Snow depth and vegetation type affect green roof thermal performance in winter

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A B S T R A C T

Green roofs reduce building energy consumption in hot seasons, but cold season thermal performance has received little attention. The goals of this study were to quantify heat flux in an extensive green roof system, relate heat flux to solar radiation, substrate temperature and snow depth, and to determine the relationships between vegetation type, snow accumulation, and substrate temperature. Over the building heating season, we found lower net heat loss from green compared to conventional roofs. Doubling green roof substrate depth had no additional impact in lowering net heat loss. We also quantified substrate temperatures and snow depths from green roofs in different microclimates and vegetation types. Different roof microclimates (sheltered, exposed, over unheated building) resulted in differential snow accumulation; deeper snow resulted in lower variability in heat flux. The benefits of green relative to conventional roofs were lower in extreme winter conditions when the substrate was frozen and/or had snow cover, but also during sunny conditions. Plant species differentially affected depth and duration of snow coverage. Substrate temperatures also differed according to plant growth form during both snow-covered and bare conditions. Net thermal benefits of green roofs in winter will depend on climate, plant choice, roof construction and location.

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1. Introduction

Green roofs provide many environmental benefits, including reduction of energy consumption, stormwater retention, and provision of habitat [1,2]. The thermal benefits of green roofs during hot seasons are well-characterized in many areas [3–5], and result from evaporative cooling [6,7], increased albedo [8,9], and the insulating properties of the growing medium [10]. For cold seasons, modeling studies predict modest reductions in heat flow out of buildings under green roofs compared with conventional roofs [8,10,11], but the overall impact on energy budgets should be less than that of cooling during hot periods. The few empirical studies of green roof thermal properties during cold seasons tend to confirm the reduction in heat flow out of buildings compared to conventional roof systems [12–15], resulting in energy savings.

In general, snow acts as an insulator, reducing temperature fluctuations and increasing average soil temperatures during winter [16]. Empirical studies of green roofs in winter suggest that snow cover reduces the magnitude of temperature fluctuations [17] and the relative advantage of green roofs compared with conventional roofs [15]. Green roofs may support greater snow accumulation [14], but there has never been a quantitative study of the effects of snow depth or coverage on green roof thermal performance nor of the effects of green roofs on the magnitude and duration of snow accumulation.

Shallow substrates on extensive green roofs challenge plant survival in cold regions [18]. Plant survival is important on green roofs as replacement of plants increases maintenance costs, and damaged vegetation can reduce aesthetic value and the performance of ecosystem services [19]. Plant overwintering survival depends greatly on substrate depth [18] and microclimate [20]. In general, snow cover promotes higher survivorship of overwintering perennial plants due to warmer soil temperatures [21]. Snow cover can also reduce the frequency of freeze–thaw cycles [16], which are detrimental to the belowground parts of overwintering plants [18].

Snow accumulation can be affected by plant structure above ground. Shrubs trap snow, leading to greater snow depths compared to more open areas [22]. The snow that accumulates around shrubs can be of lower density, with more trapped air, than snow cover in open areas; this increases the insulating value of a given depth of snow [22]. Given that most green roof plants have some presence above-ground during winter, whether as a canopy of

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dead leaves and stems (necromass), woody stems and/or evergreen leaves, it is possible that plants could influence snow accumulation and the thermal functioning of green roofs. The possibility that different vegetation types on roofs can affect depth and duration of snow coverage has never been explored.

In this study we quantified heat flux in one extensive green roof system, and soil temperatures in four different systems during the building heating season. We measured snow depths in green roof systems with different substrate depths and examined the effects of 14 plant species on snow accumulation and substrate temperatures.

