The evapotranspiration process in green roofs: a review

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Abstract

Previous research has shown that most of the green roof benefits are related to the cooling effect. In the literature available, however, it is still not clear how and how much the evapotranspiration affects the performance of a green roof. In order to fill the gap in this research topic, this study carries out a review on the cooling effect due to the evapotranspiration process of green roofs. First of all, an overview of the evapotranspiration phenomenon in green roofs, as well as the equipment and methods used for its measurement are presented. Then, the main experimental results available in literature, the physical-mathematical models and the dynamic simulation software used for the evaluation of the latent heat flux are also analysed and discussed among the available literature. Moreover, this review proposes a classification of the results carried out by previous studies as function of the main parameters affecting the evapotranspiration process (e.g. volumetric water content, stomatal resistance, Leaf Area Index, solar radiation, wind velocity, relative humidity, soil thickness, and substrate composition). Additionally, a sensitivity analysis of the results obtained from the literature allowed underlining the correlation among the main factors affecting the evapotranspiration. Finally, a vision of the world area where green roof studies were performed is provided. From the results, it is possible to emphasize that most of the studies that evaluated the evapotranspiration used high precision load cells. Furthermore, all the heat transfer models of green roofs considered in this review took into account the latent heat flux due to evaporation of water from the substrate and plants transpiration, however, only few of them were experimentally validated.

Keywords: evaporation; transpiration; latent heat flux; cooling effect;

1. Introduction

In recent years, the continued growth of high-density urban areas, characterized by extensive paved areas, have increased the overwarming and energy needs within the cities [1,2]. Furthermore, these areas often have higher air temperatures than their rural surroundings which is commonly called urban heat island (UHI) effect [3,4]. Engineers, researchers, and designers are committed to develop sustainable solutions to reduce both energy consumption and pollutant emissions by using innovative materials and technologies [5,6]. One of the most effective solutions adopted in the field of bioclimatic architecture is the replacement of materials traditionally used in flat roofs, which comprise around 25% of the total horizontal surfaces in urban areas, with green roof technologies [7].

Green roofs provide several benefits at both building and city level. The following are the most commonly observed at urban scale: mitigation of urban heat island effect [8–10]; decrease in storm water runoff [11,12]; enhancement of biodiversity in densely urban areas [13]; purification of air and water runoff [14]. At building scale, green roofs reduce the sensible heat flux due to the cooling effect [15,16] thus decreasing the heating and cooling demand of a building [17–19], and improving human thermal comfort [20,21]. This effect may vary depending on the climate conditions [22–24], and the level of insulation specially in cases of building retrofitting [25,26]. Most of these multiple benefits are linked to the cooling effect due to the evapotranspiration process (ET) that humidifies the external ambient air, reduces the surface temperature of the roof [27], and mitigates the urban heat island phenomenon [28].

Previous studies have considered the cooling effect due to the evapotranspiration process among the major energy benefits of green roofs [29,30]. The importance of evapotranspiration in energy transfer models was also highlighted in previous studies [31] in which the authors analysed the vegetation effect on horizontal surfaces in urban, suburban and agricultural environments. However, the existent literature is scarce and controversial in evaluating the physical-mathematical models and dynamic simulation software for calculating ET, the main influencing parameters that have to be considered, and the suitable equipment and methodologies for the measurement in urban contexts.

To fill these gaps in the literature, the present study carried out a wide analysis of the cooling effect due to the evapotranspiration process on green roofs. The scope of this paper includes the analysis and discussion of the following topics: the main equipment and methodologies used to measure the ET in green roofs, the correlation between evapotranspiration and the energy performance of green roofs, the main experimental results from the literature and the physical-mathematical models used to calculate the latent heat flux on green roofs. Furthermore, this paper provides an exhaustive review of the main influencing parameters of ET in green roofs and their classification according to the potential evapotranspiration capacity.

However, due to the high number of studies carried out on green roofs, this review is focused on the research that expressly evaluate experimentally or analytically the evapotranspiration process in green roofs. Therefore, all researches examining performance and benefits of green roofs without directly correlating them with evapotranspiration is out of the scope of this study. In addition, the previous studies that have evaluated the role of evapotranspiration in the hydraulic performance and water balance of green roofs, in terms of storm water management and runoff of these systems, are not included in this review.

In order to organize the reviewed data and to facilitate the understanding thereof, paper is structured in seven sections as follows: Section 2 provides a general description of evapotranspiration process, how it is defined, what does it depends on and how it can be determined. Section 3 and 4 show the main climatological parameters and characteristics of vegetation and substrate that influence the ET of green roofs, respectively. Section 5 describes the principal experimental measurement methods used to evaluate the evapotranspiration of green roofs, the results obtained from them and a summary of the different units of measurement used. Section 6 describes the mathematical models that take into account the latent heat within a green roof energy balance and their main outcomes. In section 7, the main findings derived from research performed using dynamic simulation software are reported. Finally, Section 8 presents the sensitivity analysis conducted by previous studies to determine the influence of the different parameters (volumetric water content, solar radiation, wind velocity, relative humidity, soil thickness, etc.) on the evapotranspiration effect.

2. An overview of evapotranspiration in green roofs

During recent years, evapotranspiration (ET) has received a growing interest from the green roof research community because of its impact on heat and mass transfer. This phenomenon is a combination of the water transpired by plants during their growth or retained in the plant tissue (transpiration) plus the moisture evaporated from the soil surface and vegetation (evaporation). On one hand, transpiration is the process by which moisture is carried through plants from roots to small pores on the underside and upper side of leaves, where it changes to vapour and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves. Transpiration also includes a process called guttation, which is the loss of water in liquid form from the uninjured leaf or stem of the plant, principally through water stomata. On the other hand, evaporation is the process whereby liquid water is converted into water vapour and is removed from the soil surface. It is the only form of moisture transfer from land and oceans into the atmosphere. These processes are mainly determined by solar irradiation reaching the soil surface as it supplies the necessary energy.

The level of the plant development has a considerable influence on the rate of water consumption and in the final energy balance of a green roof system. During the development of complete vegetative cover, the water consumption rate increases rapidly from low to high values. When plants are small, water is mainly lost by evaporation from the soil; later, once the vegetation is well developed and completely covers the soil surface, transpiration becomes the main process. However, the experimental data revealed that ET has a dynamic and complex behaviour that depends on both climatological parameters and soil and vegetation characteristics [32,33].

The principal climatological parameters to assess the ET process are: the solar radiation, the wind speed, the air temperature, the relative humidity, and the sky conditions. In addition, ET also depends on the characteristics of both vegetation and soil, principally the degree of shading of the canopy (leaf area and density, LAI) and the amount of water available at the soil surface. In particular, the characteristic of the vegetation that is most important from the standpoint of impacts on the heat transfer through the roof is the leaf area index (LAI). LAI is established as the one-sided green leaf area per unit ground surface area (LAI = leaf area/ground area, m^2/m^2) in broadleaf canòpies. The LAI value depends on the type and the growth phase of the plant (crop), usually ranging from 0 to 10.. E.g., if the average parcel of roof surface is beneath two leaves, the corresponding LAI is 2. Values of LAI for green roofs vary depending upon plant type, but are typically in the range of 0.5–5.0 [34]. Moreover, the stomatal resistance, the plant height, the development of the vegetation and the transpiration rate of each plant species, determine the aptitude to transfer moisture near to the surface roots and canopy, consequently, these characteristics have also influence on the ET rate.

When rain and irrigation are scarce, the water content in the substrate drops and the soil surface dries out. Thereby, in the absence of water supply the evapotranspiration decreases rapidly and may cease almost completely within a few days.

Table 1 summarizes the climatological and green roof parameters affecting evapotranspiration.

Table 1 Climatological and green roof parameters affecting ET

Climatological	Canopy	Soil	Management practice
Solar radiation	Degree of shading	Water content	Irrigation regime
Air temperature	Canopy characteristics	Soil characteristics	Cultivation practice
Air humidity	Canopy development		
Wind speed			
Rain			
Sky condition			
Season			

The evapotranspiration rate can be obtained by experimental measurements or by means of modelling approaches. Specific devices and accurate measurements of various physical parameters, or the soil water balance, are required to determine evapotranspiration.

The lysimeter is one of the most widely used equipment to measure evapotranspiration. Such device is made of a soil volume covered by plants placed in a container hydrologically separated by the surrounding soil. Lysimeters can be classified as non-weighing and weighing type. The weighing lysimeter is based on the principle of the mass continuity. The evapotranspiration (ET), expressed in mm, is calculated by Eq. 1 as the difference among precipitation (P), drainage (D), superficial runoff (O) and the variations in soil water storage (ΔS) (Figure 1).

$$ET = P - D - O \pm \Delta S \qquad (1)$$

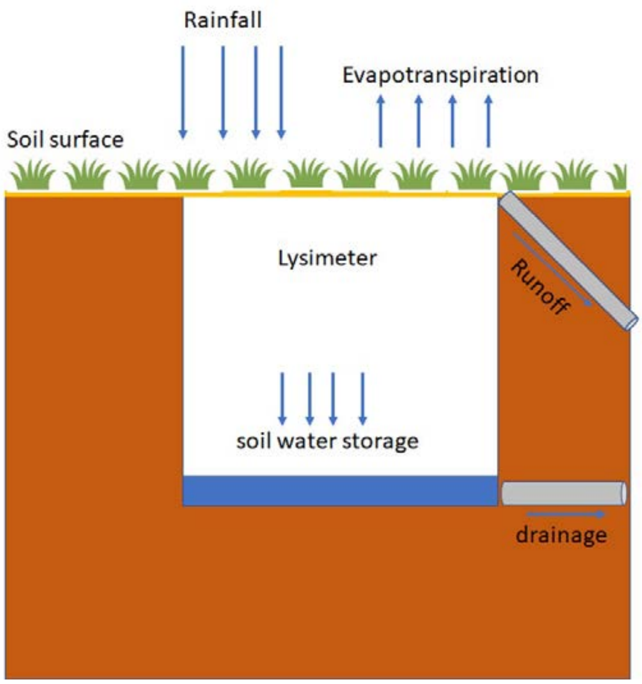

Figure 1 Schematic representation of the soil water balance in weighing lysimeter

Weighing lysimeters provide the direct measurements of evapotranspiration over time by monitoring the evolution of the tray weights (change of mass) due to the water losses. As regard the variation of water stored (ΔS), it is determined through measurement of the weight change of the soil column over time, with an accuracy of few hundredths of millimetres. Usually the following equivalence is assumed: 1 kg ≈ 1 L m^{-2} = 1 mm.

Non-weighing lysimeters allow determining the evapotranspiration, during a given time period, subtracting the drainage water collected at the bottom of the lysimeters from the total water input. Actually, few studies directly quantified ET by measuring the rate of water loss [35], since such method is often expensive and demanding in terms of accuracy of measurements.

In order to predict the evapotranspiration, therefore, numerous numerical methods have been developed based on climatological data (e.g. temperature, day length, humidity, wind, and solar irradiance) [36]. These numerical models, such as those of Hargreaves and Allen (2003) [37], Priestley and Taylor (1972) [38], Penman (1948) [39], and Penman–Monteith [40,41], estimate the so called "potential evapotranspiration" (PET or ET_0) over bare soil surface or vegetation.

Penman (1948) defined PET as the ET from actively growing short green vegetation, completely shading the ground and never suffering scarcity of moisture availability. Consequently, PET models neglect factors that, conversely, are decisive in the actual evapotranspiration (AET) that occurs under natural field conditions (i.e., variable soil water contents).

Table 2 summarizes the most common models used to evaluate ET. All these previous models are characterized by a daily time step.

