An Examination of the Effect of Building Compactness and Green Roofs on Indoor Temperature through the Use of Physical Models

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ABSTRACT

Green roofs provide energy and cost savings during summer by insulating buildings and therefore keeping them cooler. Most prior studies have used only roof area to calculate the energy savings of green roofs. This study observed four physical models for 54 days to ascertain how building geometry and compactness impact indoor temperature on buildings where a green roof has been installed. Indoor temperature was decreased due to green roof implementation by 8.1°C on a less compact building compared to 4.6°C on a more compact building. These results are more apparent on warm days. Less compact buildings have a larger relative roof size compared to the surface area of the building and thus, the impact of a green roof is more pronounced on less compact buildings. The results suggest that building compactness can be a criterion to determine the buildings that will benefit the most from installing a green roof.

Key Words: green roof, building compactness, indoor temperature, U-value, green roof contribution rate

INTRODUCTION

Green roofs are vegetated systems that provide energy savings and environmental benefits to urban areas. They can be installed during the construction of new buildings or retrofitted onto existing conventional roofs (Gedge and Kadas 2005; Getter and Rowe 2006; Youngman 2011). As a precursor to modern green roofs, roof gardens first appeared thousands of years ago in the Hanging Gardens of Babylon (Dunnett and Kingsbury 2008). In more recent times, Germany has been a leader in green roof implementation, first for aesthetic purposes beginning in the early twentieth century and later for urban ecological value in the 1950s (Dunnett and Kingsbury 2008). By the 1980s, Germany realized the benefits of green roofs for the reduction of energy use and stormwater runoff (Gedge and Kadas 2005). Green roofs have increasingly been installed in many metropolitan areas across the United States since the 1990s. Between 2004 and 2013, the total green roof area in the United States increased approximately 20,000,000 ft^2 (GRHC 2014).

For individual buildings, green roofs reduce energy consumption and increase the life span of the roof. For urban areas in general, green roofs reduce stormwater runoff, greenhouse gas emissions, and the urban heat island effect (Alexander 2004; Blackhurst et al. 2010; Dunnett and Kingsbury 2008). Energy savings are one of the main reasons to install green roofs. The City of Chicago has installed green roofs since the early 2000s with City Hall as the most prominent site. City Hall saves approximately 10,000 kWh and $3,600 per year due to its green roof (EPA 2008; Getter and Rowe 2006).

Green roofs reduce heat loss from buildings in winter and keep buildings cooler in summer (Youngman 2011) due to increased insulation and lower solar absorbance (Dunnett and Kingsbury 2008; Saiz et al. 2006). Green roofs are more effective in reducing heat gain in the summer than reducing heat loss in the winter and thus the energy savings for green roofs are greater in the summer than in the winter (Getter and Rowe 2006; Liu and Baskaran 2005). This is primarily due to the summer heat flux (rate of heat transfer) through green roofs being considerably reduced by low thermal diffusivity due to soil moisture and low solar radiation transmission due to shadowing from leaves (Del Barrio 1998).

The Florida Solar Energy Center assessed energy savings for cooling by installing 1,000 m^2 of green roofs. They found that green roofs reduced 45% of the average heat flux of conventional roofs and saved 489 kWhr per year (Cummings et al. 2007). Sonne (2006) found that a conventional light-colored roof had a solar reflectance of 58% compared to a green roof reflectance of 12%. In the summer, the average maximum temperature of the conventional roof reached 54°C, whereas the average maximum temperature of a green roof was 33°C. The average heat flux of the green roof were 18.3% less than the average heat flux of the conventional roof. These differences in heat flux allowed green roofs to reduce energy consumption 700 Watt-hours per day on a roof of 307 m^2.

When considering the heating and cooling loads of buildings and their energy demand, building shape is critical (Gratia and Herde 2003). Buildings that have the same volume but different shapes have different heating and cooling load rates. The building compactness (C, (m^3/m^2) is defined as

$$C = V/S \qquad (1)$$

where V is the inner volume and S is surface area (including the roof) of the building (Gratia and Herde 2003; Straube 2012). Gratia and Herde (2003) found that buildings of higher compactness have lower annual heating loads, the amount of heat needed to maintain the temperature. A building with a compactness of 1.24 had 7% lower heating loads than a building with a compactness of 1, whereas a building with a compactness of 0.84 had 17.9% higher heating loads.

