Plant cover and floristic composition effect on thermal behaviour of extensive green roofs

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Abstract

In the last few years an increasing attention has been paid to efficient energy construction systems in the building sector. Although in this contest extensive green roofs are reported to be very effective and sustainable systems, the fact that the main agents of this systems are living organisms have generated doubts, especially in locations where the development of plants and vegetation can be greatly affected by climate. This study aims to investigate the thermal performances of a 2000 m^2 particular proprietary extensive green roof system, located on the city of Lleida (Spain), classified as Dry Mediterranean Continental climate. First, plant cover and floristic composition analysis were carried out to evaluate the dynamic of the plant layer over the surface. Then, according to the result of the botanic analysis, summer and winter study in terms of spatial and temporal factors were conducted focusing on the substrate layer, evapotranspiration effect and comparing the different behaviour of the system in low (10%) and high (80%) plant cover conditions. In this extensive green roof, the results showed temporal and spatial changes in floristic composition, with a stable cover of Sedum sp between 20 to 40 %, and a peak of colonizing species in spring and early summer. The increase in vegetation cover appears to have few effects on the above nearby roof environment because of the low moisture level in the substrate layer so that the cooling effect provided by the evapotranspiration does not take place. In addition, the increased presence of vegetation canopy may induce a limitation in substrate night cooling whereas serves as good shield for solar radiation during the day. Finally, the study also reveals the importance of the spatial factor in extensive green roofs, which can lead to not negligible variations on the thermal performance, as well as the floristic composition.

Keywords: plant cover, floristic composition, thermal behaviour, extensive green roofs

1. Introduction

In the last few years an increasing attention has been paid to efficient construction systems in the building sector. The concern toward environmental issues, as greenhouse emission reduction, improvement of the urban air quality and the need to limit the energy consumption of buildings has induced researchers from every part of the world to investigate solutions that can offer not only energy savings but other environmental benefits at the same time. In this contest green roofs are reported to be sustainable systems and very effective providing multiple ecosystem services such as the urban heat island effect mitigation [1-3], reducing the storm water run-off which lowers risks of urban floods and improving the urban water balance [4-6], improving water run-off quality [7], removing the air pollution of city air [8] as well as enhancing rooftop membrane durability [9, 10]. From an energetic point of view, green roofs are able to lower peak roof surface temperature, suppress temperature fluctuation and, most important, are believed to attain important energy savings in buildings in summer because of the combined effects of evapotranspiration and radiative shading of the plant canopy and in winter air conditioning providing an additional insulation effect [11].

It is important to highlight the fact that there are two clearly different typologies of green roofs, intensive and extensive. Intensive green roofs, commonly called 'roof gardens', are developed to be accessible to people and are used as parks or building amenities, and are characterized by higher investment and maintenance requirements. Plant selection for intensive green roofs ranges from ornamental lawns, to shrubs, bushes and trees, which affect the weight, build-up heights and costs of the roof garden. In contrast, extensive green roofs are not designed for public use and are mainly developed for not only for aesthetic but for ecological benefits. They are distinguished by minimal maintenance requirements (1–2 times per year) and plants selected tend to be of the low maintenance and self-generative type [12]. A typical extensive green roof is made of several layers, from the bottom to the top: an anti-root and waterproof barrier often combined in a single layer, drainage and water storage layer, fabric filter, and growing media with vegetation [13].

Moreover, referring to the energy performance, green roofs has been studied according to different approaches by different researchers. Some performed simulations in order to obtain the annual or seasonal achievable energy savings. Others reported experimental analysis and results in terms of effect on the outdoor air temperature and the vertical temperatures across the different layers, often comparing with a reference roof.

Getter KL et al. [14] by means of an experimental set-up quantified the thermal properties of an inverted extensive green roof versus traditional gravel ballasted inverted. They found out that the green roof can cause reduction in temperatures of 5 °C in autumn with similar variation in spring. The most significant finding was that the peak temperature differences between gravel roof and green roof in summer showed a maximum of 20 °C. Another study conducted by Teemusk and Mander [9] in Estonia compared the temperature regime of a light weight aggregates based roof garden with a modified bituminous membrane roof in different season. The results of their study revealed that a 100-mm-thick substrate layer of the roof garden can decrease the temperature fluctuations significantly in summer periods. Jim [15] investigated the passive cooling effect of green roofs in humid, tropical Hong Kong with reference to three vegetated plots and a bare control plot. The thermal performance of the three vegetation types demonstrated pronounced variations in air temperatures at different heights, surface temperature, and material temperature at different depths. The findings indicate the key role played by biomass quantity and structural complexity in moulding the passive cooling functions.

Santamouris et al. [16], using the thermal simulation program TRNSYS, found that the building cooling load of a nursery school building in Athens was reduced by between 6% and 49% with the installation of a green roof. Spala et al. [17] with the same simulation software reported a cooling load reduction for the whole building between 15% and 39% while 58% for the last floor. Moreover, the observed decrease of heating load was between 2% and 8% for the whole building and between 5% and 17% for the last floor of the building. Jaffal et al. [18] by coupling a green roof thermal behaviour model with a building code performed simulations for a single-family house with conventional and green roof in three different climates. Finally, the green roof reduces the total energy demand in all three studied climates. Reductions of 32% for the Mediterranean climate of Athens, 6% for the temperate climate of La Rochelle, and 8% for the cold climate of Stockholm were observed.

Usually in simulations the vegetation layer is defined by several characteristics: the most important are plant height, leaf area index (LAI), fractional cover, albedo, and stomatal resistance. However, it is necessary to bear in mind that, unless it is a pre-vegetated green roof system, the vegetation takes time to develop after being installed and that the plants may die and the roof may have no vegetation for a certain period of time [19]. Previous research studies have shown that a green roof covered with plants has a different thermal performance from a green roof without plants. The different thermal performances of green roof and bare substrate roof are due to the plants shading, transpiration, and wind shielding [20]. Another key factor in the performance of vegetated systems is the role of evapotranspiration of plants. It is believed that a wet green roof loses more heat through evapotranspiration than a dry green roof. Castleton et al. [11] and Feng et al. [21] demonstrated that, when growing medium is almost saturated in the water, evapotranspiration of the plants and soil system accounted for 58.4% of the solar gain. The study of Lazzarin et al. [22] revealed that the heat lost through evapotranspiration for a dry green roof is less than half of a wet green roof. They also concluded that the value of evapotranspiration differs for various climates. Likewise, the study revealed that the wet roof provides additional evapotranspiration.

According to these considerations from previous studies it is clear that plant layer becomes a key element in thermal dynamics of vegetated roofs. But in the case of extensive green roofs, that mean minimum maintenance and the use of native plants, under extreme climates, in terms of high temperatures and long drought periods, the final plant cover may differ considerably in reference to milder climates. Thus, in these extreme climates, usually characterized by large climatic variations between seasons, vegetation cover can also vary seasonally modifying the roof thermal performance.

As these long term dynamics can only be studied along the pass of time, data obtained in case studies from green roofs placed in real buildings can provide interesting information referring to the real behaviour of the roof.

This study aims to analyse the plant cover influence on the thermal behaviour of a 2000 m^2 extensive green roof located in an office building at the city of Lleida (Spain) by comparing the results obtained in 2012 with a plant cover of 80% with those obtained in 2010 with a low plant cover of 10% [23].

In addition, the seasonal and spatial changes on the floristic composition and plant cover are analysed as well as the possible influence of those changes over the thermal behaviour of this extensive green roof, both in summer and in winter. Special attention to the thermal behaviour of substrate layer and the influence of the water content on this layer was taken.

2. Materials and Methods

2.1 Roof Description

The 2000 m^2 extensive green roof object of the study is a part of a refurbishment project located in the Gardeny Science and Technology Park in the city of Lleida (Spain) [24].

The extensive green roof system used, commercial type "ecological roof" [25], consists in the following layers: protection layer (geotextile felt), waterproofing layer, air/water chamber (plastic supports), filter layer (geotextile felt), insulation/drainage layer (slab with two layers, one for the insulation and other made with porous concrete), substrate layer and plant layer. As a particular characteristic of this system, the filter layer, by falling through the slabs joints, not only acts as filter avoiding the pass of substrate particles to the drainage layer but also allows the rise by capillarity of stored water to the substrate layer becoming it available for the plants [26, 27]). In this particular project, the extensive green roof has two different types of top finish surfaces, not passable green areas and pedestrian areas finished with gravel (Figure 1). In gravel areas, the vegetation and the substrate layer were replaced by a single 8 cm gravel layer.

Figure 1. Not passable and pedestrian areas on extensive green roofs located at the Gardeny Science and Technology Park. Lleida (Spain)

The substrate used is compounded by a mix of mulch, made from decomposition and fermentation of various plant materials, coconut fibres, and fine recycled particles of gravels. The percentage of organic matter is 40% and the other 60% is mineral matter.

