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Green roof as a passive cooling technique for the Mediterranean climate: An experimental study

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Abstract

Urban areas are undergoing increasing growth and land consumption. Through sustainable design and strategies, the built environment can contribute to mitigating the pressure on urban systems. To this aim, passive strategies can be integrated into buildings to improve their performance and that of the entire urban infrastructure system. Green roofs are among the most encouraged passive strategies, which can be added to both new and existing buildings. Green roofs reduce the Urban Heat Island effect, keeping the building and the city cooler; contribute to the stormwater management system, reducing runoff-flooding risk. However, while these advantages have been studied extensively, the actual cooling potential from evapotranspiration of green roofs has not been the subject of many studies. This work investigates the passive cooling potential of green roofs by evaporation through preliminary experimental studies on two green roofs. In greater detail, we aim to disentangle the substrate layer's peculiar role, without vegetation, during both a simulated extreme rainfall event and regular irrigation regime, and we compare it to the performance of a gravel-composed reference roof, whose performance with respect to cooling is already good. Results demonstrated that the green roof without vegetation can cool down the roof, and the intense rainfall event was the one that provided the highest thermal performance to the roof.

Keywords: Substrate layer; Thermal performance; Evapotranspiration process; Building envelope; Urban Heat Island

1. Introduction

The ongoing reduction of natural land and the increasing urbanization have resulted in environmental issues due to changing land cover into impervious surfaces. This change inhibits global evapotranspiration rates, intensifying the Urban Heat Island (UHI) effects and the building energy consumption [1, 2]. In order to address these problems, various greening measures have been proposed. In greater detail, the use of green roofs can bring multiple environmental and social benefits [3]. Green roofs are suggested as a sustainable urban design strategy able to reduce the energy consumption of buildings through solar shading, passive cooling, and thermal insulation, as well as to mitigate the increased risk of flooding in urban areas [4].

For these reasons, green roofs are increasingly encouraged to green the urban built environment. For example, in Basel, Switzerland, all the new buildings with flat roofs and all the retrofits of existing buildings with flat roofs must integrate green roofing [5], and the Basel Municipality estimates that 40% of Basel roofs are green now. However, the employment of green roofs on new and existing buildings needs careful consideration, as they constitute a peculiar architectural and construction feature. Continuing with the Basel example, indications for successful green roofs include that the substrate should be native regional soil, with a minimum thickness of 12 cm, and vegetation must be a mix of native species, characteristic of Basel [5]. Also, the architectural features of buildings should be considered, as only flat or slightly inclined roofs can host greenery. In the context of Mediterranean cities, where most buildings are historical [6], their implementation should be carefully evaluated. In addition to their integration in buildings, green roofs should be integrated with urban stormwater management infrastructures to provide relief from UHI and reduce runoff.

The passive cooling effect is attributed to the evapotranspiration process (ET), the water vapor surface flux resulting from the combination of evaporation and plant transpiration. Evaporation is the transformation of water into vapor at the surface of the wet growing media, while transpiration is the physiological process of transforming water into vapor at the plant surfaces, primarily leaves.

This process occurs when there is a vapor pressure differential between the plants and surrounding air. ET is influenced by precipitation history (intensity, duration, inter-event times), climatic conditions (net radiation, temperature, humidity, wind), vegetation characteristics (species, leaf area index, stage of growth), and substrate properties (porosity, permeability, field capacity, capillary pressure-saturation relationship) [7]. In addition, ET has recently drawn increased interest from the green roof research community because of its importance in heat and mass transfer at the level of green roof components [8, 9]. However, ET not only impacts the thermal effect and energy balance of green roofs through surface cooling but also significantly contributes to reducing the water runoff generated by rainfall on building rooftops by storing precipitation (reducing runoff volume and retarding runoff peak) and facilitating ET [10].

While several studies have documented a reduction in stormwater runoff volumes from green roofs [11], few have directly quantified rates of ET in terms of passive cooling potential, although they agree that green roofs mitigate rooftop overheating. He et al. [12] quantified the hourly rate of ET for four plant species typically planted on green roofs in Singapore through a field experiment and subsequently analyzed correlations between the rate of ET and weather parameters. The authors concluded that outdoor air temperature is the weather parameter showing the highest correlation with the rate of ET, followed by solar radiation, wind speed, and relative humidity. Chen [13] explored the effects of the meteorological variables, soil water content, and the ET in relation to the thermal performance indicated by Urban Heat Island and building energy consumption of green roofs. The author found that ET may have a higher influence on the difference in surface temperatures of green and original roofs than the meteorological variables or substrate water content, although the radiative heating is sometimes more influential than the cooling caused by ET of the green roof in thin substrate condition. Ouldboukhitine et al. [14] investigated the ET for green roofs under controlled laboratory conditions. Side-by-side experiments were used to measure evaporation compared to ET and to determine the effect of irrigation water quality on evaporative cooling. When exposed to warm ambient conditions, ET provided evaporative cooling that increased thermal resistance for a green roof, with an increase of 13% for ryegrass and 37% for periwinkle. Jim and Peng [15] investigated the effects of weather types in conjunction with soil moisture states on green-roof ET and thermal performance based on scenario and correlation analyses. The correlation analyses demonstrate stronger relationships between substrate moisture and subsurface temperatures but weaker with subaerial temperatures. Higher substrate moisture could cool soil, rockwool, and concrete tile on sunny days and warm them on rainy and cloudy days. The substrate-moisture effect on subaerial temperatures is only expressed on rainy days, with little effect on sunny and cloudy days. Boafo et al. [16] evaluated the ET effect of an extensive green roof on the annual energy consumption of an office building. Increasing the Leaf Area Index (LAI) from 20% to 100% cover increased ET flux by 10.4% in summer and 80.2% in winter. In [17], the authors studied the effect of vegetation type and climatological conditions on ET and demonstrated that substrate moisture content and atmospheric forcing are the most significant variables influencing ET. All of these results demonstrated the importance of ET in the reduction of thermal loads on a green roof.

