Effect of substrate depth, vegetation type, and season on green roof thermal properties

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Abstract

It is generally accepted that green roofs can influence thermal properties of a building, but there is some disagreement on the role that substrate depth and plant species plays in this equation. A study was conducted over a second floor roof in East Lansing, MI, comparing prevegetated mats of a mixture of sedum (depth = 5 cm) to a deeper roof (depth = 20 cm) planted with a mixture of 17 herbaceous perennials and grasses. Both roof sections were instrumented with heat flux sensors, thermocouples, moisture sensors, and infrared sensors, and ambient weather conditions were also continuously recorded by a weather station located on the roof. Data were collected for the period of almost a year to cover all four seasons. Also, the roofs were well established and had reached near 100% plant coverage by the time data collection commenced two years after planting. Most of the differences in temperatures and heat flux through the roof occurred during the summer or winter. During summer, the shallow sedum roof experienced more extreme fluctuations in diurnal substrate temperatures which tended to be warmer during the day, but cooler at night. Heat penetrating into the building on the sedum portion of the roof was consistently greater than the herbaceous section during the afternoon. However, during the night and early morning, heat gain into the building was greater on the herbaceous roof, especially on cloudy and rainy days. During winter, heat transfer through the sedum portion of the roof was affected more by outside environmental conditions, whereas the herbaceous portion of the roof was stable. Although, the sedum roof exhibited more extremes, when daily heat flux values were totaled for each month and each season, the herbaceous roof actually

experienced more heat entering the building during the summer, but less heat escaping the building during the winter. This is an advantage during the winter months as the herbaceous roof would reduce heating costs. However, contrary to conventional logic that plants with high transpiration rates are superior, during the summer months the sedum roof outperformed the herbaceous roof.

Key words: Building energy, building insulation, heat flux, plant species, thermal performance

1. Introduction

Numerous studies have shown that green roofs can lower roof surface, substrate, and waterproofing membrane temperatures, as well as moderate heat flux into and out of a building [1-2]. Thus, they can reduce energy costs for heating and cooling, especially for buildings that are poorly insulated. Getter et.al. [3] found that a shallow extensive green roof reduced heat flow through the building by an average of 13% in winter and 167% during summer. Meanwhile, summer temperature values below the growing substrate were 20°C cooler than the traditional roof located adjacent to the green portion. Attenuating temperature fluctuations of roof membranes help prolong their lifespan due to less expansion and contraction [4]. In addition, green roofs offer additional economic and ecological services such as mitigation of the urban heat island, management of stormwater, carbon sequestration, reduction of noise and air pollution, providing space for urban food production, providing habitat for wildlife, and improving human health [5-8].

Green roofs can influence the thermal properties of a roof in three ways: the substrate acts as an additional insulation layer; the plant canopy shades the roof surface; and evapotranspiration [2, 9-10]. The magnitude of this influence also depends on day to day weather conditions such as solar radiation, ambient air temperature, precipitation and thus substrate moisture, and snow cover. Controllable factors include depth and composition of the growing substrate, plant selection, and whether the roof is irrigated.

Some studies have shown that increasing substrate depth results in reductions in heat flux into or out of the building [11-13]. Solar radiation can heat the entire substrate volume much faster when the depth is shallower [14]. In contrast, Lundholm et al. [15] reported that doubling the substrate depth

from 7.5 cm to 15 cm had no impact in lowering net heat loss [15]. Part of the disagreement could be due to substrate composition and compaction. For example, Sailor and Hagos [16] reported that substrates consisting of heat-expanded slate exhibited a thermal conductivity that was two to three times that of substrates that incorporated a silica-based aggregate. Similarly, Pianella et al. [17] found differences among substrates that they tested. Besides the actual materials, their density and particle size distribution will also influence thermal conductivity. As density increases, thermal conductivity and heat flux will also increase [1]. Air pockets in the substrate will increase its ability to act as an insulator [2]. As substrates become compacted when they age, thermal conductivity is likely to increase and thus the substrate's ability to act as an insulator will decrease. Thermal conductivities of moist green roof substrates that have been in place for multiple seasons have exhibited thermal conductivities 30–40% higher than their original values due to compaction [16].

In theory, plant species with greater biomass and higher transpiration rates should provide a greater cooling effect. This has been shown to be true in some cases [18–24]. However, in other situations this has been shown not to be true [25–26]. Of course, plant species are highly dependent on substrate depth as deeper substrates allow for plants having greater biomass to survive due to greater substrate moisture. Leaf area index (LAI), stomatal resistance, height, coverage, and albedo (reflectiveness) are five characteristics of plants that can contribute to how plants influence thermal performance [2]. Plants primarily influence cooling during summer, but plant type can also influence the depth of snow cover during winter [15, 27].

