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Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate

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ABSTRACT

Green roofs, or vegetated roofs, can reduce heat flux magnitude through a building envelope as a result of insulation provided by the growing medium, shading from the plant canopy, and transpirational cooling provided by the plants. This study quantifies the thermal properties of an inverted 325 m^2 retro-fitted extensive green roof versus a traditional gravel ballasted inverted roof in a Midwestern U.S. climate characterized by hot, humid summers and cold, snowy winters. In autumn, green roof temperatures were consistently 5 °C lower than corresponding gravel roof temperatures. Even during chilly and moist conditions, the heat flux leaving the building was lower for the green roof than the gravel roof. Temperatures at the top of the insulation layer were more variable for both green roof and gravel roof on winter days with no snow cover than on days with snow cover. Variation in temperatures between roof types in spring was similar to those in autumn. Peak temperature differences between gravel and green roof were larger in summer than other seasons (sometimes by as much as 20 °C). Over the course of a year (September 2005–August 2006), maximum and minimum average monthly temperatures and heat fluxes were consistently more extreme for the gravel roof than the green roof.

1. Introduction

Green roofs, or vegetated roofs, can reduce heat flux through a building envelope because the "soil" or growing media acts as an insulation layer, the plant canopy shades the roof, and plants are believed to provide transpirational cooling [1–5]. In previous work, Theodosiou [4] found that during a Mediterranean summer, thicker growing media increased the thermal inertia, but also allowed taller plants and greater leaf area index (LAI) which provided more shading and transpirational cooling than thinner media profiles. These properties of a green roof resulted in 20 °C lower temperatures beneath a green roof compared to a conventional roof on a hot day and 10 °C warmer on a cold day in temperate regions [6]. In tropical regions the difference may be greater. Simmons et al. [7] compared six different extensive green roof designs with conventional black roofs and reflective white roofs in Texas. When ambient air temperature reached 33 °C, membrane temperatures on conventional black and white reflective roofs reached 68 °C and 42 °C, respectively, but only ranged between 31 and 38 °C on the green roofs. A study performed in the Pacific Northwestern U.S. found a 13% reduction in winter heat flux through a green roof and 72% in summer heat flux relative to a conventional gravel ballast roof [8].

Because green roofs reduce heat transport (both into and out of the building), they have the potential to reduce energy consumption for heating and cooling. Sailor [9] integrated the elements of a green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations suggested 2% reductions in electricity consumption and 9–11% reductions in natural gas consumption. Based on his model of a generic building with a 2000 m^2 green roof, savings range from 27.2 to 30.7 GJ/year of electricity and 9.5 to 38.6 GJ/year of natural gas, depending on climate and green roof design. An additional 25% reduction in electricity use was proposed from indirect heat island reduction achieved from large-scale green roof implementation throughout an urban area [10].

Since buildings consume 39% of total energy used and 71% of all electricity consumption in the U.S. [11], green roof implementation on a wide scale could significantly impact energy consumption with subsequent monetary savings and carbon emission reductions. Assuming national commercial average prices of $0.1026/kWh [12] and $10.06/Mcf [13] for electricity and natural gas, respectively, Sailor's [9] 2000 m^2 generic green roof energy reductions translate to a monetary savings of $965–1144 for electricity and natural gas combined annually ($0.48–.57/m^2 of green roof), depending

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on climate and roof design. Other research indicated that if the campus of Michigan State University implemented green roofs on all low-sloped roof surfaces, CO_2 emission reductions up to 3.64×10^6 kg/year would be possible due to decreased electricity and natural gas consumption [14]. This is the equivalent of taking 650 vehicles off the road each year [15]. In addition to CO_2 avoidance, the green roof itself can also sequester carbon in the plant material and growing medium [16].

Potential energy consumption reductions depend on many factors such as green roof growing media composition, depth, and moisture content, plant species, supplementary irrigation and local climate. In addition, building type and construction details may influence the thermal properties of a green roof building. Researchers in Athens, Greece found that energy savings by installing a green roof ranged from 2% for well-insulated buildings versus 37–48% for non-insulated buildings [17]. In the U.S. and other temperate countries, inverted roofs are constructed on buildings by placing the thermal insulation above the waterproofing layer. This protects the waterproofing from extreme changes in temperature as well as UV radiation and mechanical damage. A green roof over an inverted roof may not yield the range of thermal benefits as a non-inverted roof, although these differences have not been extensively studied.

Due to building weight restrictions and implantation costs, shallow growing media extensive green roofs are more common than deeper intensive roofs [18–21]. Older buildings will likely benefit the most from green roofs because newer buildings often contain deeper layers of insulation [22]. Snow cover may also provide a very effective natural layer of insulation [23], although very few studies have been performed on energy analysis in climates where snow cover is common during winter. The objective of this study was to quantify thermal properties of an extensive green roof installed over an inverted roof against a traditional gravel ballasted inverted roof in a Midwestern U.S. climate characterized by hot humid summers and cold snowy winters.

