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Performance monitoring of three ecoroofs in Portland, Oregon

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Abstract Ecoroofs, also known as green roofs, are becoming widely installed with relatively little data collected on their in situ performance. For this study, three large ecoroof portions (280–500 m^2) located on two different buildings in Portland, OR, USA were instrumented and monitored continuously for more almost 3 years. For the Broadway Building, a student dormitory on the campus of Portland State University, measurement of ecoroof energy conservation and rainwater discharge abatement helped qualify the building for its Leadership in Energy and Environmental Design silver award. Using an electromagnetic flowmeter, stormwater discharge was monitored and compared to rainfall. Over a 3-year period, rainwater discharge was reduced by about 25%. Rooftop heat flux was simultaneously measured using an array of temperature sensors. When compared to a rock ballast roof exposed to the same weather conditions, the ecoroof heat flux was reduced by 13% in winter and 72% in summer. Retrofit ecoroof installations on the Multnomah County Building, an office building, were also monitored for almost 3 years for two separate ecoroof sections with different plantings, using similar electromagnetic flow meters and a rain gauge. Overall reductions of rainwater discharge were 12% and 17% for those two ecoroofs. For all three ecoroofs, discharge reductions varied widely by month due to seasonal differences in the amount of rainfall. Based on the measurements taken in this study, ecoroofs in Portland, OR, USA appear to offer some performance advantages.

Keywords Ecoroof · Monitoring · Stormwater · Energy

Introduction

Ecoroofs and green roofs are basically low maintenance gardens growing on the flat roofs of commercial and institutional buildings. The primary difference between ecoroofs and green roofs is that ecoroofs are designed to be self sufficient and self sustaining, requiring

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little to no maintenance or irrigation, while green roofs normally are more heavily managed. In each case, the building's conventional roof is covered with a waterproof layer, a drainage layer, soil, and plantings of grasses, shrubs, or flowers. Many advantages are offered by ecoroofs: Aesthetics—the garden-like appearance of the roof is appealing to occupants of spaces adjacent to or in neighboring, taller buildings. Environmental—rooftop plantings, much like park spaces in the city, offer havens for birds and insects, convert carbon dioxide to oxygen, and reduce the "heat island" effect of massive horizontal reflective surfaces. Storm Water Control—during rain, the plants use water and the soil absorbs water, reducing or delaying storm water discharge. Building Energy—added layers of soil and plants insulate the roof, coupled with evapotranspiration, combine to reduce heat transmission through the building roof.

Portland, OR, USA is a city long known for its attention to environmental quality and sustainability. Ecoroofs are being installed on many new and existing buildings as demonstration and test sites, as well as drawing public awareness. In 2004, Multnomah County installed an 1,000 m^2 ecoroof on an inner-city office building, the Multnomah County Building. Incorporating both demonstration and research, the county sought assistance in evaluating the ecoroof performance from Portland State University (PSU). A program was developed to utilize students and faculty to design and install monitoring equipment, and to collect data measuring the ecoroof's effect on reducing stormwater discharge.

Portland State University also installed an 1,800 m^2 ecoroof on a newly constructed student dormitory, the Broadway Building. As a demonstration of ecoroof technology, this project was designed to attract a broad base of public interest. University administration, governmental agencies, real estate developers, and students all showed great interest and enthusiasm in having a working ecoroof on campus. As the project developed, the campus sustainability coordinator expressed a desire to have a better understanding of the ecoroof's performance when compared to that of other buildings with conventional rock ballast roofs. Specifically, the questions posed were these: Does the ecoroof reduce stormwater runoff? Does the ecoroof reduce rooftop heat transmission? To help answer these questions, PSU faculty and students were brought into the project to develop a performance monitoring system that measured and compared the new ecoroof to a conventional roof.