Although, plant species with higher transpiration rates might be expected to be more efficient at cooling, plant coverage of the surface may be more important. Shade provided by higher LAI will influence the overall albedo of the roof [11] and decrease solar radiation that reaches the substrate surface [24, 28]. The surface cooling potential of broadleaf plants was confirmed in a study performed in the UK showing a significant reduction of surface temperature up to 12°C [29]. Furthermore, Bowler et al. [30] measured the daily gain in heat on roofs containing shrubs, trees, turf, and bare soil and reported values of 0, 15.6, 29.2, and 86.6 kJ/m², respectively. All were significantly better than the conventional hard surface roof which gained 366.3 kJ/m² during the day. A mix of sedum with relatively low biomass was more effective in cooling the roof than meadow vegetation [26]. Likewise, Franzaring et al. [25] reported that monocultures of *Phedimus floriferus* and *Lotus corniculatus* provided better cooling than the larger erect species *Dianthus carthusianorum* and the grass *Koeleria*

glauca. A viable explanation may be that the low growing spreading species shaded a greater percentage of the roof than the upright species.

Because there is conflicting information in the literature, the objective of this study is to determine how substrate depth and vegetation type (*Sedum* compared to herbaceous perennials and grasses) influence the thermal properties of an extensive green roof. Measurements recorded on this site such as heat flux, substrate moisture, temperature distributions will demonstrate the influence of different plant cover and substrates.

2. Methodology

2.1 Climate

The study was conducted on a 232 m² green roof located on the Molecular Plant Sciences Building at Michigan State University in East Lansing, MI (42.7° North longitude, 84.5° West latitude). East Lansing has a temperate climate with well-defined seasons that are moderated by the Great Lakes. Winters are cold with an average overnight temperature during January of -10.1 °C and have an average annual snowfall of 119 cm. Summer can be hot and humid with an average high temperature during July of 27.8 °C. East Lansing is located within USDA (United States Department of Agriculture) Hardiness Zone 5b. Average annual precipitation equals 80.8 cm and is distributed relatively evenly throughout the growing season. Historically, seasonal rainfall for winter, spring, summer, and autumn equals 12.7, 21.5, 24.2, and 22.4 cm, respectively [31]. There are normally 175 sunny days per year. Cloudy days are more common in Michigan than in most parts of North America, in part due to the evaporation of water from the Great Lakes.

2.2. Roof construction

The 232 m² green roof covers the second floor and is surrounded by open areas to the north, west, and south. An adjacent five story building to the east shades parts of the roof until noon as the shadow moves across the roof. The green roof consists of a shallow *Sedum* area surrounding a deeper section planted with herbaceous perennials and grasses (Fig. 1). Both sections were installed on the same roof slab and are composed of identical layers with the exception of vegetation, substrate

depth, and vegetation carrier. A description of the various layers of the inverted roof assembly are shown in Table 1.

Fig. 1. Green roof during summer, autumn, winter, and spring seasons.

Table 1 – Description of roofing layers for the herbaceous perennial and sedum roof sections.

Roofing layer	Herbaceous section	Sedum section
Vegetation	Herbaceous perennials and grasses (67 m ²) planted from plugs directly into substrate (Wildtype Nursery, Mason, MI)	XeroFlor XF301 sedum mats (165 m ²) (XeroFlor America, LLC, Durham, NC)
Substrate	XeroFlor XeroTerr® proprietary growing medium (20 cm deep)	XeroFlor XeroTerr® proprietary growing medium (5 cm deep) contained on a XF301 vegetation carrier
Vegetation carrier	Not needed	XF301 vegetation carrier consisted of an inverted layer of XF108 (coils facing up) that held the media and vegetation. An additional layer of fleece that could hold up to 6.5 kg·m ⁻² of water was sewn to the bottom
Water retention fabric	Two layers of XeroFlor XF157 fleece consisting a recycled synthetic fiber mixture of polyester, polyamide, polypropylene, and acrylic fibers (each 0.75 cm thick with water retention ability equal to 10 kg·m ⁻²)	
Drainage mat	XeroFlor XF108 drainage mat consisting of a perforated geotextile filter fabric bonded to entangled polymetric filaments (coils) attached on the underside (1.5 cm thick)	
Root barrier	XeroFlor XF113 root barrier consisting of 30 mil low density polyethylene (LDPE)	
Insulation	Two layers of extruded polystyrene	
Membrane protection board	Multi-ply, semi-rigid core composed of a mineral-fortified asphaltic core formed between two outside layers of asphalt-impregnated reinforced mats, weather-coated and covered with a polyethylene anti-stick sheet, manufactured in accordance with ASTM D6506 (0.32 cm thick)	
Roofing membrane	Coal tar built-up roofing membrane	
Roof slab	Structural concrete deck	

Substrate was mounded in the middle of the roof at a depth of 20 cm in an oval shaped area of approximately 67 m². The remainder of the roof covers 165 m² and was installed by laying out pre-grown vegetated XF301 sedum mats which consisted of the carrier containing at least 5 cm of a proprietary substrate (XeroTerr®, XeroFlor America, LLC, Durham, NC) consisting of a combination of 85% heat expanded slate with a gradation of <0.5 cm (PermaTill, Carolina Stalite, Salisbury, NC) and 15% organic matter (compost). On the deeper part of the roof, herbaceous perennials and grasses were planted in the 20 cm deep substrate. Physical properties of the substrate were reported in the study of Getter et.al. [3]. Bulk density was 1.17 g/cm³, capillary pore space was 20%, non-capillary pore space was 21%, and the water holding capacity at 0.01 MPa was 17%.

