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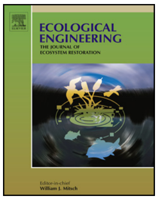

Air temperature cooling by extensive green roofs in Toronto Canada

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ABSTRACT

Vegetated roofs are a widely accepted form of green infrastructure deployed around the world to contribute to building efficiency and climate change mitigation and adaptation through improved thermoregulation and water capture. No two roofs are the same, and the evaporative cooling functions of green roofs have been linked to a number of attributes including plant species combinations and cover, substrate type, and the use of supplemental irrigation. Using a replicated extensive green roof modular array, temperature change at five thermal sensor stations along a vertical gradient was determined to examine the effects of irrigation and attributes of the vegetation and substrate. Over two seasons, a significant 2 °C difference at the surface of the substrate and 1.5 °C difference 15 cm above the substrate layer was found between the treatment combination with the highest temperature (grasses and wildflower 'meadow' mix, inorganic substrate, no irrigation) and the lowest temperature (*Sedum* plant community, organic substrate, supplemental irrigation). Vegetation type and cover were important for roof cooling, and overall, *Sedum* cooled the roof significantly more than meadow vegetation. Irrigated meadow vegetation in organic substrate performed as well as unirrigated *Sedum*. Supplemental irrigation and organic substrate were important variables for roof cooling, although these lead to additional inputs that could reduce sustainability in the overall design. *Sedum* should be promoted to improve green roof cooling due to constant, near 100% vegetative cover. However, additional study is needed to interpret additional benefits that might come from combining *Sedum* and other suitable wildflowers and grasses, as well as the role of plant and substrate diversity in improving multiple green roof functions.

1. Introduction

Vegetation plays a significant role in the performance, persistence, and aesthetics of green roofs (Castleton et al., 2010; Sutton et al., 2012; Cook-Patton and Bauerle, 2012; Lundholm and Williams, 2015). Several attributes of green roof vegetation have been linked to performance, including species type (Monterusso et al., 2005), plant traits (MacIvor et al., 2011; Farrell et al., 2012; Lundholm et al., 2015), vegetative cover (MacIvor and Lundholm, 2011; Volder and Dvorak, 2014), and diversity (Lundholm et al., 2010; Lundholm, 2015). One important feature of green roof performance is the cooling benefits provided in warm seasons. The green roof substrates provide insulation, and the vegetation contributes to cooling via shading, reflection of solar radiation, and evapotranspiration of water (Del Barrio, 1998; Takakura et al., 2000; Niachou et al., 2001; Ouldboukhitine et al., 2011; Jaffal et al., 2012). These cooling effects improve building energy balance and the resulting artificial warming of urban air temperature (Wong et al., 2007; Peng and Jim, 2013). The widespread application of green roofs on new buildings, but also on existing buildings, can have widespread and significant benefits to building owners and users by improving thermal efficiency, energy savings, and mitigation of the urban heat island (Georgescu et al., 2014).

Studies that investigate the cooling potential of green roofs examine these systems as a series of stratified layers, this includes the roof membrane layer, the substrate layer, and the canopy layer (Del Barrio, 1998). The vegetated canopy layer includes the plants which can contribute to roof surface cooling. Onmura et al. (2001) found a 4–5 °C reduction in temperature resulting directly from the green roof vegetation, and Lundholm et al. (2010) found that green roofs cooled the surface 3 °C over vegetation-free substrate only controls, as well as more than 16 °C over asphalt roof surfaces. Greater vegetation structure in the canopy layer can provide addi-