2. Methods and materials

2.1. Sheltered and raised green roof systems

Snow depth and thermal properties were examined in three different built-in green roof systems and one modular green roof system (Table 1). The first two were installed in summer 2008 on a pre-existing sod roof on the 35-year-old, north section of the Patrick Power Library at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39′N, 63°35′W) [23]. The pre-existing sod roof consists mainly of non-native grasses and some wildflowers on 45–60 cm of clay soil, and a 2–3 cm of extruded polystyrene insulation over a waterproofing membrane that covers concrete slabs and is approximately 5 m from ground level. This roof is sheltered by buildings 1 to 3 stories higher on the West, South, and East sides.

The “sheltered” system consists of three green roof panels and one control of conventional dark grey roofing shingle, each 2.4 m × 2.4 m (Fig. A1), established on the pre-existing sod roof. The panels were placed at the same level as the top of the sod, with extensive green roof drainage containers (ELT EasyGreen, Brantford, Ontario) over a plywood base fitted with holes every 3 cm for drainage (Fig. A1). The panels were separated from one another with a parapet 30 cm above the level of the surrounding sod (Fig. A1), contributing shelter from wind. Before applying the plywood base, the original substrate (soil) was removed to the roof insulation below and backfilled with construction gravel to create a well-draining level surface (Fig. A1). The four panels were assigned to three treatments: one control, two with 15 cm substrate depth and one with 7.5 cm substrate depth. The substrate was a commercially available growing medium designed for extensive green roofs (Sopraflor X, Soprema Inc., Drummondville, Quebec), and this was used in all of the experimental roofs described below. The fourth panel served as a conventional roof control and had a thin layer of dark grey shingle applied to the plywood base, with a drain in the center.

The “raised” system was on the same roof as the sheltered and used the same green and conventional roofing systems. Twelve panels, each 1 m × 1 m were installed on top of a single rectangular raised platform, in two rows of six panels each, clad around the sides with plywood (1.8 cm thick) to provide some protection from wind (Fig. A2). The original purpose of the system was to quantify stormwater runoff beneath the panels. Each panel was bordered by a parapet with the top approximately 1 m above the ground, and 20 cm higher than the base of the substrate layer. Below the substrate layer were the drainage layers described above, then a 1.3 cm plywood protection layer, a 2.5 cm rigid insulation layer (R5), another plywood board (1.8 cm thick) then approximately 15 cm of spray applied insulation (R20), resulting in a 50 cm high air space between the gravel floor and the base of the insulation. This can be considered similar to green roof construction over and unheated building such as a parking garage (a green roof setting common in Halifax). Each panel drained into a regular roof drain. Two panels (at east and west ends of the rows) were conventional (as above) and there were five each of the 7.5 cm and 15 cm substrate depth green roof panels.

Both the sheltered and raised systems were planted with the same mixture of plants (Table A.1) from plugs in 7.6 cm pots, which in turn were propagated from wild cuttings (from the two Sedum species) and seeds (all other species); plants were from 4 to 18 months old at the time of planting. These were planted in May and June 2008 with an average of 4 cm between plants, and were not weeded or irrigated for the duration of the experiment. By the time of this study in winter 2010–2011, the plants had experienced three growing seasons and had close to 100% plant cover. While there were some differences in species composition after three growing seasons between substrate depths, and between the raised and sheltered systems (the subject of ongoing analysis) overall the systems were dominated by tall grasses and weedy forbs by the time of this study.

2.2. Exposed green roof system

The “exposed” system, was installed in spring 2010 on an adjacent, newly constructed building (Fig. A3). This roof is considered more exposed as there is little shading from other buildings and it

Table 1
Summary of site characteristics and sampling dates.

