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Assessment of green roof performance for sustainable buildings under winter weather conditions

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Abstract: A green roof is a specialized roof system that supports vegetation growth on rooftops. This technology is rapidly gaining popularity as a sustainable design option for buildings. In order to contribute to an understanding of green roof in regions with cold winters and snow, an on-site experimental investigation was present with a focus on the assessment of green roof performance during the winter. This field experiment took place on a six small buildings during the winter of 2010−2011. The work monitored three buildings with green roofs, two buildings with reference roofs and one building with a bare soil coverage for the roof. These six buildings were identically constructed and instrumented with sensor networks to provide heat flux data through the roofs. The 15 min averaged data were statistically analyzed for a week under the two separate periods, first without a snow cover and second with a snow cover. The results show that the roof type is a significant factor in affecting the thermal performance of these buildings. Most importantly, green roofs reduce heat flow through the roof and thus reduce the heating energy demand during the winter. However, the energy savings for buildings with the green roofs are reduced under snow conditions because the snow diminishes thermal resistance of the roof and increases the heat transfer process through the roofs.

Key words: green roof; energy savings; building envelop; sustainable buildings

1 Introduction

Green roofs (or ecoroofs), a sustainable technology used in green buildings, are special roofing systems that include layers of vegetation and growing media. From bottom to top, a typical green roof consists of several layers: a regular roof resistance layer, drainage layer, soil layer (substrate with growing medium), and a vegetation layer.

Green roofs are becoming popular in sustainable building design due to potential energy savings, environmental benefits and building code requirements [1−2]. Green roofs can offer thermal protection, which may reduce the thermal load and energy demand applied to buildings. Green roofs also contribute to reduce storm water runoff, expand lifetime of roofing membranes, add aesthetic appeal, improve microclimate, reduce greenhouse gas emissions, and a reduction of the urban heat island effect in cities [3]. Vegetated surfaces show lower radiative temperatures than other hard surfaces with the same albedo [4−5]. The thermal benefits of green roofs result from both the soil layer and the planted vegetation layer. A wet soil layer can provide an additional insulation effect to the roof for the whole day, while a vegetated layer mainly provides sun protection during the daytime [6].

The green roof industry grew at a rate of 50% from 2001 to 2004 [7]. Heating, ventilation and air conditioning (HVAC) engineers are interested in the potential contributions of green roof to the energy savings in green buildings. Observing the heat transfer process from the indoor environment to the outdoors is a method that shows the thermal performance of green roof, because the heat loss through the building envelope contributes to the energy consumption of the building. Heat transfer through a roof is mainly in the form of conduction [8]. Heat transfer through roofs directly affects the cooling load and heating load calculations for the building, which is an important factor when evaluating the sustainability performance of the building.

For most areas in northern hemisphere, the winter season is quite cold with frequently snowy weather. Snow is a porous material consisting of ice grains that are connected by bonds, air-filled pore space, small amounts of impurities, and, in some cases, liquid water [9]. Snow layer tends to increase the mean annual ground temperatures [10−11] and snow layers on the roof play an important role in the heat transfer process from indoor environment to outside [12]. Since the snow layer on

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the roof may have either heating or cooling effect on the space below it [13], this could affect the green roof performance and indoor heating load during the winter.

Large amount of previous literatures have studied the performance of green roof during the summer season and reported that the green roof has a better performance than the reference roof due to energy-saving benefits [1, 14]. However, limited literatures have focused on the winter season, specifically related to the snow condition with regards to green roof performance, nor has the literature considered snow as a major factor while describing the winter performance conditions. In order to understand the annual performance of a green roof building, it is necessary to determine how the green roof affects the building performance during the winter season. Some researches studied this problem in locations with mild winter conditions [15], but the results may not hold true for the large areas with very cold winter and heavy snow conditions in North America.

One previous experimental research [12] studied the green roof performance in an area with a cold climate in winter, and indicated that the snow coverage has a strong influence on the heat flow through the roof system. It was also reported that when the snow layer was established on the roof, the heat flow through the green roof and the reference roof was almost the same. However, the author did not give many details to quantify and calculate the snow effects on the green roof performance. To fill this gap, this work is aimed to present an experimental investigation that focuses on the assessment of green roof performance during the winter, under conditions with and without a snow layer present on the building roofs.

