Evaluation of the development of five *Sedum* species on extensive green roofs in a continental Mediterranean climate

Abstract

Because of their easy implementation and low maintenance, extensive green roofs have become established during the last few decades as one of the best options for integrating vegetation on the built environment. The success of these systems involves having of a plant species palette well adapted to extreme conditions, especially in drought environments. Among the available ones, the *Sedum* genus has stood out due to its tolerance to climate extreme conditions and its use has been widespread throughout the world. In previous research, efforts have been mainly concentrated on selecting the most drought tolerant *Sedum* species, without considering other important parameters for the suitable provision of ecosystem services from the green roof, such as coverage capacity, shape and structure or growth strategy, among others. In this study, five species of *Sedum* (*Sedum album, S. sediforme, S. sexangulare*, *Sedum spurium* cf. 'Coccineum' (syn. *Phedimus spurius* cf. 'Coccineum') and *Sedum spurium* cf. 'Summer Glory' (syn. *Phedimus spurius* cf. 'Summer Glory') were tested in a dry continental Mediterranean climate with the aim of observing their patterns of growth and development. Results revealed that *Sedum album, S. sediforme, S. sexangulare* are recommended species for their use on extensive green roofs in this climate, whereas both varieties of *S. spurium*, particularly var. "Coccineum", present some limitations for their use, basically due to their shape, plant structure, pigmentation and lack of adaptation to winter conditions. Shape Index could be an adequate tool for decision-making in the selection of plant species in the design of green roofs because it provides information not only about the shape and size but also related to the growth strategy of these plants.

Key words

Extensive green roofs, *sedum* species, plant cover, shape index, nursery effect, drought tolerance.

1 Introduction

During last few decades, green roof systems have been established all over the world as important nature-based urban solutions that present several benefits over conventional grey solutions, not only from the environmental point of view but also as cost-effective, aesthetic and socially valuable solutions (European Commission, 2015).

Green roofs, along with other green urban infrastructures, provide several ecosystem services at both the building and city level (Pérez and Perini, 2018). At the building level, green roofs improve the building envelope performance, providing energy savings (Coma et al, 2016) and acoustic insulation. In addition, they increase the durability of waterproofing membranes and contribute to the recovery of open spaces within the urban environment, where landscaping and gardening, food production and social activities can therefore be developed. At the urban level, the benefits provided by green roofs are also significant: they mitigate the urban heat island effect, contribute to storm water management, reduce noise and air pollution, support biodiversity, offer spaces for recreation and human well-being, and improve city residents' health (Pérez and Perini, 2018).

There are two established approaches toward green roofs, extensive and intensive systems, although intermediate solutions may also be found (FLL, 2008). This general classification derives from their multilayer structure that comprises, from top to bottom, the following layers: vegetation, substrate, filter, water drainage-storage, protection and water retention, and finally the root barrier and waterproofing layer. From this general multi-layer structure, the different typologies of green roofs are furtherly distinguished in order to achieve the desired landscaping and environmental objectives and the selected plants' requirements. Table 1 shows the main green roof typologies and characteristics.

Table 1. Green roof typologies and main features. Adapted from (FLL, 2008)

Parameter	**Extensive**	**Semi-intensive**	**Intensive**
Weight at maximum water capacity	50-150 Kg/m^2	120-350 Kg/m^2	>350 Kg/m^2
Substrate layer thickness	6-20 cm	10-25 cm	>25 cm
Plant typologies	Succulent, herbaceous and grasses	Herbaceous, grasses and shrubs	Grasses, shrubs and trees
Slope	< 100%	< 20%	< 5%
Irrigation	Never or periodically	Periodically	Regularly
Maintenance costs	Low	Moderate	High
Implementation costs	Low	Middle	High
Purpose	To provide ecosystem services minimizing environmental impacts and extra costs	Intermediate purposes	To prioritize landscaping, aesthetics and recreational uses

Intensive green roofs, commonly called 'roof gardens', are designed to prioritize landscaping, aesthetics and recreational uses. They host a large range of ornamental plant species including shrubs, bushes and trees, which influence these systems' weight, build-up heights and costs. Extensive green roofs, on the other hand, are mainly developed to provide ecosystem services, minimizing environmental impacts and extra costs. Thus, they are distinguished by their minimal maintenance requirements, and the plants selected tend to be very tolerant to local climatic conditions and of the self-generative type (Wong et al., 2007).