<table>
<thead>
<tr>
<th>Roof Type</th>
<th>Sampling Type</th>
<th>Thermal Variables</th>
<th>Treatment</th>
<th>Sample Size</th>
<th>Dates</th>
<th>Air temperature (°C)</th>
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<td>Thermal Heat</td>
<td>flux and Temperature</td>
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<td>2</td>
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</tr>
<tr>
<td></td>
<td>7.5 cm 2</td>
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<td>15 cm 4</td>
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<tr>
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<td>11.0</td>
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<tr>
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<td>Jan. 7–March 7</td>
<td>−17.2</td>
<td>−1.5</td>
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<tr>
<td></td>
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<td>Jan. 7–March 7</td>
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<tr>
<td>Snow</td>
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<td>15 cm 5</td>
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<td>Jan. 7–March 7</td>
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</table>
is much higher than the first roof (approximately 25 m above the ground). Additionally, as the roof was recently constructed there is better insulation below the membrane compared to the roof with the sheltered and raised panels, further isolating the substrate and plants from heat flowing from the interior of the building. The green roof was installed as a single 24 m × 9 m rectangle, divided into eight sections roughly 6 m × 4.5 m each, with a roof drain in the center of each. Metal edging and rubber pond liner separated the sections, and preventing water moving between them. Each section was further divided into three subsections of 2 m × 4.5 m. The green roof system consisted of 7.5 cm depth of the same commercial substrate used on the sheltered and raised systems, over the same drainage containers, over the roof membrane and a 2.5 cm plywood protection board over the insulation (5–15 cm of rigid polyisocyanurate (R = 5 per 2.5 cm); thickness varies as each section is sloped with the thinnest layers closest to the roof drain; thickness at sensor locations is close to 15 cm) over the steel roof deck. The metal parapet around the edge of the green roof extends to approximately 20 cm above the base of the substrate layer (12.5 cm from the substrate surface). There were four replicates of each planting treatment and each occupied one of the 24 sub-sections with one plug (from 7.6 cm pots, propagated as described above) every 15 cm (Table A.1). By the time of this study, plants were still establishing and vegetative cover was ~50%. Conventional roof controls for the exposed system consist of four concrete pavers (50 cm × 50 cm each), placed on a 2.5 cm layer of white gravel, one adjacent to each of the four corners of the green roof portion.

2.3. Sensor locations and data collected

During construction of the roofing systems, thermocouple temperature probes (10ST, Campbell Scientific, Edmonton, Alberta) were placed in a vertical array at three levels in the conventional roof panel and five levels in the green roof panels in the sheltered system; only data from the upper two (base of substrate layer and just under the surface of the substrate later) are used in this study. For the conventional roof surfaces, the thermocouples were installed directly under the shingles. In the raised and exposed systems, thermocouples were placed at the base of the substrate layer, one per panel or sub-section. In the exposed system, control locations had the thermocouple beneath the paver, over the gravel. A heat flux transducer (Campbell Scientific, Edmonton, Alberta) was placed just under the roof assembly next to the thermocouple at the roof assembly level (under the shingles in the conventional roof and the drainage containers under the green roofs, in the sheltered system only) (Fig. A1). Each panel in the sheltered system had the sensor array replicated twice, approximately 1 m diagonally from the NE and SW corners. For the sheltered and raised systems, temperature (°C) and heat flux (W/m²) were averaged every 15 min using a datalogger from November 5, 2010 to March 31, 2011, with a gap between Dec. 15 and 31 due to an interruption in the datalogger power supply. In the exposed system, temperature data are only available from February 21 to March 31, 2011 and were also averaged every 15 min (Table 1). A weather station established approximately 4 m above the conventional roof panel on the sheltered system provided solar radiation (CM 3L pyranometer: Kipp and Zonen, Bohemia, New York) and air temperature (CS500-U temperature and relative humidity probe, Campbell Scientific, Edmonton, Alberta) readings averaged across 15-min intervals.

2.4. Modular green roof system

To test whether vegetation can influence thermal performance, we used a previously established experiment in a modular green roof system [24]. This consisted of replicated plastic modules each planted with a single species or substrate-only control (n = 10 for each treatment; 14 species (Table A.1)). The substrate was the same as the above built-in systems, and the modules were filled to a depth of 6–7 cm over the drainage layers. These were planted in spring 2009, so they had two growing seasons before we started collecting data in this experiment. The modules were set out on the same roof as the sheltered and raised panels, in a stratified random design, with two replicates per treatment in each of five rows along a solar exposure gradient due to shading from adjacent buildings [9]. Plants were considered fully-grown but there was still variation in percent cover at the end of the growing season in 2010, roughly similar to cover at the end of the first growing season [24]. Thermochron temperature loggers (Maxim, San Jose, California) were individually sealed in plastic bags and one placed at the base of the substrate layer in eight of the 10 replicate modules in each treatment. Each sensor logged a temperature reading every 2 h during the sampling period.