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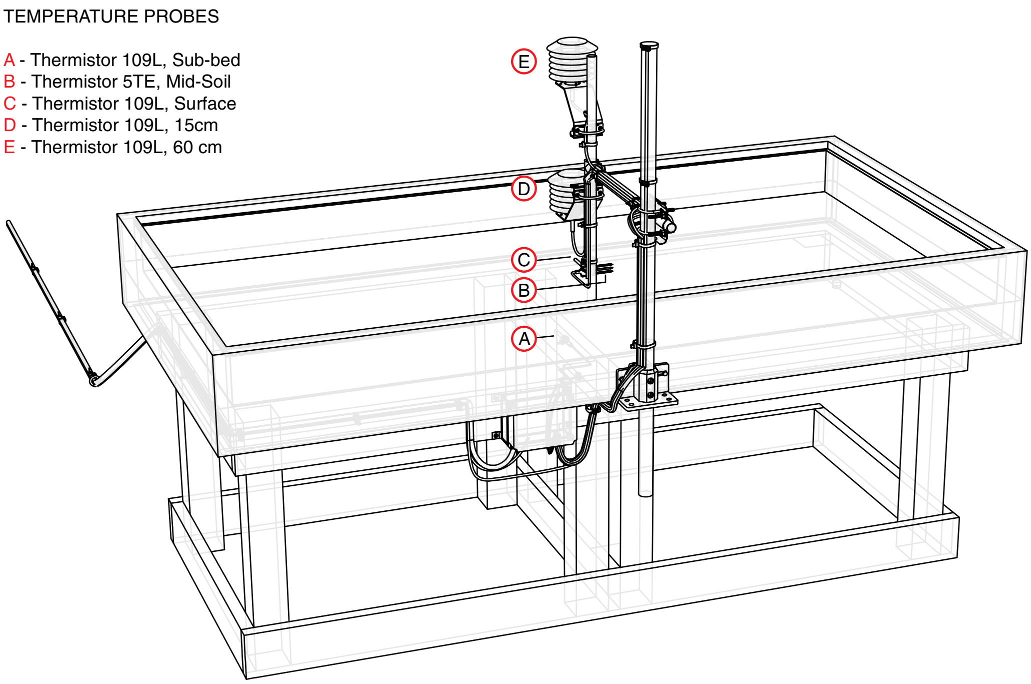

Fig. 1. Schematic of the modular test beds at the GRIT lab.

tional shading of the roof surface. Greater structure is also linked to higher leaf area index, which has a positive correlation with roof cooling (Kumar and Kaushik, 2005).

Extensive green roofs contain less than 15 cm of substrate and are the most researched because of the possibility of installing them on existing buildings without renovations to structural supports within the building. Plant species in the genus *Sedum* (Family: Crassulaceae) dominate most extensive green roof projects, but the majority of species used are exotic in North America, and so there is much interest in testing suitability of native species (Butler et al., 2012). *Sedum* is often installed pre-grown on vegetated mats at near 100% cover (Snodgrass and Snodgrass, 2006; Getter and Rowe, 2006; Oberndorfer et al., 2007; Butler and Orians, 2011; MacIvor et al., 2015). This is attractive for many designers as green building standards increasingly require green roofs that are maintained at a minimum vegetation cover. For example, the City of Toronto green roof by-law and construction standard requires a minimum of 80% vegetation cover by the second year (Toronto City Planning Division, 2013).

Although vegetative cover in two-dimensions (e.g. % vegetative cover) is a commonly used measure of green roofs when investigating performance, accounting for the three-dimensionality of the vegetation will provide additional information. In tropical Hong Kong, Jim (2012) found that the structural complexity of the vegetation was important for roof cooling, but vigorous growing grasses that covered the roof quickly were best overall. In Halifax, Nova Scotia, Lundholm et al. (2015) showed that structural heterogeneity of the vegetation was important in reducing heat flux through roofs by capturing snow in such a way that air pockets are created beneath and above the surface of the roof. Moreover, Dunnett et al. (2008) found structural heterogeneity to be an important function for water capture on a green roof. Understanding how vegetation structure impacts performance contributes to our knowledge of the underlying ecological mechanisms that impact best practices in green roof design and maintenance, and water-use efficiency (Van Mechelen et al., 2015).

In this study, the impacts of plant community type, substrate type, and supplemental irrigation regime on extensive green roof ambient air and surface temperatures were investigated. In preparation for this study two main hypotheses were developed. The first was that the availability of supplemental irrigation will increase roof cooling. The second hypothesis was that increasing vegetation structure would be positively correlated with lower green roof temperatures. Our research was carried out at the Green Roof Innovation Testing Laboratory (GRIT lab) in Toronto, Ontario, Canada. In Toronto, green roofs are mandatory for many building types through a municipal by-law and accompanying construction standard (Toronto City Planning Division, 2013).

2. Methods

2.1. Site

The GRIT lab is located on the roof of the five-storey Daniel's Faculty of Architecture, Landscape, and Design building at the University of Toronto St. George Campus. Green roof modules were installed in the summer of 2011 in an experimental set up of thirty-three 1 m by 2 m modules (only 27 modules were available for use in this study) each installed with one plant community, substrate type, and irrigation schedule (MacIvor et al., 2013) (Fig. 1).

