Green Roofs in Dry Cities. Selection of Plant Species According to Their Biological and Thermal Behaviour

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GREEN ROOFS IN DRY CITIES. SELECTION OF PLANT SPECIES ACCORDING TO THEIR BIOLOGICAL AND THERMAL BEHAVIOUR

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ABSTRACT

This paper proposes the identification of adapted plant species with high local availability feasible for implementation as green roofs in dry cities. To this end, two experiments were conducted under controlled conditions. One of them aimed at determining the biological behaviour of a sample set of fourteen species based on the measurement of three variables: plant cover, water consumption, and leaf temperature. The other test sought to determine the thermal behaviour of green roofs by comparing preselected species according to their biological response with traditional roofs. In this case, the following meteorological variables were recorded: outdoor and indoor air temperature, substrate temperature, and water content. Finally, the data obtained were statistically processed. Biological results show that the species *Aptenia cordifolia*, *Cynodon dactylon*, *Hyalis argentea*, and *Nassella tenuissima* reach plant cover higher than 70% with *Aptenia cordifolia* recording the lowest water consumption, 217 l/year. Regarding thermal behaviour, the green roof with *Nassella tenuissima* -a shrubby native species- results in the highest mitigation of outdoor temperature, reducing average indoor temperature by 3.4°C. These results show the biological and thermal fitness of local species that guarantee the sustainability of the system itself as well as higher thermal efficiency with lower water consumption.

Keywords: green roofs, native species, adapted species, thermal behaviour, dry cities.

INTRODUCTION

Implementing green roofs in urban areas is a viable option to improve the environmental conditions of built habitats. The scientific approach to this issue shows that urban greening technologies provide ecosystem services and improve the environmental performance of buildings (Berndtsson 2010). They contribute to mitigating the heat island phenomenon (Susca et al. 2011), collaborate with energy saving by improving the thermal behaviour of buildings (Simmons et al. 2008; Castleton et al. 2010; Vijayaraghavan 2012), and improve the durability of waterproof insulation and extension of roof life (Bevilacqua et al. 2016; He et al. 2016).

The contributions of this green technology are conditioned by the climate characteristics of the implantation site, which are determining factors in the growth of the implanted species and the impact on the thermal behaviour, among other aspects. In this sense, it is interesting to evaluate these two aspects together as a result of the implementation of green roofs in arid and semi-arid climates. That is, to address the selection of species and their biological response and, simultaneously, the thermal benefits provided by this green technology. In this regard, in extensive green roofs, the species must survive and guarantee adequate plant cover under restrictive environmental conditions (Rayner et al. 2016), low water availability -low relative humidity and scarce precipitation-, and high heliophany (Nagase and Dunnett 2010). These restrictive conditions not only hinder plant growth and development, but also reduce the evapotranspiration rate and cooling capacities (Parizotto and Lamberts 2011).

In arid zones, the set of plant species of the genus *Sedum* with typical characteristics of adaptation to xerophytic environments is the most widely used group of plants internationally (Dunnett and Kingsbury 2008; Nektarios et al. 2015). The ability of *Sedum* spp. to establish quickly provides good coverage of the rooftop surface and low maintenance with sustained growth rates (Butler et al. 2012).

There is scientific evidence showing alternative species to *Sedum* in terms of guaranteeing good plant cover and controlling water runoff. However, the development of knowledge associated with the integration of biological aspects with other ecosystem services, such as the cooling potential of green roofs, is incipient. The selection of plant species should not only be determined by their capacity to integrate the biological package in shallow substrates, but also by the greater potential of environmental services they offer (Blanusa et al. 2013). Nardini et al. (2012) find that both shrub-vegetated and herbaceous modules intercepted and stored more than 90% rainfall during intense precipitation events, with no significant difference between the two vegetation types despite different substrate depths. On the other hand, plant type and growth habit, defined mainly by species, influence substrate temperature in green roofs because they condition heat transfer mechanisms, that is, the cooling potential of buildings. Minimum temperatures and temperature fluctuations such as heat flow tend to be more stable under a green roof with herbaceous plants (Eksi et al. 2017).

From what has been described, the need to identify species that guarantee plant cover and provide greater environmental benefits in challenging climate zones can be inferred; for example, the potential of the species in terms of its regulatory effect on the thermal behaviour of indoor spaces (Nektarios and Ntoulas 2017). Green roofs appear to have a relatively low thermal behaviour in Mediterranean areas and in cities with hot climates. This is possibly due to the fact that commonly used species are not adapted to stress factors associated with this location (Van Mechelen et al. 2014).

In the case of dry climates, recent research suggests that drought-avoidance species with low water consumption could achieve high retention of sporadic rainfall. Similarly, Van Mechelen et al. (2014, 2015) have proposed the use of annual species for extensive green roofs in dry conditions. It is worth mentioning that desert plants - xerophytes - have evolved with adaptive strategies that can play an important role to in green roofs. These would be viable options to complement the widespread use of genus *Sedum* species (Blanusa et al. 2013; Wang et al. 2018).

Systematic comparison of the scientific literature shows that the selection of species for extensive green roofs and their thermal behaviour has been largely based on cold and temperate climate research (Farrell et al 2012; Rayner et al. 2016; Vijayaraghavan 2016). The implementation of green roofs in arid and semi-arid regions is limited, as most of the research has been carried out in the northern hemisphere in temperate, continental and dry climates of groups C -Csa (Mediterranean climate), Cwa (Monsoon-influenced humid subtropical climate), D - Dfa (Temperate continental without dry season) and Dwa (Temperate continental with dry winter), and B (Dry), according to the Köppen-Geiger classification (Kazemi and Mohorko 2017).

In dryland cities has been observed that the implementation of a vegetated layer on roofs and walls, can improve building performance, reduce energy consumption and improve indoor comfort (Wahba Sherine et al. 2018). However, studies focusing on the selection of green roof type based on identifying and evaluating different aspects such as biological and thermal behaviour (Mahdiyar et al. 2018) are scarce.

In this context, the City of Mendoza - study city- is located in Central Western Argentina (32° 40´ south latitude, 68° 51´ west longitude, and 750 masl). It has arid continental climate with low relative humidity and high heliophany -BWk, cool arid, according to the Köppen-Geiger classification (Kottek et al. 2006; Kazemi and Mohorko 2017)-. The site is located in an arid and seismic context, with an aridity index between 0.20 and 0.50 (aridity index = precipitation/evapotranspiration potential) (Atlas de Zonas Áridas de América Latina y el Caribe 2010).

The urban conglomerate presents critical environmental problems associated with the increase in urban temperature and intensity of urban heat island (UHI) of 10°C (Correa 2006). Studies carried out in the region determine that one of its main impacts is the increase of up to 20% in energy consumption for the thermal conditioning of buildings during the summer (Correa et al. 2008), deteriorates air quality and affects thermal comfort conditions, causing a decrease in the degree of habitability and use of open spaces (Ruiz and Correa 2014). A viable strategy to minimize the effects of urbanization on the microclimate, as well as their energy and environmental consequences, is the implementation of green roofs, a worldwide trend in urban planning. However, their use in the region under study requires analyzing, evaluating, and selecting appropriate plant species to be incorporated into these systems under the conditions imposed by dry cities.

In the context described, this research seeks to identify and evaluate locally available plant species adapted to climate conditions in arid zones for use in green roofs that show adequate growth with a minimum irrigation quota. The study determines the impact of the species selected for use in green roofs on the thermal behaviour of indoor spaces. In addition, it defines the influence of the variables involved -green and roofing technology as well as climate conditions- on such impact. It also compares the biological and thermal behaviour of local species with *Sedum* spp., highly recommended by the international literature and widely used in green roofs. Finally, it seeks to guarantee the sustainability of the system over time and achieve maximum efficiency from the point of view of water consumption, while decreasing the temperature of indoor spaces.

METHODOLOGY

According to the objectives set forth for the research work, the methodology used evaluates both the biological response of species and the thermal behaviour of indoor spaces.

1. BIOLOGICAL BEHAVIOUR

1.1. Selection of case studies

A set of 34 species was selected based on a vast literature review. In order to select regionally available species, interviews were also conducted with specialists in xeric landscaping and from local nurseries that sell low water consumption plants. Finally, 14 plant species were selected from the assessment and weighting (on a scale of 1 to 5) of a set of indicators such as water requirement, minimal winter vegetative growth, drought resistance, final plant size, adaptation to solar exposure, maintenance, and storage organ, among others (Razzaghmanesh et al. 2014; Oksuz et al. 2020; Liu et al. 2018; Azeñas et al. 2019). Table 1 shows the selected species, plant taxonomy and traits -origin, growth form and vegetation types-.

ID	Species	Family	Local name	Life form	Plants traits (Origin, Growth Form, Leaf Type, Vegetation Type)			
1	*Sedum lineare*	Crassulaceae	Sedum alfombra	Chamaephyte	Non-native	Creeping	Succulent	Perennial
2	*Hyalis argentea*	Asteraceae	Olivillo	Chamaephyte	Native	Shrubby	Non succulent	Perennial
3	*Zephyranthes candida*	Amaryllidaceae	Zefirantes	Geophyte	Non-native	Creeping	Non succulent	Perennial
4	*Lampranthus multiradiatus*	Crassulaceae	Rayito de sol	Chamaephyte	Non-native	Creeping	Succulent	Perennial
5	*Aptenia cordifolia*	Crassulaceae	Baby rose	Chamaephyte	Non-native	Creeping	Succulent	Perennial
6	*Cynodon dactylon*	Poaceae	Bermuda grass	Chamaephyte	Non-native	Creeping	Grass plant	Perennial
7	*Thymus vulgaris*	Verbenaceae	Tomillo	Chamaephyte	Non-native	Shrubby	Non succulent	Perennial
8	*Hymenoxys acaulis*	Asteraceae	Angelita	Chamaephyte	Non-native	Shrubby	Non succulent	Perennial
9	*Sedum spectabile*	Crassulaceae	Sedum de otoño	Chamaephyte	Non-native	Shrubby	Succulent	Deciduous
10	*Nassella tenuissima*	Poaceae	Coirón	Geophyte	Native	Shrubby	Grass plant	Perennial
11	*Verbena rigida*	Verbenaceae	Verbena papel de lija	Chamaephyte	Non-native	Creeping	Non succulent	Perennial
12	*Gazania rigens*	Asteraceae	Gazania	Chamaephyte	Non-native	Creeping	Non succulent	Perennial
13	*Sedum acre*	Crassulaceae	Pampajarito	Chamaephyte	Non-native	Creeping	Succulent	Perennial
14	*Aristida purpurea*	Poaceae	Arístida púrpura	Geophyte	Non-native	Shrubby	Grass plant	Perennial

Table 1. Description of selected species to evaluate.

1.2. Experimental design

The biological behaviour of the 14 selected species was evaluated based on two main variables- plant cover and water consumption- to determine their adaptation to the arid climate. Two further variables were added: measurement of leaf temperature, which depends on water consumption, and impact on the thermal response of green roofs.

The selected species were mounted on 1 m^2 experimental modules. Each module consists of three geotextile bags, as a plug plant. These geotextile bags contain the substrate in equal proportions of sand spent pomace, and fertile soil- with an area of 0.33 m^2 and a thickness of 0.15 m each. The same initial plant number -3 per bag and 9 per module - and size -transplanted plants had a well-developed root system and a similar height (between 0.10 and 0.12 m)- was used in order to establish a similar initial condition for all species. Table 2 shows the main physical and chemical characteristics of the substrate used. This substrate was selected because it is a widely used, low-cost crop medium available in the region that meets the nutritional requirements of any crop.

Indicator	*Substrate variables*	*Laboratory value*	*Diagnostic*
Acidity	paste pH	6.93	Normal acidity
Salinity	EC s dS/m	3.35	Light hazard
Fertility and substrate quality	Total nitrogen mg/kg	4088	High content
	Phosphorus Extraction CO_2 1:10 mg/kg ratio	43.22	High - No response to fertilization
	Potassium - AcNh4	755	High
	Organic matter	7.85	High
	C/N	11.1	Fertile substrate
Substrate bulk density	4 g/cm^3	1.5	Sandy loam texture
Capillary pore space	%	43	Sandy loam texture

Table 2: Physical and chemical characteristics of the substrate

The modules were placed on a 0,10 m thick, low density expanded polystyrene (LDSP) plate to adiabatize the thermal transfer between substrate and soil (Figure 1). A pressurized, subsurface drip irrigation system was used to avoid drifts and achieve maximum efficiency with minimum water losses. Self-compensated drippers were used to equalize pressures and irrigate evenly. A double irrigation hose with 6 drippers was placed for each geotextile bag to create a uniform wet bulb for each plant.

Each module contains a drainage channel and a collection receptacle to store and quantify drainage water. The incorporation of irrigation technology with localized systems allows the application of controlled flows, ensuring an adjusted relationship between the irrigation quota and the crop water requirements. These systems generate a wet bulb - preferably around the root zone- that constitutes the water reservoir available to the plant. At regional level, drip irrigation systems reach water efficiencies greater than 85%, provided they are adequately managed (Antúnez et al. 2010).

Given the climate limitations of the study region, differential irrigation frequencies were proposed. During winter, spring, and autumn, irrigation was applied weekly for 15 minutes with an average irrigation flow of 7.5 l/m^2. This was experimentally adjusted according to the application of deficit irrigation that allowed plants to grow. During the summer, the irrigation frequency was doubled to two weekly irrigation cycles given the high daily temperatures and the minimum relative humidity. The average irrigation flow was 15 l/m^2. Figure 1 shows the experiment and the distribution of the irrigation system.

The test was conducted under controlled conditions in the experimental area of CCT-Mendoza Conicet (32° 53'52.83" S, 68° 52'31.30" O). It started in January 2013 and extended over four vegetative cycles.