In a previous review study, Cascone et al. [18] reported that ET rates can be obtained by direct measurement or indirect approaches with mathematical models. Because the cooling effect is invisible and difficult to measure directly, many studies have calibrated empirical and analytical equations to evaluate ET rates. In 1998, the Food and Agriculture Organization (FAO) standardized the equation elaborated by Penman and Monteith as the FAO model to calculate the ET of an extensive land-surface fully covered by grass of uniform height in a well-watered condition. Jahanfar et al. [19] have reported that the FAO method underestimates ET for green roof systems, especially during dry periods. The inaccuracy of ET prediction methods in water-limited conditions is a significant gap in assessing the performance of green roofs. ET rate can be directly evaluated by measuring water losses from a roof assembly. Previous research studies have quantified ET with weighing lysimeters that directly measure water loss using a load sensor or scale. Alternatively, a few studies have used the soil-water balance approach. The soil water balance is performed by tracking changes in the substrate water content that can be measured with probes based on different measurement methods. Tabares-Velasco and Srebric [20] developed a laboratory setup that measures ET to quantify the heat and mass transfer in a vegetated green roof. The ET values obtained with a substrate water content of 0.15 (m^3/m^3) was approximately 150 (W/m^2) or 5.29 ($kg\ m^{-2}\ day^{-1}$). Higher values of ET were obtained in the study by Tan et al. [21] in small green roof plots of 1 m^2 on the National University of Singapore rooftop. The experiments were performed in a tropical rainforest climate (*Af*) according to the Köppen-Geiger climate classification. The substrate used is a 30 cm lightweight soilless consisting mainly of perlite and organic matter to improve soil water retention, and the vegetation is *Cyathula prostrata.* The nine analyzed plots reached maximum ET rates between 6 and 8 ($kg\ m^{-2}\ day^{-1}$) with a daily watering of 12 ($l \cdot m^{-2} \cdot day^{-1}$), where the maximum VWC ranged between 0.22% and 0.35%. The higher and more constant VWC values were obtained in the plots with a 5 cm water retention layer. Finally, there is a lack of information about the specific location of the watering drip system in the green roof section. Another study by Chenot et al. [22] in a Mediterranean climate (Csa) shows similar ET results.

In summary, there is no consistent agreement with respect to ET's contribution to energy balance and the green roof's thermal performance. To clarify the benefits of ET in varying conditions, a method to accurately predict the ET effect is crucial in the planning for green roofs designed especially for cooling purposes.

In order to fill the literature gaps, this paper aims to develop an experimental setup for the evaluation of the passive cooling potential of green roofs, improving the knowledge of the correlation between evaporation (EP) and the thermal performance of an extensive green roof. To this end, a new experimental setup was designed and built on the University of Lleida (Spain) rooftop. It allows for determining the latent heat flux, temperatures at different layers, substrate moisture content, and the specific microclimatic conditions of a green roof solution. Since ET in green roofs strongly depends on the water content in the substrate, the passive cooling potential was evaluated by varying the amount of water supplied by the irrigation system. Therefore, in this work, following the description of setup design and implementation, preliminary results from the experimental evaluation on passive cooling of green roofs are reported for the case without vegetation, thus considering evaporation only.

2. Methodology

The employed method consists of two experiments investigating the performance concerning evaporative cooling of two green roof fields and a reference, non-green roof portion. The following subsections illustrate the procedure in greater detail. They are structured as follows: the experimental setup is described first, then the local climate conditions, the instruments employed to monitor the experiments, the green roof and the water retention layer case study, and finally, the procedure for the experiments.

