A multi-year comparative analysis of green and conventional roof thermal performance under temperate climate conditions

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Abstract
Research suggests that—relative to conventional roofs—green roofs can significantly reduce rooftop heat exchange in moderate climates; however, limited research exists on the performance of green roofs in colder climates. This paper analyzes the comparative performance of two side-by-side roof assemblies: a conventional roof and a green roof located in the temperate climate of Ottawa, Canada. Using two years’ worth of temperature and solar radiation data, we analyze variations in the incremental thermal benefit of the green roof relative to the conventional roof. We discuss factors contributing to these variations, such as precipitation and ambient temperature. Our results indicate that the green roof under investigation reduced thermal transmittance by 31.5% on average across two years. Although the percent benefits were much higher during the summer months, reductions in thermal transmittance were consistently above 7.7% throughout both years, indicating green roofs may be an appropriate alternative to conventional roofs in climates with hot, humid summers and cold, snowy winters.

1.0 Background
In recent decades, increasing energy efficiency of the built environment has been recognized as a pathway to bring Canada 10% closer to its 2030 Paris Climate Accord commitment. In fact, the development of net-zero energy building codes is currently underway in Canada, with the hope that they will be adopted by provinces and territories by the end of the decade. Indeed, conventional envelope components such as flat roofs account for a substantial fraction of total envelope heat exchange, especially in low-rise commercial buildings, where the ratio of roof-to-wall surface area can be quite large. Although new building codes could require expensive mechanical and electrical upgrades, the use of innovative roofing constructions, such as green roofs, could play a vital role in bringing buildings into compliance.

Conventional roof assemblies are typically composed of a structural concrete slab, roofing membrane, insulation layer, waterproof drainage mat, and an outermost layer that can be a variety of materials, but is often bitumen-based shingling, aluminum, or gravel [1]. The green roof replaces the outer-most layer of a
conventional roof with a root barrier, drainage mat, geotextile filter, and soil growth substrate, within which grows vegetation that is selected to endure variations in the local climate [2]. Green roofs are intended to augment conventional roofs and are designed in part to reduce heat exchange that would otherwise occur through a conventional roof by mimicking physical processes that occur in the natural environment [2]. For example, the plant canopy of a green roof consumes solar radiation for photosynthesis while doubling as a layer of shade for the underlying growth substrate. These effects result in only a fraction of solar radiation being absorbed by the growth substrate that would otherwise be absorbed by the outer-most materials of a conventional roof. The growth substrate serves as a thermal mass by storing the absorbed radiant energy as heat, some of which is dissipated through the metabolic functioning of the vegetation [3]. Specifically, stored heat energy is consumed by the vegetation during transpiration, an endothermic process by which soil moisture is converted into water vapour that is released through the plant stomata [2].

Indeed, a review of 2002-2012 literature related to the energy-saving aspects of green roofs, [4] found that green roof vegetation reflects 27% and absorbs 60% of solar radiation, the remainder of which was transmitted to the growth substrate. Through numerical simulations, both [4] and [5] demonstrated that evapotranspiration is the dominant mechanism that moderates heat exchange in summer when vegetation is mature. By simulating heat exchange through a green roof assembly, [6] found that the U-value of the green roof in question was 55% lower than that of the conventional roof when evaluated under summer conditions. But in colder seasons, research suggests that when vegetative growth is minimal or the vegetation is covered in snow, the thermal benefit of green roofs tends to be less pronounced. For example, [7] investigated the heat flux through a green and conventional roof, demonstrating that the green roof reduced heat flux by 167% in summer but only 13% in winter. In addition, the two roofs in [7] showed similar performance during the shoulder seasons and during times of snow cover. [8] concluded that the presence of snow diminished the capability of a green roof to save on building energy expenditure. A more recent study by [9] found that snow cover stabilized growth substrate temperatures and thus heat flux through the green roof, demonstrating that snow cover may help isolate the outer-most layer of the green roof from ambient temperatures.

Two multi-year studies of green and conventional roof performance in Ottawa, Canada have been previously conducted by the National Research Council of Canada. In 2003, [10] presented average daily heat exchange through both roofs between November 2000 and September 2002, demonstrating that heat exchange was reduced by 47% on average, though more so during the summer. [11] analyzed the monthly heat exchange through the same set of roof assemblies using five years of measured data, citing greater reductions of heat exchange by the green roof from April to September and nearly equal amounts of heat exchange through both roofs from November to February. In this paper, our objective is to perform a similar evaluation of green roof performance as cited in [10] and [11], but to explicitly quantify the reduction of total heat exchange promoted by the green roof on a month-to-month basis over 2016 and 2017. Furthermore, we set out to analyze differences in the Ottawa climate throughout the seasons and interpret how these differences are regulating the heat flux through each roof.