Heat transmission through ecoroofs has been studied several times before, through experiments and through simulation. Experimental studies have included both field studies on working buildings (Niachou et al. 2001; Onmura et al. 2001; Sonne 2006; Tan et al. 2003) and laboratory or special test buildings (Liu and Baskaran 2003; Takakura et al. 2000). Computer simulations have also been developed to predict ecoroof performance (Barrio 1998; Niachou et al. 2001; Takakura et al. 2000). Experiments, in general, have used relatively short durations of data collection, typically less than 2 months. One study (Liu and Baskaran 2003), though, reported results for 2 years of continuous monitoring, but on test structures rather than an operating building. All studies, both experimental and simulation, have reported that ecoroofs reduce the heat transmission when compared to conventional roofs. The amount of energy reduction varies from a few percent to over 90%, indicating that performance depends on several factors, such as soil type, plant type, soil moisture, local climate, and season.

Similarly, others have studied stormwater discharge from ecoroofs, both using modeling (Graham and Kim 2003) and by measurements (Hunt et al. 2004; Hutchinson et al. 2003; Liu and Minor 2005). Wide varieties of experimental techniques have been employed, but all essentially compare the rainfall to runoff through the drain from the ecoroof. Reported results range from 100% retention of rainwater for isolated rain events on dry ecoroofs to just a few percent usage for heavy rain events on previously saturated ecoroofs.

Given that such a wide range of ecoroof performance had been reported in the literature and that so many factors affected the performance, the objective of this project was to measure how full-scale ecoroofs perform in the mild but relatively wet climate of Portland, OR, USA.

Materials and methods

The monitored ecoroofs were located in downtown Portland, OR, USA. Portland is characterized by a mild climate with moderate rainfall in winter and low rainfall in summer. Average annual rainfall in Portland, Oregon is 94 cm. The mean winter temperature is about 4°C while the mean summer temperature is 20°C, with an annual average temperature of 12°C.

The Multnomah County Building, an office building, had an ecoroof added to its plaza level as a retrofit installation. Because of the retrofit, access to storm drains was severely limited and some creative design work was required to satisfy both limited space available and city code officials who were reluctant to approve any modifications that might jeopardize the integrity of the original drain system. Two separate flow monitoring systems were eventually installed, which allowed for separate monitoring of two different sections of the ecoroof, the North and the South. Both ecoroof sections had identical soil with 10–15 cm depth but different plantings as listed in Table 1. Due to original drainage contouring that significantly affected local heat transfer, no reasonable method for monitoring ecoroof heat flux was available for the Multnomah County Building.

The third ecoroof monitored was located on the Broadway Building, a student dormitory on the Portland State University campus. This ecoroof was installed as part of the original construction and covered 1,800 m^2; about 500 m^2 of that total area was monitored. The roof itself was flat and made of 20 cm thick reinforced concrete. Rooftop contouring to central storm drains was supplied with wedges of rigid foam, which also provided thermal insulation. A waterproof layer was laid over the contoured roof and then covered with a drainage pad which allowed water that seeped through the ecoroof to run down to the storm drains. A lightweight soil layer about 15 cm thick overlaid the drainage layer. Plantings included grass (blue fescue) and succulents (sedums and periwinkles). Because of the installation of monitoring equipment during building construction, both stormwater discharge and roof top heat flux were measured for the Broadway Building.

Stormwater runoff monitoring for all three ecoroofs basically used the same system: Rainfall was measured with tipping bucket rain gauges connected to an internet feed. Rainfall was accumulated over a prescribed time interval and recorded with a time and date stamp, representing the average rainfall for that time period. Both 15-min and 1-h time

Table 1 Summary of three ecoroofs monitored

Building	Broadway building	Multnomah County north	Multnomah County south
Monitored ecoroof area (m^2)	500	290	280
Soil depth (cm)	15	10–15	10–15
Type of plants	Sedum, Bunchgrass	Wildflowers	Grass
Year planted	2004	2004	2004
Duration of test	01/05–present	10/04–present	10/04–present

intervals were tested. Since no significant long-term differences were detected between these two, results presented here are based on 1-h time intervals.

