Ecological Engineering 123 (2018) 10–18

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Inter-annual thermoregulation of extensive green roofs in warm and cool seasons: Plant selection matters

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ARTICLE INFO

Keywords:
Sedum
Multi-year study
Urban cooling
Green infrastructure
Climate variability
Thermal benefits

ABSTRACT

The thermoregulation of buildings and cities by green roofs is a primary driver of their integration into urban environments. In warm seasons, green roofs cool buildings (thereby reduce interior air conditioning costs), and cities (impervious surfaces contribute to urban heat islands and vegetation mitigates contributions by conventional roof surfaces). In cool seasons, green roofs insulate buildings by reducing heat flux through the roof surface. Here we investigate thermoregulation services provided by extensive green roofs in warm and cool seasons from temperature data points recorded at 5-minute intervals over a four-year period, and from modules containing either *Sedum* or perennial grasses and herbaceous flowers, mineral- or organic-based substrate, 10 cm or 15 cm substrate depth, and supplemental irrigation or none. We demonstrate that *Sedum* outperformed a mixture of perennial grasses and herbaceous flowers over the total inter-annual survey period. The meadow mixture was more dependent on supplemental irrigation than *Sedum*, but more susceptible to inter-annual climate variability. Our findings point to the durability of *Sedum* as a plant for extensive green roof cooling, as well as the importance of plant selection and identifying traits that match not just microclimatic conditions in summer, but also in winter.

1. Introduction

Green roofs are designed plant communities in specialized substrate atop conventional roof surfaces (Oberndorfer et al., 2007). Green roofs provide many social, economic and environmental benefits, for which they are now encouraged or mandated in cities around the world due to their role in mitigating the environmental impacts of urbanization (Li et al., 2004; Tzoulas et al., 2007; Fujibe, 2009; Benvenuti, 2014). Green roofs contribute to the thermoregulation of buildings and of cities, which is one of the primary drivers of their proliferation in different climates around the world in an effort to mitigate impacts of a changing climate (MacIvor and Lundholm, 2011).

In warm seasons, conventional roof surfaces which are opaque and dark absorb heat which is re-emitted to the indoor and outdoor environment. This results in additional temperature regulation costs for indoor environments, and a hotter and more extreme outdoor urban environment (Del Barrio, 1998; Rinner and Hussain, 2011; Wang et al., 2016). Through a combination of shading, solar reflectance, insulation, and evapotranspiration, green roof plants and substrate enhance building and urban thermoregulation. In cool seasons, green roofs contribute to the reduction of heat flux through roof surfaces of buildings, thereby insulating and reducing potential energy costs for heating indoor spaces. These benefits are enhanced when plant biomass is left over winter, which accumulates snow, leading to greater insulation values (Lundholm et al., 2014b).

Thermoregulation in warm and cool seasons has a demonstrable impact on green roof cooling and heating load, respectively (Jim and Peng, 2012a; Zhao and Srebric, 2012). For example, Liu and Minor (2005) found in an experimental study in Toronto, that green roofs reduced heat flux from the roof substrate to the indoor environment by up to 90% during summer, and indoor heat loss by up to 30% during the winter compared to conventional bare roof surfaces. While at the mesoscale where cityscapes can be comprised of up to 25% rooftop area (Akbari and Levinson, 2008), the wide scale implementation of green roofs could lead to a reduction in the urban heat island effect (Santamouris, 2014). For instance, a recent simulation study conducted by Sharma et al. (2016) estimated that the widespread application of green roofs through the city of Chicago could reduce peak daily urban heat island by 0.84–3.41 °C during a summer heat wave.

Rooftop microclimates are extreme growing environments for plants, and are subject to high wind speeds, temperatures and solar irradiance. As a result, when choosing plants, practitioners tend to

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https://doi.org/10.1016/j.ecoleng.2018.08.016
Received 19 April 2018; Received in revised form 4 August 2018; Accepted 14 August 2018
0925-8574/

target drought-tolerant succulent species in the genus *Sedum* (family: *Crassulaceae*) which is the most commonly used green roof plant, and the industry standard in North America and Europe (Getter and Rowe, 2006; Rowe, 2015). Green roofs planted with *Sedum* are effective at surface cooling, for example, MacIvor and Lundholm (2011) found they contributed to a reduction in substrate temperature during peak summertime hours by up to 2.39 °C, compared to a conventional asphalt rooftop in Halifax, Nova Scotia. However, as knowledge on how to successfully implement green roofs in different conditions and biogeographic regions expands, there is a growing interest in using native, perennial grasses and herbaceous flowering plants (Dvorak and Volder, 2010). These plant groups have been linked to the improvement of multiple green roof services (Lundholm et al., 2010; Lundholm et al., 2014a). For example, in addition to building thermoregulation, green roofs that include grasses and herbaceous flowering plants may provide additional mitigation of stormwater runoff (Nagase and Dunnett, 2010) and air pollution (Hunt et al., 2008), while supporting local biodiversity (Madre et al., 2013; MacIvor and Ksiazek, 2015) and urban food production (Specht et al., 2014).

In addition to plant selection, practitioners can alter additional aspects of design and post-installation maintenance (hereafter referred to as “abiotic design criteria”). These abiotic design criteria include substrate depth and type, as well as irrigation (MacIvor et al., 2013). As substrate must provide physical support and a water and nutrient reservoir for plants, altering aspects of its composition and depth impact plant establishment, growth and survival (Rowe et al., 2012; Young et al., 2014). Deep fine-textured substrates that are rich in organic matter content promote moisture and nutrient retention, and therefore support a wide range of vascular plants, especially when coupled with supplemental irrigation (Monterusso et al., 2005; Thuring et al., 2010; Nagase and Dunnett, 2011; MacIvor et al., 2013). Supplemental irrigation supplies substrate and plants with moisture that is directly available for evaporation and transpiration. This can increase evapotranspirative cooling and improve the survival of plants, especially in tropical environments but also in temperate environments that increasingly experience droughts and heat waves (Jim, 2012; Lambrinos, 2015; Szota et al., 2017).