Table 2 Models for estimating evapotranspiration

Name	Function	Reference
Penman-Monteith (1965)	$ET = \frac{0.408\,\Delta(R_n - G) + \frac{\gamma 900}{T_a + 273} u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)}$	[39]
Priestley-Taylor (1972)	$ET = \alpha\,\Delta(R_n - G) / (\Delta + \gamma)$	[38]
Hargreaves (1975)	$ET_0 = 0.0075 R_s T_F$	[37]
Hargreaves (1985)	$ET_0 = 0.0022 R_s (T_a + 17.8) TD^{0.5}$	[37]
FAO-56 Penman-Monteith (1998)	$ET_0 = \frac{0.408\Delta\,(R_n - G) + \gamma \frac{\gamma 900}{T_a + 273} u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)}$	[41]
Penman-Monteith ASCE (2005)	$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma(\frac{C_n}{T_a + 273})\, u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$	[40]

The most known PET model is the Penman-Monteith, which allow estimating the latent heat fluxes at the vegetation layer that achieve the daily evapotranspiration in a time step, taking into account numerous physical phenomena and some characteristics of the plants [42]. However, existing evapotranspiration models have substantial errors for hourly ET predictions over a range of moisture conditions to assess the hydrological performance of the green roofs during storm events. Therefore, Jahanfar et al. (2018) [43] developed a modified Penman-Monteith equation to provide improved prediction of hourly evapotranspiration specifically for green roof applications.

Alternatively, the indirect methods calculate the ET through the energy and mass balance equations [44,45]. The energy budget method (EBM) is based primarily on the concept that ET is function of the availability of energy to evaporate water (Q_{ET}), under the hypothesis that the moisture supply is not restricted.

3. Climatological parameters influencing ET

The principal meteo-climatic parameters affect the ET by removing water from the plants and soil surface are solar radiation, wind speed, relative humidity and air temperature, and sky conditions (e.g. cloudy, sunny). These climatic features have both seasonal and geographic variations.

3.1. *Solar radiation and seasonal variation*

The water depletion rate of soil reflects the solar radiation input that sustains the evapotranspiration. Tabares-Velasco and Srebric (2012) [46] performed a sensitivity analysis in order to understand which parameters greatly affect ET. Among all the environmental variables, solar radiation was the one with the strongest influence on ET. However, ET intensity varies due to the combined effect of solar radiation with the other meteo-climatic parameters.

Jim and Tsang (2011) [47] found that the transpiration rate peaked in autumn due to the high level of solar radiation and the low relative humidity. The actual solar radiation reaching the earth surface depends by the turbidity of the atmosphere and the presence of clouds, which reflect and absorb a large percentage of the radiation. Therefore, sky conditions affect ET, since they modify the energy balance of the evaporating surface.

Coutts et al. (2013) [48] evaluated the advancement of ET for both a green roof and a bare soil measuring the volumetric water content during four clear sunny summer days. In both vegetated and bare soil, the ET was rather modest, with values of about 50 W/m^2, suggesting that during the monitored summer period there was scarcity of water available in the soil to support evapotranspiration. Consequently, the cooling effect of the green roofs was significantly restricted. Jim and Peng (2012) [49] differentiated the sky conditions into three types: sunny, cloudy and rainy. Overall, sunny days registered progressive water loss from the substrate due to evapotranspiration, while during cloudy days the evapotranspiration was low so the water was maintained in the substrate. Moreover, the ET was correlated with the volume of water contained in the substrate, distinguishing between moist and dry substrates. For each weather type, wet means that the moisture content is at or near the maximum daily initial moisture level; moist means at or near the average daily initial moisture level; and dry means at or near the minimal daily initial moisture level. Thus during cloudy days both moist and dry substrate recorded similar evapotranspiration, while during sunny days the dry substrate recorded an even higher evapotranspiration than the moist.

Otherwise, Lazzarin et al. (2005) [50] compared the ET in dry and wet soil in summer and observed that the wet soil gave rise to higher evapotranspiration whereas in dry conditions that contribution was limited. In winter, despite the considerably lower solar irradiance in comparison to the summer season, the evapotranspiration flux was also appreciable. During summer, with the soil in almost dry conditions the green roof allowed an attenuation of the thermal gain entering the underneath room of about 60% with respect to a traditional roofing with an insulating layer. During the winter the evapotranspiration process was driven above all by the air vapour pressure deficit; it is not negligible weight produced an outgoing thermal flux from the roof that was 40% higher than the corresponding one of a high solar absorbing and insulated roofing.

Jim and Tsang (2011) [47] found that the seasonal transpiration rates on sunny days were, in descending sequence: autumn, summer, winter and spring. They suggested that the relatively high transpiration rate observed in summer sunny days occurs because high solar radiation and air temperatures promote photosynthesis. In winter sunny days, the transpiration rate was lower than in autumn and summer because of the solar radiation is less intense. Such result was confirmed by the modest transpiration rate observed in spring, the lowest recorded in this study, which were due to weak solar radiation and low temperatures characterizing this season.

In the study performed by Lee and Jim (2018) [51], the progressive dropping of air and green roof surface temperatures in the course of the sunny day was explained by the effective cooling brought by evapotranspiration fuelled by solar radiation input. Even though irradiance at the green roof surface was limited, the ambient warmth and relatively low surface temperature did not require a lot of latent heat absorption to cool down.

As shown in Table 3, most of the analysed studies evaluated ET during summer periods when it is expected to be higher in comparison to winter periods, due to the influence of solar radiation and relative humidity. Since sky conditions influence on the final ET process, it is important to highlight the scarce literature (6 over 21) that provide a proper description of the weather conditions.

Table 3. Classification of the studies reviewed according to the season, sky conditions and climate classification

References	Köppen classification	Weather	Season	Type of study
Feng et al. [52]	Cfa	-	Summer	Modelling
Jim and Peng [49]	Cwa	Sunny-cloudy-rainy	Summer	Experimental
Jim and Tsang [47]	Cwa	Sunny-cloudy-rainy	Whole year	-
Lazzarin et al. [50]	Cfa	-	Summer-winter	Modelling
He et al. [53]	Cfa	Clear-cloudy-rainy	Summer	Modelling
Tabares-Velasco and Srebric [54]	-	-	Summer	Experimental

Tabares-Velasco and Srebric [46]	-	-	Summer	Modelling
Ouldboukhitine et al. [55]	Cfb	-	Summer	Experimental
Coutts et al. [48]	Cfb	Sunny	Summer	Experimental
Schweitzer and Erell [56]	Csa	-	Summer-winter	Experimental
Ouldboukhitine et al. [57]	Cfb	-	Summer	Experimental
Tan et al. [58]	Af	-	Summer-winter	Experimental
Tian et al. [59]	Cfa	-	Summer	Modelling
Hodo-Abalo et al. [60]	-	Sunny	-	Modelling
Tsang and Jim [61]	Cwa	Sunny-cloudy	Summer	Modelling
Ouldboukhitine et al. [62]	-	Sunny	Summer	Modelling
Boafo et al. [63]	Dwa	-	Summer-winter	Simulation
Silva et al. [64]	Csa	-	Summer-winter	Simulation
Vera et al. [65]	Bsk Csc Cfb	-	Summer	Simulation
Lee and Jim [51]	Cwa	Sunny-cloudy-rainy	Summer	Experimental

The previous survey indicates that the solar radiation is the climatic data with the strongest correlation with evapotranspiration [49]. Such correlation will be further analysed in Section 8, assessing previous sensitivity analyses.

Otherwise, since the ET phenomena depends also by the whole meteo-climatic features, future studies have to include as much possible complete meteo-climatic description in order to correlate the ET with the main climatic conditions (e.g. sunny, cloudy and rainy days). Furthermore, because of the lack of studies that cover the ET during an entire year, further experimental studies should include a whole year analysis in order to evaluate the ET in the different seasons and in different weather conditions.

3.2. *Wind speed*

The process of vapour removal also depends by the air turbulence, which increase the convective heat fluxes between the atmosphere and the soil surface, as well as the airflow over the soil surface. Continuous vaporization of water by means of ET leads the air above the soil surface to become gradually saturated. If this vapour is not continuously replaced with drier air, the driving force for water vapour removal and ET decrease. Intense wind improved the transport not only of heat but also of water vapour, increasing the evapotranspiration fluxes.

Schweitzer and Erell (2014) [56] compared the total daily evapotranspiration for four plant species during days with weak (2 $m \cdot s^{-1}$) and strong wind (5 $m \cdot s^{-1}$). The authors concluded that there were substantial differences among the plant species, i.e. the vegetated roof with *Aptenia* losing less than half as much water as the vegetated roof with *Halimione*, about 3.0 L·m^{-2}·day^{-1} compared to 7.5 L· m^{-2}·day^{-1} under low wind conditions (2 m·s^{-1}). This rate was even less than for exposed moist soil, i.e. without plants, about 3.8 L·m^{-2}·day^{-1}. The other two species analysed, *Pennisetum* and *Sesuvium*, reached intermediate value, about 7.0 L·m^{-2}·day^{-1}. In windy conditions (5 m s^{-1}), the maximum hourly loss for *Pennisetum* was nearly 2.0 L·m^{-2}· h^{-1}, and the daily total was over 9.0 L ·m^{-2} ·day^{-1}. *Sesuvium*, moist soil, *Aptenia* and *Halimione* reached lower values of evapotranspiration, 8.8, 6.0, 5.8 and 4.0 L·m^{-2}·day^{-1}, respectively. In this study, high wind speed enhanced the ET.

In another experiment, Tabares-Velasco and Srebric (2011) [54] found that when the wind speed varied from 0.1 m·s^{-1} to 1.0 m·s^{-1} the evapotranspiration rate increased from 10% to 30%. This result confirm that air convection effectively brings water vapour from the soil or foliage to the atmosphere increasing the evapotranspiration rate.

For instance, an increase of the convection coefficient, which has a direct correlation with wind velocity, from 12.0 to 16.0 W/m^{2}K reduce the heat storage by 24% and 45% for bare and green roofs, respectively [61].

Jim and Tsang (2011) [47] found a rather modest correlation between the wind above the canopy and transpiration, so the wind should not play a major role in facilitating the transpiration rate. Figure 2 shows the sunny and rainy wind speed measured at canopy top in [47]. The wind speed was relatively higher on rainy days than on sunny ones. The wind speed on rainy and sunny days averaged at 3 ms^{-1} and 1 ms^{-1} respectively. The correlation coefficients between wind and transpiration at −0.1 to 0.1 ($p \leqslant 0.05$) was weak. Although wind speed was higher on rainy days, the associated high relative humidity suppresses transpiration.

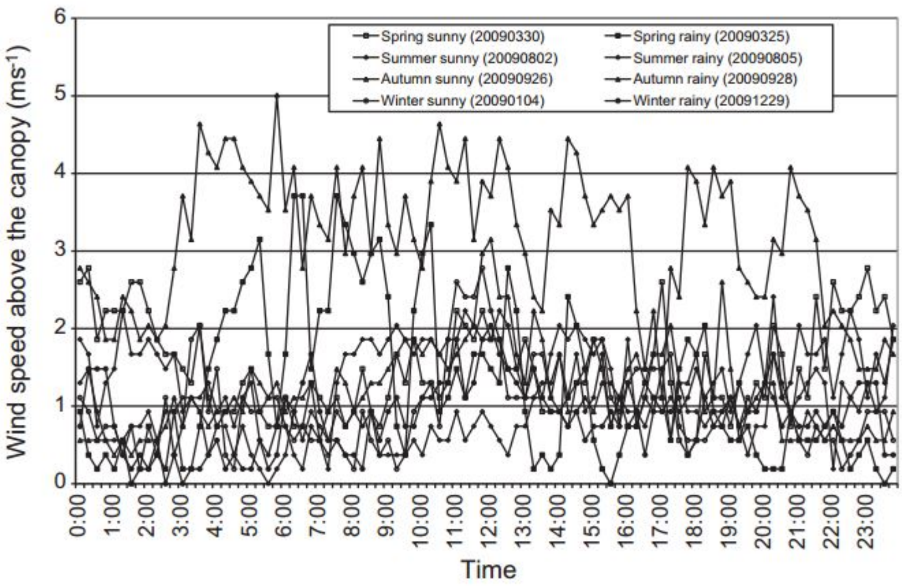

Figure 2. Seasonal and diurnal wind speed above the canopy of the sky woodland [47]

3.3. *Relative humidity and air temperature*

Even if the energy supplied by the solar radiation is the main driving force for the vaporization of water, the difference between the water vapour pressure at the soil and plants surface, and the surrounding air are other important factors that also determine the vapour removal.