2.1 Experimental setup

Two weighing lysimeters are designed and assembled (Figure 1) to evaluate the ET of two green roofs (named Substrate 1 and Substrate 2, with the same composition to duplicate the results) under different irrigation scenarios. They are made of a 3 cm section of plywood structure ($\lambda = 0.138$ W·m^{-1}·K^{-1}) with a total area of 4 m^2 (Figure 1.A) and reinforced below with rectangular laminated tubes (40 × 60 × 2 mm). Immediately after the plywood base, each lysimeter is insulated from the bottom part with 8 cm of XPS panels ($\lambda = 0.036$ W·m^{-1}·K^{-1}) and completely waterproofed with a bituminous dense layer (Figure 1.B), a drainage hole allows water runoff. The whole system is weighed with eight load cells (Figure 1.C) using four of them in each lysimeter. Since a single load cell has a maximum load service of 450 kg, each lysimeter allows a total of 1,800 kg of service. Both lysimeters are completely equal and allow testing extensive and semi-intensive green roof samples of up to 250 mm depth, as can be seen in Figure 1.D. The irrigation system is controlled by GARDENA devices (Model: 1885) that allow personalized daily irrigation schedules. The water distribution system consists of 14 auto-compensating dripping valves distributed in 4 rows (Ø 25 mm) every 50 cm (Figure 1.B).

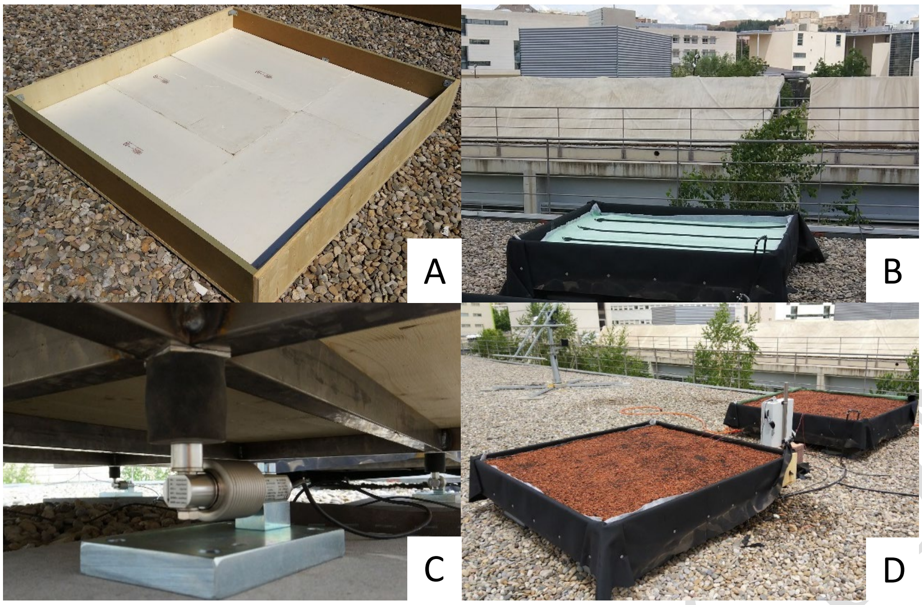

Figure 1. (A) Insulated plywood structure, (B) waterproof membrane (black), drip irrigation system, and anti-root membrane (green), (C) load cells and laminated steel tubes, (D) experimental setup based on two identical lysimeters of 4 m^2.

2.2 Climate conditions

The experimental setup is located at the University of Lleida, Spain. The specific climate conditions are considered continental Mediterranean (Cfa) according to the Köppen-Geiger climate classification. The summers are dry and hot, while the winters are cold and foggy. The mean annual precipitation is 423 mm, generally distributed between April-May and October-November. The mean temperature in Lleida is 15.2 ºC, with a maximum mean temperature of 32 ºC in July and a minimum mean temperature of 1.5 ºC in January.

2.3 Instrumentation

Figure 2 shows the distribution of the sensors in both the green roofs and the conventional flat roof that was used as a reference system. The following data was recorded at 5 min intervals:

- Temperature between plywood and insulation (Point D in Figure 2) [˚C]
- Temperature between waterproof and drainage layers (Point C in Figure 2) [˚C]
- Temperature between drainage and substrate layers (Point B in Figure 2) [˚C]
- Temperature on the surface sample (Point A in Figure 2) [˚C]
- Volumetric Water Content (VWC) in the substrate [%]
- Outdoor ambient temperature [˚C] and humidity [%] at the height of samples (60 cm)
- Global horizontal solar irradiance [W/m2]
- Wind velocity [m/s]
- Rainfall [mm]
- Constant weight of samples [kg]

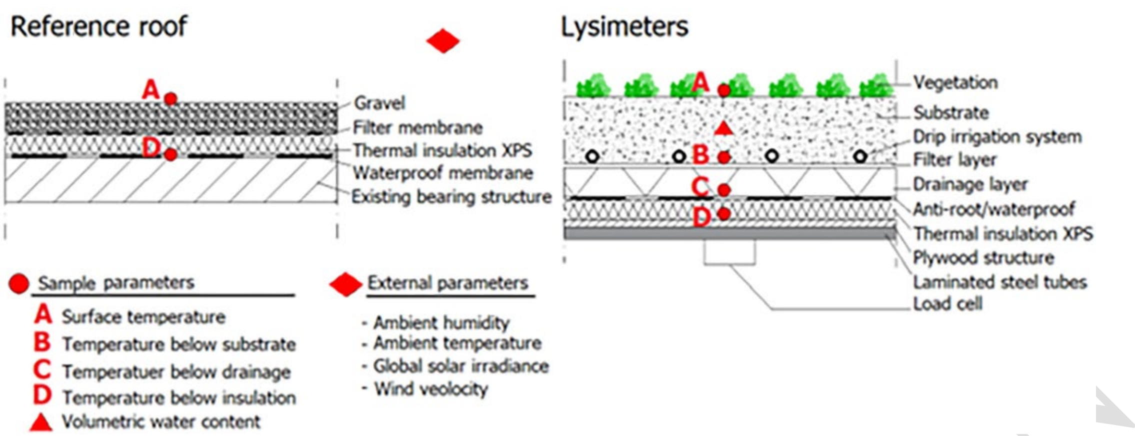

Figure 2. Distribution of the different sensors in the two lysimeters and the conventional reference roof.