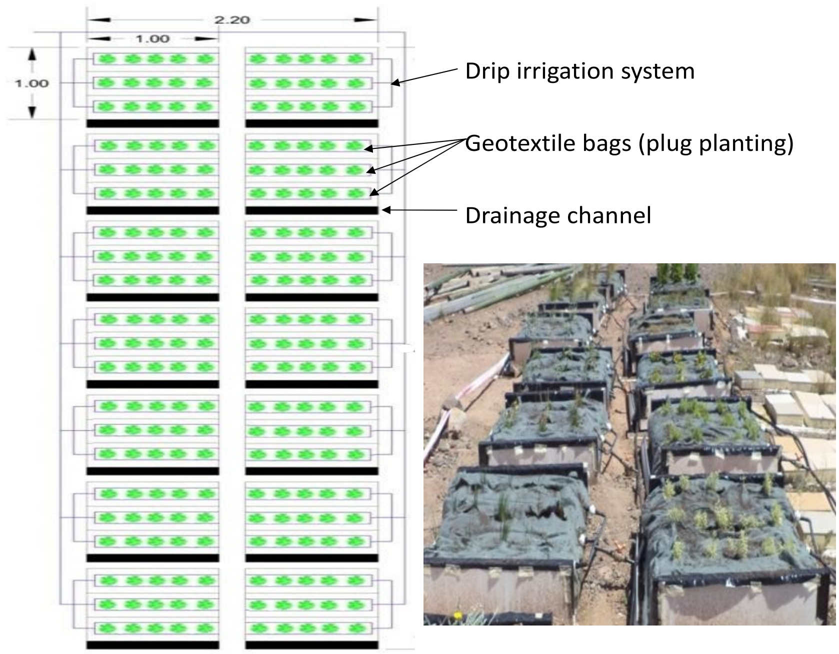


Figure 1. Experimental modules to evaluate the biological behaviour of plant species

1.3. Measurement method

i. **Plant coverage:**

ii. Photographs were taken with a digital camera of 12 mp resolution at the beginning and at the end of each growing season -summer, autumn, winter and spring- over four vegetative cycles between 2013 and 2017, to estimate and contrast the temporal variations of the plant cover. The images were processed with the free software MultiSpec© (2011). This tool allowed analyzing multispectral and hyperspectral images differentiating surface components according to pre-established RGB ranges for different classes: plant, flowering, geotextile, and substrate. **Water consumption**

Annual water consumption was determined from the sum of data resulting from the calculation for each irrigation applied of the difference between the flow of irrigation water and the flow of drainage water per unit area of the experimental module (Equation 1). Thus:

Equation (1):

$$\text{Annual water consumption } (l/m^2) = \sum \frac{(\text{Irrigation flow - Drainage flow})}{\text{Experimental module area}}$$

The flow of irrigation water was quantified by means of a hydrometer, whereas drainage flow was collected in airtight containers and measured using graduated test tubes. It allows simultaneously evaluating the set of species under study with acceptable precision and low cost. This procedure was applied during the experiment period, December 2013 - March 2017.

iii. **Leaf temperature**

Surface leaf temperature was measured by using Decagon Devices' leaf porometer model SC-1 during the warm season on fully exposed leaves in a time slot close to solar noon (11 am - 2 pm). Measurements were made for each species on four plants (two randomly selected leaves from each) before and after planned irrigation for at least three sunny days during three consecutive years.

2. THERMAL BEHAVIOR

2.1. Selection of case studies

From the biological responses obtained, a set of four species was selected to evaluate the thermal behaviour of the regionally adapted green roofs: *Sedum spectabile*, *Aptenia cordifolia*, and *Nassella tenuissima*. These species were compared with the thermal behaviour of one of the most widely used species, *Sedum lineare*. The first three species were chosen based on two variables: plant cover and water consumption. Table 3 shows the selected species and their main characteristics.

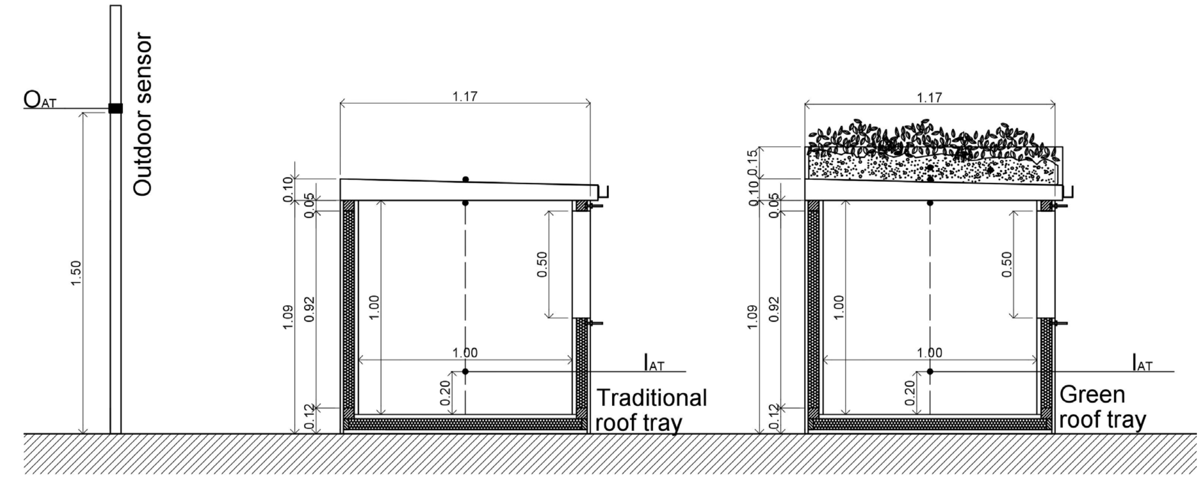
Traditional roof TR	**Green roofs GR**			
				
Species / **Characteristic**	*Aptenia cordifolia* GR_{Ac} 	*Sedum spectabile* GR_{Se} 	*Sedum lineare* GR_{Sl} 	*Nassella tenuissima* GR_{Nt} 
Origin with respect to Argentina reference	Non-native	Non-native	Non-native	Native
Plant coverage percentage (%)	88	43	48	72
Average water consumption (liters.m^2/year)	217	227	220	223
Growth form	Creeping species	Shrubby species	Creeping species	Shrubby species
Leaf type	perennial	deciduous	perennial	perennial
Local availability	high	low	low	high

Table 3. Biological characterization of selected species to evaluate thermal behavior

2.2. Experimental design

The thermal behaviour of green roofs was evaluated against traditional roofs in an experiment under controlled conditions according to the methodology proposed by La Roche (2009) for hot and dry climates. For this purpose, three thermal testing trays were mounted in the experimental area to compare two vegetated systems of different species with a traditional roof. The experimental trays constitute blind volumes of 1 m^3 with walls and floors made up of three layers: a cementitious plate on the inner side (10 mm thick), a thermal insulation of expanded low-density polystyrene (50 mm thick) and a phenolic plate on the outer face (18 mm thick) finished with white synthetic enamel. The traditional roof is made of reinforced concrete with a thickness of 150 mm, a specific weight of 2400 Kg/m^3. It is hydraulically insulated with a Sika® Sarnafil F610-12 Felt membrane. The roof was shaped to represent the type of traditional roof commonly used in buildings of the Mendoza Metropolitan Area.

In green roofs a Sika® GR Aquadrain Extensive layer was placed in order to generate an anti-root barrier and to allow water drainage. A diagram of test trays is presented in Figure 2.



Variable	ID	Type
Outdoor air temperature	O_{AT}	Onset® HOBO® temp/RH logger UX100-003
Indoor air temperature	I_{AT}	Onset® HOBO® temp/RH logger UX100-003
Upper face slab surface temperature	U_{FSST}	Thermocouple EL-USB-TC
Inner face slab surface temperature	I_{FSST}	Thermocouple EL-USB-TC
Substrate temperature	S_T	Onset® HOBO® 12-bit Temp Sensor S-TMB-M002 associated to a datalogger HOBO® U30
Substrate water content	S_{WC}	Onset® HOBO® SoilMoisture EC5 S-SMC-M005 associated to a datalogger HOBO® U30

Figure 2: Experimental and instrumental design.

The thermal behaviour of green roofs and indoor spaces was evaluated by recording the following meteorological variables: outdoor and indoor air temperature, substrate temperature and water content, and slab surface temperature. These variables were recorded for two measuring cycles of 14 days during the summer periods of 2015-2017.

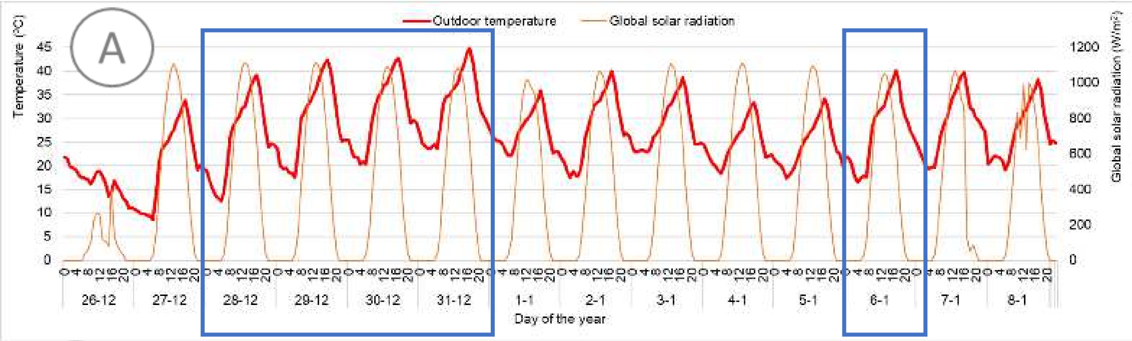
The data were recorded every 15 minutes according to the following scheme: five data micro-acquirers per tray with green roof, three sensors in the tray with traditional roof, and a reference sensor in the outdoor space (Figure 2).

In the outdoor environment, total solar radiation (W/m^2) was measured with a Star Pyranometer Mod3040-A Weather Tronic. Wind speed (km/h) was measured with a Micro Response Anemometer, Mod 2030 Weather Tronic.

In each measurement cycle, two green roofs with different species were simultaneously compared with a traditional roof. During the first cycle, two green roofs, one with *Sedum lineare* (GRSl) and another with *Nassella tenuissima* (GRNt), and a traditional roof (TR) were monitored. In the second cycle, two green roofs, one with *Aptenia cordifolia* (GRAc) and another with *Sedum spectabile* (GRSe), and a traditional roof (TR) were examined.

2.3. Selection of analysis days (Figures 3 and 4)

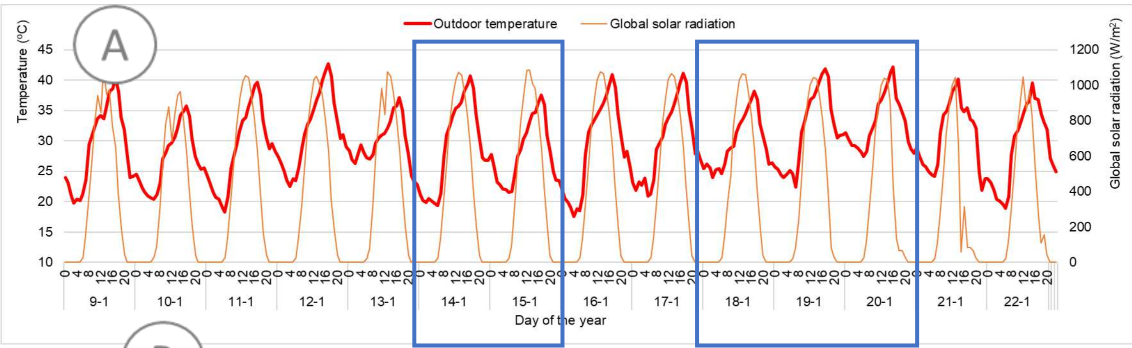
For the analysis of thermal behaviour, within each measurement cycle, a set of days representative of the summer season were selected, characterized by the highest temperatures, heliophany and thermal amplitudes. These characteristics are typical of the climate in the study area, BWk, according to the Köppen-Geiger classification (Kottek et al. 2006; Kazemi and Mohorko 2017).



B

	Temperature (ºC)	Average Radiation (W/m^2)
Absolute maximum	44.8	1114.7
Maximum average	41.8	1098.9
Average	29.3	390.9
Minimum average	19.4	0.0
Absolute minimum	12.5	0.0

Figure 3. A- Selection of analysis days of the first measurement cycle, B- Average data of outdoor temperature and solar radiation of selected days



B

	Temperature (ºC)	Average Radiation (W/m^2)
Absolute maximum	42.1	1118.8
Maximum average	40.1	1100.8
Average	30.3	362.09
Minimum average	22.9	0.0
Absolute minimum	19.3	0.0

Figure 4. A- Selection of analysis days of the second measurement cycle, B- Average data of outdoor temperature and solar radiation of selected days

3. STATISTICAL DATA ANALYSIS

Data processing and preparation of tray-plot graphs was carried out using the Infostat software (Di Rienzo et al., 2017) to analyze and plot the biological and thermal behaviour of green roofs.

To explain the incidence of the different species used and their effect on indoor thermal behaviour, multivariate statistical methods were used to investigate the relationship among the variables considered. The data were analyzed with the Pearson correlation coefficient, which represents the covariance of standardized sample values (Balzarini et al., 2008).

RESULTS

1. Biological behaviour

1.1. Plant cover

Figure 5 shows the initial and final coverage for each species for the full experiment. The species with the greatest growth and coverage at the end of the test are *Cynodon dactylon* (89.5%) and *Aptenia cordifolia* (87.90%).

When organizing plant cover in three ranges, the species *Aptenia cordifolia*, *Cynodon dactylon*, *Hyalis argentea*, and *Nassella tenuissima* belong to the range of maximum final coverage (72.4 - 89.5%), which indicates their adaptation to the system and potential use for green roofs. *Lampranthus multiradiatus*, *Sedum acre*, *Sedum spectabile*, and *Aristida purpurea* fall within a medium range of plant cover (42.6-56.5%), while *Sedum lineare*, *Gazania rigens*, and *Zephyranthes candida* are within the range of minimum plant cover (17.0-23.0%).

Sedum spectabile and *Zephyranthes candida* had an initial increase in coverage with oscillations in some periods according to the seasonal behaviour of each species and their periods of vegetative recess -winter for the first and summer for the second-. *Thymus vulgaris* had a period of active growth during the first year but from the second summer, its coverage declined sharply (below 10%), despite its perennial nature. *Hymenoxys acaulis* and *Verbena rigida* showed low adaptability to the system since their seasonal maximum coverage ranged between 10 and 20%.

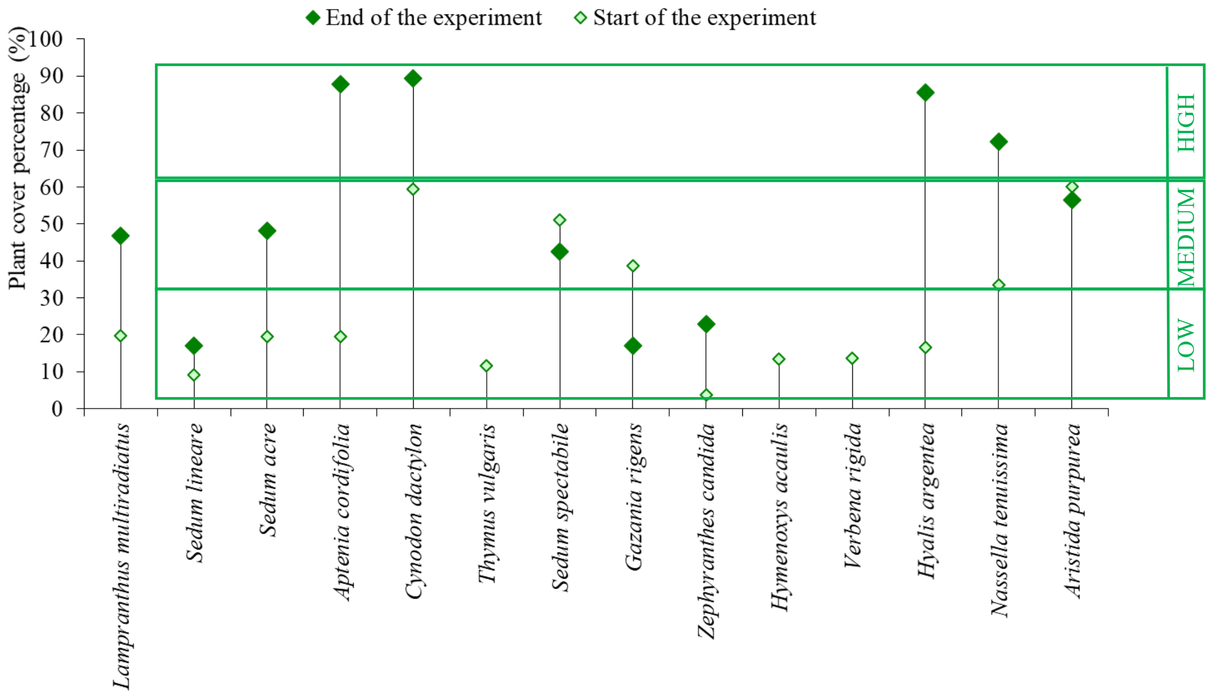


Figure 5. A- Percentage of plant cover per species in the initial stage and at the end of the experiment (2013-2017).