2.3. Plant material

Plant species on the pre-grown sedum mats included *Sedum acre*, *S. album*, *S. floriferum*, *S. kamtschaticum*, *S. reflexum*, and *S. spurium*. The deeper section of the roof consisted of a mixture of 17 herbaceous perennials and grasses native to Michigan and included *Allium cernuum*, *Anemone virginiana*, *Asclepias tuberosa*, *Aster laevis*, *Aster olentangiensis*, *Campanula rotundifolia*, *Coreopsis lanceolata*, *Echinacea purpurea*, *Geum triflorum*, *Liatris aspera*, *Monarda fistulosa*, *Penstemon hirsutus*, *Tradescantia ohiensis*, and the grasses *Eragrostis spectabilis*, *Koeleria macrantha*, *Schyzachyrium scoparius*, and *Sporobolus heterolepis* (Wildtype Nursery, Mason, MI). All plants were installed October 8-10, 2011. A controlled release fertilizer (Osmocote Plus X 15 N–9 P₂O₅–12 K₂O 5-month release, Everis International BV) was applied the following spring at a rate of 11.0 g/m² and irrigation was supplied with an overhead oscillating garden sprinkler (Melnor, Inc., Winchester, VA) through a hose on an as-needed basis during 2012 to aid in establishment. Thereafter, no supplemental irrigation was applied so plants had to rely on natural rainfall. Since the plants were installed in 2011, the roof was well established and had reached near 100% plant coverage by the time data collection commenced on June 24, 2013.

2.4. Experimental setup and instrumentation

Both roof sections were instrumented with heat flux sensors, thermocouples, moisture sensors, and infrared sensors (Fig. 2). A total of three heat flux, nine temperature, three moisture, and two infrared sensors were placed at various locations within the roof profile for each roof type. Ambient weather conditions were recorded by a weather station located on the roof. All data were continuously recorded on a CR10X Datalogger (Campbell Scientific, Inc., Logan, UT) while utilizing a series of AM25T 25-Channel Solid-State Multiplexors (Campbell Scientific, Inc., Logan, UT). Data were collected for the period between June 24, 2013 and May 23, 2014.

Fig. 2. Locations of heat flux, temperature, moisture, and infrared sensors in the roof layers.

Universal heat flow sensors (Concept Engineering, Old Saybrook, CT) were placed at the water proofing membrane and top of the insulation layers to measure the heat flux through the roofing membrane and thermal insulation (Fig. 2). The sensor, which was deployed so that negative and positive readings would measure heat entering and leaving the building, respectively, had an accuracy of $\pm 5\%$. Thermocouples (Campbell Scientific Type T105T-L) measured temperature values for each layer (roofing membrane, root barrier and growing substrate). During spring, we were unable to measure the heat flux through the roofing membrane under the herbaceous portion because of sensor malfunctions. The heat flux sensors at the roofing membrane and insulation stopped responding on January 22 and April 28, respectively. The three thermocouples at each layer were spaced horizontally 1 m apart from each other. Thermocouple accuracy ranged from $\pm 0.365^\circ\text{C}$, $\pm 0.1^\circ\text{C}$, and $\pm 0.25^\circ\text{C}$ for temperatures in the range of -73°C , 20°C , and 50°C , respectively. Roof surface temperatures were measured by four infrared sensors with an accuracy of $\pm 1\%$ and 2:1 field of view ratio (OS211-LT Series IR Temperature Sensors, Omega Engineering, Stamford, CT). Two infrared sensors were located 1 m above the roof surface for each roof portion, spaced 1 m apart.

Time-Domain Reflectometer moisture probes (Moisture Sensor CS605-L 3-rod TDR probe-RG58, Campbell Scientific) in each section were installed horizontally into the *Sedum* blanket and 20 cm deep in the substrate. The moisture sensors had a rod measure of 30 cm in length, 0.475 cm in diameter, and a radius of influence of 50 mm. The calibration process was based on multiple studies using PCTDR software (Campbell Scientific, Inc., Logan, UT) [32-34].

Precipitation was measured using a tipping bucket rain gage (TE525WS, Campbell Scientific, Inc., Logan, UT) with an accuracy of $\pm 1\%$, $+0$ and -2.5% , and $+0$ and -3.5% for rainfalls <25.4 mm/h, 25.4 – 50.8 mm/h, and 50.8 – 76.2 mm/h, respectively. Precipitation data were polled every minute, then totaled and reported at half-hour intervals. In the winter months, precipitation data were excluded from the dataset due to the inability of measuring solid precipitation. Other meteorological parameters such as wind speed, wind direction, solar radiation, air temperature, and relative humidity were recorded by sensors mounted on a weather station (CM10 Tripod, Campbell Scientific, Inc., Logan, UT). Wind speed and direction was recorded with a 03001 R.M. Young Wind Sentry Set (Campbell Scientific, Inc., Logan, UT) which had an accuracy of ± 0.5 ms⁻¹ for wind speed and $\pm 5^\circ$ for wind direction. Air temperature and relative humidity measurements were performed with CS500 Temperature and Relative Humidity Probe (Campbell Scientific, Inc., Logan, UT) which had an accuracy of $\pm 3\%$ RH at 20°C between 10 to 90% of RH. The solar radiation sensor used in this study (LI200X Pyronometer, Campbell Scientific, Inc., Logan, UT) had a typical accuracy of $\pm 3\%$. The datalogger was programmed using Loggernet Edlog Software (Campbell Scientific, Inc., Logan, UT). All data were sampled every 30 minutes. These data were averaged and reported at hourly and daily intervals.

