Building and Environment 70 (2013) 266–276

Contents lists available at ScienceDirect

Building and Environment

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

Assessing practical measures to reduce urban heat: Green and cool roofs

Andrew M. Coutts [a, c, *], Edoardo Daly [b, c], Jason Beringer [a, c], Nigel J. Tapper [a, c]

[a] School of Geography and Environmental Science, Monash University, Melbourne, VIC 3800, Australia
[b] Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia
[c] CRC for Water Sensitive Cities, Australia

ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form
2 August 2013
Accepted 4 August 2013

Keywords:
Green roofs
Cool roofs
Surface energy balance
Evapotranspiration
Irrigation

ABSTRACT

As cities continue to grow and develop under climate change, identifying and assessing practical approaches to mitigate high urban temperatures is critical to help provide thermally comfortable, attractive and sustainable urban environments. Green and cool roofs are commonly reported to provide urban heat mitigation potential; however, their performance is highly dependent upon their design, particularly green roofs that vary in substrate depth, vegetation species, and watering regime. This study compares the insulating properties, the radiation budget and surface energy balance of four experimental rooftops, including a green roof (extensive green roof planted with *Sedum*) and a cool roof (uninsulated rooftop coated with white elastomeric paint), over the summer of 2011–12 in Melbourne, Australia. For the roof treatments explored here, results suggest that cool roofs, combined with insulation, provide the greatest overall benefit in terms of urban heat mitigation and energy transfer into buildings. The high albedo of the cool roof substantially reduced net radiation, leaving less energy available at the surface for sensible heating during the day. Under warm and sunny conditions, when soil moisture was limited, evapotranspiration from the green roof was low, leading to high sensible heat fluxes during the day. Irrigation improved the performance of the green roof by increasing evapotranspiration. Daytime Bowen ratios decreased from above four during dry conditions, to less than one after irrigation, yet sensible heat fluxes were still higher than for the cool roof. These results demonstrate that rooftops must be designed accordingly to target specific performance objectives, such as heat mitigation.

1. Introduction

Governments, city managers and urban residents are seeking practical approaches to improve urban heat mitigation at least cost as adaptation to global warming, extreme heat events and urban heat effects. Green roofs are commonly purported as a key approach for mitigating heat in urban areas [1–4] because of their thermal benefits, including the insulating effect of the soil substrate and vegetation, the shading from the plant canopy and transpirational cooling [5]. In a review of green roof studies, Chen and Wong [6] found that green roofs could greatly reduce rooftop surface temperatures and create energy savings for buildings, while also reducing ambient air temperatures. Likewise, cool roofs (white and/or reflective roofs) may also provide efficient mitigation of atmospheric heating and building energy savings through an increase in surface albedo [7,8].

Several studies have been undertaken comparing the benefits of green and cool roofs in terms of building energy efficiency and rooftop microclimates. Takebayashi and Moriyama [4] used both experimental and modelling approaches to compare green and white roofs in Kobe, Japan. They found that, during the day, peak sensible heat fluxes (Q_H) were small for the white roof (153 W m^{-2}) due to the low net radiation (Q^*) achieved by high solar reflectance. Q_H was also relatively small (361 W m^{-2}) on the green roofs because of the large evapotranspiration (Q_E), which peaked between 400 and 600 W m^{-2}. However, despite the energy spent for evapotranspiration, Q_H of the green roof was still twice as high as the white roof. Scherba et al. [9] modelled the performance of green and white roofs, finding that peak daytime Q_H was similar, but the total daily Q_H was higher for green roofs because the thermal mass of the green roof maintained positive Q_H at night. Scherba et al. [9] acknowledged that only one green roof configuration was modelled, and noted that factors such as irrigation specifications

* Corresponding author. School of Geography and Environmental Science, Monash University, Room 205, Building 28, Wellington Rd., Clayton, VIC 3800, Australia. Tel.: +61 03 9905 8284.
E-mail address: Andrew.Coutts@monash.edu (A.M. Coutts).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.08.021

could impact green roof Q_H. In a review of green and cool roof effectiveness, Santamouris [10] deemed that, when the albedo of reflective roofs is 0.7 or higher, cool roofs present a higher heat island mitigation potential compared to green roofs. Santamouris [10] also argued that green roofs could deliver similar cooling potential during peak temperature periods if Q_E exceeds 400 W m^{-2}; this would be possible for very well irrigated vegetated roofs (in studies reviewed, solar radiation varied between 500 and 1000 W m^{-2}).

Accordingly, of critical importance in green roof design is the hydrological performance, which influences the rooftop surface energy balance and, hence, rooftop microclimate. For instance, the choice of substrate type and depth affects Q_E, due to different water retention [11], as well as the insulating effects of green roofs [12]. Vegetation type affects the rate of water loss from green roofs through transpiration and the subsequent cooling effect; additionally, plants can have different shading effects on roof surface cooling [13]. Many green roofs are constructed using a combination of shallow soils and drought tolerant plant species that can survive harsh rooftop environments and low water availability [14,15]. Such environments may compromise plant transpiration due to stomatal closure [16] and limit green roof cooling potential via Q_E. If the specific goal of green roofs is for urban heat mitigation, then they need to be designed carefully to maximize the benefits, as green roof performance varies widely [17].