2.2. Vegetation

Two different plant communities were examined. The first was a mixture of twenty-eight *Sedum* species and cultivars (see Supplement Table 1) installed as mature mats (Sedum Master, Burlington, ON) on July 6th 2011 that by 2013, comprised less than seven species (MacIvor, unpublished data). The second community included a 'meadow' mix of fifteen grasses and wildflowers spread on May 31st and July 13th 2011 (each time 17 g of seed mix/module; OSC Seed, Waterloo, ON) (see Supplement Table 2 for a complete list of species).

2.3. Substrate

The substrate treatment level included two different mixtures (GroBark, Georgetown, ON) at 10–15 cm depths (this varied between modules slightly due to wind scour, substrate settling, and biomass accumulation over several years): an ‘inorganic’ aggregate mix using FLL criteria (FLL, 2008) (45% maximum water holding capacity), and an ‘organic’ mix containing 25% organic content by weight (>60% water holding capacity) (MacIvor et al., 2013).

2.4. Irrigation

Supplemental dripline irrigation (DH Water Management, Toronto, ON) was given to some treatment combinations using an irrigation timer or a soil moisture sensor while others were not irrigated (MacIvor et al., 2013). The amount of water provided differed between years because it was determined that less supplemental water was needed to ensure plant survival. In 2013, treatment combinations that were irrigated on a timer received water for five minutes per day and those with a moisture sensor were given a maximum of ten minutes of irrigation per dosing with no cap on the number of doses. In 2014, combinations on timers were irrigated for two minutes per day and those with moisture sensors were given a maximum of two minutes of irrigation per dose and limited to one dose per day. An onsite weather station at GRIT lab records ambient air temperature (°C) and relative humidity (%) (HMP45C Probe, Campbell Scientific), as well as solar radiation (W/m^2) (Kipp & Zonen CMP 11 Pyranometer).

2.5. Vegetative structure and cover

Vegetative structure and cover sampling occurred four times in 2013 from May to end of June, and nine times in 2014 from May to the end of September. Sampling consisted of cover measurements using a pin-frame (MacIvor and Lundholm, 2011). At four equal-sized height intervals (every 15 cm on the pin frame pins) beginning at the base of the substrate, cover measurements were recorded for each interval. An index equation was created to quantify the vegetation cover at different heights as a proxy for vegetation structure, whereby cover (as measured by the proportion of pins touched out of 16 pins on the frame) at each height was weighted equally into quarters and summed together $S = \sum_{n=1}^{P} \frac{1}{4}C$). In the equation, S represented the% index of vegetation structure, P was the pin frame height category (there were four height categories), and C was the proportion of pins touched per pin frame height category (out of 16). This index provided a value that increases from 0 to 1 as vegetation structure increased. On each sampling day, cover and structure measurements were taken twice per module and the mean used in analysis.

2.6. Thermal performance

The test modules were equipped with five thermistors (109-L thermistor, Campbell Scientific) installed along a vertical center axis to generate a thermal profile for each module. Sensor ‘A’ was fixed to the bottom surface of the bed underneath the substrate; sensor ‘B’ was inserted in the base of the substrate; sensor ‘C’ was inserted just beneath the surface of the substrate; sensor ‘D’ was mounted 15 cm above the top of the substrate; and sensor ‘E’ was mounted 60 cm above the top of the substrate. Sensors ‘D’ and ‘E’ were outfitted with a radiation shield (RM Young, Campbell Scientific), which was clamped to a vertical aluminum tube (Fig. 1). Temperature (°C) from each of the five temperature sensors (A, B, C, D, E) were recorded every five minutes over the week leading up to and the week following the vegetative cover sampling day.

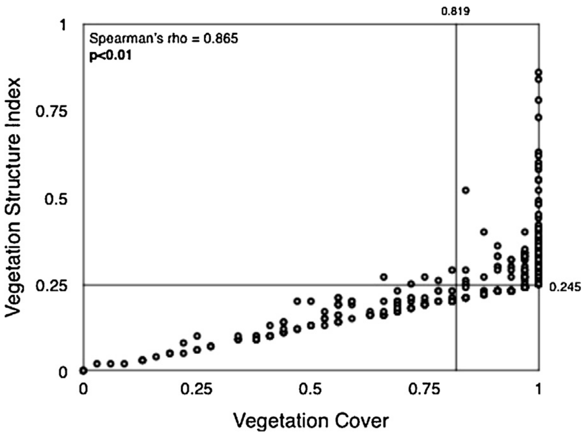

Fig. 2. Scatterplot of vegetation cover and vegetation structure illustrating their significant correlation. Lines overlaying the plot show the mean for each variable.