Data were analyzed using One-Way ANOVA tests and Fisher's LSD comparison in Minitab® 16.2.2 (Minitab Inc., State College, PA). All data were checked for normality prior to analysis of variance by using the Kolmogorov-Smirnov test (Minitab Inc., State College, PA).

3. Results and Discussion

During the research period, average monthly maximum and minimum ambient air temperatures recorded 1.5 m above the roof surface ranged from -12.1°C in January to 28.2°C in July. These temperatures were similar to temperature data obtained 1.5 m above ground level at a nearby weather station (Michigan Enviro-weather Network, East Lansing) which ranged from -15.7°C to 28.4°C (Fig. 3). Ambient air temperatures 1.5 m above the green roof were warmer during the winter than at ground-level, but there was little difference during the rest of the year. The hottest day of the study period was July 19, 2013, when the daily average ambient temperature reached 28.3°C and the coldest temperature of -19.4°C was recorded occurred on January 7, 2014. Monthly precipitation patterns was also similar. Precipitation totaled 580.1 cm at the Enviro-weather station and 530.6 mm

on the roof during the measurement period (Fig. 4). Due to the inability of measuring snow during the winter months, precipitation data represented in the study on the roof only includes rainfall. The heaviest rain event of 53.8 mm occurred October 5, 2013. The longest period of drought was nine days between August 13 and August 21, 2013.

Fig. 3. Comparison of monthly average maximum and minimum air temperatures (°C) on study area (GR) and nearby Enviro-weather (Michigan Automated Weather Network's) Weather Station (WS).

Fig. 4. Comparison of monthly total precipitation recorded on the study area (GR) and at a nearby Enviro-weather (Michigan Automated Weather Network's) Weather Station (WS) during the study period.

3.1 Summer

Most of the notable differences in temperatures and heat flux through the various layers of the roofing envelope occurred during the summer season (June 24 to August 30). The surface temperature on both the sedum and herbaceous perennial green roofs generally mirrored the ambient air temperature. The major exception was on sunny days when surface temperatures and the range in temperatures on both roofs were often higher (Fig. 5). This was especially true for the sedum roof. Daily surface temperature fluctuations on the sedum portion were as much as 32.8 °C, whereas they ranged up to 21.2 °C on the herbaceous roof. Thermal protection provided by herbaceous plants was greater, presumably due to its deeper growing substrate and shade provided by the plant canopy. During the afternoon, the surface of the sedum roof was as much as 13 °C warmer than the surface of the herbaceous roof. The spike in temperatures occurred shortly after noon when the area being measured passed from the shade into the sun and these readings remained higher through late afternoon. Over the entire season, the daily average surface temperature of the sedum roof was 4°C warmer than the herbaceous portion. This agrees with the work of Blanus et al. [29] who found that the leaf surface temperature was lowest for the broadleaf *Stachys byzantina* compared to a mix of sedum. In contrast, MacIvor et al. [26] observed that the lowest surface temperatures (2°C lower) and air temperatures 15 cm above the surface (1.5°C lower) occurred for a sedum plant community compared to a grasses and wildflower meadow mix. When the meadow vegetation was irrigated it performed as well as the unirrigated sedum.

Temperatures of the substrate and at the top of the roofing insulation followed the same general trend as surface temperature. However, diurnal fluctuations in temperature on sunny days were much greater under the sedum due to its shallow substrate depth. Diurnal substrate temperature differences increased up to 27.5 °C in the sedum, but only fluctuated by a maximum of 9 °C in the herbaceous portion. The shallower substrate of the sedum dried out faster and the limited substrate moisture produced the higher temperature fluctuations. As with surface temperature, peak substrate temperatures occurred during the afternoon and differences were sometimes as much as 14 °C between these two roof systems. However, temperatures of the substrate and at the top of the insulation tended to be lower during the night and morning hours under the sedum. The diurnal pattern observed here agrees with the work of Franzaring et al. [25] who recorded the highest summer

substrate temperatures during the afternoon, whereas the substrates retained this heat during the night such that these temperatures were actually higher than the night time ambient air temperatures.

Measurements below the insulation at the roofing membrane showed no significant differences in temperature between the two roof types. Since the green roof was installed on an inverted roof, the insulation layer above the roofing membrane limited extreme temperature fluctuations, thus demonstrating one of the advantages of inverted roofs.