The plant species chosen for this project were sedum type, being the main criteria the adaptation capacity to the local climate conditions. In percentage, the species planted were 40% *Sedum album*, *Sedum rupestre*, and *Sedum moranense* and the remaining 60% were a mixture of *Sedum spurium*, *Sedum sediforme*, *Sedum acre*, and *Sedum album coral carpet*.

Referring to the plant development, the planting took place in 2009. In 2010 plants were in the growth phase reaching a plant cover of 10%. During 2011 plants continued growing finishing their whole development being 80% the achieved cover plant in 2012.

However, in spite of having reached this plant cover, as maintenance was minimal and due the existence of bare substrate areas, a high number of colonizing species have been settled on the roof, mostly annual growth plants. Those plants showed a great development during spring and summer periods contributing to achieve the observed 80% plant coverage. But those plants compete with sedum sp during those seasons but afterwards disappear, at least the aerial part, during autumn and winter.

2.2 Site climate

Lleida has a climate classified as Dry Mediterranean Continental, characterized by its great seasonal variations. It has low rainfall, that is divided in two seasons, spring and autumn and it has a thermometric regime with large differences between a long winter (between the spring and the last frost may take more than 160 days) and a very hot summer. The average annual rainfall is between 350-550 mm and the mean annual temperatures oscillate between 12-14 ºC, with thermal amplitudes of 17-20 ºC. A special mention must be made to the fog, typical of the region in the months of November, December and January that can give a period of up to 55 days in the absence of sunlight. Table 1 summarizes the normal climatic values for the area of Lleida.

Table 1. Normal climatic value of Lleida [28]

Month	T	TM	Tm	R	H	DR	DN	DT	DF	DH	DD	I
January	5.3	9.6	1.0	26	81	4	1	0	12	13	5	116
February	7.9	13.7	2.2	14	70	3	0	0	5	8	7	167
March	10.8	17.5	4.2	27	61	4	0	0	3	3	8	226
April	13.2	19.8	6.5	37	58	5	0	1	1	0	6	248
May	17.3	24.0	10.5	49	58	6	0	3	1	0	5	279
June	21.4	28.5	14.4	34	54	4	0	3	0	0	9	313
July	24.7	32.2	17.2	12	51	2	0	2	0	0	14	348
August	24.5	31.6	17.4	21	56	3	0	4	0	0	12	313
September	20.7	27.3	14.1	39	63	4	0	2	1	0	8	250
October	15.3	21.2	9.4	39	71	4	0	1	4	0	6	200
November	9.3	14.2	4.4	28	79	4	0	0	11	5	5	137
December	6.0	9.8	2.1	28	83	4	0	0	14	10	5	96
Year	**14.7**	**20.8**	**8.6**	**369**	**66**	**46**	**1**	**18**	**53**	**37**	**91**	**2685**

Note

T	Monthly / annual temperature average (°C)
TM	Monthly / yearly maximum daily temperatures average (°C)
Tm	Monthly / annual minimum daily temperatures average (°C)
R	Monthly / annual precipitation average (mm)
H	Relative humidity average (%)
DR	Monthly / annual days of precipitation greater than or equal to 1 mm average
DN	Monthly / annual snow days average
DT	Monthly / annual storm days average

DF	Monthly / annual fog days average
DH	Monthly / annual frost days average
DD	Monthly / annual clear days average
I	Monthly / annual sunshine hours average

2.3 Monitoring system

To obtain data on the effect of the extensive green roof over the nearby environment conditions, that is temperatures and humidity at 5 cm and at 30 cm above the roof surface, as well as to know the temperatures and moisture of the substrate layer, the roof was completely monitored in three points. Two of them were placed on a vegetated area (plot 1 and plot 3), and the third one was placed on an area finished with gravel, to be used as pedestrian area (plot 2). Plot 2 and 3 (Figure 2) are located on the same side of the roof, that is, exposed to the solar radiation in the morning and shaded by the roof railing in the afternoon. Plot 1 is located on the other side of the roof that results shaded during the morning.

To obtain data on the effect of the extensive green roof over the nearby environment conditions, that is temperatures and humidity at 5 cm and at 30 cm above the roof surface, as well as to know the temperatures and moisture of the substrate layer, the roof was completely monitored, and divided in three different plots, as shown in Figure 2. Two of them were placed on a vegetated area (Plot 1 and Plot 3), and the third one was placed on an area finished with gravel, to be used as pedestrian area (Plot 2).

Plot 2 and 3 are located on the same side of the roof, therefore both are exposed to the same solar radiation during the morning and shaded by the roof railings in the afternoon. On the other hand, Plot 1 is located in front of Plot 2 and 3 which are shaded by the roof railing during the morning, and irradiated by the sun during the afternoon.

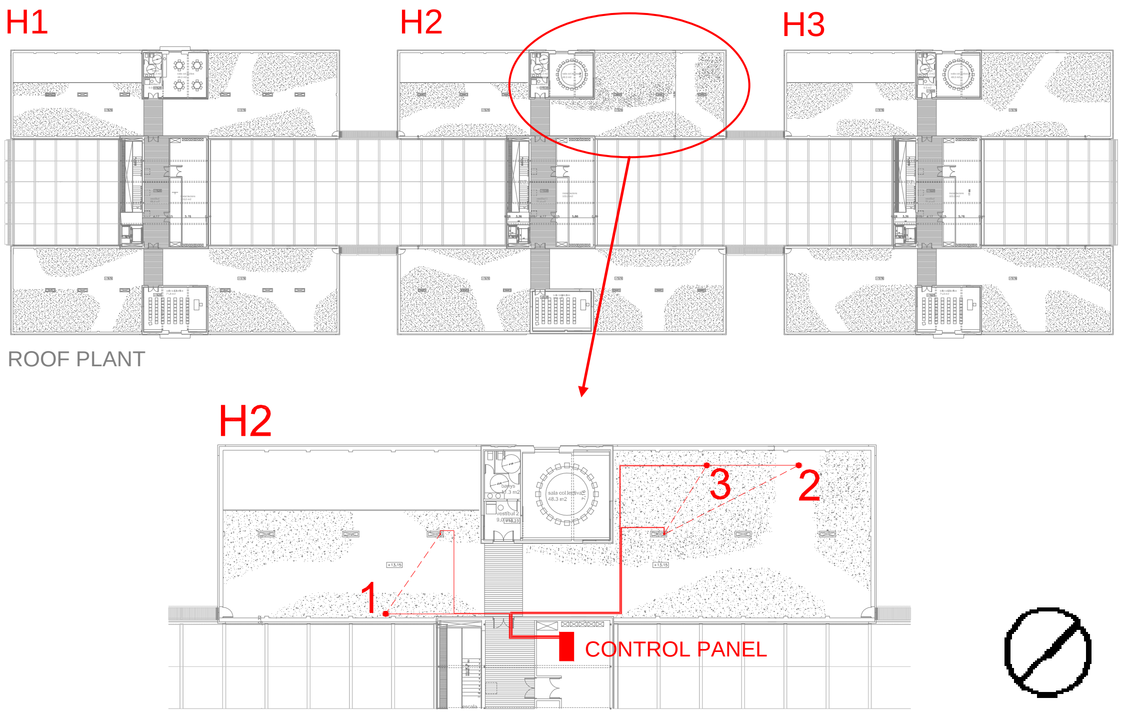

Figure 2. Locations of data acquisition points (Plot 1, Plot 2 and Plot 3)

Table 2 summarizes the parameters recorded and the used instrumentation at each area.

Data were recorded every five minutes during the whole 2010 and 2012 years for each parameter and then the graphics are made from this data. Thus, in the graphics the evolution of every parameter throughout the year can be observed. For the analysis of the experimental data representative days or weeks in 2012 and 2010 were selected.

During 2010 data collection period, indoor offices were not operating, therefore temperature and humidity indoors values reflect the free floating conditions without any conditioning (heating or cooling). During 2012 data collection indoor offices were operating, and the indoor values for temperature and humidity reflect the environment in the air gap between the roof structure and the false ceiling in the office room.

Table 2. Recorded parameters and used instrumentation

Parameter	Unit	Instrumentation	Recording point	
			Green areas (Plot 1 and 3)	Gravel area (Plot 2)
Outdoor temperature at 30 cm over the substrate surface	ºC	Testo 6651	Yes	Yes
Outdoor temperature at 5 cm over the substrate surface	ºC	Testo 6651	Yes	Yes
Substrate temperature at 2 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	No
Substrate temperature at 4 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Substrate temperature at 8 cm below the substrate surface	ºC	Temperature sensor PT-100	Yes	Yes
Under roof structure temperature at 48 cm below the substrate surface	ºC	Surface temperature sensor GE9020 0000 000004	Yes	Yes
Indoor temperature	ºC	Testo 6651	Yes	Yes
Relative Humidity 30 cm over the substrate surface	%	Testo 6651	Yes	Yes
Relative Humidity 5 cm over the substrate surface	%	Testo 6651	Yes	Yes
Indoor Relative Humidity	%	Testo 6651	Yes	Yes
Volumetric water content in the substrate at 4 cm below the substrate surface	%	Water soil content ECH2O EA-10	Yes	No
Volumetric water content in the substrate at 8 cm below the substrate surface	%	Water soil content ECH2O EA-10	Yes	No
Water level in the cistern	cm	Water level (buoy valve)	*	*

* The water level was installed in the gravel area because it was easier to install it there than in an vegetated area

2.4 Plant cover and floristic composition

Considering the observed variability on plant cover during 2012, the analysis of the floristic composition and the vegetation cover evolution was conducted during a whole year, starting on May 2013. The main focus of this study was to study the seasonal and spatial plant variability in the roof trying afterwards to link those results with the obtained results for the thermal behaviour study conducted during 2012.

