CLIMATE-SMART CITIES™

The benefits of green infrastructure for heat mitigation and emissions reductions in cities

THE TRUST FOR PUBLIC LAND

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The benefits of green infrastructure for heat mitigation and emissions reductions in cities:

A review of the literature

Executive Report

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Table of contents

List of figures, images and tables

Figures

Images

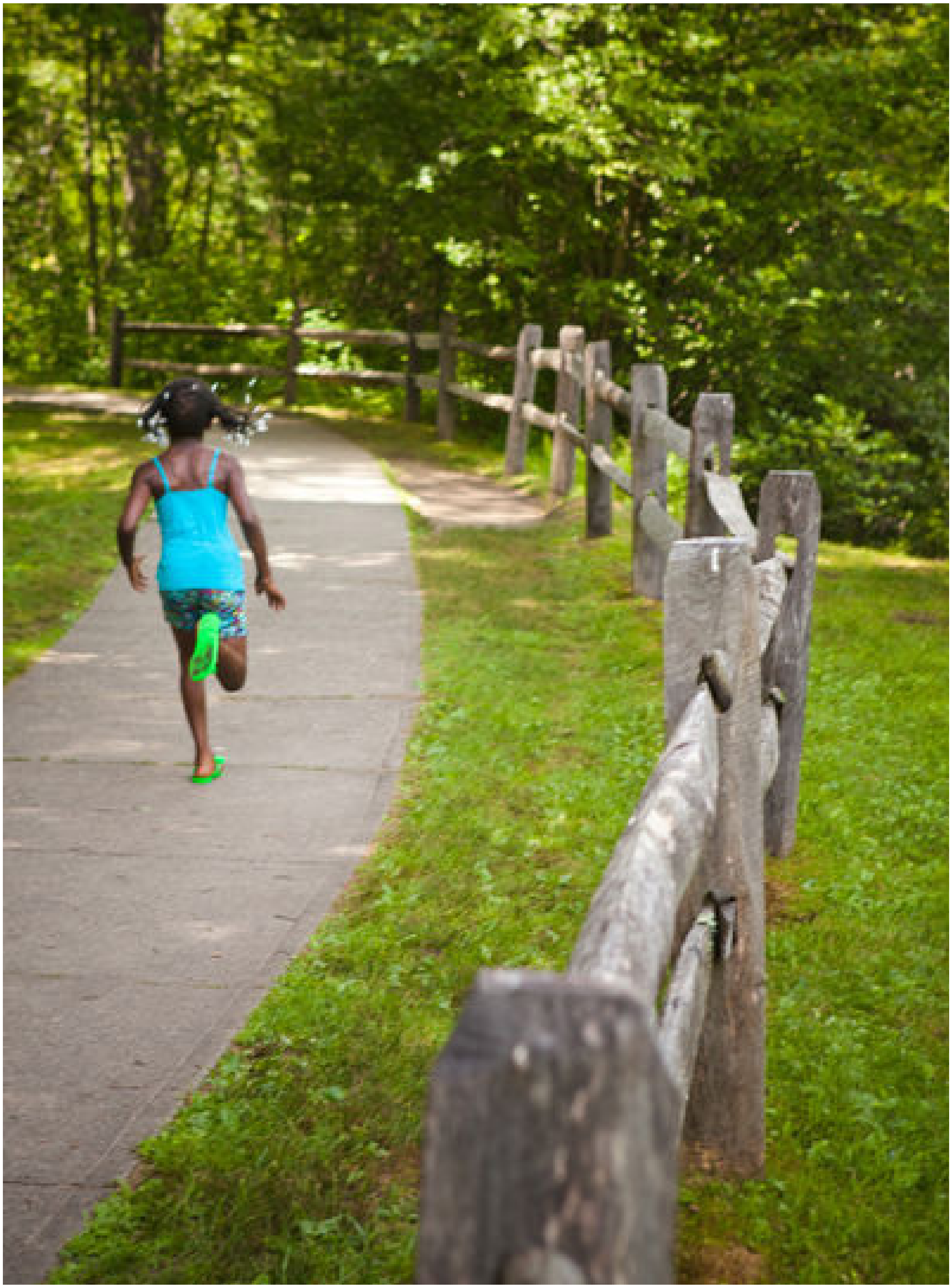
Tables

1 Introduction

With the recent conclusion of an eight-year campaign to plant one million trees, New York is arguably the first large US city to fund green infrastructure at a level comparable to traditional grey infrastructure. At a cost of more than $600 million, New York's expanded tree canopy is expected to offer much more to residents than leafy urban streets: the urban forest is viewed as a first line of defense against rising temperatures, intensifying storm events, and exacerbated air pollution with climate change. The first to attain the one million new trees mark, New York is unlikely to be the last. For, as the environmental and economic values of green infrastructure as a complement to engineered storm sewer systems are well demonstrated, green infrastructure offers a strategy for combating a growing public health risk in cities for which no grey infrastructure exists: the risk posed by a rising frequency of extreme heat.

To date, the principal adaptive measure for reducing heat exposures in US cities is mechanical air conditioning (Anderson & Bell, 2009; Braga et al., 2002; Chestnut et al., 1998). While expanded access to air conditioning among urban residents has been found to lower the risk of heat-related illness and mortality, this adaptation fails to address outdoor exposures to heat for urban populations, or indoor exposures for those lacking continuous access to mechanical cooling. Perhaps most problematic is the potential heat exposure during electrical grid failure events, which are occurring in US cities with a greater frequency. Confronted with the need to manage a growing risk of extreme temperatures in cities, a threat compounded by the very design of the city itself, a large number of municipal governments are undertaking or exploring significant investments in green infrastructure to lessen climate-related risks to urban populations.

In this paper, we survey the most recent peer-reviewed literature on green infrastructure to assess its demonstrated effectiveness in moderating urban temperatures and, as a result, lessening energy consumption and associated greenhouse gas emissions. The paper addresses several key questions. First, what physical changes are driving the rise of temperatures in cities and to what extent can municipal governments manage changing urban climates? Second, what is known about the effectiveness of tree canopy, open greenspace, and building-integrated vegetation, such as green roofs and walls, in moderating temperatures and reducing energy consumption by buildings? Third, what non-heat-related benefits are associated with green infrastructure in cities, as well as limitations and costs associated with this class of adaptation strategies? Last, what specific recommendations can be incorporated into the work of the Trust for Public Land in developing green infrastructure projects for cities?



2 Urban scale climate change

2.1 Drivers of climate change in cities

Climate change in cities is driven by both global and regional warming phenomena. At the global level, rising greenhouse gas concentrations are enhancing the natural greenhouse effect that serves to trap outgoing longwave radiation from the Earth's surface and warm the atmosphere. At the regional scale of cities, four specific changes in urban environments give rise to a separate warming mechanism, the urban heat island (UHI) effect, which has been found in recent decades to be the principal driver of rising temperatures in cities (Stone et al. 2014). These physical changes in cities include: 1) the loss of natural vegetation to urban construction; 2) the introduction of non-vegetative surface materials that are more efficient at absorbing and storing thermal energy than natural land covers; 3) high density urban morphology that traps solar radiation; and 4) the emission of waste heat from buildings and vehicles.

