Assessing the Impact of Green Roofs on Urban Heat Island Mitigation: A Hardware Scale Modeling Approach

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ABSTRACT

As urban areas and the number of people living in urban areas grow, it is important to assess different mechanisms for mitigating the resulting urban heat island. Two hardware scale models (16 ft² footprint), identical except for their roofing material, were constructed and monitored to assess the impact of green roofs on urban temperature and humidity. During the daytime, indoor and outdoor temperatures of the green roof model were 4.2°C and 0.3°C cooler respectively than the black roof model. The green roof indoor temperature was 0.7°C warmer during the nighttime. Humidity differences between the models were minimal likely because of the relatively small size of the models and the interaction with the ambient atmosphere. Differences between the models were most pronounced under calm, clear, warm, and dry atmospheric conditions. While further study is necessary, the results suggest that widespread implementation of green roofs could reduce the urban heat island effect.

Key Words: green roof, urban heat island, model

INTRODUCTION

As the geographic footprint and population size of cities worldwide increases, researchers are investigating techniques to minimize the environmental impact associated with urban areas. One such technique is the implementation of green roofs on urban structures. Green roofs have numerous potential benefits including: reducing storm water runoff (Bliss et al. 2009), acting as additional insulation for roof tops (Castleton et al. 2010), providing biodiversity (Gedge and Kadas 2005), sequestering carbon (Getter et al. 2009), and reducing urban temperatures (Gaffin et al. 2009). Warmer temperature associated with urban areas compared to surrounding rural areas is commonly referred to as the urban heat island (UHI) (Landsberg 1982;
While the physical mechanism whereby green roofs could reduce the magnitude of the UHI is fairly straightforward, little documentation exists at the city scale of the actual impact that green roofs have on city temperatures.

UHIs result from differences in the physical properties of the materials that make up urban and rural environments. Materials such as asphalt, brick, and concrete absorb heat more readily and release heat less efficiently than trees, grass, and water bodies (Solecki et al. 2005). In addition, the canyon structure created by tall buildings enhances warming by creating multiple solar reflections and therefore multiple opportunities for absorption. Canyon structures also provide multiple opportunities for emitted thermal energy to be absorbed (Chapman 2005). The increased surface friction associated with taller buildings reduces wind speeds and therefore limits heat transport from the city (Voogt 2004). The relative lack of vegetation in urban areas and the corresponding decrease in evapotranspirative cooling also serve to enhance the UHI (Sailor and Dietsch 2007). Finally, the UHI is enhanced due to anthropogenic waste heat from a range of sources including automobiles, air conditioning equipment, and industrial facilities (Sailor and Dietsch 2007). Urban-rural temperature differences are usually most extreme in the nighttime hours, and may exceed 10°C (Chapman 2005). This increase in urban temperatures can affect human health, air quality, and energy consumption (EPA 2003).

One potential way to reduce the UHI and therefore limit many of the negative consequences associated with warmer urban environments is green roofs. Green roofs involve growing plants on rooftops, thus replacing the vegetated footprint that was destroyed when the building was constructed (Getter and Rowe 2006). The earliest documented roof gardens were the Hanging Gardens of Semiramis in what is now Syria. In the 1600s to 1800s, Norwegians covered roofs with soil for insulation and then planted grasses and other species for stability. Germany is recognized as the place of origin for modern-day green roofs (Getter and Rowe 2006). In the 1970s, growing environmental concern, especially in urban areas, created opportunities to introduce progressive environmental thought, policy, and technology in Germany (Oberndorfer et al. 2007). Green-roof coverage in Germany alone has been increasing by approximately 13.5 million m² per year (Oberndorfer et al. 2007).

Greens roofs are classified into two categories, intensive and extensive. Intensive green roofs involve intense maintenance and include shrubs, trees, and deeper planting medium. Extensive green roofs require less maintenance and usually consist of shallower soil media, different plants such as herbs, grasses, mosses, and drought tolerant succulents such as sedum (Getter and Rowe 2006).

Green roofs help reduce temperatures by creating a buffer zone between the roof and the sun's radiation and therefore shading the roof, preventing its surface from heating up (FEMP 2004). Increased evapotranspiration from the green roof also serves to cool both the building and the surrounding area (Sailor and Dietsch 2007). Hein (2002) determined that gardens in Singapore reduced roof ambient temperature by 4°C and also that heat transferred into the rooms below was decreased.