1.2. Water consumption

The water consumption of each species corresponds to three full years of experimentation: 2014, 2015, and 2016 (Figure 6). The analysis of average annual water consumption reveals that the most efficient, lowest water consumption species is *Aptenia cordifolia* with 217 l/year, while the highest consumption species is *Sedum acre* with 229 l/year.

By establishing ranges of water use efficiency, the species *Aptenia cordifolia*, *Sedum lineare*, *Cynodon dactylon*, and *Zephyranthes candida* are in the lowest water consumption range (217-221 l/year). *Nassella tenuissima, Gazania rigens,* and *Hyalis argentea* are within a medium range (221-225 l/year). *Lampranthus multiradiatus*, *Sedum spectabile*, *Aristida purpurea*, and *Sedum acre* are in the highest water consumption range (225-229 l/year).

Although differences in water consumption do not show significant variations, it is necessary to consider that they refer to a one-square-meter ($1m^2$) area. In addition, the mass implementation of green roofs on an urban scale could mean large vegetated areas and, consequently, recording water consumption becomes relevant.

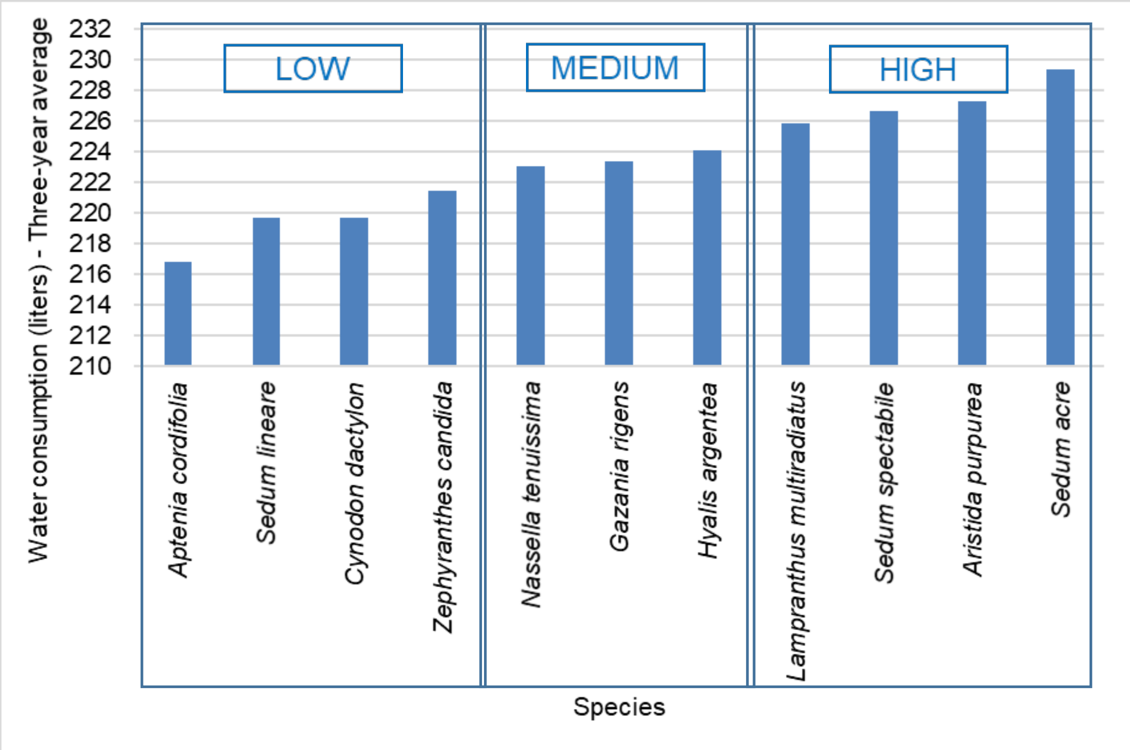


Figure 6. Average annual water consumption by species and consumption range.

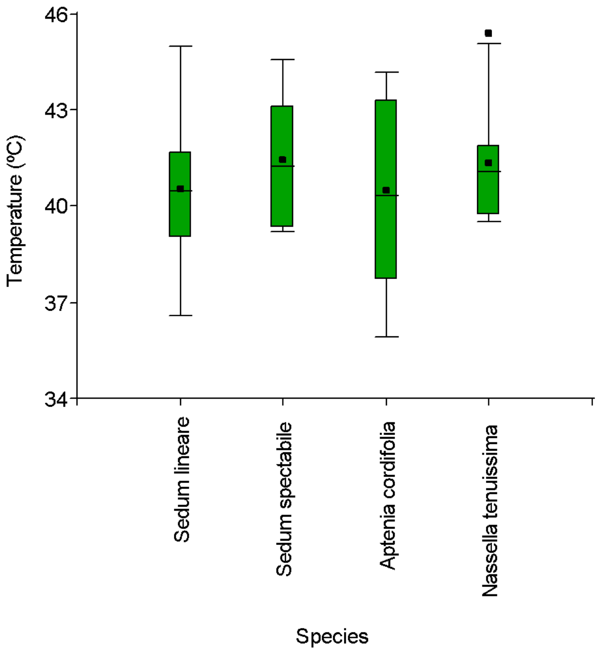
Although deficit irrigation was applied, some species drained water, which demonstrates adaptability to the system and local weather conditions. *Aptenia cordifolia and Cynodon dactylon*, in particular, are the two species that reached the highest plant cover and recorded the lowest water consumption, while the native species *Hyalis argentea* and *Nassella tenuissima* are also in the group with the highest plant cover, but within a medium range of water consumption. Although *Cynodon dactylon* has a high coverage capacity, in certain periods it showed signs of temporary yellowing and even stem death.

1.3. Leaf temperature (Figure 7)

Average leaf temperature values ranged between 40.5 and 41.5°C. Leaf temperature showed variations throughout the day in the order of 4.7°C to 7.4°C depending on the growth habit. However, the difference in the average values between species was minimal due to the deficit irrigation quota that slows down internal plant metabolism.

The data measured for this variable indicate differences among species concerning plant growth habits: creeping species such as *Sedum lineare* and *Aptenia cordifolia* had the greatest variability (P_{95}-P_{05}) with amplitudes of 7.0 and 7.4°C, respectively. In contrast, shrubby species showed a lower oscillation in leaf temperature (P_{95}-P_{05}), with amplitudes of 4.7°C for *Sedum spectabile* and 5.5°C for *Nassella tenuissima*. It should be noted that the highest P_{75} species are *Sedum spectabile* and *Aptenia cordifolia* with temperatures of 43.1ºC and 43.3ºC, respectively. *Sedum lineare* and *Nassella tenuissima* had P_{75} temperatures of 41.7 ºC and 41.9 ºC, respectively.

Concerning P_{25}, shrubby species recorded the highest thermal values (*Sedum spectabile* = 39.2ºC; *Nassella tenuissima* = 39.5ºC). Among creeping species, *Aptenia cordifolia* had the lowest P_{25} temperature with a value of 36.2ºC.



Species	n	Avg.	Min.	Max.	P(05)	P(25)	P(75)	P(95)
Aptenia cordifolia	56	40.5	35.9	44.2	36.2	37.7	43.3	43.6
Nassella tenuissima	40	41.4	39.5	45.4	39.5	39.7	41.9	45.0
Sedum lineare	56	40.5	36.6	45.0	37.2	39.0	41.7	44.2
Sedum spectabile	56	41.4	39.2	44.6	39.2	39.3	43.1	43.9

Figure 7. Leaf temperature in species tested.

2. Thermal behavior

2.1. Analysis of substrate temperature, slab surface temperature, and indoor air temperature

The results obtained were analyzed comparing a traditional roof with two green roofs. The variables analyzed in the experiments were: substrate temperature, slab surface temperature, and indoor temperature. For each of the variables analyzed, the data were averaged on an hourly basis. The results obtained from comparing the green roofs with *Sedum lineare* (GRSl) and *Nassella tenuissima* (GRNt) with a traditional roof (TR) are shown in Table 4, and its graphical representation related with data dispersion in Figure 8.

The average green roof indoor temperatures ranged between 27.7ºC (*Nassella tenuissima*) and 28.2ºC (*Sedum lineare*), while in the traditional roof the average indoor temperature was 31ºC; that is to say, approximately 3ºC higher. Thermal amplitudes (P_{95}-P_{05}) in the trays with green roofs were 14°C as opposed to 23°C in the traditional roof with a maximum P_{95} of 34.8ºC (GRSI), 34ºC (GRNt) and 42.3ºC for the traditional roof.

Table 4 shows that the average substrate temperature on green roofs yielded similar values. The average temperature of the substrate corresponding to the cover with *Sedum lineare* (GRSl) was slightly higher (0.4ºC) and showed greater thermal amplitude (2.7ºC). On green roofs, the average slab surface temperature (both on its lower and upper face) was similar (27ºC).

The upper and lower slab surface temperatures of the green roofs show differences of less than 0.4°C, while in the traditional roof, this difference reaches 4°C. The upper slab average surface temperature in the traditional roof was 29ºC, while the lower slab average surface temperature was 33ºC. This demonstrates the effect of green roofs on the attenuation of solar radiation and the increase in thermal inertia. In the traditional roof, both average temperatures were different and higher.

Species	Variable	n	Avg	Min.	Max.	Median	P(05)	P(25)	P(75)	P(95)
Sedum lineare	ST	120	26,4	16,1	35,1	26,8	17,9	23,2	30,0	33,5
Sedum lineare	IFSST	120	27,2	21,0	33,7	27,1	21,4	25,0	29,6	31,9

Sedum lineare	UFSST	120	27,4	19,6	34,0	27,5	20,5	25,0	30,0	32,5
Sedum lineare	IAT	120	28,2	19,0	36,3	28,3	20,4	25,0	31,5	34,8
Nassella tenuissima	ST	120	26,0	18,1	33,4	26,3	19,0	23,6	28,5	31,9
Nassella tenuissima	IFSST	120	26,9	20,5	32,9	26,9	21,0	24,7	29,2	31,4
Nassella tenuissima	UFSST	120	27,3	18,1	34,4	27,5	19,9	24,6	30,1	33,6
Nassella tenuissima	IAT	120	27,7	18,4	35,6	27,8	20,2	24,7	30,9	34,0
Traditional roof	IFSST	120	33,2	14,3	49,0	32,9	18,8	25,4	41,1	46,8
Traditional roof	UFSST	120	29,3	12,8	43,8	29,1	16,8	22,4	36,3	41,8
Traditional roof	IAT	120	31,0	16,8	44,6	30,5	19,5	24,7	37,9	42,3

Table 4. Statistical variables for the first measurement cycle. Avg, min., max., median and percentiles -05, 25, 75, 95- for green roof with *Nassella tenuissima, Sedum lineare* and traditional roof. ST= substrate temperature, UFSST= upper slab surface temperature, IFSST= lower slab surface temperature, IAT= indoor air temperature.

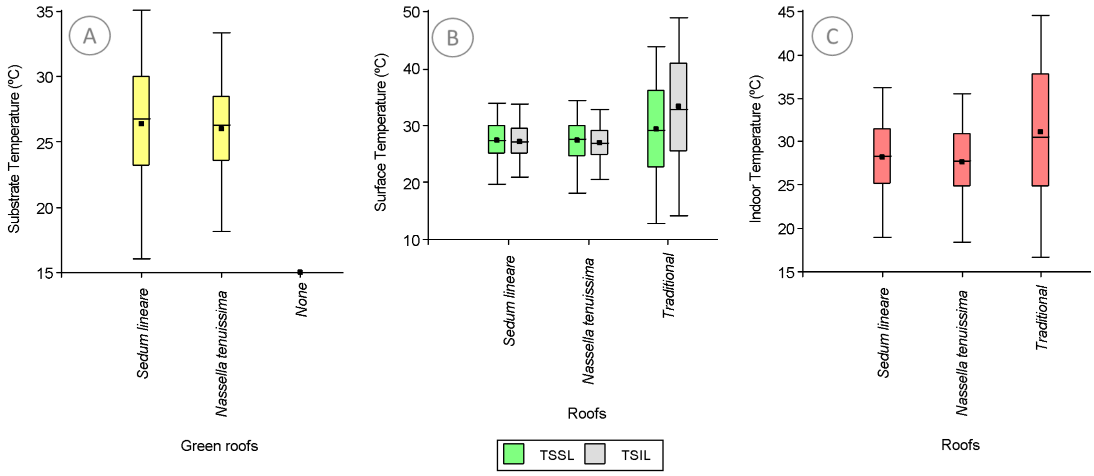


Figure 8. Green roof with Sedum lineare, Nassella tenuissima and traditional roof. A- ST=Substrate temperature, B- UFSST= *upper slab surface temperature,* IFSST= *lower slab surface temperature, C-* IAT= *indoor air temperature.*

The results obtained from comparing green roofs with *Aptenia cordifolia* (GRAc) and *Sedum spectabile* (GRSe) with a traditional roof (TR) are shown in Table 5, and its graphical representation related with data dispersion in Figure 9.

The average indoor temperatures of the experiments with green roofs were around 31 ºC, while in the traditional roof, the temperature was 3°C -2ºC higher-. Regarding thermal amplitudes (P_{95}-P_{05}), green roofs they were around 9ºC, and in the traditional roof, they were 18ºC with maximum amplitudes (P_{95}) of 35.5ºC (GRAc), 35.1ºC (GRSe), and 42.5ºC for the traditional roof.

In the case of green roofs with *Aptenia cordifolia* and *Sedum spectabile*, the average substrate temperature showed differences of 1.2ºC and the amplitude showed difference of 0.5°C; with higher average temperature and thermal amplitude in the case of *Sedum spectabile* (*Aptenia cordifolia* AVG ST 30.2°C and thermal amplitude P_{95}-P_{05}: 9.7°C. *Sedum spectabile* AVG ST 31,4 °C and thermal amplitude P_{95}-P_{05}: 10.4°C).

Therefore, Table 5 shows that on the green roofs slab, the upper average surface temperature was higher than the lower average surface temperature (0.8ºC), while the traditional roof behaved just the opposite.

The average upper surface temperature of the slab was lesser than the average lower surface temperature (4ºC). This behaviour indicates that green roofs mitigate outdoor temperatures. This phenomenon is also verified for green roofs with *Sedum lineare* (GRSl) and *Nassella tenuissima* (GRNt) although with lower intensity.