Stormwater flow through rooftop drains was measured with electromagnetic flowmeters located in the drain lines. Electromagnetic flowmeters require full flooding for operation, so drains were modified to locate each flowmeter in the bottom of a gooseneck arrangement with horizontal orientation to accommodate the previously mentioned space limitations. In addition, overflow piping was included to allow emergency diversion of drainage around the flowmeter if it were to plug or if the flow exceeded the hundred-year rain event. To enhance the low flow capability of the system, original 15 cm diameter drains were reduced to 3.8 cm diameter in the throat of the flowmeter. Flowmeter readout was logged on the building's existing direct digital control (DDC) system and subsequently converted to an Internet format for downloading and processing.

For rooftop heat flux measurement, a direct comparison of ecoroof performance to a conventional roof construction required installation of a section of control roof completely surrounded by ecoroof. The only difference between the two roof sections was the replacement of the ecoroof materials with rock ballast. The rock ballast layer was about 4 cm thick and comprised of 2.5 cm nominal diameter washed river rock. Careful location of the control roof assured the same thickness of the contoured insulating foam for both roof sections at the location chosen for heat transmission measurement, so that the roof baseline insulation (R-19) was identical at both test sites.

Heat transmission into or out of the conditioned space immediately beneath the roof resulted in a load on the heating, ventilation and air conditioning system, so that value was targeted for monitoring. While heat flux meters mounted directly to the bottom surface of the roof could sense heat transmission, the estimated signal level was very low and projected to exhibit unacceptably high uncertainty. Instead, temperature sensors were chosen for two main reasons: (1) Signal levels were high enough to provide good accuracy. (2) Temperature readouts, especially on the upper roof surface, provided a more tangible and intuitive measure of ecoroof behavior. Hence, resistance temperature detector (RTD) temperature sensors were located on the top and bottom surfaces of the roof, as illustrated in Fig. 1. Thin-film RTD elements imbedded in 1.0 mm thick thermal ribbon packages were mounted directly to the roof surfaces and minimally affected local heat transfer.

Measurement of heat transmission through temperature difference basically turned the roof into a heat flux meter according to $q = \left(T_{\mathrm{top}} - T_{\mathrm{bottom}}\right)/R$, where q is heat flux, T_{top} and T_{bottom} are the temperatures at the top and bottom of the roof, respectively, and R is thermal resistance. This approach has been previously used for ecoroofs (Sonne 2006; Tan et al. 2003) and was used in this study.

Results and discussion

Monitoring of the Multnomah County Building ecoroofs began in October, 2004, and has continued since. For the ecoroof on the Broadway Building, monitoring began in January, 2005, and has continued since. Use of electromagnetic flow meters for measurement of stormwater discharge proved to be very stable, with no problems of flow meter plugging or overflow. RTD temperature sensors have proven less reliable, as sustained exposure to moisture has caused some failures in the encapsulation. Periodic replacement has been necessary. Use of building DDC systems for data collection has also worked well, although intermittent problems or program changes initiated by building maintenance personnel has led to periods of missing data.