2.5. Snow sampling

Snow was sampled from January 7 to March 7, 2011, between 12:00 pm and 1:30 pm on Monday, Wednesday and Friday of each week. Snow depths were recorded to the nearest cm at the center of each experimental panel (sheltered, raised, exposed and modular) by forcing a ruler down to the top of the substrate layer or conventional roof surface, except exposed roof controls which were not sampled.

2.6. Statistical analyses

Analysis of variance was used to compare heat flux, snow depth and duration, and substrate temperatures among roofing treatments (separately for built-in systems and modules). Multiple linear regression was used to predict heat flux from substrate depth, substrate temperature, snow depth, solar radiation and air temperature in the sheltered system, using values from each sensor averaged across all days where snow depth was sampled. Time series multiple regression was used to determine whether heat flux could be predicted from substrate temperature. All analyses were conducted with the R package, v. 2.15; [25] for more details about analyses, see Text A.1.

3. Results and discussion

3.1. Heat flux

When averaged across all weather/temperature conditions, the green roof panels showed less heat loss than the conventional roof (roughly one-third less), but there was no difference between 7.5 cm and 15 cm substrate depth green roof panels (Fig. 1; Table A.3; Nov. 5–March 31). At current local electricity rates for commercial buildings, this translates into a savings of roughly $1(Canadian)/m² (commercial rate: $0.112 (kWh)−1) for the entire winter. Green roof substrates were not frozen for the majority of the study period (10,472 15-min intervals with substrate temperatures above 0 °C vs. 1794 with frozen substrates; Nov. 5–March 31), and the difference in heat losses between conventional and green roofs was more pronounced during the unfrozen intervals (Fig. 1). This is likely due to increased thermal conductivity of frozen soils [26]. Heat flux through the conventional roof panel greatly depended on solar radiation, having net heat gain during sunny periods and approximately three times greater heat loss than green roof panels when the sun was not shining, thus overall savings will depend on the solar regime of a given roof site. Moreover, conventional roof panels tracked diurnal fluctuations in solar radiation, while the green roof panels had relatively constant heat flux.
indicate 3.2.  

(Figs. A.4 and A.5; Table A.3). This is likely due to greater insulation provided by substrate layers on the green roofs [14], higher albedo of green roofs resulting in less solar heat gain during sunny periods when there was no snow cover [9,10], and possible effects of vegetation on reducing convective heat losses compared to the conventional roof surface [26]. A previous study showed little or no difference in winter-long heat flux between 75 mm and 100 mm depth green roofs [13]. Modeling studies suggest that as substrate depth increases so should energy savings in winter [27,28], as the insulating value of any substrate increases linearly in proportion to its thickness [26]. The insulation provided by green roofs in winter, however, can undermine energy savings by reducing heat gain by the building when outdoor conditions are relatively warm and sunny [29,30]. This may explain why there was no net difference between the two substrate depths tested.

When snow covered the roof, both green and conventional roof panels showed relatively constant heat flux (Figs. A.4–A.6), confirming the findings of two previous studies [14,15]. Climatic conditions during the study period (winter 2010–2011) indicate lower minimum temperatures and greater precipitation, both rain and snow, compared to 30-year climate normals (Table A.2). Warmer temperatures in a more typical year would result in greater differential savings from green roofs (as substrates would be less frequently frozen), but it is not clear what to expect in a year with less snow, as heat gain by conventional roofs depended on whether the sun was shining (Fig. 1).