Species	Variable	n	Avg	Min.	Max.	Median	P(05)	P(25)	P(75)	P(95)
Aptenia cordifolia	ST	120	30,2	23,8	36,1	30,1	25,4	27,6	33,0	35,2
Aptenia cordifolia	IFSST	120	30,2	26,3	33,5	30,4	27,0	28,7	31,6	33,1
Aptenia cordifolia	UFSST	120	31,0	23,2	44,8	30,8	24,8	28,5	32,0	40,8
Aptenia cordifolia	IAT	120	31,0	25,3	36,3	31,0	26,8	28,7	33,1	35,5

Sedum spectabile	ST	120	31,4	24,8	37,7	31,1	26,3	28,7	33,9	36,7
Sedum spectabile	IFSST	120	30,5	27,5	33,6	30,7	28,0	29,3	31,5	32,9
Sedum spectabile	UFSST	120	31,2	23,0	40,9	31,5	24,4	28,5	33,9	37,2
Sedum spectabile	IAT	120	30,8	25,1	35,9	30,8	26,5	28,7	32,8	35,1
Traditional roof	IFSST	120	34,7	21,5	47,4	33,9	25,2	28,7	41,1	45,8
Traditional roof	UFSST	120	30,6	16,5	42,3	30,2	20,0	25,2	36,3	41,3
Traditional roof	IAT	120	33,1	22,1	43,7	32,8	24,4	28,3	38,4	42,5

Table 5. Statistical variables for the second measurement cycle. Avg, min., max., median and percentiles -05, 25, 75, 95- for Green roof with *Aptenia cordifolia, Sedum spectabile,* and traditional roof. ST= Substrate temperature, UFSST= upper slab surface temperature, IFSST= slab lower surface temperature, TI = indoor air temperature.

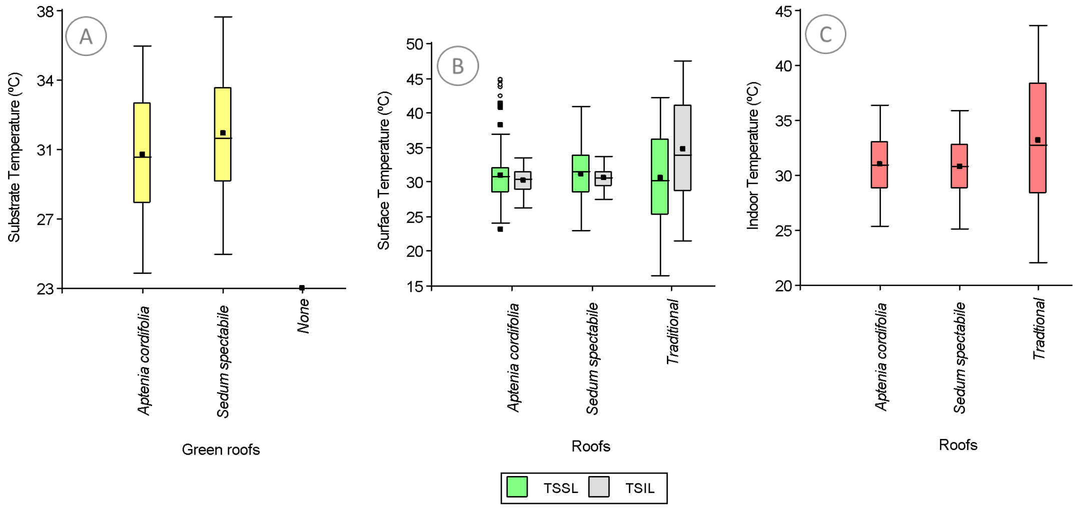


Figure 9. Green roof with Aptenia cordifolia, Sedum spectabile, and traditional roof. A-ST= Substrate temperature, B- UFSST= *upper slab surface temperature,* IFSST= *slab lower surface temperature, C-* IAT= *Indoor air temperature.*

2.2. **Analysis of indoor air temperature differences between traditional and green roofs** (Figure 10)

This analysis seeks to identify the effect of the selected species on the thermal behaviour of indoor spaces. The tray with the traditional roof had higher indoor temperatures than trays with green roofs during the day while they were lower at night. These differences range between 7ºC and 10ºC (day time) and between 2ºC and 3ºC (night time). For example, on the first day of measurement, at 6 p.m., the green roof with *Nassella tenuissima* (GRNt was 10.3ºC cooler than the traditional roof, and at 8 a.m., it was 2ºC warmer. This would indicate that the most efficient coverage during the day is that with the greatest differences in indoor temperature while, during the night, the most efficient coverage is that with the lowest temperature difference compared with the indoor temperature of the traditional roof (TR).

Regarding green roofs, differences were observed in indoor thermal behaviour associated with the growth habits of different species. Compared with a traditional roof, the shrub species *Nassella tenuissima* and *Sedum spectabile* showed larger temperature differences during the day than the creeping species *Aptenia cordifolia* and *Sedum lineare*. Shrub species showed smaller temperature differences during the night generating a positive effect throughout the whole day. This behaviour could be explained by the growth habit of shrubby species that contributes to reducing heat transfer due to substrate shading while allowing air circulation between substrate and foliage. This condition improves the roof insulating capacity during the day while allowing better cooling conditions during the night.

The tray with *Nassella tenuissima* had a greater average difference in indoor temperature compared with the traditional roof tray of around 3.5ºC, with an absolute maximum difference of 10.3ºC and an average maximum of 9.7ºC. Therefore, this native species shows the highest capacity to mitigate outdoor temperatures during the day and is the least conservative during the night hours, since it records the lowest minimum indoor temperatures (Figure 12).

Sedum lineare -a creeping species recommended by the international literature- showed average differences in indoor temperature of 2.8ºC, comparing the tray with a traditional roof, with an absolute maximum difference of 9.5ºC and an average maximum of 8.9ºC.

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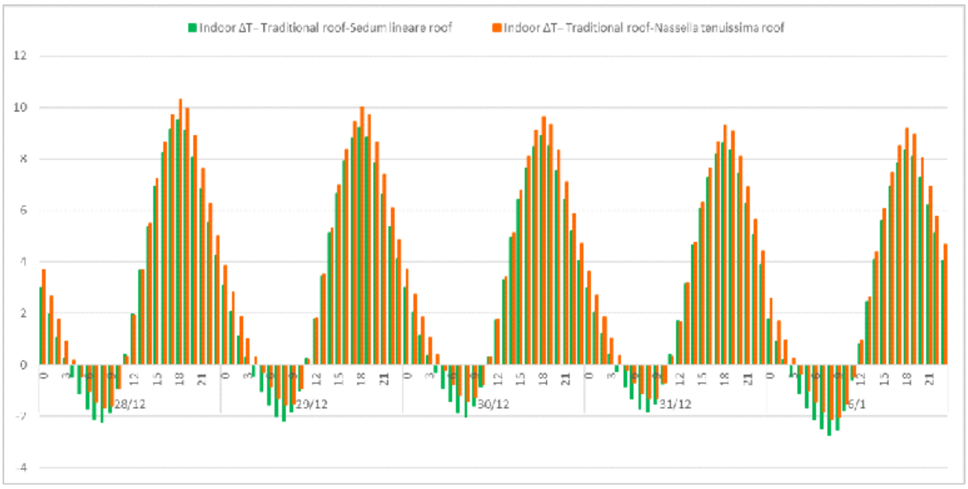
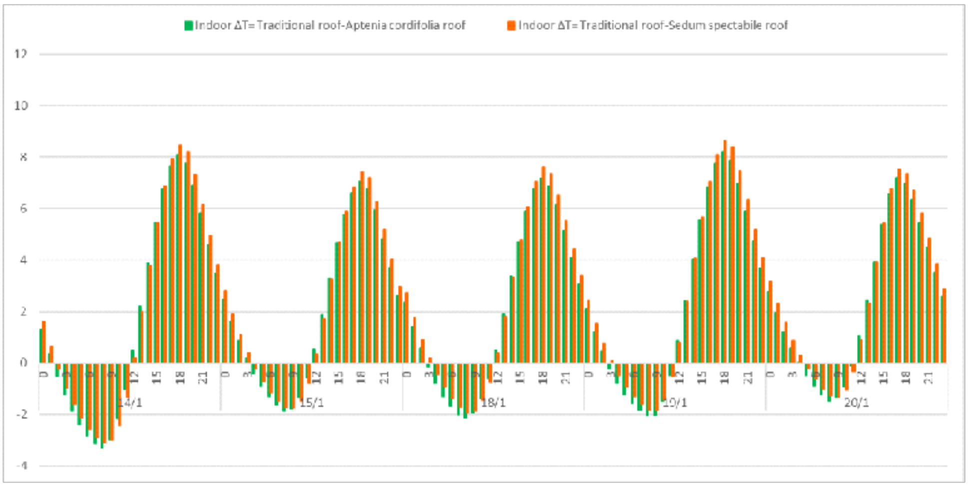
Green roofs indoor temperature
ΔT=T (ºC) Traditional roofs indoor-T (ºC) Green roofs indoor

Sedum lineare and *Nassella tenuissima*



Sedum lineare: (Absolute minimum: -2.7 ºC; Absolute maximum: 9.5 ºC; Average: 2.8 ºC; Minimum average: -2.2 ºC; Maximum average: 8.9 ºC).
Nassella tenuissima: (Absolute minimum: -2.0 ºC; Absolute maximum: 10.3 ºC; Average: 3.4 ºC; Minimum average: -1.6 ºC; Maximum average: 9.7 ºC).

Aptenia cordifolia and *Sedum spectabile*



Aptenia cordifolia: (Absolute minimum: -3.3 ºC; Absolute maximum: 8.2 ºC; Average: 2.1 ºC; Minimum average: -2.2 ºC; Maximum average: 7.5 ºC).
Sedum spectabile: (Absolute minimum: -3.1 ºC; Absolute maximum: 8.6 ºC; Average: 2.3 ºC; Minimum average: -2.0 ºC; Maximum average: 7.9 ºC).

Figure 10. Differences in indoor air temperature between the traditional and green roof.

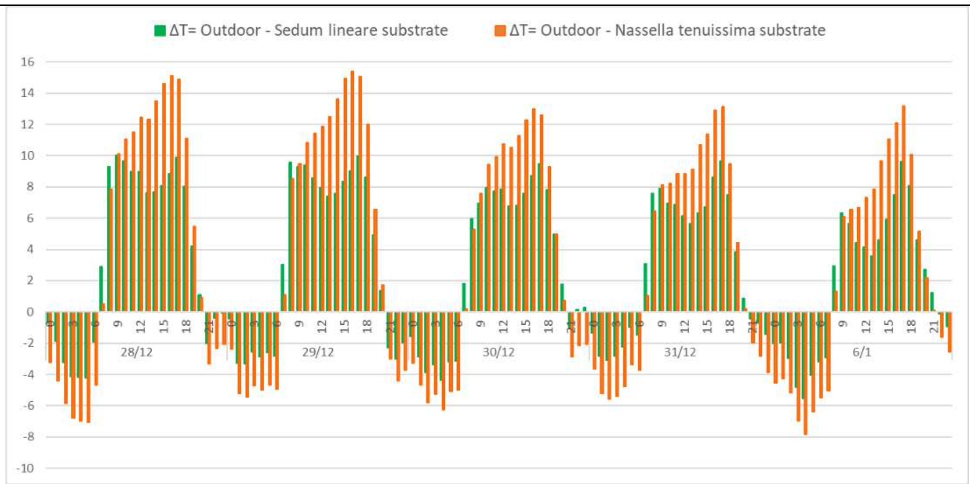
2.3. Analysis of differences between outdoor temperature and substrate temperature of green roofs

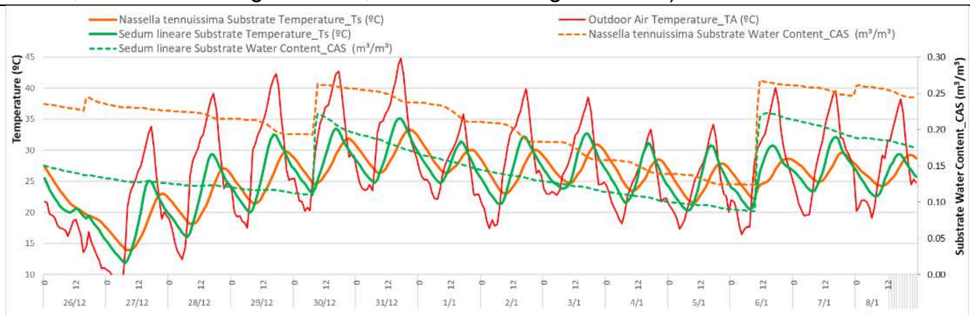
The following analysis seeks to identify whether the attenuation effect of outdoor temperature on the indoor space is related to substrate temperature in green roofs. This would reflect the ability of the biological package to regulate the flow of heat inwards -heating period- or outwards -cooling period-. Figure 11 shows that the substrate of *Nassella tenuissima* had larger temperature differences with respect to outdoor air temperature both during the day and at night. It reached an absolute maximum difference of 15.4ºC, a maximum average of 13.9ºC, and an average of 3.3ºC. The substrate recorded lower temperatures than the outdoor temperature during the day, but they were higher at night (absolute min. Δ -7.82ºC, avg. min. Δ -6.4ºC). During the day, this thermal condition showed greater thermal inertia of the *Nassella tenuissima* substrate compared with the rest of the species under study. Thermal inertia was related to the density, thermal conductivity and specific heat characteristics of each substrate. If the water content of all substrates is observed, *Nassella tenuissima* had the highest water content increasing its specific heat; that is to say, its heat storage capacity. During the night, the shrubby habit of the species improved substrate radiative and convective cooling. This behaviour was also verified for *Sedum spectabile,* a species of shrubby habit.

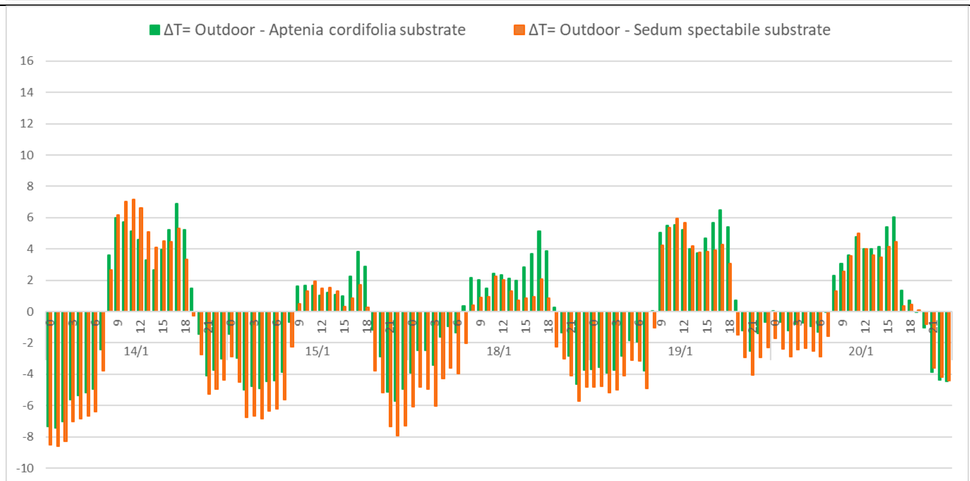
The *Sedum lineare* substrate showed the opposite behaviour: it was less conservative during the day (absolute max. Δ 10.0ºC, avg. max. Δ 9.7ºC) and had higher inertia at night (absolute min. Δ -5.5ºC, avg. min. Δ -4.1ºC). This substrate showed lower water content and lower nocturnal radiative and convective cooling capacity associated with the plant creeping habit.