2.0 Methodology
2.1 Experimental Setup
The heat exchange through a green and conventional roof at Carleton University was calculated and analyzed over two calendar years: 2016 and 2017. Both roof assemblies consist of a 300 mm concrete slab, 5 mm rubberized asphalt waterproof roof membrane, modified bitumen sheet, 100 mm of RSI 3.52
rigid type 4 extruded polystyrene insulation, and a drainage mat. Differences between each roof assembly exist above the drainage mat, where on the green roof, 100 mm of soil and Sedum spurium foliage exists in basket-style modules. On the conventional roof, a layer of coarse rock aggregate with an average thickness of 25 mm covers the drainage mat. Thermocouples have been installed on the ceiling (bottom of concrete slab) of the room beneath each roof assembly to measure interior temperature, which serves as the inside boundary for the heat transfer calculation (note these thermocouples have an average measurement uncertainty of ± 0.2 °C). Similarly, thermocouples have been installed above each roof’s drainage mat to measure the outside boundary temperature used for the heat transfer calculation. Note that groupings of 6 and 2 thermocouples were installed on the green and conventional roof, respectively, and average temperatures per grouping are reported. An HC2-S3 Relative Humidity and Air Temperature Probe located 1.5 m above the green roof surface was installed to measure ambient temperature, and four SP-LITE Silicon Pyranometers were installed on the green roof and were used to measure incident shortwave radiation; the average of the four measurements are presented. The profile of each roof assembly is shown in figure 1.

2.2 Analysis of Heat Transfer

Hourly heat flux across both roofs was calculated using Fourier’s method for one-dimensional steady-state heat transfer. For both roofs, the heat flux calculation was carried out over the concrete layer and insulation layer. The concrete layer had an average thickness of 300 mm and thermal conductivity of 0.600 W/m·°C and the RSI 3.52 rigid insulation layer had a thickness of 100 mm and thermal conductivity of 0.030 W/m·°C. The harmonic mean of thermal conductivity was computed and used to represent the overall thermal conductivity of both the concrete and insulation layers. Equation 1 shows the calculation used to calculate heat flux through the layered roof assembly.

\[
q_{tot} = \frac{T_{DM} - T_{Room}}{\frac{d_c}{k_c} + \frac{d_l}{k_l}} = \frac{T_{DM} - T_{Room}}{R_{tot}}
\]  

(1)
Where $q_{\text{tot}}$ is the total heat flux through the concrete and insulation composite layer (W/m$^2$), $T_{\text{DM}}$ is the temperature measured on top of the drainage mat that overlies the insulation layer ($^\circ$C), $T_{\text{Room}}$ is the temperature measured on the bottom surface of the concrete layer which is the ceiling of the room beneath the roof ($^\circ$C), $k_c$ is the thermal conductivity of the concrete layer (W/m$\cdot$°C), $k_i$ is the thermal conductivity of the insulation layer (W/m$\cdot$°C), and $R_{\text{tot}}$ is the thermal resistance of the concrete and insulation composite layer (m$^2$\cdot°C/W). Negative and positive heat flux represented heat loss (out of building interior) and heat gain (into building interior), respectively. The hourly heat gains and losses were computed each month and were converted to cumulative monthly values. The reduction of total heat exchange by the green roof was computed for each month to define the thermal performance of the green roof. To understand how effective each roof assembly was at mitigating heat transfer throughout 2016 and 2017, cumulative monthly heat exchanges were evaluated based on hourly variations of ambient temperature, roof temperatures, rain precipitation, and ground snow cover data. It should be noted that daily rain precipitation and daily ground snow cover depth data were obtained from the Environment and Climate Change Canada weather station located at the Ottawa International Airport, which is approximately 6.5 km from Carleton University.

3.0 Results and Discussion

3.1 Heat Exchange

The roof temperatures, hourly heat fluxes, and precipitation data over 2016 and 2017 are presented in figure 2, followed by figure 3, which shows the cumulative monthly heat gains and losses across both roofs during 2016 and 2017. Note that negative and positive values indicate heat loss and gain, respectively. Following figure 3 is table 1, which presents the monthly performance of the green roof in terms of total heat exchange reduction relative to the conventional roof, monthly ambient temperature averages and extremes, cumulative monthly solar radiation, cumulative monthly rainfall, and monthly average snow depth.