Pt-100 DIN B probes (accuracy ± 0.3 ºC) are installed to measure the surface temperatures across the green roof section. The air temperature and humidity were measured with a TESTO transmitter (model 6651) with an accuracy of ±0.2 ºC and ±1.7 %, respectively. An anemometer AN046 (G.I.S Iberica) with an accuracy of ± 3% and 0.1 m/s of resolution is used to measure the wind velocity. Volumetric water content (VWC) is measured with Decagon EA-10 Soil moisture sensors with an accuracy of ±0.03 m^3/m^3 typical in mineral soils (± 3%) and ±0.02 m^3/m^3 in any porous medium (± 2%). A Middleton Solar pyranometer SK08 is used to capture the global solar irradiance. Finally, the load cells (UTILCELL Model 300) with accuracy class 3000 (a minimum division of 30g) were used to measure the weight evolution of the lysimeters.

2.4 Green roof

The extensive green roof consists of five different layers, from the top to the bottom: 80 mm of substrate, 2.4 mm of water distribution filter, 40 mm water retention layer, and 3 mm protective layer (Figure 3). Without considering plants, the total thickness of the system is about 130 mm, and it weighs approximately 83 kg/m^2 (dry) and 127 kg/m^2 (saturated), allowing up to 44 l/m^2 of water retention capacity.

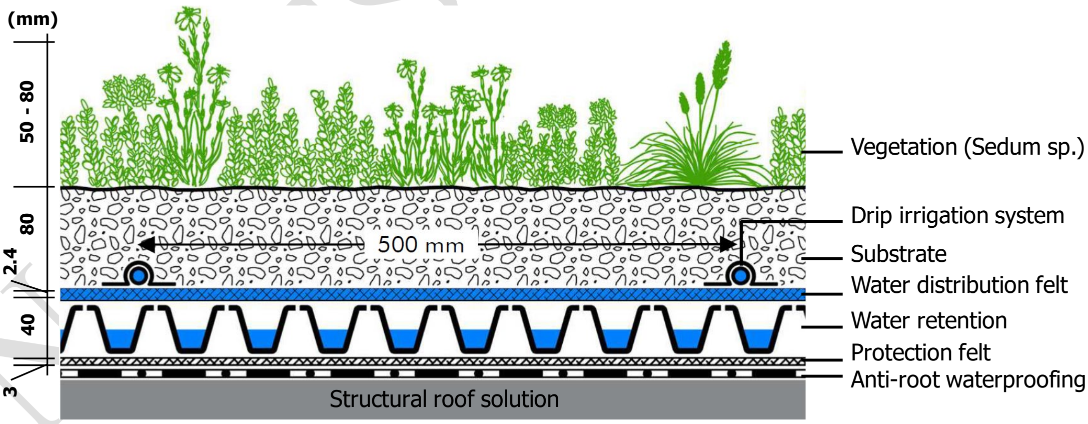

Figure 3. Detailed section of the extensive green roof system.

2.5 Water distribution and water retention layers

These are the two most important layers of the green roof system that manage the water available for plants. The water distribution felt (100% polyacrylic) spreads the water over the entire green roof surface and temporarily stores from 3 to 4 l/m^2 before releasing it into the retention layer. Once the felt is completely wet, the water permeability is approximately 20 $L \cdot m^{-2} \cdot S^{-1}$. Then, water comes into the retention layer, allowing an extra storage of 5 l/m^2 in case of drought periods. In addition, the engineered design of water storage also contains air to have oxygen for better root development.

2.6 Methodology of experiments

Two different types of experiments were carried out to evaluate the evaporative cooling potential of the specific substrate commonly used in extensive green roofs in a continental Mediterranean climate, one simulating an intensive rainfall event and the other obtaining the maximum field capacity. Summer data was collected between June 30th and September 18th, 2018.

In addition to the weighing capacity of the lysimeters, during all the experiments, the global horizontal solar irradiance [W m^{-2}], wind speed [m s^{-1}], relative humidity [%], and air temperature [ºC] were monitored because they are the principal meteorological parameters affecting the evaporation [kg m^{-2} day^{-1}] by removing water content from substrate and plants.

