in medians inside parking lots or along the length of streets. Strategically placed shade trees also can benefit playgrounds, schoolyards, ball fields, and similar open spaces.

Trees are not the only vegetation option. There are many areas where trees either do not fit or grow too slowly to be effective over the short term, in which case vines may work better. Vines need less soil and space and grow very quickly. Vines grown on the west side of a building, for example, will shade the exterior wall and reduce its surface temperature, thus reducing heat gain inside the building. The vines will provide some air cooling benefits through evapotranspiration as well.

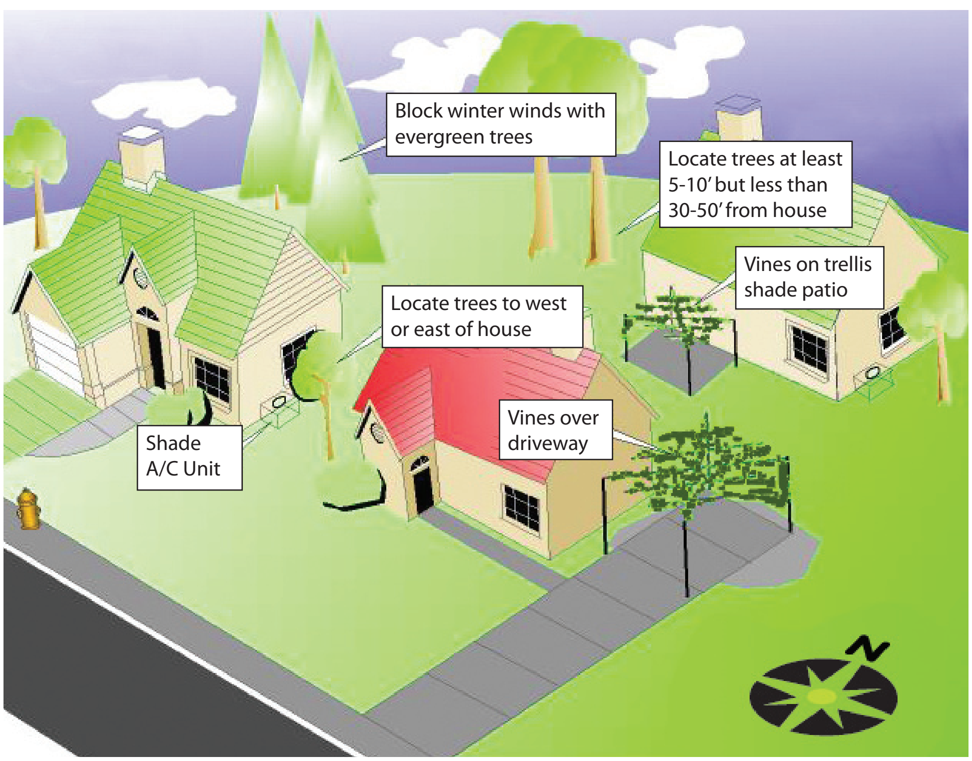
Figure 6: Vines to Shade a Wall



Trellis Structures, Inc.

Vines grown on trellises can provide a quick, simple source of shade.

Figure 5: Tree Placement to Maximize Energy Savings



Picking the right trees and putting them in the right location will maximize their ability to shade buildings and block winds throughout the year.

3. Benefits and Costs

The use of trees and vegetation in the urban environment brings many benefits, including lower energy use, reduced air pollution and greenhouse gas emissions, protection from harmful exposure to ultraviolet (UV) rays, decreased stormwater runoff, potential reduced pavement maintenance, and other quality-of-life benefits. At the same time, communities must also consider the costs of an urban forestry program and any potential negative impacts of increasing tree and vegetation cover. The following sections address these benefits and costs in more detail. Section 6 of this chapter summarizes software tools that calculate the range of potential benefits from urban tree and vegetation initiatives.

U.S. Department of Agriculture (USDA) Forest Service research centers offer links to publications about studies of trees and their benefits to urban areas. See <www.fs.fed.us/ne/syracuse/Pubs/pubs.htm> and <www.fs.fed.us/psw/programs/cufr/>.

3.1 Benefits

Reduced Energy Use. Trees and vegetation that provide direct shading reduce energy needed to cool buildings. Benefits vary based on the orientation and size of the plantings, as well as their distance from a building. Large trees planted close to the west side of a building will generally provide greater cooling energy savings than other plants.

The examples below from a variety of studies highlight cooling and year-round energy savings from trees and vegetation.

- Joint studies by the Lawrence Berkeley National Laboratory (LBNL) and the Sacramento Municipal Utility District (SMUD) placed varying numbers of trees around houses to shade windows and then measured the buildings' energy use.[12,13] The cooling energy savings ranged between 7 and 47 percent and were greatest when trees were planted to the west and southwest of buildings.[14]
- A USDA Forest Service study investigated the energy savings resulting from SMUD's residential tree planting program. This study included over 250 program participants in the Sacramento, California, area, and estimated the effect of new shade trees planted around houses. An average of 3 new trees were planted within 10 feet (3 m) of each house.[15] Annual cooling energy savings were 1 percent per tree, and annual heating energy use decreased by almost 2 percent per tree. The trees provided net wintertime benefits because the positive wind shielding effect outweighed the negative effect of added shade.
- Another LBNL study simulated the effects of trees on homes in various communities throughout the United States. Assuming one tree was planted to the west and another to the south of a house, the model predicted that a 20-percent tree canopy over the house would result in annual cooling savings of 8 to 18 percent and annual heating savings of 2 to 8 percent.[16] Although this particular model included benefits from trees planted to the south of a building, experts generally suggest planting to the west and east of buildings, taking care when planting to the south to avoid blocking desired solar heat gain in the winter.[17]

Reduced Air Pollution and Greenhouse Gas Emissions. In addition to saving energy, the use of trees and vegetation as a mitigation strategy can provide air quality and greenhouse gas benefits:

- Leaves remove various pollutants from the air, referred to as "dry deposition"
- Shade trees reduce evaporative emissions from parked vehicles
- Trees and vegetation remove and store carbon
- Trees and vegetation reduce greenhouse gas emissions from power plants by reducing energy demand.

Researchers have investigated the potential for expanding urban tree and vegetative cover to address air quality concerns, such as ground-level ozone. One study predicted that increasing the urban canopy of New York City by 10 percent could lower ground-level ozone by about 3 percent, which is significant, particularly in places needing to decrease emissions to meet air quality standards for this pollutant.[18]

Pollutant Removal through Dry Deposition. Plants generally take up gaseous pollutants, primarily through leaf stomata, that then react with water inside the plant to form acids and other chemicals. Plants can also intercept particulate matter as wind currents blow particulates into contact with the plants' surfaces. Some particulates are absorbed into the plant while others adhere to the surface, where they can be resuspended into the atmosphere by winds or washed off by rain to the soil beneath.[19] These processes can reduce various pollutants found in the urban environment, including particulate matter (PM), nitrogen oxides (NO_X), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3).