2. Methodology

2.1. Roof construction

A 325.2 m^2 (3500 ft^2) extensive green roof was installed on a portion of the Plant and Soil Sciences Building roof on the Michigan State University campus in East Lansing, MI on 21 May 2004. Structural reinforcement of the building was not necessary because the vegetated section had a saturated weight of less than eight pounds per square foot, which is roughly equivalent to the removed gravel ballast. This building is a steel-deck inverted roof assembly insulated with extruded polystyrene. The study area was covered with a root barrier (XF112; Xero Flor America LLC, Durham, NC) installed over the existing roof insulation. A drainage mat (XF108H) was placed over the root barrier, followed by a water retention fleece (XF159). The growing media and plants were installed by laying out pre-grown vegetated mats (XF301) which consisted of a carrier containing at least 5 cm (2.0 in) of proprietary media (XeroTerr®) consisting of a combination of heat expanded slate (PermaTill, Salisbury, NC), sand, and organic matter. Physical properties of the growing medium were sampled and analyzed (Great Lakes Laboratories, Inc., Fort Wayne, IN) and consisted of 91.18% total sand (21.96% very coarse sand (1.0–2.0 mm), 40.8% coarse sand (0.5–1.0 mm), 24.06% medium sand (0.25–0.5 mm), 3.36% fine sand (0.10–0.25 mm), 0.4% very fine sand (0.05–0.1 mm)), 7.16% silt, and 1.66% clay. The bulk density was 1.17 g/cm^3, capillary pore space was 19.96%, non-capillary pore space was 21.43%, and the water holding capacity at 0.01 MPa was 17.07%.

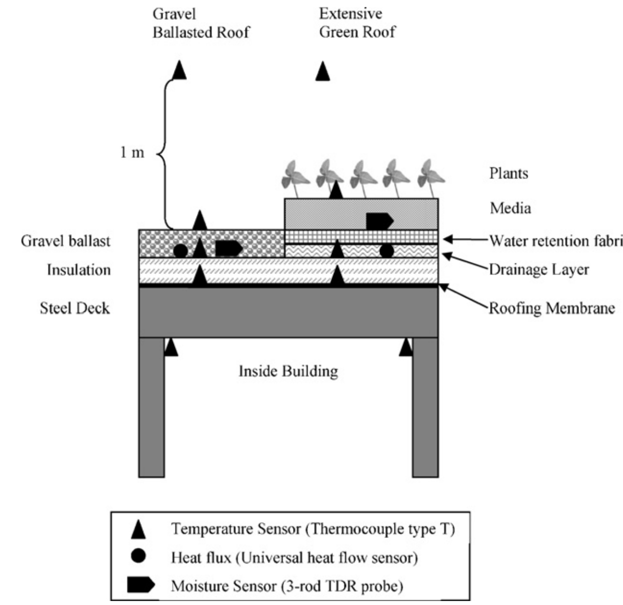

Fig. 1. Location of temperature, heat flux, and moisture sensors on extensive green roof and gravel ballasted roof.

2.2. Plant material and culture

Plant species on the pre-grown mats were *Hylotelephium spectabile*, *Hylotelephium verticillatum*, *Saxifraga granulate*, *Sedum acre*, *Sedum album*, *Sedum ellacombianum*, *Sedum floriferum*, *Sedum kamtschaticum*, *Sedum pulchellum*, *Sedum reflexum*, *Sedum sexangulare*, and *Sedum spurium* 'Coccineum'. Slow release fertilizer (LESCO 14-14-14 Professional Landscape and Ornamental All-Purpose Fertilizer; Cleveland, OH) was applied on 15 April 2005 at a rate of 14 g/m^2 and again yearly each spring. Irrigation, which occurred on an as-needed basis by hand watering during 2004, ceased thereafter.

2.3. Environmental monitoring

Temperature, heat flux, soil moisture, and ambient weather conditions were recorded using a CR10X Datalogger (Campbell Scientific, Inc., Logan, UT), three AM25T 25-Channel Solid-State Multiplexors (Campbell Scientific, Inc., Logan, UT), and a TDR-100 Time-Domain Reflectometer (Campbell Scientific, Inc., Logan, UT). The gravel portion of the roof and the vegetative side of the roof each had three measurement stations, spaced 3.0 m (10 ft) apart. Each station had five thermocouples (Campbell Scientific Type T 105T-L) installed in the following profile locations: 1 m (3.3 ft) above the roof inside a non-aspirated solar radiation shield; on top of the growing media (or gravel); on top of the insulation; on top of the roofing membrane; and inside the building directly against the ceiling (Fig. 1). Thermocouple accuracy ranged from ±0.365 °C, ±0.1 °C, and ±0.25 °C for temperatures in the range of −73 °C, 20 °C, and 50 °C, respectively. A universal heat flow sensor (Concept Engineering, Old Saybrook, CT) was installed on top of the roof insulation at each measurement station. The sensor, which was deployed so that negative and positive readings would measure heat entering and leaving the building, respectively, had an accuracy of ±5%.

A soil moisture probe (Moisture Sensor CS605-L 3-rod TDR probe-RG58, Campbell Scientific) was installed horizontally at each site either directly on top of the water retention fabric (for the green roof) or directly on top of the insulation (for the gravel roof) so that all prongs were covered either below the media or below