Therefore, the plant species that can be used in a green roof for a specific project will strongly depend on the type of green roof (extensive, semi-intensive or intensive) that it is possible to apply to the roof construction system of the given building, as well as these species' adaptability to local climatic conditions. Moreover, the facility with which maintenance procedures may be applied to the roof is also a factor: greater access will contribute to plant development and, consequently, guarantee plant survival during the operational phase.

In a general and simplified way, Table 2 summarizes the main factors and parameters influencing plant growth and development on green roofs, and therefore the key aspects to be considered when choosing the most appropriate species for this use.

Table 2. Main influencing factors for plant growth and development on green roofs

Influencing factors		Parameters	Observations
Climate	Macro-climate	Solar radiation, temperature, precipitation, relative humidity, dominant winds	City level Köppen climate classification, which is based on temperature and precipitation, is a suitable reference when working with vegetation (Kottek et al., 2006).
	Micro-climate	Shadows, air currents, smoke emissions and residual heat from the building	Building level
System	Substrate layer	Thickness and composition	Physical support for plants. Water retention capacity, amount of nutrients and their availability for plants
	Drainage and storage layer	Thickness, shape and composition	Water retention capacity and its availability for plants. Drainage capacity.
	Irrigation system	Availability and quantity applied	
	Density of plantation and palette of species	Competition and nursery effect between plants	
Maintenance		Nutrients supply	
		Pruning	
		Pest and weed control	
		Weed removal	

After having analysed Tables 1 and 2 it can be deduced that the real challenge arises specifically for extensive green roofs with small substrate thicknesses, and usually with minimum levels of maintenance and irrigation, in which the selection of plant species implies the consideration of multiple variables. As a consequence, previous research experiences have revealed the difficulty of achieving 100% coverage on extensive green roofs in extreme climates such as the dry continental Mediterranean climate (Csa; warm temperate; dry summer; hot summer) (Pérez et al., 2015; Bevilacqua et al., 2015).

In this context, the ability of plant species to develop under these extreme conditions is one of the most concerning issues for all parties involved, i.e. the scientific community, manufacturers and owners. Essentially, the selection of plant species must be appropriate to guarantee survival in the face of the various adversities the plants may encounter: reduction of water consumption due to sustainability requirements, long periods of drought, or an irrigation system failure.

According to Vijayaraghavan (2016), and considering the common extreme environment on rooftops, the favourable characteristics of vegetation for extensive green roofs are: the ability to withstand drought conditions, to survive under minimal nutrient conditions, to achieve good ground coverage, to require little maintenance, to present rapid multiplication with short and soft roots, and to be capable of phytoremediation.

Some previous studies highlight that *Sedum* species are the most appropriate plants to apply on extensive green roofs, due to their shallow root systems, Crassulacean acid metabolism (CAM), and their efficient water use, as well as their tolerance to extreme conditions of heat and drought (Ondoño et al. 2015; Benvenuti and Bacci, 2010).

After performing a comprehensive literature review, Table 3 summarizes the number of times that each *Sedum* species has been used in different studies, as well as the author and year. The main *Sedum* species used in previous investigations are *S. acre*, *S. album*, *S. dasyphyllum*, *S. hispanicum*, *S. kamtschaticum*, *S. pulchellum*, *S. reflexum*, *S. rupestre*, *S. sediforme* and *S. spurium*.

