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Thermal behavior of green roofs under Nordic winter conditions

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A B S T R A C T

To understand how green roofs affect building energy performance under cold climatic conditions, a proper thermal analysis of the roof and its components is required. To address this, we measured the thermal conductivity of each layer of experimental green roofs, as well as equivalent thermal resistance of the complete green roof system during winter conditions in southern Finland. Three experimental green roof platforms (1 m × 2 m) with heated boxes and three identical bare roof platforms (without substrate, vegetation and other green roof layers) were equipped with thermocouples that continuously measured a vertical temperature profile through the roofs. A steady-state heat transfer analysis was performed to assess the functioning and relative thermal performance of the green roof systems. Layer analysis at various intensities of frost penetration showed that the thermal conductivity of each layer decreased when penetrated by frost. In particular, thermal conductivity of the substrate and vegetation layers decreased from 0.41 $Wm^{-1}K^{-1}$ and 0.34 $Wm^{-1}K^{-1}$ prior to freezing, to 0.12 $Wm^{-1}K^{-1}$ and 0.10 $Wm^{-1}K^{-1}$ after freezing, respectively. This phenomenon is explained by a reduction in bridge-water connectivity during freezing and a volumetric water content that was below the critical threshold value. Overall, a frost depth that extended through the complete green roof yielded the greatest equivalent thermal resistance. During times of snow cover, snow acted as an insulator and reduced the relative energy saving benefits achieved by green roofs. These results provide information for designing the substrate and vegetation layers of green roofs for optimal insulation.

1. Introduction

To make buildings more environmentally friendly, new energy efficient technologies and designs are continually sought after. A green, or vegetated roof, is a structural design approach that brings nature and engineering together to provide a sustainable alternative to conventional roofing [1]. Among the multifunctional benefits that a green roof provides, improved building envelope thermodynamics has been an important aspect for reducing energy consumption within the building sector [2,3]. As a living system, a green roof's thermal behavior is highly influenced by the surrounding climate. While it has been shown that they are effective tools for reducing cooling energy demands in warm and sunny climates [4–6], in cold climates, where heat energy demands dominate, there is still general uncertainty and a lack of research about how beneficial a green roof may be [3].

Winter thermal benefits achieved from a green roof system depend on vegetation type and material properties of the layers, including thickness, physical structure and thermal conductivity [7–9]. Commonly, the layers of a green roof from the top down consist of surface vegetation, substrate, filter/water retaining mat, drainage/root barrier, and a waterproofing membrane that all sit atop the structural support. When necessary, green roofs also utilize synthetic insulation at their base in order to ensure adequate thermal resistance [10].

A green roof will keep itself, and the building below, cool in the summer by means of evapotranspiration, photosynthesis and shading and yet remain an effective thermal mass in winter when vegetation is dormant and evapotranspiration negligible [11]. In comparison, an insulation system of only synthetic materials works well but is limited in performance due to constant thermal properties throughout the year. The synthetic system can thus only be optimized in terms of material thickness. Therefore, in designing for best annual energy use, indoor thermal comfort, and sustainability, application of a vegetated system in conjunction with

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minimal synthetic insulation, may provide the greatest thermal performance for Nordic climates [6,11–13].

A modelling study on four different climates in the United States has shown that green roofs have had greater heating energy savings in colder climates [14]. It has also been shown that roof and wall vegetation could considerably reduce heat loss through the building's façade in winter by reducing convective heat loss [15,16]. Thermal mass of the green roof has been shown to reduce heat flux through the green roof during winter, by 1–2 Wm^{-2}, and create more stable internal temperatures compared to a conventional roof [17,18]. Two studies conducted in the sub-tropical winters of Hong Kong have shown beneficial results for an extensive green roof (traditionally defined as green roofs with shallow substrates, see Ref. [19]) and negative results for an intensive green roof (with thicker substrates [19]). In the case of the extensive roof, roofing materials acted as a heat sink that released heat into the building during cooler nights [20]. In the case of the intensive roof, heat was lost from the substrate to the air, drawing warmer indoor air outwards [21]. In the French temperate climate, a green roof was shown to have very little impact on overall heating demands due to reduced heat losses during cold winter days along with a reduction in positive solar gains during sunny winter days [22]. Furthermore it was shown that snow effectively insulates buildings but scales down the relative benefits that a green roof can have compared to a conventional roof [2,23,24]. In the case of extreme weather conditions with sub-zero temperatures and severe wind and rain, the benefits of green roofs tend to increase [25], however, ice transfers heat energy more efficiently through its medium compared to liquid water [26], suggesting greater heat loss for frozen green roofs. Overall, given the variable performance in cold climates, a detailed understanding of energy loss and heat flux through green roof systems is still required.

