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Functional green roofs: Importance of plant choice in maximising summertime environmental cooling and substrate insulation potential

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ABSTRACT

Green roof plants can reduce local air temperatures and heat load to a building in the summer, improving thermal comfort of residents. Little is known, however, about how different plants compare in their potential to provide these two ecosystem services. Consequently, this study investigated whether some plants can offer more potential summertime environmental cooling and substrate insulation than others. Over two summers (2012/2013), canopies of two succulent and four broad-leaved plant genotypes, with contrasting plant traits, were monitored alongside bare substrate in Reading, UK. Plants were studied outdoors within small plots ($1.5 \times 1.5 \times 0.1$ m). Continuous monitoring took place during warm days and nights and included variables (leaf surface temperatures) and fluxes (long-wave radiation, sensible heat flux and transpiration) that are indicative of cooling potential. The strength of substrate insulation was estimated by comparing the ground heat flux below the canopies to that of the bare substrate. Plant traits (leaf colour or thickness), structural parameters (height and leaf area index, LAI), radiative properties (albedo and emissivity), and stomatal conductance were also measured to help explain the differences in cooling potential among the species. Non-succulent canopies, in particular light-coloured ones, with high leaf stomatal conductance and high LAI provided maximum potential for substrate insulation and environmental cooling in hot periods, particularly compared to bare substrate and thick-leaved succulents. These results suggest that succulent plants are not best suited to provide significant summertime environmental cooling and substrate insulation and that others (e.g. *Salvia* and *Stachys*) might be preferable where the delivery of these benefits is a priority. Our findings highlight that, in addition to survival, aesthetics and cost, the plants' ability to deliver a range of ecosystem services should be considered in the plant selection/green roof planning process.

1. Introduction

Urban landscapes are typically warmer than adjacent rural areas [1]. This phenomenon, (the urban heat island, UHI), is partly due to anthropogenic activities which generate heat that becomes trapped within the urban fabric. It is also due to a widespread use of impervious materials, which alter the thermal and radiative properties of the land surface, significantly influencing the surface energy balance [2,3] . In urbanised areas, latent heat flux (i.e. evapotranspiration) is thus reduced compared to more rural, vegetated areas, while heat storage and the resulting re-emission of heat as long-wave radiation or sensible heat are increased. The heat absorbed, stored and re-released as long-wave radiation by the urban fabric to the atmosphere can also be intercepted by air pollutants and redirected back to the urban environment, contributing to further warming [3].

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Nomenclature

ANOVA	Analysis of variance
C_p	Air specific heat (1010 J kg^{-1} K^{-1})
d	Zero plane displacement height (m)
G	Substrate heat flux (W m^{-2})
g_s	Leaf stomatal conductance to water vapour (mmol m^{-2} s^{-1})
H	Sensible heat flux (W m^{-2})
h	Surface height (m)
k	von Karman's constant (0.41)
LAI	Leaf area index (m^2 m^{-2})
LE	Latent heat flux (W m^{-2})
L_i	Incoming long-wave radiation (W m^{-2})
L_o	Outgoing long-wave radiation (W m^{-2})
LSD	Least significant difference
r_a	Aerodynamic resistance (s m^{-1})
REML	Residual maximum likelihood
R_n	Net radiation (W m^{-2})
S_i	Incoming short-wave radiation (W m^{-2})
S_o	Outgoing short-wave radiation (W m^{-2})
SMC	Substrate moisture content (m^3 m^{-3})
T	Substrate temperature (°C)
T_a	Air temperature at 2 m (°C)
T_{max}	Maximum air temperature (°C)
T_{min}	Minimum air temperature (°C)
T_s	Leaf/substrate surface temperature (°C)
U_z	Wind speed at 2 m (m s^{-1})
z	Height/depth of sensors (m)
z_{oh}	Surface roughness length for heat and vapour transfer (m)
z_{om}	Surface roughness length for momentum transfer (m)
Greek symbols	
α	Albedo
ε	Surface emissivity
λ	Substrate thermal conductivity (W m^{-1} K^{-1})
σ	Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
ρ_a	Air density (1.2 kg m^{-3})

The UHI generally has a negative impact on human thermal comfort and health, and this impact is predicted to increase due to a warming climate. For example, by the 2080s, mean summertime maximum air temperatures in southern England are estimated to rise by an average of 5.4 °C, compared to 1961–1990 [4]. Heat wave events, which amplify human mortality rates, are also expected to increase in intensity, duration and frequency [5]. Residents in urban areas will be particularly susceptible to such events, owing to the already enhanced temperatures associated with the UHI effect.

