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Thermal regulation capacity of a green roof system in the mediterranean region: The effects of vegetation and irrigation level

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ABSTRACT

The increasing interest in green roof implementation and research is based on the environmental benefits of this technique. The thermal regulation capacity of a green roof system is considered a very relevant benefit due to its environmental and economic interest.

In this study, an experimental modular evaluation was performed to quantify the contribution of vegetation cover by evaluating two Mediterranean native species and the effect of irrigation water volume on the thermal capacity of a green roof system in a Mediterranean area.

A positive effect of the vegetation presence was evidenced, with important substrate temperature reductions during spring and summer. Daily heat gain and loss were reduced as a consequence of vegetation presence. *Sedum sediforme* performed as a better insulator than *Brachypodium phoenicoides* during the experimental period in spring and summer, with few differences in autumn and winter. The modules with the 25% of potential evapotranspiration applied as limited irrigation reported lower heat flux values than well irrigated module (considered as 50% of potential evapotranspiration) in all seasons. The plant response to irrigation treatment is here evaluated to explain the thermal regulation effect during the whole year. The main conclusion is that there is a positive influence of species selection and irrigation management in the thermal regulation properties of green roofs under Mediterranean conditions.

1. Introduction

Green roofs are considered an ancient technique [1] and are currently defined as a living system that is an extension of a roof. A green roof system typically contains a high quality water proofing membrane and root barrier, drainage system, filter fabric, a lightweight growing medium, and plants [2,3]. Modern green roof systems have been receiving increasing attention because of the synergy of their multiple ecosystem benefits, and extensive green roofing technologies are considered an alternative to addressing environmental challenges, especially in urban areas. It is generally recognized that green roof implementation provides several ecological benefits, such as biodiversity improvement in urban areas [1,4,5], runoff management [6], atmospheric and acoustic pollution reduction [7,8] and thermal regulation [9–15].

In recent decades, extensive green roofs have been considered a useful tool for sustainable development, which has largely increased the research performed on green roofs and their benefits around the world. Most of the green roof research and implementation has been developed in temperate climates without a dry season [16,17] and in arid and tropical climates [2,11]; less attention has been traditionally devoted to other climate areas such as the Mediterranean. However, this situation is changing, and several recent studies provide evidence of the major impact of climate on green roof performance and suggest the importance of local research [18,19].

The "Mediterranean" climate is defined in the Köppen–Geiger climate classification as a hot dry-summer (*Csa*), and is characterized as a temperate climate (above 0 °C but below 18 °C of mean temperature) in its coolest month with hot and dry summer period with less than 30 mm of precipitation and an average temperature in the warmest month above 22 °C [20]. Therefore, in Mediterranean climate areas, the long summer dry period has

Abbreviations: Q_d, Daily transferred heat; ET_0, Potential evapotranspiration; q, Instantaneous heat flux; SE, Standard error; (T_{air}), air temperature; $T_{subst\ (-7\ cm)}$, Temperature measured at 7 cm below substrate surface; *U*, Heat transfer coefficient; *VWC*, Volume water content; *dt*, Time interval; *WL*, Water-limited irrigation treatment; *WW*, Well-watered irrigation treatment.

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been considered as a major constraint for green roof implementation as water availability for irrigation is also a limiting factor in those areas. However, recent studies have shown sustainable green roof performance under water stress conditions in Mediterranean areas [3,6,9,19,21], suggesting that green roofs may benefit these areas. Nevertheless, quantitative approximations for understanding the influence of green roof components and climate over green roof efficiency and performance in Mediterranean climate areas are still needed.

Among the different benefits provided by green roofs, the thermal regulation of buildings and surroundings has been highlighted as one of the most relevant from both an economic and environmental point of view [22–25]. Several studies have demonstrated that extensive green roofs reduce temperature and incident radiation by shading the roof surface and through enhanced evaporation [3,6,11,24,26]. Moreover, heat flux through the building envelope has been shown to be reduced by the presence of green roofs during cold and warm seasons, which would decrease the energy demand for both cooling and heating [19,27,28]. However, seasonal differences in heat flux reduction have been reported, and shown to be higher in summer than in winter, partially as a consequence of different plant developments between seasons, although irrigation and climatic factors, such as precipitation patterns and extreme temperatures, also largely affect heat flux reduction [13,21,29,30].

The green roof thermal insulation capacity is a consequence of the insulation ability of its components. Among those components, substrate properties and water content as well as the plant presence and traits account for most of the green roof thermal insulation. In this sense, vegetated green roofs have been shown to reduce the temperature under the roof surface and the heat flux to a larger extent than do non-vegetated (bare soil) ones [12,18,26,29,31]. Plants, through their biological functions such as photosynthesis, transpiration, respiration and evaporation, absorb a significant proportion of solar radiation, changing the heat transfer process to the vegetated roof [23].