The National Research Council of Canada conducted a field study over a two year period (2000-2002) to evaluate the thermal performances of green roofs. The study found that the daily maximum membrane temperature underneath the green roof was significantly lower than the daily maximum membrane of the reference roof (FEMP 2004). The temperature of the same green roof exceeded 30°C on only 18 days out of 660-days, whereas the non-green rooftop exceeded 30°C on 63 days out of the 660-days. Also, the NRCC predicted that if only 6 percent of Toronto's roofs, or 1,600 acres (6.5 square kilometers), were green roofs, summer temperatures could potentially be reduced by 1°C to 2°C in the urban center.
A regional climate simulation model using 50% green-roof coverage distributed evenly throughout Toronto showed temperature reductions as great as 2°C in some areas due to green roofs (Oberdorfer et al. 2007).

In 1995, a heat wave killed more than 800 people in the United States, including 525 in Chicago alone. In response, the city of Chicago established the Chicago Urban Heat Island Initiative to reduce urban air temperatures, ameliorate effects of dark surfaces, and reduce pollution (Changnon et al. 1996). More than 60 percent of Chicago’s rooftops are dark and absorb and trap heat emitted from the sun. To lessen the effect, the city is replacing asphalt in alleys with light-colored paving, constructing light-colored roofs, and installing rooftop gardens (Czarnecki 2003).

In 2001, a green roof was installed on Chicago’s City Hall (FEMP, 2004). The overall roof measures about 3600 m², with approximately 2000 m² converted to green roof. Comparing instantaneous afternoon surface temperatures of the green and black roofs as well as the black roof on the adjacent building on August 9, 2001 showed the green roof to be approximately 12°C and 25°C cooler than the two black roofs. A more methodical analysis of nine test plots at the Chicago Center for Green Technology indicated that an average of six different green roofs was 12.9°C cooler than a black tar roof (MWH 2007). It is important to note that these cooling effects associated with green roofs were realized during the daytime hours. Due to the insulating properties associated with green roofs, nighttime temperatures of green roof buildings can often be warmer than a traditional building (EPA 2003).

While the localized effects of green roofs on individual buildings have been examined, relatively little work has been done on the impact of green roofs on overall city temperatures. The main reason is that major cities with significant numbers of green roofs don’t exist for empirical analysis. Much of the work regarding this issue has occurred using scaled urban models. Richards (2000) used a 1/8 scale, outdoor model with a simplified geometry and assessed the spatial patterns of urban dew and surface moisture in Vancouver, Canada, during the summer in a residential neighborhood. Spronken-Smith and Oke (1999) used a 1:625 scale model to simulate the effects of radiation geometry, thermal properties, and surface wetness upon nocturnal surface cooling in urban parks of different size, vegetative cover, and soil conditions.

The purpose of this study was to create two hardware scale models (one “green” and one “black” roof) that would each be equipped with the appropriate equipment to monitor for indoor and outdoor temperatures, relative humidity, dew point temperature, wind, and rain, to assess the green roof’s ability to assist in mitigating the UHI. The models were used to answer two questions:

Is there a difference between the model cities as measured by indoor and outdoor temperature, relative humidity, and dew point temperature?

Do rain and wind affect the temperature and humidity differences between the models?

By studying a model city, it is possible to begin to assess the impact of green roofs at the city scale.

DATA AND METHODS

The model cities were located at an elementary school in Franklin County Pennsylvania, approximately 3.5 km east of Chambersburg in the south-central part of the state. They were built within a 5 x 11 m fenced garden area approximately 16 m west of the school building. The models were created to replicate the downtown area of Hagerstown, MD which is approximately 40 km from the study site. Hagerstown was used for scaling and building purposes only. Given the limitations of the building materials, the models were built at an approximate horizontal scale of 1 inch to 8 feet and vertical scale of 1 inch to 3 feet.
To simplify matters, the model with the green roof will be referred to as the green model and the model with the standard roof will be referred to as the black model. Model measurements are in English units to conform to the units associated with the construction materials. Each model consisted of typical building materials including concrete pavers, brick pavers, roof felt, outdoor paint, and in the case of the green model, live plants. Each model was built upon a 4 x 4 ft piece of ¾ inch-thick plywood that rested approximately 8 inches above the ground on cinder blocks. The plywood was wrapped in roof felt to help protect it from the weather during the duration of the experiment. On top of the roofing felt, 12 x 12 x 1 inch concrete pavers were used to simulate sidewalks and roads. The roads themselves were spray painted using outdoor black spray paint and a template of the road layout in downtown Hagerstown. The buildings were built out of brick pavers and capped with plywood roofs that were covered with roofing felt and green roof material. The edges of the roof caps were painted with outdoor paint to protect the plywood from the elements.

The plants for the green roofs were a typical green roof species: *Sedum acre*, commonly known as goldmoss sedum. Due to the relatively small size of the model green roofs it was not practical to use pre-planted containers intended for actual green roof installations. The model plants were taken from a backyard garden and transplanted into a special soil mix consisting of equal parts compost, peat moss, and topsoil. Watering was required for the first two weeks to establish the transplanted plants on the new roofs.