Figure 11 shows that shrubby species had higher average water content in the substrate. This is probably due to a decrease in evaporation caused by lower direct solar gain and an increase in roughness that generates a frictional force that opposes and tends to stop air exchange.

It is verified that shrubby species have the highest water content in the substrate. This behaviour is probably due to higher substrate shading, which decreases its evaporation. Among shrubby species, *Sedum spectabile* substrate had a water content greater than 0.14 m^3/m^3-, (with average CAS = 0.16 m^3/m^3) as seen in Figure 11. The substrate of *Nassella tenuissima* had the highest average water content (0.22 m^3/m^3). This could be associated with its status as a native species adapted to soil conditions different to those used in the experiment. Among creeping species, *Aptenia cordifolia* substrate had low water content (0.09 m^3/m^3) because it could conserve more water in its plant structure to survive in arid contexts. In contrast, *Sedum lineare* that has a similar growth habit, maintains higher water content in the substrate (0.15 m^3/m^3).

<table>
<tr><th></th><th></th><th>Substrate temperature and water content</th></tr>
<tr><td rowspan="2">Sedum lineare and Nassella tenuissima</td><td>ΔT= O_{AT}- S_T</td><td>


Sedum lineare: (Absolute minimum: -5.5 ºC; Absolute maximum: 10.0 ºC; Average: 2.9 ºC; Minimum average: -4.1 ºC; Maximum average: 9.7 ºC).
Nassella tenuissima: (Absolute minimum: -7.82 ºC; Absolute maximum: 15.4 ºC; Average: 3.3 ºC; Minimum average: -6.4 ºC; Maximum average: 13.9 ºC).</td></tr>
<tr><td>S_T and S_{WC}</td><td>


</td></tr>
<tr><td>Aptenia cordifolia and Sedum spectabile</td><td>ΔT= O_{AT}- S_T</td><td>


Aptenia cordifolia: (Absolute minimum: -7.4 ºC; Absolute maximum: 6.9 ºC; Average: 0.0 ºC; Minimum average: -5.2 ºC; Maximum average: 5.7 ºC).
Sedum spectabile: (Absolute minimum: -8.6 ºC; Absolute maximum: 7.2 ºC; Average: -1.1 ºC; Minimum average: -6.4 ºC; Maximum average: 4.5 ºC).</td></tr>
</table>

Figure 11. Outdoor air temperature, substrate temperature, and substrate water content for both measurement cycles

2.4. Variable correlation

A statistical analysis was carried out to determine the relationship between the variables evaluated and their incidence on the occurrence of a given phenomenon. The correlated variables were Substrate temperature (ST), Substrate water content (SWC=CAS), Lower slab surface temperature (IFSST), Upper slab surface temperature (UFSST), Indoor air temperature (IAT), Outdoor air temperature (OAT), Radiation (R) and Wind speed (WS).

Variables of the environmental context: as observed in Tables 6 and 7, outdoor air temperature (OAT) had a high Pearson correlation coefficient concerning radiation (R) for the two cycles evaluated (0.68 and 0.72). Wind speed (WS) does not correlate with outdoor air temperature (OAT) or with radiation (R) probably because the variable responds mostly to advection, or other phenomena, and not to natural convection phenomena resulting from the solar radiation effect.

Tray with traditional roof: it was observed that the variables that determined indoor temperature were outdoor air temperature (OAT) and slab surface temperatures (IFSST, UFSST). The correlation coefficients for indoor temperature as a function of outdoor temperature were 0.63 and 0.51, demonstrating dependence on the environmental context. These values indicate the existence of other variables that influence indoor temperature. The traditional slab is a massive and conductive element that plays a crucial role to determine indoor thermal behaviour. This is reflected in the correlation between slab surface temperature on the inner face (IFSST 0.97) and indoor air temperature.

Regarding slab surface temperature on the upper face (IFSST), the correlation levels were lower (0.65 and 0.55) because the upper face was exposed to solar radiation and the effect of wind. The surface temperature of the membrane on the slab showed high dependence on outdoor temperature (0.98 and 0.89) and solar radiation (0.75 and 0.76). In addition to this, the traditional roof waterproof insulation behaved like a cold selective material, and its high reflectivity decreased its surface temperature reducing thermal transmittance.

Tray with green roofs: the variables that determined indoor temperature in the trays evaluated with the four species were substrate temperature (ST), with correlation values ranging from 0.85 to 0.96, and slab surface temperatures (IFSST, UFSST) ranging from 0.53 to 0.99. In the case of *Sedum lineare* and *Nassella tenuissima,* indoor temperature also correlates with air temperature (OAT), although to a lesser extent (GRSl: 0.56, GRNt: 0.59). In the case of *Sedum spectabile* it also correlates with substrate water content (SWC: 0.54).

These results would indicate that the variables with the greatest influence and potential to manipulate in the determination of indoor temperature of spaces with green roofs are substrate temperature and slab surface temperatures. Regarding substrate temperature, it depends to a greater extent on the temperature of outdoor air. In the case of green roofs with *Sedum lineare* and *Aptenia cordifolia,* the correlation is GRSl: 0.83, GRAc: 0.74, while for green roofs with *Sedum spectabile* and *Nassella tenuissima,* it is smaller (GRSe: 0.64; GRNt: 0.38). These results allow inferring that the plant's growth habit - creeping or shrubby -determines the influence of external conditions on substrate temperature. Shrubs have a positive impact on indoor thermal condition.

On the one hand, slab surface temperatures correlate strongly not only with indoor temperature, but also with substrate temperature in a range of 0.51 to 0.97. This shows the influence of roofing technology and the importance of its adequate combination with species and substrate characteristics for suitable energy behaviour.

On the other hand, substrate temperature (ST) correlates slightly with substrate water content (SWC) in the case of green roofs with *Sedum lineare* and *Sedum spectabile* (GRSl: 0.54, GRSe: 0.47). This allows to infer that substrate water content, of varying impact on substrate temperature, is related in this case with plant genus.

Treatment = Sedum lineare_green roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	2.9E-10	0.00	0.00	0.00	0.00	3.1E-05	0.07
CAS	0.54	1.00	1.2E-05	6.6E-07	2.0E-08	1.4E-08	2.6E-03	0.82
TSIL	0.66	0.39	1.00	0.00	0.00	0.01	2.7E-04	0.35
TSSL	0.73	0.44	0.98	1.00	0.00	5.7E-04	1.1E-03	0.74
TI	0.89	0.49	0.88	0.93	1.00	4.1E-11	0.47	0.16
TA	0.83	0.49	0.25	0.31	0.56	1.00	0.00	0.09
R	0.37	0.27	-0.33	-0.29	-0.07	0.72	1.00	0.37
V	0.16	-0.02	-0.09	-0.03	0.13	0.15	0.08	1.00

Treatment = Nassella tenuissima_green roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	4.8E-04	0.00	0.00	0.00	1.8E-05	0.01	0.68
CAS	0.31	1.00	1.0E-03	3.3E-06	1.1E-05	1.1E-07	1.3E-03	0.29
TSIL	0.97	0.30	1.00	0.00	0.00	5.9E-04	0.01	0.37
TSSL	0.95	0.41	0.90	1.00	0.00	0.00	0.64	0.20
TI	0.96	0.39	0.90	0.99	1.00	1.1E-12	0.89	0.16
TA	0.38	0.46	0.31	0.60	0.59	1.00	0.00	0.09
R	-0.23	0.29	-0.25	0.04	-0.01	0.72	1.00	0.37
V	0.04	0.10	-0.08	0.12	0.13	0.15	0.08	1.00

Treatment = Traditional roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	sd	sd	sd	sd	sd	sd	sd
CAS	sd	1.00	sd	sd	sd	sd	sd	sd
TSIL	sd	sd	1.00	0.00	0.00	0.00	0.01	3.1E-04
TSSL	sd	sd	0.77	1.00	0.00	0.00	0.00	0.05
TI	sd	sd	0.97	0.65	1.00	0.00	0.82	1.2E-03
TA	sd	sd	0.75	0.98	0.63	1.00	0.00	0.09
R	sd	sd	0.23	0.75	0.02	0.72	1.00	0.37
V	sd	sd	0.32	0.18	0.29	0.15	0.08	1.00

Table 6. Pearson correlation coefficients: Green roof with Sedum lineare (GRSl), Nassella tenuissima (GRNt) and traditional roof (TR). The probabilities of occurrence are indicated in the upper right quadrant.

Treatment = Aptenia cordifolia_green roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	0.56	1.4E-03	2.9E-09	0.00	0.00	5.8E-05	0.01
CAS	0.05	1.00	0.86	0.05	0.15	0.11	2.5E-04	0.68
TSIL	0.29	-0.02	1.00	3.3E-04	0.00	0.29	1.2E-09	0.06
TSSL	0.51	-0.18	0.32	1.00	5.7E-10	1.2E-04	0.44	0.45
TI	0.85	-0.13	0.63	0.53	1.00	1.0E-06	0.08	0.05
TA	0.74	0.15	-0.10	0.34	0.43	1.00	0.00	0.19
R	0.36	0.33	-0.52	0.07	-0.16	0.68	1.00	0.04
V	-0.25	0.04	-0.18	-0.07	-0.18	-0.12	-0.19	1.00

Treatment = Sedum spectabile_green roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	5.9E-08	5.7E-10	0.00	0.00	0.00	0.06	0.09
CAS	0.47	1.00	6.4E-06	1.2E-06	1.5E-10	1.9E-06	0.01	0.02
TSIL	0.53	0.40	1.00	7.7E-08	0.00	0.70	3.2E-12	0.39
TSSL	0.83	0.43	0.47	1.00	0.00	0.00	0.04	0.60
TI	0.92	0.54	0.78	0.80	1.00	5.6E-08	0.25	0.04
TA	0.64	0.42	-0.04	0.66	0.47	1.00	0.00	0.19
R	0.17	0.24	-0.58	0.19	-0.11	0.68	1.00	0.04
V	-0.16	-0.22	-0.08	-0.05	-0.19	-0.12	-0.19	1.00

Treatment = Traditional roof

Pearson correlation: Coefficients \ probabilities

	Ts	CAS	TSIL	TSSL	TI	TA	R	V
Ts	1.00	sd	sd	sd	sd	sd	sd	sd
CAS	sd	1.00	sd	sd	sd	sd	sd	sd
TSIL	sd	sd	1.00	0.00	0.00	0.00	0.04	0.09
TSSL	sd	sd	0.70	1.00	6.0E-11	0.00	0.00	1.8E-04
TI	sd	sd	0.97	0.55	1.00	1.9E-09	0.69	0.13
TA	sd	sd	0.65	0.89	0.51	1.00	0.00	0.19
R	sd	sd	0.18	0.76	-0.04	0.68	1.00	0.04
V	sd	sd	-0.16	-0.34	-0.14	-0.12	-0.19	1.00

Table 7. Pearson correlation coefficients: Green roof with Aptenia cordifolia (GRAc), Sedum spectabile (GRSe) and traditional roof (TR). The probabilities of occurrence are indicated in the upper right quadrant.

DISCUSSION

Internationally, extensive green roofs are mainly cultivated with species of the genus *Sedum* (Blanusa et al. 2013; Li and Yeung 2014; Dirks et al. 2016). They are characterized by their generally creeping growth habit, succulent leaves and tolerance to high daily thermal amplitudes, typical of arid regions.

In this work, from the group of species evaluated, only *Aptenia cordifolia* -a species with the previously mentioned characteristics- showed greater suitability from the point of view of its biological behaviour. It was followed by native species *Nassella tenuissima* and *Hyalis argentea*, which showed high coverage and intermediate water consumption. These results are comparable with those obtained by Schweitzer and Erell (2014), who studied four local plant species for use in extensive green roofs in hot dry climates. These authors identified that *Aptenia cordifolia* is a drought-efficient plant with the lowest water consumption. However, unlike the experiments carried out by these researchers, minimum irrigation quotas were applied in the present work, and even so, common behavioural trends were observed.

Regarding the genus *Sedum*, none of the locally evaluated species -*Sedum acre, Sedum lineare, Sedum spectabile*- showed any suitability in terms of the relationship between plant cover and water consumption. Although *Sedum spectabile* achieved high coverage, it fell within the range of highest water consumption. In contrast, *Sedum lineare*, although in the range of species with the lowest consumption, did not show acceptable levels of coverage.

In this sense, although Azeñas et al. (2019) recommend the use of *Sedum sediforme* due to its low water consumption, they find that under limited or deficit irrigation conditions, biomass production is low. This is consistent with the results achieved in this study for *Sedum lineare*. Besides, Azeñas et al. (2018) state that some species of *Sedum* do not tolerate alternating drought periods with concentrated precipitations that generate waterlogging in the substrate. This supports the low suitability of *Sedum* for use in green roofs in arid zones, whose climate characteristics -alternation of prolonged drought periods and concentrated rainfall- are similar to those described by the authors.

This paper identifies two native species with high potential to be incorporated into green roofs in arid zones, *Nassella tenuissima* and *Hyalis argentea*. This species demonstrated a high adaptability to the limitations imposed by substrate thickness and deficit irrigation in the environmental conditions of growth. They guarantee adequate coverage and acceptable water consumption. Although several authors (Rayner et al. 2016; Panayiotis and Nektarios 2018; Mahdiyar et al. 2018) evaluate the suitability of different native species associated with arid contexts, they have not studied the species identified in this work as potentially suitable. Most international studies propose the use of xerophytic and succulent leaf species as a strategy for adaptation to drought; while the results of the experiments carried out in this work show that xerophytic species with other adaptation mechanisms (grasses and plants with pubescent greyish leaves) respond better in terms of greater coverage and less water consumption.

In relation to thermal behaviour, *Nassella tenuissima -a* native, shrubby species with low water requirement and high coverage- has shown both the lowest leaf temperature (1.5°C) and substrate temperature (5.5°C). It allowed to obtain the lowest slab surface temperature and indoor temperature (3.5°C) due to its shrubby growth habit, which positively affects convective exchanges and reduces direct solar gain on the substrate. Consequently, it helps to conserve more water in the substrate, and it has also proven to be the only species tested where substrate temperature does not depend on outdoor temperature. Blanusa et al. (2013) also identified leaf temperature as significantly lower in plants under water deficit treatments compared to on-demand irrigation treatments for *Stachys* -grasses- and *Sedum* -succulent- species. This shows the influence of adequate species selection on the thermal benefits of green roofs.

The widely used genus *Sedum* recommended by the international literature (Dunnett and Kingsbury 2008; Butler et al. 2012) shows differential capabilities in Central Western Argentina according to the architecture of the species evaluated. *Sedum spectabile*, a succulent species of shrubby growth habit, shows a better capacity to mitigate outdoor temperatures than *Sedum lineare*, a species of creeping growth habit. However, the impact of this species on indoor thermal behaviour is less than that of *Nassella tenuissima,* a local shrub-type grass. This study shows that the impact of a green roof on indoor temperature depends on the growth habit of the species in the biological package. Shrubby species *Nassella tenuissima* and *Sedum spectabile* show better thermal behaviour than creeping species *Aptenia cordifolia* and *Sedum lineare*, generating a positive effect throughout the day. This behaviour could be explained by shrubby plant architecture that reduces heat transfer due to substrate shading, thus enabling air circulation between foliage and substrate. This condition benefits the insulation capacity of the roof during the day and allows for better cooling conditions at night.