These four warming mechanisms in cities elevate the quantity of thermal energy retained and emitted into the urban environment through distinct pathways. The loss of trees and other natural land covers contributes to a warmer environment through a reduction in shading and, most importantly, a reduction in evaporative cooling – the process through which plants use solar energy to convert water to water vapor (EPA, 2008; EPA, 2013; Bowler et al., 2012). Shading reduces solar heat gain on windows, walls, and roofs, which has a direct effect on energy consumption for cooling and is directly associated with greenhouse gas emissions such as carbon dioxide (Dimoudi & Nikolopoulou, 2003). As water is transmitted through plant cells and released to the atmosphere as water vapor, heat energy is also transported away from the land surface in a latent form that does not contribute to rising temperatures at the surface. The displacement of trees and other vegetation by urban development results in less evaporative cooling, as less moisture is retained by impervious land covers.

Compounding the loss of surface moisture is the resurfacing of the urban environment with the bituminous and mineral-based materials of asphalt, concrete, brick, and stone – materials that contribute to higher temperatures through three mechanisms. First, urban construction materials such as asphalt are less effective in reflecting away incoming solar radiation, a physical property known as "albedo." As the albedo or reflectivity of cities is lowered through urban development, the quantity of incoming solar radiation absorbed and retained is greater. Second, mineral-based materials tend to be more effective in storing solar energy than the natural landscape – a property that results in the retention and release of heat energy in the late evening and into the night, keeping urbanized areas warmer than nearby rural areas. Lastly, urban construction materials such as street paving and roofing shingle are generally impervious to water, and thus further reduce the amount of moisture that is absorbed and retained in cities for evaporative cooling.

A third physical driver of the UHI effect is the morphology or three-dimensional character of the urban landscape. In densely developed downtown districts, tall buildings and street canyons limit the extent to which reflected solar energy from the surface can pass unimpeded back to the atmosphere. As this reflected energy is absorbed by the vertical surfaces of the city, more heat is retained in the urban environment.

Lastly, cities are zones of intense energy consumption in the form of vehicle usage, the cooling and heating of buildings, and industrial activities. As immense quantities of energy are consumed in urban environments, waste heat is produced that is ultimately vented to the atmosphere, contributing to rising temperatures. In some US cities, waste heat from energy consumption has been estimated to account for about one-third of the UHI effect (Hart & Sailor, 2009).

2.2 Public health

Heat is the primary weather-related cause of death in the United States, and heat-related morbidity and mortality is expected to increase in cities as a result of warming global temperatures and intensification of the urban heat island (Davis et al., 2003; Harlan et al, 2011; Knowlton et al., 2007). One study predicts an annual increase of 28,000-34,000 heat-related deaths in the United States by mid-century (Voorhees et al., 2011).

One of the most significant impacts of the urban heat island is elevated nighttime temperatures. During a heat event, people need the relief of lower nighttime temperatures in order to recover from compounding heat stress that builds throughout the day (Moriyama, 1988). As the urban heat island retains heat and re-emits it through the night, this relief does not always occur. Sustained elevated temperatures pose a variety of risks to human health, including cardiovascular stress; thermal exhaustion and heat stroke; respiratory distress; kidney or liver failure; and blood clots (Kleerekoper et al, 2012).

Due to these risks, it is important that those exposed to high temperatures gain access to methods of cooling, usually by means of air conditioning. However, extended periods of extreme heat can also result in power outages from excessive electricity demand for air conditioning (Miller et al., 2008). If this occurs, even those who can afford to own and use air conditioning become as vulnerable as those without. Certain social groups are particularly vulnerable to high heat, including those who are living below the poverty line, are elderly, or are socially isolated (Reid et al., 2009). Implementing passive cooling strategies like vegetation in areas with vulnerable populations can substantially reduce heat-related morbidity and mortality without reliance on electricity.

2.3 Green infrastructure

Green infrastructure was originally identified with floodways, wetlands, or parks that would provide stormwater services like water filtration and flood control. More recently the definition has been expanded to include a variety of environmental or sustainability goals in cities through a mix of natural approaches (EPA, 2014; Foster et al., 2011). In this paper we limit our primary focus to vegetative green infrastructure and the associated cooling benefits gained from shading and evapotranspiration. The three major vegetative green infrastructure categories analyzed in this paper are urban trees and forests, parks and open greenspace, and building-integrated vegetation.

Urban trees and forests range from individual trees found in proximity to buildings to stands of trees on public or private land to larger scale urban forests. Parks and open greenspace include vegetated areas that consist of a combination of turf, shrubs, and trees, and that are not exclusively dedicated to forested land. Building-integrated vegetation includes green roofs and green walls Green roofs come in two varieties: extensive and intensive. Extensive green roofs use low-lying plants, like succulents, mosses, or herbaceous plants and grasses, while intensive green roofs utilize shrubs and trees, as well as shorted stemmed plants, and tend to mirror street level parks as areas of recreation and relaxation (FLL, 2002; Foster et al., 2011).

In addition to air temperature reductions, green infrastructure provides several direct and indirect benefits. Reducing surface and air temperatures around buildings leads directly to a reduction in energy use associated with cooling, thereby lowering carbon emissions. Vegetation also has a positive effect on human health through reductions in smog and other air pollution, reduced recovery times from mental / physical stress and fatigue, and can improve the overall health and well-being of urban residents (Akbari, 2002; Qin et al., 2013; Velarde et al., 2007). We discuss these cobenefits in greater detail in the following sections.

3 Green infrastructure strategies

In this section, we review the literature on green infrastructure to document consensus evidence on the extent to which urban trees, open space, and building-integrated vegetation influence microclimates and lessens building energy consumption and carbon emissions, as well as any evidence on the optimal design of vegetative strategies for climate-related benefits.

3.1 Urban trees and forest

As described above, the urban forest of a city is composed of street trees, individual trees on private lots, and forest fragments in parks, along riparian corridors, and otherwise protected from development. Both observational and modeling studies have sought to document the benefits of trees for moderating ambient temperatures in cities.

3.1.1 TEMPERATURE IMPACTS

The significance of tree loss for a warming regional climate was first documented in rural zones subject to extensive deforestation. The widespread loss of rainforest canopy in the Amazonian basin of Brazil, for example, has been associated with a rise in regional temperatures of between 2 and 7°F (Pielke et al., 2007; Snyder et al., 2004; Costa and Foley, 2000). This warming effect through a reduction in evapotranspiration from trees is further compounded in urban environments, where tree canopy is often displaced by the impervious surfaces of roads, parking lots, and buildings.

In urban settings, tree canopy reduces local temperatures through both shading and evapotranspiration. While shading results in a direct cooling of surface temperatures, evapotranspiration can reduce local ambient temperatures not in the direct shade of the tree. Because this cooling effect is highly localized and context-dependent, the literature does not currently quantify a cooling potential per tree or per unit green area. However, several studies do explore average cooling potential in proximity to urban trees. Figure 1 documents a clear negative association between tree cover and land surface temperature.

Tree shading produces substantial benefits in the form of reduced surface temperatures, which are a major driver of the urban heat island. Shading can reduce surface temperatures on building walls and rooftops by as much as 45°F, and can further reduce solar gain through windows to reduce interior temperatures (EPA, 2008).