2.7. Analysis

Temperature was subset by daylight hours only (as determined by presence of solar radiation from the pyranometer) and the mean, maximum, and minimum were analysed for each sensor over the sampling week. Mean temperature at each sensor level was compared between sampling periods using an analysis of variance. A Spearman’s r test demonstrated vegetation cover and structure were correlated and so structure rather than cover was used in subsequent analyses because it provided additional information about each plant community that had reached 100% cover (Fig. 2).

To examine which of the variables explained observed temperature changes and values recorded at each temperature sensor level, backwards stepwise regression analysis was used to test each combination of all variables in model equations for each of the four temperature sensors of interest (A, B, C, D; not E because it was above the vegetation line for all modules and equally exposed at all sites), as well as the temperature differences (B–E, and the daily minimum of B – the daily maximum of E). The variables included in the model combinations were: irrigation (yes OR no; irrigation levels were combined), substrate (organic OR inorganic), plant community type (*Sedum* OR ‘meadow’), and plant structure (% structure index, as in equation described earlier), as well as the interaction between plant community type and plant structure. Multiple regression analysis was used to evaluate the significance of the equation and a Tukey-HSD post hoc analysis was conducted in order to examine the significance of each variable individually. Finally, since there was a reduction in the volume of supplemental irrigation provided from 2013 to 2014, the difference between the average, maximum, and minimum temperature at each sensor level by year and the mean, maximum, and minimum air temperature recorded from the GRIT lab weather station were compared using regression analysis. All statistics were completed using the RStudio program v0.99.484 (RStudio Team, 2015).

3. Results

3.1. Vegetative structure and cover

Vegetative structure and cover were significantly correlated as determined by the Spearman’s correlation test (Fig. 2). Treatment combinations with the greatest vegetation cover included *Sedum* and organic substrate, with irrigation having no effect (Fig. 3). The

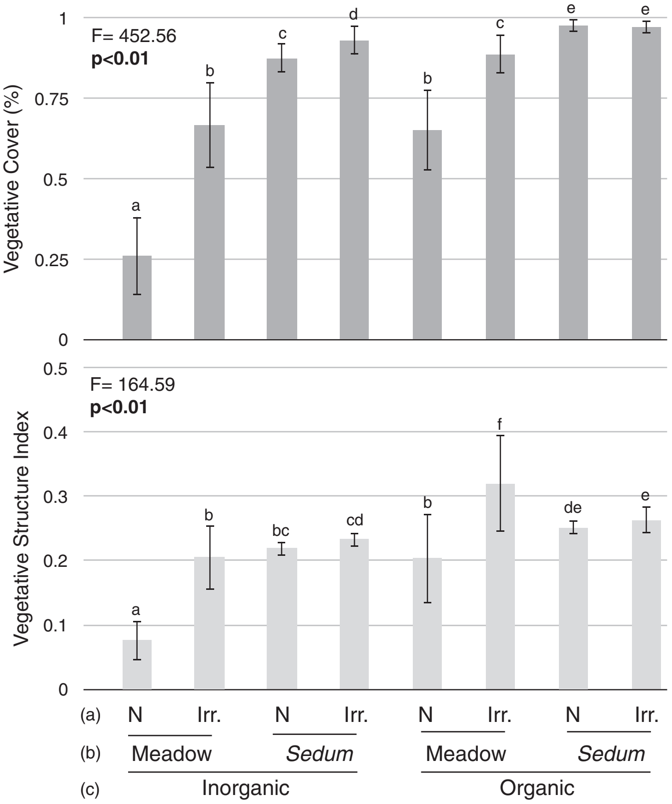

Fig. 3. Differences in mean ± standard error (SE) of vegetative cover and structure among treatment combinations. (a) irrigation (N = no, Irr. = yes), (b) vegetation type, (c) substrate type. Alphabetical lettering above the bars indicate significant differences, with treatment combinations sharing a letter being not significantly different.

combinations with the highest vegetative structure were irrigated, meadow plantings in organic substrates (Fig. 3). The effect of irrigation was most striking in the meadow vegetation which suffered a 2.6x decrease in cover and 2.7x decrease in structure in the 'inorganic' mix. The effect was less pronounced in the organic substrate with meadow mix declining in structure and cover by 1.4x and 1.6x respectively, without irrigation. Structure and cover in *Sedum* vegetation were unaffected by irrigation, remaining unchanged from when they were first installed as *Sedum* mats in 2011. From the analysis, one treatment combination, 2 W (Irrigated, meadow vegetation in organic substrate) was omitted because the irrigation system malfunctioned and the module received significantly more water than the others.