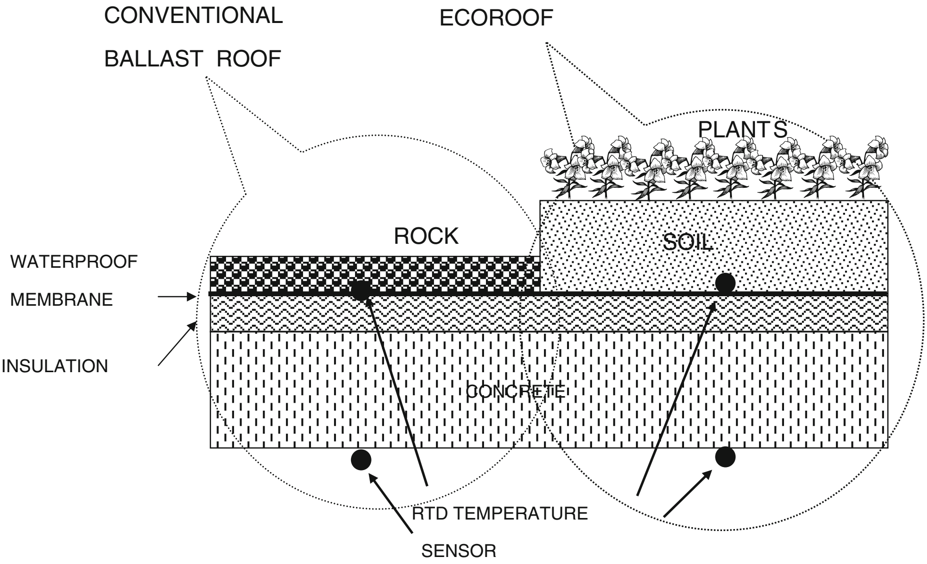

Fig. 1 Location of temperature sensors in ecoroof and control roof sections

Time histories of rainfall and drain discharge track closely, as can be seen for a specific 2-day event in Fig. 2. For this event, the discharge peaks occur about 1 h later than the rainfall peaks, indicating that time delay about 1 h between the two. Approximately 1 h of discharge delay was typical for all rain events. Peak values of rainfall and discharge are comparable and differences are within the range of experimental uncertainty. For this particular event, the total integrated discharge and rainfall were exactly the same, so zero overall retention rate was realized.

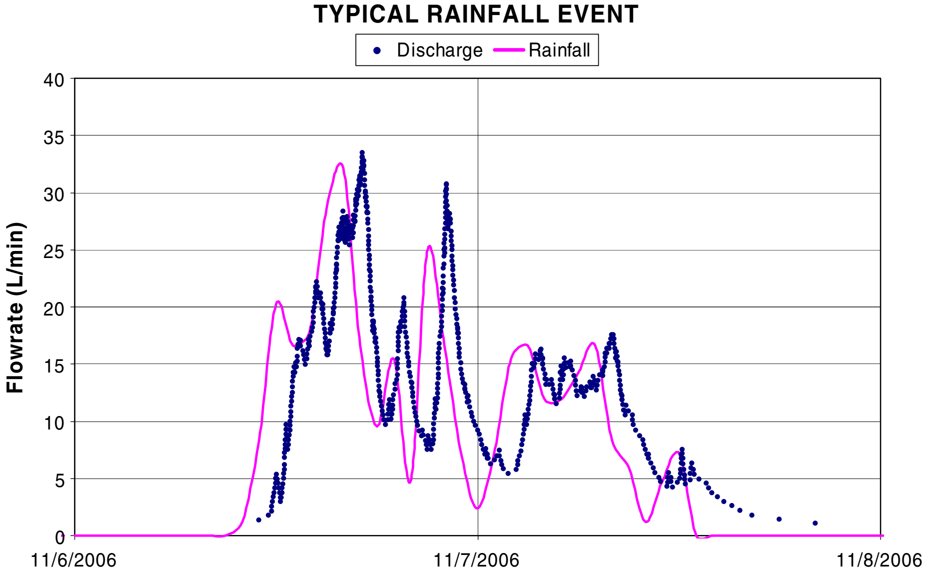

Fig. 2 Typical measured rainfall and discharge for a rainstorm event

In general, these monitored ecoroofs tend to retain more water, thereby reducing stormwater discharge more, when rainfall events happen to a dry ecoroof. Since that happens more often during summer than winter in Portland, OR, USA then, these ecoroofs' effectiveness in reducing stormwater discharge has been greater during summer than winter. A series of 20 rain events for the Multnomah County Building ecoroofs, selected for similar total rainfall, were compared for summer and winter. Retention rates for summer rain events ranged from 7% to 85%, with an average of 42%; those for winter rain events ranged from 0% to 52% with an average of 12%. These retention rates for rain events are somewhat lower than those reported elsewhere, which typically ranged from 78% to 85% for summer (Van Seters and Rocha 2007).