3.2. Snow depth and duration

The 15 cm substrate depth green roof panels had higher average snow depths than the control roofs, and green roof panels of both substrate depths had greater snow depths than all other treatments (Fig. 2; Table A.4; Jan. 7–March 7). The duration of snow cover showed a similar pattern. Greater snow depths and durations can also partly explain the lower variability in heat flux and temperatures experienced by the green roofs compared to the conventional roof panels (Figs. A.4 and A.5): the greater insulation value and albedo contributed by snow cover should lead to less heat gain and loss on the green roof panels. Greater average snow depths suggest that green roofs can either accumulate more snow when it is falling (by facilitating a higher, less dense snow layer among plant stems) or trap blowing snow, or that the green roofs result in lower rates of snow melting/sublimation [22]. This could happen if the snow layer is below a canopy of dead/evergreen plant material where less solar radiation would reach the snow surface. Snow loads equivalent to controls on raised and exposed roofs may result from greater losses due to wind, compared to the sheltered roof panels, but low replication in this study also reduced statistical power to detect significant differences.

In the modular system plant species significantly affected snow depth: Festuca rubra had deeper snow than several other species (Fig. 2; Table A.5; Jan. 7–March 7), and almost significantly greater than substrate-only controls (Tukey HSD post-hoc test: \( P = 0.10 \)), with about 3 cm range in mean snow depth between species. When species were grouped by growth form, sod-forming graminoids had significantly greater snow depths than controls, creeping shrubs and tall forbs (Fig. A.6; Table A.5). Species and groups also differed in the duration of deeper snow, with a difference of about five days between shortest and longest average duration (Fig. 2, Fig. A.6; Table A.5). These results suggest that plant species and growth forms affect the snow variables quantified, due to differences in accumulation and/or loss rates. The graminoids had relative high

Fig. 1. Mean net heat flux (± standard error) during winter 2010–2011 in sheltered system (Nov. 5–March 11) across green and conventional roof panels (negative values indicate heat flowing upward, from the building to the atmosphere). Data compiled using 15-min sampling intervals; control roof \(( n = 2 \), 7.5 cm substrate depth green roof \(( n = 2 \), 15 cm substrate depth green roof \(( n = 4 \)).
canopy leafing densities in summer [24] and the dense canopies of dead material in the winter likely resulted in deeper accumulation and slower loss of snow. Since this study quantified snow depths at regular intervals, regardless of the timing of snowfalls, there are no data on snow depths immediately after snowfall, so accumulation and loss cannot be separated here.

3.3. Predictors of heat flux

Linear modeling shows complex relationships between heat flux and snow depth, substrate depth and air temperature (the three-way interaction term was significant) (Table A.6; Jan. 7–March 7). Heat flux was relatively constant through conventional and green roof panels when there was snow cover, but fluctuated greatly on the conventional roof when snow was at low depths or absent (Figs. A.5 and A.6). For control and green roof panels considered together, the range of heat flux values significantly declined with the cube root of snow depth (heat flux range = 69.55–26.93 [snow depth $^{-1/3}$]); $R^2 = 0.66$, $P < 0.0001$; Jan. 7–March 7).

The best predictive model for heat flux using time series data in the 7.5 cm substrate depth green roof panel showed positive linear effects of substrate temperature, air temperature and solar radiation, with a negative effect of snow depth, with substrate temperature being the strongest effect by far (Table A.7; Jan. 7–March 7). To test the robustness of the model, we cross-validated using inputs from the other sensor location within the same green roof panel. We found a fairly strong linear relationship between predicted and measured values ($R^2 = 0.70$, $P < 0.0001$). While we did not use these models to predict heat flux where it was not directly measured, we consider substrate temperature to be a general indicator of heat flux in these systems, thus higher temperatures are associated with more positive heat flux values, indicating greater energy savings in winter, and suggesting that energy savings should be greater in the sheltered compared with the raised and exposed systems.