Various studies have documented how urban trees can reduce pollutants. A 2006 study estimated total annual air pollutant removal by urban trees in the United States at 784,000 tons, with a value of $3.8 billion.[20] The study focused only on deposition of ground-level ozone, PM less than 10 microns in diameter (PM_{10}), nitrogen dioxide (NO_2), SO_2, and CO. Although the estimated changes in local ambient air quality were modest, typically less than 1 percent, the study noted that additional benefits would be gained if urban temperature and energy impacts from trees and vegetation were also included.

Reduced Evaporative Emissions. Tree shade can keep parked cars—particularly their gas tanks—cooler, which lowers evaporative emissions of volatile organic compounds (VOCs), a critical precursor pollutant in the formation of ground-level ozone. Most large urban areas have a wide range of control programs to reduce these emissions, and tree shading programs can be part of those strategies. For example, one analysis predicted that light-duty vehicle evaporative VOC emission rates throughout Sacramento County could be reduced by 2 percent per day if the community increased the tree canopy over parking lots from 8 to 50 percent.[21]

Carbon Storage and Sequestration. As trees grow, they remove carbon from the atmosphere and store, or sequester, it. As trees die or deposit litter and debris on the ground, carbon is released to the atmosphere or transferred to the soil. The net effect of this carbon cycle is a substantial level of carbon storage in trees, vegetation, and soils.

The net rate of carbon sequestered by urban trees in the continental United States in 2005 is estimated to have been around 24 million tons per year (88.5 million tons

Plants and Carbon: Storage versus Sequestration

Storage: Carbon currently held in plant tissue (tree bole, branches, and roots).

Sequestration: The estimated amount of carbon removed annually by plants, through the process of photosynthesis.

CO_2eq)[22], while current total carbon storage in urban trees in the continental United States is approximately 700 million tons of carbon. The national average urban forest carbon storage density is just over 25 tons per hectare (100,000 square feet, or 9,300 m^2), but varies widely from one community to another and corresponds generally to the percentage of land with tree cover and to tree size and health.[23] The California Air Resources Board recently approved guidelines that will allow carbon sequestered from forests to help meet the carbon emissions reductions stipulated by California's law AB32.[24]

Reduction in Greenhouse Gas Emissions through Reduced Energy Demand. As noted above, trees and vegetation can decrease energy demand. To the extent that reduced energy consumption decreases fossil fuel burning in power plants, trees and vegetation also contribute to lower carbon emissions from those power plants. One modeling study estimated that the direct energy savings from shading alone by trees and vegetation could reduce carbon emissions in various U.S. metropolitan areas by roughly 1.5 to 5 percent.[25] The study assumed that eight shade trees would be placed strategically around residential and office buildings and four around retail stores. As urban forests also contribute to air temperature reductions, the study found that there would be additional reductions in energy use and carbon emissions from those indirect effects as well.

Full Life-cycle Carbon Reductions. In order to investigate the full life-cycle impact of urban trees on annual CO_2 emissions, researchers consider:

- Annual CO_2 carbon sequestration rates
- Annual CO_2 releases from decomposition
- Annual CO_2 releases from maintenance activities
- Annual CO_2 avoided emissions because of reduced energy use.

By combining these four variables, researchers can estimate the net CO_2 reductions from urban forest resources for a specific community and calculate the associated net monetary benefits. A 2006 field study found that about 15,000 inventoried street trees in Charleston, South Carolina, were responsible for an annual net reduction of over 1,500 tons of CO_2. These benefits were worth about $1.50 per tree, based on average carbon credit prices.[26]

Improved Human Health. By reducing air pollution, trees and vegetation lower the negative health consequences of poor air quality. Also, similar to the benefits of cool roofs discussed in the "Cool Roof" chapter, shade trees can reduce heat gain in buildings, which can help lower indoor air temperatures and minimize the health impacts from summertime heat waves.

A third health benefit from trees and vegetation involves reducing direct exposure to UV rays. The sun's UV rays can have adverse health effects on the skin and eyes.

High levels of long-term exposure to UV rays are linked to skin cancer. The shade provided by dense tree canopies can help to lower UV exposure, although this should not be considered a primary preventive measure (see text box below).[27,28]

Enhanced Stormwater Management and Water Quality. Urban forests, vegetation, and soils can reduce stormwater runoff and adverse impacts to water resources. Trees and vegetation intercept rainfall, and the exposed soils associated with plants absorb water that will be returned to ground water systems or used by plants.

Rainfall interception works best during small rain events, which account for most precipitation. With large rainfalls that continue beyond a certain threshold, vegetation begins to lose its ability to intercept water. Stormwater retention further varies by the extent and nature of a community's urban forest. During the summer, with trees in full leaf, evergreens and conifers in Sacramento were found to intercept over 35 percent of the rainfall that hit them.[29]

Reduced Pavement Maintenance Costs. Tree shade can reduce the deterioration of street pavement. One field study compared pavement condition data based on different amounts of tree shade.[30] The study found that slurry resurfacing costs on a residential street could be reduced by approximately 15 to 60 percent, depending on the type of shade trees used. Although the specific costs and benefits will vary based on local conditions and paving practices, the study suggests that pavement maintenance benefits are another area to consider in evaluating the potential benefits of a street shade tree program.

Enhanced Quality of Life. Trees and vegetation can provide a range of quality-of-life benefits. Adding trees and vegetation to urban parks, streets, parking lots, or roofs can provide a habitat for birds, insects, and other living things. A well-placed row of

Reducing Exposure to UV Radiation

EPA's SunWise program <www.epa.gov/sunwise> promotes a variety of actions people can take to reduce exposure to harmful UV radiation; seeking shade is just one of them. To reduce the risk of skin cancer, cataracts, and other health effects, the program recommends:

- Wearing a hat with a wide brim
- Wearing sunglasses that block 99 to 100 percent of UV radiation
- Always using sunscreen of SPF 15 or higher
- Covering up with long-sleeve, tightly woven clothing
- Watching for the UV Index to help plan outdoor activities when UV intensity is lowest
- Avoiding sunlamps and tanning salons
- Limiting time in the midday sun (from 10:00 a.m. to 4:00 p.m.)
- Seeking shade whenever possible.

Trees and Property Value Benefits

Many studies show that trees and other vegetative landscaping can increase property values. For example, shopping centers with landscaping can be more prosperous than those without, because shoppers may linger longer and purchase more.[36,37,38,39] Other studies have found general increases of about 3 to 10 percent in residential property values associated with the presence of trees and vegetation on a property.[40] The specific impacts on residential property values vary widely based on the property, the buyer's socioeconomic status, and other factors.