To study the annual plant layer development, three square plots of 1 m^2 area were located in the same position of the sensors that record thermal parameters (Figure 3). From May 2013 to April 2014, once a month, both floristic surveys and plant cover for each species were carried out in each plot.

The cover of each species was recorded following the Sigmatic Method [29]. This method assigns to the cover of each species a value between + (sparse and covering a small area) and 5 (covering more than 75% of the area). These values are transformed into the mean value of the Braun-Blanquet cover-abundance scale (+ = 0.01%; 1 = 5%, 2 = 17.5%, 3 = 37.5%, 4 = 62.5%, 5 = 87.5%). Plants were identified following local flora [30].

In order to analyse the differences in floristic composition of each plot, non-metric multidimensional scaling (NMDS) using Bray–Curtis dissimilarity distance was performed, which has been proved to be the most suitable unconstrained ordination method in community ecology [31]. Smooth surfaces of survey dates were applied on the NMDS plot so as to find temporal differences in floristic composition. In NMDS analysis, a biplot is obtained, where graphic distance among surveys is function of the similarity in floristic composition. Therefore, those surveys with similar floristic composition will appear closer in the biplot.

Finally, to quantify the diversity variables, the richness (total number of species by plot) and the Shannon Diversity Index ($H' = \sum p_i Lnp_i$, where pi is de cover value of species I in the plot for each plot on each month was calculated. Shannon diversity index is sensible both to the number of species and to the relative cover-abundance of the species. Hence, this index gets higher values when the richness of species increases and the relative abundance of those species are more equitable. Statistical analyses were performed using R [32].

Figure 3. Plot 1 plant cover. May, July and November 2013

3. Results and Discussion

This section presents the most interesting findings concerning the influence of the plant cover evolution on the green roof thermal behaviour.

Usually plant layer is considered as a homogeneous layer so that the entire surface has the same characteristics (level of cover, foliage density, Leaf Area Index, albedo, etc.). But plant layer on a green roof is usually composed of different plant species, with different morphological and physiological characteristics, which leads indeed to a heterogeneous layer. Even within species, big differences can be found. For instance, the most used genus for green roofs, that is Sedum sp, shows large variations between species. This heterogeneity can affect the whole green roof thermal behaviour.

In addition, besides the floral diversity the rigor of certain climates must be added, such as the Mediterranean Continental climate, with large temperature variations and long periods of drought, which implies more different plant growth rates in comparison to other milder climates.

3.1 Plant cover and floristic composition evolution

As it has been mentioned previously, the roof was built in 2009 and all originally planted species were genus *Sedum* typology. In 2010 plants were in the growth phase, being the vegetation cover only around 10% of the surface. In 2011, sedums were already full-grown, reaching vegetation cover up to 80%. During 2012 the plant cover remained stable, although the apparition of a large number of colonizing plant species was noticeable. Those spontaneous plants, mainly local with annual development, started to compete for space with *Sedum* species. This new dynamic, with the emergence of native plants mixed with sedum repeated again and fully consolidated during the year 2013 (Figure 6).

Figure 6. Colonizing plants apparition during years 2012 and 2013

It is worth mentioning that plant cover never reached 100%, and even only a maximum of 80% plant cover was reached during 2013, possibly due to the recession of *Sedum* spp in front of the annual plants establishment, which have a large seasonal development.

This section presents the main results from the study of vegetation cover and floristic composition that was carried out during a whole year, starting on May 2013 to April 2014. The aim of this study was not only to better understanding the changes of vegetation layer but the possible influence of those changes on the thermal behaviour of the green roof.

A total of 31 species were recorded (including the Sedum species sowed in the original roof). Plots 1 and 3 (green areas) had similar number of species (24 and 23 species, respectively) but plot 2 (gravel area) had a lower number of species (12 species). The most dominant species in each plot are showed in Table 3.

Results of NMDS are presented in Figure 7. First axis of NMDS (31.01 % of correlation of the original distance matrix with the ordination distance) shows that there are temporal changes in floristic composition in each plot changes. There is a high temporal dispersion in the composition of plot 2, whereas the changes along time in plot 1 and 3 are minor. In the second axis of NMDS (28.67 % of correlation of the original distance matrix with the ordination distance) the floristic composition varies depending on the location of the plot can be seen. Plot 2, located on a gravel area, has the most differenced composition compared with the plots located on green areas (plots 1 and 3), mostly due to the lack of substrate and the absence of sowed Sedums. Differences between composition of plot 1 and 3 can also be found. Although most of the species are similar in both plots, the dominant species are different between plots (Table 3).

On the other hand, the number of species changes along the year, having a peak in spring and declining through the year until reaching a minimum in winter (Figure 8). Plot 1 and 3 (green areas) reach a maximum of 16-18 species during spring, but these values progressively decrease through the year, being 8-10 species in winter. Plot 2 presents a lower number of species and it never contains more than 10 species (gravel area).

Regarding the Shannon index (Figure 9), maximum values are in the beginning of the spring and decline along the year. The values of Shannon in plot 2 are more heterogeneous due to the low number of species that it contains.

Concerning the cover values of species, cover of Sedum is less variable along the year than the cover of the rest of the species. These latter species reach the maximum cover at the beginning of the spring and summer in plots 1 and 3 and the minimum in winter. In the plot 2, cover of species is practically zero. Thus, temporal changes are not detected.

Results show that there are two main factors behind the differences in floristic composition, richness and diversity found among the plots. On the one hand, the temporal factor and on the other hand the spatial factor, represented by the location of the plots.

Temporally, phenological changes over the year in all the plots can be observed. These temporal changes are reflected in the cover values of the species (Figure 10). In summer, high temperatures and lack of precipitation provoke the removal of practically all the cover of annual species in all plots, whereas in the beginning of spring there is a quick increase of cover of plants due to the seedling of seeds of the seed bank.

Plot 2 shows the highest differences in all the analysed variables. The location of this plot, in an area without organic substrate, seems to be the factor behind the scarce number of species and the low value of diversity. Plot 1 and 3, although less than plot 2, also shows differences in composition. These results agree with those of Madre et al. [33], supporting the major role of the substrate in the diversity and composition of wild species on the green roofs.

The cover of colonizing species and the total richness of species seem to be inversely related with the cover of Sedum spp. This result seems to contradict previous studies that show that Sedum species favour the growth of nearby plants on green roofs under drought conditions [34], but is the annual life form of the colonizing species the fact that explains this apparently lack of synchronism in cover values. In fact, peaks of cover of colonizing plants in plots 1 and 3 (green areas) occur in spring and beginning of summer, coinciding with the bloom of seedling of annual plants that happened due to the high values of precipitation in these seasons in the year of the survey.

Table 3. Mean cover (in percentage) and frequency of occurrence of sowed and colonizing species along the sampling (May 2013-April 2014)

PLOT 1 (green area)			PLOT 2 (gravel area)			PLOT 3 (green area)		
Species	**Mean % Cover**	**Frequency**	**Species**	**Mean % Cover**	**Frequency**	**Species**	**Mean % Cover**	**Frequency**
Sowed species								
Sedum sediforme	25.91	11	*Sedum sediforme*	1.88	11	*Sedum sediforme*	20.45	11
Sedum rupestre	5.94	11	*Sedum album*	0.08	9	*Sedum rupestre*	10.00	11
Sedum spurium	5.00	11				*Sedum album*	5.47	11
Sedum album	4.14	11				*Sedum acre*	0.08	9
Colonizing species								
Trifolium campestre	24.10	11	*Avena barbata*	3.65	7	*Trifolium arvense*	15.45	6
Medicago lupulina	12.27	6	*Senecio vulgaris*	1.82	4	*Trifolium campestre*	3.50	5
Crepis sp.	8.65	11	*Crepis sp.*	0.47	3	*Arenaria sp.*	2.74	5
Oxalis pes-caprae	5.03	11	*Medicago polymorpha*	0.05	5	*Sonchus tenerrimus*	2.06	9
Sonchus tenerrimus	3.68	11	*Sonchus tenerrimus*	0.05	5	*Lactuca serriola*	1.83	5
Arenaria sp.	3.18	5	*Lactuca serriola*	0.04	4	*Conyza canadensis*	1.39	6
Cerastium sp.	2.73	5	*Cerastium sp.*	0.03	3	*Cerastium sp.*	0.93	4
Lactuca serriola	1.85	7	*Stellaria media*	0.02	2	*Spergularia diandra*	0.91	1