Heat penetrating (negative flux) through the sedum portion of the roof was consistently greater (inward or more negative) in magnitude than the herbaceous section during the afternoon (Fig. 5). However, during the night and early morning, heat gain (inward and negative) was greater on the herbaceous roof, especially on cloudy and rainy days. Overall, heat gain and the magnitude of temperature change on the sedum was higher on sunny days than on cloudy or rainy days due to higher solar radiation levels, higher ambient air temperatures, lower precipitation, and limited substrate moisture. Heat flux correlated with the moisture level of the growing substrate and precipitation. Increases in substrate volumetric moisture contributed to the removal of heat energy from the roof and building (data not shown) through evapotranspiration. In drought periods heat gain into the building was greater due to lack of evaporation from the substrate.

Fig. 5. Thermocouple and heat flux data over 24-h periods for various environmental conditions during the summer season. Time shown in military time. Data symbols only shown on every other data point for clarity of graphing. Negative and positive heat flux readings represent heat entering and leaving the building, respectively.

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296 On a representative rainy summer day (August 27, 2013), volumetric moisture content of the
297 sedum portion rose immediately to 0.13 after a rain event, whereas the deeper substrate in the
298 herbaceous perennial and grasses increased steadily throughout the day, but only reached 0.07. As
299 precipitation significantly affects moisture content it also affects the heat balance of the roof portions.
300 When the volumetric moisture increased with the beginning of precipitation at 7:30 h and after
301 precipitation stopped at 9:00 h, heat flux for the sedum portion was outward (loss) due to evaporation.
302 Heat flow under the herbaceous portion was steadier throughout the day, gaining a small amount of
303 heat until precipitation began at 7:30 h. Then during the rain event (7:30 – 9:00 h), the inward heat
304 flow stopped and reversed to outward flow six hours after precipitation. Even though the larger volume
305 of substrate in the herbaceous portion could retain more water, it was slower to change in
306 temperature. The water retention ability of the deeper substrate in the herbaceous portion was evident
307 in consecutive rainless days. On the sedum portion, volumetric moisture content sharply decreased in
308 drought periods during summer while the deeper portion retained more water.

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310 *3.2 Autumn*

311 During autumn (September 1 - November 30), diurnal patterns for surface, substrate,
312 insulation, and membrane temperatures as well as heat flux were similar to those observed in summer
313 (Fig. 6). Although overall temperatures were lower, the amplitude of change was sometimes higher
314 due to much lower night temperatures. As for summer, substrate and insulation temperatures were
315 higher in the sedum portion during the afternoon, but were warmer in the perennials the rest of the day
316 and night. This was the case on both sunny and cloudy days, but not during rain events. During the
317 afternoon, substrate temperatures were up to 4.1 °C warmer in the sedum, whereas during the early
318 and late hours of the day the opposite was true: the sedum was up to 5.3 °C cooler. Roof membrane
319 temperatures were nearly identical to summer temperatures even though ambient air temperatures
320 were significantly lower. The temperature distribution on the membrane was almost even under both
321 roof surfaces and significantly lower than the upper layers due to the insulation.

322 Greater fluctuations in temperatures were observed during autumn, especially in September
323 and October due to larger differences between day and night temperatures. In September, roof
324 surface temperatures on the sedum portion fluctuated by as much as 45 °C, whereas, the herbaceous

part only fluctuated by a maximum of 30°C. Similar fluctuations were observed on the layers beneath. By the end of autumn, with the steady decrease in solar radiation and ambient air temperatures, the temperature variations were lower. Temperature fluctuations at various points in the roof profile show that both roof types have an ability to protect the roofing membrane from extreme temperature changes. However, even though temperature fluctuations in the herbaceous part of the roof were lower than the sedum portion it appears that the largest factor in protecting the membrane was the roof insulation.

In the afternoon hours, heat flow was into the building on the sedum portion of the roof. Heat tended to leave the roof over the remainder of the day. On the herbaceous perennial and grasses part, there was no significant heat transfer in either direction. On a specific autumn day (October 5) when the heaviest rain event of the season occurred (53.8 mm), heat flux out of the building through the sedum portion of the roof was extreme (Fig. 6). This was especially evident early in the day when the most intense rainfall occurred. This high heat loss from the sedum portion reduced the temperature of the roofing membrane considerably compared to the deeper herbaceous portion of the roof.

On another rainy day (October 31), volumetric moisture content had an impact on temperature values at the insulation and membrane and correlated with heat flux. As volumetric moisture increased in the substrate, heat flux occurring at the roof membrane under both roof portions was out of the building (heat loss). Heat flux peaked at 500 h when the highest precipitation rate was occurring. When the rain stopped, the sedum portion of the roof drained quickly and heat flux through the roofing membrane started to diminish. However, the heat flux through the roofing membrane under the herbaceous portion of the roof remained relatively stable.

(A) Autumn Sunny (3September2013)

(B) Autumn Cloudy (15September2013)

(C) Autumn Rainy (5October2013)

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Fig. 6. Thermocouple and heat flux data over 24-h periods for various environmental conditions during the summer season. Time shown in military time. Data symbols only shown on every other data point for clarity of graphing. Negative and positive heat flux readings represent heat entering and leaving the building, respectively.