Buildings usually gain heat from roof or wall heat transfer from the building exterior, solar radiation through windows, building internal heating from people, equipment, and artificial lighting, and the ventilation of air (ASHAE 2001; Byrne and Ritschard 1985). Exterior walls are significant components of the building thermal mass (the building's resistance to temperature change) and make a considerable impact on the heating and cooling rate of buildings (Byrne and Ritschard 1985). Heat transfer (Q) through walls and roofs is calculated by

$$Q = UA(T_o - T_i) = A(T_o - T_i) / R \qquad (2)$$

where U is the thermal conductance coefficient (U-value), A is the heat transfer area (walls and roofs), T_o and T_i are the outdoor and indoor air temperatures respectively, and R is the overall unit thermal resistance

(R-value) or the ratio of the temperature difference between the inside and outside of the building and the heat flux through the building exterior) (ASHAE 2001). R is also the inverse of U. Installing a green roof changes the R and U values and therefore changes in heat transfer and energy savings due to the installation can be calculated. For example, Clark et al. (2008) used heating and cooling degree days for Ann Arbor, Michigan and the R-value analysis to calculate energy savings from green roofs based on energy costs for 2003 and adjusted to 2006 dollars. They assumed that an R-value of conventional roofs was 11.34 $ft^2 \times °F \times h/Btu$ (conductance of 0.50 $W/m^2/K$) and an R-value of green roofs was 23.4 $ft^2 \times °F \times h/Btu$ (conductance of 0.24 $W/m^2/K$). Their results show that 2000 m^2 of green roofs can save 66.1 MWh of heating and cooling energy per year, which is equal to $1670 per year.

Most studies for analyzing the energy savings associated with green roofs have used a two-dimensional (2D) method by calculating only the roof area of buildings (Carter and Keeler 2008; Clark et al. 2008; Cummings et al. 2007). However, indoor building temperatures are affected by building shape, compactness, insulation of a building envelope, and internal heat gains from humans and equipment (Gratia and Herde 2003). Therefore, this study uses model buildings to assess the relationship between building shape and indoor temperature to determine the impact of building compactness and green roof implementation.

MATERIALS AND METHODS

Four physical models of buildings were constructed in a 25 m × 5 m area on the playground of the elementary school on the campus of Shippensburg University in south-central, Pennsylvania during summer 2014. The four models differed in dimensions, compactness, and roof type. The models were labeled "less compact black roof", "less compact green roof", "more compact black roof", and "more compact green roof". Table 1 shows the dimensions of the model buildings and Figure 1 shows a photograph and schematic diagram of the four models. The models were built with wood framing and plywood siding and were painted gray. Black roofing paper covered the roofs of all four models. Four 0.61 m × 0.61 m × 12 cm pre-grown plant modules were installed on each of the two green roof models. The plant modules consisted of 14 species of sedum. These plants are classified as the most useful green roof plants because they are low-growing and shallow-rooted perennial plants that have a high disease tolerance (Snodgrass and Snodgrass 2006). We used one micro station data logger and four 12-bit temperature smart sensors to collect indoor temperature data. The temperature sensors were suspended in the center of the interior of each building and have an accuracy of ±0.2 °C.

We collected hourly temperature data from each of the buildings over a 92-day period from May 26 to August 25, 2014. The data collection occurred during the late spring

Table 1. Description of physical models.

	Model 1 Less Compact	Model 2 Less Compact	Model 3 More Compact	Model 4 More Compact
Elements	**Black Roof**	**Green Roof**	**Black Roof**	**Green Roof**
Width	1.22 m	1.22 m	1.22 m	1.22 m
Length	1.22 m	1.22 m	1.22 m	1.22 m
Height	0.61 m	0.61 m	1.22 m	1.22 m
Volume	0.91 m^3	0.91 m^3	1.82 m^3	1.82 m^3
Surface Area	5.95 m^2	5.95 m^2	8.93 m^2	8.93 m^2
Compactness	0.15	0.15	0.20	0.20