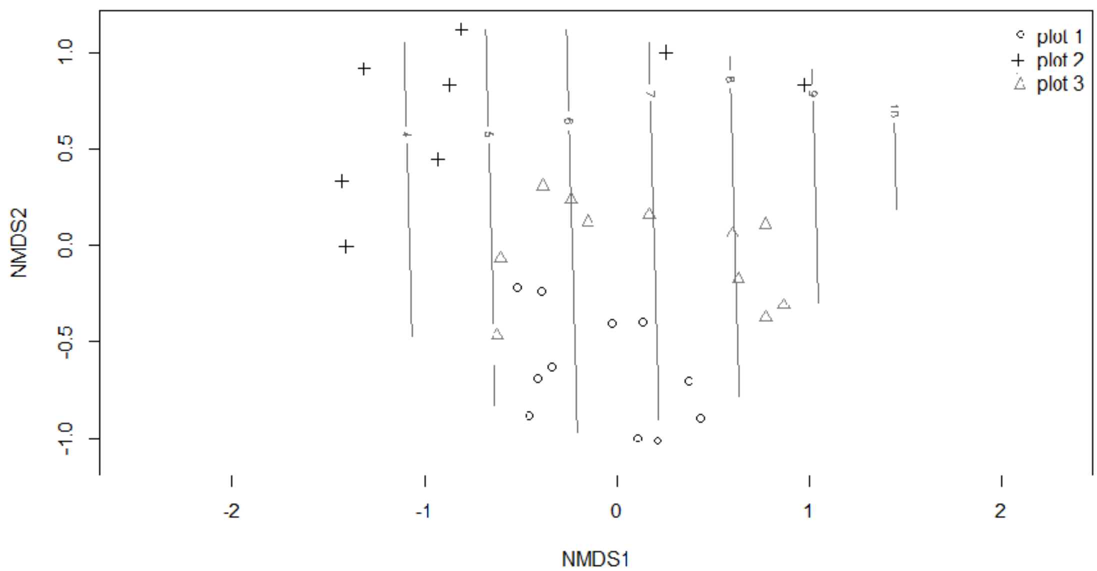

Figure 7: Non-metric multidimensional scaling ordination of the floristic surveys. Smooth surface lines represent the months of the surveys. Green areas (plots 1 and 3). Gravel area (plot 2)

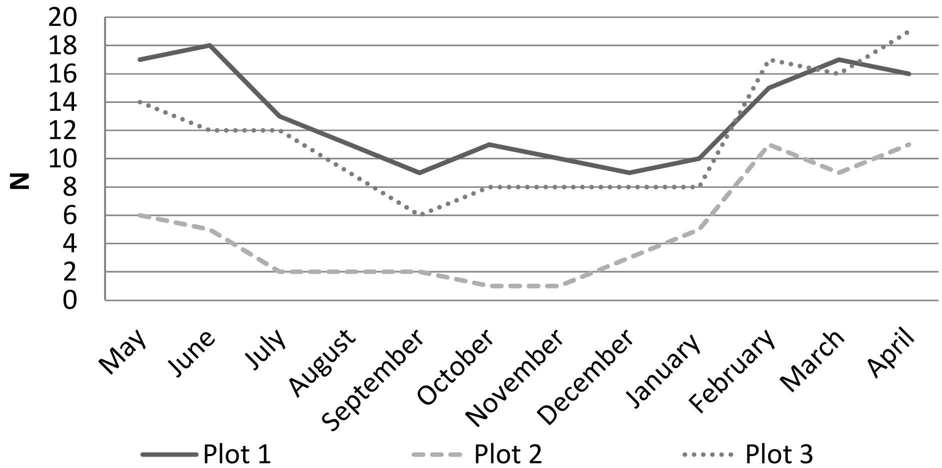

Figure 8. Richness of species along the sampling (May 2013-April 2104) in the different plots.

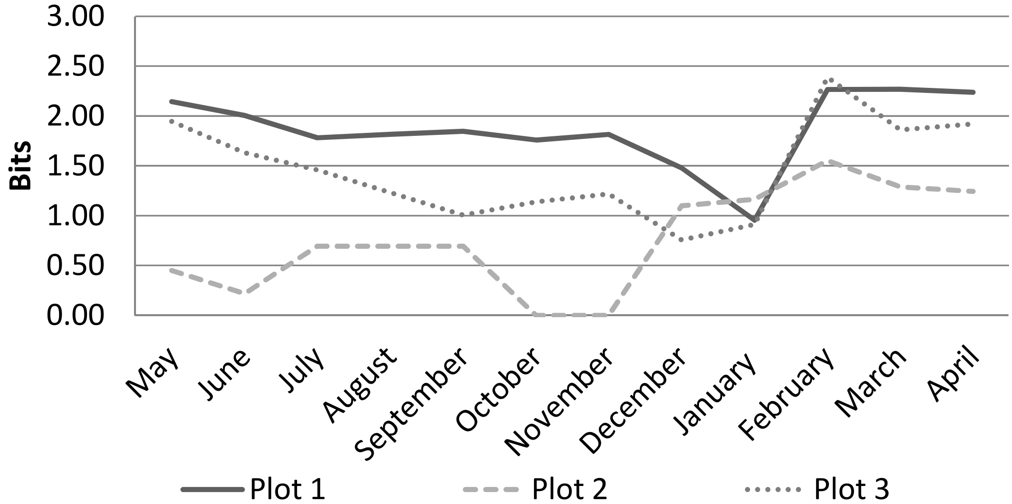

Figure 9. Shannon index in the different plots along the sampling (May 2013-April 2104)

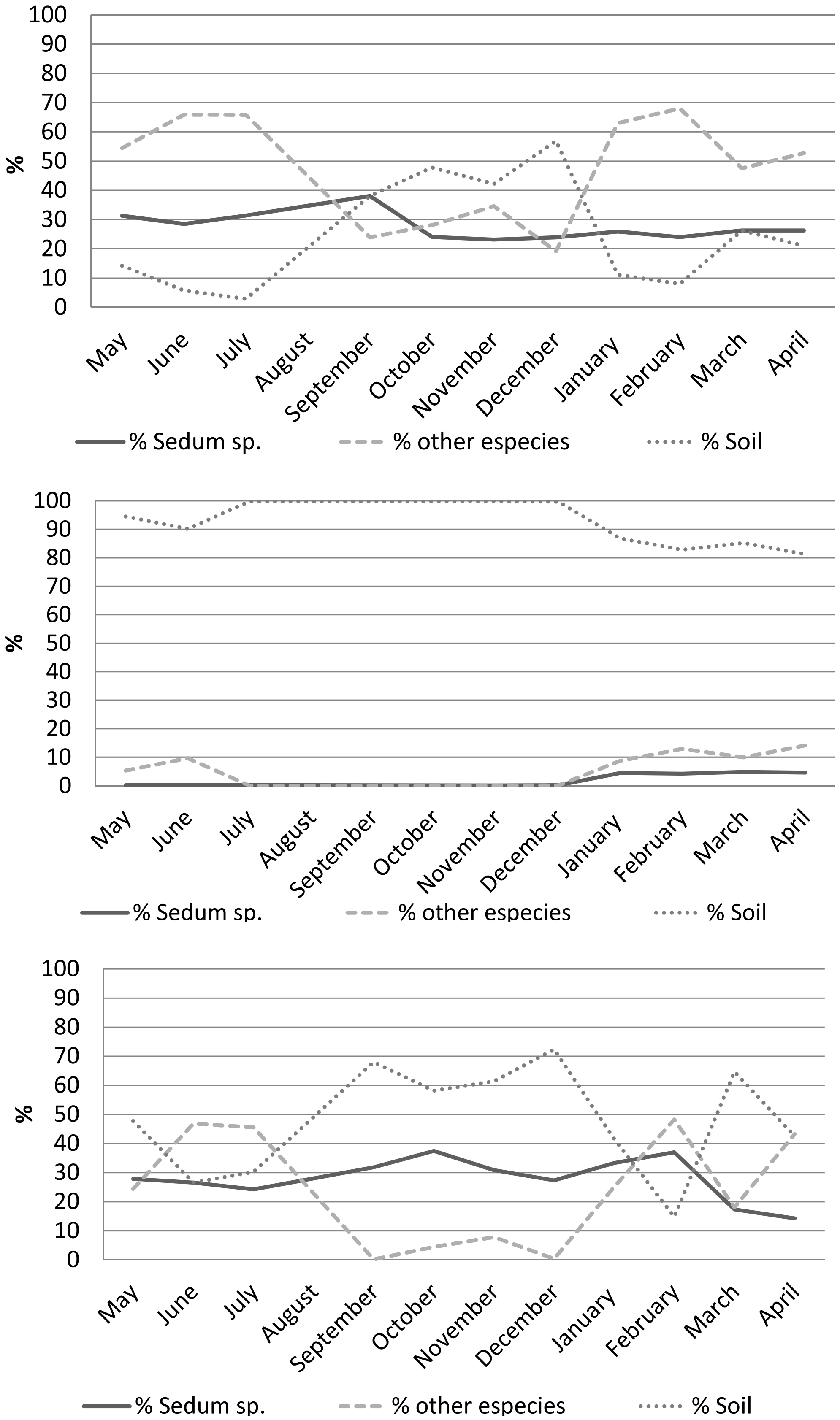

Figure 10a 10b and 10c. Percentage of cover of Sedum spp., other colonizing species and soil in the different plots along the sampling (May 2013-April 2104).