Shrubby species also prove to be more efficient than creeping species given the same substrate thickness. Lundholm et al. (2014) studied the performance of green roofs in winter comparing fourteen species grouped according to their growth habit. They also showed that the shrubby type improves energy savings in indoor spaces. Therefore, the integration of both results suggests strong benefits for the use of shrubby species throughout the year.

Similarly, Eksi et al. (2017) compared green roofs with creeping and shrubby species associated with different substrate thicknesses, finding a better behaviour in the case of thicker roofs and shrubby species. In contrast, Getter and Rowe (2008) examined several species of the genus *Sedum* and identified a minimum substrate depth of 0.07 m to achieve full coverage. The present work used a substrate thickness of 0.15m and three *Sedum* species that resulted in medium or low plant cover.

Regarding the benefits of green roofs for outdoor spaces, the results of leaf temperature indicate that the average value on green roofs is in the order of 40.5°C to 41.5°C for the species evaluated under deficit irrigation conditions. Those of creeping habit -*Sedum lineare* and *Aptenia cordifolia*- show a greater leaf temperature amplitude than the shrubby species (7.5°C vs 4.7°C) in line with the data reported by Niachou et al. (2001), Theodosiou (2003), Simmons et al. (2008) and Parizotto & Lamberts (2011). These authors show that the surface temperatures of green roofs range between 26°C and

40°C depending on species, building insulation, and weather. However, it should be noted that various species under conditions of drought stress gradually increase leaf temperature, bringing their values closer to air temperature. This response is probably due to a reduction in cooling by transpiration (Canavar 2013). Blanusa et al. (2013), when comparing species with different growth habits in the United Kingdom, showed that under conditions of water restriction, leaf surface temperatures, in the case of the creeping species *Sedum*, reach values of 35°C, while the shrubby species *Stachys* shows values of 28.3°C.

Although the values reported in this study are high compared with the values provided by the literature (Voyde et al. 2010; Canavar 2013; Fernandez et al. 2016), it is necessary to highlight the benefits of green roofs for dry zones, in comparison with traditional roofing with waterproof insulation whose surface temperature ranges between 44°C and 83°C depending on colour and finish (Parker et al. 2002; Araújo and Lourenço 2005; Alchapar and Correa 2016). Therefore, the surface temperatures of green roofs are lower than those of the roofs built with traditional materials, even under water deficit conditions.

Sanyé-Mengual et al. (2015) stated the need to explore the potential of combining different roofing technologies and biological packages -plant plus substrate-. The statistical analysis showed that slab and substrate surface temperatures correlated with indoor temperature. Blanusa et al. (2013) and Eksi et al. (2017) reported substrate temperatures of 22.2°C and 34.2°C, comparable with the variation range obtained in the present study (26.0°C to 31.4°C).

Finally, this work discusses results in a comprehensive way relating the species selection and the thermal behaviour of extensive green roofs in arid zones, aspects that have been mostly evaluated in isolation in the international literature.

CONCLUSIONS

A. Biological behavior

This study has identified species that show better suitability to integrate the biological package in extensive green roofs in arid zones. For this purpose, plant cover and water consumption related to the species origin and growth habit have been evaluated.

The native species evaluated are non-succulent plants of shrubby growth habit. They showed an intermediate water consumption due to the fact that as species adapted to arid contexts, they have reserve organs, which in case of a greater water availability -by irrigation, rain or dew-, metabolize it completely to store it together with carbohydrates. This strategy allows to reserve water in periods of prolonged drought and ensure regrowth. On the other hand, the non-native species evaluated are distributed equally among the three ranges of water consumption. In the third group of lowest water consumption, all species analyzed are creeping and 50% are succulents (*Aptenia cordifolia* and *Sedum lineare*). While in the third group of highest consumption, there are species with different growth habits, 75% of the succulent type. That is, a trend is detected that associates the lower water consumption rate with growth habit, regardless of leaf type in the context of the hypothesis in which the experiment was developed: to evaluate consumption in the framework of the application of a minimum irrigation quota.

Regarding coverage, the native species analyzed reached values of 70 to 90%, have a shrubby growth habit and are non-succulent plants (*Hyalis argentea* and *Nassella tenuissima*). Only 17% of the non-native species with a creeping growth habit and without a defined pattern regarding leaf succulence (*Aptenia cordifolia* and *Cynodon dactylon*) showed high coverage. For the non-native species evaluated, the highest coverage was associated with the creeping growth habit.

Finally, the plants species identified with less water consumption and greater coverage -*Aptenia cordifolia* and *Cynodon dactylon*- correspond to non-native and creeping plants. The native species with shrubby growth habit -*Hyalis argentea* and *Nassella tenuissima*- showed high coverage and intermediate water consumption. Regarding the genus *Sedum*, widely used internationally for incorporation into green roofs, in this study, only *Sedum lineare* showed low water consumption and low coverage. In contrast, *Sedum spectabile* showed high coverage and high water consumption. Therefore, this validates the importance of local experimentation in plant-species selection.

B. Thermal behaviour

The results of this study show that the use of green roofs in dry zones allows decreasing average indoor temperature during the hot season between 2°C and 3ºC, maximum temperature between 7°C and 8ºC, and thermal amplitude between 7°C and 9ºC. Consequently, it constitutes a viable strategy for the thermal conditioning of indoor spaces.

The magnitude of the impact depends on the species growth habit. Shrubby species *Nassella tenuissima* and *Sedum spectabile* show better thermal behaviour than creeping species *Aptenia cordifolia* and *Sedum lineare,* generating a positive effect throughout the day. This behaviour could be explained by the architecture of the shrubby plant that reduces heat transfer by shading the substrate and improving the circulation of air between substrate and foliage. This condition enhances the insulating capacity of the roof during the day and allows better cooling conditions during the night.

With respect to the genus *Sedum* -, it shows differential capabilities according to the architecture of the species evaluated. *Sedum spectabile*, a plant of shrubby growth habit, shows a higher capacity to dampen outdoor temperatures compared to the creeping species *Sedum lineare*. However, the impact of this species on indoor thermal behaviour is less than that of the local shrub-type grass *Nassella tenuissima*.

The Pearson correlation analysis indicates that the variable with the greatest influence and with possibilities to modify the indoor temperature of a space with a green roof is substrate and slab surface temperature. Regarding substrate temperature, the shrubby habit of the species evaluated shows a positive impact on indoor thermal condition. In turn, substrate water content is related to plant genus.

Finally, this work has identified species with low water requirements and good coverage that show adaptability to the extensive green roof. Additionally, they display better thermal behaviour compared with the internationally proposed species. This represents a contribution to the development of knowledge that promotes the sustainable implementation of green technologies in regions of high environmental vulnerability such as Mendoza, Argentina, where urban greening represents a viable mitigation and adaptation strategy to climate change.

In future stages, the effect of different substrates will be analyzed as well as other roofing technologies associated with biological packages adapted to areas with limited water availability.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The authors` state the ethics approval and informed consent to participate in the publication of this paper in the Urban Ecosystems Journal.

CONSENT FOR PUBLICATION

The authors` consent for publication of this paper in the Urban Ecosystems Journal.

AVAILABILITY OF DATA AND MATERIALS

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AUTHORS' CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by JUAN EMILIANO FLORES ASIN, CLAUDIA FERNANDA MARTINEZ, MARIA ALICIA CANTON and ERICA NORMA CORREA. The first draft of the manuscript was written by JUAN EMILIANO FLORES ASIN and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

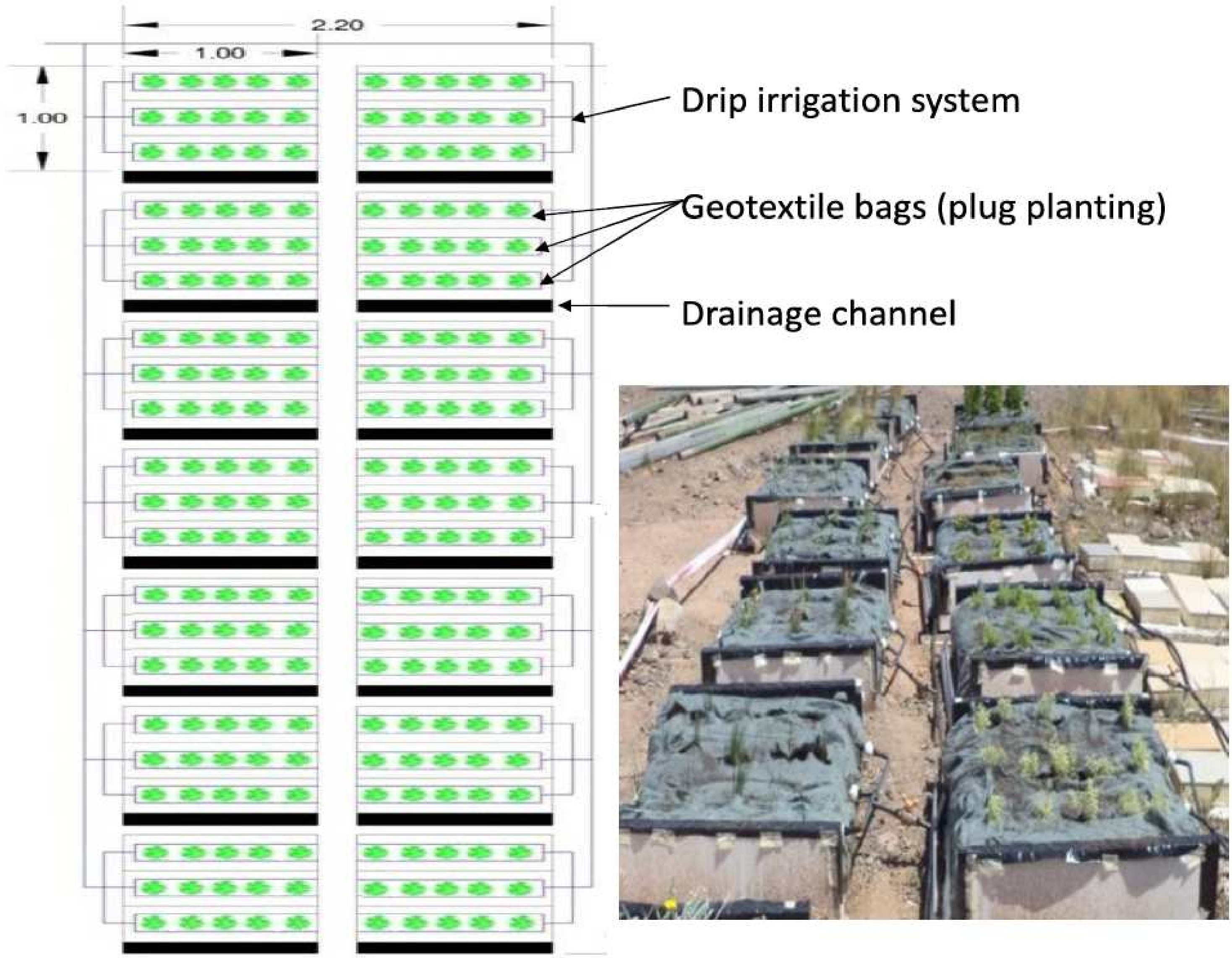
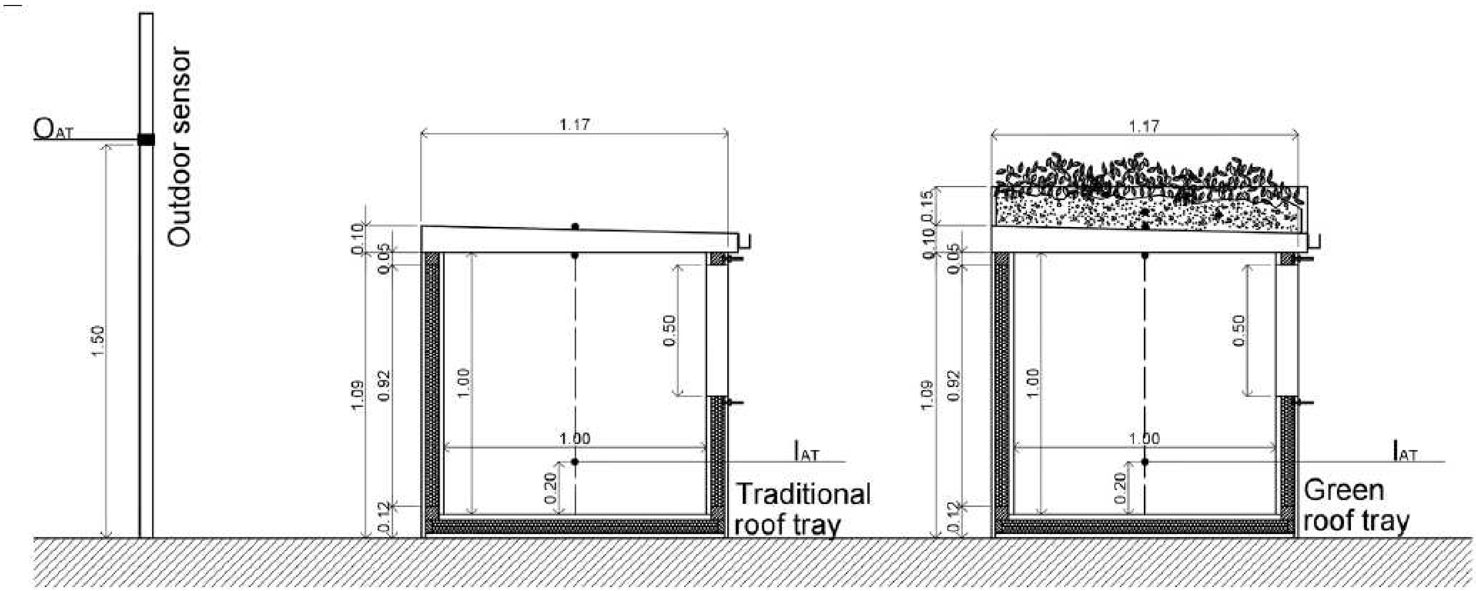


Figure 1

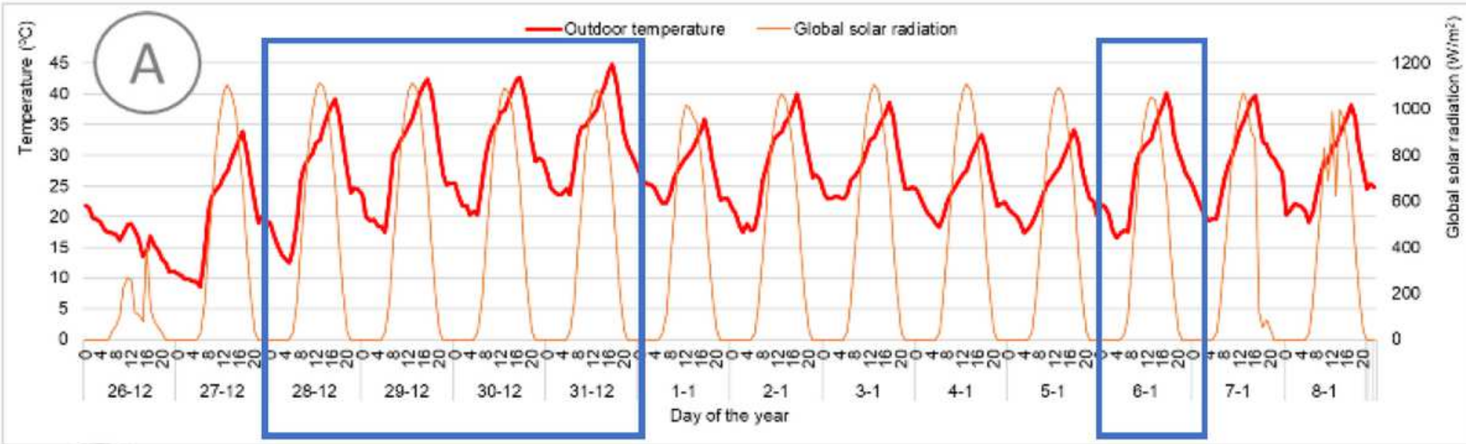
Experimental modules to evaluate the biological behaviour of plant species



Variable	ID	Type
Outdoor air temperature	O_{AT}	Onset® HOBO® temp/RH logger UX100-003
Indoor air temperature	I_{AT}	Onset® HOBO® temp/RH logger UX100-003
Upper face slab surface temperature	U_{FSST}	Thermocouple EL-USB-TC
Inner face slab surface temperature	I_{FSST}	Thermocouple EL-USB-TC
Substrate temperature	S_T	Onset® HOBO® 12-bit Temp Sensor S-TMB-M002 associated to a datalogger HOBO® U30
Substrate water content	S_{WC}	Onset® HOBO® SoilMoisture EC5 S-SMC-M005 associated to a datalogger HOBO® U30

Figure 2

Experimental and instrumental design.