![Figure 2](image-url)  
*Figure 2 – Primary vertical axis: green roof (GR) and conventional roof (CR) hourly heat flux; exterior thermocouple temperatures measured beneath the drainage mat of each roof. Secondary vertical axis: snow cover (cm) and rain precipitation (mm)*
Figure 3 – Cumulative monthly heat exchange through green and conventional roof assemblies during 2016 and 2017

Table 1 – Monthly Green Roof Thermal Performance and Relevant Climate Parameters

| Season | Month-Year | Monthly Heat Exchange Reduction (%) | Total Shortwave Radiation (MJ/m²) | Ambient Min (°C) | Average Temperature (°C) | Max (°C) | Total Rainfall (mm) | Average Snow Cover (cm) |
|--------|------------|-------------------------------------|-----------------------------------|------------------|-------------------------|---------|-------------------|-----------------------|
| Winter | Jan-2016   | 33.0                                | 3.0                               | -15.6            | -6.4                    | 3.1     | 20.2              | 18.3                  |
|        | Feb-2016   | 20.0                                | 5.2                               | -23.1            | -6.7                    | 4.3     | 30.6              | 22.5                  |
|        | Mar-2016   | 13.8                                | 8.8                               | -13.9            | 0.4                     | 9.5     | 64.2              | 15.6                  |
| Spring | Apr-2016   | 24.7                                | 13.4                              | -5.9             | 5.2                     | 15.1    | 20.0              | 10.0                  |
|        | May-2016   | 45.1                                | 15.9                              | 6.8              | 16.2                    | 25.1    | 26.2              | 0.0                   |
|        | Jun-2016   | 52.3                                | 16.4                              | 12.0             | 20.5                    | 27.0    | 66.2              | 0.0                   |
| Summer | Jul-2016   | 62.4                                | 15.8                              | 17.3             | 23.1                    | 27.6    | 57.2              | 0.0                   |
|        | Aug-2016   | 55.7                                | 13.5                              | 18.0             | 23.6                    | 29.0    | 91.6              | 0.0                   |
|        | Sep-2016   | 43.4                                | 10.3                              | 12.2             | 18.4                    | 24.2    | 38.8              | 0.0                   |
| Fall   | Oct-2016   | 13.1                                | 5.4                               | 0.8              | 10.1                    | 17.7    | 96.8              | 1.0                   |
|        | Nov-2016   | 12.7                                | 3.2                               | -2.6             | 4.2                     | 11.9    | 30.8              | 5.5                   |
|        | Dec-2016   | 13.4                                | 2.6                               | -18.7            | -4.2                    | 6.2     | 29.6              | 31.1                  |
| Winter | Jan-2017   | 19.2                                | 3.3                               | -14.7            | -4.3                    | 4.1     | 20.2              | 40.6                  |
|        | Feb-2017   | 15.9                                | 5.0                               | -13.6            | -3.9                    | 6.8     | 24.8              | 41.6                  |
|        | Mar-2017   | 15.8                                | 8.2                               | -15.7            | -3.8                    | 5.2     | 50.4              | 11.6                  |
| Spring | Apr-2017   | 22.5                                | 9.4                               | 2.6              | 8.4                     | 18.4    | 147.6             | 0.9                   |
|        | May-2017   | 31.0                                | 11.5                              | 3.1              | 13.5                    | 25.5    | 176.8             | 0.0                   |
|        | Jun-2017   | 56.4                                | 14.0                              | 11.9             | 19.3                    | 28.4    | 130.0             | 0.0                   |
3.1.1 Heat Exchange in the Winter Season
As reported in table 1, the percent benefit in heat exchange reduction by the green roof during the winter season ranged from 13.8% to 33.0% over 2016 and 2017. The greater percent benefit of the green roof during the winter can be largely attributed to the presence of the growth substrate and additional snow accumulation relative to the conventional roof, which caused the outside boundary temperature (measured above the drainage mat) to stabilize around 1°C. This result demonstrates the insulative capacity of the growth substrate and accumulated snow cover against cold ambient temperatures and is consistent with [9]. Note that the measured temperatures and corresponding heat flux are reported in figure 4. In the absence of a growth substrate, the conventional roof drainage mat temperature fluctuated in response to ambient temperatures, resulting in more heat loss across the conventional roof during the winter seasons in both years. In March of 2016 and 2017, drainage mat temperatures on the conventional roof did exceed the room temperature periodically as snow on the roof melted, allowing for earlier heat gain across the conventional roof. However, on the green roof, the thermal resistance of the growth substrate and absorption of solar radiation by the vegetation still promoted a percent benefit in heat exchange reduction compared to the conventional roof. Note the percent benefits during the winter season are consistent with [10].