2 Experimental site description and data

2.1 Description of experimental site

There are six 4.65 m^2 buildings for the on-site experiments. These buildings are located at the Russell E. Arson Research Center of the Pennsylvania State University near Rock Springs, PA, which is 24 km (15 miles) south of State College, PA, USA. The buildings have a 1.8 m×2.6 m×2.6 m footprint, and they are arranged in a 2×3 grid spaced 6 m apart. This separation helped to reduce the mutual effects between the buildings, which may result from the blocking of wind, rain and snow; this ensured independent indoor and outdoor environments for all of the buildings. In addition, this arrangement allowed for consistent exposure to the sun and weather elements. Among the six buildings, three of them were green roof buildings with both a vegetation layer and a soil layer (growth substrate); one building had a bare soil roof with only a soil layer and no vegetation layer; two buildings were reference roof buildings with neither a soil layer nor a vegetation layer beyond the original roofs. Each building had a water collection tank to measure the precipitation, which made them hydrologically independent. The door and windows were located on the north side of each building. There was a light roof slope (1/12) from the bottom edge of the roof to maximize the solar effectiveness for the buildings. An overview of the building arrangement is shown in Fig. 1.

Fig. 1 Facilities of green roof test site at Penn State University, PA, USA

All of the six buildings were built with identical insulation levels with identical heating devices and air conditioning systems. The heating device was a 1 kW thermostatically controlled standing heater leaned against the south wall, and a 3 kW air conditioning system which was installed in the window of north wall in each building.

The materials of the wall, in the order of inside to outside, are 6.35 mm plywood, 89 mm fiber glass batting insulation with a thermal resistance (*R*-value) of 2.3 (m^2·K)/W and 6.35 mm oriented strand board (OSB) sheets. The materials of the original roofs with the order from the inside to the outside are 6.35 mm OSB sheets, 89 mm fiber glass batting insulation, 19.05 mm plywood, and water proofing layer. The insulation in the walls and roofs of each building contained 89 mm fiberglass batting insulation with a thermal resistance of 2.3 (m^2·K)/W.

2.2 Green roof components used in experiment

The components of the green roof were identical for each green roof building. Beyond having the same original roof as the reference buildings, the green roof buildings had additional layers, in order from bottom to top, which included a drainage layer, a soil layer and a vegetation layer. The bare soil roof had the similar layer components except for the vegetation layer. Both the green roof and bare soil roof buildings had a treated lumber framework around the edge of the soil layer to protect and contain the medium. The depth of the soil layer was around 90 mm.

The vegetation used was Sedum spurium which is commonly used for extensive green roofs. The height of the vegetation layer was from about 12.7 mm to 19 mm. The substrate was a mixture of sphagnum peat moss, coir (coconut fiber), perlite and hydrolite.

2.3 Data acquisition system

In addition to the six buildings stated above, there was another building where the control computer and data acquisition system were located. The data collected in the experiments can be divided into two parts. The first part was the local meteorology data collected by a weather station, which was located on the northeast corner of the control building roof. The collected meteorology data included relative humidity, rain fall, solar radiation, temperature, wind direction, wind gust, and wind speed. The data were collected every 30 s and averaged every 15 min.

The second part was the parameters related to the operation of the buildings which included temperature data and heat flux through the roofs. Different kinds of sensors were used to measure these parameters, and the variances were translated into electronic signals and sent to the two dataloggers which were connected to the computer in the control building.

Temperature sensors were used to measure the temperature for each layer of the roof systems during the experiment. The positions of the sensors were identical in each building, but the quantities of sensors were different for the different types of buildings. This is because of the differences in the roof systems. The sensors were arranged in a vertical line if there were more than one sensor in the same position. One heat flux meter with the size of 114.3 mm×114.3 mm×3.175 mm was installed on the inside part of the roof system for each building. The heat flux sensor measured the heat flux through the whole roof system. The sensors were calibrated so when the heat flux was positive, it meant that the heat was coming from outside environment into the building. The negative heat flux meant that the building was losing heat from the inside environment to the outside. The collected data was averaged every 15 min.

3 Method

The major method of this work was to conduct a field experiment and quantify the differences of thermal performance between the green roof and the reference roof. The experiment process lasted for the whole winter season from November 2010 to February 2011.

The measured heat flux data were used to evaluate the building performance as an indicator of energy loss from the buildings. This is because one of the factors that cause energy losses in buildings is the heat transfer from the warm inside air to the outside air through the roofs. As stated above, the snow layer on the roofs could have either cooling or heating effects on the space below, thereby affecting the *R*-value of the whole roof system and the heat transfer process through the roof. Therefore, in order to better describe the winter conditions, this work divided the measured data into two types of periods: days with a snow layer on the top of the roofs and days without a snow layer on the roofs. The analysis of the results was done for the two different conditions separately in order to make a comparison. Since the snow precipitation was limited during the experimental winter, only one continuous week could be used as the observed period with the accumulated snow layer on the roofs. Also, this period included a transition from fresh snow fall to melted snow. For better comparison, another week with no snow precipitation or accumulated snow layer was considered as the no snow period.