3.2 Consequences on the roof energy performance

3.2.1 Plant cover percentage influence

With the aim to study the effect of plant cover evolution along the time on the extensive green roof thermal behaviour, a comparison between data recorded during 2010, with 10% plant cover, and data recorded during 2012, with 80% plant cover, was done. The main results of this comparison are showed in this section. In addition, the possible effect of seasonal changes of plant cover, due mainly to the emergence of colonizing annual plants especially on spring and summer periods, was studied as well.

As plant cover and plant floristic composition showed a seasonal pattern, in order to conduct this analysis, summer and winter data have been analysed separately.

3.2.1.1 Summer analysis

Summer analysis was carried out by means the comparison of two representative weeks of summer behaviour in years 2010 and 2012 respectively. The chosen weeks were characterised by high external air temperature, high total solar radiation on horizontal and absence of rainfall.

Referring to the conditions observed at 5 cm and 30 cm above the roof surface during summer 2012 (80% plant cover), no appreciable differences can be seen in the daily patterns between green and gravel areas, nor for the temperature neither for the relative humidity. Even though the low levels of air relative humidity would allow the evapotranspiration to take place, no considerable effect was found as result in the air temperature analysis. The reason can be attributed to the scarce role of evaporative cooling due to the limited water content in the substrate. According to Wong et al. [12] when the substrate is very dry after a drought period, the evaporative cooling effect can be marginal.

In this regard, it seems that the role of soil moisture is far more important than the percentage of vegetation cover regarding the effect on ambient air temperature. Thus, even though in 2012 the roof presented an augmented presence of vegetation, as already explained, the limited water content in the substrate did not allow exploiting the potential of vegetation in activating evapotranspiration.

Moreover the floristic composition during 2012 may also influence. Although 80% plant cover was reached, it can be observed from the floristic study conducted during 2013 that, the presence of colonizing species was high and the surface of sedum, which has a higher foliar density as well as higher shadow capacity than colonizing ones, was only around 40 %.

In Figure 11a the evolution of substrate temperature at three different depths (T -2 cm, T -4 cm, T -8 cm), the volumetric water content of the substrate (VWC) and external air temperature (Tout), during a representative week of summer 2012 are shown.

The substrate displays a characteristic bell-shaped curve, indicating accumulation of solar heat after sunrise, gradually raising soil temperature to the maximum peak in the early afternoon and then reaching a minimum value at early morning [15].

At -2 cm the profile reached peak values considerably higher than the outdoor ambient air, with maximum temperature between 47.6°C and 52.4 °C and minimum between 23.1°C and 25.8 °C.

The daily average fluctuation was 25.6°C. The substrate is more affected by the external conditions at -2 cm and -4 cm, which is noticeable looking at the temperature profiles that follow the pattern of external air temperature. The -8 cm profile, however, demonstrates the thermal mass effect of the growing media. The figure also indicates the dampening of temperature fluctuations across the vertical section; the daily maximum amplitude registered is reduced from 28.8 °C at -2 cm to 14.9 °C at -8 cm, and the temperature peak is delayed from 16:30 to 17:30. That suggests the important role of the growth medium in stabilizing the temperature and enhancing the thermal performances of a green roof.

Even though the literature presents higher time delay, often related to the whole green roof system including all the layers, the results are in agreement with Liu and Minor [10] indicating that a thicker substrate can performs better in terms of thermal performances.

According to Theodore G. [35] the main effect of soil layer thickness on the thermal characteristics of the planted roof is on the thermal inertia; thicker planted roof can be distinguished from the noticeable time lag and the smaller variation of thermal flux.

Clearly a small 8 cm substrate layer was sufficient to reduce the peak of temperature and consequently to reduce the heat flow throughout the roof section. However, the high temperatures recorded in the top few centimetres, can affect the normal development of plant cover, especially in the early years of growth. This fact may explain the difficulties that *Sedum sp* has had to extend his surface, being relegated only to between 20 to 40 % cover. This affected the richness of the roof, which was invaded by colonizing species that germinate strongly in spring and early summer, but then swiftly disappear due to both the lack of rain and the high surface temperatures, creating holes of vegetation on the plant layer, and consequently leaving exposed the bare substrate.

For given similar weather condition, the substrate behaves differently when the plant cover is lower. Figure 11b shows the temperature at different substrate depths for a 2010 typical summer week. At -2 cm and -4 cm the substrate is heated and cooled very quickly with a rapid fall of temperature after the daily peak, whereas at -8 cm, similar to the trend in 2012 summer week, the thermal mass effect is observed.

The -2 cm profile during 2010 summer period clearly reaches higher values than in 2012 with the daily peak values varying from 46.7 °C to 57 °C. Also an important difference is seen in the minimum daily values of temperature that range from 16.5 to 24.4 °C being considerably lower in 2010, compared to the 2012 data. The average diurnal fluctuation was 34.1 °C. The increased presence of vegetation canopy may induce a limitation in substrate night cooling whereas serves as good shield for solar radiation during the day. That can explain the higher peaks and lower minimum temperatures in low plant cover condition (2010, 10% plant cover), where an increase in the daily fluctuation of 8.5 °C is observed.

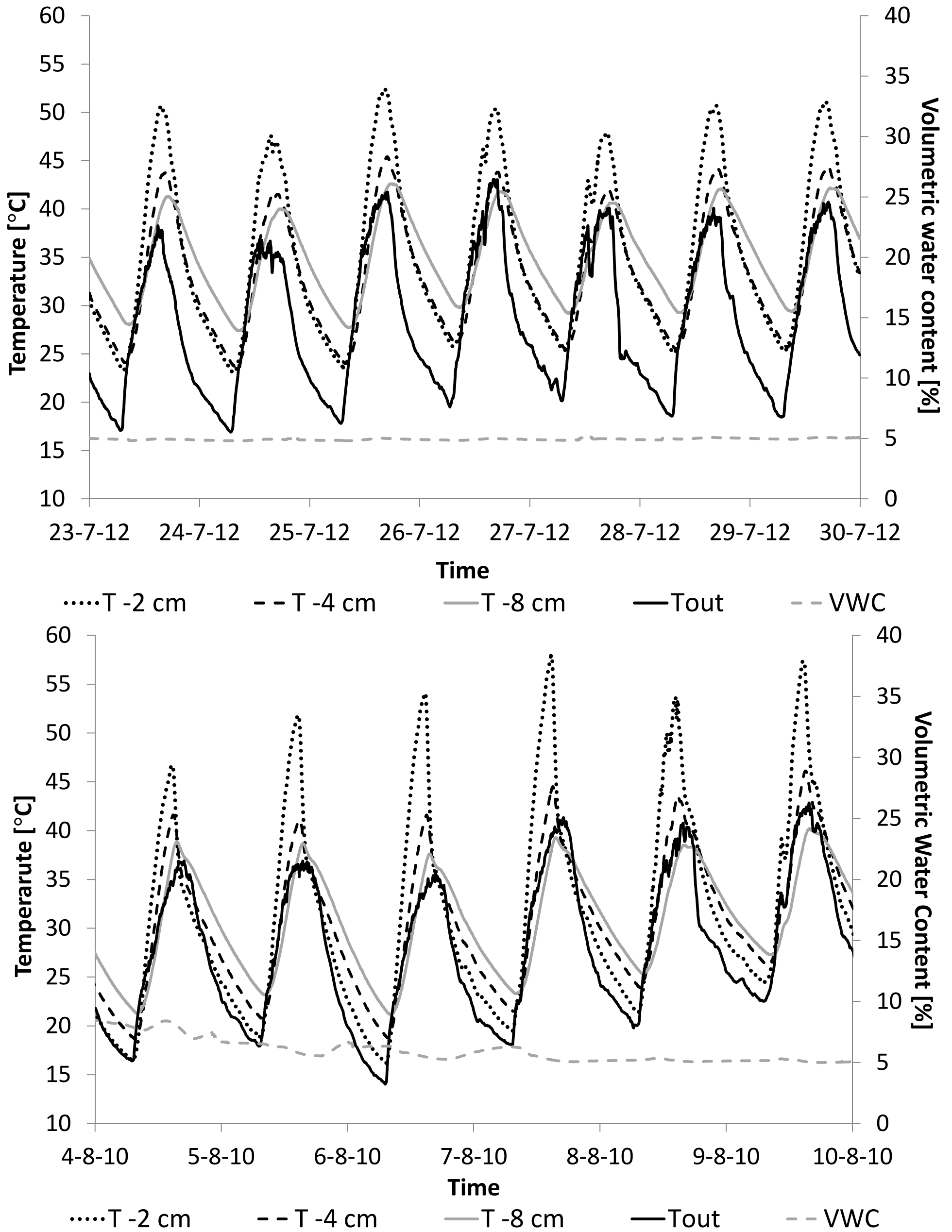

Figure 11. Substrate temperatures and volumetric water content. (a) Summer 2012. (b) Summer 2010

Finally, in reference to the measurements done below of the substrate layer, as expected, the presence of an insulation layer and a deep cistern filled with air and water heavily strangles the upward and downward heat fluxes making negligible the influence of the upper layers toward the indoor environment. From the measurements it can be observed that the ceiling temperature was fairly stable during the whole summer week with an average value of 30.8 °C. Also the indoor temperature exhibited small fluctuation with an average value of 29.9 °C.