High temperatures combined with lower relative humidity (RH) enhance the evapotranspiration process [66]. Tabares-Velasco and Srebric (2012) [46] stated that ET was strongly influenced by the environmental conditions, in terms of air temperature and relative humidity in the vicinity of the green roof.

Generally, during night-time the outdoor air reach low temperatures that conversely cause the increase of RH until 100%, so reducing the ET process. On the contrary, during day-time the higher air temperature induces a fall of RH so allowing the evaporative process to take place [49].

In a Cwa climatic area where the relative humidity and the air temperature varied between 50%, 23 °C in autumn, and 80%, 36 °C in summer, Jim and Tsang (2011) [47] found that the highest transpiration rate is observed in autumn rather than in summer, because of low relative humidity and mild air temperature. According to this study, evapotranspiration is minimized in a humid environment and the high relative humidity is the crucial factor that dampens the transpiration rate.

Unlike the green roof in the temperate region, the experiment carried out by Jim and Tsang [47] showed that the transpiration rate of an intensive green roof in the humid-subtropical region, dominated by the Monsoon climate system, depends mainly on photosynthetically active radiation and relative humidity.

As with all the other processes that take advantage of evaporation, planted roofs do not have much to offer in terms of ET rate in a humid environment compared with an arid one [50].

3.4. Irrigation regime

Azeñas et al. (2018) [67] analysed the relationship between irrigation regime and heat flux through green roofs. In particular, the authors considered well-watered and water-limited condition. Surface drip irrigation at 50% and 25% of potential evapotranspiration (ET_0) was applied twice a week during the calculated time according to the nominal drippers flow (2 l h^{-1} for each dripper) and considering the number of drippers (9 drippers for each module). Results showed lower heat flux in water-limited than in well-watered treatments in both non-vegetated and vegetated modules, suggesting that the lower heat transfer with air in comparison to water would counteract the cooling effect of evapotranspiration that is supposed to be higher in the well-watered modules, where the volumetric water content is higher. In particular, water-limited irrigation treatment was shown to increase the thermal insulation capacity when compared to complete well-watered irrigation treatment, by reducing the total transferred heat between 25% and 71% along the different seasons of the year, suggesting that the air/water substrate content has a greater effect on insulation than evapotranspiration.

3.5. The geographic area

The review conducted by Pérez et al. (2014) [68] concluded that the Köppen climate classification is the most suitable reference to compare research results about green infrastructures. In order to provide a continuous framework in the literature, this review used the same climate classification for all the reviewed papers (Table 4).

Table 4. Climate classification of experimental, modelling and simulation studies

Ref.	Authors	Year	Location		Climate according to the author	Köppen classification
[49]	Jim and Peng	2012	Hong Kong	Hong Kong	Humid-subtropical	Cwa
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[54]	Tabares-Velasco and Srebric	2011	USA	Pennsylvania	-	Dfb
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[55]	Ouldboukhitine et al.	2012	France	La Rochelle	-	Cfb
[48]	Coutts et al.	2013	Australia	Melbourne	-	Cfb

[56]	Schweitzer and Erell	2014	Israel	Tel Aviv	Mediterranean	Csa
[57]	Ouldboukhitine et al.	2014	France	La Rochelle	-	Cfb
[58]	Tan et al.	2017	Singapore	Singapore	-	Af
[52]	Feng et al.	2010	China	Guangzhou	-	Cfa
[70]	Djedjig et al.	2012	France	La Rochelle	-	Cfb
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[50]	Lazzarin et al.	2005	Italy	Vicenza	-	Cfa
[53]	He et al.	2016	China	Shanghai	North subtropical monsoon	Cfa
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[59]	Tian et al.	2017	China	Chongqing	Humid subtropical monsoon	Cfa
[60]	Hodo-Abalo et al.	2012	Togo	-	-	Aw
[61]	Tsang and Jim	2011	Hong Kong	Hong Kong	-	Cwa
[62]	Ouldboukhitine et al.	2011	France	La Rochelle	-	Cfb
[63]	Boafo et al.	2017	Republic of Korea	Incheon	Humid continental	Dwa
[64]	Silva et al.	2016	Portugal	Lisbon	Mediterranean	Csa
			USA	Albuquerque	Semi-arid	Bsk
[65]	Vera et al.	2017	Chile	Santiago	Semi-arid	Csc
			Australia	Melbourne	Marine	Cfb

Most of the studies reviewed in this paper (71%) were carried out considering temperate climatic conditions, first letter C according to the Köppen classification. About 17%, 8% and 4% of the studies were developed in tropical (D), arid (A) and cold climates (B), respectively.

The 71% of the studies performed in temperate climates are located in areas without dry seasons (Cf according to the Köppen classification). About 17% of these studies were performed in climates with dry summers, second letter s (Cs according to the Köppen classification). Finally, only a few of the studies analysed, about 12%, are located in climates with dry winters, second letter w (Cw according to the Köppen classification).

Figure 3 shows the analysed studies located on the world evapotranspiration map. The Water Holding Capacity is the total amount of water available for plants that is held against gravity in a soil and is usually estimated as the amount present at -0.03 MPa average water potential minus the amount present at -1.5 MPa water potential. In [71], the authors stated that it is a very important soil characteristic strongly and positively correlated to the inherent productivity of soils.

Most of the studies were performed in the western part of the world under temperate climatic conditions (Figure 3). However, other regions could allow achieving high rates of ET that have not yet deeply explored or at least there is a lack of data in literature. Consequently, future studies should encompass experimental study in tropical and arid climates where green roofs could enhance the cooling effect on buildings thanks the potential high ET rates.

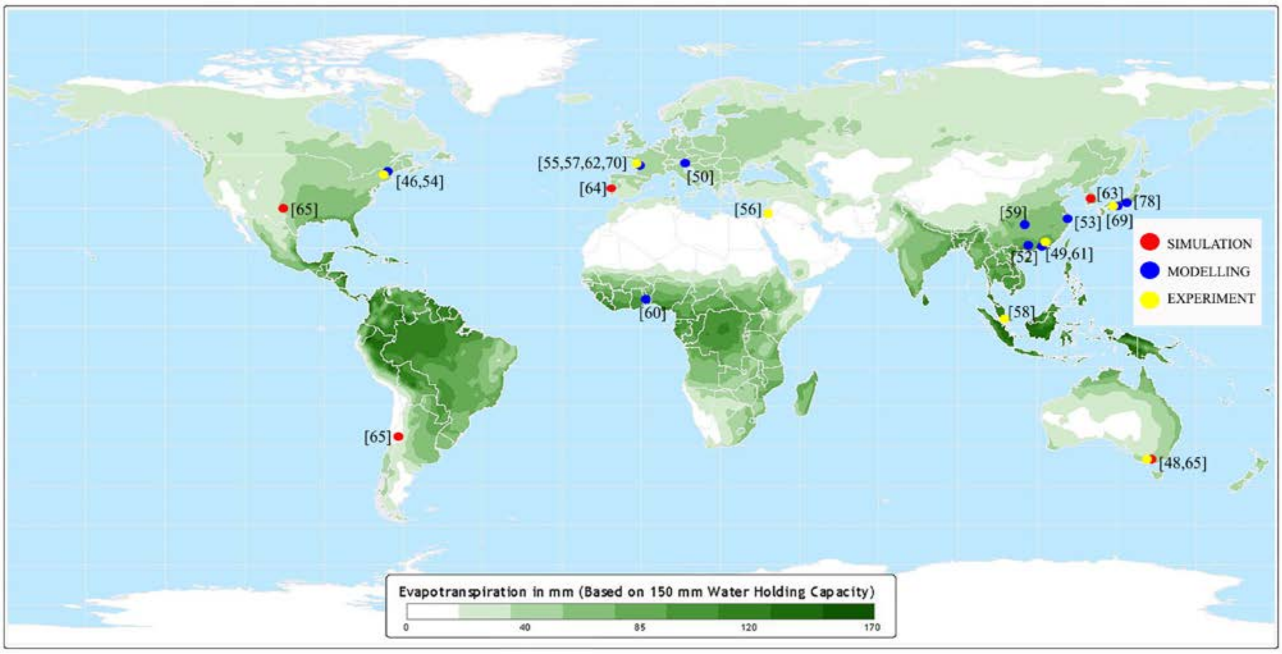

Figure 3. Location of simulation, modelling and experiment studies in the world Evapotranspiration map [72]

However, it has to be underlined as in hot arid regions green roofs need to be well watered, due to the abundance of solar energy and dry air, consequently they consume large amounts of water. On the other hand, in humid tropical regions, since the air is frequently close to saturation, less additional water can be transferred from the green roof to the atmosphere, and hence the evapotranspiration rate is lower than in arid regions.

The world evapotranspiration map presented in Figure 3 is obtained by considering all the environmental parameters of a specific geographic area affecting natural evapotranspiration, such as solar radiation, relative humidity, annual average temperatures and annual average precipitation, which are the most important parameters for the vegetation development.

In some geographic areas of the world presented in Figure 3, such as in the African desert area, where potential evapotranspiration is high due to solar radiation and air temperatures, there is no evapotranspiration due to the lack of water. Therefore, if there were enough amounts of natural water (e.g. rain and water wells), these geographic areas could be enabled to take advantage of the cooling effect of green roofs.

An analysis of Figure 3 underlines that further experimental studies about ET should be carried out in regions of the world that have not been yet deeply investigated.

It is worth mentioning that the ET in green roofs differs from the phenomenon of natural evapotranspiration since, in addition to the above-mentioned climatic variables, it is also affected by the inherent properties of a green roof system. Some of these properties are; type of plants, substrate characteristics (thickness and composition), and irrigation regime that provides water for evapotranspiration in the absence of precipitation.

4. Plant-substrate parameters influencing ET

4.1. *Volumetric water content*

The cooling performance of a green roof depends on the water content of the substrate that determines the availability of water for evapotranspiration. Volumetric water content in the soil is related to the green-roof hydrological cycle because the green roof gains water from rainfall and irrigation, and loses it through evapotranspiration, surface runoff and drainage.

Djedjig et al. (2012) [70] found that when the green roof was characterized by a VWC in the soil of 10% of the maximum value, evapotranspiration was reduced to its minimum. On the contrary, evapotranspiration increased when the substrate had high water content.

Jim and Peng (2012) [49] found that during rainy days, antecedent VWC in the soil reduces the infiltration rate, thus increasing the runoff quantity. On successive sunny or cloudy days when drainage and run-off are negligible, the water stored in the substrate depends by irrigation and evapotranspiration. Previous studies [27,73,74] identified volumetric water content in the soil as the key factor for the evapotranspiration process, especially when irrigation is not present. In Bevilacqua et al. (2015) [75] even though the environmental conditions would allow evapotranspiration to take place, no considerable ET was found due to the limited water content in the substrate.

In the research conducted by Tan et al. (2017) [58] on conventional garden soil and artificial substrates, consisting mainly of perlite, the evapotranspiration rates exhibited strong positive correlations with the volumetric water content. In fact, when volumetric water content in the soil decreased ~~gradually~~, the plant evapotranspiration rate was restricted. In addition, the ET decreased because of the low plant transpiration activity due to the lack of available water even if high solar irradiance occurred.

The use of a water retention layer below the green roof substrate makes it possible to maintain the VWC consistently higher. The water retention layer, therefore, sustains plant life by providing an additional availability of moisture, i.e. a liquid such as water in the form of very small drops, either in the air, in a substance, or on a surface. In green roof systems planted with *Sedum mexicanum* and *Disphyma austral*, Voyde et al. (2010) [35] observed a rapid water loss via latent heat flux in the days after watering. This water loss gradually decreased because the water available was reduced until plants stopped transpiring to preserve water.