Similar to retention rates for specific events, the total monthly retention for all three monitored ecoroofs was lower in winter than in summer. Since most of Portland's rainfall occurs during winter, this result probably reflects more the effectiveness based on amount of rain rather than season. This effect is illustrated in Fig. 3, which plots the total monthly retention as a function of monthly rainfall. In spite of the data scatter, there is a clear trend that retention is higher during low rainfall months. Monthly retention rates for each ecoroof are provided in Table 2, along with the total for the entire test duration. Since winter rainfall was much greater, though, the total accumulated reduction was more heavily weighted toward winter performance. An additional factor that contributed to the overall results is irrigation. As can be seen for late summer on the Multnomah County Building, significant stormwater discharge was measured even though no rain fell on the ecoroof due to irrigation that was not fully being utilized by the plants. If irrigation were not employed, one would expect much higher retention for those summer months. However, no objective basis for deleting those data was identified in this study, and the discharge of unused

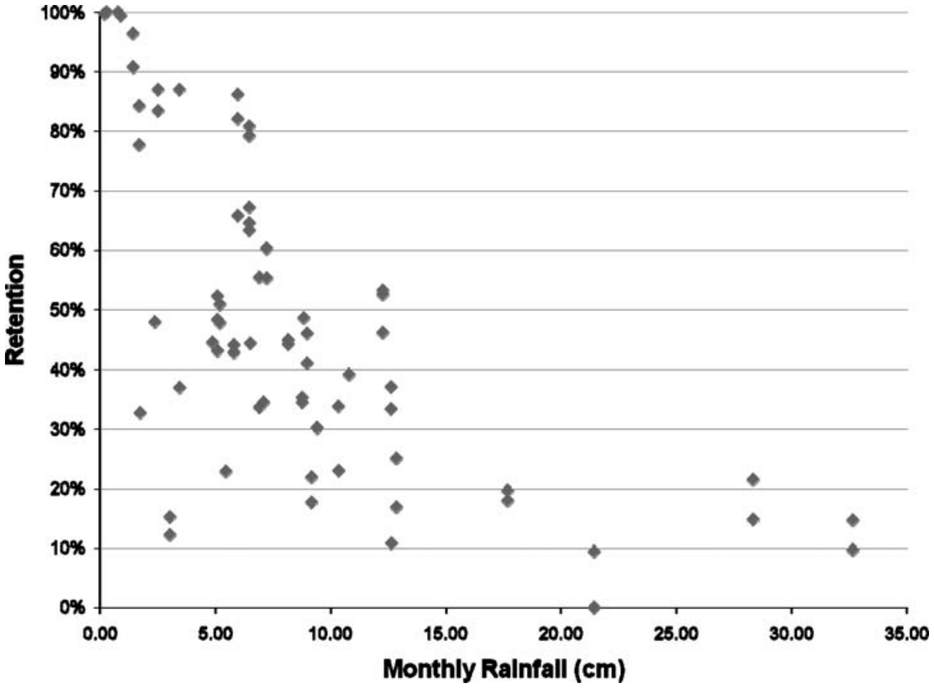

Fig. 3 Monthly ecoroof rainfall and discharge for ecoroofs

Table 2 Monthly and cumulative rainwater retention for ecoroofs

Year	Month	MCB north		MCB south		Broadway	
		Rain (cm)	Retention (%)	Rain (cm)	Retention (%)	Rain (cm)	Retention (%)
2004	October	9.0	46	9.0	41		
2004	November	5.8	44	5.8	43		
2004	December	9.2	22	9.2	18		
2005	January	5.1	43	5.1	48	5.1	52
2005	Feb	2.5	87	2.5	83	2.4	48
2005	Mar	8.2	0	8.2	0	10.3	23
2005	April	6.9	34	6.9	55	8.8	49
2005	May	12.3	52	12.3	53	12.3	46
2005	June	6.0	86	6.0	82	6.0	66
2005	July	0.8	32	0.8	35	0.8	10
2005	August	0.9	0	0.9	0	0.9	99
2005	September	4.9	0	4.9	0	4.9	44
2005	October	8.2	44	8.2	45	8.5	10
2005	November	12.9	17	12.9	25	12.9	0
2005	December	21.4	0	21.4	9	22.2	0
2006	January	28.4	15	28.4	21		
2006	February	5.2	51	5.2	48	5.5	23
2006	March	7.2	55	7.2	60	7.1	34
2006	April	6.5	65	6.5	63	6.5	67
2006	May	6.5	79	6.5	81	6.5	44
2006	June	1.7	84	1.7	78	1.7	33
2006	July	0.3	5	0.3	0	0.3	100
2006	August	0.2	0	0.2	0	0.2	100
2006	September	2.0	0	2.0	0		
2006	October	3.0	12	3.0	15		
2006	November	32.7	10	32.7	15		
2006	December	17.7	18	17.7	20		
2007	January	8.8	34	8.8	35	3.4	37
2007	February	12.6	33	12.6	37	12.6	11
2007	March	10.3	34	10.8	39		