STRATUM, a USDA Forest Service tool that uses tree inventory data to evaluate the benefits and costs of street and park trees, assumes an increase in residential property values from tree planting measures. For an example, see the discussion on net benefits and Figure 9 later in this chapter, which summarize data from a study that used the STRATUM tool.[41] In areas with high median residential sales prices, these are often among the largest single category of benefits for a community.

trees and shrubs can reduce urban noise by 3 to 5 decibels, while wide, dense belts of mature trees can reduce noise by twice that amount, which would be comparable to noise reduction from effective highway barriers.[31] Urban trees and vegetation have been linked to reduced crime,[32] increased property values,[33] and other psychological and social benefits that help decrease stress and aggressive behavior.[34,35]

3.2 Potential Adverse Impacts

Before undertaking an urban forestry program, it is important to know which types of trees are likely to be most beneficial and to avoid those that could cause other problems. Evapotranspiration not only cools the air but also adds moisture to it, raising humidity levels. This increase may be problematic in already humid climates. However, there is little research on the human health and comfort trade-off between temperature reductions and humidity increases in different climates.

Although beneficial in limiting ground-level ozone production by lowering air temperature and filtering ground-level ozone and precursor pollutants from the air, trees and other plants also emit VOCs. These emissions are referred to as biogenic emissions. The biogenic emissions from urban vegetation might counteract some of the air quality benefits from trees. Biogenic VOC emission rates, however, are in part dependent on temperature. Thus, to the extent that the increased use of trees and vegetation contributes to reduced temperatures, the overall biogenic VOC emissions in an urban area might still be reduced.[42]

Biogenic VOC emissions are affected by sunlight, temperature, and humidity. The emission rates of different tree species vary tremendously; even trees in the same

For more information on the **ozone-forming potential (OFP) of various trees**, see <www.fraqmd.org/Biogenics.htm>.

family and genus show wide variation in VOC emissions.[43,44] Researchers calculate an ozone-forming potential (OFP) value to rate the potential effect a tree species can have on ground-level ozone formation in a given environment. To minimize the contribution to ground-level ozone, a mitigation program can consider low-OFP species. Table 1 provides example OFP ranges for common tree species in the Los Angeles area. Communities can check with USDA Forest Service staff in their region to determine if there are additional resources to help select low-OFP tree species for a particular area and climate (see Table 5 for links to regional Forest Service web sites).

Figure 7: The Ozone-Forming Potential of Trees

Susan McDougal/USDA NRCS PLANTS database

Red maple, on the left, has a low ozone-forming potential, whereas Oregon scrub oak, above, has a high potential. Communities that want to plant trees may consider biogenic emissions as well as other properties of trees, such as their ability to survive in urban conditions.

Table 1: Examples of VOC Emissions from Trees in the Los Angeles Climate [45]

Common Name	Genus and Species	Ozone-Forming Potential L	Ozone-Forming Potential M	Ozone-Forming Potential H
Oaks				
White Oak	*Quercus alba*		✓	
Oregon White Oak	*Quercus garryana*			✓
Scrub Oak	*Quercus laevis*		✓	
Valley Oak	*Quercus lobata*		✓	
Pines				
Sand Pine	*Pinus clausa*			✓
Red Pine	*Pinus densiflora*	✓		
Longleaf Pine	*Pinus palustris*		✓	
Maples				
Red Maple	*Acer rubrum*	✓		
Silver Maple	*Acer floridanum*	✓		
Citrus				
Lisbon Lemon	*Citrus limon*		✓	
Meyer Lemon	*Citrus limon 'Meyer'*	✓		
Valencia Orange	*Citrus sinensis 'Valencia'*	✓		

Other potential adverse effects include increased water demand, additional solid wastes from pruning and tree removal, and possible damage to sidewalks, power lines, and other infrastructure from roots or falling branches.

3.3 Costs

The primary costs associated with planting and maintaining trees or other vegetation include purchasing materials, initial planting, and ongoing maintenance such as pruning, pest and disease control, and irrigation. Other costs include program administration, lawsuits and liability, root damage, and tree stump removal. However, as the following section indicates, the benefits of urban trees almost always outweigh these costs.

3.4 Benefit-Cost Considerations

To help communities determine the value of investments in urban trees and vegetation, groups have developed tools to quantify the value of trees (see Section 6). These tools factor in the full range of urban forest benefits and costs, such as energy savings in buildings, air quality improvements, stormwater retention, property value increases, and the value of mulch or hardwood recovered during tree pruning and removal. Some tools also track greenhouse gas emissions or CO_2 reduction. The tools weigh these benefits against the costs of planting, pruning, watering, and other maintenance throughout a tree's life.

In calculating benefits, it is important to note that trees grow slowly, so it may take as long as five years for some benefits from trees, such as energy savings, to take effect. After 15 years, an average tree usually has matured enough to provide the full range of benefits.[46]

Although the benefits can vary considerably by community and tree species, they

Figure 8: Tree-Stump Removal

City of New Haven

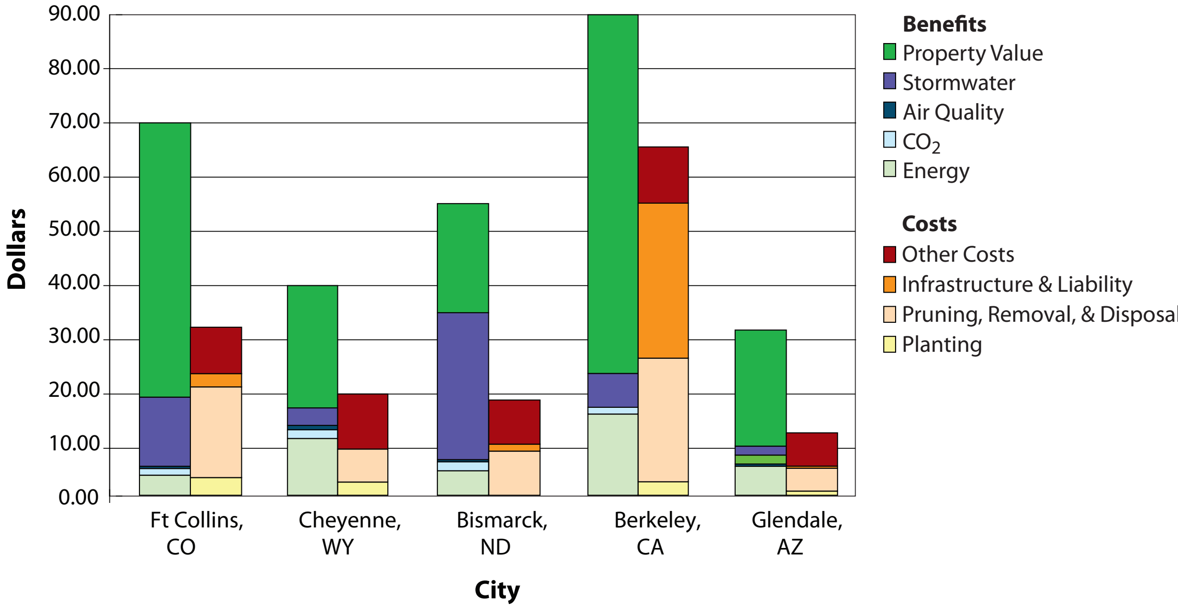
Tree programs will incur certain costs, such as tree removal.

almost always outweigh the expense of planting and maintaining trees. For example, one five-city study found that, on a per tree basis, cities accrued benefits ranging from roughly $1.50 to $3.00 for every dollar invested. These cities spent about $15-65 annually per tree, with net benefits ranging from approximately $30-90 per tree. In all five cities, the benefits outweighed the costs, as shown in Figure 9.[47] Figure 9 also compares how the categories of annual costs and benefits associated with trees varied between these cities.