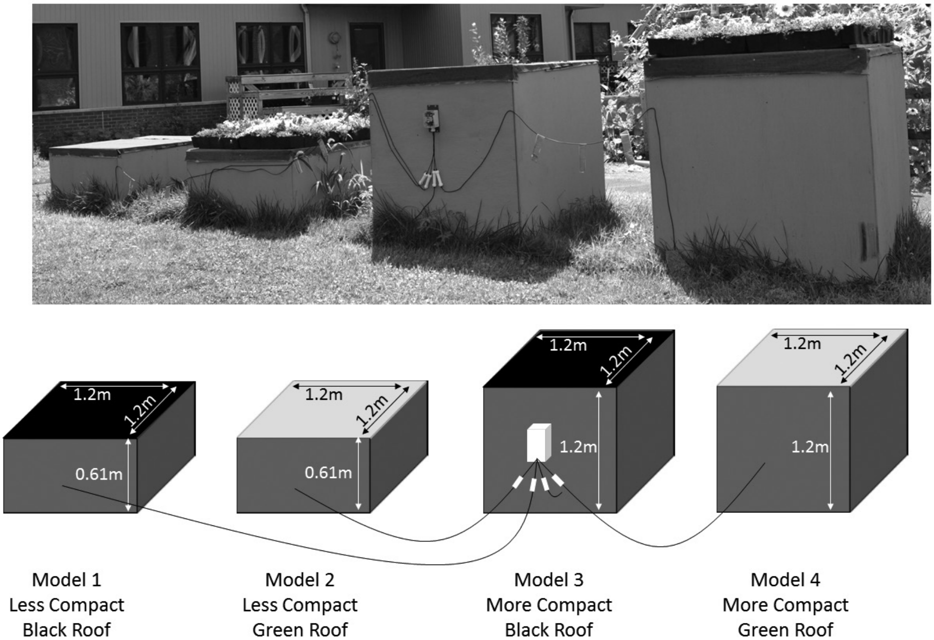

Figure 1. Photograph and schematic diagram of the physical models.

and summer because green roofs are more effective in controlling heat gain in spring and summer when solar heating is more important, than in reducing heat loss in fall and winter (Liu and Baskaran 2005). A subset of the 54 warmest days where the average temperature inside the "less compact black roof" building was greater than 32.2°C (90F°) between 11AM and 4PM were selected and analyzed. Temperature differences between the four buildings were assessed for these days.

Green roofs increase roof insulation as measured by a reduced U-value (Castleton et al. 2010; Niachou et al. 2001). Based on equation 2, we developed a Green Roof Contribution Rate (GRCR) which shows the reduction of the building heat flux after installing green roofs. The building heat transfer for the conventional black roof buildings was calculated as

$$Q_{CR} = (A_W U_W + A_{CR} U_{CR})(T_o - T_i) \quad (3)$$

where A_W is the combined area of the four walls, U_W is the wall U-value, A_{CR} is the black roof area, U_{CR} is the black roof U-value, and (T_o-T_i) is the temperature difference between the outside and inside of the building. Building heat transfer for the green roof buildings was calculated as

$$Q_{GR} = (A_W U_W + A_{GR} U_{GR})(T_o - T_i) \quad (4)$$

where A_{GR} is the green roof area and U_{GR} is the green roof U-value. The green roof contribution rate to the building heat gain, or the impact that that the green roof has on reducing heat gain compared to a black roof, was calculated as

$$GRCR = (Q_{CR} - Q_{GR}) / Q_{CR} = (A_{CR} U_{CR} - A_{GR} U_{GR}) / (A_W U_W + A_{CR} U_{CR}) \quad (5)$$

U-values for this equation came from Niachou et al. (2001) who estimated U-values for 10 types of conventional and green roofs. Table 2 shows U-values for three different scenarios

Table 2. U-values that were applied to the four physical models. (Source: Niachou et al. 2001)

	U-value (W/m²K)		
	Black Roof	Green roof	Wall
Scenario 1	0.26	0.24	0.26
Scenario 2	7.76	1.73	7.76
Scenario 3	18.18	1.99	18.18

from Niachou et al. (2001) and assumed the walls had the same U-value as a conventional roof. The three scenarios represent different insulation conditions of roofs and were chosen to assess the range of the relationship between the GRCR and indoor temperature reduction. The calculation of GRCR was limited by the fact that U-values were estimated from Niachou et al. (2001) and not measured, only heat gains through the walls and roofs were considered, and each wall was assigned the same U-value despite the fact that U-values vary depending on the orientation of the wall (Byrne and Ritschard 1985). Addressing all of these assumptions was well beyond the scope of this study. It's likely that thorough measurements of the parameters where assumptions were made would increase the precision of the results but would not change the overall general conclusions.

RESULTS AND DISCUSSION

Figure 2 shows the average hourly indoor temperature for the four models during the 54-day study period. Indoor temperatures generally increased from 7:00 AM to a high temperature around 3:00 - 5:00 PM. The less compact black roof building was the warmest during the day with a maximum indoor temperature of 39.1°C at 2:00 PM and 3:00 PM. The less compact green roof was the coolest building during the day with a maximum indoor temperature of 32.4°C at 4:00 PM. Cooling of all buildings generally occurred from 5:00 PM until 6:00 AM. Both the more and less compact black roof buildings were the coolest during this time and were essentially equal in their indoor temperatures.