3.3 Winter

During winter (December 1 – February 28), roof surfaces were covered with snow most of the season. Nearly identical surface temperatures were observed on the roof portions (Fig. 7). This is not surprising as snow cover acts as an insulation layer during the winter [15, 27, 35, 36]. However, substrate temperatures of the herbaceous portion were up to 10 °C warmer during the coldest time of the year in January. As with other seasons, solar radiation on sunny days produced large fluctuations in substrate and insulation temperatures on the sedum roof, but not for the herbaceous roof. Substrate depth influenced the heat balance on the roof by reducing the solar energy gain of the layers beneath the green roof. On both roofs, heat flux was outward (heat loss), but was generally more pronounced from the sedum as it lost more heat. Also, when it could be measured (water not frozen), volumetric moisture content was higher in the herbaceous portion than the sedum part.

On a day when the roof was completely covered with snow (November 12), temperatures recorded in the substrate and above the insulation layer under the sedum were consistently below zero. Meanwhile, above freezing temperatures were observed at the same locations in the herbaceous portion of the roof. These differences may be due to vegetation type as plants with greater biomass (the herbaceous roof in our case) have been shown to trap more snow, reduce substrate temperatures and heat loss, and moderate any fluctuations in heat flux [15, 27]. However, in our study, we did not measure snow depth, but similar results were observed regardless of snow cover, suggesting that snow cover served as a less important factor compared to the substrate depth. Like in summer, temperature differences between the roof portions were not observed at the roofing membrane although the membrane was slightly warmer under the herbaceous perennials.

Heat flux through the insulation layer was outward for both roof portions. However, heat transfer through the sedum portion of the roof was affected more by outside environmental conditions, whereas the herbaceous portion of the roof was stable. The herbaceous portion of the roof reduced heat losses by 61.4% compared to the sedum portion. At the peak hours of solar radiation, heat loss from the insulation layer of the building decreased under the sedum portion, but not as much as the herbaceous roof.

(A) Winter Sunny (03 January 2014)

(B) Winter Roof Portions Are Snow Covered (11 December 2013)

(C) Winter No Snow Cover (31 December 2013)

Fig. 7. Thermocouple and heat flux data over 24-h periods for various environmental conditions during the winter season. Time shown in military time. Data symbols only shown on every other data point for clarity of graphing. Negative and positive heat flux readings represent heat entering and leaving the building, respectively.

3.4. *Spring*

Patterns for surface, substrate, top of insulation, and membrane temperatures during the spring season (March 1 – May 31) were similar to autumn (Fig. 8). However, a major difference was that during spring heat flux was generally out of the building (heat loss) instead of into the building as in autumn (heat gain). This difference was likely due to lower air temperatures and higher volumetric moisture content during this time period. During spring, in a total of 83 days in the measurement period, average ambient air temperature was below freezing (with a minimum of -13 °C) for 15 days. The spring season was cold and rainy and solar radiation levels were generally low. Even so, heat flow through the sedum portion was slightly higher than the herbaceous portion.

(A) Spring Sunny (29April2014)

(B) Spring Cloudy (27April2014)

(C) Spring Rainy (12May2014)

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397 Fig. 8. Thermocouple and heat flux data over 24-h periods for various environmental conditions during
 398 the spring season. Time shown in military time. Data symbols only shown on every other data point for
 399 clarity of graphing. Negative and positive heat flux readings represent heat entering and leaving the
 400 building, respectively.

3.5. Annual pattern

Over the course of a year (June 2013 – May 2014), average maximum and minimum roof temperatures and heat fluxes demonstrate the differences between the two roof systems that varied in substrate depth and vegetation type (Fig. 9). Surface temperatures were relatively equal throughout except during summer when the sedum roof was warmer. Temperatures in the substrate and at the top of the insulation were similar, but more extreme temperatures were recorded in the sedum compared to the herbaceous perennials. There were minimal differences between roof types at the membrane, again suggesting that vegetation and substrate depth are not a major factor on an inverted roof as long as adequate insulation exists.

Fig. 9. Daily maximum and minimum temperatures values averaged for each month over the course of a year for (A) surface, (B) top of roof insulation, (C) substrate, (D) Top of roofing membrane for Sedum and herbaceous portion of the green roof.

Temperatures and heat flux values on the sedum portion of the roof exhibited greater swings in heat loss or heat gain than on the herbaceous portion. During drought periods, heat flux was

generally inward (negative), whereas, when precipitation was present, heat flux was outward (positive). Factors likely influencing measurements included plant species or plant type, percentage of plant cover that provided shade, substrate depth acting as an insulator, substrate moisture content, evapotranspiration, and weather conditions such as ambient air temperature and solar radiation.