Studies in California also have shown net annual benefits ranging from zero to about $85 per tree.[48,49,50] A community can develop similar analyses for its mitigation program. Places as diverse as Florence, Alabama;[51] Cedar Rapids, Iowa;[52] Portland, Oregon;[53] and Hyattsville, Maryland,[54] have all quantified the net benefits of their trees. See Section 6 for more resources on existing studies and tools that can aid this type of assessment.

For a simple, **online tree benefit calculator**, see <http://usage.smud.org/treebenefit/>.

Figure 9: Total Annual Benefits versus Costs (Per Tree)



Net benefits were positive for all five cities, ranging from $21 per tree in Cheyenne to $38 per tree in Ft. Collins. Blue and green categories indicate benefits; red, orange, and yellow indicate costs.

4. Other Factors to Consider

4.1 Planting Considerations

Buildings

To reduce temperatures and cooling energy needs, trees planted for summer shade should shelter western and eastern windows and walls and have branches high enough to maintain views or breezes around the windows. Trees in these locations block the sun when it is at its lowest angle: in the morning and afternoon. Planting trees at least 5 to 10 feet (1.5 to 3 m) away from the building allows room for growth, but shade trees should be no more than 30 to 50 feet (9 to 15 m) away. A building with deciduous trees for summer shade will also allow for winter heat gain to the building, especially if branches are pruned to maximize sun exposure.

It might also be beneficial to shade air conditioner condenser units and other building cooling equipment with trees, vines, or shrubbery, as these units work less efficiently when hot. It is important to follow manufacturer guidelines for ensuring adequate space to allow for proper air flow around the equipment.

In an urban setting, neighboring buildings, driveways, fences, and other features can make it difficult to follow these guidelines for planting trees. The following are the best use of trees and vegetation:

- Optimize the shade coverage from trees planted in less favorable locations by pruning tree branches to a height that blocks the summer sun, yet lets the winter sun through.
- Use bushes, shrubs, or vines to shade windows and walls in places where

For overall energy efficiency, some communities might promote the use of **evergreens** to block winter winds and **reduce heating needs.** A row of evergreens might be planted perpendicular to the main wind direction, usually to the north or northwest of a home.

Figure 10: View of a Shaded Street

E.G. McPherson

Placing trees next to the curb positions them well to shade the street, sidewalk, and any automobiles parked along the road.

trees will not fit. Shrubs and bushes can shade windows or walls without growing too large or tall. Vines grow very quickly on vertical or overhead trellises and can be used in places with little available space or soil.

- Consider a green or garden roof in addition to landscaping around a building (see the "Green Roofs" chapter).

Paved Surfaces

Trees and large shrubbery also can shade pavements to reduce their surface temperatures. Planting trees at regular intervals of 20 to 40 feet (6 to 12 meters) along both sides of a street (see Figure 10), as well as along medians is a common way to provide valuable shading.

Trees can also shade the perimeter and interior space of parking lots. Although end islands are often used for planting trees within parking lots,[55] planting strips that run the length of a parking bay can provide greater lot shading (see Figure 11). Some communities have ordinances that require a certain percentage of tree shade in parking lots. For example, Davis, California, and Sacramento each require 50 percent of the parking area to be shaded within 15 years after the lot is constructed.[56,57]

Permeable grass pavers can also provide some of the heat reduction benefits of larger plantings without taking up space. Grass pavers can replace traditional pavements in low-traffic parking areas, pedestrian walkways, driveways, patios, fire lanes, and other paved areas that are seldom used for vehicular traffic. Pavers are usually prefabricated lattice structures made of concrete, plastic, or metal that are specifically designed to let water drain to the soil below while they support pedestrians and light traffic loads. The openings in the lattice blocks are filled with soil and planted with grass or ground cover, or topped with gravel or sand. See the "Cool Pavements" chapter for further discussion of alternative paving options.

Playgrounds, schoolyards, and sports fields are open spaces that often offer opportunities for increasing urban tree and vegetation coverage. In addition to their cooling benefits, trees in these areas can provide increased shade to protect people, especially children, from the sun's UV rays. Shade trees are most beneficial in specific locations where people are likely to congregate, such as around team seating, spectator stands, jungle gyms, sandboxes, swings, and picnic tables. Because trees can take some time to mature, a project sponsor may wish to consider a quicker alternative, such as fast growing bushes or

Figure 11: Shaded Parking Lot

E.G. McPherson

Shading in parking lot medians can provide extensive shading coverage.

Communities can consider the use of hardy, native trees and plants in **selecting landscaping options**. See <www.epa.gov/glnpo/greenacres> for further information.

vines on trellises over seating and other areas, either in place of trees or as a first phase of adding shade vegetation.

4.2 Maintenance

Education, skill, and commitment are necessary for planting and maintaining an aesthetically, environmentally, and structurally effective urban landscape. By adhering to good landscape design and maintenance practices, many common problems may be avoided. Local cooperative extension offices can provide additional information on soil conditions and other important considerations. Also, local planting guides are often available from urban forestry agencies, utility companies, arboricultural organizations, and plant nurseries. The following are steps to consider when maintaining trees in an urban area,[58,59] helping vegetation grow faster and live a longer, healthier, and more productive life.

- *Choose the right plants*. Because trees and vegetation that are hardy enough to survive in a specific climate require little maintenance, communities might want to start by considering native species. Other characteristics to consider include:
  - The vegetation's projected height and canopy spread
  - Size and growth habits of the roots
  - The plant's sun, soil, water, and temperature requirements
  - The types of leaves, berries, and flowers it produces
  - Allergens and biogenic emissions that can contribute to ground-level ozone formation.

Local nonprofit tree organizations, cooperative extension offices, urban foresters and arborists, garden clubs, landscape architects, landscaping contractors, and other groups can provide detailed information about the best trees for a specific community's climate, along with advice about planting and maintaining them. See Section 6 for a list of plant selection resources.

- *Avoid maintenance problems*. Communities will want to avoid interference with utilities, sidewalks, and other infrastructure when planting trees to avoid future maintenance problems. Another important consideration is that trees must have adequate soil and access to water.
- *Make arrangements for regular care*. Especially in the early years after initial planting, trees require regular maintenance to survive. Maintenance requirements and costs generally decline after a tree becomes established.