2007	April	5.4	0	5.4	0		
2007	May					1.2	0
2007	June					1.9	0
2007	July					1.4	91
2007	August					1.4	96
2007	September					3.5	87
2007	October					9.4	30
Total		262.7	12	262.7	17	157.6	25

irrigation was a real effect for these ecoroofs. Hence, is included in the results reported here.

The retention rates for the three Portland ecoroofs monitored in this study were generally lower than those for other green roofs, as reported in the literature with a summary given in Table 3. No clear reason for this discrepancy arises. For the most part, all green roofs monitored appear to have similar soil composition and plantings. Those tests reporting just during summer months would be expected to display higher retention rates and that appears to be borne out. When more long-term monitoring studies are reported, perhaps overall

Table 3 Comparison of ecoroof stormwater retention

Average annual retention (%)	Building type	Location	Monitoring duration and time	Reference
29	Dormitory	Portland, OR, USA	20 months	This study
18	Offices	Portland, OR, USA	28 months	This study
69	Apartments	Portland, OR, USA	15 months	Hutchinson et al. 2003
49	Various	Sweden	July–Dec	Bengtssan 2005
75	Various	Germany	Various	Mentens et al. 2006
63–66	Test	Michigan	Sept–Oct	Rowe et al. 2003
16	Public Library	Vancouver, CD	8 months July-Feb	Johnston et al.2004
55	University Classroom	Toronto, CD	May–Nov	MacMillan 2004
57	Community Center	Toronto, CD	Full year	Liu and Minor 2005
57–87	Storage, Office	North Carolina	18 mo	Moran et al. 2005

retention rates for other ecoroofs will prove to be similar to those in this study. In the meantime, the relatively low retention of the ecoroofs monitored in this study is a real and true phenomenon and must be perceived as a likely performance for similarly constructed roofs.

Rooftop temperature was measured on the Broadway Building only, and the heat flux was calculated in to or out of the conditioned space beneath. The time history of the temperature for typical summer conditions is presented in Fig. 4. It is interesting to compare the temperature at the base of the rock ballast and the temperature beneath the ecoroof soil to the air temperature immediately above the roof. Due to shading from plants and insulating effect of the soil layer, the ecoroof temperature is moderated when compared to the air temperature. By contrast, radiant gain from sunlight in daytime and radiant losses at night yield much greater temperature swings for the conventional rock ballast roof. Heat