Evapotranspiration moderates air temperatures across a larger spatial extent than does shading. Placing trees in downtown urban canyons can reduce air temperatures by as much as 7°F (Loughner et al., 2012). Trees in residential neighborhoods have been observed to decrease local ambient temperatures by roughly 1-5°F (Ellis et al., 2015; EPA, 2008; Shasua-Bar et al., 2009; Sung, 2013). Climate modeling studies find the extensive planting of trees throughout cities to produce significant cooling benefits. A study focused on tree planting throughout the Los Angeles, California, basin, for example, finds reductions in late afternoon temperatures of up to 3°F for the metropolitan area as a whole, offsetting much of the city's average summer heat island (Rosenfeld et al., 1998).

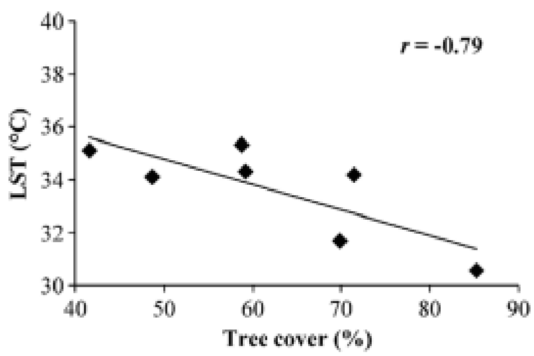


Figure 1. Tree cover and land surface temperature in seven study neighborhoods (Sung, 2013).

In addition to the direct cooling of urban air through shading and evapotranspiration, tree planting throughout a metropolitan region can lessen temperatures in downtown districts by cooling air currents flowing toward city centers. A product of extensive impervious cover found in downtown districts, heated and rising summer air tends to create low pressure zones in these districts, serving to draw in air from surrounding suburbs. A study focused on Atlanta, Georgia, for example, finds the addition of tree canopy throughout a metropolitan region but outside of the urban core to reduce temperatures in the city center (Stone et al., 2013). Other work focused on Atlanta, finds a doubling of the region's tree canopy – both inside and around the urban center – to reduce summer afternoon temperatures by as much as 12°F (Zhou & Shepherd, 2010).

Work by the Urban Climate Lab at Georgia Tech finds the cooling effects of new tree canopy and other vegetation to be greatly enhanced when combined with the installation of cool materials, such as highly reflective roofing and paving (Stone et al., 2014). In this sense, the combination of new vegetation and cool materials at the project to neighborhood level yields significantly greater cooling benefits that the expansion of green infrastructure alone. This outcome is, in part, attributable to the spatial complementarity of these two heat management strategies, with cool material installations ideally targeted to areas less suitable for tree planting, such as expansive parking lots or rooftops.

3.1.2 CARBON IMPACTS

Trees can significantly reduce carbon emissions by reducing electricity consumption associated with air conditioning, but with various magnitudes of benefits, depending on context and scale. One study found that a 10% increase in shade coverage reduces electricity consumption by 1.29 kWh per day on average for residences in a suburban environment, equivalent to 2% of daily energy use (Pandit & Laband, 2010). Other studies find that shading can save up to 4.8 kWh per day for residential housing with associated annual carbon emissions reductions of 10-11 kg carbon per tree (Akbari et al., 1997; Akbari, 2002). While the evidence is highly case-dependent, the literature suggests that shading can measurably reduce cooling-associated energy use.

At a larger scale, urban forests also contribute to regional cooling and can therefore reduce carbon emissions. One study estimates average annual savings of 36 kWh per tree, with savings in warmer urban areas up to 96 kWh per tree, or about 7% of total annual residential energy use (McPherson & Simpson, 2001). This evidence suggests that tree planting at any scale can have significant benefits on both the local and regional scale.

There is some evidence to suggest that urban trees sited in proximity to buildings are more effective at mitigating climate change than those in a forest far from development. One study finds that a tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, while at the same time sequestering 4.5 - 11 kg of carbon (Akbari, 2002). That tree, due to the added shading benefits, is 3 - 5 times more effective at reducing atmospheric carbon as a city tree than as a rural tree. Because of this added benefit associated with the shading of buildings, yard trees are found to reduce electricity consumption by over 11 kWh per tree per year, compared to a 1.4 kWh reduction for non-yard trees (City of Portland Bureau of Environmental Services, 2010). This evidence suggests that tree planting initiatives should attempt to gain these additional cooling benefits, wherever possible, to maximize carbon reductions over the lifetime of the tree. Importantly, however, these findings may suggest the need to balance tree plantings designed principally to lessen energy consumption with those designed principally to moderate ambient temperatures, which may benefit most from planting sites away from buildings and adjacent to surface paving.

3.1.2 DESIGN STRATEGIES

There is clear evidence that tree placement has a strong influence on cooling potential and carbon savings. Both models and direct observations suggest that trees configured in an east-west orientation have the greatest potential for cooling. Planting trees on the west side of buildings produces the greatest energy savings, but studies recommend placing three trees per building (one to the east, two to the west) for the greatest effect (Donovan & Butry, 2009; Rosenfeld & Romm, 1996; Simpson & McPherson, 1996). Similarly, placing trees along east-west oriented streets cools ambient air temperatures more than along north-south oriented streets, up to 2.1°C for E-W, and only 0.9°C for N-S (Oliviera et al., 2011; Sanusi et al., 2015).

It should be noted that some studies have found planting trees on the north side of buildings to increase summertime electricity usage by a small amount. This is believed to be due to the fact that a tree to the north of a building provides little to no shading and may reduce cooling from wind currents. Overall, this potential cost is found to be outweighed by the cooling benefits of shading and evapotranspiration associated with trees distributed around a building (Donovan & Butry, 2009).

Trees planted for shade should be relatively inexpensive to obtain and have a dense but moderate-sized crown to provide significant cooling benefits while at the same time reducing excessive pruning, watering, and removal expenses (Akamphon & Akamphon, 2014). Urban tree selection should also be prioritized by species placement within regional hardiness zones (zonal temperature ranges to which trees are most well adapted). Recent work finds climate change to be shifting hardiness zones northward, rendering some species no longer suitable for planting in a particular city. One study finds more than one-third of trees historically adapted to Atlanta, Georgia, to be unsuitable for planting due to shifting hardiness zones over the next few decades (Lanza & Stone, in press).

A common finding in the literature is that mature trees yield greater cooling benefits than immature trees, so any tree planting initiative should prioritize the potential for tree longevity in site selection (Donovan & Butry, 2009; Sawka et al., 2013; Skelhorn et al., 2014). Selecting deciduous trees over coniferous will provide shading in the summer when it is needed, but restore sunlight to buildings in the winter when the leaves fall, thereby reducing heating costs (Pandit & Laband, 2010). While design aspects such as orientation may improve the efficiency of cooling, taking a long-term perspective on the savings over the lifetime of the tree may ultimately produce greater benefits.

3.2 Parks and open greenspace

The vegetative open space of parks, most typically characterized by a mix of turf, shrubs, and trees, can yield important cooling benefits to urban environments, and a range of benefits that can differ temporally or spatially from the urban forest.

3.2.1 TEMPERATURE IMPACTS

Parks and open greenspace cool primarily through evapotranspiration rather than shading. Due to their extensive area, the open greenspace of urban parks can produce an "oasis effect" with much cooler temperatures within them compared to the surrounding city. The magnitude of this effect ranges from roughly 2.7 to 7.2°F (Bowler et al., 2010; Doick et al., 2014; Shasua-Bar et al., 2009; Sugawara et al., 2015) and can extend beyond the park's boundary. Even small urban greenspaces have been observed to make a big difference in local temperature, up to 12°F in one study (Oliveira et al., 2015).