Similarly, the presence of vegetation has been suggested to reduce the surrounding air temperature and to increase albedo [11,15,25,32]. Moreover, significant effects of plant selection and species interaction over temperature and heat flux have been reported [10,32,33]. Plant traits such as plant height, leaf area index and plant responses to drought have been suggested to exert a great influence on the green roof thermal insulation capacity [3,21,31,34–36]. Plants with a high density and height are able to provide more shading and transpiration cooling, suggesting that plant phenology, plant water consumption and its interaction are key points to understand seasonal differences in the relative contribution of each plant species to the thermal insulation capacity of the green roof [33,37]. Canopy architecture and perenniality have also been shown to affect green roof thermal insulation capacity [13,21,26,33].

In addition to the vegetation, the substrate water content largely determines the green roof thermal performance, although its effects have been considered a controversial issue [35,38,39]. Some authors have suggested that a higher substrate water content results in a larger thermal insulation capacity [3,26,40]. However, other results showed that a low substrate water content could enhance energy savings with a lower heating demand during summer and winter [19,38]. These results suggest the relevance of irrigation strategies in green roofs to maximize thermal insulation benefits when water availability is limited [25,36,41,42].

As has been previously mentioned, green roof thermal insulation capacity has been supported by mathematical approaches and modeling. In this study, we provide experimental data through an accurate monitoring observation and field measurement on simulated green roof modules, with the aim to estimate the green roof thermal regulation potential in Mediterranean climate areas considering four seasons via three specific objectives: (i) to quantify the contribution of vegetation to the thermal regulation capacity in a green roof system; (ii) to evaluate the effect of two different plant types and canopy architectures (grasses and succulents) on thermal regulation capacity; and (iii) to assess the effect of irrigation treatment on thermal regulation capacity.

2. Materials and methods

2.1. Green roof system modules construction

The experiment was carried out in the island of Mallorca at the experimental field of the University of the Balearic Islands (Spain, Western Mediterranean Basin, 39° 38′ N, 2° 38′ E, 80 m a.s.l.). The climate is typical Mediterranean, with hot and dry summers and cool, wet winters. The Palma de Mallorca mean accumulated annual rainfall is 408.5 mm, and the mean annual air temperature is 18.1 °C [43]. Experimental metal modules of 0.56 m^2 (0.75 m × 0.75 m) and 0.15 m depth were installed one meter above the soil. The modules' filling followed a commercial pattern and proceeded from the top to the bottom in the following layers: (1) 0.12 m of substrate composed by a recycled product based on specially processed clay tiles and 10.6% organic material, with a bulk density of 1120 g/l. This substrate is considered to be suitable for extensive green roofs due to its stable structure, with multi-layer build-ups that reduce water loss. The substrate thickness is considered within the range commonly given for extensive green roof definition [2]. The substrate water content at field capacity (27.9%) was determined by gravimetric methods (watering to saturation and allowing 12 h of drainage and 48 h of drying at 105 °C); (2) filter sheet of polypropylene (Filter system SF; ZinCo GmbH); (3) drain system of recycled polyolefin (Floral Drain FD 40-E, ZinCo GmbH) and (4) protection mat of recycled synthetic fibers (Protection mat SSM 45; ZinCo GmbH) (Fig. 1).

2.2. Plant material and watering

The experiment was conducted with three different vegetation treatments: two non-vegetated modules (bare soil), two modules vegetated with *Sedum sediforme* and two modules vegetated with *Brachypodium phoenicoides. Sedum* species are commonly used in Mediterranean green roofs because of their low water consumption, their ability to withstand mild cold winters and hot summers due to their CAM metabolism. *Sedum sediforme* canopy architecture is characterized by fleshy leaves and inflorescence opened into various branches, yellow flowers, formed at the top of a fertile stem. *B. phoenicoides* (Poaceae) is a grass with long leaves concentrated at the base of the plant, with spikelets usually arched and rigid, usually showing a high water consumption, but it is able to keep green leaves during summer dry period with relatively low irrigation. The seeds of both species were germinated in seed benches with horticultural substrate (Prohumin Sustrato Klasmann-Deilmann, Comercial Projar S.A., Valencia, Spain) between October and November 2012 under greenhouse conditions. Seedlings were grown until February 2013, when they were placed outdoors to facilitate plant acclimation. In mid-March, after 45 days outdoors,9 plants of the same species were planted in each module (16 plants•m^{-2}). Water treatments were imposed according to the average species coefficient (Ks), estimated to be 0.5 [44]. According to this Ks, the irrigation with 50% of ET_0 (Potential evapotranspiration) can be considered as a well-watered (WW) condition, since this irrigation provides 100% of the estimated water requirements; and the irrigation with 25% of ET_0 can be considered as a water-limited (WL) condition, since it provides 50% of plant water requirements. ET_0 was calculated from data recorded