Table 3. Most used *Sedum* species in previous green roof research

	2005	2005	2005	2006	2007	2008	2008	2008	2009	2009	2010	2010	2010	2011	2012	2012	2012	2013	2013	2013	2013	2013	2014	2014	2014	2015	2016	2017	2018		
	Monterusso et al.	**Van Woert et al.**	**Emilsson and Rolf**	**Köhler**	**Durhman and Rowe**	**Dunnett et al.**	**Emilsson**	**Wolf and Lundholm**	**Getter et al.**	**Getter and Rowe**	**Lundholm et al.**	**Nagase and Dunnett**	**Thuring et al.**	**Butler and Orians**	**Barker and Lubell**	**Clark ans Zheng**	**Rowe et al.**	**Dvorak and Volder**	**Moritani et al.**	**Nagase and Dunnett**	**Bates et al.**	**MacIvor et al.**	**Heim and Lundholm**	**Starry et al.**	**Van Mechelen et al.**	**Nektarios et al.**	**Rayner et al.**	**Agra et al.**	**Azeñas et al.**	**Total by specie**	**Total by family**
S. acre	X	X	X	X	X	X	X	X			X					X	X				X	X	X		X		X			16	
S. acre 'Minor'												X																		1	
S. acre 'Oktoberfest'									X													X								2	**19**
S. album	X	X	X				X						X	X	X	X				X		X		X	X					12	
S. album 'Bella d'Inverno'					X												X													2	
S. album 'Coral carpet'									X			X																		2	**16**
S. dasyphyllum																									X					1	
S. dasyphyllum 'Burnati'					X												X													2	
S. dasyphyllum 'Lilac Mound'					X												X													2	**5**
S. hispanicum				X	X					X							X					X									**5**
S. kamtschaticum					X				X								X	X	X			X		X						7	
S. kamtschaticum 'ellacombianum'	X	X																				X								3	
S. kamtschaticum var. Floriferum															X															1	**11**
S. pulchellum	X	X							X							X						X									**5**
S. reflexum	X	X		X	X				X							X	X					X								8	
S. reflexum 'Blue Spruce'										X																				1	**9**
S. rupestre			X	X								X		X	X															5	
S. rupestre 'Angelina'										X																				1	**6**
S. sediforme					X					X							X									X		X	X		**6**
S. sexangulare			X	X						X			X	X	X	X						X									**8**
S. spurium				X				X			X			X	X															5	
S. spurium 'Coccineum'	X	X							X			X										X								5	
S. spurium 'Dragons Blood'																X														1	
S. spurium 'John Creech'										X																				1	
S. spurium 'Royal Pink'	X																													1	
S. spurium 'Summer Glory'		X			X												X					X								4	
S. spurium 'voodoo'																						X								1	**18**

In these previous studies, focus has been put on the tolerance of *Sedum* species to the green roofs' extreme conditions, the most determining factor being their ability to tolerate water shortages. From the results, it has been demonstrated that *Sedum* species are able to survive in conditions of prolonged events of extreme drought, even when the substrate layer is very thin and therefore unable to retain moisture. In addition to these abilities, some references relating to the ecosystem services provided by *Sedum* species, such as water runoff control, energy savings, etc., were also found.

However, beyond plant survival studies, there is a lack of knowledge regarding the patterns of growth and development of the different species of *Sedum* used on green roofs. This topic is of special interest because it influences their ability to provide optimal vegetal coverage and consequently not only to guarantee roof sustainability (i.e. the survival of plants through the nursery effect (Van Mechelen, 2014), but also to properly provide the associated ecosystem services (Pérez et al., 2015; Bevilacqua et al., 2015).

Thus, in this paper five species of *Sedum* under dry continental Mediterranean climate conditions (Csa) were experimentally studied. The main aim consisted in observing their growth patterns and specific development in a green roof system to draw conclusions about their individual potential to contribute to the rooftop coverage, sustainability of the green roof and also its linked ecosystem services.