3.1.2 Heat Exchange in the Spring Season
As reported in table 1, the percent benefit in heat exchange reduction by the green roof during the spring season was greater than that observed during the winter season and ranged from 22.5% to 56.4% over 2016 and 2017. During the beginning of the spring season, the stabilization of the drainage mat temperature at 1°C on the green roof only occurred intermittently, increasing with ambient temperature as the season progressed, whereas no temperature stabilization was observed by the drainage mat temperature on the conventional roof. With increasing ambient temperatures observed later into the spring season, drainage mat temperatures on both roofs were more responsive to ambient temperatures, though the amplitude of fluctuation observed across the conventional roof was greater during mid-day solar radiation and during cooler ambient temperatures observed at night, due to the absence of growth substrate and vegetation layer. Compared to [10], green roof performance is 23% less on average, though conventional roof temperatures in [10] exceed 60°C by early April because the exterior thermocouple was only shielded by a thin roofing membrane.

3.1.3 Heat Exchange in the Summer Season
As reported in table 1, the percent benefit in heat exchange reduction by the green roof during the summer season was greatest across all seasons, ranging from 43.4% to 62.8%. Note, also, that the amounts of cumulative monthly heat exchange across both roofs were lowest during the summer, as shown in figure 2. During the summer, drainage mat temperatures on both roofs fluctuated both above and below room temperatures, but note that on numerous days, the entire range of fluctuation was above the respective room temperature. This effect caused continuous heat gain across multiple days. Nevertheless, the green roof resulted in less heat gain across the summer, as drainage mat temperatures on the conventional roof...
far exceeded room temperature during mid-day peak solar radiation due to the absence of substrate and additional cooling via evapotranspiration promoted by the green roof. Toward the end of the summer, when ambient temperatures became cooler, the opposite trend in drainage mat temperatures on both roofs was observed, where the entire range of drainage mat temperature fluctuation was below the respective room temperatures, causing continuous heat loss. In comparison, the summer green roof heat exchange percent reduction reported in [10] was consistently upwards of 85%, though the absence of gravel aggregate on the conventional roof studied in [10] may have promoted a greater thermal benefit by the adjacent green roofs compared to the experimental setup used in this paper. Furthermore, a relatively high albedo growing medium was used in one green roof system studied in [10], which was found to reduce heat flow in summer by an additional 3% compared to the darker growing medium used in the adjacent green roof.

3.1.4 Heat Exchange in the Fall Season
As reported in table 1, the percent benefit in heat exchange reduction by the green roof during the fall season was smallest across all seasons for both years, ranging from 7.7% to 18.9%. Notably, the first half of the fall season during both years exhibited lesser amounts of snow accumulation compared to the second half of November through December. As such, drainage mat temperatures on both roofs fell below room temperature in response to colder ambient temperatures, though drainage mat temperatures measured on the green roof remained above 0°C despite subfreezing ambient temperatures, unlike on the conventional roof. Lower incident solar radiation appeared to dampen the amplitude drainage mat temperature fluctuation on the conventional roof during mid-day in the first half of the fall season, inhibiting heat gain on most days. Similar to the behaviour observed during the winter season, significant snow accumulation toward the end of the fall season caused the green roof drainage mat temperature to stabilize at 1°C while no stabilization was observed on the conventional roof. Percent reduction of heat exchange in fall reported in [10] was much greater, especially in October; on average, heat exchange was reduced by 46% during the fall in [10].

4.0 Conclusion
In this paper, we assessed the comparative performance of a green roof relative to that of a conventional roof under temperate climate conditions over two years. The comparative performance of the green roof across the seasons was heavily dependent on the seasonal variability of ambient temperature, solar radiation, and snow cover. The green roof promotes the greatest percentage reduction in heat exchange during the hotter months of the year, presumably when solar radiation is intercepted by the plant canopy, as well as absorbed by the soil layer and released via evapotranspiration. During the colder months of the year, when vegetation growth was at a minimum or covered in snow, the comparative performance of the green roof was substantially reduced. Greater snow cover in winter tended to promote less heat loss through the conventional roof, and thus the relative reduction of heat exchange by the green roof was decreased under these conditions. By season, the average percent reductions in heat exchange by the green roof across the two years of analysis were as follows:

- 19.6% in winter (January 1 to March 31),
- 38.7% in spring (April 1 to June 30),
- 55.4% in summer (July 1 – September 30); and,
- 12.5% in fall (October 1 – December 31).
The analysis presented in this paper focused on quantifying the total heat exchange reduction by a green roof relative to that of a conventional roof using a simplified 1D steady-state heat transfer approach. However, this approach neglected the effects of heat energy storage within the roof assembly materials. To build on the research presented in this paper, a resistor-capacitor (RC) thermal model will be developed to account for the transient behaviour of heat storage and transfer through the green roof assembly, which will provide insight into how the thermal properties of the green roof vary throughout the seasons. By coupling the RC thermal model with a genetic algorithm, the thermal capacitance and thermal resistance of the soil layer, as well as the amount of latent heat dissipation by the vegetation, will be deduced. Once known, these properties will be applied to a building simulation tool to enhance the design and cost optimization of green roofs in temperate climates.

5.0 References

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