The sensitivity test performed by Feng et al. (2010) [52] has shown that an increase from 30% to 60% in volumetric water content in the soil showed a reduction of 24% the heat stored within the green roofs, thanks to the increasing latent heat. On the contrary, Tabares-Velasco and Srebric (2012) [46] found that the water content in the substrate did not have the most significant impact on ET. However, a change in substrate conditions from the driest to the wettest led to a decrease in the substrate temperature of about 10.0 °C and a reduction in the incoming heat flux by 40%. This reduction was mainly due to an increase in the evapotranspiration rate (from 8.0 to 230.0 W/m^2) despite of an increase of 70% in substrate thermal conductivity and a decrease of 50% in substrate reflectivity, measured with a Portable Spectroradiometer using a calibrated lamp different that the fluorescent lamps directly above plants. Soil reflectivity depends on soil type and water content that typically varies from 0.10 for wet soil to 0.35 for dry soil.

He et al. (2017) [76] found that a higher water ratio helped to increase the evapotranspiration intensity while it decreased the thermal resistance of soil layer. As it was evaluated in some studies, the relation between the increment in the substrate volumetric water content and the increment of ET was not linear [49,54].

Evapotranspiration-substrate water content curves have an elongated ‘‘S’’ shape with low evapotranspiration rates when water is scarce in the substrate and high evapotranspiration rates when water is abundant. In the middle of the substrate water content range, the relationship is approximately linear (Figure 4). Experimental data revealed that samples with higher water content provided higher latent fluxes and lower convective fluxes [52].

As result this section highlight that substrate water content plays an important role in decreasing temperatures on the green roof surface and the total incoming heat flux through the roof.

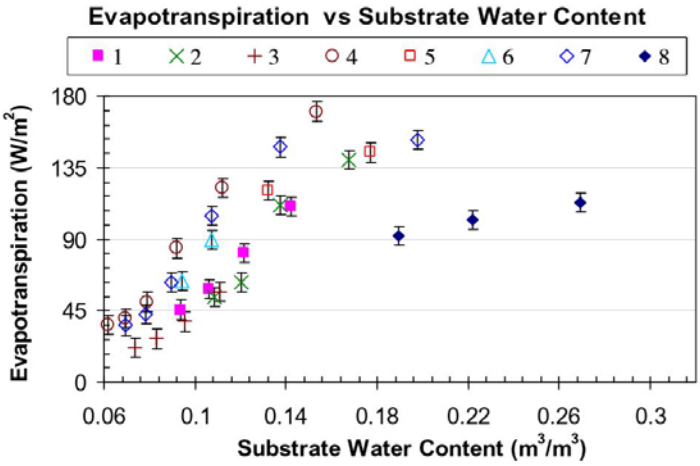

Figure 4. Relationship between evapotranspiration and substrate water content [54]

4.2. *Vegetation*

The transpiration process of plants contributes to the evaporation from the substrate, moreover the plant layer shades the roof surface and further reduces the heat fluxes incoming into the roof.

The species of plants, their physiology and growth typology, influence the green roof cooling effect by means of the ET process. Succulent plants, which store excess water in their thick leaves, are generally well adapted to extreme climates, and particularly in dry conditions. The *Sedum* family, capable of activating *Crassulacean Acid Metabolism* (CAM) photosynthesis, is recommended for extensive roofs where the depth of the soil layer is very shallow [77]. Under dry soil conditions, the evapotranspiration in a green roof with *Sedum* may be mostly evaporation from soil, with little transpiration from plants. Voyde et al. (2010) [35] found that planted treatments of *Sedum mexicanum* and *Disphyma australe* attained a latent heat flux of 2.19 mm/day and 2.21 mm/day, respectively, when the plants were not water stressed. Irrigated green roofs showed a latent heat flux higher than 200 $W\cdot m^{-2}$, suggesting that despite the presence of drought-tolerant *Sedum*, irrigation increased evapotranspiration when water was available.

Schweitzer and Erell (2014) [56] compared a well-watered roof covered with and without plants and observed that ET was the least effective cooling mechanism without the shade provided by plants. *Aptenia* lost less than half as much water as *Pennisetum*, about 3 L $m^{-2}day^{-1}$ and 7 L m^{-2} day^{-1} respectively. The *Pennisetum* loss rate was even less than in bare moist soil, about 3.8 L m^{-2} day^{-1}. Coutts et al. (2013) [48] evidenced that soil without plants may deliver greater latent heat fluxes, as the resistance to water loss from the vegetation surface is not present. The peaks of latent heat flux afterwards a cycle of irrigation are lower on the green roofs than the bare soil, this because the green roofs retained water in the substrate and vegetation over a longer period. The samples with plants consistently show an average reduction of the heat flux transferred into the spaces beneath the roof of about 25% compared to samples without plants. This is because plants provide extra shading to the roof, additional water storage, and a better water control by means of evapotranspiration and photosynthesis [54].

It was found that the Leaf Area Index (LAI) factor and the amount of evapotranspiration from the top surface have a large effect on the heat flow transferred into the spaces beneath the roof [78]. In a Mediterranean climate, results have shown that the LAI greatly influences the thermal performance of the vegetated roof since it enhances shading, convective heat transfer, and evapotranspiration. Higher LAI values allow to achieve higher cooling effect due to the increase of evapotranspiration [79,80].

Tabares-Velasco and Srebric (2012) [46] pointed out that among the green roof design variables, the most significant factor that allowed a reduction in temperature and heat flux through the substrate was the LAI.

In agreement with the findings obtained by Tabares-Velasco and Srebric [62], Hodo-Abalo et al. (2012) [60] found that evapotranspiration is more intense when the foliage is sufficiently dense. In addition, the LAI has important effects on the energy phenomena in the vegetation layer, thanks to the shading and transpiration that it provides, reducing solar flux penetration, stabilizing fluctuating values and reducing the indoor temperature.

Theodosiou (2003) [66] revealed large heat flows from the substrate surface to the atmosphere for surfaces on sunny days and relatively small flows on cloudy days, when the value of LAI was up to 3.0. Therefore, under such operative conditions there was a significant increase the cooling effect on the room space. It was an office building. The floor beneath the planted roof had an area of 70 m^2, internal gains of 1.10 kWh during working hours (08:00–16:0 h) and 0.1 kWh during the rest of the day. The air conditioning functions during the 8 h period with a thermostat set at 26 ºC and.

Lee and Jim (2018) [51] concluded that the dense foliage of the woodland vegetation should have provided greater shading and evapotranspirative cooling than an Indian green roof with herbaceous vegetation but 0.4 m-deep substrate used by Kumar and Kaushik (2005) [81]. The green roof used in [51] achieved only half the maximum air temperature of 12 °C on the Indian intensive green roof. The authors concluded that such disparity could be caused by variations in vegetation characteristics.

4.3. Stomatal resistance

Plant transpiration or latent heat flux depends on the physiological properties of the plants and their stomatal resistance or conductance that controls water loss. Stomatal resistance is opposed to the transport of water vapour and carbon dioxide to or from the stomata on the leaves of plants, the lower the value of stomatal resistance, the greater the ET. It depends by the water content in the interior of the stomata cavity and on the exterior surface of the leaf, but also by air density and moisture flux.

The dimension of stomatal resistance is time over distance that is the inverse of velocity, its values depend on plant selection. Grass plants with stomatal resistance of 60 s·m^{-1} produce evapotranspiration fluxes that are 3-4 times higher than those produced by succulent plants (e.g. *Sedum*) [46].

Generally, plant species with low values of stomatal resistance allow achieving higher ET if there is sufficient water in the soil.

4.4. Stomatal conductance

Otherwise, the stomatal conductance gives an estimation of the rate of exchange of gases and transpiration through the stomata of the plants, which depends by solar radiation, temperature, humidity and water availability. Higher stomatal conductance tends to correspond to higher evapotranspiration rates. The stomatal conductance is usual measured in mmol·mo$^{-2\cdot}$ s^{-1}.

Tan et al. (2017) [58] have studied the variation of the stomatal conductance of *Cyathula prostrata* in function of both the cycle of irrigations and the type of soil (i.e. artificial soil, consisting mainly of perlite, and normal garden soil), which is a commercially available soil mix commonly used in urban landscapes. It was observed that during periods of regular irrigation, average stomatal conductance of *Cyathula prostrata*, which is a creeping shrub, was about 600.0 mmol·m^{-2}·s^{-1}. When irrigation was withheld, the stomatal conductance of *Cyathula prostrata* planted into the artificial soil was reduced to around 100.0 mmol· m$^{-2\cdot}$ s^{-1}, while in a normal garden soil the stomatal conductance was reduced to 50.0 mmol m^{-2}s^{-1}. For the case of the artificial soil equipped with a water retention layer, when irrigation was withheld the stomatal conductance slightly reduced to 425 mmol·m^{-2}·s–^{1}. When irrigation was resumed, stomatal conductance levels increased to 375.0 mmol· m−2· s−1[1] both in the case of artificial and normal garden soil.

This section has highlighted that the choice of the type of plants entails to different stomatal conductance, which in turns affects the ET.

4.5. *The substrate and drainage layer*

Several studies [33,82,83] have revealed that the characteristics of the substrate and drainage layer affect the evapotranspiration phenomena in the green roof.

The characteristics of the substrates that influence evapotranspiration are porosity, size of the soil particles, compaction of the material and permeability (or hydraulic conductivity), as well as the thickness of the material. Several studies have investigated the thermo-physical and hydrological properties of different types of substrate [84,85], which could be constituted of both organic and inorganic material.

However, less attention was paid in assessing the impact of the drainage layer on the green roof evapotranspiration, although the evapotranspiration varies considerably depending on the type of solution adopted for the drainage layer. The most common solutions used as drainage layers in green roofs are constituted by modular plastic panels with a water retention layer, or in alternative by natural granular materials such as expanded clay, pumice, natural pozzolana, perlite, etc. Recently new granular materials deriving, in whole or in part, from the recycling of materials have been proposed as drainage layer [86,87]. The benefits derived by the use of such materials are their low environmental impact, in terms of reduction of natural resource consumptions in comparison to traditional drainage layer materials [88].

Regarding different types of substrates for green roofs, Tan et al. (2017) [67] have analysed the performance of an artificial substrate characterized by a higher porosity compared to a garden soil, which drain water faster than topsoil (natural soil). Hence, when irrigation was being withheld, less water was available for transpiration or evaporation from the substrate. As consequences, lower volumetric water content and evapotranspiration rates were experimented in this artificial soil compared to a normal garden soil.

Getter et al. (2011) [89] suggested that increasing substrate depth would allow the use of plants with greater biomass and leaf area, leading to a higher latent heat flux. In the thin substrate of common extensive green roofs, due to the limited substrate mass effect, solar energy heating the whole substrate increasing its temperature, which in turn increase the evapotranspiration and the water depletion [49].

However, it has to be reminded that when the VWC decreases below specific threshold also the ET is reduced.

This section has highlighted how the substrate and the drainage layers affects the ET. Generally, artificial soil characterized by higher porosity drain water faster than topsoil (natural soil). Hence, when irrigation is withheld less water is available for transpiration or evaporation from the substrate.

5. Equipment used in the reviewed green roof set-ups

Evapotranspiration is difficult to measure in a direct way, since it is a complex physical-physiological phenomenon that depends on both the phase change of the water contained in the substrate and the physiological processes occurring in the plant species used in green roofs.

As a result, several studies [47,49,52,69,70] have estimated the evapotranspiration rate from plants and soil through data derived from the substrate water content ("indirect" measurements). Sensors located at different depths of the soil layer measured the volumetric water content (VWC). Other studies carried out by Lazzarin et al. (2005) [50], and He et al. (2016) [53] have used the volumetric water content in the soil to calculate the heat transfer model of green roofs.

Table 5 summarizes the main equipment used to evaluate ET and the monitoring periods adopted in literature studies reviewed. On one hand, the "indirect" measurements presented within this table refer to ET estimation using data derived from the substrate water content. In this case, the water content variation is assumed equal to the ET. On the other hand, "direct" measurements refer to ET estimation using data collected by a lysimeter or load cells, monitoring the evolution of sample weight and not the water content variation in the substrate.