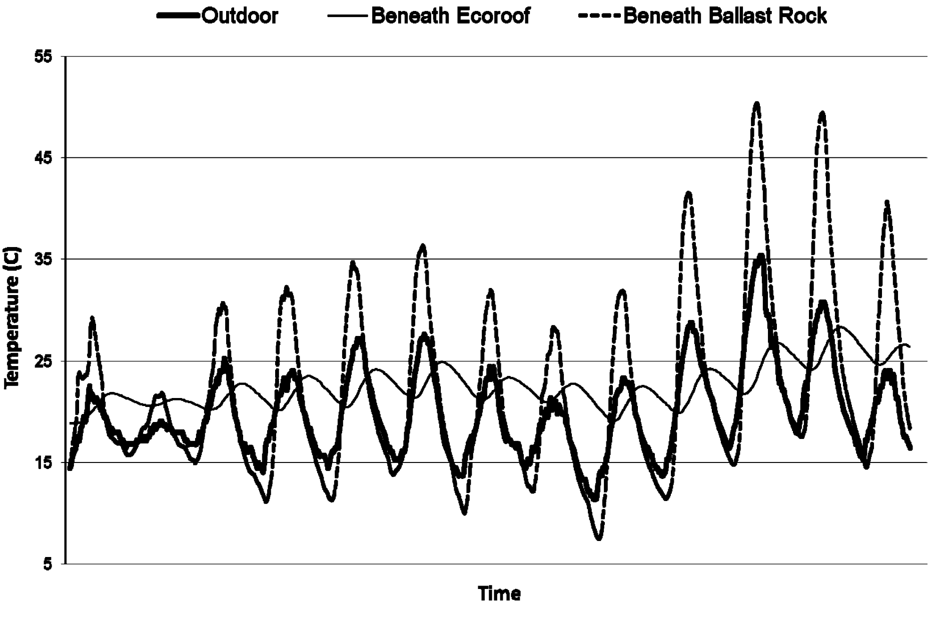

Fig. 4 Typical temperature histories for ecoroof and rock ballast roof

transfer into the conditioned space caused by those relatively high temperature peaks dramatically increases summer heat flux into the building that must subsequently be removed by mechanical cooling equipment. Also noteworthy is the timing of the temperature peaks, which are 4–6 h out of phase for the two roof types. This delay could be important during seasons when buildings need heating during night and cooling during daytime. Thermal energy absorbed during the day and conducted into the space at night would reduce the building heating load, and vice versa for daytime cooling. The potential savings allowed by this behavior was not explicitly included in this study.

When roof heat flux was integrated over an entire month, summer months and winter months show distinctly different results. These results are listed in Table 4 (in this table, heat flux with a positive sign is directed into the conditioned space while heat flux with a negative sign is directed out). Two significant results are readily apparent from Table 4: (1) average winter heat flux is five times as great as summer heat flux. (2) percent reduction of heat flux for the ecoroof is much larger in summer than winter. During the mild, dry summer in Portland, the ecoroof reduces roof heat flux by 72%, on average. These findings are similar to those of others (Liu and Minor 2005). Winter performance is much lower, with only an average of 13% reduction. This large difference is likely due to the facts that summer's dry soil is a better insulation and that the conventional roof does not warm up as much with less sunlight in winter. None-the-less, the absolute savings for summer and winter are comparable but Portland typically has ten times as many heating degree days and cooling degree days per year, so that the major energy benefit of ecoroofs in Portland happens during winter.

Conclusions

1. Ecoroofs can and should be monitored to assure anticipated performance:
    - The monitoring system developed and employed long-term for this project proved to be stable, robust, and automatic.
    - Performance may differ significantly, as was the case for this study, for projections based on other similar roofs in different locations and vendor claims.

Table 4 Comparison of ecoroof and conventional rock ballast roof heat transfer by season

Rooftop heat flux	Month	Year	Ecoroof	Conventional	Average	Average reduction (%)
			Average hourly heat flux (W/m2)			
Winter	Dec	2005	−3.73	−4.22	−3.74	13
	Jan	2006	−2.89	−3.39		
	Feb	2006	−3.35	−3.79		
	Jan	2007	−4.33	−4.92		
	Feb	2007	−3.12	−3.70		
Summer	Jul	2006	0.77	1.59	0.75	72
	Aug	2006	0.25	1.05		
	Jul	2007	0.59	1.56		
	Aug	2007	0.18	0.87		
	Sep	2007	0.06	0.56		