2.6.1 Experiment 1: natural precipitations

This experiment quantified the substrate's field capacity and water evaporation after simulating an intensive rainfall event. As a starting point, the samples were irrigated before sunrise until they reached the saturated condition of the system. Then, the lysimeters were evaluated under free-floating conditions until the mean VWC of the substrate was 0 (dry condition). The total period of this experiment was from August 7th to 23rd, 2018. It is important to highlight that there were no additional irrigations except the punctual natural precipitations.

2.6.2 Experiment 2: irrigation

The second experiment only aims to obtain the maximum field capacity using the drip irrigation system below the substrate layer. This will help evaluate the system's evaporation potential by comparing two irrigation methods, the natural precipitations, and the actual maintenance irrigation, to guarantee the survival of Sedum sp. in summer conditions.

At the beginning of the experiment, the samples were irrigated from the bottom part until reaching the drainage layer saturation that occurred when water input and drained water were equal. Then, the system worked under free-floating conditions until reaching the dry condition.

3. Results and Discussion

3.1 Experiment 1: natural precipitations

3.1.1 Cooling potential

Figure 4 shows the daily evolution of the ambient parameters that affect the ET in the setup. The highest ET_{Rate} was 5.1 (kg m^{-2} day^{-1}) with a mean VWC of 15.5 % on August 7th, 2018, as expected, because it was the day of the rain simulation event. Notice that this date was the warmest day of the period with a mean daily temperature and solar radiation of 31 ºC and 451 W m^{-2}. During this experiment, three relevant natural rainfall events on August 8th, 12th, and 17th, 2018 have added 6.6, 3.6 and 3.5 (kg m^{-2} day^{-1}) into the system, respectively. On the same rainy days, the bare substrate showed significant evaporation rates of about 3.8, 2.1, and 1 (kg m^{-2} day^{-1}), respectively, because the rainfall events occurred after 7:30 p.m. in all cases. In addition, the water stored during the evenings was the reason why the days after a rainfall event showed higher ET values than the days before (Figure 4). From saturated to dry conditions, the total evaporated water from the bare substrate in this period was 39.3 (kg m^{-2}), and the entire water input (rain) was 15.9 (kg m^{-2}).

The negative water balance and the hot summer conditions directly affected the trend of VWC, which showed a fast decrement in the first week despite the received rainwater (Figure 4). The rain on August 8th increased the VWC from 11.9 to 13.3 %, while the rainfalls on the 12th and 17th only cushioned the fast decrement of VWC. From August 20th, the ET was below 1 (kg m^{-2} day^{-1}), and the VWC was almost 0%.

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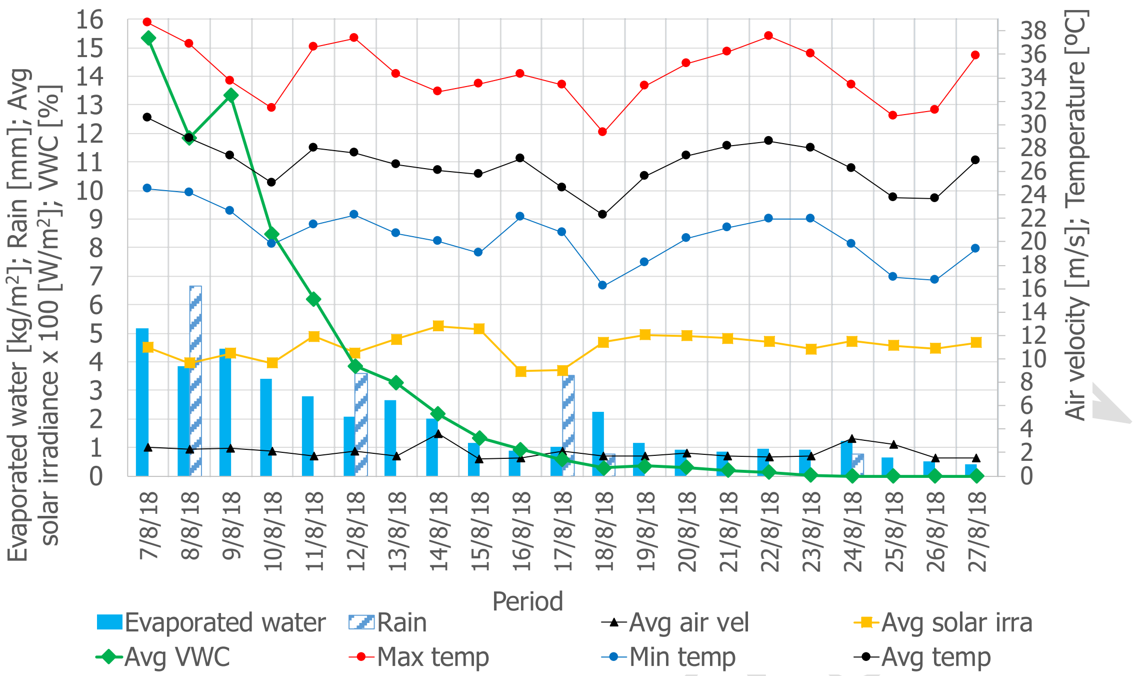

Figure 4. Water evaporation from saturated to dry conditions and daily ambient parameters during the experimental summer period.