Table 5. Summary of the main instrumentation used in the reviewed set-ups and the length of monitoring periods

References	VWC sensor	Load balance	Portable closed chamber	Indoor test	Outdoor test	Monitoring period	Type of measurements
[52]	X	-	-	-	X	11 days	Indirect
[49]	X	-	-	-	X	2 months	Indirect
[70]	X	-	-	-	X	3 weeks	Indirect
[69]	X	-	-	-	X	1 month	Indirect
[47]	X	-	-	-	X	1 day	Indirect
[50]	X	-	-	-	X	2 months	Indirect

[53]	X	-	-	-	X	2 weeks	Indirect
[90]	X	-	-	X	-	6 days	Indirect
[54]	X	X	-	X	-	2-6 days	Direct and indirect
[46]	X	X	-	X	-	2-6 days	Direct and indirect
[55]	-	X	-	X	-	7 days	Direct
[48]	X	-	X	-	X	4 days	Direct and indirect
[56]	-	X	-	X	-	1 day	Direct
[57]	-	X	-	X	-	Two days	Direct
[58]	X	X	-	-	X	2 months	Direct and indirect

The devices used for evaluating ET depend on the aim of the research. In fact, if the objective is to validate an energy and mass balance model, researchers have frequently used volumetric water content sensors. On the other hand, when the aim of the research consists in estimating the rate of evapotranspiration, high precision scales combined with volumetric water content sensors are commonly used.

Most of the studies that used load cells were carried out in a laboratory (indoor test) set-up installing samples with reduced size, while only a few studies evaluated ET directly in-situ (outdoor test)[48,58]. Finally, the monitoring period varied widely, from one day to two months (see in Table 5). An important gap in the literature review is detected since the duration of almost all experimental studies (12 over 16) do not provide long periods of measurement (shorter than one month) that include the ET behaviour within the different seasons of a specific climate. Only four studies [49,50,58,69] overcome the duration of a month period monitoring. Besides the experimental set-ups of the following studies [46,50,52,70] were basically used for validating numerical models, they also contributed in providing methodologies to evaluate ET at both levels, theoretical and experimental.

In the following, a brief description of the different sensors and devices used for the ET measurement in previous experimental studies is given.

Schweitzer and Erell (2014) [56] associated the water consumption in extensive green roofs to the ET process, using mini-lysimeters. Ouldboukhitine et al. (2014) [57] evaluated the amount of water transpired by the plants using wind tunnel to control the wind speed. The hydrologic transfer was measured using a load cell installed under two green roof tray to track the weight loss due to water evapotranspired during the test.

The only difference between the two samples was that one of them was planted with vegetation and the other without. While water was evapotranspired by the test trays with vegetation, it was only evaporated by the tray without vegetation. The difference between the two trays allowed an estimation of the quantity of water transpired by the plants. Ouldboukhitine et al. (2012) [55] measured the amount of water lost by evapotranspiration and its impact on the prediction of water content variations using a setup to measure the weight of trays suspended on the traction-compression sensor balance.

Liang Tan et al. (2017) [58] evaluated ET by using both direct (with load cell) and indirect methods (with volumetric water content sensors). In such study, the authors divided green roof plots into three treatment combinations characterized by different substrate type as well as the adoption of the water retention layer or not. Sensors were embedded at 0.1 m depth in the middle planters in order to monitor volumetric water content in the soil for each of the set-ups; then, evapotranspiration was measured by weighing the middle planter box. Coutts et al. (2013) [48] used a portable closed-chamber to measure evapotranspiration rates from green roof and soil without vegetation. With this method, chambers restrict the volume of air available for the exchange between the surface and the atmosphere and the net emission or uptake of gases can be measured as a change of water concentration. The latent heat flux, therefore, was determined from the change in the mass concentration of water over time. Green roof samples were also instrumented with volumetric water content into the soil probe at a depth of 0.08 m.

Ayata et al. (2011) [90], Tabares-Velasco and Srebric (2011, 2012) [46,54] evaluated evapotranspiration rates by tracking continuously both, the variations in weight of the green roof sample with high-resolution load cells, and the changes in the volumetric water content of the substrate. In these studies, the total water loss measured with the water balance method were 10–20% larger than the load cell. Thus, the authors used evapotranspiration data measured directly from the load cell to validate the heat transfer model proposed.

At the end of this survey, it is possible to observe that load cell is the most widely used device for assessing in a direct way the evapotranspiration in green roofs. Thus, such equipment could be recommended in future studies on ET.

5.1. Units of measurement used for expressing the evapotranspiration rate

The evapotranspiration rate is frequently expressed in millimetres (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. Furthermore, the time unit has large variability, it can be assumed equal to an hour, day, ten-day period, month or even an entire growing period.

The evapotranspiration rate can be stated or in terms of the energy necessary for the water evaporation, namely the latent heat of vaporization (L_e), expressed in MJ m^{-2} day^{-1}, or, using the lysimeter (load cell) to evaluate evapotranspiration by monitoring the evolution of the tray weights due to water loss over time, expressed the evapotranspiration in kg m^{-2} day^{-1}.

Thus, a plethora of units of measurement are used to express evapotranspiration (mm, kg, W/m^2, etc.), so it becomes rather complicate to compare the results obtained from different studies. Therefore, it could be useful to provide the conversion factors among the units of measurements used to characterize the evapotranspiration process in green roof.

Table 6 summarizes the conversion factors among the units of measurements used to express the evapotranspiration rate.

Table 6. Conversion factors for evapotranspiration process measurement

	Depth	**Volume per unit area**		**Energy per unit area**	**Mass per unit area**	**Power per unit area**
From \ To	mm day^{-1}	m^3 ha^{-1} day^{-1}	L m^{-2} day^{-1}	MJ m^{-2} day^{-1}	kg m^{-2} day^{-1}	W m^{-2}
mm day^{-1}	1	10	1	2.45	1	28.36
m^3 ha^{-1} day^{-1}	0.1	1	0.1	0.245	0.1	2.836
L m^{-2} day^{-1}	1	10	1	2.45	1	28.36
MJ m^{-2} day^{-1}	0.408	4.082	0.408	1	0.408	11.57
kg m^{-2} day^{-1}	1	10	1	2.45	1	28.36
W m^{-2}	0.035	0.35	0.035	0.0864	0.035	1

5.2. Evapotranspiration rate carried out by literature studies

Besides providing valuable technical details regarding the methods for measuring ET, experimental set-up tests also offer useful information on the real quantification of the ET process.

Liang Tan et al. (2017) [58] developed a study on both conventional garden soil, which is a commercially available soil mix commonly used in urban landscapes, and K-soil, which is a proprietary lightweight soilless media, consisting mainly of perlite and organic matter. They found that evapotranspiration ranged between 2.0 and 7.0 kg m^{-2} d^{-1}. Moreover, the authors also observed that plant evapotranspiration decreased gradually in a similar manner to the corresponding soil water content, to approximately 2.0 kg m^{-2} d^{-1} in both conventional garden soil and K-soil. On the contrary, evapotranspiration was around 4 kg m^{-2} d^{-1} when an artificial soil, consisting mainly of perlite, was tested.

Other studies demonstrated that the evapotranspiration for trays with plants was always higher than the evaporation of trays without vegetation [57], especially for trays using periwinkle (leafy plant) than for ryegrass. In the periwinkle test, the water lost by evapotranspiration after 48 hours was 5.2 kg, about twice as much as that lost only by evaporation that was about 3.0 kg. While the water loss was 3.5 kg after 48 hours for the ryegrass sample.

A substantial variation of water loss among some plant species was found also in other literature studies. In the tests performed by Schweitzer and Erell (2014) [56], *Aptenia* lost less than half as much water as *Pennisetum*, about 3 L $m^{-2}$$day^{-1}$ and 7 L m^{-2} day^{-1} respectively. The *Pennisetum* loss rate was even less than in bare moist soil, about 3.8 L m^{-2} day^{-1}. Ouldboukhitine et al. (2012) [55] measured that daily evapotranspiration with a grass tray (2.34 mm) was greater than that with a *Sedum* tray (1.42 mm). The cumulative evapotranspiration over three days was around 8.0 mm, 5.0 mm, and 4.0 mm for grass, *Sedum*, and bare soil, respectively. These results are in contrast with those found by Coutts et al. (2013) in [48], where the plants limited the ET. In addition, the daily evapotranspiration measured for grass (2.53 mm) is greater than that calculated by the Penman-Monteith equation (1.66 mm). This difference is probably due to the "tray factor", as defined by Ouldboukhitine et al. (2012) in [55], and to the input parameters taken in the Penman-Monteith equation such as temperature, aerodynamic resistance, and vapour pressure.

Some studies calculated the latent heat flux after measuring the quantity of water lost. In Coutts et al. (2013) [48], the higher latent heat flux on soil (with maximum value about 280 W m^{-2}) compared to green roof (with maximum value about 210 W m^{-2}) suggested that wet soil freely evaporated while evapotranspiration from the green roof was limited by the lower surface temperatures and water uptake by vegetation. After irrigation, there was a substantial increase in latent heat flux for both green roof and bare soil. Maximum rates of latent heat flux increased on green roof and soil a mean of 100 W m^{-2} and 90 W m^{-2}, respectively.

Other studies analysed the relationship between ET and different weather conditions. Jim and Peng (2012)

[49] evaluated both different typical days (sunny, cloudy, and rainy) and different substrate water content. The authors found that for a sunny day with moist soil, about 4.0 mm of water is extracted from the substrate to satisfy evapotranspiration (9.3 mm considering 5 mm due to irrigation). The water depletion during a sunny day with dry soil was 13.1 mm and it was notably higher in comparison to a sunny day with moist soil, despite the lower water content in the substrate. On the contrary, a cloudy day with limited solar gains and dry soil notably suffered a subdued depletion, at merely 5.8 mm.

Tabares-Velasco and Srebric (2012) concluded in their study [46] that the latent heat flux due to ET reached maximum values during the experiment with high wind speed, around 170 W m^{-2}, while minimum values occurred when there was low solar radiation, around 20 W m^{-2}. Takebayashi and Moriyama (2007) [69] found that the quantity of evaporation from the green surface in November, with maximum value of 0.06 g m^{-2} s^{-1}, was higher than in August with maximum value of 0.02 g m^{-2} s^{-1}.

In the study conducted by Tabares-Velasco and Srebric in (2011) [54], they observed that latent heat rates vary the substrate water content. The green roof sample achieved the largest and nearly constant evapotranspiration rates over 135 Wm^{-2} when VWC was above 0.14 m^3 m^{-3}. Evapotranspiration decreased linearly with the VWC up to approximately 0.07 m^3 m^{-3}, showing values between 135 and 45 Wm^{-2}. Evapotranspiration rates dropped in a nonlinear way when VWC was lower than 0.07 m^3m^{-3} with values below 45.0 W m^{-2}. The daily evapotranspiration ratio was about 3.0 when the substrate was wet, with 20.0 and 60.0 W m^{-2} latent heat flux during night and day respectively, while the day/night ratio was about 5.0 when the substrate is dry, with 50.0 and 150.0 W m^{-2} latent heat flux during night and day, respectively.

Since the presented results about evapotranspiration rates make difficult to perform a comparative analysis because of the different units of measurement used by authors, Table 7 shows all data summarized and converted into kg/m^2 to facilitate the cross-comparison of the findings.