Substrate characteristics are limited by building rooftop weight restrictions and therefore shallow (< 15 cm), mineral-based and porous substrates are often used (Sutton, 2015). These substrates adequately support *Sedum* (Snodgrass and Snodgrass, 2006) and are less prone to wind scour and decomposition than substrate high in organic matter content (Emilsson and Rolf, 2005). Supplemental irrigation is expensive. For example, Schroll et al. (2011) estimated that a standard irrigation regime may amount to 105–457 L of water valued at up to $77 USD, over a 90-day period on a typical building in Portland, Oregon. Additionally, supplemental irrigation decreases substrate water retention capacity (Hill et al., 2017). However, since both promote herbaceous plant growth, there is significant interest in increasing the proportion of organic matter in green roof substrates and the application of supplemental irrigation to support greater diversity of plant species and abundance (Nagase and Dunnett, 2011).

Studies that explore green roof ecosystem services typically span no longer than two years (Rowe, 2015). In practical application, green roofs are intended to operate in-situ in the long-term and are therefore subject to ecological succession dynamics and climatic variability (Getter et al., 2009). For example, plant cover is dependent on inter-annual variation in summertime temperature and rainfall (Bates et al., 2013). Plant cover modulates both shading of the underlying substrate and total evapotranspiration and therefore contributes to potential summer thermal benefits (Jim, 2012; Jim, 2015; Santamouris, 2014). During the winter, green roofs demonstrate species-dependent differences in snow accumulation. For example, Lundholm et al. (2014b) found that tall species with dense canopies, particularly grasses, have the greatest snow depth. In turn, snow depth is positively correlated with substrate temperature and negatively correlated with heat flux through building rooftops (Lundholm et al., 2014b; Zhao et al., 2015; Eksi et al., 2017). Thus, the assessment of inter-annual climatic variation in parameters such as temperature, rain and snowfall may circumvent appropriate conclusions relating green roof design to building thermoregulation.

A previous study at the Green Roof Innovation Testing (GRIT) lab (www.grit.daniels.utoronto.ca) at the University of Toronto in Toronto, Canada showed that extensive green roofs planted with a mixture of *Sedum* in an organic-based substrate at a depth of 15 cm and receiving supplemental irrigation confer the greatest summer cooling potential (MacIvor et al., 2016), but at this facility winter benefits remain unexplored. In this study, thermoregulation of extensive green roof modules constructed with varied abiotic design criteria and planted with a standard mixture of 1) *Sedum* or 2) grasses and herbaceous flowering plants (hereafter referred to as ‘meadow’) are compared. Abiotic design criteria include substrate composition which is either mineral-based (inorganic) or organic-based, substrate depth which is either 10 cm to 15 cm, and the choice of watering through only natural rainfall or with additional irrigation (http://grit.daniels.utoronto.ca/data/green-roof/). Data are compared over four years (2013–2016) at the GRIT lab. Although conditions are typically mild, warm and cool seasons feature great inter-annual variation in average temperature and precipitation (Fig. 1).

2. Methods

2.1. Experimental design

The data were obtained from experimental green roof modules located at the GRIT lab at the Faculty of Architecture, Landscape, and Design building at the University of Toronto St. George campus, Toronto, Ontario, Canada (43°39′42″N, 79 °23′42″W). The experimental system was installed in 2011 and consists of an array of 33 extensive green roof modules (2.4 m × 1.2 m raised bed; see MacIvor et al. (2013) for complete description), in an 11 × 3 arrangement. Each module was assigned a treatment consisting of 1) a *Sedum* mixture planted in mats at maturity or a seed mixture of 16 flowering native plants and grasses (see Table S1 for a list of species), 2) an FLL compliant inorganic ‘mineral-based’ substrate (“Ecoblend” Bioroof™ Systems, Burlington, Ontario) or an ‘organic-based’ substrate (“EuroBlend A” Bioroof™ Systems, Burlington, Ontario) containing 25% organic content by weight (see Table S2 for substrate specifications), 3) substrate depth (10 cm or 15 cm), and 4) supplemental irrigation from April to October (none or irrigated) (see MacIvor et al., 2013).

Twenty-seven of the 33 modules were used in this study (the rest having additional parameters excluding them from analysis). Each module is outfitted with a wide variety of climatic sensors connected to a centralized climatic data repository server (see http://grit.daniels.utoronto.ca/data/green-roof/); among the sensors, data is logged at 5-minute intervals (from 2013 to 2016). Each module was outfitted with a temperature sensor embedded mid depth within the substrate (Decagon 5TE sensor) to measure substrate temperature, and another placed 60 cm above the substrate surface (100K6A thermistor, Betatherm) to measure above canopy temperature. In each year of sampling and during both the warm and cool seasons, some substrate temperature sensors malfunctioned. This resulted in a loss of 31 ‘data’ points (where one data point corresponds to a temperature summary statistic calculated using data collected at a single sensor for the duration of a single season) during the warm season and a loss of 49 sampling points during the cool season (all substrate temperature sensors malfunctioned during the cool season of 2015). Therefore, all 108 ‘data’ points (27 modules × 4 years) were available for analysis of above canopy temperature. While for substrate temperature, 85 data points were available during the warm season and 65 were available during the cool season.