Using the conversion table created by Cascone et al. [18], the total amount of water evaporated can be easily translated into energy and directly compared with the results from similar studies. For example, considering the water evaporated on 18/8/2018, i.e., 2.2 kg/m^2, it corresponds to 0.90 MJ/m^2 because the conversion factor from mass to energy is 1 kg/m^2 = 0.408 MJ/m^2.

The aim of the study was to evaluate how substrate composition and depth affect the moisture behavior and plant development in a Mediterranean context. A total of 96 trays of 1 m^2, varying the depth from 5 to 15 cm and the substrate composition with different % of coarse and fine materials, were tested in the summer and autumn periods of 2016. A mean ET rate of 4.23 (kg m^{-2} day^{-1}) was obtained using the Thornthwaite method after a rainfall of 77.28 mm distributed over 18 days in summer (from June 17th to July 18th).

The VWC in the samples was collected manually every two days after a rain event. The results showed a maximum moisture content of 12% and 8% in 5 cm and 15 cm substrates, respectively, one day after rain. After three days, this result was inverted: the 5-cm substrates dried up more rapidly than the 15-cm substrates, which had longer moisture content. The moisture amount of the 15-cm substrates tended to be stable five days after rain and higher than that of the 5-cm substrates, where moisture was near 0%. The experimental correlation between the daily evaporation and the VWC of the bare substrate is presented in Figure 5.

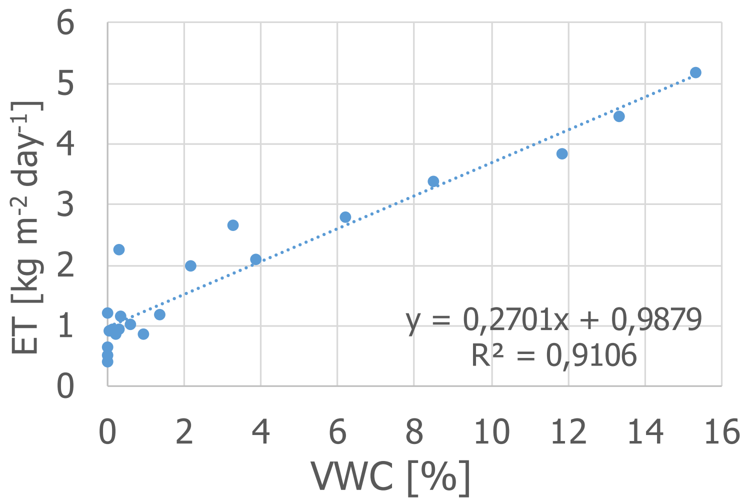

Figure 5. Experimental correlation of the daily evaporation rates and volumetric water content (VWC) of the substrate.

3.1.2 Discussion about cooling potential in Experiment 1

For comparison and discussion purposes for this specific experiment, it is interesting to highlight the results of similar studies that employ similar methods. Tabares-Velasco and Srebric [20] results related to laboratory measures of ET to quantify the heat and mass transfer in a vegetated green roof are similar to those obtained in the present experimental setup under real conditions, namely 5.1 (kg m^{-2} day^{-1}) with a mean VWC of 15.5% on August 7th, 2018. Results were higher in the study of Tan et al. [21], while the work of Chenot et al. [22] in a Mediterranean climate (Csa) shows comparable ET values with respect to the results obtained in Experiment 1.

The substrate composition, thickness, vegetation, and watering system are the two main technical differences when the results of previous studies are compared to those of this experiment. However, the moisture content and ET rate values showed similar trends in all the studies, such as fast decrements of VWC after a week from the last rainfall or watering, especially for the thinner substrates of 5 to 8 cm, and similar daily ET rates.

With respect to the correlation between the daily evaporation and the VWC of the bare substrate, this linear correlation confirms the similar expected results by Tabares-Velasco and Srebric [20] in their study in which they have stated that a linear relationship for evaporation and the bare substrate water content (without plants) could be obtained.

However, the same authors obtained a non-linear correlation between VWC and ET when using plants in laboratory experiments because of the different parameters affecting their water loss, such as photosynthesis and stomatal resistance.

3.1.3 Temperature evolution

The thermal performance of the substrate showed an important reduction of the surface temperatures by adding water at the beginning of the experiment, as expected (Figure 6). The gravel reference system registered higher daily peak temperatures of about 14 ºC compared to the saturated substrates. However, the fast reduction of moisture content after nine days, represented in Figure 6, had a direct impact on increasing the surface temperature of the substrate (Figure 6).

From August 16th onwards, both substrates and gravel systems showed similar temperatures on the surface because of the low daily ET rates. Only from August 18th to 21st, there were small reductions of peak temperatures in the substrate compared to the gravel system due to the rainfall (3.5 mm) on August 17th.