3.1.1. Air temperature cooling

There were significant differences in temperature recorded at all sensor heights among the green roof treatment combinations (Table 1; Supplement Table 3). Ambient air temperature recorded at the GRIT lab weather station was significantly positively correlated with the change in green roof surface temperature (sensor C), but there was no correlation with relative humidity (%) or solar radiation (Fig. 4). Increasing vegetation structure led to a significant reduction in the minimum temperature recorded at sensor 'C' (placed at the surface of the substrate) and the mean, maximum, and minimum recorded at sensor 'D' (placed 15 cm above the substrate layer) (Table 1). Similarly, *Sedum* significantly reduced temperatures over the meadow mix combination at all C and D sensors as well as the maximum temperature at sensor B, beneath the substrate (Table 1). Only vegetation structure and plant community type (*Sedum*) were significant in reducing temperature from the maximum at sensor E (60 cm above the module) to the minimum at sensor B (Table 1). Irrigation had a significant positive effect on roof cooling at sensor C and D. Organic substrate was also significant in improving roof cooling at sensor C and D and the maximum and minimum temperatures at sensor B, which is beneath the substrate (Table 1).

Over two sampling years, we found an average of 2 °C difference at sensor C and 1.5 °C difference at sensor D between the hottest treatment combination (meadow vegetation, inorganic substrate, no irrigation) and the coolest combination (*Sedum* vegetation, organic substrate, irrigation). The greatest change in daily average temperature from sensor E located above each module and sensor B located in the substrate of each module occurred in the same time period and were 4.96 °C and 4.88 °C in module 4 W which contains an irrigated *Sedum* mat in 'inorganic' substrate, and module 3E which contains irrigated meadow vegetation in 'inorganic' substrate, respectively. For temperature sensors C (at substrate surface) and D (15 cm from surface), the greatest effect size among all variables came from vegetation type. At sensor D all *Sedum* combinations had significantly lower temperatures than meadow plantings, but no difference at sensor C was recorded between non-irrigated *Sedum* with 'inorganic' substrate and irrigated meadow plantings with organic substrate (Fig. 5). At sensor C, there was a 7 °C increase in the maximum green roof surface temperature recorded between the top (irrigated *Sedum* plantings in organic substrate) and the worst (irrigated meadow planting in 'inorganic' substrate) treatment combination (Supplement Table 3). Lastly, the effect of irrigation on temperature recorded from the sensors was evident inter-annually: among all treatments, cover and structure were greater, and temperature differences between most sensors and ambient air temperature recorded at the weather station were significantly greater in 2013 compared to 2014 after irrigation levels were reduced, except the mean temperature at sensor E, which was 60 cm above the substrate (Supplement Table 4).

4. Discussion

Over two years of sampling during the summer months, extensive green roof temperature was significantly reduced when irrigated, and installed with an organic based substrate (Table 1) (10–15 cm substrate depths). As a result, the first hypothesis that the availability of supplemental irrigation will result in greater roof cooling in the warm seasons was accepted, as more water will be available for evapotranspiration. The second hypothesis, that increasing vegetation structure would provide increase green roof cooling, was accepted as plant structure significantly reduced temperatures at multiple sensors across the vertical gradient. In the following sections the contributions of the variables analysed are examined in detail.

4.1. Irrigation

Modules receiving supplemental irrigation had air temperatures that were significantly cooler than non-irrigated modules (Fig. 5). Irrigated modules received less supplemental water in 2014, and this was related to lower plant structure and cover, as well as slightly higher air temperatures (Supplement Table 4). Irrigation was expected to improve green roof cooling, since evapotranspiration of water from the substrate and vegetation is an endothermic process (Lazzarin et al., 2005; Starry et al., 2014). However, additional cooling resulting from supplemental irrigation is not desirable as it is a tradeoff of one resource (potable water) for another (building cooling) (Butler and Orians, 2011). Some supplemental irrigation can be important for keeping vegetation alive during hot summer seasons and so including irrigation allows one to benefit from cooling while broadening the plant

Table 1
Multiple regression analysis output for each temperature sensor height and the change along the vertical gradient (B-E) over all samples over both years. F-stat indicates the effect size of the significance level *p*, for the regression "output" and significant differences are annotated with an "*". The variables that were not included in the top model identified using stepwise regression analysis values per temperature sensor are indicated with a "-". Variables that were included in the top model and were significant factors are in bold. "Type" signifies the treatment that was significantly important for the observed trend in sensor temperature (S = *Sedum*, yes = irrigated).