Plants in cities have an important role in reducing local summertime air temperatures and can mitigate local UHI [6–9]. However, the area available in highly urbanised cities for green infrastructure expansion is scarce. Roofs can occupy around 30% of the horizontal surface within a city [10], making them prime spaces to be vegetated. In addition to being able to reduce local air temperatures [11], plants on roofs (i.e. green roofs) can further reduce the energy load to the buildings during the day in summer, thereby leading to a reduced reliance on artificial air conditioning, saving energy [12,13].

Such ecosystem services (i.e. both in terms of summertime air temperature regulation and the plants' ability to reduce the summertime conductive heat load, thus increasing the insulation of the rooftop) can be provided by a variety of mechanisms. Plants hold, and can subsequently release, relatively large volumes of water. The vapourisation of liquid water consumes about 2450 J per g of water [14]. This latent energy is retained in the water molecules that exit through the leaf stomata [15], allowing radiation absorbed by well-watered plants to dissipate without an increase in air temperature within the immediate environment. Plants on roofs may also absorb less heat than bare roof surfaces [12], due to higher reflectance, at least compared to dark surface materials such as bitumen or slate. Additionally, plants in urban areas partially absorb the long-wave energy re-emitted by the adjacent built surfaces [16] as well as shade a built surface [17]. Thus, when placed on roofs they can reduce the radiation received by the roof surface. A model simulating the thermal behaviour of green roofs when several parameters, including LAI, were manipulated, found that an increase in LAI from 2 to 5 led to a decrease of almost 250 W m^{-2} in solar radiation transmitted to the soil [18]. When combined, these features lead to green roofs (consisting of the canopy and the below-canopy rooftop) being considerably cooler in the summer than their non-green counterparts. This will result in a decrease in the heat conducted to the inner parts of the building, but also reduces the release of sensible heat and long-wave radiation by the roof, thereby decreasing the extent of warming to the wider urban environment.

While plants differ in their surface temperature when compared to inert roof materials, variations in leaf characteristics and canopy structure, substrate factors and physiological traits can vary the thermal properties of canopies associated with different species. Leaf temperature is strongly influenced by substrate moisture content and leaf stomatal conductance [19,20]. Morphological traits such as leaf colour, thickness and pubescence also influence leaf temperature [20,21].

Many green roofs are planted with succulents such as *Sedum*, as they tolerate the dry conditions common on extensive green roofs [22,23] . However if sustainable irrigation was possible, other low-growing plants with higher water requirements could survive too [24]. More water-demanding plants, if possessing the 'right' traits, could potentially generate greater environmental cooling and substrate insulation in the summer than succulents. A previous study within a Mediterranean climate, however, could not justify the use of green roofs (with succulent, grass, perennial or small shrub covering) solely on the basis of beneficial cooling effects, particularly taking into account the water use and associated costs [25]. In contrast though, in climates where natural precipitation is higher and evenly distributed over the seasons, the economic benefits of using more water-demanding plants (in terms of reduced air conditioning, for example) may outweigh costs linked to supplementary irrigation. Despite preliminary evaluations on how different roof plant communities affect the surrounding environment and the thermal performance of a roof [26–29], there is still a lack of knowledge on how key plant traits influence the energy balance of the combined substrate/vegetation layer and the implications for using different plants to provide direct cooling or insulation services.

The main aim of this research was to determine the extent to which plant genotype affects the thermodynamic properties of the substrate-vegetation system during summer. A range of plants potentially useful for green roof situations, were evaluated within the context of the UK's temperate maritime climate. This study deliberately does not account for any factors (e.g. roof/building material, roof orientation, building energy efficiency etc.) that may influence the cooling attributes of green roofs *per se*. Such an experimental set-up would struggle to be comprehensive and would be too complicated from an in-depth monitoring point of view, thereby limiting the amount, and potentially compromising the quality, of the micrometeorological and plant physiological