Quantifying Thermal Impacts of Green Infrastructure: Review and Gaps

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ABSTRACT

Green infrastructure, that is, wet weather management approaches and technologies that infiltrate, evapotranspire, capture, and reuse stormwater to maintain or restore natural hydrologies, can affect temperature in different aspects of the urban environment. Restoration of natural landscape features and local installations of rain gardens, green roofs, green walls, infiltration planters, permeable pavement, or trees and tree boxes can have beneficial effects that reduce (1) stormwater runoff temperatures, (2) heat loss and heat gain in buildings, and (3) the urban heat island effect (UHIE).

Rainfall and streamflow in urbanized areas pick up heat from unshaded, exposed man-made surfaces like pavement and rooftops and deliver the excess heat to downstream surface waters to the detriment of stream habitat. Green infrastructure techniques minimize local pavement and rooftop thermal absorption through increased shading and evaporative cooling. These practices also decrease the volume of runoff flowing across heated surfaces and slow the delivery of runoff, allowing more time for heat to dissipate prior to conveyance to surface water bodies.

In addition to the insulative properties of green roofs, the increased shading and evaporative cooling result in cooler interior temperatures for buildings during warm weather periods. The insulative properties of green roofs also mitigate heat loss in winter, resulting in reduced energy needs throughout the year. When technologies such as green roofs and green walls are integrated into the design process, greater energy savings for buildings can be realized through reduced heating, ventilation and air conditioning (HVAC) installation size.

When green infrastructure is applied at a greater scale in neighborhoods and cities, it tends to reduce the UHIE in understandable though not well-quantified ways, including reductions in exposed heat-absorbing surfaces, increased evaporative cooling, and decreased heat due to reduced HVAC system use. The thermal benefits of green infrastructure can extend well beyond the future city, as reduced cooling needs lower the demand for power during peak loading periods and result in fewer greenhouse gas emissions and less water consumption for power generation.

This paper reviews current knowledge on the thermal benefits associated with the use of green infrastructure, identifies gaps in knowledge, and indicates possible directions for future research. Understanding and quantifying the thermal benefits of green infrastructure from the perspectives of emissions avoidance and economic benefits will aid the (re)design of cities to handle energy and water appropriately as climate change and economic transformations alter the future cityscape.

KEYWORDS

Thermal pollution, thermal loading, green infrastructure, bioretention, permeable pavement, green roofs, stormwater runoff, urban heat island effect, building heat gain, building heat loss, energy savings, climate change

INTRODUCTION

Modern cities contain massive quantities of concrete, asphalt, stone, and steel that serve as the building blocks of parking lots, streets, sidewalks, buildings, and other urban infrastructure. These structures and the materials they are composed of have thermal bulk properties and surface radiative properties that facilitate absorption and storage of solar energy much more effectively than a typical rural or undeveloped area with trees, shrubs, and other vegetation, which can moderate temperatures. This absorbed solar energy increases the temperature of the material, which in turn can increase the temperature of whatever is surrounding it.

In the modern city, this absorbed solar energy can contribute to a broad range of issues. It can increase the temperature of stormwater runoff, which can have deleterious effects on aquatic life and habitats within urban waterbodies. It can increase building temperatures, leading to higher energy consumption and costs required to cool buildings. It can also contribute to the urban heat island effect (UHIE), which has a number of public health implications.

Management and mitigation of these thermal issues are critical for the city of the future. One solution that may assist in the mitigation of thermal pollution is green infrastructure. Green infrastructure is a term used to describe forested or vegetated open space as well as stormwater management practices that mimic natural hydrologic processes on a local level. Green infrastructure practices are engineered structures like green roofs, bioretention, vegetated swales, permeable pavement, rain barrels and cisterns, as well as natural practices like planting trees and native landscaping. While stormwater management is the primary function of green infrastructure, it has also been shown to mitigate thermal pollution through shading and insulation and to facilitate evaporative cooling, among other mechanisms.