Table 7. Summary of the minimum and maximum values obtained from the parameters reviewed in experimental studies

Reference	Parameter	Description	Minimum value	Maximum value	Units	Climatic conditions	Minimum value kg m^{-2} day^{-1}	Maximum value kg m^{-2} day^{-1}
	Sky conditions	Sunny day+wet soil	-	9.3			-	9.3
		Sunny day+moist soil	-	9.0			-	9.0
[49]		Sunny day+dry soil	-	13.1	mm	Hong Kong (Cwa)	-	13.1
	Moisture soil	Cloudy day+wet soil	-	8.1			-	8.1
		Cloudy day+moist soil	-	5.0			-	5.0

		Cloudy day+dry soil	-	5.8			-	5.8
[69]	Season Vegetation	August	-	0.08	g m^{-2} s^{-1}	Kobe (Cfa)	-	6.9
		November	-	0.02			-	1.72
		Bare soil	-	0.05			-	4.3
[46,54]	Solar radiation Relative humidity Wind speed Air temperature	**Soil UVA.** Solar radiation simulated with UVA lamps for the experiment with a green roof sample without plants.	30	130	W m^{-2}	Pennsylvania (Dfb)	1.1	4.6
		Soil Day. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample without plants.	40	100			1.4	3.6
		UVA plants. Solar radiation simulated with UVA lamps for the experiment with a green roof sample with S. spurium	95	115			3.3	4.0
		Base. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample with Delosperma nubigenum.	45	120			1.6	4.2
		Humidity. Conditions equal to ‘Base’ experiment, except that relative humidity was set to 50%.	50	140			1.8	4.9
		Solar. Conditions equal to ‘Base’ experiment, except solar radiation decreased by 50%.	25	55			0.9	1.9
		Wind. Conditions equal to ‘Base’ experiment, except wind speed increased to 1 m/s.	40	170			1.4	6.0
		Temperature. Conditions equal to	60	140			2.1	4.9

		‘Base’ experiment, except air temperature changed to 26 °C.						
		Base II. Conditions equal to ‘Base’ experiment in order to duplicate the measurements.	40	150			1.4	5.3
[55]	Vegetation	Sedum	-	5.0	mm	La Rochelle (Cfb)	-	5.0
		Grass	-	8.0			-	8.0
		Bare soil	-	4.2			-	4.2
[48]	Vegetation	Sedum	20	210	W m^{-2}	Melbourne (Cfb)	0.7	7.4
		Bare soil	20	280			0.7	9.9
[56]	Vegetation	Soil moist	4.0	6.0	L m^{-2} day^{-1}	Tel Aviv (Csa)	4.0	6.0
		Pennisetum	7.0	9.0			7.0	9.0
		Aptenia	3.0	6.0			3.0	6.0
		Sesuvium	6.5	7.5			6.5	7.5
		Halimione	7.5	4.0			7.5	4.0
[57]	Vegetation	Periwinkle	0.5	5.0	kg m^{-2} day^{-1}	La Rochelle (Cfb)	0.5	5.0
		Grass	0.5	3.5			0.5	3.5
		Soil bare	0.5	3.0			0.5	3.0
[58]	Substrate	Normal soil	2.0	6.0	kg m^{-2} day^{-1}	Singapore (Af)	2.0	6.0
		Artificial soil	2.0	6.0			2.0	6.0
		Artificial soil + water retention	4.0	7.0			4.0	7.0

The variability of the results depends on both the instrumentation and the parameters (plant species, substrate type, climatic conditions, etc.) influencing the ET process.

In terms of weight, the ET maximum values were 7.0 kg m^{-2} day^{-1} and 3.0 kg m^{-2} day^{-1} respectively, using artificial soil with water retention layer below the substrate and bare soil. In terms of water lost by evapotranspiration, the maximum values during a sunny day were 13.1 mm with dry soil and 8.0 mm using grass. Latent heat flux reached the maximum value with high wind speed conditions (170 W m^{-2}) and using bare soil (280 W m^{-2}) compared to *Sedum* (210 W m^{-2}).

Most of the analysed studies performed a comparison between green roof evapotranspiration (plants + substrate) and bare soil evaporation (only substrate). However, few of them evaluated ET when different solutions of green roof layer were alternated and compared, and/or varying the plant species [55–57]. Moreover, only Tan et al. (2017) [58] measured evapotranspiration rates varying the substrate type.

Few studies evaluated the evapotranspiration under different environmental boundary conditions. In particular, in [49], the weather was differentiated into three types: sunny, cloudy and rainy. Interestingly, Jim and Peng (2012) [49] claim that the dry soil reached 13.1 kg m^{-2} day^{-1} and the wet soil 9.3 kg m^{-2} day^{-1} during sunny days. This assumption underlines the importance in evaluating, not only the substrate water content, but also the climatic conditions. Because the limited substrate-moisture effect on ET and associated cooling that could be explained due to sufficient water supply by occasional rainfall events and regular irrigation confined soil moisture variations to a small range during the summer period and to the relatively weak capability of the substrate to hold water tightly during the dry state to resist ET water extraction.

This survey has highlighted a lack of studies concerning the effect of the drainage layer on ET. This could be an interesting field for future studies considering that the drainage layer is particularly important since it has the aim of ensuring an optimal balance between air and water within green roof system.

Further researches also should focus on optimizing green roof technology with a water retention layer inside the drainage layer in order to increase ET.

6. Mathematical models to characterize ET on green roofs

6.1. Heat and mass transfer models for ET in green roofs

Due to the heat and mass transfer through the roof resulting from shading, insulation, cooling (evapotranspiration) and wind effects, modelling the latent heat flux of green roofs is not a simple process. Many researchers have explored the heat exchange between green roofs and the environment in which the heat and mass transfer in soil were mostly taken as a quasi-steady-state process.

The energy exchanged between the green roof surface and the outside environment consists of latent and/or sensible heat. Latent heat is the heat loss by evapotranspiration that involves soil surface evaporation and vegetation transpiration. Evapotranspiration affects the net heat flux by modulating incoming/outgoing heat transfer mechanisms, depending on the plant species and on environmental conditions. An increase in the evapotranspiration rate decreases the convection heat flux related to sensible heat and storage [61]. Several studies obtained numerical results of each heat flux in order to quantify the latent heat flux.

Most of the studies used the following equations to evaluate latent heat flux on the plant canopy (L_F) and the soil surface (L_G) [91]:

$$L_F = LAI \frac{\rho_{af} c_{pa}}{\gamma(r_a + r_{sto})} (q_c - q_{af}) \tag{2}$$

$$L_G = \frac{\rho_{af} c_{pa}}{\gamma(r_g + r_a)} (q_g - q_{af}) \tag{3}$$

Stomatal resistance for transpiration r_{sto} is influenced by factors including solar radiation and vapour pressure difference, volume water content, temperature of soil. Air resistance for transpiration r_a is associated with plant height and wind speed [92].

The evapotranspiration rate from plant canopy and soil surface can be calculated by the following equations:

$$E_c = L_c/\mu \tag{4}$$

$$E_g = L_g/\mu \tag{5}$$

Feng et al. (2010) [52] simplified heat losses by transpiration (L_c) and evaporation (L_g) in one equation, so the heat loss by evapotranspiration is given by:

$$L_{et} = L_c + L_g = E_{et}\mu \tag{6}$$

where, E_{et} is the evapotranspiration rate and is given by $E_{et} = E_c + E_g$. Evapotranspiration rates can be measured by weighing or by using soil hygrometers, as explained above. This approach was used by Quezada-Garcia et al. (2017) [93] to develop a heterogeneous model of heat transfer for green roofs.

Table 8 summarizes all the references regarding the ET phenomenon within green roofs studies. This table reports that a heat transfer model for green roofs is based on different approaches and equations to evaluate the required parameters for the calculation of latent heat flux.

Table 8. Equations and/or models adopted in heat transfer models for green roofs and their validation parameters

References	Previous equation utilized	Input parameters	Validation parameters
[70]	-	Meteorological data Substrate temperature	Temperature at 2 cm below soil Degree of saturation in substrate
[50]	Rana-Katerji [94]	-	-
[46]	-	Air temperature Air relative humidity Air speed Sky temperature Incoming solar radiation Substrate water content LAI	Evapotranspiration Incident incoming short-wave radiation Incident incoming long-wave radiation Outgoing long-wave radiation Heat fluxes through green roofs Convective heat transfer fluxes Substrate top and bottom layer temperatures

		Substrate temperature	Substrate thermal conductivity Plant temperatures Average substrate volumetric water contents Air velocities Room air relative humidity levels and temperatures Spectral reflectivity of green roof samples Leaf Area Index (LAI)
[93]	Feng et al. [52]	-	Green layer temperature
[59]	Diedjig et al. [70]	Weather data Characteristics of vegetation Characteristics of soil	Soil surface temperature Temperature at 2 - 8 cm below soil
[60]	Banna [95]	-	-
[61]	Levallius [96]	-	-
[62]	Deardoff [97]	Weather data Characteristics of vegetation Characteristics of soil	Soil surface temperature
[76]	Choudhury and Monteith [98] Philip and De Vries [99]	Height of plant Minimum stomata resistance Average LAI Soil thermal capacity Soil depth Soil conductivity Reflectivity of leaves Soil water conductivity Soil water capacity	Temperature Moist distribution Heat flux

Most of the developed mathematical models that analyse the energy performance of green roofs were then validated through experimental analysis. Table 8 also shows the principal parameters used to validate the green roof models.

Unlike the models presented in section 2, which were developed to evaluate evapotranspiration on bare and/or vegetated soils, the models listed in Table 8 concern green roofs were developed to analyse the energy performance of green roofs. They considered latent heat and not having the ultimate aim of evaluating the phenomenon of evapotranspiration.

Among all the models, only Tabares-Velasco and Srebric (2012) [46] measured evapotranspiration in a laboratory set-up to validate the model. Most of the models used soil and/or plant temperatures measured in-situ to validate the proposed models.

Some studies, around 35% of the literature reviewed, adopted simplified energy balance models because of the complex structures of green roofs that include canopy and soil. In particular, Tian et al. (2017) [59] analysed the loss of water in the soil through evapotranspiration considering that it occurred only on the surface of soil while He et al. (2016) [53] assumed that the change of soil water content is equal to water loss through evapotranspiration.

Hodo-Abalo et al. (2012) [60] developed a model for evaluating the cooling potential of green roofs. The authors solved the heat transfer equations using a finite difference scheme and Thomas algorithm. The authors developed a numerical model based on an implicit finite difference method for discretizing time-average Navier-Stokes equations and for calculating evapotranspiration variations. Evapotranspiration was obtained by summing the hourly values of local latent heat flux from different layers within the canopy, added to the hourly value of soil evaporation.

Djedjig et al. (2012) [70] developed a thermo-hydric model considering the thermal inertia of the whole green roof system. This model allowed an explicit calculation of the evapotranspiration, and the thermo-physical properties of the substrate were calculated according to the volumetric water content. The results demonstrate the effectiveness of the explicit calculation of evapotranspiration, unlike the Penman–Monteith equation, which does not incorporate water stress.

Tabares-Velasco and Srebric (2012) [46] included a complete validation of heat transfer fluxes, such as evapotranspiration rates. The study had laboratory-rated acquisition equipment for the detailed measurement of evapotranspiration rates by the gravimetric method, while simultaneously measuring the total energy balance on the green roof sample. Thus, the authors used the experimental data to calibrate the green roof evapotranspiration model.

The study conducted by Tsang and Jim (2011) [61] modelled a quadratic-like relation between evapotranspiration and the water content in green roofs that allowed an analysis of the latent heat flux of green roofs in terms of volumetric water content in the soil and the relative humidity. This model considers the combined effect of evaporation and transpiration to reduce calculation complexities.

He et al. (2017) [76] analysed energy balance of plant and soil layer using a coupled hydro-thermal transfer model validated by field experiments in Shanghai area. In particular, the authors assessed the effects of thickness of soil layer and leaf area index of plant layer on green roof energy and thermal performance. In the model, it was assumed that the water content variation of soil layer equals to the water loss through evapotranspiration.

All heat transfer models of green roofs take into account the latent heat flux due to evaporation of water from the substrate and transpiration of plants. However, only a few of them considered experimental data for their validation. Future models should include experimental measurements of ET rates for the validation process.

6.2. Latent heat flux results

This section describes the results found by the studies that used mathematical models to characterize ET on green roofs in order to evaluate the surface energy, focussing on the latent heat flux.

