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Spatial environmental heterogeneity affects plant growth and thermal performance on a green roof

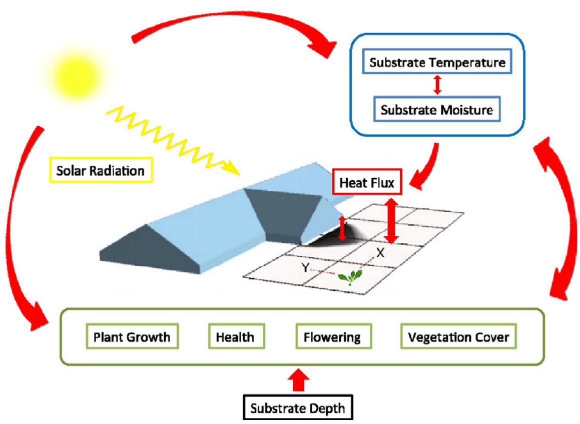
Michael Buckland-Nicks, Amy Heim, Jeremy Lundholm *

Departments of Biology and Environmental Science, Saint Mary's University, 928 Robie St., Halifax, Nova Scotia B3H 3C3, Canada

HIGHLIGHTS

- Spatial variation in insolation and substrate depth affects green roof vegetation
- Vegetation cover affected heat flux and evapotranspiration
- Plant species had different responses to spatial environmental heterogeneity
- Shading has opposite effects on thermal vs. hydrological properties

GRAPHICAL ABSTRACT



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ABSTRACT

Green roofs provide ecosystem services, including stormwater retention and reductions in heat transfer through the roof. Microclimates, as well as designed features of green roofs, such as substrate and vegetation, affect the magnitude of these services. Many green roofs are partially shaded by surrounding buildings, but the effects of this within-roof spatial environmental heterogeneity on thermal performance and other ecosystem services have not been examined. We quantified the effects of spatial heterogeneity in solar radiation, substrate depth and other variables affected by these drivers on vegetation and ecosystem services in an extensive green roof. Spatial heterogeneity in substrate depth and insolation were correlated with differential growth, survival and flowering in two focal plant species. These effects were likely driven by the resulting spatial heterogeneity in substrate temperature and moisture content. Thermal performance (indicated by heat flux and substrate temperature) was influenced by spatial heterogeneity in vegetation cover and substrate depth. Areas with less insolation were cooler in summer and had greater substrate moisture, leading to more favorable conditions for plant growth and survival. Spatial variation in substrate moisture (7%–26% volumetric moisture content) and temperature (21 °C–36 °C) during hot sunny conditions in summer could cause large differences in stormwater retention and heat flux within a single green roof. Shaded areas promote smaller heat fluxes through the roof, leading to energy savings, but lower evapotranspiration in these areas should reduce stormwater retention capacity. Spatial heterogeneity can thus result in trade-offs between different ecosystem services. The effects of these spatial heterogeneities are likely widespread in green roofs. Structures that provide shelter from sun and

* Corresponding author.
E-mail address: jlundholm@smu.ca (J. Lundholm).

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wind may be productively utilized to design higher functioning green roofs and increase biodiversity by providing habitat heterogeneity.

1. Introduction

The process of urban development replaces original land surfaces, usually containing soils and vegetation that provide many ecosystem functions (Nowak et al., 2002), with impervious surfaces, such as roads and buildings (Pauleit et al., 2005). This can result in a loss in ecosystem functioning (Alberti, 2005) and issues with controlling stormwater runoff (Scholz-Barth, 2001). The installation of a green roof system produces several benefits, some of which can help mitigate these impacts (Dunnett and Kingsbury, 2004). Green roofs provide a layer of "soil" and vegetation to offset the original loss of these landscape features. Most green roof systems support shallow substrates, often <15 cm deep ("extensive green roofs"). These systems remain the focus of green roof research due to their lower cost, use of fewer materials, and the fact that they can be retrofitted on many pre-existing buildings with little or no additional structural support needed, which offers the possibility of widespread use (Dunnett and Kingsbury, 2004). The shallow substrate limits the number of plant species that can be grown on them. Since there is much less soil, growing conditions on extensive green roofs tend to be much harsher for plants, as there tends to be less water availability and room for roots to grow (Wolf and Lundholm, 2008). Other challenges for plants growing in these systems can include high wind and sun exposure (Dunnett and Kingsbury, 2004).