	Output		Plant:Structure		Plant Community			Structure		Irrigation			Substrate		
	F	*p*	t	*p*	type	*t*	*p*	*t*	*p*	type	*t*	*p*		*t*	*p*
A – Avg	3.851	**0.049***	–	–	–	–	–	1.96	**0.049**	–	–	–	–	–	–
A – Max	0.677	0.641	–	–	–	–	–	–	–	–	–	–	–	–	–
A – Min	0.315	0.904	–	–	–	–	–	–	–	–	–	–	–	–	–
B – Avg	0.521	0.761	–	–	–	–	–	–	–	–	–	–	–	–	–
B – Max	9.424	**<0.01***	–	–	S	−3.494	**<0.01**	–	–	–	–	–	Org	2.16	**0.030**
B – Min	4.481	**0.034***	–	–									Org	−2.12	**0.034**
C – Avg	30.14	**<0.01***	–	–	S	−10.11	**<0.01**	1.49	0.18	yes	−3.12	**<0.01**	Org	−4.49	**<0.01**
C – Max	162.90	**<0.01***	−1.98	0.048	S	−2.07	**0.04**	−1.74	0.08	yes	−13.21	**<0.01**	–	–	–
C – Min	22.46	**<0.01***	2.43	0.02	S	−2.51	**0.01**	4.11	**<0.01**	yes	5.11	**<0.01**	Org	3.38	**<0.01**
D – Avg	38.11	**<0.01***	–	–	S	−10.59	**<0.01**	1.97	**0.049**	–	–	–	Org	−2.62	**0.01**
D – Max	100.70	**<0.01***	–	–	S	−15.38	**<0.01**	−3.64	**<0.01**	yes	−5.07	**<0.01**	Org	−9.65	**<0.01**
D – Min	41.42	**<0.01***	–	–	S	−4.96	**<0.01**	7.30	**<0.01**	yes	2.66	**<0.01**	Org	4.49	**<0.01**
B_{min} to E	38.11	**<0.01***	3.15	**<0.01**	S	−3.63	**<0.01**	10.12	**<0.01**	yes	2.93	**<0.01**	Org	−3.23	**<0.01**
B_{min} to E_{max}	10.98	**<0.01***	3.05	**<0.01**	S	−3.60	**<0.01**	3.10	**<0.01**	–	–	–	–	–	–

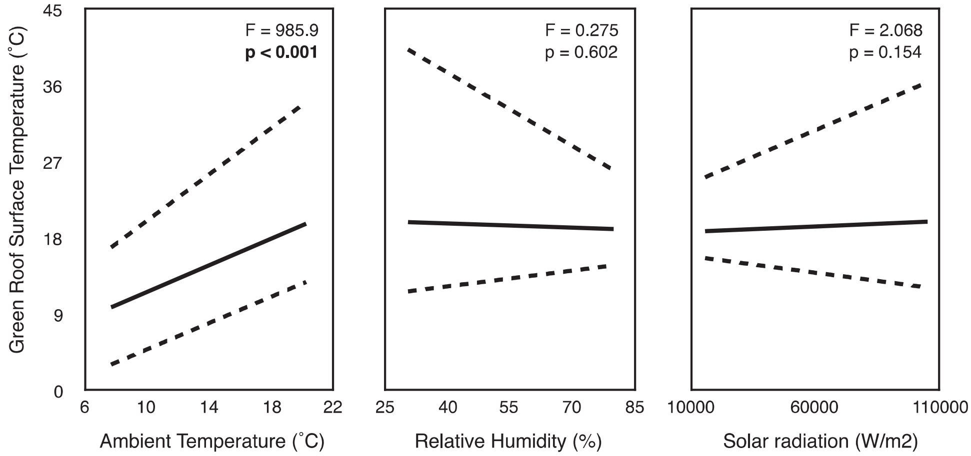

Fig. 4. Relationships between green roof surface temperature from all modules and GRIT lab microclimate data recorded from the weather station. The dotted lines represent the maximum and minimum values.

palette. Including ways of re-using greywater instead of irrigating with potable water is one sustainable alternative and increasingly incentivized in some municipalities. Where irrigation is permitted, combinations that included organic substrate and 'meadow' mix cooled equivalently to unirrigated *Sedum* and organic substrates at sensor C (Fig. 5), and so roof cooling can still be achieved with non-*Sedum* plantings, offering more interesting species combinations (Lundholm et al., 2010; Dvorak and Volder, 2010; Jim, 2012).