2 Material and methods

2.1 Site of the study

The study was conducted in the botanical garden of Lleida, Spain (Arboretum *Pius Font i Quer*, 41°37'40.0"N 0°36'07.3"E). The local climate is dry continental Mediterranean with a mean annual temperature of 15 °C and average annual rainfall of approximately 385 mm, concentrated in spring and autumn. A summary of the annual weather data from the study is presented in Table 4.

Table 4. Climatic data during the year of study

	T	TM	Tm	DTV	R	H
January	3.8	9.1	-0.1	9.2	12.1	81
February	5.8	12.4	0.2	12.2	20.8	70
March	11.5	18.6	5.3	13.4	29.2	65
April	14.4	22.8	6.7	16.1	4.9	62
May	19.2	28.1	11	17.1	3.7	55
June	24.5	33.0	15.3	17.4	23.8	58
July	28.0	36.3	19.2	16.5	64.7	56
August	24.0	32.3	17.4	15	16.1	65
September	18.8	26.7	12.4	14.3	11.7	69
October	15.1	22.7	8.9	13.8	6.1	74
November	10.1	15.2	5.9	9.3	60.8	83
December	**5.7**	**10**	**2.3**	**7.7**	**4.1**	**94**
Year	**14.8**	**22.2**	**8.8**	**13.5**	**258**	**69**

Note.
T: Monthly/annual temperature average (ºC).
TM: Monthly/yearly maximum daily temperature average (ºC).
Tm: Monthly/annual minimum daily temperature average (ºC).
DTV: Monthly/annual diurnal temperature variation average (ºC).
R: Monthly/annual precipitation average (mm).
H: Relative humidity average (%).

2.2 Experiment design

The experiment was conducted using two growing tables made of wood with a dimensions of 120 x 80 x 20 cm in which a multilayer green roof system was installed. From the bottom to the top, the green roof consisted of 5 cm of volcanic gravel material (pozzolana) for the drainage layer, geotextile felt for the filter layer, and 10 cm thickness for the substrate layer (growing media). The thickness of the whole system was 15 cm. The substrate used was a conventional one for green roofs, with an approximate composition of 40% compost, 20% coarse grained sand, and 40% pozzolana.

The two wood growing tables were placed side by side in order to ensure that the differences in the growing patterns were not biased by differences in the environmental conditions.

Seedlings of five *Sedum* species were transplanted from pots to the cultivation samples and placed in the tables in a quincunx planting pattern of 20 x 20 cm. A total of 5 individuals from each species were planted (Figure 1 and Figure 2). The species selected were *Sedum album* (White stonecrop)*, S. sediforme* (Pale stonecrop)*, S. sexangulare* (Tasteless Stonecrop)*. Sedum spurium* cf. ‘Coccineum’ (syn. *Phedimus spurius* cf. ‘Coccineum’) (Two-row stonecrop) and *Sedum spurium* cf. ‘Summer Glory’ (syn. *Phedimus spurius* cf.‘Summer Glory’). “cf.” means that it cannot be affirmed with certainty but the fenotype of the two varieties is compatible to ‘Coccineum’ and ‘Summer Glory’. The selection of these species was based on the knowledge acquired from previous studies and these plants’ widespread presence in most of the commercial mixtures for green roofs in the geographical area of the study (Pérez et al., 2015; Bevilacqua et al., 2015). It is worth highlighting that pigmentation changes are common in *Sedum* species during the different stages of plant development as well as due to temperature changes between seasons. This fact can lead to misinterpretations at the selection of species in the plant nursery phase that may have further consequences on green roof development and in the provision of ecosystem services.