As stated from other authors [36], if the green roof is above a well-insulated roof, then the green roof energy balance would be decoupled from that of the building, and the green roof will have an impact mainly on the outdoor environment.

3.2.1.2 Winter analysis

The chosen winter weeks were characterized by similar external climatic conditions, with no rainfall and slightly lower temperature in 2012 selected week than 2010 week. .

In winter a difference between the air temperature above green and gravel area either at 30 cm and 5 cm was observed. Above the gravel, the temperature at 30 cm reached up to 5.7 ºC more than in the green areas, in the early afternoon (15:40). The difference was more accentuated at -5 cm proving the evaporative cooling effect of the green roof. No difference in the minimum values was observed, fact that can be explained considering the role of the relative humidity (RH). During the night due to the low temperature the outdoor air is completely saturated and therefore the relative humidity is recorded to be 100 %, while during the day the gradual increase in the air temperature induces a fall in the relative humidity so that evapotranspiration allows the evaporative process to take place. It can be easily recognized that RH assumed higher values above the green area more than in the gravel, owing to the mentioned processes. Accordingly, in [35, 37] it was shown that relative humidity is the most important climatic factor affecting evapotranspiration.

During 2010, in low plant cover conditions, similar results were found, but the gravel air temperature was between 1 °C and 3 °C higher than green area. The greater fractional vegetative cover (80%) in 2012 resulted in an increased evapotranspiration; so it can be deducted that plants transpiration effect added to the substrate evaporation provided an overall enhanced air cooling above the green area.

In winter (Figure 12a), the temperatures of the substrate were more variable than in summer, following the same pattern than external air temperature. The maximum value reached at -2 cm during the analysed week was 20.6 °C and 12.9 °C at -8 cm whereas the minimum were -1.1 °C and 1.7 °C respectively. Again, the growing media seemed to be more affected by external conditions at -2 cm and -4 cm depth where the substrate heated and cooled quickly. The minimum temperatures are found to be equal to the minimum of external air, whereas higher values are found at the daily peaks. This can be explained considering that in winter some of the plant can wilt, especially annual colonizing species, and the Sedum sp are usually at the minimum yearly development, compared to summer conditions. As a consequence the night radiative and sensible heat exchanges can be more effective in lowering the substrate temperature. The augmented fractional cover in 2012 did not result in different winter behaviour. At -8 cm the thermal mass effect is observed as well as the reduction of daily temperature amplitude which maximum value was 8.8 °C. The ability of the green roof in stabilizing the temperature at the bottom of the substrate and acting as an insulation device is confirmed. As reported from other authors [9] the green roof provides effective thermal insulation in winter.

In terms of daily pattern, winter behaviour of the substrate in low plant condition in 2010 was similar to that of 2012 (Figure 12b). In winter the external forces acting on a green roof are limited compared to summer, minor evapotranspiration effect and lower amplitude of temperature oscillations, so the main role of a green roof is to act as an additional resistance layer and prevent heat lost to the outdoor environment.

In reference to the thermal behaviour below the substrate layer, no relevant information can be deducted because, as it has been mentioned above, the insulation layer together with the cistern intercepts the heat flux and there is no remarkable change below these layers.

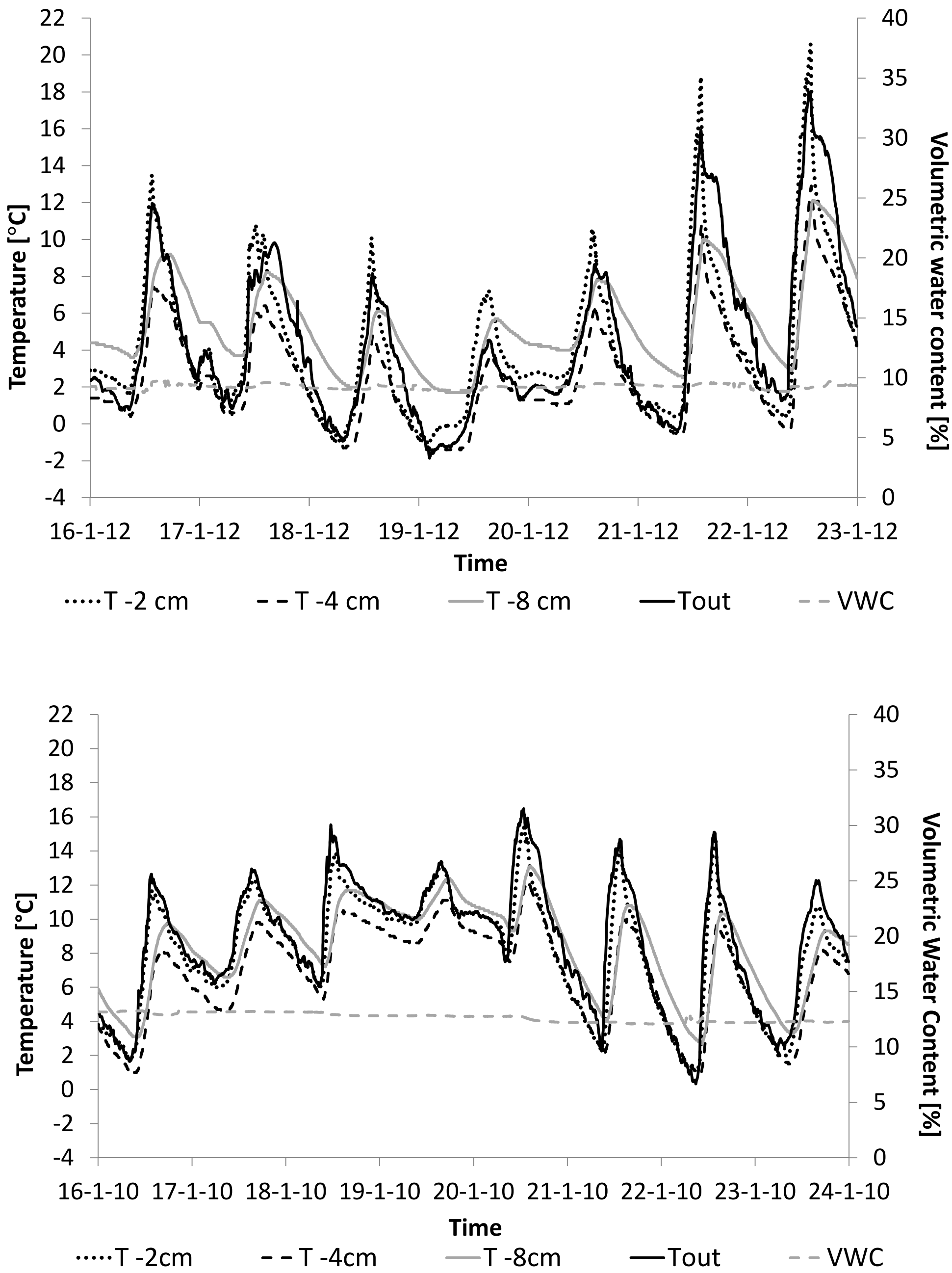

Figure 12. Substrate temperatures and volumetric water content. (a) Winter 2012. (b) Winter 2010

3.2.2 Spatial influence

As mentioned before, the results from the floristic study showed an important spatial influence. Therefore, vegetation mustn't be considered as a homogeneous layer, nor from the point of view of floristic composition neither from the point of view of plant cover. Regarding to the thermal behaviour of the green roof, the spatial influence must be also considered because usually, especially for simulations, it is considered a simple homogeneous behaviour for the whole surface and actually the final behaviour of the green roof may vary considerably in different areas of the roof, due to the position of the constructive elements, such as perimeter walls, booths lift on the roof, chimneys, etc.

Below an analysis which shows the influence of the spatial factor in the thermal behavior of the green roof is presented, which is also directly related to the variations on floristic composition and plant cover.