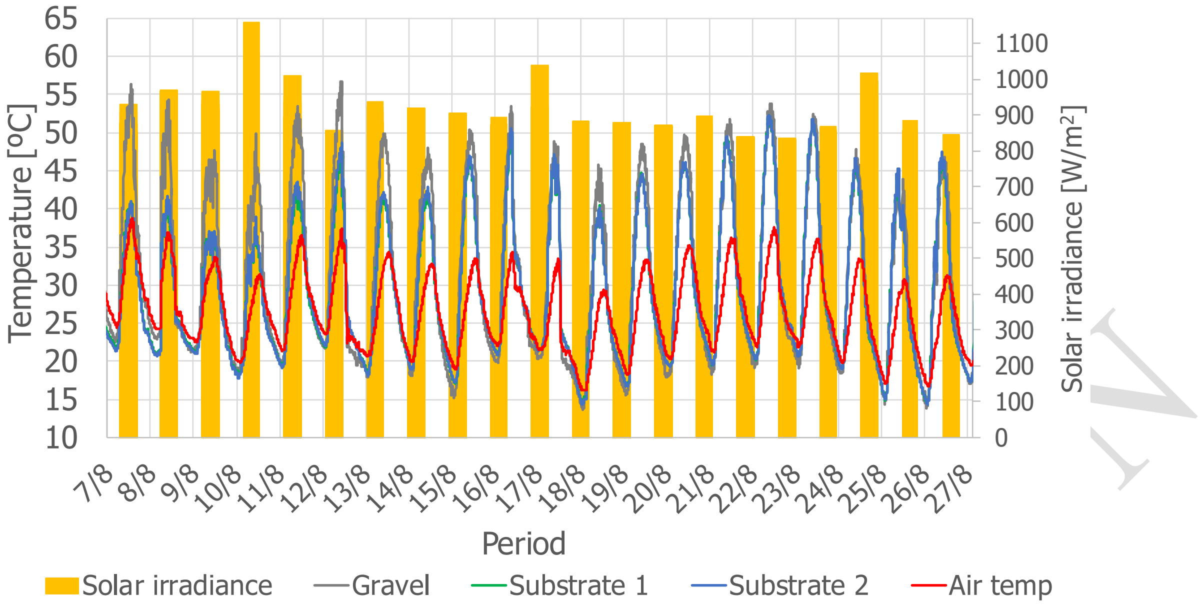

Figure 6. Thermal performance of the surface of substrate and gravel systems (probe A in Figure 2).

3.2 Experiment 2: irrigation

3.2.1 Cooling potential

Figure 7 shows the evolution of VWC, which registered a peak of 5.3% four days after the irrigation event. This value represents approximately one-third of the maximum water content registered in experiment 1 (15.5%), which was saturated, simulating an intense rainfall event. Thus, an important difference in the peak and the time lag of the VWC peak was observed when two different irrigation systems were compared; a delay of 4 days after the system's saturation was observed in the moisture content peak. Since the water input in experiment 2 is from a drip watering system allocated below the substrate (Figure 7) instead of the outermost surface as in experiment 1, the water movement is mainly characterized by water sorption of the substrate and because of evaporation but not by precipitation. Thus, a drip irrigation system cannot provide the same water distribution to a substrate as a rainfall event.

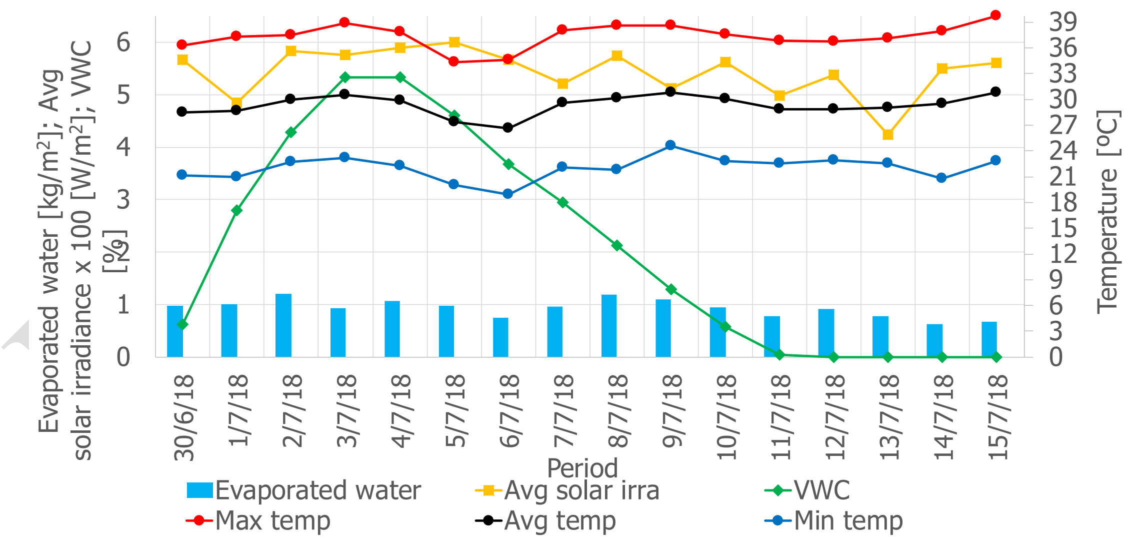

Figure 7. Water evaporation from saturated to dry conditions using an internal drip irrigation system and daily ambient parameters during the experimental summer period.