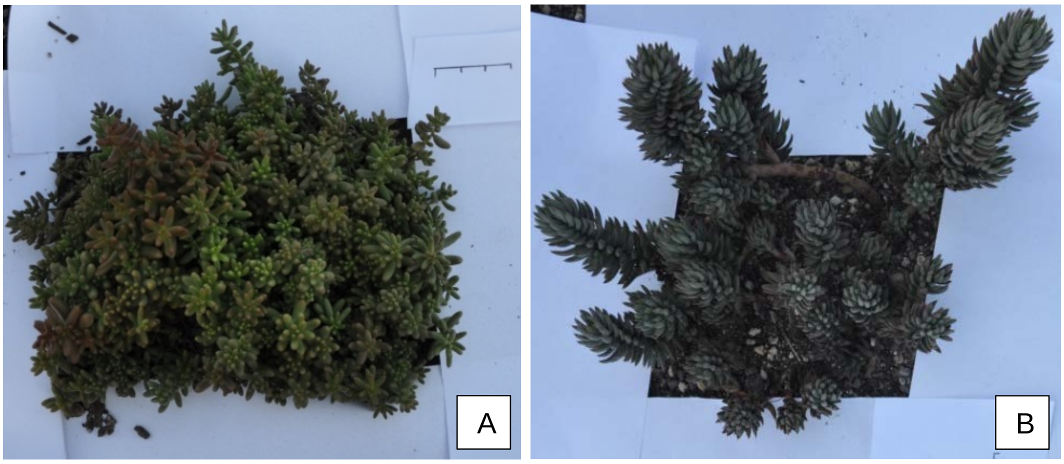

Figure 1. Pictures of the five studied Sedum species. A) Sedum album B) S. sediforme C) S. sexangulare D) S. spurium cf. 'Coccineum' and E) S. spurium cf. 'Summer Glory'

Figure 2. Zenithal view of one of the trays containing five individuals of each species. In the picture *Sedum sexangulare*, *S. spurium* cf. 'Coccineum' and *S. spurium* cf. 'Summer Glory'

The experimental green roof trials took place outdoors in order to conduct the experiment under local climate conditions. The two growing tables were placed side by side to guarantee equal environmental conditions in order to ensure that the differences in the growing patterns were not biased by differences in the environmental conditions. No irrigation was provided during the experiment. However, occasional manual irrigations were carried out, both during the first few days after planting to ensure the plants' establishment, as well as on a monthly basis to guarantee the plants' survival in the summer months.

2.3 Image processing and data analysis

In order to analyse the growth pattern of the *Sedum* species, aerial images of the individuals were taken on a monthly basis until the species overlapped (this happened after 11 months).

The shape of each individual was digitalized using *Image J software* (Rasband, 1997-2018) (Figure 3), and from the binary images obtained the individual area and individual perimeter were measured, to further calculate the following indexes:

- **Total area (cm^2)** by species: The sum of the five individual areas of each species in a specific time. The analysis focuses basically on the monthly evolution of this parameter, in order to be able to observe the capacity of growth and surface coverage of each species, as well as the seasonal pattern (Seccion 3.1; Table 5).

- **Individuals' average area (cm^2)** by species: The average of the five individual measured areas for each species, in a specific time (monthly). These measures allow analysing the growth of each species individually (Section 3.2). The results are presented in two different formats in order to be able to observe the differences between species at a specific time of the year (Figure 4), as well as differences within the same species over time (Table 6). The analysis of differences in both cases was carried out according to ANOVA test with significance $p < 0.001$.
  In addition, the monthly increase of the individuals' average area in % (Figure 5), and the increase of individuals' average area compared to the initial individuals' average area by species (Figure 6) were studied in order to provide additional information about the seasonal growth performance of each species.

- **Shape index (SI)**
  The SI can easily be calculated from the geometric data monthly measured in individuals, to subsequently analyse its monthly evolution by species (Section 3.3, Figure 7). The SI formula is as follows (Garigal and Marks, 1995):

$$SI = \frac{Pi}{2\sqrt{\pi Ai}}$$

Where P_i = perimeter of each individual "i". Ai= area of each individual "i"

Values of SI close to 1 indicate shapes approximated to a circle (maximum compaction) and higher values indicate that the shape is disaggregated. Plant associations of circular shape (shortest perimeter compared to its area patches) are considered to be the most stable and resistant against outer negative effects in an ecological sense. SI index has been widely used in urban landscape studies (Gyenizse, 2014).