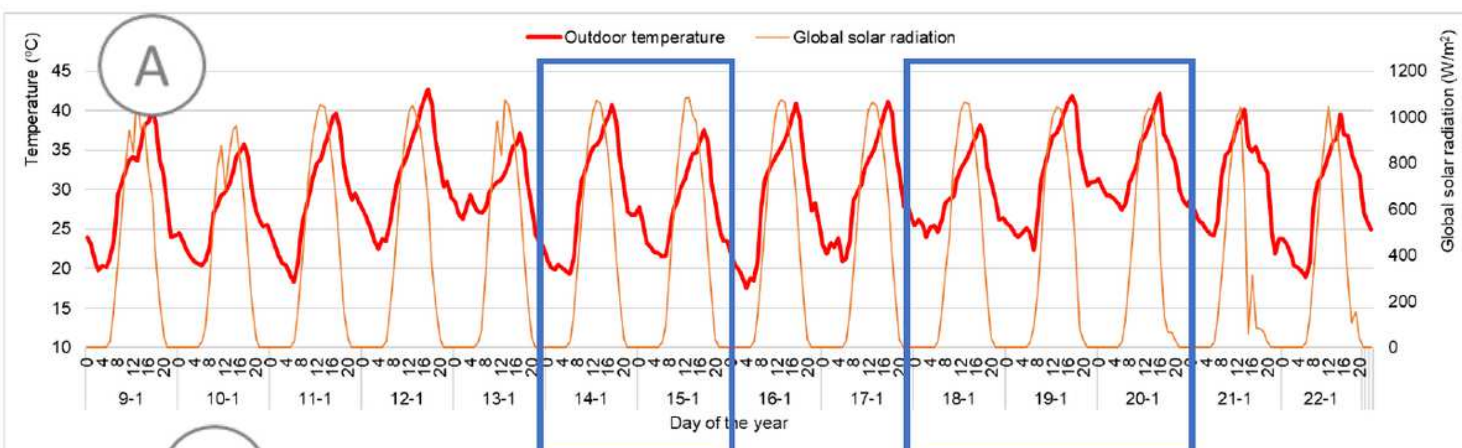


B

	Temperature (ºC)	Average Radiation (W/m²)
Absolute maximum	44.8	1114.7
Maximum average	41.8	1098.9
Average	29.3	390.9
Minimum average	19.4	0.0
Absolute minimum	12.5	0.0

Figure 3

A- Selection of analysis days of the first measurement cycle, B- Average data of outdoor temperature and solar radiation of selected days



B

	Temperature (ºC)	Average Radiation (W/m²)
Absolute maximum	42.1	1118.8
Maximum average	40.1	1100.8
Average	30.3	362.09
Minimum average	22.9	0.0
Absolute minimum	19.3	0.0

Figure 4

A- Selection of analysis days of the second measurement cycle, B- Average data of outdoor temperature and solar radiation of selected days

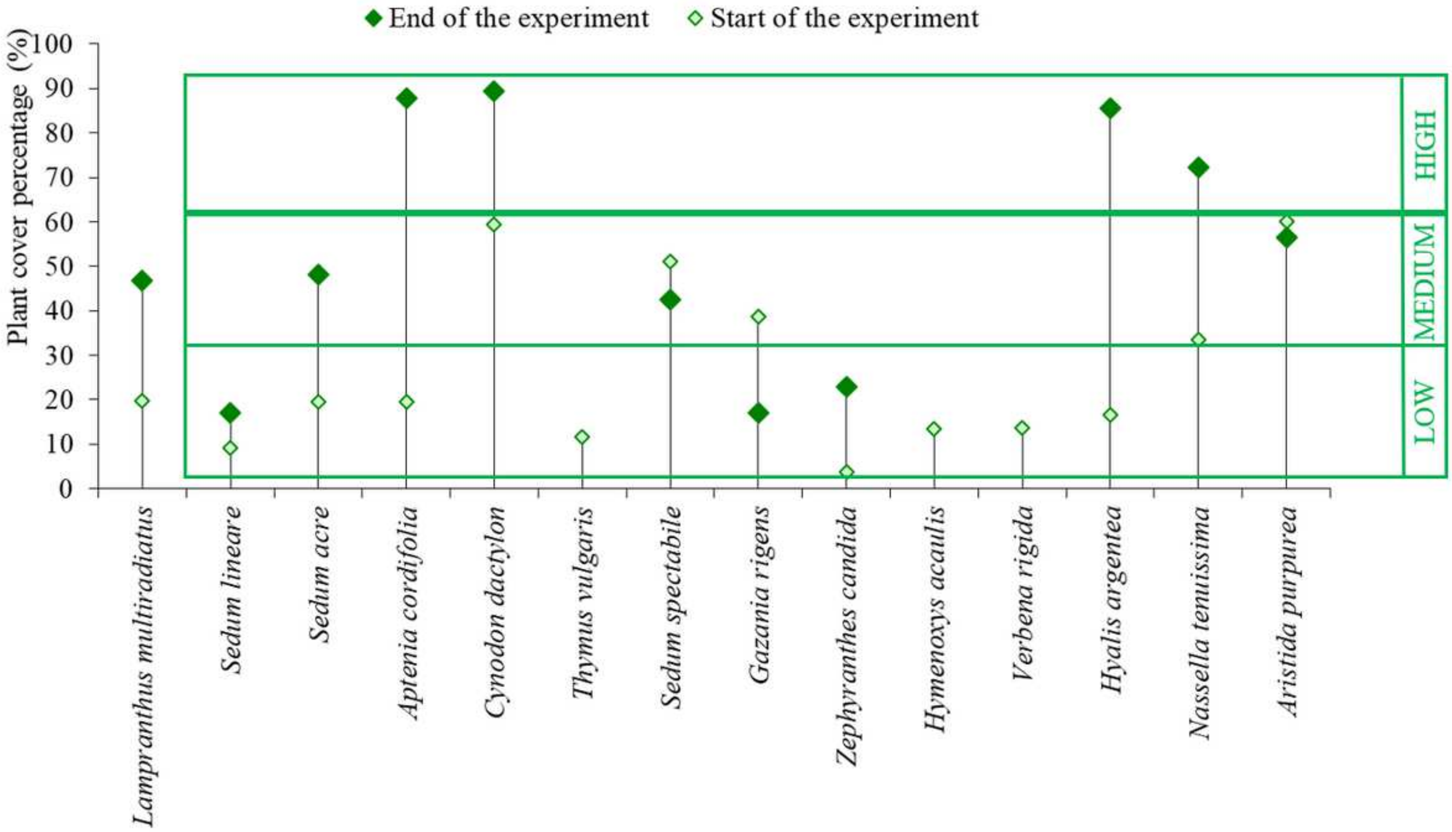


Figure 5

A- Percentage of plant cover per species in the initial stage and at the end of the experiment (2013-2017).

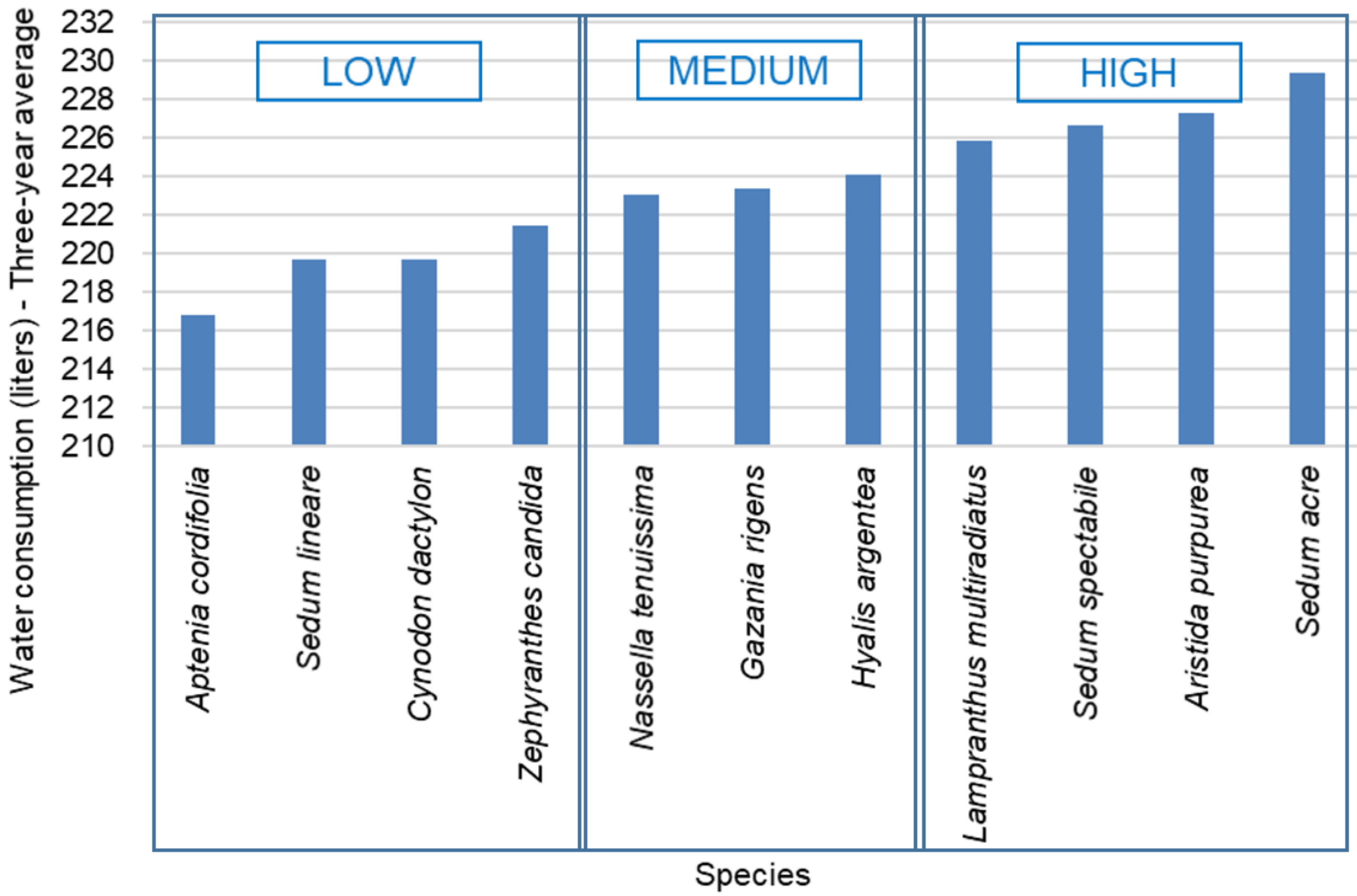
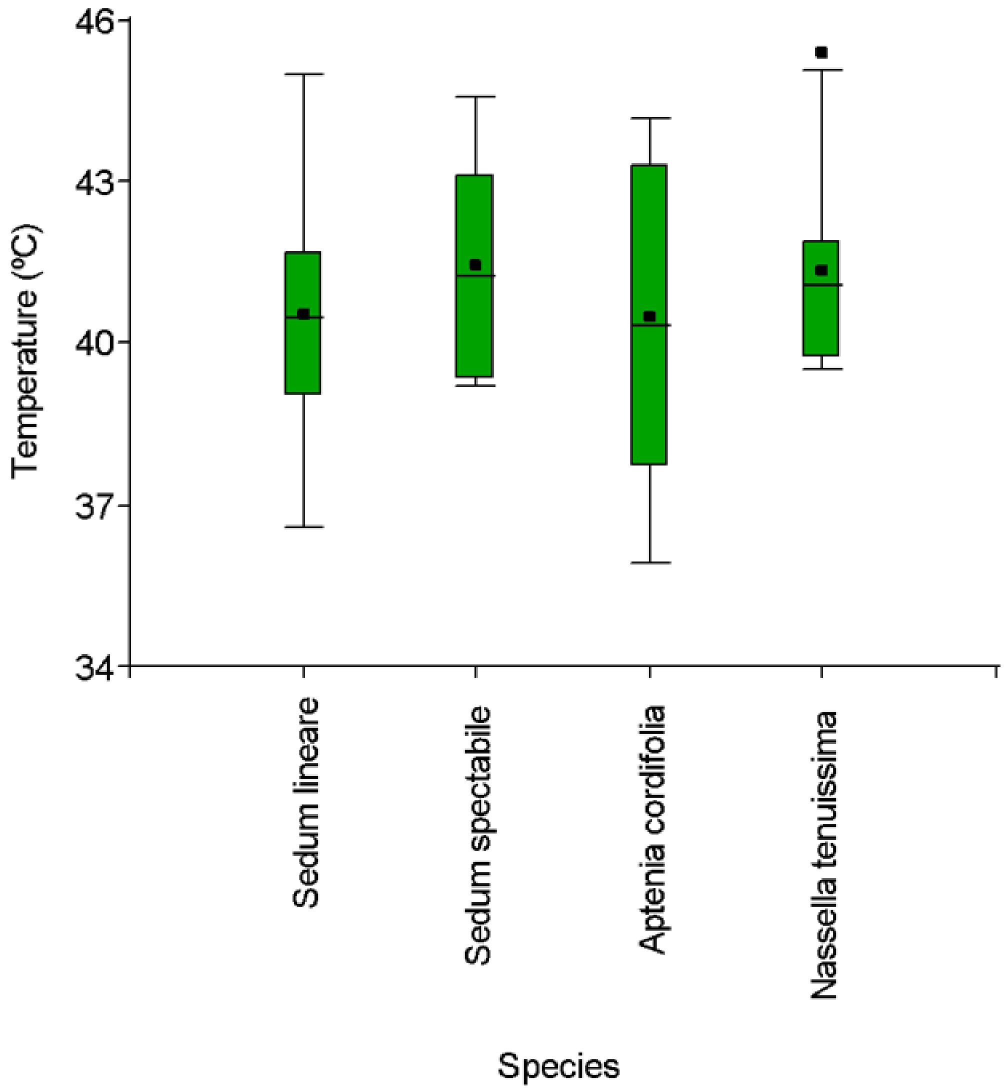


Figure 6

Average annual water consumption by species and consumption range.