Once established and due to the mild summer, no other watering was required. Minor trimming and maintenance was performed during the monitoring period as needed.

It should be noted that the results of this study are potentially limited due to unavoidable issues associated with using scale models. Due to available building materials, the models were not scaled equally in the horizontal and vertical directions, resulting in models that do not represent the dimensions of the city of Hagerstown. The model dimensions may be representative of other built environments however. The thickness of both the building walls as well as the planting media does not simulate actual building conditions and therefore may produce thermal properties that differ from reality. Finally, because of the small size of the models as well as the lack of surrounding buildings in the models, the advective and buoyant air flow associated with the models will differ from reality. While it will never be possible to perfectly model reality, the results of this study agree well with previously published results, suggesting that important information can be gleaned through the use of scaled models.

Temperature, relative humidity, and dew point data were collected in the center of each city using HOBO Pro v2 data loggers situated within radiation shields. Temperature data were also collected within a building in each city using HOBO 12-Bit Temperature Smart Sensors. The sensors were mounted inside the roofs and transmitted data to a HOBO microstation to log the data. Wind speed and rain data were collected using HOBO sensors and were logged with the

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Range</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
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<tr>
<td>12-bit temperature</td>
<td>-40 to 75°C</td>
<td>±0.2°C</td>
<td>0.03°C</td>
</tr>
<tr>
<td>Pro v2 temperature</td>
<td>-40 to 70°C</td>
<td>±0.2°C</td>
<td>0.02°C</td>
</tr>
<tr>
<td>Pro v2 relative humidity</td>
<td>0-100%</td>
<td>±2.5%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Wind sensor</td>
<td>0-45 m/s</td>
<td>±11 m/s</td>
<td>0.38 m/s</td>
</tr>
<tr>
<td>Rain sensor</td>
<td>0-50°C</td>
<td>±1%</td>
<td>0.2 mm</td>
</tr>
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</table>

Table 1: Instrument specifications.
Table 1 shows the instrument specifications and Fig. 1 shows the layout of the cities and the instruments.

Hourly data for all the instruments were collected from May 27th to September 4th, 2009. Hourly averages were calculated for each data type and differences were calculated between the black and green models. Daytime (9:00 to 20:00) and nighttime (21:00 to 8:00) averages were also calculated and compared between the models. Daytime was defined as the time when indoor temperatures for the black roof model were warmer than green roof model.

Statistical significance of all differences between the models was calculated using the Mann-Whitney U statistic. The U statistic is a non-parametric statistic that serves a similar purpose as the more familiar t statistic. To account for the non-normal distribution of most of the data, the U statistic is calculated by ranking the data and then assessing differences in mean rank of the data based on model type.

To determine the impact of weather on the differences between models, daily averages of all data types were calculated and the top and bottom 5% of the days (5 days) were selected as a subset based upon rainfall, wind speed, outdoor temperature, and relative humidity. Differences between the cities were calculated based on these subsets of data. For example, the five windiest and five calmest days were compared to determine what impact wind speed had on the differences between the black and green models. Because of the small sample size associated with this component of the analysis, statistical significance of the differences could not be assessed.

RESULTS

Table 2 shows the average, maximum and minimum differences between the black and
Table 2: Average, maximum, and minimum differences between model cities (black minus green). $T_{in}$ = inside temperature; $T_{out}$ = outside temperature; RH = relative humidity; $T_d$ = dew point temperature; *= differences that are significant at the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>$T_{in}(\degree C)$</th>
<th>$T_{out}(\degree C)$</th>
<th>RH(%)</th>
<th>$T_d(\degree C)$</th>
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<tbody>
<tr>
<td>Avg. difference</td>
<td>1.8*</td>
<td>0.2</td>
<td>-0.7</td>
<td>0.1</td>
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<tr>
<td>Avg. day difference</td>
<td>4.2*</td>
<td>0.3*</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Avg. night difference</td>
<td>-0.7*</td>
<td>0.2</td>
<td>-0.6</td>
<td>0.1</td>
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<tr>
<td>Max. difference</td>
<td>12.8</td>
<td>2.1</td>
<td>15.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Jun 15, 14:00</td>
<td>Aug 21, 11:00</td>
<td>Jun 26, 17:00</td>
<td>Jun 26, 17:00</td>
</tr>
<tr>
<td>Min. difference</td>
<td>-2.1</td>
<td>-1.0</td>
<td>-12.7</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>Jun 14, 8:00</td>
<td>Jun 29, 8:00</td>
<td>Jun 15, 20:00</td>
<td>Jul 12, 18:00</td>
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green models for temperatures, relative humidity and dew point. Indoor temperatures showed the largest differences and were all significant. For the entire study period, the black model was 1.8 °C warmer. During the daytime hours, the black model was 4.2°C warmer. At night, the green model was 0.7°C warmer. The maximum difference between the cities was 12.8°C (black warmer). The minimum difference was -2.1°C (green warmer). For the outdoor temperatures, the black model was always warmer on average. During the daytime hours, this difference was 0.3°C and significant. For relative humidity and dew point, the differences were minimal and not significant. The sign of the relative humidity differences for day and night mirrored the indoor temperature differences. Dew points were on average higher in the black model.

