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Air temperature cooling by extensive green roofs in Toronto Canada

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A B S T R A C T

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.

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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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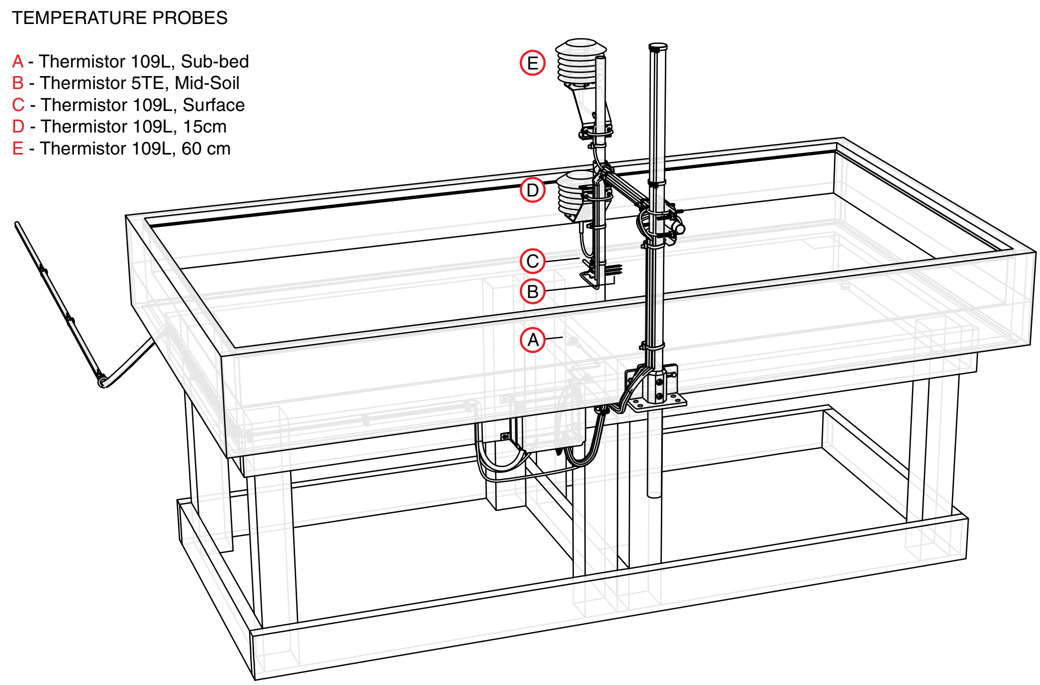

Fig. 1. Schematic of the modular test beds at the GRIT lab.

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).

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