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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.

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

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[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 m^2 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 m^2 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.

Substrate was mounded in the middle of the roof at a depth of 20 cm in an oval shaped area of approximately 67 m^2. The remainder of the roof covers 165 m^2 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/cm^3, 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. refexum*, 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* (Wildtytpe Nursery, Mason, MI). All plants were installed October 8–10, 2011. A controlled release fertilizer (Osmocote Plus X 15 N–9 P_2O_5–12 K_2O 5-month release, Everis International BV) was applied the following spring at a rate of 11.0 g/m^2 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.