The current understanding of the thermal benefits of green infrastructure is discussed further in the following section, followed by the identification of knowledge gaps and possible directions for future research.

THERMAL BENEFITS OF GREEN INFRASTRUCTURE

The following subsections highlight the current state of the science on the thermal benefits of green infrastructure. Three specific areas of interest for the future city are highlighted: stormwater runoff temperature attenuation, heat loss and heat gain in buildings, and urban heat island effect. Each subsection discusses the thermal processes of the existing cityscape and green infrastructure that affect thermal performance, including the effect of various design parameters on performance. Existing monitoring and modeling data and research findings are summarized as well.

Stormwater Runoff Temperature Attenuation

As stormwater runoff flows over solar-heated surfaces (e.g., rooftops and pavement), heat is transferred and runoff temperature can increase significantly. In one study, stormwater runoff temperatures from solar-heated urban surfaces were observed to be 20.9^{o}C on average in August with maximum temperatures up to 32.2^{o}C. The temperature differential between rainfall temperature (assumed to be dew point temperature) and urban runoff was on average 2.7^{o}C higher, with a maximum differential of 14.8°C (Janke et al., 2009).

The discharges of thermally enhanced stormwater runoff to nearby surface water bodies can be problematic for cold-water habitats. A number of cold-water fish (like trout and salmon) as well as many aquatic macroinvertebrates require cool (generally between 7 and 17^{o}C), well-oxygenated water (Lyons et al., 1996). As stream and lake temperatures increase, dissolved oxygen levels in water decrease. In recognition of this basic property of water, a number of states identify and regulate temperature as a water quality constituent.

Traditional stormwater management ponds often exacerbate thermal pollution because of their large surface areas, relatively shallow ponding depths, and general lack of shading. A North Carolina State University monitoring study of wet ponds and wetlands showed water temperatures were significantly increased (consistently higher than 21^{o}C) during the summer months when solar radiation was most intense (Jones and Hunt, 2009). Researchers observed that the outlet location within the water column had considerable influence on the temperature of the water ultimately discharged to receiving waters. Outlets at the bottom depths discharged the coolest water.

Green infrastructure practices, like permeable pavement, and vegetated practices, like bioretention, swales, and green roofs, have been found to be effective at reducing or preventing thermal loading from stormwater runoff. A laboratory study of pavement installations at the University of Guelph showed that runoff temperatures from permeable pavement were between 2 and 4^{o}C cooler than those from otherwise comparable asphalt pavement (Verspagen, 1995). A North Carolina State University study of the thermal performance of bioretention showed that runoff temperatures were reduced approximately 3 and 6^{o}C (Jones and Hunt, 2009). Reduced runoff volume associated with these practices appears to be the primary factor in reducing thermal loading (Jones and Hunt, 2009). Other factors that influence thermal loading are shading, media depth and type, surface area, and drain configuration.