Figures 2 and 3 show the average hourly differences between models. Black indoor temperatures were warmer from 9:00 to 21:00. These differences were significant from 10:00 to 20:00, with a maximum value of 6.4°C at 14:00. Green indoor temperatures were warmer during the nighttime hours of 22:00 to 8:00. These differences were significant from 2:00 to 4:00, with a maximum difference of 0.9°C at 4:00. Black outdoor temperatures were warmer for the entire daily cycle except from 7:00 to 9:00. None of the outdoor temperature differences were significant. The largest difference was 0.5°C at 15:00. Hourly humidity differences between the models were minimal and none were significant. Relative humidity differences mirrored the diurnal cycle of temperatures. The black model had a higher relative humidity from 8:00 to 10:00. This corresponded to the time period where temperatures were warming for the day and the green model had a higher dew point. For the rest of the daily cycle, the green model had a higher relative humidity despite the fact that the black model had a slightly higher dew point. Negative relative humidity differences were greatest during the warmest part of the day.

Table 3 shows the differences between models under different meteorological conditions. Significance of differences cannot be determined using this methodology because the sample size (10 days) was too small. For all four meteorological conditions examined (wind, rain, temperature, relative humidity), the pattern of differences was nearly identical. Calm, clear, warm, and dry (CCWD) conditions all promoted the largest differences between the black and green models. Indoor and outdoor temperatures for the black model were warmer during the day but the differences were greater during CCWD conditions. During the night, larger temperature differences still generally
Figure 2: Indoor and outdoor temperature differences between model cities (black minus green). Bold portions of the lines indicate differences are significant at the 95% confidence level.

Figure 3: Relative humidity and dew point temperature differences between model cities (black minus green). No differences are statistically significant.
occurred during CCWD conditions but the green model was warmer for indoor temperature while the black model was warmer for outdoor temperature. The exceptions to the pattern are that nighttime indoor differences were larger during cold conditions and nighttime outdoor differences were equal under rainy and clear conditions. The magnitudes of the indoor temperature differences were nearly all larger than the magnitude of the outdoor temperature differences. Differences in relative humidity were greater as well during CCWD conditions with the green model having higher values. Dew point differences under all conditions during both the daytime and nighttime were close to equal and there is no clear pattern to the differences.

**DISCUSSION**

The results indicate that in general green roofs do have a mitigating effect on the UHI primarily by decreasing daytime temperatures. It is likely that the primary reason for this effect is the increased insulation provided by the green roofs. The green model was consistently cooler during the daytime. Furthermore, differences in indoor daytime temperatures were larger between the models than differences in outdoor temperatures. The insulating cooling effect of the green roofs was most apparent directly inside the building compared to the area surrounding the buildings. At nighttime, the insulating effect of the green roof served to keep the indoor green temperatures warmer. Cooler indoor temperature during the day and warmer indoor temperature at night supports the notion that green roofs reduce the amount of heat transferred through the roof, thereby lowering the energy demands on a building’s heating and cooling system (Oberndorfer et al. 2007). Reduced energy demand also reduces waste heat generated by the buildings’ mechanical heating and cooling systems which in turn will decrease the UHI.

The black outdoor temperatures were slightly warmer for most of the diurnal cycle but the difference between the models was smaller during the nighttime hours. The magnitude of the daytime cooling associated with the green roof is much larger than nighttime warming suggesting that during the summertime, the overall impact of green
For differences in temperature and humidity over the course of a summer. One model was built with traditional roofing material while the other was built with a green roof. The results of the analysis can be summarized as follows:

Green indoor and outdoor temperatures were cooler during the daytime and warmer during the nighttime. The magnitude of these differences was larger for the indoor temperatures.

Humidity differences between the models were minimal and mostly mirrored temperature differences.

Differences between the black and green models were greatest under calm, clear, warm, and dry atmospheric conditions.

These results are a first step in demonstrating the impact that extensive green roof implementation may have on a city’s UHI. These impacts may be most noticeable in warm, dry climates during the summertime. Future research should attempt to construct larger and more realistic urban models that better simulate both the city itself and perhaps more importantly simulate the interactions with the ambient atmosphere.

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