Figure 12: Regular Tree Care

J. David Mattox/City of Manhattan, Kansas

Proper pruning and other regular care will help trees last longer and provide greater benefits to the community.

4.3 Safety

The use of trees and vegetation around buildings can increase fire risks. Communities, especially those in fire prone areas, can find information on tree selection and placement that minimizes those risks:

- The National Interagency Fire Center offers suggestions for tree placement and landscape maintenance to avoid losses to wildland fires. See <www.nifc.gov/preved/index.html>.
- The USDA Forest Service helps homeowners determine and minimize fire risk from landscaping via an interactive, graphical tool. See <www.ecosmart.gov/firewise>.

Project sponsors can also check with local fire departments or street tree agencies to evaluate and minimize fire risks for a specific tree and vegetation initiative.

5. Urban Forestry Initiatives

Communities can use various mechanisms to increase their vegetative cover. These efforts include forming public-private partnerships to encourage voluntary action in the private sector to enacting ordinances. As discussed in the chapter "Heat Island Reduction Activities," communities already have developed a wide range of voluntary and policy approaches for using urban trees and vegetation. For public-sector projects, local governments and organizations have undertaken efforts to expand the use of trees and vegetation in public spaces and adopted minimum landscaping policies for public buildings. Tree planting programs, used throughout many communities, often involve collaboration with non-profit groups and electric utilities. Some states fund urban forestry program initiatives dedicated to addressing urban heat islands and other community concerns.

Figure 13: Urban Forestry Surveys and Plantings

USDA Center for Urban Forest Research

Urban forestry initiatives can take multiple forms, such as creating an inventory of existing trees or planting additional ones.

In addition, communities have enacted various ordinances to foster the urban forest, including those focused on:

- Tree protection
- Street trees
- Parking lot shade
- General landscaping.

The "Heat Island Reduction Activities" chapter provides a detailed description of these initiatives. Table 2 briefly summarizes them.

Table 2: Examples of Urban Forestry Initiatives

Type of Initiative	Description	Links to Examples
Research	USDA Forest Service programs	**<www.fs.fed.us/research/>** - USDA Forest Service operates research centers throughout the United States, including the Pacific Southwest Research Station, which specializes in urban forestry. USDA also collaborates with states and universities; for example, the Northeast Center for Urban and Community Forestry involves the Forest Service, the University of Massachusetts, and seven states.
	University programs	**<www.cfr.washington.edu/research.envmind/index.html>** - The University of Washington College of Forest Resources supports Human Dimensions of Urban Forestry and Urban Greening, a research program that focuses on the interaction of vegetation and humans in cities.
		<www.lhhl.uiuc.edu/> - A similar program at the University of Illinois, Landscape and Human Health Laboratory, studies the connections between greenery and human health and behavior.
Voluntary efforts	Demonstration projects	**<www.arborday.org/takeaction/homedepot2007/>** - Beginning in 2006, the Home Depot Foundation and the National Arbor Day Foundation partnered together to plant 1,000 trees in 10 cities across the country over a three-year period. This demonstration project is designed to increase awareness of the importance of urban trees and to create healthier communities in urban areas.
	Incentive programs	**<www.ladwp.com/ladwp/cms/ladwp000744.jsp>** - Trees for a Green LA provides Los Angeles residents with free shade trees if they participate in a tree planting and maintenance workshop and submit a program application that includes a site plan.
		<www.ci.seattle.wa.us/neighborhoods/nmf/treefund.htm> - The Tree Fund, a component of the Neighborhood Matching Fund, provides trees to neighborhood groups in Seattle to enhance the city's urban forest. The city government provides the trees, and neighbors share the work of planting and caring for them.
	Urban forestry programs	**<www.treevitalize.net/>** - TreeVitalize is a public-private partnership that uses regional collaboration to address the loss of tree cover in the five-county Southeastern Pennsylvania region. Goals include planting 20,000 shade trees; restoring 1,000 acres of forests along streams and water protection areas; and training 2,000 citizens to plant and care for trees.
		<www.groundworkelizabeth.com/> - Groundwork Elizabeth is a non-profit corporation created to "foster sustainable community regeneration" in Elizabeth, New Jersey. It is an outgrowth of a program developed by the National Park Service called Groundwork USA.
Voluntary efforts	Urban forestry	<**www.milliontreesla.org>** - Million TreesLA is a cooperative effort among the City of Los Angeles, community groups, businesses, and individuals working together to plant and provide long-term stewardship of 1 million trees.

Table 2: Examples of Urban Forestry Initiatives (continued)

Type of Initiative	Description	Links to Examples
	Outreach & education	**<www.epa.gov/heatisland/>** - EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from urban forestry and other heat island mitigation strategies.
		<http://cfpub.epa.gov/npdes/home.cfm?program_id=298> - EPA's Office of Water highlights design options, including trees and vegetation that reduce stormwater runoff and water pollution.
		<www.treeutah.org/> - TreeUtah is a statewide, volunteer driven, non-profit organization dedicated to tree planting and education. Since 1989, TreeUtah has worked with over 100,000 volunteers to plant over 300,000 trees throughout Utah, providing training workshops for adults and teens, education for elementary students, service learning opportunities through the University of Utah, and alternative spring break for college students to plant trees in urban neighborhoods.
		<www.ladwp.com/ladwp/cms/ladwp001087.jsp> - The Los Angeles Cool Schools Program provides students with an educational curriculum about trees and the environment, in addition to planting trees around schools.
Policy efforts	Resolutions	**<www.ci.annapolis.md.us/upload/images/government/council/Adopted/R3806.pdf>** - The Annapolis, Maryland, City Council established an Energy Efficiency Task Force in 2005 to make recommendations on how the city could reduce energy costs, energy consumption, and its reliance upon foreign petroleum. One of the Task Force's recommendations was to increase the urban tree canopy to 50 percent of the city's land area by 2036. The recommendations were approved by the City Council in 2006.
		<www.ci.austin.tx.us/trees/res_985.htm> - The Austin, Texas, City Council adopted a resolution in 2001, acknowledging the urban heat island and available mitigation efforts. The resolution called on the City Manager to evaluate the fiscal impact and cost benefits of recommendations made by the City's Heat Island Working Group.