In addition, this work made some assumptions to simplify this problem. We considered one-dimensional heat transfer through the roof systems. The thermal storage of the plants and the soil layer was neglected by assuming a quasi-steady-state heat transfer process. Since the buildings were built with an identical structure and equipment, the indoor and outdoor conditions for the buildings were taken to be identical and it was assumed that they did not cause differences to the measured results.

The goal of the analysis was to figure out whether the roof type affects the energy loss through the roof and also to compare the energy loss between the three types of identical buildings. The following hypotheses for the study were developed under conditions when the roofs had, and did not have, the snow layer:

Null Hypothesis 1: The energy loss through the roof of the green roof building is not significantly different ($p>0.05$) from that of the reference roof building in the heating season.

Alternative Hypothesis 1: The energy loss through the roof of the green roof building is significantly different ($p<0.05$) from that of reference roof building in the heating season.

Null Hypothesis 2: The energy loss through the roof of the reference roof building is not significantly different ($p>0.05$) from that of the bare soil roof building in the heating season.

Alternative Hypothesis 2: The energy loss through the roof of the reference roof building is significantly different ($p<0.05$) from that of the bare soil roof building in the heating season.

Null Hypothesis 3: The energy loss through the roof of the bare soil building is not significantly different ($p>0.05$) from that of the green roof building in the heating season.

Alternative Hypothesis 3: The energy loss through the roof of the bare soil building is significantly different (P<0.05) from that of the green roof building in the heating season.

To support these hypotheses, the measured heat flux data were examined for the following two periods:

1) From 12/31/2010 to 01/06/2011 as the observed week with no snow on the rooftop,

2) From 02/21/2011 to 02/27/2011 as the observed week with snow on the rooftop.

By adapting the analysis, each building was regarded as a block to eliminate the effects caused by the differences between the buildings. Time was the measured interval (15 min) and considered as a random factor. The main analysis was done by the R Project for Statistical Computing.

4 Results and discussion

4.1 Statistical results and analysis under no snow condition

Tables 1−3 present the results from ANOVA for the observed week under no snow condition, indicating the hypothesis stated above, separately. The results suggest that the experimental procedure was adequate and no unintended factors were present.

The results from all of the three tables suggest that, as expected, the p-value for the roof type is much smaller than 0.05, indicating that the null hypothesizes are wrong and the alternative hypothesizes are supported. Therefore, the energy performances of the three kinds of buildings were different from each other when there was no accumulated snow on the roofs. However, it needs to be noted that because there was only one bare soil roof building among the six buildings, the results related to the bare soil building may be relatively susceptible to outlier conditions, as compared to other results, although the original data measured and analyzed were large in quantity.

Table 1 Results from ANOVA for green roof building and reference roof building under no snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	359.6	359.62	62.097 9	4.424×10^{-15}
Building	3	2 684.6	894.86	154.520 1	$<2.2\times10^{-16}$
Time	95	668.7	7.04	1.2154	0.07888
Error	3 245	18 792.5	5.79	—	—
Total	3 344	22 505.4	—	—	—

Table 2 Results from ANOVA for bare soil roof building and reference roof building under no snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	37.0	36.962	13.160 2	0.000 293 5
Building	1	204.1	204.089	72.664 8	$<2.2\times10^{-16}$
Time	95	776.6	8.174	2.910 5	$<2.2\times10^{-16}$
Error	1 909	5 361.7	2.809	—	—
Total	2 006	6 379.4	—	—	—

Table 3 Results from ANOVA for bare soil roof building and green roof building under no snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	37.0	36.962	13.160 2	0.000 293 5
Building	1	204.1	204.089	72.664 8	$<2.2\times10^{-16}$
Time	95	776.6	8.174	2.9105	$<2.2\times10^{-16}$
Error	1 909	5 361.7	2.809	—	—
Total	2 006	6 379.4	—	—	—

4.2 Statistical results and analysis under snow condition

Tables 4−6 present the results from ANOVA for the observed week under snow condition, indicating the hypothesis stated above, separately.