Currently, very few studies have examined the thermal behavior of green roof layers during ice and snow conditions and none have exclusively evaluated overall or layer-specific thermal conductivity (k-values, see Ref. [26]). Since the thermal properties of a green roof vary significantly with moisture [7,27], and the thermal behavior of soil is affected by degree of frost penetration [28–30], it is important to develop k-values for the green roof and its component layers during winter conditions. Knowledge on the thermal behavior of the individual layers during times of freezing and thawing and different levels of frost intensity would enable a better understanding of green roof thermal performance and resulting heat flux under various winter conditions. A particular focus of this study is on the behavior of the substrate layer because of its complexity for design applications and because there are no current guidelines for the type of substrate to use for best thermal performance in freezing conditions.

In this study we hypothesized that (i) frost penetration will increase green roof and green roof layer k-values, (ii) substrate is expected to exhibit a positive relationship between volumetric water content and k-values above 0 °C and a positive relationship between frost intensity and k-values below 0 °C, (iii) heat flux through the green roof will be less than the bare roof for the majority of the winter period, and (iv) snow cover will act as an additional insulation layer, reducing heat flux through both roofing systems.

2. Methods

2.1. Experimental setup

The experiment was carried out at Jokimaa, a University of Helsinki research station located in Lahti, southern Finland (60°52′N, 25°52′E), where winter is the dominant season, with long periods of sub-zero temperatures and snow cover that typically last 135–145 days [31].

Twenty-five roof platforms, each 1 m × 2 m in size at a height of 1.5 m were constructed at the station. Six of the platforms were used in this study (three green roofs and three bare or control roofs) (Fig. 1). The base, or supporting layer, was a 24 mm thick hardwood plywood. The bare roofs consisted only of the hardwood plywood support layer. For the green roofs, directly atop the plywood was an "Antico Rankka" moisture barrier sheet followed by a 25 mm thick water retaining and drainage layer made of molded polystyrene ("Nophadrain" [32]), hereafter referred to as the "drainage" layer. On top of the drainage layer was a 10 mm thick water holding filter fabric ("VT-filt": water storage capacity 8 l m^{-2} [32]) used to prevent the loss of substrate particles and to retain water, hereafter referred to as the "fabric" layer. On top of these layers was a 50–60 mm thick substrate layer made of crushed recycled brick (85%), bark chippings (5%), peat (5%) and compost (5%; all percentages by fresh volume) (see Fig. 2 for particle size distribution).

The top layer was a pre-grown vegetation "Veg Tech" mat with a nominal thickness of 40 mm and supported drought resistant species of sedum, moss, and grass [32]. The dry density of the substrate and vegetation layers was on average 1.37 g cm^{-3} and 1.17 g cm^{-3}, respectively. A closed 0.30 m^3 (internal volume) insulated box was placed below each of the six roofing structures. The box had five walls made of extruded polystyrene, a housing insulation material ("Finnfoam 300/50") attached to the bottom surface of the plywood layer. All boxes were equipped with identical heating sources: a 25 W incandescent light bulb running at 90% inefficiency, 24 h per day.

2.2. Data collection

For the green roofs, thermocouples with moisture sensors were placed on the vegetation surfaces, within the substrates, on the top surface of the supporting structures (plywood), and inside the insulated boxes. For the bare roofs, they were placed on the supporting structures, and inside the insulated boxes (Fig. 1). Together the thermocouples were arranged in a vertical line that passed through the centroid of the insulated box. Temperature and moisture data were recorded at 20-min time intervals, 24 h per day at an accuracy of ±1 °C and ±3% VWC [33]. VWC data were determined by measuring the dielectric constant of the media using capacitance/frequency domain technology at 70 MHz frequency and are reliable only in soil [33]. Data loggers ("Decagon devices Em50") collected the data. The on-site Vaisala WXT520 Micro Weather Station provided data on ambient air temperature and precipitation, and recorded data at 10-min intervals. Snowfall and snow depth information was obtained from the Finnish Meteorological Institute's Laune weather station, located 5 km from the experimental site. The measurement period for the roof ran from the beginning of October 2013 to the end of March 2014.

A linear one-dimensional temperature gradient was assumed in the vertical direction [34] and when the temperature of the thermocouple decreased below zero degrees, it was assumed that the layer and those above it, were penetrated by frost equal to the depth of the thermocouple. When temperatures decreased further, it was assumed that frost was penetrating further downward into the green roof. Since the fabric and drainage layer did not have thermocouples within them, temperatures from the thermocouple on the plywood surface were used to indicate that these bottom layers had frozen. All data were averaged over the three replications. Means and standard deviations reported assume normally distributed data.

Temperature data were separated into phases determined by level of frost depth penetration (Table 1). This was done in order to