Table 2: Examples of Urban Forestry Initiatives (continued)

Type of Initiative	Description	Links to Examples
	Tree & landscape ordinances	**<www.cityofsacramento.org/parksandrecreation/urbanforest/ordinance.htm>** - Sacramento, California, has a performance-based parking lot shading ordinance with detailed design and maintenance guidelines to help owners with compliance.
		<www.ci.austin.tx.us/trees/programs.htm> - Austin's tree preservation ordinance specifies that new development projects are evaluated on a case by case basis to ensure tree preservation and planting of high quality native and adapted trees.
Policy efforts	State Implementation Plans (SIPs)	**<www.treescleanair.org>** - This web site, sponsored by the USDA Forest Service, evaluates options for including urban forest initiatives in a SIP, a federally-enforceable air quality management plan.
		<www.houstonregionalforest.org/Events/SIPTreeWorkingSession> - This link provides materials available from a working session on issues and ideas about incorporating urban forest initiatives into a SIP.
		<www.fs.fed.us/ne/syracuse/Emerging%20Measures%20Summary.pdf> - This paper provides a brief summary of relevant EPA SIP guidance and details actions to help facilitate the inclusion of urban tree canopy increases within SIPs to meet clean air standards.
		<www.fs.fed.us/psw/programs/cufr/products/cufr_668_SacAirQualityInit6-21-06.pdf> - This link profiles the Sacramento, California, area project that is evaluating tree planting as a SIP reduction strategy for ground-level ozone.

6. Resources

6.1 Plant Selection

One of the key factors in a successful tree or vegetation mitigation project is choosing the right plants. Various web-based plant selection guides are available, including those listed in Table 3. For local information on tree selection, communities can contact tree planting organizations, community arborists, horticultural organizations, or landscape design consultants. Also, the land development codes and guidelines in many communities include lists of recommended and prohibited species, along with guidance on planting methods and site selection.

Figure 14: Green Walls

EOA/Elmslie Osler Architect

In places where it may be difficult to plant more vegetation, green roofs and green walls, such as this one on a store in Huntsville, Alabama, offer an alternative. See the "Green Roofs" chapter.

Table 3: Web-Based Plant Selection Guides*

Name	Description	Web Link
General Information		
International Society of Arboriculture Tree Selection	Overview of variables to consider, including tree function, form, size, and site conditions.	<www.treesaregood.com/treecare/tree_selection.aspx>
Databases		
Tree Guide Advanced Search	Database of trees that can be searched by variables including sun exposure, hardiness zone, tree shape, and height.	<www.arborday.org/trees/treeguide/advancedsearch.cfm>
PLANTS Database	Database of information about U.S. plants, with an advance search by name, location, and environmental variables, such as soil type, fire tolerance, and flower color.	<http://plants.usda.gov>
SelecTree for California	Database of California trees that can be searched by name or environmental variable.	<http://selectree.calpoly.edu/>
Lists of Recommended Trees		
Tree Link	List of recommended trees by USDA hardiness zone; links to regional tree information.	<www.treelink.org/docs/zonemap.phtml>; <www.treelink.org/linx/?navSubCatRef=20>
Recommended Urban Trees	Description of recommended urban trees for USDA hardiness zones 1-6, listed by tree size and planting conditions.	<www.hort.cornell.edu/uhi/outreach/recurbtree>
Cleaner Air, Tree by Tree: A Best Management Practices and Guide for Urban Trees in Southern Nevada	Handbook for cultivating recommended trees to mitigate urban heat islands in southern Nevada.	<www.forestry.nv.gov/docs/shades%20_green_bmp_guide07.pdf>
Tree Selection Guide for South Carolina	List of trees recommended for South Carolina and tips on what to consider when selecting trees.	<www.state.sc.us/forest/refsel.htm>

* For information on the ozone-forming potential of various trees, see the list in *Estimating the Ozone-forming Potential of Urban Trees and Shrubs*.[60]

6.2 Benefit-Cost and Other Tools

Mitigation programs can use existing research and tools to conduct benefit-cost analyses for urban forest projects. Some of these resources include:

Table 4: Urban Forestry Tools and Resources

Name	Description	Web Link
Tree Inventory, Benefit, and Cost Resources		
i-TREE software suite	Developed by the USDA Forest Service, the *i*-TREE software suite is available free-of-charge on CD-ROM by request. The software suite uses data gathered by the community to provide an understanding of urban forest structure, information on management concerns, cost-benefit information, and storm damage assessment. The software allows for analyses of a single street tree, a neighborhood, or an entire urban forest. *i*-Tree combines STRATUM and UFOREthe Mobile Community Tree Inventory (MCTI) (see below).	<www.itreetools.org/index.shtm>
Street Tree Resource Analysis Tool for Urban forest Managers (STRATUM)	STRATUM is a USDA Forest Service tool that uses tree inventory data to evaluate the benefits and costs of street and park trees and estimate management needs.	<www.itreetools.org/street_trees/introduction_step1.shtm>
Urban Forest Effects (UFORE)	UFORE is a USDA Forest Service tool that uses tree inventory data to model and quantify urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass, species diversity), environmental effects, and value to communities.	<www.ufore.org>
The Mobile Community Tree Inventory (MCTI)	MCTI is a USDA Forest Service tree inventory tool that can be customized to individual communities. Data can be collected either by paper tally sheet, or the Tree Inventory PDA Utility, which simplifies data input. Data collected can then be used with the STRATUM or UFORE applications.	<www.itreetools.org/applications/mcti.shtm>
ecoSmart	The Center for Urban Forest Research publishes a web-based software program designed to evaluate the economic trade-offs between different landscape practices on residential parcels. The program estimates the environmental and cost impacts of strategic tree placement, rainfall management, and fire prevention practices.	<www.ecosmart.gov/>

Table 4: Urban Forestry Tools and Resources (continued)

Name	Description	Web Link
Tree Inventory, Benefit, and Cost Resources (continued)		
Municipal Forest Resource Analysis	The Center for Urban Forest Research publishes a series of reports on benefits and costs of tree programs in various U.S. regions and communities.	<www.fs.fed.us/psw/programs/cufr/products.shtml> See "Tree Guides" and "Municipal Forest Resource Analysis."
Urban Forestry Index (UFind)	Database of current and historic urban forestry and arboriculture publications and other media compiled by the USDA Forest Service, the University of Minnesota, and TreeLink with the goal of increasing access to urban forestry material and preventing duplication of products.	<www.urbanforestryindex.com/>
A Practical Approach to Assessing Structure, Function, and Value of Street Tree Populations in Small Communities	This 14-page report gives step-by-step instructions for estimating benefits and costs of trees in a specific community, using Davis, California as a case study.	<www.fs.fed.us/psw/programs/cufr/products/cufr_128.pdf>
The Community and Urban Forest Inventory and Management Program (CUFIM)	Produced by the Urban Forest Ecosystems Institute of California Polytechnic State University, the Community and Urban Forest Inventory and Management Program (CUFIM) is a free Microsoft Excel-based program that helps to inventory urban trees and estimate an economic value of wood recovery.	User guide: <www.ufei.org/files/ufeipubs/CUFIM_Report.pdf> Program files: <www.ufei.org/files/ufeipubs/CUFIM.zip>
CITYgreen	American Forests developed CITYgreen, a graphical information system application based on the UFORE model that is available for purchase. The software calculates ecologic and economic benefits from urban trees, including energy savings, air quality, stormwater improvements, water quality, and carbon storage and sequestration. CITYgreen also models changes in land cover and can be used in planning green infrastructure.	<www.americanforests.org/productsandpubs/citygreen/>
Comfort Tool		
OUTdoor COMfort Expert System (OUTCOMES)	The USDA Forest Service developed the OUTdoor COMfort Expert System (OUTCOMES), which calculates a human comfort index by considering weather variables, tree density and shade pattern, and other neighborhood features.	<www.fs.fed.us/ne/syracuse/Tools/tools.htm>