Most research on green roofs focuses on quantifying thermal and water retention properties (Lundholm and Williams, 2015), but very little research has considered how spatial environmental variability can affect these functions. Green roofs can result in savings in the costs of heating or cooling buildings (Saiz et al., 2006; Sailor, 2008). To assess green roof thermal performance, researchers usually model or measure net vertical heat flux across the roof (Sailor, 2008; Getter et al., 2011). Vegetation properties can have a substantial influence on thermal performance (Lundholm and Williams, 2015). It is also well-known that abiotic factors, such as exposure to wind and different amounts of solar radiation, can directly or indirectly influence the growth of plants and the composition of plant communities (Hoefs and Shay, 1981; Chapin et al., 1987; Theodosiou, 2003; Getter et al., 2009). Spatial heterogeneity in microenvironments caused by shading from adjacent buildings is common on many green roofs, and is likely to affect plant growth, vegetation patterns and ecosystem functions (Piana and Carlisle, 2014). To improve our understanding of the ecological services provided by green roofs and how they can be optimized, we need to gain a better understanding of the relationship between spatial and temporal environmental variability on green roofs and the responses of different plant species. Geographic Information Systems (GIS) provide a way to visualize spatial data and can be used to help reveal patterns and relationships that might not be apparent from traditional methods of data analysis (Piana and Carlisle, 2014).

The overall goals of the study were to determine the relationships between spatial heterogeneity in the green roof environment and patterns of variation in plant growth, vegetation patterns and the thermal performance of a green roof in summer and winter. We selected individual plants from two dominant species on an extensive green roof in Halifax, Nova Scotia. We quantified plant growth, health, and reproductive success during the growing season in 2014, as well as variables characterizing the growth environment of these individual plants. Using GIS, we incorporated target plant locations in order to visualize the relationships between measured environmental and plant growth variables and modelled solar radiation over the surface of the green roof. Finally, we examined correlations between plant growth, associated environmental variables and thermal performance indicators of the green roof.

2. Materials and methods

2.1. The study roof

We assessed spatial environmental variability and plant performance on an extensive green roof located on top of the Atrium building at Saint Mary's University, Halifax, NS. Halifax has a cold, humid, maritime climate (Tables A.1, A.2). This study roof was installed in the spring of 2010 and measures approximately 24 by 9 m in the shape of a rectangle (Fig. 1). The green roof system consists of: 7.5 cm of commercial substrate used for extensive green roofs (Sopraflor X, Soprema Inc., Drummondville, Quebec); extensive green roof drainage containers (ELT EasyGreen, Brant-ford, Ontario); a roof membrane; a 2.5 cm thick plywood protection board; and rigid polyisocyanurate ($R = 5$ per 2.5 cm) with a thickness ranging from 5 to 15 cm, which sits on top of the steel roof deck. A parapet around the edge of the green roof rises 20 cm above the base of the substrate (approximately 12.5 cm from the surface of the substrate on average).

The green roof contains eight separate sections, each 4.5 m × 6 m (Fig. A.2). All sections have their own roof drain and are separated by metal edging and rubber pond liners to prevent water from moving between sections. We planted plugs of four species with a 15 cm spacing in 2010 and within several years plants became established and approximately 50% cover of vascular plants was achieved. Initial planting included equal numbers of *Sibbaldiopsis tridentata* (Aiton) Rydb., *Danthonia spicata* (L.) Beauv., *Deschampsia flexuosa* (L.) Trin. and *Solidago bicolor* L. By the time of this study in the 2014 growing season, *S. tridentata* and *S. bicolor* were dominant in the vegetation. Within one year of the original planting, the mosses *Ceratodon purpureus* (Hedw.) Brid., *Funaria hygrometrica* Hedw. and *Bryum argenteum* Hedw. had spontaneously colonized areas with low coverage of vascular plants. At planting time in 2010, substrate depth was uniform at 7.5 cm, but by the time of this study, depths ranged from 4 cm to 10 cm.

2.2. The study plants

We selected two plant species for this study: *Sibbaldiopsis tridentata* (three-toothed cinquefoil) and *Solidago bicolor* (white goldenrod). Both species are native to North America and occur naturally in Atlantic Canada. *S. tridentata* is an evergreen dwarf shrub and *S. bicolor* is an herbaceous perennial forb (USDA, 2014). We planted both species four years before the beginning of this study and selected them due to their high abundances on the site and their contrasting growth forms: *S. bicolor* produces a basal rosette, and reproductive individuals have a spike-like inflorescence borne on a tall vertical stem; *S. tridentata* spreads via rhizomes and produces numerous flowers from leafy stems.

2.3. The sampling design

We selected individual target plants growing on the green roof to achieve a uniform distribution, capturing maximal spatial variation over the whole roof (Figs. A.1, A.2). We selected nine sample points within each of the eight green roof sections, and found the closest plant of each species for each point (Appendix A). If we encountered no plant of a species within 1 m of that sample point, that location would be omitted from the study for that species. Following these