3.2.2.1 Summer analysis

Figure 13 (left a) shows the evolution of temperature at 30 cm and 5 cm for the three different acquisition points in a 2012 summer day (01/08/2012). A small difference between plot 2 and plot 3 profiles can be observed. The green area (plot 3) temperature decreases from midnight until 7:00. Then, temperature rises up until a maximum of 44.4 °C is attained at 15:30, being in this time slightly higher than that of the gravel (plot 2). After the peak, the temperature decreases again with a steeper slope than the gravel area. It is interesting to note the different temperature behaviour measured in plot 1. After 07:00 the gravel temperature (plot 2) is conspicuously higher than in plot 1 that reaches the peak at 17:30. The maximum difference between plot 2 and plot 1 during the selected day is 6.8 °C.

The same pattern occoured at 5 cm above the surface (Figure 13 left b). The peak is reached at 19:30 with a value of 47.9 °C. The main reason of this behavior can be attributed to the position of the measurement points. Plot 1 is located in a shaded area during the morning because the perimeter wall of the roof. On the contrary, plot 2 and 3 become shaded during the afternoon whereas plot 1 is receiving the last sun radiation of the day from the west. As a consequence the temperature increase with a time delay when compared with plot 2 and plot 3 and the peak is attained later in the afternoon.

At -4 cm (Figure 13 felft c) the effect of spatial influence is also visible. Gravel temperature in plot 2 rises to the value of 52.8 °C at 17:00; the substrate temperature in plot 3 reaches the peak at the same time but with a value of 46.7 °C, substantially lower than gravel. Again substrate in plot 1 behaves differently. During night time and in the early morning the temperature is significantly higher than both plot 2 and 3. Owing to the different exposure to sun radiation the peak, although with similar value of plot 3, is attained at 18:40. The process of charging the growing media starts later in plot 1 so that consequently the discharge period is delayed, and the temperature during the night assumes higher value.

In addition, as previously mentioned in the floristic composition section, large differences in floristic composition between plot 1 and 2 were observed. Differences on plants species could result on different thermal behaviour in the roof, although it is not an easy effect to asses due to the mixture plant composition, and therefore it was not confirmed in this study. Future studies should address this issue more thoroughly, since the contribution of different plant species may actually be different (transpiration effect, shade provided, growth typology, etc.). According to the results obtained, the spatial effect was related to solar radiation exposition, which is the key factor that directly influences not only the substrate temperatures performance but also the floristic composition. Spatial effect is not despicable and it must be taken into account for future studies and designs of extensive green roofs.

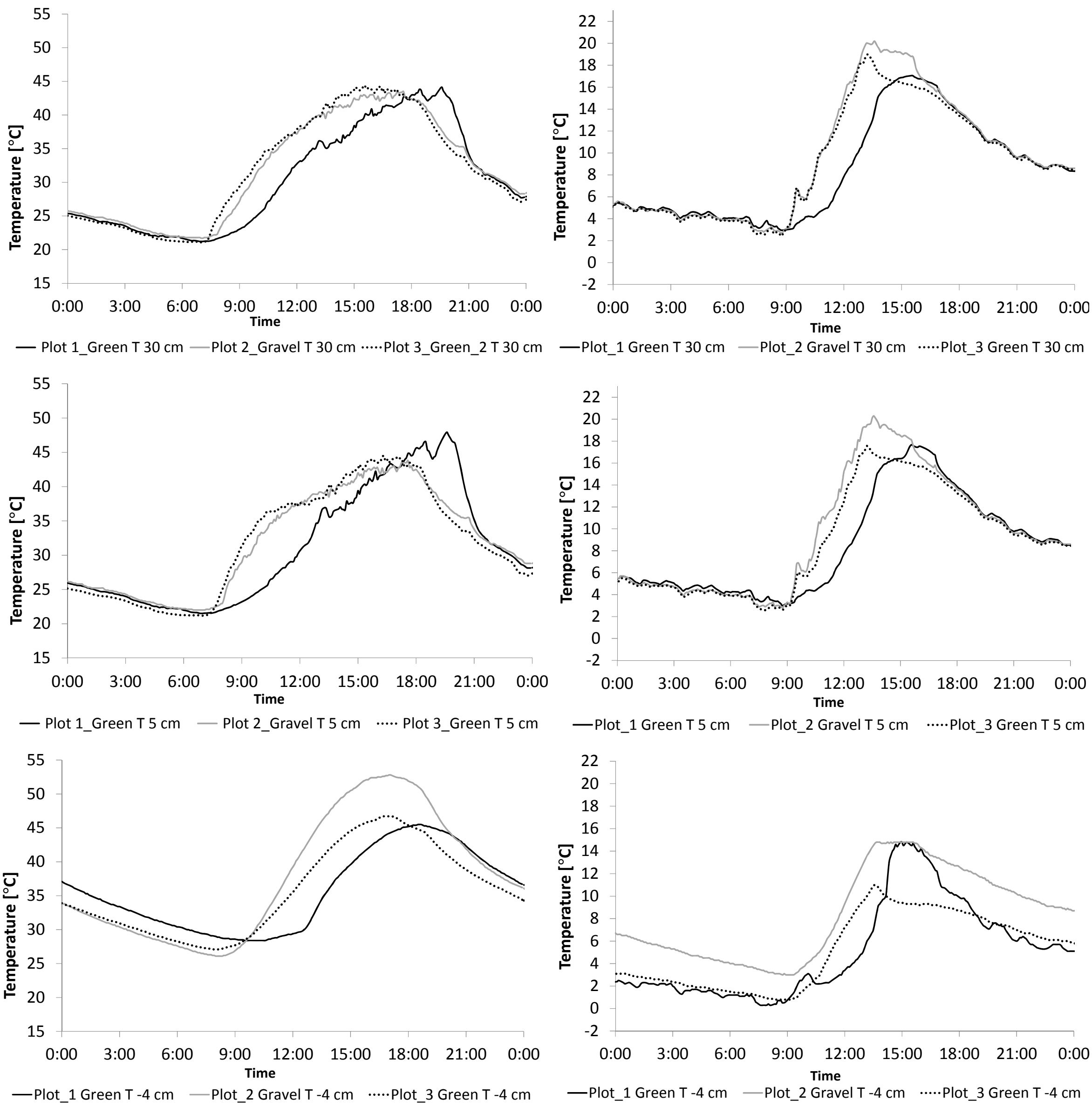

Figure 13. Left column, from top to bottom, daily temperature profile at 30 cm (left), at 5 cm (right) and at -4 cm in the substrate above green and gravel area in 01/08/2012. Right column, from top to bottom, daily temperature profile at 30 cm (left), at 5 cm (right) and at -4 cm in the substrate above green and gravel area in 04/01/2012

3.2.2.2 Winter analysis

In winter (04/01/2012) the evolution of the daily temperature above the roof follow the same pattern than summer (Figure 13 right a and b), but the differences between gravel and green area are more accentuated, either at 30 cm and 5 cm, due to evapotranspiration. The temperature measured in plot 1 shows the typical time delay of the peak, due probably to the different exposure.

In terms of substrate behaviour, due to the plants species recession, the level of substrate exposure to solar radiation and environmental conditions was higher during winter period. Becasuse of the lower plant cover in winter, the substrate was extremely heated during the morning, reaching nearly the same level than gravel area. The differences between plot 1 and 3 in the daily evolution of the substrate temperature show the great impact that the spatial factor may have on the green roof thermal performance (Figure 13 right c).

3.3 Evapotranspiration effect assessment

Results of the thermal analysis of the green roof have showed how the effect of evapotranspiration could be very limited for the particular weather condition of Lleida (Mediterranean Continental climate).

From the previous sections it is evident how in winter, when the volumetric water content of the substrate is higher the evapotranspiration is more appreciable. Moreover, after a rainfall event in summer, visible thank to the increase of water content in the growing media (from 5 % to 8 %) it is also possible to appreciate the evapotranspiration effect. The rainfall is associated with a cooling load that produces an overall lowering of temperatures in all layers (Figure 14a). Owing to the rain event the temperatures profiles for the different areas tend to overlap, but in the following days the solar radiation causes the evaporation of substrate moisture so that gravel temperature rises quicker than the growing media both in plot 1 and 3. This is probably due to the different retention capacity of the two types of materials: gravel drains water faster than substrate that keep showing lower temperature due to the higher water content. Three days after the rainfall the peak temperature of gravel at -4 cm equals the value of the day before the rain, while for the substrate 5 days are necessary. The phenomenon is also evident in Figure 14b where the temperatures within the substrate are shown. The temperature drops during the rain event; after that the top layers of the growing media (-2 cm) that are strongly affected by the climatic condition dry up rapidly most likely because of evapotranspiration of the water hold close to the surface. This finding gives a further confirmation how the evaporative cooling of a green roof can be restrained if the water content of the substrate is not adequate.