Table 4: Urban Forestry Tools and Resources (continued)

Name	Description	Web Link
Carbon Calculators		
Individual tree carbon calculators	The USDA Forest Service has developed spreadsheet programs to estimate the carbon storage and sequestration rates for a sugar maple and a white pine. These spreadsheets provide a rough approximation of tree carbon storage and sequestration rates based on user-inputs of tree growth rates.	<www.fs.fed.us/ne/syracuse/Tools/tools.htm>
Carbon dioxide calculators for urban forestry	The USDA Forest Service provides guidelines for urban foresters and arborists, municipalities, utilities, and others to determine the effects of urban forests on atmospheric CO_2 reduction.	<www.fs.fed.us/psw/programs/cufr/products/cufr_43.pdf>
Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings	The Department of Energy has developed guidance to calculate carbon sequestration by trees in urban and suburban settings. The guidance is intended for participants in the Voluntary Reporting of Greenhouse Gases Program and provides a methodology and worksheet for calculations.	<ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/sequester.pdf>

6.3 General Information

Table 5 lists organizations and web sites that contain additional information and reference materials on urban forestry.

Table 5: Urban Forestry Organizations and Web Sites

Name	Description	Web Link
Center for Urban Forest Research, part of the USDA Forest Service's Pacific Southwest Research Station	Publishes research on the benefits and costs of urban trees, including urban heat island, energy, air quality, climate change, and water impacts. Is involved with developing the California urban forestry greenhouse gas reporting protocol and developed STRATUM and ecoSMART.	<www.fs.fed.us/psw/programs/cufr>
Urban Forest Research Unit, part of the USDA Forest Service's Northeastern Research Station	Provides research on urban forest structure and the quantification of urban forest benefits, particularly air quality. Developed the UFORE and COMFORT models and conducts national urban forest assessments.	<www.fs.fed.us/ne/syracuse>
Urban Natural Research Institute, part of the USDA Forest Service Northern Research Station	Provides monthly web casts and other online resources targeted to the science of urban forestry.	<www.unri.org>
Urban and Community Forestry Program, Northeastern Area, part of the USDA Forest Service's State and Private Forestry mission area	Resources on tree planting and care, urban forest management, and outreach and marketing. The Urban and Community Forestry Program provides technical, financial, educational, and research services to states, cities, and nonprofit groups so they can plant, protect, maintain, and utilize wood from community trees and forests to maximize environmental, social, and economic benefits.	<www.na.fs.fed.us/urban/index.shtm>
Urban Forestry South, part of the USDA Forest Service's Southern Research Station	Published the Urban Forestry manual, a 12-chapter guidebook including cost-benefit information, public policy strategies, and tree planting suggestions. Urban Forestry South also hosts the Tree Failure Database.	<www.urbanforestrysouth.org/>
TreeLink	Provides a links database, listserves, web casts, advice on grant writing, and links to local community forestry groups.	<www.treelink.org>

Table 5: Urban Forestry Organizations and Web Sites (continued)

Name	Description	Web Link
National Alliance for Community Trees (ACT)	Operates the NeighborWoods Program, offering grants to community forestry groups. The web site also has links to local community forestry groups, public policy updates, case studies of tree planting programs, a media kit, and a bi-monthly e-newsletter, and monthly web casts.	<www.actrees.org>
National Arbor Day Foundation	Provides information about local tree planting programs and events and resources for environmental educators and parents.	<www.arborday.org/>
Sustainable Urban Landscape Information Series	Covers urban landscape design, plant selection, installation, and maintenance.	<www.sustland.umn.edu/>
American Society of Landscape Architects (ASLA)	Professional association for landscape architects. Includes a search tool to locate ASLA firms. ASLA is developing a sustainability rating system for land-scaped sites, comparable to the USGBC LEED standard for buildings, as well as regional guides to best practices.	<www.asla.org>

Endnotes

1 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

2 Nowak, D.J., Principal Investigator. 2005. Houston's Regional Forest. U.S. Forest Service and Texas Forest Service. September 2005.

3 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

4 Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148.

5 Sandifer, S. and B. Givoni. 2002. Thermal Effects of Vines on Wall Temperatures—Comparing Laboratory and Field Collected Data. SOLAR 2002, Proceedings of the Annual Conference of the American Solar Energy Society. Reno, NV.

6 Scott, K., J.R. Simpson, and E.G. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture. 25(3).

7 U.S. Geological Survey. 2007. The Water Cycle: Evapotranspiration. Retrieved 12 June 2007 from <http://ga.water.usgs.gov/edu/watercycleevapotranspiration.html>.

8 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

9 Kurn, D., S. Bretz, B. Huang, and H. Akbari. 1994. The Potential for Reducing Urban Air Temperatures and Energy Consumption through Vegetative Cooling. ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy. Pacific Grove, CA.

10 Simpson, J.R., and E.G. McPherson. 2001. Tree planting to optimize energy and CO_2 benefits. In: Kollin, C. (ed.). Investing in Natural Capital: Proceedings of the 2001 National Urban Forest Conference. September 5-8., 2001, Washington D.C.

11 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

12 H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, and W. Bos. 1993. Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results. Paper LBNL-34411. Lawrence Berkeley National Laboratory, Berkeley, CA.

13 H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, and W. Bos. 1993. Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results. Paper LBNL-34411. Lawrence Berkeley National Laboratory, Berkeley, CA.

14 Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148.

15 Simpson, J.R. and E.G. McPherson. 1998. Simulation of Tree Shade Impacts on Residential Energy Use for Space Conditioning in Sacramento. Atmospheric Environment. 32(1):69-74.

16 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

17 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

18 Luley, C.J. and J. Bond. 2002. A Plan to Integrate Management of Urban Trees into Air Quality Planning. Report prepared for New York Department of Environmental Conservation and USDA Forest Service, Northeastern Research Station.

19 Nowak, D.J. 2000. The Effects of Urban Trees on Air Quality. USDA Forest Service: 4. Syracuse, NY.

20 Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry and Urban Greening. 4(2006):115-123.

21 Scott, K., J.R. Simpson, and E.G. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture. 25(3).

22 U.S. EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. Retrieved 15 December from <http://www.epa.gov/climatechange/emissions/downloads06/07CR.pdf>.

23 Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution. 116(2002):381-389.

24 California Air Resources Board. 2007. Forestry Greenhouse Gas Accounting Principles. 25 October. Retrieved 14 January 2008 from <http://www.arb.ca.gov/cc/forestry/forestry_protocols/forestry_protocols.htm#Public>.