3.4. Substrate temperatures

Across the entire sampling period, substrate temperatures varied the least in the 7.5 cm and 15 cm depth sheltered systems, and all green roof treatments had a smaller temperature range than their corresponding controls (Fig. 3a; Table A.8; Nov. 5–March 31). For the 48 day period at the end of the study where temperature data were available for all three roof systems (Feb. 21–March 31), raised and sheltered green roof panels had the smallest temperature range (Fig. 3b, Table A.8), and while the exposed green roof had a lower range than its corresponding control it still had very low minimum substrate temperatures, comparable to the raised and exposed controls and lower than the sheltered control (Fig. 3, Table A.8). While minimum air temperatures are similar for the

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**Fig. 2.** (a): Mean snow depth and (b) duration of snow cover (±standard error) for green roof systems with different substrate depths (7.5 cm, 15 cm), compared with conventional roof panels (controls) [Jan. 7–March 31] (sheltered, raised and exposed systems). “Raised” refers to panels raised ≥60 cm above the roof surface on top of unheated enclosures; “Exposed” refers to panels on the higher, more exposed roof. (c) Vegetation effects on snow depth (days without snow cover not included) and (d) duration of snow cover (Jan. 7–March 31) (modular system). For species codes see Table A.1. Means sharing letters are not significantly different at $\alpha = 0.05$. 

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two intervals, and temperatures on the raised and exposed systems might be expected to be similar to air temperatures, this was not the case for the raised green roof systems (Table 1, Fig. 3b). Colder minima for the longer interval in the exposed green roofs (Fig. 3a) may be due to the longer periods where air temperature was low. From February 21 to March 31, while air temperatures still went as low as −13.1 °C the raised green roof panels did not show a corresponding drop in temperature (Table 1, Fig. 3b). This may be due to saturated soils creating a high thermal mass that is coupled with relatively short intervals where air temperatures were below zero preventing the substrate temperatures from equilibrating with air temperature. The exposed system was not saturated and more exposed to wind, possibly leading to quicker lowering of substrate temperature in response to cold air.

In terms of substrate temperature, differential benefits seem greatest for green roofs in our sheltered system. While the exposed green roof had similar minimum temperatures to its corresponding conventional roof, this could be due to the greater exposure to high winds, thereby reducing the ability for the plants and soil to prevent heat loss, or the modern insulation layers below both green and conventional roofs may isolate the upper layers from heat from the building below, resulting in colder substrates and lower relative benefits from the green roof [4,31]. The raised roof panels had the influence of cold outdoor air below both green and conventional roofing, despite the insulation under both roof types, minimizing the ability of green roofs to differentially trap heat released by the building below. On the sheltered roof, the average temperatures over the entire study (Nov. 5–March 31) declined from the soil surface to the top of the roof membrane (Fig. A8). While there is a thick layer of gravel between the roof surface and the lowest temperature sensor location in the sheltered system, it is still slightly colder under the gravel under the conventional roof, likely reflecting overall greater heat flux out of the conventional roof and the poor insulative ability of wet gravel, and consistent with the winter-long average heat flux values (Fig. 1). The relative thermal benefits of green roofs in winter will depend greatly on the construction of the roof (especially the insulation), the setting of the building, and other factors that influence the microclimate. More empirical work on heat flux in a variety of green roof settings is warranted.