Thermal resistance (units $L^2T/(E/t)$) is defined from the global and ideally steady-state formula $K = \Delta T/Q$, where ΔT is the temperature difference across the material and Q is the net heat flux across the material which in this case is the green roof substrate along with the insulation and membrane layers. In transient situations the temperature difference ΔT can lag the heat flux Q in everyday cases where, for example, the heat flux changes sign from negative (in) to positive (out) through zero. In such cases transient spikes are observed in K [3] which must be filtered to produce a reliable K -value. This behavior indicates that K is a steady-state quantity whose measurement at certain times of the day will be problematic. A scientifically more accurate definition of the heat flux is through the Fourier conduction law, $q'' = -k\partial T/\partial x$, where coordinate x aligns with the heat-flow direction and k is the pointwise or local thermal conductivity. The latter is very difficult to measure for composite materials such as soils supporting branched in-depth root structures in addition to varying levels of moisture. This appears to be a discipline warranting serious study.

Regarding plant species, in an experiment where different green roofs were planted with either shrubs, trees, turf, or bare substrate, the total amount of heat gained was 0, 15.6, 29.2, and 86.6 kJ/m², respectively [30]. These values compared to 366.3 kJ/m² for the conventional roof without plants. Wong et al. [37] also found that energy consumption was less for tree and shrubs relative to turfgrass and Blanus et al. [29] reported that the broadleaf *Stachys byzantina* experienced lower leaf surface temperatures and a higher transpiration than a sedum mix under both moist and dry conditions. In contrast, Zhao et al. [38] reported that there were no differences in heat flux among plant species or substrates although the building they studied was well insulated. Morphological and physiological differences in plants include albedo (reflection coefficient), height and width, LAI, form of metabolism (C3, C4, or CAM), and stomatal resistance which influences transpiration [11, 39-41]. Takakura et al. [42] reported that 30% of the cooling on a green roof was due to transpiration.

Even though our study shows that plant type does make a difference, other studies suggest that the percentage of plant cover may be a more important factor influencing thermal properties than plant species. Shade decreases substrate surface temperatures by decreasing the solar radiation that

reaches the substrate surface [28]. Coverage also influences leaf area index and albedo, a reflection coefficient that describes the amount of solar radiation reflected by the surface [11].

Franzaring et al. [25] reported that the succulent *Phedimus floriferus* (synonymous to *Sedum kamtschaticum* var. *floriferum*), performed better at cooling the roof on individual days and over the long term than the grass *Koeleria glauca*, the legume *Lotus corniculatus*, the herb *Dianthus carthusianorum* and the evergreen mini-shrub *Thymus serpyllum*). *Phedimus floriferus* exhibits a much lower rate of transpiration, but the authors attributed its superiority to its low, spreading growth habit which shaded a higher percentage of the substrate relative to the more upright species. Also, the drought tolerant nature of *P. floriferus* allowed it to survive and remain green for the duration of the experiment, thus providing a longer cooling window [25]. Similarly, MacIvor et al. [26] made the same conclusion, suggesting that sedum should be promoted to improve green roof cooling due to its consistent, near 100% vegetative cover. Results of additional studies also support this assumption [15, 27, 37]. In the present study, both the sedum and herbaceous portions of the roof were near 100% coverage so plant cover should not have been a factor.

Tied to plant species is substrate depth. Many studies have shown that deeper substrates are better at reducing the heat gain/loss through the roof [2, 27, 37]. Wong et al. [13] reported that for every 10 cm increase in substrate depth, thermal resistance of a dry clay soil increased by 0.4 m² K/W. Sailor et al. [11] addressed the importance of depth by claiming that substrate depth was a larger factor than vegetation. Solar energy heats a shallow substrate layer more quickly resulting in higher ET and faster water depletion [14]. In contrast, one study showed that doubling substrate depth from 7.5 cm to 15 cm had no effect on reducing net heat loss [15]. Shallow depths dry quicker, but in some cases with greater depths, more water is distributed near the bottom, thus limiting ET [43].

In our study, throughout the year, moisture content of the deeper herbaceous portion of the green roof ranged from 0.04 to 0.20, whereas moisture content of the sedum portion varied from 0.04 to 0.15. The herbaceous substrate was generally higher because of the greater water retention capability of the deeper substrate and the larger canopy of the herbaceous plants helped shade the surface.

Several studies have shown that moisture increases the thermal conductivity of the substrate [16, 17, 21, 38, 44]. Sailor and Hagos [16] showed that thermal conductivity nearly tripled as substrate moisture increased from dry to saturated. In contrast, Tabares-Velasco and Srebric [24] reported that

the lowest summer heat flux occurred on a wet roof, despite the higher substrate thermal conductivity, possibly because the radiant influx went to moisture evaporation rather than heating. Differences in results could be due to weather conditions as higher substrate moisture can cool the substrate on sunny days, but warm it on rainy and cloudy days [14]. Generally, it is thought that heat will be drawn out of a building when ET rates are high. For example, a wet green roof lost twice as much heat via ET during the summer than a dry green roof [21].

Evapotranspiration can be a huge factor for cooling. Sun et al. [43] found that irrigating a green roof in Beijing was a more cost effective cooling strategy than operating air conditioners. Mankiewicz et al. [44] arrived at the same conclusion in New York. They attributed this finding to increased ET and that there is a significant amount of water needed to produce the electricity needed to operate the air conditioners. However, Jim and Peng [14] found that substrate moisture was effective in regulating substrate temperature, but had a limited influence on ET and the associated cooling which is largely dependent on solar radiation, relative humidity, and wind speed.