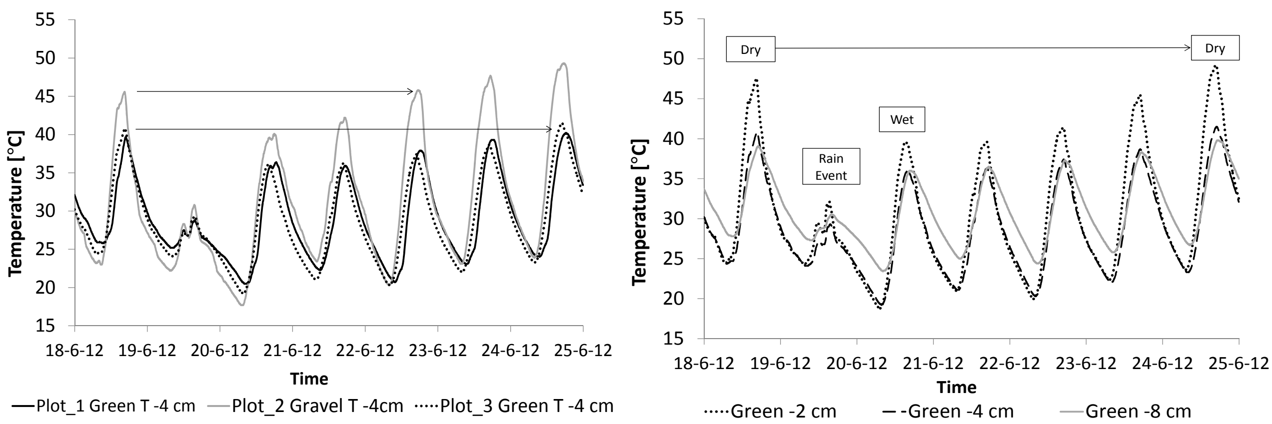

Figure 14. (a) Temperature profiles at -4 cm in substrate and gravel. (b) Substrate temperatures at different depths. June 2012

4. Conclusions

An extensive green roof installed in a public building in the city of Lleida (Catalonia, Spain), has been investigated in terms of vegetation development and thermal behaviour in low and high plant cover conditions, in order to better understanding its performance in a typical dry Mediterranean Continental climate.

- Referring to the floristic composition, both temporal and spatial changes were found, implying therefore that plant cover in this extensive green roof was not homogeneous, not only spatially on the roof surface but also seasonally over time. According to this dynamic, the cover provided by the original planted Sedum sp was less variable, ranging from 20 to

40%, than that offer by the colonizing species which reached the maximum of cover and floristic richness at the beginning of spring and summer seasons, and the minimum in winter.

- From the thermal behaviour study, it was observed that an increment in plant cover, from 10% in 2010 to 80% in 2012, did not imply a great improvement in terms of energy performance, whereas the lack of moisture in the substrate layer can be considered a problem in terms of spoiling the possibility of activate the cooling effect from the evapotranspiration.
- As for the substrate thermal conductivity, it can be concluded that due to the existence of substrate bare areas large temperature variations were registered in the upper layer, fact that added to moisture scarcity, hinders the sedum species development and promotes the emergence of annual colonizing plants at the same time. Moreover, although the large surface variations observed, it can be concluded that 8 cm were enough stabilizing the temperature at the bottom of the substrate layer, acting as an effective insulation layer.
- Finally, it was confirmed that the spatial effect was related basically to solar radiation exposition, which is the key factor that directly influences not only the substrate temperatures performance but also the floristic composition.

In general, it can be concluded that an extensive green roof is very heterogeneous, both spatial and temporary, which directly affects not only the floristic composition and plant cover but the thermal behaviour. This fact should be taken into account especially in those climates where vegetation has difficulties to achieve by its own a full cover, leaving consequently areas of bare substrate. In these cases, the definition and choice of a growing media with proper thermal properties that can assure good insulation characteristic in winter and compensate the lack of vegetation in summer grows in importance.

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References

[1] Takebayashi H, Moriyama M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Building and Environment 2007; 42:2971–2979.

[2] Susca T, Gaffin SR, Dell'Osso GR. Positive effects of vegetation: Urban heat island and green roofs. Environmental Pollution 2011; 159:2119–2126.

[3] Alexandria E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment 2008; 43:480–493.

[4] Czemiel Berndtsson J. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering 2010; 36:351–360

[5] Carter TL, Rasmussen TC. Hydrologic behavior of vegetated roofs. Journal of the American Water Resources Association 2006; 42 (5):1261–1274.

[6] DeNardo JC, Jarrett AR, Manbeck HB, Beattie DJ, Berghage RD. Stormwater mitigation and surface temperature reduction by green roofs. Transactions of the American Society of Agricultural Engineers 200; 48 (4):1491–1496.

[7] Czemiel Berndtsson J, Bengtsson L, Jinno K. Runoff water quality from intensive and extensive vegetated roofs. Ecological Engineering 2009; 30:271–277.

[8] Yang J, Yu Q, Gong P. Quantifying air pollution removal by green roofs in Chicago. Atmospheric Environment 42 2008; 31:7266–7273.

[9] Teemusk A, Mander U. Green roof potential to reduce temperature fluctuations of a roof membrane: a case study from Estonia. Building and Environment 2009; 44:643–50.

[10] Liu K, Minor J. Performance evaluation of an extensive green roof. Toronto: National Research Council of Canada; 2005.

[11] Castleton HF, Stovin V, Beck SBM, Davison JB. Green roofs; building energy savings and the potential for retrofit. Energy and Buildings 2010; 42:1582–91.

[12] Nyuk Hien W, Puay Yok T, Yu C. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Building and Environment 2007; 42:25–54.

[13] Theodosiou T. Green Roofs in Buildings: Thermal and Environmental Behaviour. Advances in Building Energy Research 2009; 3:1, 271-288.

[14] Getter KL, Rowe DB, Andresen JA, Wichman IS. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy and Buildings 2011; 43:3548–57.

[15] Jim CY. Effect of vegetation biomass structure on thermal performance of tropical green roof. Landscape Ecological Engineering 2012; 8:173–187.

[16] Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, Hatzibiros A, Patargias P. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. Energy 2007; 32:1781–1788.

[17] Spala A, Bagiorgas HS, Assimakopoulos MN, Kalavrouziotisa J, Matthopoulos D, Mihalakakou G. On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece. Renewable Energy 2008; 33:173–7.

[18] Jaffal I, Ouldboukhitine S-E, Belarbi R. A comprehensive study of the impact of green roofs on building energy performance. Renewable Energy 2012; 43:157-164.

[19] Olivieri F, Di Perna C, D'Orazio M, Olivieri L, Neila J. Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate. Energy and Buildings 2013; 63:1–14.

[20] Tabares-Velasco PC, Srebric J. A heat transfer model for assessment of plant based roofing systems in summer conditions. Building and Environment 2012; 49:310-323.

[21] Feng C, Meng Q, Zhang Y. Theoretical and experimental analysis of the energy balance of extensive green roofs. Energy and Buildings 2010; 42:959–65.

[22] Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modelling of a green roof. Energy and Buildings 2005; 37:1260–1267.

[23] Perez G, Vila A, Sole C, Coma J, Castell A, Cabeza LF. The thermal behaviour of Extensive green roofs under low plant cover conditions. Energy Efficiency. ENEF-D-13-00192R1. In press.

[24] Puigdemasa JM, Picharchitects, (2009). Project. Agrifood Technological Science Center, Lleida.

[25] www.intemper.com

[26] Machado M, Britto C, Neila FJ. La cubierta ecológica como material de construcción. Informes de la Construcción 2001; 52:15-29.

[27] Neila FJ, Bedoya C, Acha C, Olivieri F, Barbero M. Las cubiertas ecológicas de tercera generación: un nuevo material constructivo. Informes de la Construcción 2008; 60:15-25.

[28] State Meteorological Agency. Spanish Ministry of Environment. Period: 1971-2000 – Altitude (m): 192 - Latitude: 41 º 37 '33"N - Longitude: 00 º 35' 42"E. http://www.aemet.es/es/portada

[29] Braun-Blanquet J. Fitosociología: Bases para el estudio de las comunidades vegetales. Madrid: Editorial Blume. 1979.

[30] Bolòs O, Vigo J. Flora dels Països Catalans. Volume 1–4. Barcelona: Barcino 1984–2001.

[31] Leps J, Smilauer P. (2003) Multivariate analysis of ecological data using CANOCO Cambridge University Press.

[32] R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

[33] Madre F, Vergnes A, Machon N, Clergeau P. Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. Landscape and Urban Planning 2014; 122:100-107.

[34] Butler C, Orians CM. Sedum cools soil and can improve neighbouring plant performance during water deficit on a green roof. Ecological Engineering 2011; 37 (11): 1796-1803.

[35] Theodosiou T. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings 2003; 35:909–917.

[36] Berardi U, GhaffarianHoseini A, GhaffarianHoseini A. State-of-the-art analysis of the environmental benefits of green roofs. Applied Energy 2014; 115:411–428

[37] Parizotto S, Lamberts R. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. Energy and Buildings 2011; 43:1712–1722 .