Species	n	Avg.	Min.	Max.	$P_{(05)}$	$P_{(25)}$	$P_{(75)}$	$P_{(95)}$
Aptenia cordifolia	56	40.5	35.9	44.2	36.2	37.7	43.3	43.6
Nassella tenuissima	40	41.4	39.5	45.4	39.5	39.7	41.9	45.0
Sedum lineare	56	40.5	36.6	45.0	37.2	39.0	41.7	44.2
Sedum spectabile	56	41.4	39.2	44.6	39.2	39.3	43.1	43.9

Figure 7

Leaf temperature in species tested.

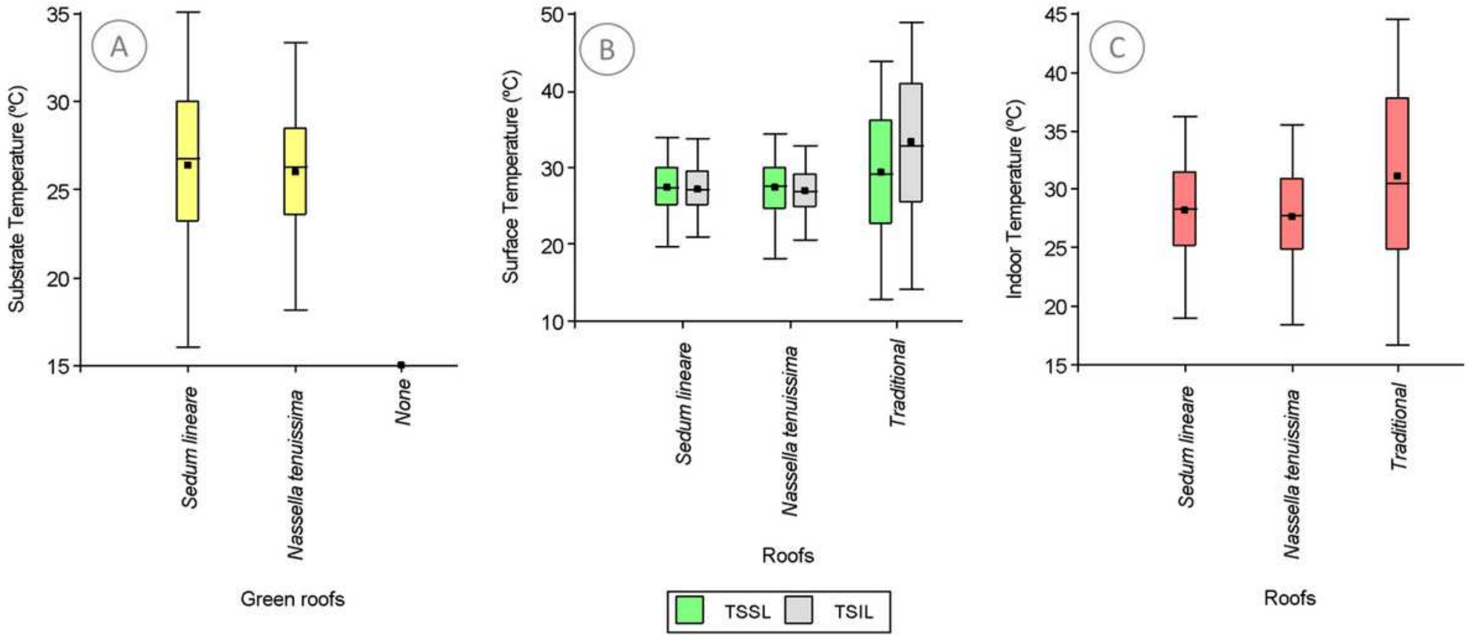


Figure 8

Green roof with Sedum lineare, Nassella tenuissima and traditional roof. A- ST=Substrate temperature, B- UFSST= upper slab surface temperature, IFSST= lower slab surface temperature, C- IAT= indoor air temperature.

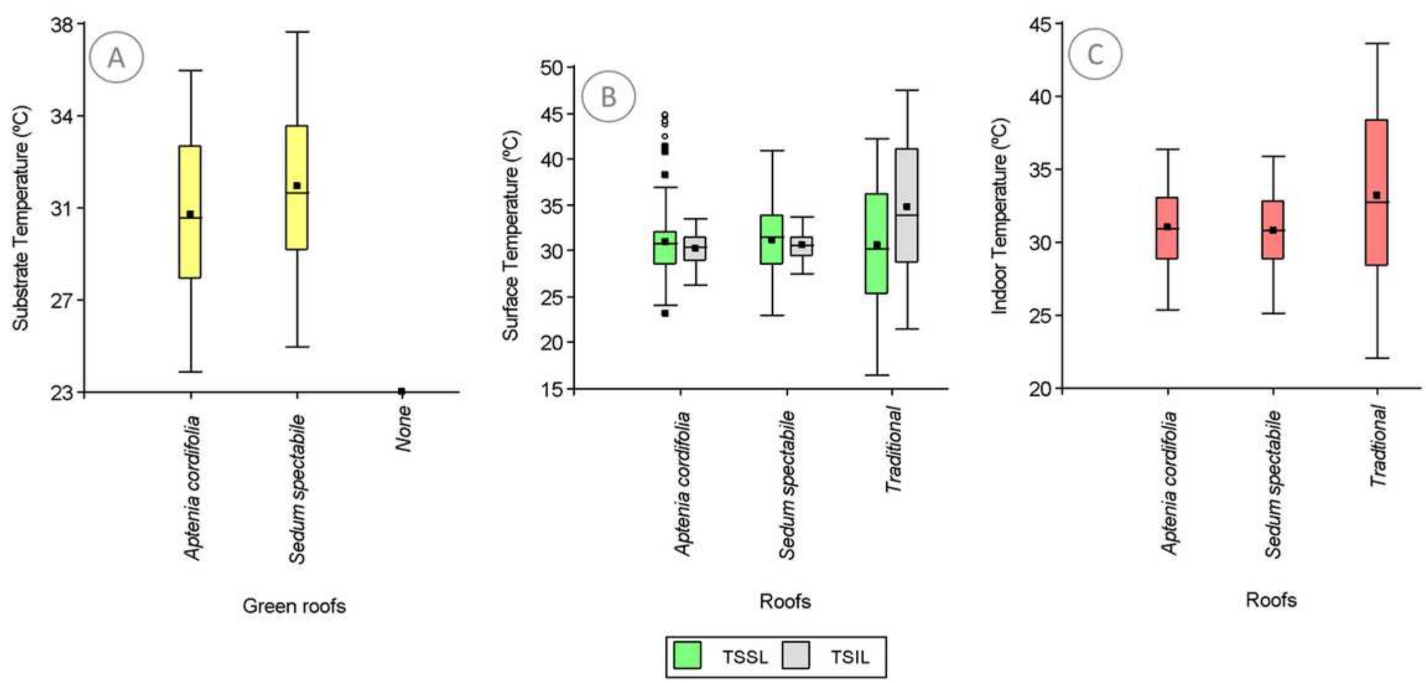


Figure 9

Green roof with Aptenia cordifolia, Sedum spectabile, and traditional roof. A-ST= Substrate temperature, B- UFSST= upper slab surface temperature, IFSST= slab lower surface temperature, C- IAT= Indoor air temperature.

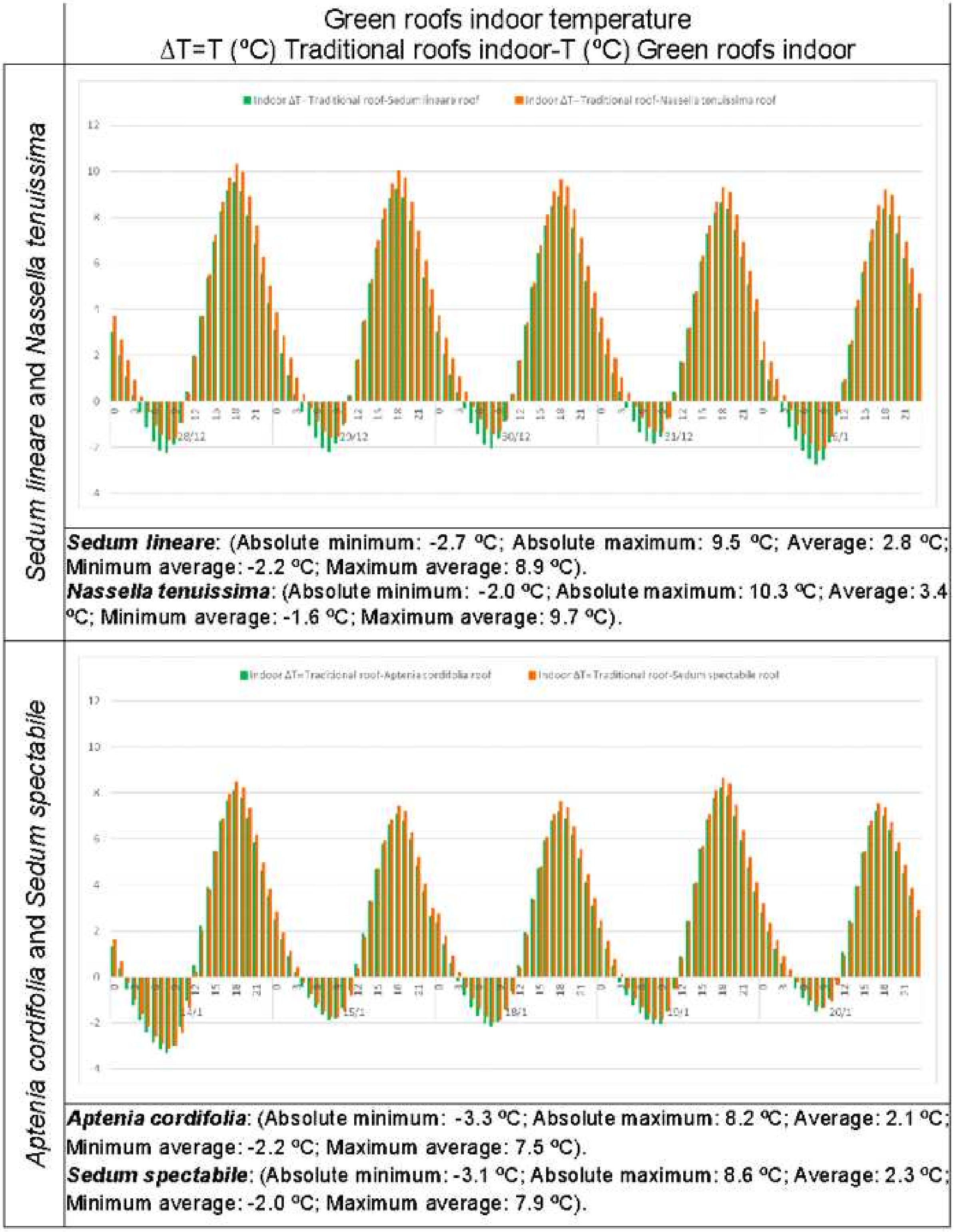


Figure 10

Differences in indoor air temperature between the traditional and green roof.

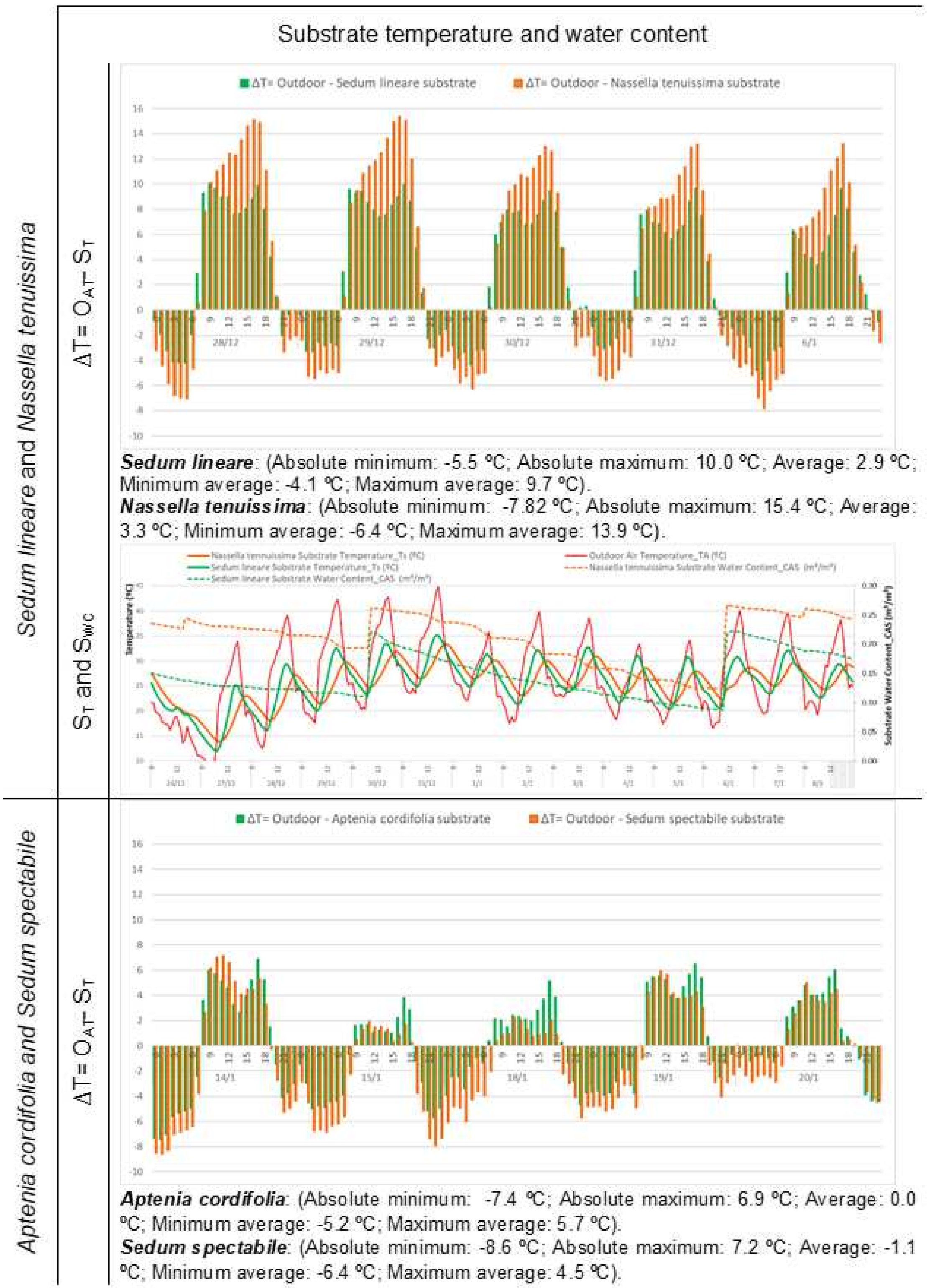


Figure 11

Outdoor air temperature, substrate temperature, and substrate water content for both measurement cycles