In contrast to tree canopy, parks often provide greater cooling benefits during the night than during the day, with faster cooling rates if irrigated (Bowler et al., 2010; Gober et al., 2010; Taha et al., 1991). As noted above, this cooling effect – at both day and night – has been found to exceed the area of the park itself. Though the cooling effects of parks are found to drop off exponentially with increased distance, cooling has been observed to extend as far as 840 meters (0.52 miles) from the park boundary (Doick et al., 2014; Lin et al., 2015). The cooling extent is heavily dependent on wind patterns of the city. One study finds a cooling extent of 65 meters on the upwind side of a large park, but 450 meters on the downwind side (Sugawara et al., 2015). Cooling reach also depends on topography, as cooler air from the park will flow to lower elevation areas. Even on calm nights, the temperature differential can create a cool breeze from the parks extending as far as 200 meters. The cooling extent of parks can be improved by ensuring good air flow around the greenspace, with dense urban development tending to limit the flow of cooler air (Hamada et al., 2010).

3.2.2 CARBON IMPACTS

While many studies investigate the cooling potential of parks and greenspace, it is not yet well established in the literature how this translates to carbon reduction potential. One of the few studies focused on this issue finds a park in Tokyo to provide a cooling potential of 7.8 MW of electricity, or the equivalent of 2,600 room air conditioning units (Sugawara et al., 2015). More studies on this topic will be needed, however, prior to drawing informed conclusions on the emissions mitigation potential of parks and open space.

3.2.2 DESIGN STRATEGIES

There is strong evidence that the cooling potential of parks is directly proportional to park size, with larger parks producing greater cooling benefits (Bowler et al., 2010). Size has also been shown to be more important than shape, suggesting that bigger is better regardless of location (Jaganmohan et al., 2016; Lin et al., 2015). As described above, locating a park at a high elevation may enhance its cooling extent as the cool air sinks into lower elevation areas.

Park composition also has a strong impact on cooling potential. Several studies show that the inclusion of trees can enhance cooling over parks or greenspaces that have grass only. Even very small parks that are heavily forested can produce greater cooling effects than parks or lawns with only grass (Jaganmohan et al., 2016; Wang et al., 2016). In fact, grass alone has a relatively small effect on temperature, while increasing water demand if irrigated. Parks that incorporate both grass and trees have been associated with a larger cooling effect and can reduce water demand by over 50% (Shasua-Bar et al., 2009).

3.3 Building-integrated vegetation

Building-integrated vegetation assumes the form of green roofs or green walls. Due to the need for an engineered roof membrane or scaffolding system for green walls, these approaches tend to be more costly per unit of area than tree planting or open space strategies, but can nevertheless yield significant reductions in building surface temperatures (Figure 2).

Image 1. Green wall in Paris (Huhmagazine.co.uk).

3.3.1 TEMPERATURE IMPACTS

Through direct shading and increased albedo, green roofs can significantly lower rooftop surface temperatures. The albedo of green roofs ranges from 0.7 to 0.85, which is much more reflective than conventional bitumen, tar, and gravel roofs, with albedos ranging from 0.1 to 0.2 (Berardi et al., 2014). This higher albedo results in substantially lower surface temperatures, as less solar radiation is absorbed by the roof. With added cooling from shading, green roofs can lower rooftop surface temperatures in excess of 100°F (Foster et al., 2011). Figure 3 illustrates the differential performance of conventional and green roof treatments.

The increased evapotranspiration of building-integrated vegetation also has the potential to reduce local air temperatures. One study observed a reduction in local ambient temperatures up to 9°F in proximity to green roof or wall installations (Foster et al., 2011). A study in Toronto found that greening just 5% of the city's area via rooftop gardens reduced city-wide temperatures 1°F (Yu & Hein, 2006). Scaling this up, studies have found that converting 50% of available roofing area to green roofs is associated with a reduction in air temperatures of 1.4 to 3.5°F, depending on the extent of irrigation (Liu & Bass, 2005). With rooftops accounting for 40% of the total land area in the Manhattan borough of New York, for example, green roofs offer an essential green infrastructure strategy in dense urban environments (Stone, 2012).

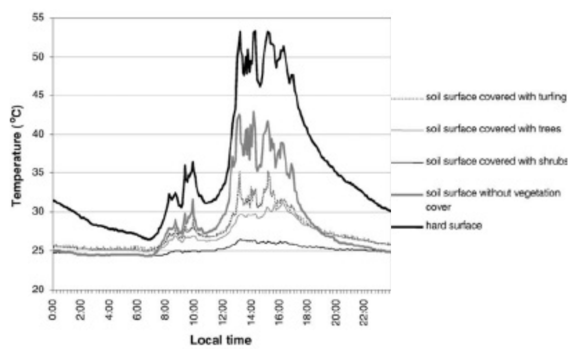


Figure 2. Roof thermal performance by type (Wong et al., 2002)

3.3.2 CARBON IMPACTS

Green roofs reduce energy use for cooling by directly lowering rooftop surface temperatures, thereby reducing the solar heat gain on the building and its interior. Studies find that green roofs can reduce annual building energy consumption for cooling by 60%, depending on building insulation (Berardi et al., 2014). The savings drop off quickly if the building is well insulated, as a well-insulated roof is already largely protected from solar heat gain. Energy savings are greatest on sunny days in the summer, and the benefits are greatest for the top floor of multistory buildings (Jim, 2014).

Green roofs also aid in carbon sequestration through their growth, consuming an estimated 375 grams of carbon/ft2 (Foster et al., 2011), suggesting that about every 12 - 30 square feet of green roof area sequesters roughly the same amount of carbon as the average shade tree. A large scale study of green roofs in Portland estimates that their roofs collectively reduce carbon emissions by up to 7.1 metric tons per acre per year (City of Portland Bureau of Environmental Services, 2010).

3.3.3 DESIGN STRATEGIES

Green roofs are ideal for dense urban areas that do not otherwise have space for trees or parks (EPA, 2014). Green roofs are thus an important component of larger city-wide initiatives siting trees and parks where there is land available, and green roofs where it is limited. Where building design will support deeper planting mediums, the addition of shrubs and trees to intensive green roofs can greatly enhance the cooling benefits of such roofs, as well as energy savings relative to low-stemmed plants alone (Wong et al. 2002). While such roofs remain rare in the US, over 12% of all flat roofs in Germany are green roofs, yielding significant cooling and stormwater management benefits (Stone, 2012).

For multistory buildings, the construction of green walls may produce greater cooling benefits than green roofs, which tend to most directly lower cooling loads for the top floors. One study finds that vegetated walls used in conjunction with green roofs can reduce energy consumption for cooling buildings between 32 and 100%, depending on the scale of implementation (Alexandri & Jones, 2008). Another study finds green walls to lower outside wall temperatures by 30°F (USEPA, 2008). Given the small number of green walls constructed in the United States, and the limited availability of commercial support systems for such walls, this approach may be the least cost effective of the surveyed options.