Table 4 Results from ANOVA for green roof building and reference roof building under snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	20.4	20.444	11.450 6	0.000 723 2
Building	3	600.9	200.315	112.193 2	$<2.2\times10^{-16}$
Time	95	200.5	2.110	1.181 8	0.112 930 6
Error	3 260	5 820.5	1.785	—	—
Total	3 359	6 642.3	—	—	—

Table 5 Results from ANOVA for bare soil roof building and reference roof building under snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	6.4	6.411	3.870 6	0.049 28
Building	1	232.5	232.450	140.337 5	$<2.2\times10^{-16}$
Time	95	285.9	3.009	1.816 9	4.33×10^{-16}
Error	1 918	3 176.9	1.656	—	—
Total	2 015	3 701.7	—	—	—

Table 6 Results from ANOVA for bare soil roof building and green roof building under snow condition

Source	DF	Sum Sq.	Mean Sq.	F	P
Roof type	1	37.0	36.962	13.160 2	0.000 293 5
Building	1	204.1	204.089	72.664 8	$<2.2\times10^{-16}$
Time	95	776.6	8.174	2.910 5	$<2.2\times10^{-16}$
Error	1 909	5 361.7	2.809	—	—
Total	2 006	6 379.4	—	—	—

Similar to the observed week without snow, the tables indicate that the roof type is a significant factor, affecting the heat flux through the roof systems. However, it needs to be mentioned that, when comparing the bare soil roof building and the reference roof building, the p-value is quite close to 0.05 (with the value of 0.049 28), which means that it is very close to a value that would reject the null hypothesis. In this case, the heat flux difference between the bare soil roof building and the reference building was not obvious, as compared to other calculated results. This may be due to the fact that the snow layer on the top of the roof affected the heating transfer process and reduced the differences between the bare soil roof building and the reference roof building during the observed period.

4.3 Comparison results of mean heat flux

The statistical results have proved that different kinds of roofs caused different values of energy loss through the roof system. The next step is to figure out how large the difference is by comparing the mean heat flux. Therefore, for each kind of building, the results were analyzed using a One Sample T-test based on the Minitab R15 statistical software package to calculate the mean value of heat flux and 95% confidence interval. Figure 2 and Figure 3 show the comparison of the results bars.

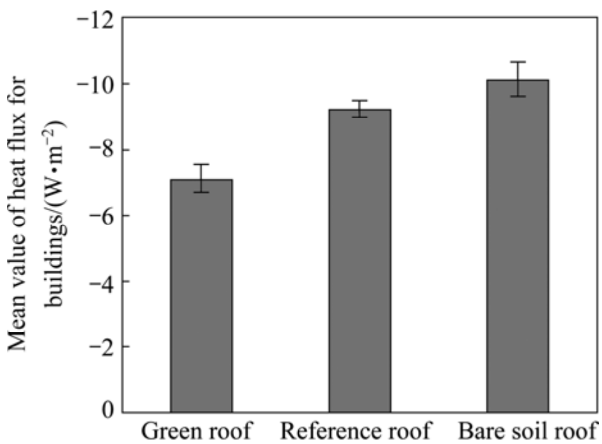

Fig. 2 Mean heat flux under no snow conditions, shown with individual 95% confidence interval bars

Figure 2 shows the results under the condition that there is no snow layer on the roofs. It can be seen that the green roof building had the lowest mean heat flux during this observed week, while the bare soil roof building had the highest and the reference building had the heat flux in between. According to Fig. 3, the green roof building also had the lowest mean heat flux during the period when there was a snow layer on the roofs. However, the reference roof building became the one with the highest

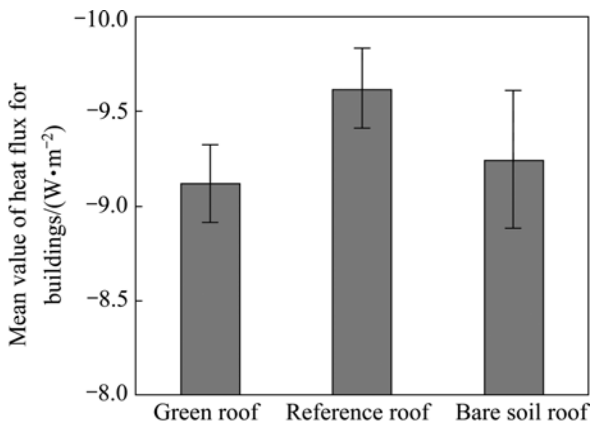

Fig. 3 Mean heat flux under snow conditions, shown with individual 95% confidence interval bars

mean heat flux. The two figures indicate that, during the heating season, no matter if there was a snow layer on the roofs, the green roof buildings had the least energy loss through the roofs as compared to the other two types of buildings. This means that energy savings can be achieved with the addition of a green roof to the buildings.