4.2. Vegetative structure and cover

Vegetative structure was significantly correlated with cover (Fig. 2). Combinations with the top plant cover values were *Sedum* plantings regardless of substrate and irrigation, while the combinations with the top vegetative structure values were irrigated meadow plantings with organic substrate (Fig. 3). Calculating vegetative structure complexity by partitioning cover by height allows for investigation of alternative measures of the plant community and could provide additional information about green roof performance. Altogether, two-dimensional plant cover appears to be a strong factor in explaining roof cooling, with no significant additional information provided by measuring vegetation structure, which requires more effort to collect (Bonham, 2013). Jim (2012) found plant type to be more important than characteristics of structural complexity; rather species that were the most rigorously growing (e.g. grasses) cooled the best. The findings of this study indicate roof cooling could be maximized another way: using dense, short, clump-forming *Sedum* with substrate depths at 15 cm and minimal supplemental irrigation. Greater and more complex vegetation structure on green roofs can provide several additional advantages that make it attractive, potentially in complement with *Sedum* mats. For example, vegetation structure has been linked to higher stormwater capture (Dunnett et al., 2008; Nagase and Dunnett, 2012), positive aesthetic impressions of green roofs (Loder, 2014; Lee et al., 2015), and to overwinter thermal benefits by capturing snow, contributing additional thermal mass (Lundholm et al., 2015). Additional study and measurement protocols for vegetation structure are necessary for study of roof cooling and other green roof functions.

4.3. Vegetation type

Sedum mats provided significantly greater cooling than green roof combinations containing the meadow plantings (Table 1; Fig. 5). *Sedum* provides substandard water evapotranspiration compared to some grasses and wildflowers in combinations (Lundholm et al., 2010) but stores significant amounts of water in the fleshy vegetative parts and in the substrate their dense mat-forming biomass shields from the sun (VanWoert et al., 2005). *Sedum* can restrict evapotranspiration which is an endothermic reaction pro-