4 Co-benefits and costs of green infrastructure

Beyond its well established benefits for moderating urban temperatures, green infrastructure has been demonstrated to yield a range of additional ecological and human health-related benefits. Most extensively documented are the benefits of urban vegetation for lessening the volume of stormwater runoff and enhancing urban water quality. Urban canopy and other vegetation in cities slows the rate at which rainfall reaches storm sewers through two mechanisms. First, the interception of precipitation by the dense canopy of trees reduces the volume and slows the rate at which rainfall reaches ground surfaces. Second, vegetation increases the land area available for rainwater infiltration, as well as the rate of infiltration, due to soil aeration resulting from plant respiration occurring in subsurface root systems (Voskamp & Van de Ven, 2015). Studies have found that trees can reduce runoff by 3.2 - 11.3 kL per tree per year, with associated savings of between almost $3 and $48 per tree, depending on the size of the tree and the local cost of stormwater management (Mullaney et al., 2015). This amounts to 20 - 75% of total surface runoff depending on the design and amount of vegetation implemented (Armson et al., 2013). Green roofs have been found to reduce building runoff by up to 60% (Foster et al., 2011).

Urban vegetation can also have significant benefits for human health and well-being (Qin et al., 2013). Trees have been found to encourage physical activity, reduce physical and mental stress and fatigue, and even improve physical recovery from illness (Mullaney et al., 2015; Velarde et al., 2007). Vegetation can also reduce smog and other air pollutants directly linked to respiratory illnesses like asthma (Abhijith et al., 2015; Akbari, 2002; Nowak et al., 2006; Nowak et al., 2014; Scott et al., 1998; Tallis et al., 2011).

Other benefits of green infrastructure in cities include increased property values and business income (Burden, 2006; Donovan & Butry, 2010; McPherson et al., 2005; Pandit et al., 2010; Sander et al., 2010; Wolf, 2005), as well as social benefits ranging from crime reduction to enhanced community engagement by residents (EPA, 2014; Mullaney et al., 2015). Given this wide variety of co-benefits, increasing green infrastructure in urban areas is beneficial independent of heat and carbon-related risks.

4.1 Green infrastructure costs/ limitations

While green infrastructure in cities has been found to measurably enhance climate resilience and human health and well-being, its installation and maintenance carries greater costs than vegetative systems in natural settings. One major consideration in the maintenance of green infrastructure is the frequent need for irrigation, particularly when establishing new plantings. Parks characterized by extensive areas of turf grass and few trees may require high levels of irrigation for maintenance. Research, however, finds the addition of trees to open parkland to reduce water consumption by as

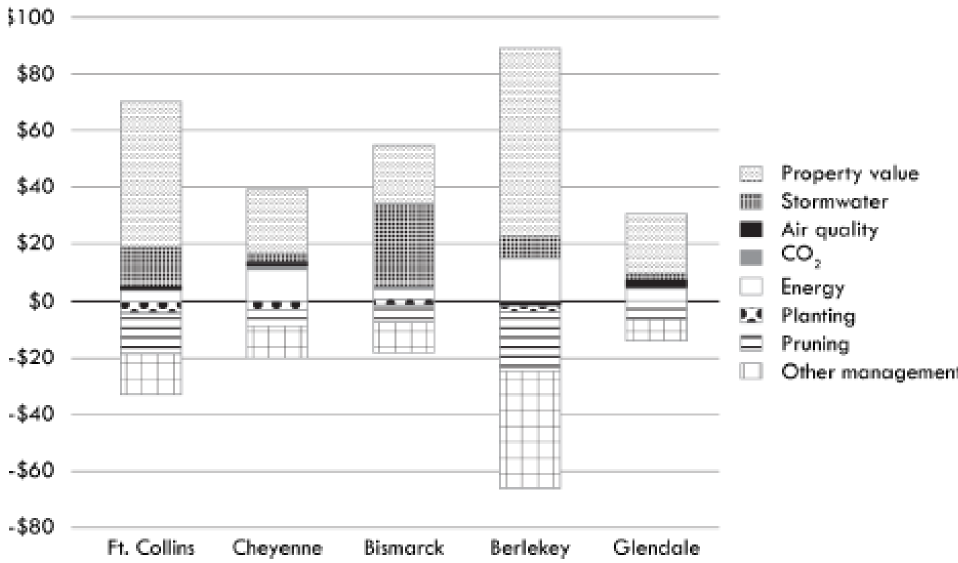


Figure 3. Benefits and costs of trees in five US cities (McPherson et al., 2005).

much as 50% (Shasua-Bar et al., 2009).

Trees can also produce street litter from leaves, cause damage to buildings, clog storm sewers, and even increase some forms of air pollution, such as pollen and biogenic volatile organic compounds that accelerate ozone formation (Mullaney et al., 2015). Tree maintenance is especially difficult in urban areas, as there is limited fertile soil, low access to water due to impervious surface cover, and many impediments to root growth. Because of these challenges, urban trees have a lower life expectancy than their rural counterparts (Mullaney et al., 2015), further increasing the cost of maintenance and replacement over time.

Other potentially negative effects of urban vegetation include a reduced effectiveness of cooling via breezes that are impeded by tree canopy (Sanusi et al., 2015), increased humidity due to greater rates of evapotranspiration, and lower rates of cooling at night in locations where dense tree canopy traps outgoing thermal radiation (Ellis et al., 2015; Hass et al., 2015). Yet, these costs notwithstanding, studies accounting for both the positive and negative effects of urban vegetation find the net effects of green infrastructure to be highly positive for urban environments (Cardelino & Chameides, 1990; Nowak et al., 2014).

Finally, the cost of installation and maintenance can be a significant barrier to green infrastructure strategies. New York City, for example, estimates average annual expenditures of $37 per urban tree planted, including all purchasing, planting, and maintenance costs. This results in total annual expenditures of almost $22 million for the urban forest (Peper et al., 2007). These costs, however, when annualized over the life of the tree, are found to be less than the economic benefits provided by trees in the form of enhanced property values and environmental services. In a comprehensive study of assessed economic costs and benefits of tree planting in five medium-sized US cities, McPherson et al. (2005) find the annual benefits of trees to exceed the annual costs by a factor of 1.4 to 3.1 (Figure 4). Importantly, while this study accounts for energy savings from reduced temperatures, it does not assess the benefits associated with reduced heat illness and mortality, found in other work to be significant (Stone et al., 2014).

In terms of building-integrated vegetation, green roofs can cost $10 - 20/ft2 more than conventional roofs, with intensive green roofs costing as much as $85/ft2 (Foster et al., 2011; ASLA, 2011). This initial investment often makes them a cost-prohibitive strategy for building owners. Like urban trees, however, once installed, the energy and stormwater runoff savings can more than cover the additional cost of the green roof, making it an economically viable strategy in the long run (ASLA, 2011).

5 Recommendations

The literature demonstrates clearly that, in regions with sufficient annual rainfall to support green infrastructure, urban vegetation is the most effective strategy to reduce the urban heat island, especially when trees are involved (O'Malley et al., 2015; Stone et al., 2014). While cooling potential and carbon reductions are generally found to be greater for urban trees and forests than for open greenspace or building-integrated vegetation, the varying benefits of different approaches by time of day and season militate for a combination of greening strategies across cities. Research shows that the extent and types of green infrastructure are more important than the typology of urban development in which these strategies are located (Jaganmohan, 2016).