Substrate temperatures in the modules differed by plant species and groups (Fig. 4; Table A9; Nov. 5–March 31). Tall forbs had higher maximum and lower minimum temperatures than other species, but were similar to substrate-only controls. *Symphyotrichum novi-belgii* had some of the highest maximum temperatures and had significantly higher substrate temperatures than *Solidago puberula*, another tall forb. Both graminoid groups (sod- and bunch-forming) had a significantly lower range of substrate temperatures compared to the other species (Fig. 4). These vegetation types are also similar to the grass dominated green roof panels in the sheltered system, which showed lower variability in heat flux and temperatures compared with conventional roof panels (Figs. A4 and A5). For the three days during the snow sampling period where modules had no snow cover, species and group effects were significant for maximum temperatures. Sod-forming and bunch-forming graminoids had significantly lower maximum temperatures than substrates in controls or other vegetation, and sod-forming graminoids had the lowest maxima (Fig. A9; Table A9; Jan. 7–March 7), suggesting that energy savings would be lowest with such species, likely due to direct effects of the canopy biomass/necromass. Such effects could result from increased reflectivity, a documented effect of higher leaf area index [26], or lower convective heat gain from warmer air due to trapping of still, colder air near the substrate surface [26]; these effects can account in part for the lower heat flux and temperature variability seen in the sheltered green roof panels compared to the conventional roof. Minimum temperatures did not differ between species or groups during the no-snow period. For days where modules had differential snow cover, maximum substrate temperatures did not differ among species or groups but the sod-forming graminoid group had significantly lower minimum temperatures than all others (Fig. A9; Table A9; Jan. 7–March 7), suggesting that greater snow depths reduced substrate warming during sunny periods; the other groups

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**Fig. 3.** Substrate temperatures for different green roof systems (means ± standard error), (a) entire study period November 2010–March 2011 (sheltered and raised roofs only); (b) February 21, 2011–March 31, 2011, including exposed roof.
and species had higher minimum temperatures similar to that for controls. The groups that supported greater snow depths and longer snow cover also had the lowest range in temperatures during times of snow cover, and lower temperatures when there was no snow, suggesting that such plants would result in lower energy savings.

For the interval where snow data and temperature from all roofs were collected (Table 1; Feb. 21–March 7), average snow depth and average substrate temperature were positively related, measured between 12:00pm and 1:00pm (Fig. A.10), although there was no relationship when only raised panels were analyzed ($P=0.70$), and the relationship strengthened when raised green roof panels were removed ($R^2=0.79, P<0.0001$). Snow depth can thus improve thermal performance on the most exposed roof settings, but is likely to have little effect when green roofs cover unheated buildings. When directly included as a predictor of heat flux in a model including substrate temperature, snow depth was weakly negatively related to heat flux (Table A.7), suggesting that the main effect of snow depth on heat flux is to reduce heat transfer to the atmosphere, raising substrate temperature, thereby reducing the temperature differential between the substrate and the building interior.

Snow depth and substrate temperature were also positively related in the modules (Fig. A.10; Jan. 7–March 7). While the sod-forming graminoid modules had lower average substrate temperatures than other groups, both during snow-covered and bare conditions, when analyzed alone, we still detected a positive relationship between snow depth and substrate temperature within this group ($R^2=0.33; P=0.003$). The plants with the thickest canopies thus typically have greater snow coverage (Fig. 5), and likely have lower energy benefits (due to lower substrate temperatures overall), but even within this group, greater snow coverage leads to higher substrate temperatures. The effects of vegetation on overall thermal benefits are complex and result from several, often opposing processes. Modeling studies suggest that as leaf area index (LAI) rises, winter benefits relative to conventional roofing decrease, due to a reduction in solar heat gain under the vegetation (Fig. 6) [28], so vegetation types that produce strong cooling effects in summer may be a liability in winter.