2. Stormwater retention for three ecoroofs in Portland, OR, was marginally effective:
    - Long-term, year-round performance yielded overall reduction of stormwater discharge between 12–25%. For combined stormwater-sewer treatment plants, like those of Portland, this represents a reasonable reduction in the effluent volume that must be treated.
    - For individual rain events, the stormwater reduction varied from a high of 85% during summer to a low of 0% for large winter rain events, with a time lag of about 1 h. Since effluent flow capacity must be sized to handle the worst case scenario, no system size reduction would be realized even for wide-spread adoption of ecoroofs of the type monitored.
3. Rooftop heat transfer is reduced by ecoroofs:
    - Winter heat loss of the ecoroof-covered buildings, which dominates building loads in Portland's climate, was reduced about 13% by the ecoroof. The result could be important for large, low buildings where roof heat loss contributes significantly to the total heating load.
    - Summer heat gain is significantly lower due to an ecoroof. Several factors could contribute to this measured difference: better insulation for dry soil, rooftop shading by plants, or evapotranspiration. Which of these contributes most was undiscovered in this study, but further work will focus on identifying and optimizing this advantage of ecoroofs.

References

Barrio EPD (1998) Analysis of green roofs cooling potential in buildings. Energy build 27:179–193

Bengtsson L (2005) Hydrological function of a thin extensive green roof in Southern Sweden. Nord hydrol 36(3):259–268

Graham P, Kim M (2003) Evaluating the stormwater management benefits of green roofs through water balance modeling. In Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago. Cardinal Group, Toronto

Hunt B, Moran A, Jennings G (2004) North Carolina green roof stormwater quantity and quality field evaluation. In Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Portland, OR, USA. Cardinal Group, Toronto

Hutchinson D, Abrams P, Retzlaff R, Liptan T (2003) Stormwater monitoring two ecoroofs Portland, Oregon, USA. In Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago. Cardinal Group, Toronto

Johnston C, McCreary K, Nelms C (2004) Vancouver Public Library green roof monitoring project. In Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Portland. Cardinal Group, Toronto

Liu K, Baskaran B (2003) Thermal performance of green roofs through field evaluation. In Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago. Cardinal Group, Toronto

Liu K, Minor J (2005) Performance evaluation of an extensive green roof. National Research Council of Canada, Ottawa, NRCC-48204

MacMillan G (2004) York University rooftop garden stormwater quantity and quality performance monitoring report. In Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Portland. Cardinal Group, Toronto

Mentens J, Raes D, Hermy M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century. Landsc Urban Plan 77(33):217–226, Elsevier Science

Moran A, Hunt B, Smith J (2005) Hydrologic and water quality performance from greenroofs in Goldsboro and Raleigh, North Carolina. In Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Washington, D.C. Cardinal Group, Toronto

Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G (2001) Analysis of the green roof thermal properties and investigation of its energy performance. Energy build 33(7):719–729

Onmura S, Matsumoto M, Hokoi S (2001) Study on evaporative cooling effect of roof lawn gardens. Energy build 33(7):653–666

Rowe DB, Rugh CL, VanWoert N, Monterusso MA, Russell DK (2003) Green roof slope, substrate depth, and vegetation influence runoff. In Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago. Cardinal Group, Toronto

Sonne J (2006) Evaluating green roof energy performance. ASHRAE J 48(2):59–61

Takakura T, Kitade S, Goto E (2000) Cooling effect of greenery cover over a building. Energy build 31(1):1–6

Tan PY, Wong NH, Chen Y, Ong CL, Sia A (2003) Thermal benefits of rooftop gardens in Singapore. In Proc. of 1st North American Green Roof Conference: Greening Rooftops For Sustainable Communities, Chicago. Cardinal Group, Toronto

Van Seters T, Rocha L (2007) Evaluating the runoff quantity and quality performance of an extensive green roof in Toronto, Ontario. In Proc. of 5th North American Green Roof Conference: Greening Rooftops For Sustainable Communities, Minneapolis. Cardinal Group, Toronto