The daily mean of the air temperature during this period was 28.9 ºC with a mean RH and solar irradiance of 60.2%

and 321 W/m^2, respectively. The highest ET rate was 1.2 (kg m^{-2} day^{-1}), with a mean VWC of 2.1 % on July 8th, 2018. Water evaporation is limited for this specific watering system because of the substrate's low VWC. The incremental trend of VWC was not linear, being 2.18% on July 1st, 1.49% on July 2nd, and 1.05% on July 3rd until it reached the peak of 5.3% on July 4th. However, the VWC trend showed a linear decrement from the peak until it reached the dry conditions with a daily reduction of about 0.75%.

3.2.2 Discussion about cooling potential in Experiment 2

The results presented in Experiment 2 highlight the importance of the irrigation system, as also demonstrated in previous studies, such as Chenot et al. [22], where it is demonstrated that the substrate moisture behavior during summer dry periods in Avignon, South-eastern France (Csa), is influenced by the type of rainfall event (intensity, duration).

3.2.3 Temperature evolution

Compared to Experiment 1, where a higher quantity of water was provided by manual irrigation, the differences in temperatures are reduced in Experiment 2 (Figure 8). Substrate surface temperatures were always higher than both air temperatures and gravel roofs. This is due to the white color of the gravel and its reflective capacity, which allows the gravel to maintain lower temperatures [23]. In this experiment, the water provided by the drip irrigation could not reduce substrate temperatures through the evaporation phenomena.

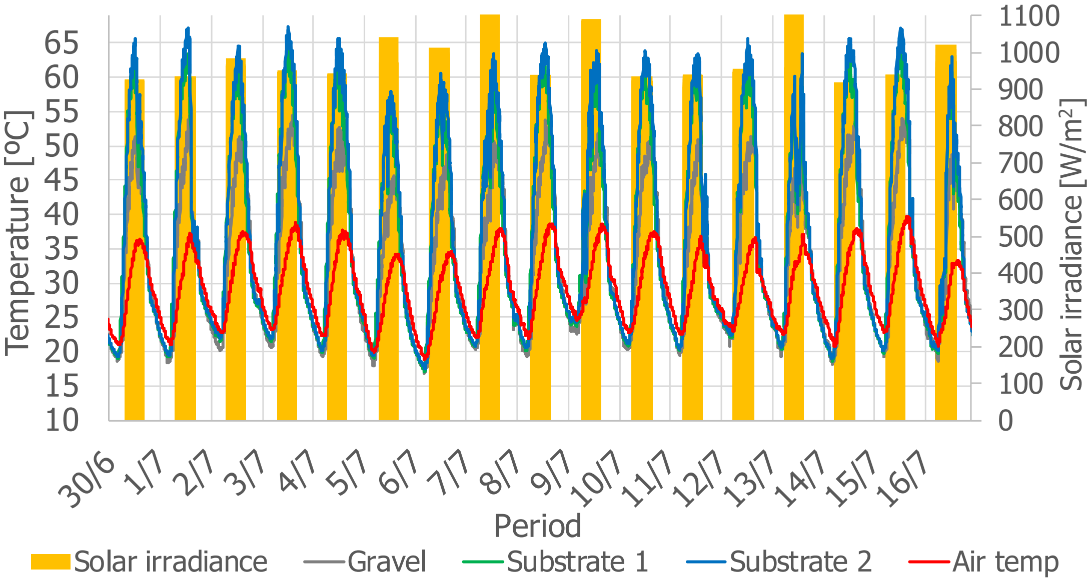

Figure 8. Thermal performance of the surface of substrate and gravel systems (probe A in Figure 2).

4. Conclusions

In this paper, an experimental setup was developed for the evaluation of the passive cooling potential of green roofs to improve the knowledge of the correlation between ET and thermal performance. The passive cooling potential was evaluated by varying the water supplied by the irrigation system simulating natural precipitations and irrigation regime. First, results from the experimental evaluation on passive cooling of green roofs showed that when a high quantity of water was provided manually (Experiment 1), simulating an intensive rainfall event, it increased the thermal performance of the green roof. On the other hand, when the water was provided only by the drip irrigation system, the thermal performance was not so far from that of one of the bare reference roofs covered by high-reflectance cool gravels. It should be highlighted that these are only the first results from the experimental setup, mainly carried out to check that the experimental setup works properly and to establish preliminary settings by comparing the results to similar studies. The ongoing research will evaluate the cooling effect following the vegetation installation, comparing its thermal performance with the performance of green roofs without vegetation. The second step of the research will be the comparison between the cooling effects of two different plant species to identify the vegetation with the highest cooling potential in the continental Mediterranean climate. Finally, this work considers green roof solutions for flat buildings in the Mediterranean climate. Still, future studies could include other solutions that could fit the varied architectural panorama of Mediterranean historical buildings. Still, the findings and methodology of the study are of general relevance and useful for other types of green roofs.

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Author Contributions

S.C. conceived and designed the analysis, collected the data, contributed data, and performed the analyses, and S.C. and F.R. wrote the paper.

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