25 Konopacki, S. and H. Akbari. 2002. Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City). Paper LBNL-49638. Lawrence Berkeley National Laboratory, Berkeley, CA.

26 McPherson, E.G., J.R. Simpson, P.J. Peper, S.L. Gardner, K.E. Vargas, J. Ho, S. Maco, and Q. Xiao. 2006. City of Charleston, South Carolina Municipal Forest Resource Analysis. Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station.

27 Heisler, G.M. and R.H. Grant. 2000. Ultraviolet radiation in urban ecosystems with consideration of effects on human health. Urban Ecosystems. 4:193-229.

28 Heisler, G.M., R.H. Grant, and W. Gao. 2002. Urban tree influences on ultraviolet irradiance. In: Slusser, J.R., J.R. Herman, W. Gao, eds. Ultraviolet Ground and Space-based Measurements, Models, and Effects. Proceedings of SPIE, San Diego, CA.

29 Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Ustin. 1998. Rainfall Interception by Sacramento's Urban Forest. Journal of Arboriculture. 24(4):235-244.

30 McPherson, E.G. and J. Muchnick. 2005. Effects of Street Tree Shade on Asphalt Concrete Pavement Performance. Journal of Arboriculture. 31(6).

31 Nowak, D.J. and J.F. Dwyer. 2007. Understanding the Benefits and Costs of Urban Forest Ecosystems. In: Kuser, J.E. Handbook of Urban and Community Forestry in the Northeast. New York: Kluwer Academic/Plenum Publishers. 25-46.

32 Kuo, Francis E. and W.C. Sullivan. 2001. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior. 33(3):343-367.

33 Laverne, R.J. and K. Winson-Geideman. 2003. The Influence of Trees and Landscaping on Rental Rates at Office Buildings. Journal of Arboriculture. 29(5):281-290.

34 Wolf, K. 1998. Urban Nature Benefits: Psycho-Social Dimensions of People and Plants. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #1. Seattle, WA.

35 Hansmann, R., S.M. Hug, and K. Seeland. Restoration and stress relief through physical activities in forests and parks. Urban Forestry & Urban Greening. 6(4):213-225.

36 Wolf, K. 1998. Growing with Green: Business Districts and the Urban Forest. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #2. Seattle, WA.

37 Wolf, K. 1998. Trees in Business Districts: Comparing Values of Consumers and Business. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #4. Seattle, WA.

38 Wolf, K. 1998. Trees in Business Districts: Positive Effects on Consumer Behavior. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #5. Seattle, WA.

39 Wolf, K. 1998d. Urban Forest Values: Economic Benefits of Trees in Cities. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #3. Seattle, WA.

40 The values cited for the increase in selling price reflect both the literature reviews and the new data in: Des Rosiers, F., M. Theriault, Y. Kestans, and P. Villeneuve. 2002. Landscaping and House Values: An Empirical Investigation. Journal of Real Estate Research. 23(1):139-162. Theriault, M., Y. Kestens, and F. Des Rosiers. 2002. The Impact of Mature Trees on House Values and on Residential Location Choices in Quebec City. In: Rizzoli, A.E. and Jakeman, A.J. (eds.). Integrated Assessment and Decision Support, Proceedings of the First Biennial Meeting of the International Environmental Modeling and Software Society. iEMSs, 2002. I:478-483.

41 McPherson, E.G., J.R. Simpson, P.J. Peper, S.E. Maco, and Q. Xiao. 2005. Municipal Forest Benefits and Costs in Five US Cities. Journal of Forestry. 103(8):411-416.

42 Nowak, D.J. 2000. The Effects of Urban Trees on Air Quality. USDA Forest Service: 4. Syracuse, NY.

43 Benjamin, M.T., M. Sudol, L. Bloch, and A.M. Winer. 1996. Low-Emitting Urban Forests: a Taxonomic Methodology for Assigning Isoprene and Monoterpene Emission Rates. Atmospheric Environment. 30(9):1437-1452.

44 Benjamin, M.T. and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.

45 Benjamin, M.T. and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.

46 McPherson, E.G. 2002. Green Plants or Power Plants? Center for Urban Forest Research. Davis, CA.

47 McPherson, E.G., J.R. Simpson, P.J. Peper, S.E. Maco, and Q. Xiao. 2005. Municipal Forest Benefits and Costs in Five US Cities. Journal of Forestry. 103(8):411-416.

48 McPherson, E.G., J.R. Simpson, P.J. Peper, K.I. Scott, and Q. Xiao. 2000. Tree Guidelines for Coastal Southern California Communities. Local Government Commission & Western Center for Urban Forest Research and Education. Sacramento, CA.

49 McPherson, E.G., J.R. Simpson, P.J. Peper, and Q. Xiao. 1999. Benefit-Cost Analysis of Modesto's Municipal Urban Forest. Journal of Arboriculture. 25(5):235-248.

50 McPherson, E.G., J.R. Simpson, P.J. Peper, Q. Xiao, D.R. Pettinger, and D.R. Hodel. 2001. Tree Guidelines for Inland Empire Communities. Local Government Commission & Western Center for Urban Forest Research and Education. Sacramento, CA.

51 Stokes, Trevor. 2007. Trees give more to the community than shade. Times Daily. 24 November. Retrieved 14 January 2008 from <http://www.timesdaily.com/article/20071125/NEWS/711250345/-1/COMMUNITIES>.

52 Hadish, C. 2007. Benefits of trees measured. Gazette. 15 October. Retrieved 16 October 2007 from <http://www.gazetteonline.com/apps/pbcs.dll/article?AID=/20071015/NEWS/71015023/1006/NEWS>.

53 Portland Parks and Recreation. 2007. Portland's Urban Forest Canopy: Assessment and Public Tree Evaluation. Retrieved 2 October 2007 from <http://www.portlandonline.com/shared/cfm/image.cfm?id=171829>.

54 Maryland Department of Natural Resources Forest Service. 2007. New DNR Study Shows Hyattsville's Trees Benefit The Bay, Save On Energy Bills And Mitigate Global Warming. 29 October. Retrieved 1 November 2007 from <http://www.dnr.state.md.us/dnrnews/pressrelease2007/102907b.html>.

55 McPherson, E.G. 2001. Sacramento's parking lot shading ordinance: environmental and economic costs of compliance. Landscape and Urban Planning. 57:105-123.

56 City of Davis. 1998. Parking Lot Shading Guidelines and Master Parking Lot Tree List Guidelines. Davis, CA.

57 City of Sacramento. 2003. Tree Shading Requirements for Surface Parking Lots. Sacramento, CA.

58 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

59 Tree City, U.S.A. 2001. Tree Care Information. National Arbor Day Foundation, Tree City USA bulletin 19. Nebraska City, NE.

60 Benjamin, M.T., and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.