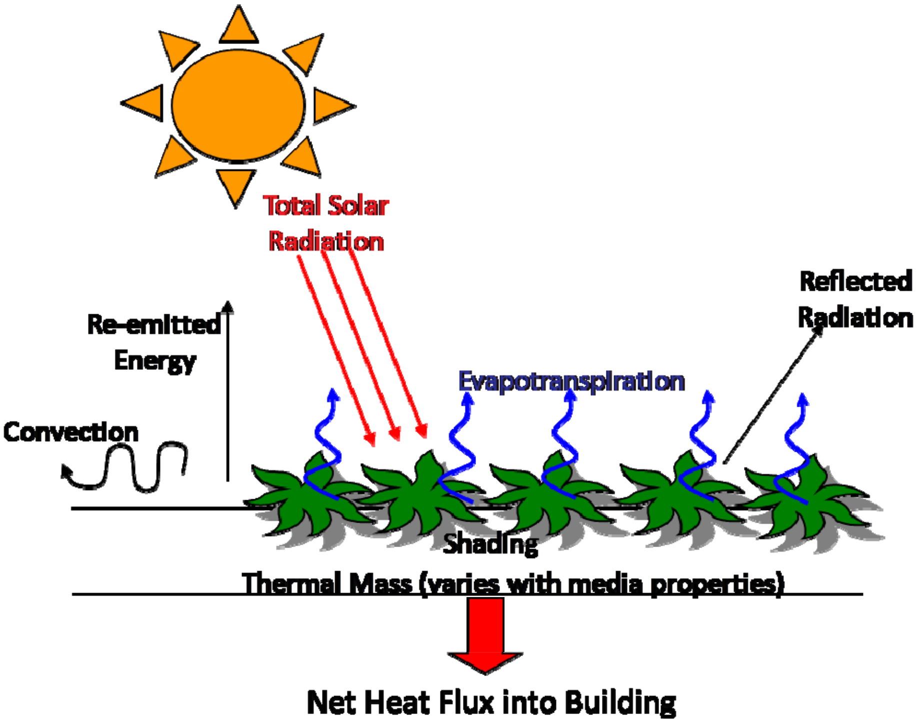
Several groups have created models that attempt to estimate runoff temperatures in urban watersheds. University of Minnesota researchers have created a simple, one-dimensional model that simulates runoff temperatures from heated impervious surfaces (Janke et al., 2009).
The University of Wisconsin–Madison and the Dane County (Wisconsin) Land Conservation Department developed the Thermal Urban Runoff Model (TURM) to predict the temperature increase in runoff from impervious surfaces (Roa-Espinosa et al., 2001). The TURM can also predict runoff temperature reductions associated with various green infrastructure practices, such

as vegetated swales and infiltration trenches or basins. Researchers at North Carolina State University have developed the Bioretention Thermal Model to facilitate assessment of the thermal impact of bioretention areas on receiving waters and to optimize design configurations to minimize thermal impacts (Jones and Hunt, 2009).

Heat Loss and Heat Gain in Buildings

The reduction of direct energy consumption by implementing green infrastructure at the building scale is accomplished by planting trees and other shade plants on the ground or by applying a green roof or green wall to the building façade. Vegetation plays a role in lowering surface temperatures through latent heat removal from soils via evaporation and transpiration in the presence of high moisture levels (Taha et al., 1991). Figure 1 depicts the factors in the energy balance for a vegetated roof system.

Figure 1 - Energy balance for a green roof system.



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Simpson and McPherson (1996) summarized several modeling studies indicating that shade from a mature tree (about 7.62 m in crown diameter) would reduce annual air-conditioning use by 2–8% (40–300 kWh) and would reduce peak cooling demand by 2–10% (0.15–0.5 kW) for cities across the United States.

Similar to earlier tree studies, much of the energy research on green roofs focuses on their ability to reduce the flux of solar radiation into a building during summer months (Del Barrio, 1998). A study by Takebayashi and Moriyama (2007) on the surface heat budget of a green roof and a highly reflective (white) roof found that both systems have a smaller sensible heat flux than a concrete roof surface. The small heat flux on the white roof was a result of the low net radiation, whereas that of the green roof was attributed to the large latent heat flux by evaporation. Thick soil layers reduced cooling needs during summer months, while thin substrate layers resulted in vlittle to no cooling benefit (Theodosiou, 2003).

Recent investigations have included observations throughout the year. Teemusk and Mander (2010) observed reduced roof temperatures in summer months for a green roof and sod roof as compared to a steel roof and a SBS (Styrene Butadiene Styrene) modified bitumen roof. Temperatures were also observed during the other seasons, and in winter, the temperatures of the substrate layers of the planted roofs were higher than those of the surfaces of the conventional roofs with average amplitudes of $1^{o}C$ for the planted roofs versus $7–8^{o}C$ for the conventional roofs (Teemusk and Mander, 2010).

Two main parameters influence the solar radiation that reaches the roof deck: leaf foliage and soil media. The more extensive the foliage density of a particular plant, the greater the decrease of the heat flux through the roof (Del Barrio, 1998; Theodosiou, 2003) and the greater the decrease in surface temperatures (Wong et al., 2003). In addition, a dry environment and faster wind speed increase the rate of evapotranspiration, thereby aiding the absorbance of solar radiation by plants (Theodosiou, 2003). In general, heat transfer is greater on roof surfaces that are not vegetated (Wong et al., 2003).