Evapotranspiration and net long wave radiation dominate the energy balance of the green roof. In particular, He et al. (2016) [53] found that, under both free-floating and air-conditioned scenarios, the evapotranspiration flux accounted for 58.15% and 63.93% respectively of all the dissipated heat by the green roof. When the moisture content of the soil is low, the proportion of evapotranspiration decreases greatly while heat convection rises. Similar results were obtained by Feng et al. (2010) [52], who found that the heat loss through the evapotranspiration of the plants–soil system accounted for 58.4% of the total energy flux and played the most important role. The net long-wave radiative exchange between the canopy and the atmosphere as sensible heat accounts for 30.9%, and the net photosynthesis of plants accounts for 9.5%. Only 1.2% was stored by plants and soil, or transferred into the room beneath. During the day, Tian et al. (2017) [59] found that most of the absorbed radiation (about 40%) is dissipated as latent heat on the canopy.

However, other studies found controversial results regarding the role of evapotranspiration in the green roof energy balance. Schweitzer and Erell (2014) [56] estimated that the contribution of evaporation was the least important of these mechanisms (about 4%). In addition, Coutts et al. (2013) [48], through an experimental analysis, evaluated the surface energy balance for green roof and bare soil, showing that only a small portion of the overall heat flux was partitioned into latent heat (0.15%) for green roof and for bare soil (0.13%). These results show that when succulent vegetation with coverage less than 100% and in absence of irrigation the evapotranspiration achieves modest benefits. The mean daytime evaporative fraction is strictly connected with the time of irrigation. It increased about 41% for green roof and 51% for bare soil immediately after the irrigation, while by the third day of having watered the latent heat flux was reduced by 26% in the green roof and by 38 % in the bare soil.

The study conducted by Lazzarin et al. in 2005 [50] evaluated the performance of a green roof system in summer in both dry and wet conditions. The wet soil gave rise to an evapotranspiration rate of about 25.0% of the overall heat flux, whereas in dry conditions that contribution was limited to 12.0%.

Tsang and Jim (2011) [61] observed that the peaks of latent heat flux (about 7 Wm^{-2}) were achieved when long period of high solar radiation occurred. Thus, solar radiation could expedite the evapotranspiration rate and increase the latent heat loss.

These results show the importance of evapotranspiration in reducing thermal loads in a green roof. As a general outcome of this section, it is possible to observe that the latent heat flux calculated through mathematical models showed a wide range of values on the overall heat flux in a green roof, depending on the mathematical model used and the boundary conditions assumed (climatic conditions).

7. Evaluation of ET through dynamic simulation

7.1. EnergyPlus software

This section shows the ET results obtained by using EnergyPlus [63–65] dynamic simulation software.

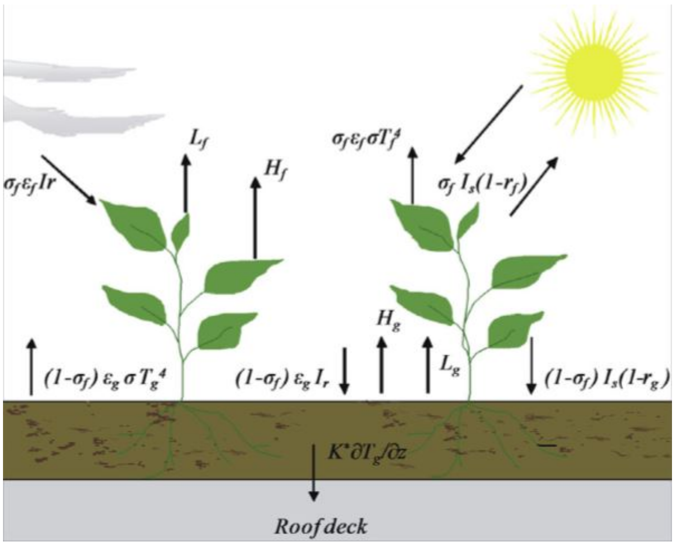

Figure 5. Energy balance of a green roof [17]

EnergyPlus integrates a green roof model developed by Sailor (2008) [100] and based on an Army Corps of Engineers' FASST vegetation model [101]. This model considers simultaneously the foliage surface and soil temperatures at each time step. The “Ecoroof” module is a one-dimensional model containing energy budgets for both the foliage layer and the soil surface. It considers long and short wavelength radiation exchanges, the effects of vegetation on convective (sensible heat) thermal flux, evapotranspiration (latent heat), heat storage and transfer through the substrate (Figure 5).

The energy balance for the foliage is the following (Eq. 1):

$$F_f = \sigma_f\left[I_s\left(1-\alpha_f\right) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4\right] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_f + L_f \qquad (9)$$

where $\left[I_s\left(1-\alpha_f\right) + \varepsilon_f \sigma T_f^4\right], \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right), H_f \; and \; L_f$ are shortwave solar radiation, long wave radiation exchange between sky and foliage, convective heat transfer between air and foliage as sensible heat flux, and evapotranspiration on the foliage surface as latent heat flux, respectively.

The energy balance for the soil surface is the following (Eq. 2):

$$F_g = (1-\sigma_f)\left[I_s\left(1-\alpha_g\right) + \varepsilon_g I_{ir} - \varepsilon_g T_g^4\right] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_g + L_g + k \times \frac{\delta T_g}{\delta z} \qquad (10)$$

where all the terms have the same meaning as in Equation (1), but are referred to the soil layer. The last term represents the conductive heat transfer in the soil substrate.

The “Ecoroof” module allows to specify various features of the green roof, including height of plants, leaf area index (LAI), leaf reflectivity, thickness/density/thermal conductivity and specific heat of soil.

Table 9 provides input data for the green roof model in EnergyPlus reported by Peri et al. (2016) [79]. However, many previous studies assuming theoretical data for the features of substrate and plant species have already been developed. Therefore, the thermo-physical values used in the simulations not always may be confirmed through experimental test. As rule, it is necessary to use only realistic thermo-physical values, which have to be associated with specific plant and substrate types.

Table 9 Range of values provided by Peri et al. (2016) [79] *for an EnergyPlus model*

Input Parameter	Range of values	
	Minimum	Maximum
LAI	0.1	5
σ_f	0	1
Canopy albedo	0.1	0.4
ρ_g	0.04	0.4
k_l	0.3	0.83
σ_t	0.11	0.5
τ_t	0.2	0.2

7.2. ET results using EnergyPlus

Boafo et al. (2017) [63] investigated the potential contribution of the evapotranspiration in green roofs on the annual energy consumption of an office building located in Incheon, Republic of Korea. So this study could be representative of the Dwa climate according with the Köppen classification (2006) [102]. The evapotranspiration flux was evaluated varying the LAI (from 1 to 5) as well the irrigation regime. They found that the average monthly evapotranspiration ranged from 1.80 mm·day^{-1} to 4.79 mm·day^{-1} for high LAI, from 0.31 mm·day^{-1} to 4.16 mm·day^{-1} for low LAI from 1.31 mm·day^{-1} to 4.28 mm·day^{-1} for high irrigation. For the scenarios without irrigation the ET varied from 1.31 mm · day^{-1} to 3.92 ·mm day^{-1}, in December and May respectively. As expected, the highest and lowest evapotranspiration fluxes were found during summer and winter, respectively. The latent heat flux, associated to the evapotranspiration, increasing the LAI from 1.0 to 5.0, was grown-up by 10.4% in summer and 80.2% in winter keeping soil thickness constant. Silva et al. (2016) [64] analysed the thermal performance of intensive and extensive green roofs located in Lisbon, Csa climate according to the Köoppen classification. The evapotranspiration was significantly different in extensive green roofs (max value 2 mm·day^{-1}·10^{-4}) when compared to semi-intensive (max value 6 mm·day^{-1}·10^{-4}) and intensive roofs (max value 9 mm·day^{-1}·10^{-4}), particularly in summer when the solar radiation was higher. Vera et al. (2017) [65] investigated the effect of the variation of the LAI of the green applied over an uninsulated concrete slab and lightweight metal roofs, in different climate, i.e. Bsk (Albuquerque), Csc (Santiago) and Cfb (Melbourne) according to the Köppen classification. In this study, the LAI values were varied between 0.1 and 5.0 that represent the range of potential values for vegetated roofs. The results show that the cooling load of the room decreases when LAI increases because of the increase in the evapotranspiration that diverts incoming solar heat gains through the roof, for the three evaluated cities. A heat flux reduction of about 20.0 W/m^2 was calculated when a vegetated roof without plant was compared to a vegetated roof with plants having a LAI equal to 5.0. Finally, the highest evapotranspiration flux was achieved with a LAI of 4.79 mm·day^{-1}) and irrigation of 4.28 mm·day^{-1} during the summer period.

8. Sensitivity analysis of green roof ET

The above performed review have highlighted that there is a plethora of parameters, as well as their reciprocal meddling, that affect the evapotranspiration process. Thereby, several studies from the literature review have tried to perform sensitivity analysis to understand which parameter most affects ET.

Tsang and Jim (2011) [61] have investigated the influence of the volumetric water content and the air convection coefficient on the performance of the green roofs. Their sensitivity test showed that an increase from 30 to 60 % of VWC implies a reduction of heat stored in the green roofs by 24 %. While, the increase from 12 to 16 W·m-2·K-1 of the convection coefficient reduces the heat stored by 45 %.

Tabares-Velasco and Srebric (2012) [46] carried out a sensitivity analysis of the energy performance of the green roof, considering the effect of soil thickness, wind velocity, volumetric water content, solar radiation, and stomatal resistance. The results of this study provide, in function of the parameters and their range of variation analysed, the evapotranspiration rate expressed as latent heat flux. Starting from these results, Figure 6 has been developed in this review study with the aim to synthetize and systemize the reading of the performed study by Tabares-Velasco and Srebric (2012).