Figure 3 shows the indoor temperature differences between the green and black roofed buildings for both the more and less compact sets of buildings. For the less compact buildings, the green roof reduced indoor temperature by a maximum of 8.1°C at 1:00 PM. From 8:00 AM to 7:00 PM, the average reduction in indoor temperature due to the green roof was 5.3°C for the less compact buildings. For the more compact buildings, the green roof reduced indoor temperature by a maximum of 5.1°C at 11:00 AM. The green roof reduced indoor temperatures for the

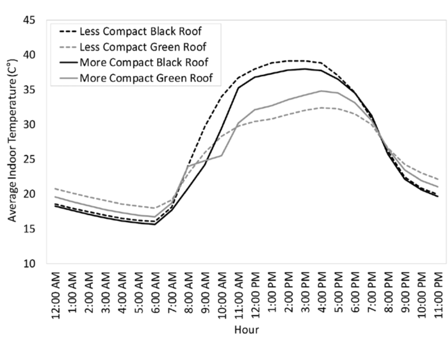

Figure 2. Average hourly indoor temperature of the model buildings during the 54 warmest days.

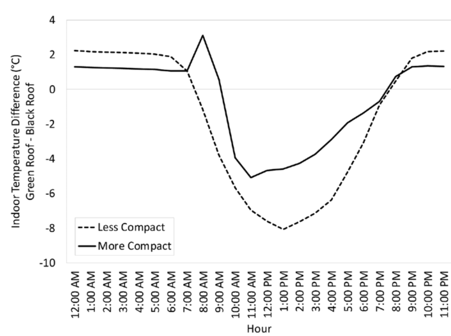

Figure 3. Indoor temperature differences between green and black roof buildings for the more and less compact models.

more compact buildings for a shorter time and to a lesser extent than for the less compact buildings. From 10:00 AM to 7:00 PM, the average reduction in indoor temperature due to the green roof was 3.1°C for the more compact buildings. From 8:00 PM until 7:00 AM for the less compact buildings and 9:00 AM for the more compact buildings, green roofs served to keep the indoor temperature warmer by an average of 1.9°C for the less compact buildings and 1.3°C for the more compact buildings. The overall effect of green roofs was a cooling effect as the 24-hour average indoor temperature difference was 1.7°C for the less compact buildings and 0.6°C for the more compact buildings.

Table 3 shows the indoor maximum and minimum temperatures, as well as the ranges from Figure 2 for the four models. For both sets of buildings, the maximum temperature was cooler for the green roof and the minimum temperature was warmer. These differences were more pronounced in the less compact buildings. Correspondingly, the green roof building in each pair also had a smaller diurnal temperature range. These results are in line with Jaffal et al. (2012) and Niachou et al. (2001).

Figure 4 shows the indoor maximum temperature differences between the green and black roof buildings for both the more and less compact sets of buildings for the entire study period. Green roofs are thus more effective at reducing maximum temperatures for the less compact buildings, a finding in line with previous studies (Gratia and Herde 2003; Straube 2012). The average reduction due to the green roofs was 7.3°C for the less compact buildings and 4.2°C for the more compact buildings. This green roof cooling effect becomes less pronounced for the less compact buildings as the study progresses into August as evidenced by the significant trend line. This may be due to changes in humidity but requires further analysis. More humid air does not fluctuate temperature as much due to the higher heat capacity of water. The impact of increased humidity on the less compact buildings is potentially greater because the impact of the green roofs is greater for this set of buildings. There is not a significant trend for the differences in the more compact buildings.

Of the 54 days analyzed, July 1 and August 16 had the warmest and coldest indoor temperatures respectively. Figure 5 shows the indoor temperature differences between the green and black roof buildings during the afternoon on these days for the more and less compact building pairs. As evidenced by the negative values, green roof indoor temperatures were cooler in all cases compared to the black roofs. For both the hot and cold day, the cooling effect of the green roofs was more pronounced in the less compact buildings (dashed lines compared to solid lines). The less compact buildings had a maximum cooling due to the green roofs of 8.6ºC on the hot day and 7.4ºC on the cold day. For the more compact building set, there was not an apparent difference between the hot and cold day. The compactness of the buildings was of greater importance on the hot day (black lines compared to gray lines) when the green roof reduced temperatures by an average of 3.6 ºC on the hot day compared to 2.2ºC on the cold day.

Table 4 shows a comparison of compact-

Table 3. Maximum and minimum indoor temperature of four models.