While much of the focus on energy savings of green infrastructure has been on the effects of foliage, the thermal properties of soil also affect heat transfer, particularly for green roofs or green walls. Sailor et al. (2008) evaluated eight different samples of green roof soil media with different percentages by volume of pumice, expanded compost, and sand. Results indicated that thermal properties varied significantly as a function of composition and moisture content. Thermal conductivity and specific heat capacity both had lower ranges for dry samples (0.25–0.34 W/(m K) and 830–1123 J/(kg K), respectively) than when water was added (0.31–0.62 W/(m K) and 1085–1602 J/(kg K), respectively) (Sailor et al., 2008). Albedo decreased with increasing surface soil moisture, while thermal emissivity remained relatively constant regardless of moisture content. Results suggest that moisture content — both bulk moisture and surface moisture — should be incorporated into building energy modeling of green roofs.

While Niachou et al. (2001) observed that heat transfer through roofs without vegetation is greater than heat transfer through roofs with vegetation, the energy savings benefit of green roofs is reduced as the insulation underneath the green roof is increased. For non-insulated roofs, green roofs reduced the heat transfer coefficients by 6–16 W/(m^2 K), while greening reduced heat transfer coefficients of moderately insulated roofs by 0.2 W/(m^2 K) and of well-insulated buildings by 0.02–0.06 W/(m^2 K) (Niachou et al. 2001). Despite the small changes in heat transfer, greening resulted in annual energy savings of 37%, 4%, and approximately 2%, respectively (Niachou et al., 2001).

The contribution of green roofs to total building energy consumption was integrated into EnergyPlus v2.0.0, a building energy simulation software program supported and made available by the U.S. Department of Energy. The ecoroof module, developed and described by Sailor et al. (2008), allows the exploration of green roof design options including soil media thermal properties, depth of soil media, plant type, plant height, and leaf area index. According to Clark et al. (2008), the model indicated that if a one-floor commercial facility in Detroit, Michigan, installed a 2,000-m^2 green roof, the roof system would reduce energy consumption by 16.4 MWh (with savings from both electricity and heating taken into account).

Urban Heat Island Effect (UHIE)

Extended land surface modifications, buildings, traffic, and heat generated by air-conditioning and other indoor climate control technologies contribute to elevated temperatures in urban areas, a phenomenon commonly referred to as the urban heat island effect (UHIE). Under natural conditions, evaporative cooling from the ground surface and vegetation moderates near surface temperatures. Development creates impervious, artificial surfaces that increase the amount of heat stored in an area and reduce the ability for evaporative cooling to occur. Anthropogenic heat and pollution can further intensify the UHIE by creating an inversion layer, resulting in a higher demand for air-conditioning and increasing the amount of heat delivered to the urban environment (Rosenfeld et al., 1995). Building density and configuration limit ventilation and sky view and further restrict long-wave radiant losses at night (Rizwan et al., 2008). The conditions that contribute to the UHIE can be categorized as controllable and uncontrollable variables, as shown in Table 1. While climate and weather patterns drive the uncontrollable variables, mitigation strategies may target those variables that are controllable.

Table 1 - Variables that contribute to the UHIE.

Controllable Variables	Uncontrollable Variables
Anthropogenic heat	Anticyclone conditions
Air pollutants	Season
Building materials	Diurnal conditions
Vegetated areas	Wind speed
Sky view factor	Cloud cover

These variables influence parameters in the surface energy balance, which describes the total heat generated and contained in an area, as shown below (Oke, 1988; Rizwan et al., 2008):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

where Q^* is the net short and long radiation captured in an area; Q_F is the anthropogenic heat release; Q_E is the turbulent sensible heat flux; Q_H is the turbulent latent heat flux; ΔQ_S is the sensible heat storage of an area; and ΔQ_A is the net heat advection from an area. Green infrastructure mitigation strategies primarily affect the latent heat flux. According to Spronken-Smith et al. (2000), parks could moderate temperatures through greater evaporation (more than 300%) when compared to surrounding areas. According to a review of mitigation studies by Rizwan et al. (2008), increasing vegetation is the most widely applied mitigation measure with the potential for significant temperature reduction.