A key function of green roofs is to capture and retain rainfall on the roof and they are often implemented to help manage urban stormwater. While a number of studies have documented a reduction in stormwater runoff volumes from green roofs [18,19], few have directly quantified rates of evapotranspiration [20], although agreeing that green roofs mitigate high rooftop heating partly through an increase in Q_E [21,22]. In greenhouse trials of green roof systems planted with *Sedum mexicanum* and *Disphyma austral*, Voyde et al. [20] observed that the rapid water loss via Q_E in the days following watering gradually reduced as water supplies became limited, until plants stopped transpiring to conserve water. Similarly, using a weighing platform as part of an environmental chamber laboratory setup, Tabares-Velasco and Srebric [23] found that Q_E decreased as substrate water content decreased. Evapotranspiration occurred both during the day and night time periods, and Tabares-Velasco and Srebric [23] determined that substrate water content was the most important factor in determining Q_E. These results highlight the risk that green roofs may not be able to provide a strong benefit to rooftop microclimates during extreme heat events when it is most needed because of water shortage in the substrate. It therefore becomes fundamental to define the desired performance characteristics of urban roofs and the appropriate design to meet those criteria. As such, if heat mitigation is a primary goal, then irrigation may be necessary to support vegetation health and promote Q_E.

The design of rooftops has a strong influence on the partitioning of energy at the roof surface, and hence the adjacent rooftop microclimate and internal building temperatures. To help identify and compare the effectiveness of rooftop treatments to mitigate urban heat, this study examines the thermal performance of different roofs, focussing on green and cool roofs. The comparison is based on a) energy storage and heat transfer through each rooftop, and b) the surface energy balance of each rooftop. The emphasis here was on retrofitting existing roofs, so an extensive green roof with shallow soil substrate was used in the experiments. Due to the importance of design and water availability on the performance of green roofs for cooling by evapotranspiration, we also assessed the role of irrigation on the surface energy balance. Because green roofs are considered a form of water sensitive urban design (WSUD) and given our exploration of irrigation effects, our study also touches upon issues of urban stormwater management. As such, the study concludes by assessing the performance of different roofs within the context of urban stormwater management, discussing strategies to best promote urban cooling and improved human thermal comfort [24].

2. Methodology

2.1. Experimental setup

Four experimental roofs were compared: a conventional steel sheet roof (STEEL), a steel sheet roof covered with white, high albedo paint (WHITE), a vegetated roof (VEG), and a roof with just the soil layer (no vegetation) (SOIL). These experimental roofs were 2.4 m × 2.4 m wooden platforms erected on stilts at a height of 1 m (Fig. 1). They were in close proximity (<2 m) to each other and were inclined at a slope of 15°. STEEL had a base of 20 mm plywood, with

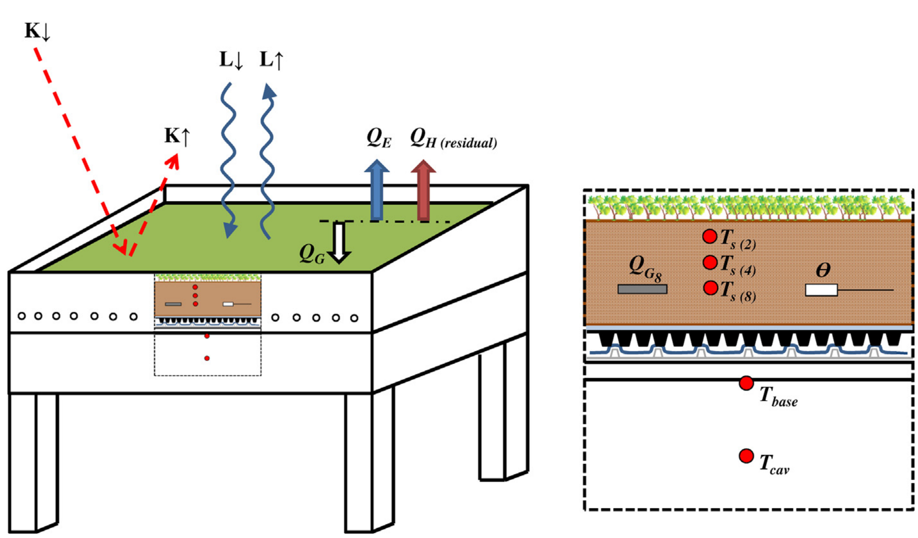

Fig. 1. Construction of the vegetated roof (VEG) and experimental approach. VEG consisted of a plywood base, steel sheet, black poly membrane, plastic 'egg cup' sheet, geotextile layer and a scoria-soil mixture. The vegetation type was *Sedum rubrotinctum*. The measured daytime energy balance is represented schematically (left) along with the measured soil and cavity variables (right).