	Less Compact				More Compact		
	Black	**Green**	**Green-Black**		**Black**	**Green**	**Green-Black**
Maximum T (ºC)	39.1	32.4	-6.7		38.0	34.8	-3.2
Minimum T (ºC)	16.0	17.9	1.9		15.6	16.7	1.1
Range T (ºC)	23.1	14.5	-8.6		22.3	18.1	-4.2

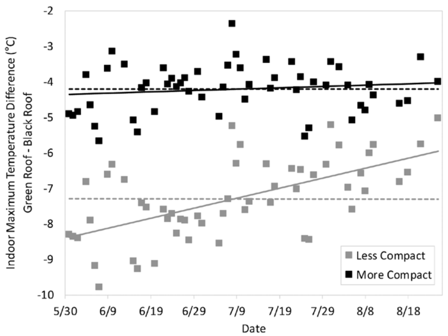

Figure 4. Time series of indoor maximum temperature differences between green and black roof buildings for the more and less compact models. Dashed lines show the average value while solid lines show trends.

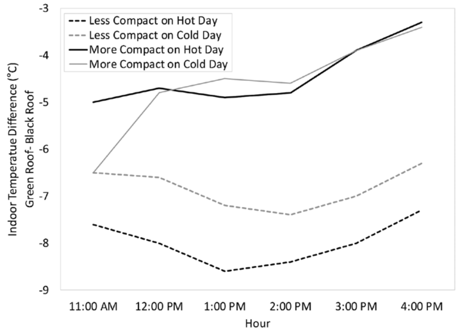

Figure 5. Indoor temperature differences between green and black roof buildings for the more and less compact models on the hottest and coldest days of the study. Hot day was July 1. Cold day was August 16.

ness, temperature reduction due to green roofs, geometric ratios, and green roof contributions rates for the more and less compact building pairs. GRCR's are greater by 36-40% depending on the scenario for the less compact building. The corresponding temperature reduction due to the green roof is 3.5°C greater for the less compact building. The four models had the same roof area but different height and thus the percentage of roof area to overall surface area was greater for the less compact building. Thus, the impact of the green roof was more pronounced on the less compact building. Most previous studies about indoor temperature reduction with green roofs considered only roof areas. However, building compactness and the GRCR calculation illustrate the important relationship of building shapes (as described by compactness), U-values, and indoor temperature reductions due to green roof installation.

CONCLUSION

We collected data for four model buildings during the summer to assess the impact of green roofs and building compactness on indoor temperature. Results suggest that:

Green roofs reduce daytime and maximum indoor temperatures and increase nighttime and minimum indoor temperatures.

Green roofs are more influential for temperature reduction on less compact buildings when buildings have the same roof area.

The impact of a green roof on a less compact building to reduce indoor temperature is more pronounced on warmer days.

Table 4. Comparison of compactness, temperature reduction due to green roofs, geometric ratios, and green roof contributions rates.

	Less Compact	**More Compact**
Building Compactness	0.153	0.204
Indoor Maximum Temperature Reduction	8.1°C	4.6°C
Percentage of Roof Area to Surface Area	25%	17%
GRCR Scenario 1	0.015	0.011
GRCR Scenario 2	0.155	0.111
GRCR Scenario 3	0.178	0.127

The enhanced impact of green roofs on less compact buildings is due to the relatively large size of the roof on less compact buildings. Because of this relatively large roof area, less compact buildings require a greater heating and cooling load than more compact buildings (Gratia and Herde 2003) and thus, less compact buildings have higher energy costs when using conventional roofs. Implementation of a green roof on a less compact building will provide greater benefit in terms of energy and monetary savings due to enhanced insulation provided by the green roof.

It's important to recognize that this study was limited by the fact that it did not use detailed U-value calculations but instead used U-values for external walls and conventional and green roofs from prior studies. Also, physical models are not perfect representations of real buildings and thus the impact of a green roof on a model may differ from an actual building. The relatively short study period also limits the ability to assess the impact of green roofs during different times of the year. Despite these limitations, this study effectively showed the impact of green roofs on indoor summer temperatures for buildings of different compactness. Future studies will examine results from other times of the year when the impact of green roofs is likely to be less significant in magnitude (spring and fall) or perhaps opposite in sign but not as pronounced in magnitude (winter) and apply the results to the selection of actual buildings to construct green roofs. It would also be informative to examine more closely the role of building volume in summertime temperature reduction. Our study focused on buildings with the same roof size but different compactness values. Future experiments could focus on the effectiveness of green roofs when compactness and/or roof area were held constant while building volume changed.

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