Takebayashi and Moriyama (2009) evaluated the mitigation effect of converting asphalt parking lots to grass-covered parking lots. The experimental methods for measuring and estimating thermal properties are typical for determining the benefits of green infrastructure. A parking lot in the central ward of Kobe City was selected for experimentation. Thermocouples were installed at various depths to record the temperature of the different material layers including the soil and surface layers. Solar radiation, infrared radiation, air temperature, relative humidity, and wind speed and direction were recorded nearby. The surface and air temperature were used to estimate the sensible heat flux. The estimated reduction in sensible heat flux of an asphalt parking lot converted to a grass covered lot was 100–150 W/m^2 during the day and approximately 50 W/m^2 at night (Takebayashi and Moriyama, 2009). The estimated air temperature reduction for the central ward area if all parking lots were converted to grass-covered parking lots (about 6% of the total land area in the ward) was 0.1^{o}C (Takebayashi and Moriyama, 2009).

Two studies considered the mitigation benefits of widespread implementation of green infrastructure systems within cities. Rosenzweig et al. (2006) found that greening 50% of New York City rooftops would reduce the average surface temperature by an estimated 0.1–0.8^{o}C. Banting et al. (2005) determined that greening 30–100% of available rooftops in Toronto, Ontario, could reduce average temperatures by 0.5–2^{o}C. Small, disparate vegetated areas on roofs or on the ground spread throughout a city or neighborhood extend the thermal effect of vegetation beyond its physical boundary more effectively than a large, continuous vegetated area of similar size in a central location (Honjo and Takakura, 1990/1991). According to Shashua-Bar and Hoffman (2000), in Tel-Aviv the cooling effect is perceivable to 100 m from observed, small green sites.

It is important to consider the design of vegetated sites according to local factors. When trees are planted along heavily trafficked roads or intersections, adequate ventilation is needed or the mitigation potential is greatly reduced (Shashua-Bar and Hoffman, 2000). Alexandri and Jones (2008) evaluated the effects of green roofs and green walls in urban canyons. The climate characteristics of nine cities were incorporated into a two-dimensional, microscale model that assessed three urban canyon geometries, two canyon orientations, and two wind directions. They found that generally, vegetation had a greater effect on urban temperatures in drier and hotter cities than in cooler, humid cities, although these cities could also benefit from greening especially when both roofs and walls were vegetated (Alexandri and Jones, 2008). Wider canyons resulted in weaker observable effects from the green roofs and green walls. In general, green walls had a stronger effect on temperatures within the canyon, while green roofs had greater effect at the roof level and the urban scale.

KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

A review of research on the thermal benefits of green infrastructure disclosed several knowledge gaps. Quantitative stormwater runoff models exist for estimating temperature reductions by green infrastructure. Integration of these models within larger watershed models could inform planning through assessments of potential temperature mitigation scenarios. For green infrastructure and building energy savings, research has focused on temperature, climate, and moisture data to verify models. The integration of heat flux models with quantitative building energy performance data has yet to be verified with green infrastructure on an existing building. Verification of these models could reduce the financial risk of employing green infrastructure mitigation strategies on buildings. Verification of models is also needed in urban heat island mitigation research. Because of the logistical challenges and expense of changing the surface of urban areas, the majority of the research in this field relies on models with verification done via individual plots or buildings. This field could benefit from collaborative efforts with city development plans to conduct long-term studies as green infrastructure is implemented.

ACKNOWLEDGMENTS

Work at Argonne National Laboratory was supported by the U.S. Department of Energy under contract DE-AC02-06CH11357.

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