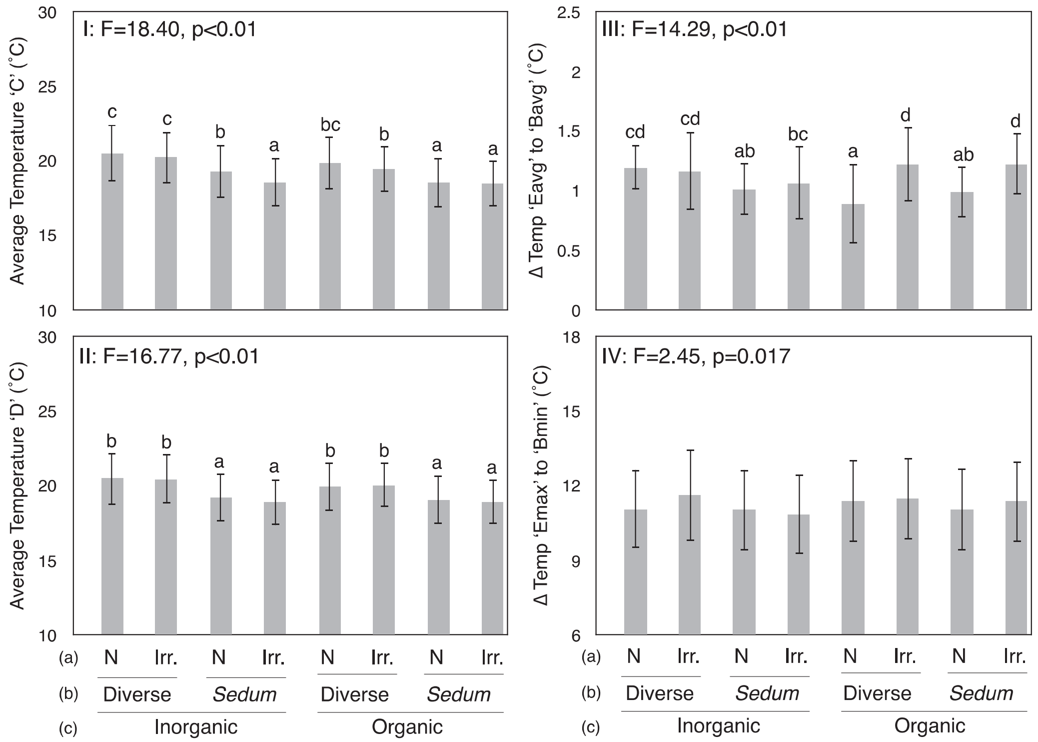

Fig. 5. Differences in mean ± SE of temperature sensor readings among treatment combinations I. average temperature (°C) at sensor C, II. Average temperature at sensor D, III. Difference in average temperature from sensor E (above each module) and sensor B (in the substrate), and IV. Difference in temperature from the maximum of sensor E to the minimum recorded at sensor B. Alphabetical lettering above the bars indicate significant differences, with treatment combinations not sharing a letter indicating a significant difference.

ducing a cooling effect, especially during hot and dry weather because of physiological adaptations that make these plants different from most grasses and wildflowers (Getter and Rowe, 2006). The cooling benefits recorded in the *Sedum* treatment combinations might be a result of water remaining in the substrate longer, thereby cooling the sensors. However, even *Sedum* that was not given supplemental irrigation out performed the meadow mix in roof cooling (Fig. 3; Fig. 5). This illustrates why *Sedum* is a desirable extensive green roof plant around the world; even native grasses and wildflowers adapted to a local region may require irrigation because green roofs are different from ground level, and this is an input that undermines sustainability (Butler et al., 2012). If the *Sedum* selected are healthy their ability to withstand periods of drought on green roofs is immense (VanWoert et al., 2005; Monterusso et al., 2005; Rowe et al., 2012). The ability of *Sedum* to store water contributes to its cooling effect, and this can benefit neighbouring non-*Sedum* plants (Butler and Orians, 2011). In one example, Heim and Lundholm (2014) found the growth of a native wildflower was promoted by the presence of lichen and moss which kept the extensive green roof substrate cooler resulting in less stress to the plant.

Although this study examined community level effects of plants on green roof cooling, understanding the contributions to roof cooling of individual species is important. In one study, Blanusa et al. (2013) compared roof cooling potential of *Sedum* species to *Stachys* (e.g. Lamb's Ear) and found *Stachys* cooled the roof significantly more than *Sedum* at the hottest times of the year. *Stachys* have reflective white hairs that make them particularly adapted to dissipating solar radiation. Other plants have these structures including *Rudbeckia hirta*, which is one of the native perennial flowering forb species used in this study. Two plant communities were evaluated without controlling for number of individuals per module, and so it could not be determined whether any individual grass or wildflower species had roof cooling potential that is significantly greater than any *Sedum* species. Lundholm et al. (2010) found that extensive green roofs in *Sedum* mixes or as *S. acre* monocultures were among the top plant combinations leading to significant roof cooling. In another study comparing roof cooling potential of fifteen different green roof species, MacIvor and Lundholm (2011) found one top performing species, *Carex argyrantha* cooled the roof surface on average 3.44 °C over the season. Determining the cooling potentials of individual plants and of different species could help develop models for planning 'super' cooling green roof plant communities.

5. Conclusion

In this study it was found that roof cooling was significantly improved on extensive green roofs when they were irrigated, constructed with organic substrate and planted with *Sedum* near 100% cover. Our modular green roof set up gives the opportunity to manipulate plant, substrate, and management variables but because of their restricted size (1 m × 2 m) other factors might contribute to lessening cooling potential, and there may be limitations in extrapolating our findings to installed green roof systems which would presumably contribute even greater cooling efficacy. As a result, our findings are likely conservative. We found that combinations that contained wildflowers and grasses had more vegetative structure than combinations containing *Sedum*. However, plant structure did not factor significantly for roof cooling over the the variation explained by plant cover measured in two dimensions. The benefits of more structurally complex vegetation on extensive green roofs requires additional study as these community-level traits have been linked to several other important functions. Since the decision to build a green roof depends on a suite of benefits that include cooling, but also water capture, habitat value, aesthetics, among other values, the combination of *Sedum* with other plant types, including wildflowers and grasses, is the recommended approach to planting (Thuring and Grant, 2015). *Sedum* plants can be top performers, and should not be omitted from green roof plantings solely because they are ‘exotic’.

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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.ecoleng.2016.06.050.

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