Figure 3. *Sedum album*. Digitization of the perimeter using *Image J* software (Rasband, 1997-2018)

3 Results

3.1 Total area by species

Table 5 shows the monthly evolution of the total area (cm^2) for all the individuals of each species. In the studied period, all the individuals survived except one individual of *S. spurium* cf. 'Coccineum' which died in summer. For the rest of the species, the autumn growth (October) caused the overlap of some individuals. This trend was most noticeable in *S. album,* whose five individuals merged after the summer period.

Table 5: Total cover (cm^2) by species.

Species		**Jun.**	**Jul.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**
S.album	───	750.2	1088.6	1169.6	2554.1	2620.5	2315.1	2253.2	2692.7	2724.4	2558.6
S.sediforme	– – –	513.3	517.6	576.3	1751.7	1369.9	2272.0	1354.9	1914.0	1926.6	2446.4
S.sexangulare	······	588.9	727.3	734.9	1969.0	2301.2	2224.4	2017.5	2552.5	2569.7	2607.2
S. spurium cf. 'Coccineum'	– ·	457.7	408.1	267.7	462.5	343.8	314.3	279.1	422.8	426.4	506.3
S. spurium cf. 'Summer Glory'	– –	866.4	786.8	665.4	1471.1	996.6	835.5	777.0	1210.7	1271.6	1607.0

3.2 Individuals' average area by species

Figure 4 and Table 6 show the evolution of the individuals' average area (cm^2) in each analysed species. The area of the five species in the initial period of the study (June) was very similar (values between 173 and 114 cm^2) with an individual average area of 137 cm^2. Thus, at the beginning of the study there were no significant differences between the five species (Figure 4).