3.5. General discussion

The net benefit of any vegetation type will again depend on the relative balance of air temperature, snow, and solar radiation characterizing winter climate regimes (Fig. 6), and while heat flux is the sum of many energy transfer processes [26], the effects seen here appear to relate mainly to substrate temperature, which drives the temperature differential across roof layers, assuming a constant indoor temperature. While the thermal conductivity of the substrate layer likely varies over time in response to the proportion of liquid vs. frozen water, in response to changing air temperature and solar radiation over the winter, the effects of snow (e.g. Figs. A.4 and A.5) point to the importance of the atmosphere-substrate interface as a key driver of winter performance of green roofs. Greater snow coverage will tend to reduce the differential benefits of green vs. conventional roofs, but will result in lower overall energy consumption. Greater solar radiation when there is no snow cover tips the balance in favor of dark-colored conventional roofs. The relative exposure of the roof influences snow depth, which directly affects substrate temperature and heat flux (Fig. 6). Species composition in the vegetation can influence snow depth, and thus thermal performance as well, and this likely occurs primarily through the accumulation of canopy biomass (Fig. 6). Even within a species, it is likely that the depth of growing medium will affect canopy biomass/necromass, although this was not quantified here. Dead or evergreen plant canopies also have different optical properties which could also affect snow melting rates due to differential surface temperatures (Fig. 6). In this region, green roofs are unlikely to be implemented solely on the basis of winter thermal benefits. Rather, the overall reduction in heat loss attributable to green roofs detected in this study can be considered an ancillary benefit of green roof construction that targets roof cooling in warm seasons.
stormwater retention, habitat creation, aesthetic values or other purposes. More research is required to determine long-term benefits of different roof types and geographic regions experiencing winter with snowfall.

Other climatic and microclimatic conditions not accounted for in this study could also have affected the recorded thermal performance. We were not able to differentiate night times with or without cloud cover, and this could influence the overall energy balance, nor did we compare cloudy day (low solar radiation) with nighttime (no solar radiation) conditions, thus other factors inherently different during day and night (e.g. differential energy use and heating inside of building, foot traffic) might explain variation in thermal performance between these time periods had they been explored. Different types of snow and solid precipitation (e.g. hail, ice pellets, sleet) accumulated on green roofs too could impact melting rates, heat capacity and thermal conductivity of these layers and subsequent changes to thermal performance in winter. Further, the winter studied here (2010–2011) deviates from past climatic norms in that there was more precipitation for some months, coupled with lower solar radiation (Table A.2). While most years will show some deviation from climate normals (as normals represent long-term averages), it is not clear whether the conditions in 2010–2011 represent the results of climate change, toward wetter winters, thus whether we can expect more winters like that one.

While the focus here is on the thermal benefits of green roofs in winter, the effects of vegetation on snow accumulation and loss, and on substrate temperature regimes could have other

**Fig. 5.** Differential accumulation of snow in green roof modules planted with different vegetation. Left module in image: Carex argyranthra, a sod-forming graminoid; Right: Symphyotrichum novi-belgii, a tall forb.

**Fig. 6.** Conceptual diagram that links variables affecting green roof thermal performance in winter. Variables in parentheses were not quantified in this study.
implications. Diminished temperature fluctuations due to greater snow coverage and/or thicker plant canopies are more protective of roof membranes [17], adding to the economic value of green roofs. Snow coverage can positively affect plant survival by raising average temperatures, preventing freezing damage and reducing temperature fluctuations, which can damage plants via “reverse hardening” [18] and lead to lower vegetation productivity [20]. Species that trap snow could thus facilitate their own survival, with further potential for inter-species facilitation, where other species growing under the graminoid canopy could benefit from more shelter.

While the “sheltered” and “raised” green roofs included Sedum spp., favored by the green roof industry in North America and Europe, the dominant biomass in these systems by the time of the study was formed by graminoids, and Sedum was not included in the modular system experiment. The relatively low profile of most Sedum species suggests that they would also support relatively low snow depths (comparable to our controls or growth forms such as creeping shrubs). Future studies should compare Sedum roofs to roofs planted with different growth forms in winter.

3.6. Conclusions

Both biotic and engineered components of green roof systems affect their thermal performance. While there was a net benefit of green roofs compared with conventional roofs from the perspective of heat flux, other considerations, such as the relative exposure of the roof and the thickness of the insulation layer will also affect the relative benefits of green roof construction. Plant species selection deserves more scrutiny in climates where winters are severe as plant type can alter snow accumulation and substrate temperatures. Overall benefits will also depend on winter climates, driven by solar intensity, air temperatures and snow loads.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2014.07.093.

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