Because older, larger trees are found to have greater benefits for cooling, air pollution reduction, and stormwater management, we recommend prioritizing tree preservation over tree planting, if possible, and that larger diameter trees be prioritized over smaller diameter trees (Donovan & Butry, 2009; Mullaney et al., 2015; Sawka et al., 2013; Skelhorn et al., 2014). When planting new trees, site selection and preparation should be based on the potential to support the longevity of plantings, as opposed to short-term cooling benefits. From a policy standpoint, tree protection stardards requiring tree removal permits and minimum tree sizes for replanting can greatly reduce the urban heat island. One study finds that neighborhoods with such policies have on average 2.7 - 7°F lower surface temperatures than comparable neighborhoods without such policies (Sung, 2013).

The following table highlights a set of specific, design-related recommendations drawn from our review of the literature on green infrastructure benefits for temperature moderation and carbon reductions in urban environments. Recommendations are categorized by green infrastructure type and are informed by best practices for both ambient cooling and reduced building energy consumption.

TABLE 1: GREEN INFRASTRUCTURE STRATEGIES AND RECOMMENDATIONS

Strategy	Recommendations
Urban trees & forests	Prioritize tree preservation over new plantings. Plant trees appropriate to local hardiness zone(s), but prioritize species also found one hardiness zone to the south. Integrate tree planting with high albedo materials for maximum cooling benefits. Plant trees in an east-west orientation, where possible.
Parks & open greenspaces	Include a mix of grass and trees for greatest cooling benefits. Create large, continuous greenspaces wherever possible for greater cooling magnitude and extent. Site open greenspaces where there is good air flow and at a locally high elevation to maximize offsite cooling benefits.
Building-integrated vegetation	Utilize green roofing or walls wherever high density development prevents tree planting. Prioritize green walls over roofs for multistory buildings. Use green roofs and green walls in conjunction for greatest cooling benefit.

5 Conclusion

The intent of this literature review has been to document broadly supported best practices for the use of green infrastructure for climate change adaptation and mitigation in cities. While important data and gaps in our understanding of the potential for urban vegetation to advance climate management objectives remain, such as an absence of monitoring data from long-term and spatially comprehensive green infrastructure programs, sufficient evidence from theoretical and modeling studies, combined with small scale observational studies, provide a strong basis to support presentday investments in urban vegetation for these purposes. In particular, when assessed over the productive lifetime of green infrastructure investments, and with respect to a full array of potential co-benefits, green infrastructure strategies in cities can be recognized as a very low risk policy response to climate-related challenges. This work has sought to summarize and better characterize the benefits and costs that may be associated with TPL Climate Smart Cities programs emphasizing green infrastructure investments in partner cities.

References

Abhijith, K. V., & Gokhale, S. (2015). Passive control potentials of trees and on-street parked cars in reduction of air pollution exposure in urban street canyons. Environmental Pollution, 204, 99–108. http://doi.org/10.1016/j.envpol.2015.04.013

Akamphon, S., & Akamphon, K. (2014). Cost and Benefit Tradeoffs in Using a Shade Tree for Residential Building Energy Saving. Environment Asia, 7, 104–111.

Akbari, H., Kurn, D. M., Bretz, S. E., & Hanford, J. W. (1997). Peak power and cooling energy savings of shade trees. Energy and Buildings, 25(2), 139–148. http://doi.org/10.1016/S0378-7788(96)01003-1

Akbari, H., Pomerantz, M., Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, Volume 70, Issue 3, p 295-310, ISSN 0038-092X, http://dx.doi.org/10.1016/S0038-092X(00)00089-X

Akbari, H. (2002). Shade trees reduce building energy use and CO_2 emissions from power plants. Environmental Pollution (Barking, Essex : 1987), 116 Suppl , S119–26. http://doi.org/10.1016/S0269-7491(01)00264-0

Akbari, Hashem; & Konopacki, Steven J.(2003). Streamlined energy-savings calculations for heat-island reduction strategies. Lawrence Berkeley National Laboratory. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory. Retrieved from: http://escholarship.org/uc/item/4543b14t

Akbari, H. Konopacki, S. (2005). Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy, Volume 33, Issue 6, p 721-756, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2003.10.001.

Akbari, H., United States. Environmental Protection Agency. Climate Change Division., Lawrence Berkeley Laboratory., & United States. Department of Energy. (1992). Cooling our communities: A guidebook on tree planting and light-colored surfacing. Washington, D.C. : Pittsburgh, PA (P.O. Box 371954, Pittsburgh 15220-7954): U.S.

Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment, 43(4), 480–493. http://doi.org/10.1016/j.buildenv.2006.10.055

Anderson, B. G., & Bell, M. L. (2009). Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiology, 20(2), 205-213. doi: 10.1097/EDE.0b013e318190ee08 ASLA. (2011). ASLA green roof demonstration project fact sheet. American Society of Landscape Architects. Retrieved from http://www.asla.org/uploadedFiles/CMS/Green_Roof/Green%20roof%20Fact%20sheet%201-pager%20101111%20final_doc.doc

Berardi, U., Ghaffarian-Hoseini, A., Ghaffarian-Hoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs, Applied Energy, Volume 115, p 411-428, ISSN 0306-2619

Bowler, D., Buyung-Ali, L., Knight, T., Pullin, A. (2010). Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landscape and Urban Planning 97(3), 147-155

Braga, A. L., Zanobetti, A., & Schwartz, J. (2002). The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Perspect, 110(9), 859-863.

Burden, D. (2006). 22 benefits of urban street trees. Retrieved from www.michigan.gov/documents/dnr/22_benefits_208084_7.pdf

Cardelino, C. A. and W. L. Chameides (1990). "Natural hydrocarbons, urbanization, and urban ozone." Journal of Geophysical Research 95(D9): 13,971-913,979. CDC. (2006). Heat-related deaths—United States, 1999-2003 Morbidity & Mortality Weekly Report (MMWR) (pp. 796-798): Centers for Disease Control and Prevention.

Chestnut, Lauraine G., Breffle, William S., Smith, Joel B., & Kalkstein, Laurence S. (1998). Analysis of differences in hot-weather-related mortality across 44 U.S. metropolitan areas. Environmental Science & Policy, 1(1), 59.

Clark, C. & Adriaens, P. (2010). "Quantifying Thermal Impacts of Green Infrastructure: Review and Gaps." Presented at Cities of the Future 2010: Urban River Restoration: Boston, MA.

Costa, M. H. and J. A. Foley (2000). Combined Effects of Deforestation and Doubled Atmospheric CO_2 Concentrations on the Climate of Amazonia. Journal of Climate 13(1): 18-34.

Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M., & Demuzere, M. (2013). Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress In Physical Geography, 37(1), 2-28. doi:10.1177/0309133312461032

Davis, R. E., Knappenberger, P. C., Michaels, P. J., & Novicoff, W. M. (2003). Changing Heat-Related Mortality in the United States. Environmental Health Perspectives, 111(14), 1712–1718. http://doi.org/10.1289/ehp.6336

Dimoudi, A., & Nikolopoulou, M. (2003). Vegetation in the urban environment: Microclimatic analysis and benefits. Energy and Buildings, 35(1), 69–76. http://doi.org/10.1016/S0378-7788(02)00081-6

Doick, K. J., Peace, A., & Hutchings, T. R. (2014). The role of one large greenspace in mitigating London's nocturnal urban heat island. Science of The Total Environment, 493, 662–671. http://doi.org/10.1016/j.scitotenv.2014.06.048

Donovan, G. H., & Butry, D. T. (2009). The value of shade: Estimating the effect of urban trees on summertime electricity use. Energy and Buildings, 41(6), 662–668. http://doi.org/10.1016/j.enbuild.2009.01.002

Donovan, G., Butry, D. (2010). Trees in the city: Valuing street trees in Portland, Oregon. Landscape and Urban Planning, 94. 77-83

Ellis, K. N., Hathaway, J. M., Mason, L. R., Howe, D. A., Epps, T. H., & Brown, V. M. (2015). Summer temperature variability across four urban neighborhoods in Knoxville, Tennessee, USA. Theoretical and Applied Climatology. http://doi.org/10.1007/s00704-015-1659-8

FLL. (2002). Guideline for the planning, execution and upkeep of green-roof sites. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. Retrieved from http://www.greenroofsouth.co.uk/FLL%20Guidelines.pdf

Foster, J., Lowe, A., & Winkelman, S. (2011). The Value of Green Infrastructure for Urban Climate Adaptation, (February), 52.

Gober, P., Brazel, A., Quay, R., Myint, S., Grossman-Clarke, S., Miller, A., Rossi, S. (2010). Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool Phoenix? Journal of the American Planning Association 76(1)

Hamada, S., Tanaka, T., & Ohta, T. (2010). Impacts of land use and topography on the cooling effect of green areas on surrounding urban areas. Urban Forestry and Urban Greening, 12, 426–434. http://doi.org/10.1016/j.ufug.2009.10.002

Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. Current Opinion in Environmental Sustainability, 3(3), 126– 134. http://doi.org/10.1016/j.cosust.2011.01.001

Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. Theoretical and Applied Climatology 95(3), 397-406. doi:10.1007/s00704-008-0017-5

Hass, A. L., Ellis, K. N., Mason, L. R., Hathaway, J. M., & Howe, D. A. (2016). Heat and Humidity in the City : Neighborhood Heat Index Variability in a Mid-Sized City in the Southeastern United States. http://doi.org/10.3390/ijerph13010117

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jaganmohan, M., Knapp, S., Buchmann, C. M., & Schwarz, N. (2016). The Bigger, the Better? The Influence of Urban Green Space Design on Cooling Effects for Residential Areas. Journal of Environment Quality, 45(1), 134. http://doi.org/10.2134/jeq2015.01.0062

Jim, C.Y. (2014). Air-conditioning energy consumption due to green roofs with different building thermal insulation, Applied Energy, Volume 128, 1 September 2014, p 49-59, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2014.04.055.

Karachaliou, P., Santamouris, M., Pangalou, H. (2015). Experimental and numerical analysis of the energy performance of a large scale intensive green roof system installed on an office building in Athens, Energy and Buildings, Available Online. ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2015.04.055.

Kleerekoper, L., Van Esch, M., Salcedo, T. (2012). How to make a city climate-proof, addressing the urban heat island effect. Resources, Conservation and Recycling 64, 30-38

Knowlton, K., Lynn, B., Goldberg, R., Rosenzweig, C., Hogrefe, C., Rosenthal, J., & Kinney, P. (2007). Projecting Heat-Related Mortality Impacts Under a Changing Climate in the New York City Region. American Journal of Public Health, 97(11), 2028–2034. http://doi.org/10.2105/AJPH

Konopacki, S. and H. Akbari (2000). "Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacramento and Salt Lake City." Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory.

Lanza, K., & Stone, B. Climate adaptation in cities: What trees are suitable for urban heat management? Landscape and Urban Planning (in press).

La Roche, P., & Berardi, U. (2014). Comfort and energy savings with active green roofs. Energy and Buildings, 82, 492–504. http://doi.org/10.1016/j.enbuild.2014.07.055

Li, T., Horton, R. M., & Kinney, P. L. (2013). Projections of seasonal patterns in temperature-related deaths for Manhattan, New York. Nature Climate Change 3, 717-721.

Lin, W., Yu, T., Chang, X., Wu, W., & Zhang, Y. (2015). Calculating cooling extents of green parks using remote sensing: Method and test. Landscape and Urban Planning, 134, 66–75. http://doi.org/10.1016/j.landurbplan.2014.10.012

Liu, K. & Bass, B. (2005). Performance of green roof systems. National Research Council Canada.

Loughner, C. P., Allen, D. J., Zhang, D. L., Pickering, K. E., Dickerson, R. R., & Landry, L. (2012). Roles of urban tree canopy and buildings in urban heat island effects: Parameteriztion and preliminary results. Journal of Applied Meteorology and Climatology, 51(10), 1775–1793. http://doi.org/10.1175/JAMC-D-11-0228.1

Luber, George, & McGeehin, Michael. (2008). Climate Change and Extreme Heat Events. American Journal of Preventitive Medicine, 35(5), 429 - 435. doi: 10.1016/j.amepre.2008.08.021

McPherson, E.G. and J.R. Simpson. (2001). Effects of California's urban forests on energy use and potential savings from large-scale tree planting. Davis, CA: USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research

McPherson, E., Simpson, J., Peper, P., Maco, S., Xiao, Q. (2005). Municipal forest benefits and costs in five U.S. cities. Journal of Forestry, 103. 411-416.

Miller, N. L., Hayhoe, K., Jin, J., & Auffhammer, M. (2008). Climate, Extreme Heat, and Electricity Demand in California. Journal of Applied Meteorology and Climatology, 47(6), 1834–1844. http://doi.org/10.1175/2007JAMC1480.1

Moriyama, M., Matsumoto, M. (1988). Control of urban night temperature in semitropical regions during summer. Energy and Buildings 11(1-3), 213-219

Mullaney, J., Lucke, T., & Trueman, S. J. (2015). A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134, 157–166. http://doi.org/10.1016/j.landurbplan.2014.10.013

Norton, B., Coutts, A., Livesley, S., Harris, R., Hunter, A., Williams, N. 2015. Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes, Landscape and Urban Planning, Volume 134, p127-138, ISSN 0169-2046, http://dx.doi.org/10.1016/j.landurbplan.2014.10.018.

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

Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. Environmental Pollution, 193, 119–129. http://doi.org/10.1016/j.envpol.2014.05.028

Oliveira, S., Andrade, H., & Vaz, T. (2011). The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. Building and Environment, 46(11), 2186–2194. http://doi.org/10.1016/j.buildenv.2011.04.034

O'Malley, C., Piroozfar, P., Farr, E. R. P., & Pomponi, F. (2015). Urban Heat Island (UHI) mitigating strategies: A casebased comparative analysis. Sustainable Cities and Society, 19, 222–235. http://doi.org/10.1016/j.scs.2015.05.009

ONeill, M. S., Carter, R., Kish, J. K., Gronlund, C. J., White-Newsome, J. L., Manarolla, X., . . . Schwartz, J. D. (2009). Preventing heat-related morbidity and mortality: new approaches in a changing climate. Maturitas, 64(2), 98-103. doi: 10.1016/j.maturitas.2009.08.005

Pandit, R., & Laband, D. N. (2010). Energy Savings from Tree Shade. Ecological Economics, 69(6), 1324-1329. doi:http://dx.doi.org.prx.library.gatech.edu/10.1016/j.ecolecon.2010.01.009

Peper, P., McPherson, E., Simpson, J., Gardner, S., Vargas, K., Xiao, Q. (2007). New York City, New York Municipal Forest Resource Analysis, Center for Urban Forest Research. Accessed March 4, 2016 http://www.milliontreesnyc.org/downloads/pdf/nyc_mfra.pdf

Pielke Sr, R. A., et al. (2007). An Overview of Regional Land-Use and Land-Cover Impacts on Rainfall. Tellus B 59(3): 587-601.