Although, our sedum roof exhibited more extremes, when daily heat flux values were totaled for each month and each season, the herbaceous roof actually experienced more heat entering the building (or less heat leaving the building) (Table 2). This is an advantage during the winter months as the herbaceous roof would save on heating bills. However, contrary to conventional logic that plants with high transpiration rates are superior, during the summer months the sedum roof outperformed the herbaceous roof. During summer, a sum of positive and negative heat flux values at the membrane showed that the herbaceous roof transferred $432 \text{ W}\cdot\text{m}^{-2}$ of heat into the building, whereas the sedum roof lost $1136 \text{ W}\cdot\text{m}^{-2}$ of heat out of the building.

This was due in part to the quick saturation of the shallower substrate during a rain event and subsequent rapid drying by ET. Also, the larger volume of substrate on the herbaceous roof acted as a heat sink and continued to transfer heat into the building during the evening and early morning hours. Jim [45] reported similar results in sub-tropical Hong Kong where summer energy consumption (energy transferred into the building) was higher for a roof covered with the herbaceous perennial, *Arachis pintoii*, relative to a roof planted with the succulent, *Sedum mexicanum*. Likewise, Franzaring et al. [25] reported that as substrates warmed during the day, they often retained this heat to the point where night time substrate temperatures were often higher than ambient air temperatures. The deeper substrate layers for the herbaceous perennials were capable of holding more moisture and the higher

thermal capacity of the wet substrates slowed temperature drop which led to more heat being transferred, by conduction, into the building during the night [19].

As stated by Jim and He [46] temporal heat-flux fluctuations are strongly correlated with meteorological variables and temperature is one of the key determinants of heat flux. During our study differences between heat fluxes on the two green roofs were greatest during summer due to environmental conditions. Different seasonal ambient temperatures and solar radiation levels influenced the heat flux.

Table 2. Monthly and seasonal cumulative heat flux ($\text{W}\cdot\text{m}^{-2}$) of the different green roof types.

Season	Month	Cumulative Heat flux (W·m ⁻²)				Monthly cumulative heat flux averaged over a season (W·m ⁻²)				Change (%) in heat flux comparing herbaceous to sedum roof	
		Membrane		Insulation		Membrane		Insulation			
		Sedum	Herb.	Sedum	Herb.	Sedum	Herb.	Sedum	Herb.	Membrane	Insulation
Summer	June	178	-52	83	31	379	-144	-93	-102	137.9	9.7
	July	315	-510	-402	-361						
	August	643	130	39	22						
Autumn	September	1413	990	1005	1181	2758	2232	2826	2535	19.1	10.3
	October	3076	2605	3126	2823						
	November	3786	3102	4346	3599						
Winter	December	5767	4613	7056	5729	5485	3303	7464	5271	39.8	29.4
	January	5054	1993	6897	4240						
	February	5635	-	8438	5845						
Spring	Mar	5561	-	6334	6318	3432	-	4683	4487	-	4.2
	April	3083	-	3032	2657						
	May	1651	-	1291	-						

Sedum = Roof portion covered with Sedum pre-grown mats.
Herb. = Roof portion planted with herbaceous perennials and grasses.
Membrane =Roofing membrane under roof portions.
Negative and positive reading signifies heat entering and leaving the building respectively.

4. Conclusions

Results demonstrate the influence of vegetation type and depth on heat flux and temperature distribution over the course of a year in Michigan. Thermal protection provided by herbaceous plants was greater due to its deeper growing substrate and shade provided by the plant canopy. Maximum and minimum temperatures, fluctuations in temperature, and heat flux tended to be more stable under

the herbaceous roof. It is difficult to determine whether plant species or substrate depth is the more important factor. Although, the sedum roof exhibited greater extremes, the herbaceous roof actually experienced more heat entering the building (or less heat leaving the building). This is an advantage during the winter months as the herbaceous roof would save on heating bills, but not in the summer when a greater amount of air conditioning would be required. However, contrary to conventional logic that plants with high transpiration rates are superior, during the summer months the sedum roof outperformed the herbaceous roof.

As stated, the conclusions drawn from this study applies to Michigan and locations with a similar climate. But how would these results translate to other climates? In a warmer climate such as the southern United States, night-time radiation of heat into the building from a deep substrate layer would likely be more severe because sun exposure and warmer air temperatures would heat the substrate to a higher temperature. In contrast, in a cooler summer climate such as that experienced on the east coast of Canada, this night-time heat gain may not even occur. Likewise, Michigan normally experiences snow cover throughout winter which acts as an extra insulation layer on the roof. Thus, snow diminishes the amount of heat that could escape the building through a shallow extensive green roof. Lake-effect snow is common, a phenomenon that would not occur in areas where large bodies of water did not exist. In locations that experience cold temperatures with limited snowfall, the loss of heat through a shallow extensive roof would be more pronounced than it is in Michigan. Regardless of roof location or depth and plant species used, installing a green roof vastly improves energy efficiency relative to a standard roof without vegetation.

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