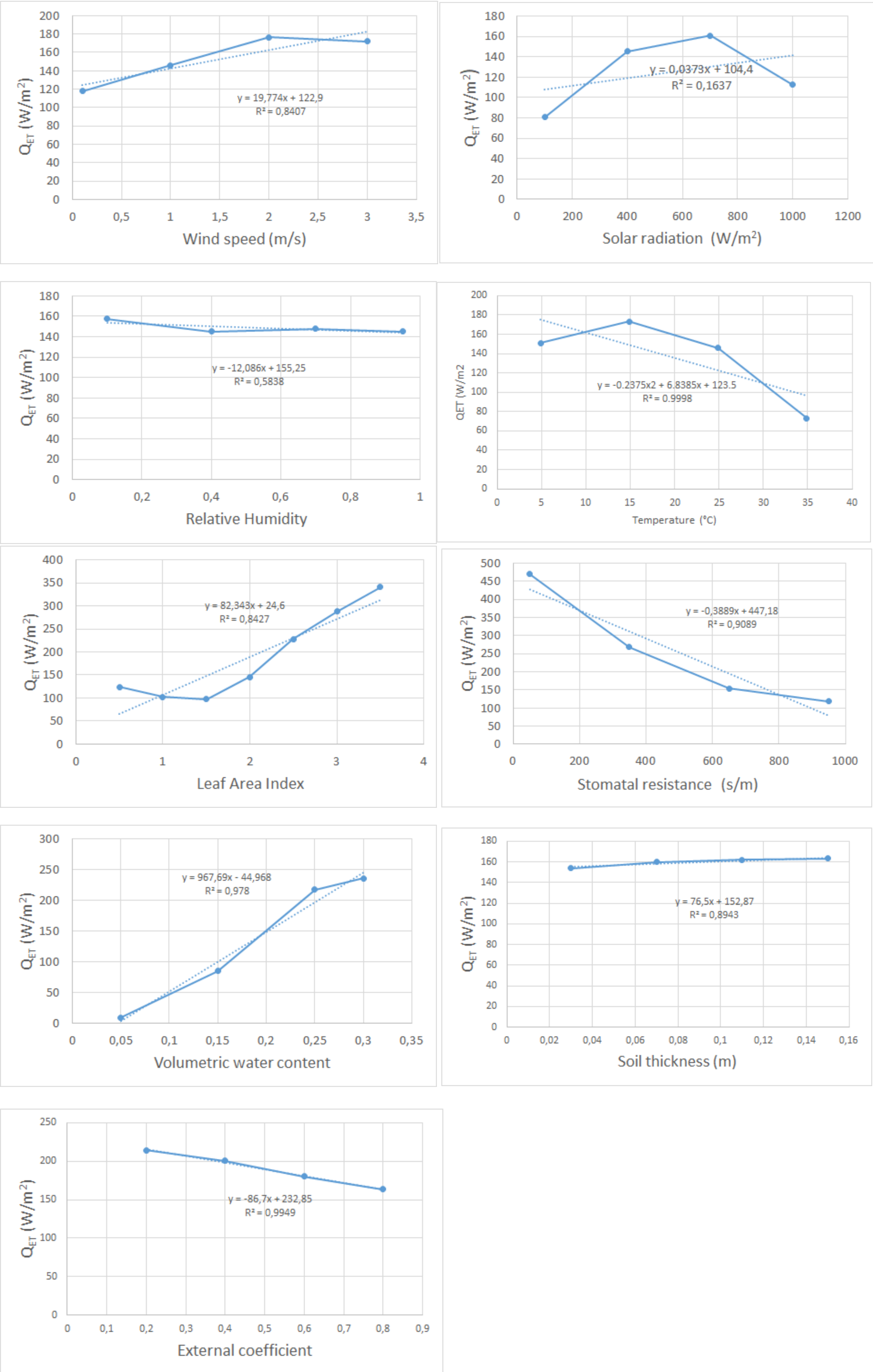

Figure 6. ET Sensitivity analyses

This sensitivity analysis highlighted that the highest values of evapotranspiration were obtained with high volumetric water content in the substrate (0.25 and 0.30), reduced stomatal resistance (50 and 350 s/m), high values of LAI (2.5, 3.0 and 3.5), and with low values of external coefficient, i.e. incoming long and short wave radiation, (0.2 and 0.4). Where the radiation emitted from earth/atmosphere is terrestrial or longwave radiation and the radiation emitted from sun is solar or shortwave radiation. These results can be inferred by observing the value assumed for the different percentage between the minimum and maximum values of ET (ΔQ_{ET}). The volumetric water content is the variable with the largest difference (ΔQ_{ET} =96.3%) between the minimum and maximum value of evapotranspiration, from 8.8 to 235 W/m^2.

Stomatal resistance and LAI also produce considerable variations in the ET, with values between 469.5 and 118.5 W/m^2 (ΔQ_{ET} =74.8%) and between 340.6 and 97.4 W/m^2, (ΔQ_{ET} =71.4%), respectively.

In a similar manner, the variables with less influence on evapotranspiration process were identified. When substrate thickness and relative humidity vary, the evapotranspiration flux remains almost constant, with a ΔQ_{ET} variation of 5.8 and 7.8 %, respectively. Values of evapotranspiration lower than 145 W·m^{-2} are never reached whatever was the variations in relative humidity, substrate thickness, and long and short wave radiation.

Furthermore, Figure 6 shows that wind speed, volumetric water content, and leaf area index have a positive correlation with ET, i.e. the higher these values, the higher the ET. Otherwise, air temperature, external coefficients (long and short wave radiation), and stomatal resistance are characterized by a negative correlation with ET. Finally, relative humidity and soil thickness present a neutral correlation.

The performed elaboration allows to evidence as all the parameter variations can be represented by means of a second order polynomial regression, which shows rather high value of the correlation coefficient R^2. Therefore, this correlation could constitute a reference for comparing set of experimental results coming from different studies.

Moreover, a frequency analysis on the results coming from Tabares-Velasco and Srebric (2012) [62] was also carried out. It is possible to observe that the highest frequencies of Q_{ET} are in the range 100-149 and 150-199 Wm^{-2} (Figure 7, left). The cumulative curve (Figure 7, right) indicates that 90% of the values of Q_{ET} are lower than 249 Wm^{-2}.

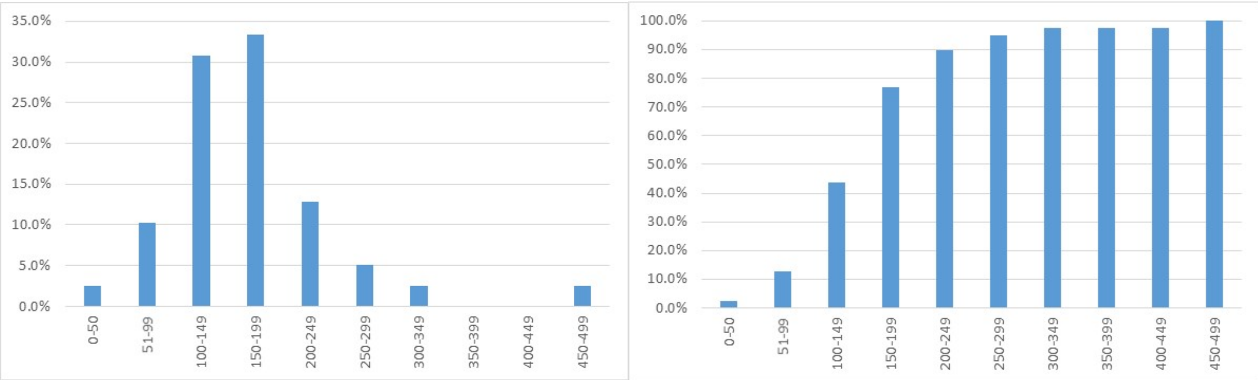

Figure 7. A frequency analysis of energy for evapotranspiration Q_{ET} (left) and the cumulative curve (right)

This section has highlighted which factors are influencing ET and how their variation has positively or negatively affect evapotranspiration. Moreover, after having analysed data from the literature the correlations, as well as the range of variation of ET found, helps in establishing a comparative framework between different researches.

9. Conclusions

The purpose of this study was to review the impact of ET on green roofs. Although most of the studies agree to consider evapotranspiration among the main factors affecting the behaviour of green roofs, only few studies experimentally assessed evapotranspiration rates. The following general conclusions can be drawn:

- The experimental studies carried out have made use a wide variety of equipment and techniques for the measurement of ET. When the objective is directly to assess the evapotranspiration of green roofs, high precision load cells that determine the evolution of weight over time are the most widely used equipment.
- Many of the mathematical models used to evaluate the performance of green roofs take into account the latent heat flux due to evaporation of water from the substrate and transpiration of plants. However, only few models were validated considering experimental data of evapotranspiration rates, and in many cases, the experiments were conducted in laboratory conditions and for short periods. Therefore, more research that experimentally analyses all factors that affect the ET phenomenon under real conditions will help to fill the gap in the current state of the art.
- The high variability of technical-constructive solutions and climatic conditions affecting the energy

performance of green roofs, the different units of measurement used to quantify evapotranspiration, the lack of information regarding the duration of the experiments, and the specific climatic conditions make it difficult to compare the results obtained from different studies. Thus, some guidelines to develop a correct experimental methodology could help in providing better comparative analysis for future research.

- Some studies evaluated evapotranspiration in green roofs by comparing roofs with and without vegetation and by implementing different plant species. However, only few of them evaluated the evapotranspiration rate by varying the type of substrate. Finally, an important lack of studies considering the role of the drainage layer in the ET process of a green roof was also detected.
- There are geographic areas of the world with high potential ET rates where this phenomenon has not yet sufficiently evaluated for green roofs.
- There are no studies correlating ET with external surface temperatures of the green roof, although many studies determined that one of the main advantages of using green roofs is the reduction of surface temperatures and the consequent mitigation of the urban heat island effect.

Furthermore, the following are the specific conclusions:

- Load cells are the equipment that could be recommended for future studies to assess the evapotranspiration of green roofs in a direct and high precision way. They allow monitoring the evolution of the tray weights due to water loss over time in kg m^{-2} day^{1} that is the most appropriate unit of measurements to estimate the evapotranspiration at any desired time-step.
- The sensitivity analysis highlighted that the highest values of evapotranspiration were achieved with high volumetric water content in the substrate, reduced stomatal resistance and high values of LAI.
- On one hand, the variation of the volumetric water content in the substrate causes the largest fluctuation between the minimum and maximum values of evapotranspiration. On the other hand, the variation in the substrate thickness and relative humidity showed the minimum variation on the heat flux, being the parameters that less affect the ET in a green roof.
- Here the importance of testing experimentally the ET process during enough extended periods of time, covering all the different seasons and climate conditions to correlate the ET with the main meteorological scenarios (e.g. sunny, cloudy, and rainy days) have to be highlighted.

- Moreover, further studies should be carried out to assess the evapotranspiration of different green roof solutions considering the influence of the drainage, as well as to investigate those geographic areas of the world, which has high potential for green roof evapotranspiration.

Globally, this review analysis provides valuable information for building companies, architects, engineers, designers and stakeholders, on the ET of various green roof solutions and the different materials used. In addition, this paper highlighted the principal gaps in the current literature that will lead researchers to perform new studies within this topic.

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Nomenclature

C_d	Denominator constant that changes with reference type and calculation time step, s/m
C_n	Numerator constant that changes with reference type and calculation time step, K mm s3 M/g/d or K mm s^3M/g/h
C_{pa}	Specific heat of air at constant pressure, J/kg/°C
e_a	Actual vapour pressure, kPa
e_s	Saturation vapour pressure
E_g	Evaporation rate on soil surface, kg/m^2/s
E_c	Transpiration rate on plant canopy, kg/m^2/s
E_{et}	Evapotranspiration rate, kg/m^2/s
ET	Evapotranspiration rate, mm/h
ET_0	Reference evapotranspiration rate from a grass surface, mm/h
ET_{sz}	Reference evapotranspiration rate from a standardized surface, mm/h
F	Net heat flux, W/m^2
G	Soil heat flux, W/m^2
H	Sensible heat flux, W/m^2
K	Dry soil thermal conductivity W/m/K
I_{ir}	Total incoming long wave radiation, W/m^2
I_s	Total incoming short wave radiation, W/m^2
L	Latent heat flux, W/m^2
L_c	Latent heat flux on plant canopy, W/m^2
L_g	Latent heat flux on soil surface, W/m^2
L_{et}	Latent heat flux from evapotranspiration, W/m^2
LAI	Leaf area index, -
PET	Potential ET rate, mm/h
q_{af}	Vapour pressure of the air within plant canopy, Pa
q_c	Vapour pressure of the air in contact with plants, Pa
q_g	Vapour pressure of the air in contact with soil, Pa

Q_{ad}	Energy transported by evapotranspirated water, W/m^2
Q_a	Sensible heat flux to the air, W/m^2
Q_s	Heat flux to the soil, W/m^2
Q_c	Heat storage in the crop, W/m^2
Q_p	Energy available for photosynthesis, W/m^2
R_n	Net solar irradiance, W/m^2
R_s	Incoming solar irradiation, $MJ/m^2/d$ or $MJ/m^2/h$
r_a	Aerodynamic resistance to transpiration, s/m
r_{sto}	Stomatal resistance to vapour diffusion, s/m
r_g	Aerodynamic resistance to evaporation on soil surface, s/m
T	Temperature, K
T_a	Mean monthly/daily/hourly air temperature, °C
TD	Mean maximum minus mean minimum temperature, °C/day
T_F	Mean monthly/daily/hourly air temperature, °F
u_2	Wind speed at 2m height, m/s
z	Height or depth, m

Greek letters

α	Albedo, -
Δ	Slope of saturation vapour pressure with air temperature, kPa/°C
ε	Thermal emissivity, -
ε_1	View factor, -
γ	Thermodynamic psychometric constant, kPa/K
ρ_a	Air density, kg/m^3
ρ_{af}	Density of air within plant canopy, kg/m^3
λ	Latent heat of evaporation, MJ/kg
μ	Latent heat of vaporization of water, J/kg
σ	Stefan-Boltzmann constant, $W\ m^{-2}\ K^{-4}$
σ_f	Fractional vegetation coverage, -

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