Qin, J., Zhou, X., Sun, C., Leng, H., & Lian, Z. (2013). Influence of green spaces on environmental satisfaction and physiological status of urban residents. Urban Forestry & Urban Greening, 12(4), 490–497. http://doi.org/10.1016/j.ufug.2013.05.005

Qiu, G. et al. (2013). Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture. Journal of Integrative Agriculture, 12(8), 1307–1315. http://doi.org/10.1016/S2095-3119(13)60543-2

Reid, C. E., O'Neill, M. S., Gronlund, C. J., Brines, S. J., Brown, D. G., Diez-Roux, A. V., & Schwartz, J. (2009). Mapping community determinants of heat vulnerability. Environmental Health Perspectives, 117(11), 1730–1736. http://doi.org/10.1289/ehp.0900683

Rosenfeld, A. H. and J. J. Romm (1996). "Policies to Reduce Heat Islands: Magnitudes of Benefits and Incentives to Achieve Them (PDF) (18 pp, 6.5MB)" Pacific Grove, CA.

Rosenfeld, A. H., et al. (1998). Cool communities: strategies for heat island mitigation and smog reduction. Energy and Buildings 28(1): 51-62.

Sander, H., Polasky, S., Haight, R. (2010). The value of urban tree cover: A hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA. Ecological Economics, 69. 1646-1656.

Sanusi, R., Johnstone, D., May, P., & Livesley, S. J. (2015). Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. Journal of Environment Quality, 0(0), 0. http://doi.org/10.2134/jeq2015.01.0039

Sawka, M., Millward, A., Mckay, J., Sarkovich, M. (2013). Growing summer energy conservation through residential tree planting, Landscape and Urban Planning, Volume 113, Pages 1-9, ISSN 0169-2046

Scott, K., McPherson, E., Simpson, J. (1998). Air pollution uptake by Sacremento's urban forest. Journal of Arboriculture, 24. 223-234.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. Landscape and Urban Planning, 92(3-4), 179–186. http://doi.org/10.1016/j.landurbplan.2009.04.005

Simpson, J.R. and E.G. McPherson. (1996). Potential of tree shade for reducing residential energy use in California. Journal of Arboriculture. 22(1) :10-18

Skelhorn, C., Lindley, S., & Levermore, G. (2014). The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK. Landscape and Urban Planning, 121, 129–140. http://doi.org/10.1016/j.landurbplan.2013.09.012

Snyder, P., et al. (2004). Evaluating the influence of different vegetation biomes on the global climate. CLIMATE DYNAMICS 23(3): 279-302.

Stone, Brian. (2012). The city and the coming climate: climate change in the places we live. Cambridge ; New York: Cambridge University Press.

Stone, B., et al. (2013). Climate change adaptation through urban heat management in Atlanta, Georgia." Environmental Science & Technology 47(14): 7780-7786.

Stone, B., Vargo, J., Liu, P., Habeeb, D., DeLucia, A., Trail, M., Hu, Y., &… Russell, A. (2014). Avoided heat-related mortality through climate adaptation strategies in three US cities. Plos One 9(6), 1-8.

Sugawara, H., Shimizu, S., Takahashi, H., Hagiwara, S., Narita, K., Mikami, T., & Hirano, T. (2015). Thermal Influence of a Large Green Space on a Hot Urban Environment. Journal of Environment Quality, 0(0), 0. http://doi.org/10.2134/jeq2015.01.0049

Sun, R., Chen, L. (2012). How can urban water bodies be designed for climate adaptation? Landscape and Urban Planning 105(1-2). 27-33

Sung, C. Y. (2013). Mitigating surface urban heat island by a tree protection policy: A case study of The Woodland, Texas, USA. Urban Forestry and Urban Greening, 12(4), 474–480. http://doi.org/10.1016/j.ufug.2013.05.009

Taha, H., Akbari, H., Rosenfeld, A. (1991). Heat island and oasis effects of vegetative canopies: Micro-meteorological fieldmeasurements. Theoretical and Applied Climatology 44(2): 123-138.

Tallis, M., Taylor, G., Sinnett, D., Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landscape and Urban Planning, 103. 129-138.

Theeuwes, N.E., Solcerova, A., Steeneveld, G.J. (2013). Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. Journal of Geophysical Research: Atmospheres 118(16)

USEPA. (2008). Reducing Urban Heat Islands: Compendium of Strategies. US Environmental Protection Agency. Retrieved from http://www.epa.gov/heat-islands/heat-island-compendium

USEPA. (2013). Trees and vegetation. US Environmental Protection Agency. Retrieved from http://www.epa.gov/heatisland/mitigation/trees.htm

USEPA. (2014). Stormwater homepage. US Environmental Protection Agency. Retrieved from http://water.epa.gov/polwaste/npdes/stormwater/index.cfm

USEPA. (2014). What is green infrastructure? US Environmental Protection Agency. Retrieved from http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm#raingardens

USGS. (2014). Specific heat capacity of water. United States Geological Survey. Retrieved from http://water.usgs.gov/edu/heat-capacity.html

Velarde, M. D., Fry, G., & Tveit, M. (2007). Health effects of viewing landscapes – Landscape types in environmental psychology. Urban Forestry & Urban Greening, 6(4), 199–212. http://doi.org/10.1016/j.ufug.2007.07.001

Voorhees, A. S., Fann, N., Fulcher, C., Dolwick, P., Hubbell, B., Bierwagen, B., & Morefield, P. (2011). Climate changerelated temperature impacts on warm season heat mortality: a proof-of-concept methodology using BenMAP. Environ Sci Technol 45, 1450–1457.

Voskamp, I. M., & Van de Ven, F. H. M. (2015). Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. Building and Environment, 83, 159–167. http://doi.org/10.1016/j.buildenv.2014.07.018

Wang, Z.-H., Zhao, X., Yang, J., & Song, J. (2016). Cooling and energy saving potentials of shade trees and urban lawns in a desert city. Applied Energy, 161, 437–444. http://doi.org/10.1016/j.apenergy.2015.10.047

Wolf, K. (2005). Trees in the small city retail business district: Comparing resident and visitor perceptions. Journal of Forestry, 103. 390-395.

Wong, N. H., Cheong, D. K. W., Yan, H., Soh, J., Ong, C. L., & Sia, A. (2003). The effects of rooftop garden on energy consumption of a commercial building in Singapore. Energy and Buildings, 35(4), 353–364. http://doi.org/10.1016/S0378-7788(02)00108-1

Yahgoobian, N., Srebric, J. (2015). Influence of plant coverage on the total green roof energy balance and building energy consumption. Energy & Buildings, Volume 103:1-13

Yu, C. & Hein, W. (2006). Thermal benefits of city parks. Energy and Buildings, 38, 105-20.

Zhou, Y. & Shepherd, J. (2010). Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. Natural Hazards 52(3): 639-668.

The Trust for Public Land
101 Montgomery St., Suite 900
San Francisco, CA 94104
415.495.4014

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BACK, KYLE LANZER

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