4.4 Comparison of energy savings by green roof buildings

In order to further compare the performance of the green roof buildings and the reference roof building, Table 7 gives the energy savings during the two observed periods. It can be seen that, compared to the reference roof buildings, the green roof buildings saved energy as much as 22.9% when there was no snow layer on the roofs. However, the presence of snow reduced these energy savings to 5.2%. The results agree with the previous findings that the green roofs reduce the heat flow in the winter by 10%−30% [3]. The results also indicate that the snow layer could have affected the green roof performance as expected. The possible explanation for the results could be as follows:

1) The green roofs and the reference roofs have different surface albedo and emissivity which affect the solar radiation and long-wave radiation to the roof surface. The existence of the snow layer on the top of roofs diminishes this roof difference and reduces energy savings of the green roof.

2) The snow layer results in the freezing of the growing medium and reduces its insulation value.

It should be noted that this energy saving calculation was only based on the heat flow through the roof systems because the buildings were identical. The energy savings for the whole sustainable building in real-life practice also depend on many other factors, such as the efficiency of heating/cooling equipment and other parts of building envelope.

Table 7 Energy savings of green roof building under different conditions during winter

Condition	Mean heat flux of building/ ($W \cdot m^{-2}$)		Energy saving/%
	Green roof	Reference roof	
No snow layer	−7.12	−9.23	22.9
With snow layer	−9.12	−9.62	5.2

4 Conclusions

1) The results show that all calculated p-values are less than 0.05 and the hypotheses are rejected, indicating that the roof type is a significant factor to affect the heat loss through the roof from the building indoor environment.

2) The comparison of mean heat flux shows that the green roof buildings have the least heat loss among the three types of buildings, regardless of the accumulated snow layer.

3) The green roof buildings save as much as 22.9% of the heating energy as compared with the energy used by the reference roof buildings when there is no snow on the roofs. Despite this result, energy savings decrease to 5.2% when the snow layer is present. This may be due to the fact that the existence of the snow layer assimilates the surface differences between the green roofs and reference roofs. The snow layer affects the R-value of the whole roof system and the heat transfer process through the roofs, thereby reducing the thermal performance of the green roof. However, in principle, the green roof buildings still have a different energy performance pattern as compared to the reference roof buildings.

References

[1] SAILOR D J. Thermal property measurements for ecoroof soils common in the western US [J]. Energy and Buildings, 2008, 40(7): 1246−1251.

[2] TABARES-VELASCO P C, SREBRIC J. The role of plants in the reduction of heat flux through green roofs: Laboratory experiments [C]// ASHRAE Transactions, 2009: 1−8.

[3] LIU K K Y, BASKARAN B A. Thermal performance of extensive green roofs in cold climates [C]// 2005 World Sustainable Building Conference. Tokyo, Japan, 2005: 1−8.

[4] WILMERS F. Effects of vegetation on urban climate and buildings [J]. Energy and Buildings, 1990, 15(3/4): 507−514.

[5] LIU K K Y, BASKARAN B A. Green roof infrastructure-technology demonstration, monitoring and market expansion project [R]. Institute for Research in Construction, B1054.1, 2004.

[6] WONG N. Investigation of thermal benefits of rooftop garden in the tropical environment [J]. Building and Environment, 2003, 38(2): 261−270.

[7] MILLER C, NAREJO D. State of the green roof industry in the united states [M]. Geo-Frontiers, 2005: 4057−4064.

[8] PITA. Air conditioning principles and systems [M]. Upper Saddle River, New Jersey: Pearson Education, Inc. 2002: 47−55.

[9] KAEMPFER T U. Phase-field modeling of dry snow metamorphism [J]. Physical Review E, Statistical, Nonlinear, and Soft Matter Physics, 2009, 79(3): 031502−031502.

[10] GOLD L W. Influence of the snow cover on the average annual ground temperature at Ottawa, Canada [J]. International Association of Scientific Hydrology, 1963, 61: 82−91.

[11] GOODRICH L E. Influence of snow cover on the ground thermal regime [J]. Canadian Geotechnical Journal, 1982, 19(4): 421−432.

[12] LIU K K Y. Energy efficiency and environmental benefits of rooftop gardens [R]. Ottawa: National Council of Canada, 2002.

[13] ZHANG T. Influence of the seasonal snow cover on the ground thermal regime: An overview [J]. Reviews of Geophysics, 2005, 43(4): 23−23.

[14] TABARES-VELASCO P C, SREBRIC J. Experimental quantification of heat and mass transfer process through vegetated roof samples in a new laboratory setup [J]. International Journal of Heat and Mass Transfer, 2011, 54(25/26): 5149−5162.

[15] SANTAMOURIS M. Investigating and analyzing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece [J]. Energy, 2007, 32(9): 1781−1788.

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