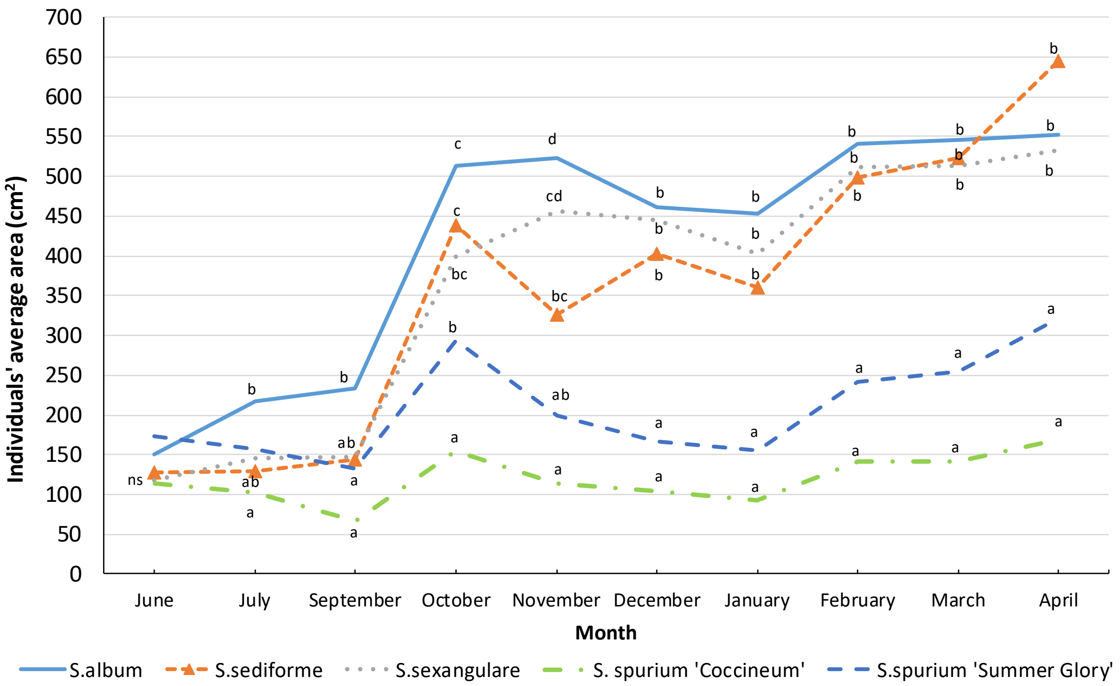

Figure 4: Monthly evolution of the individuals' average area (cm^2) by species. ANOVA analysis: Different letters mean significant differences ($p < 0.001$) among species on each date. ns= non-significant differences.

Table 6. Monthly evolution of the individuals' average area (cm^2) by species. ANOVA analysis: Different letters mean significant differences ($p < 0.001$) among dates for each species.

Species		Jun.	Jul.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
S.album	—	150	218	234	513	523	460	453	542	546	552
Tukey		a	ab	b	cd	cd	cd	c	cd	cd	d
S.sediforme	- - -	128	129	144	438	326	403	361	499	523	644
Tukey		a	a	a	bc	b	bc	b	c	cd	d
S.sexangulare	·····	118	145	147	400	456	445	402	512	513	532
Tukey		a	a	a	b	b	b	b	b	b	b
S. spurium cf. 'Coccineum'	– ·	114	102	67	154	115	105	93	141	142	169
Tukey		ab	ab	a	a	ab	ab	ab	ab	ab	b
S.spurium cf. 'Summer Glory'	– –	173	157	133	294	199	167	155	242	254	321
Tukey		ab	a	a	d	abc	ab	a	bd	cd	d

The first three months of the study, coinciding with the summer period, corresponded to the stabilization phase of the species. On the one hand, *S. album, S. sediforme* and *S. sexangulare* showed a slight increase in their mean area from 132 cm^2 in June to 175 cm^2 in September while *S. spurium* cf. 'Coccineum' and *S. spurium* cf. 'Summer Glory' were always below these values, with a decreasing trend. *S. album* showed significantly higher average individual area values than the two species of *S. spurium* in this period.

From September to October there was an increase in the average individual area in all the species that corresponded to a generalized decrease in average temperatures. Within this general increase, it was possible to differentiate two main trends, which were maintained until the end of the study. On the one hand, *S. album, S. sediforme* and *S.*

sexangulare, with an average value of 450 cm^2, kept their area values stabilized until the following spring. On the other hand, the two varieties of *S. spurium* presented a significantly lower growth rate, with an average value of 224 cm^2.

These two tendencies were reflected in an autumnal growth in total area per species (Table 5), which continued until November for *S. album* (2620.50 cm^2) and *S. sexangulare* (2301.16 cm^2) and until December for *S. sediforme* (2271.95 cm^2), while the two *S. spurium* stopped growing in October.

During the winter dormancy period, all *Sedum* species reduced their total coverage values (Table 5). The total area reduction rate during the winter period by species is as follows: *S. sexangulare* (12.33%), *S. album* (14.36%), *S. sediforme* (15.76%), *S. spurium* cf. 'Coccineum' (39.47 %) and *S. spurium* cf. 'Summer Glory' (47.18%). However, in February, all the species reactivated their spring growth after the winter dormancy (Figure 4 and Table 5).

The growth rates of the total area by species at the end of the experiment from highest to lowest were as follows: *S. sediforme* (374.57%), *S. sexangulare* (342.71%), *S. album* (241.10%), *S. spurium* cf. 'Summer Glory' (85.47%) and *S. spurium* cf. 'Coccineum' (10.62%).

Regarding monthly growth by species (Table 6), only *S. album* showed a significant increase during the first period (June-September).

S. album and *S. sexangulare* significantly increased their areas between September and October and maintained them without significant changes until the end of the following spring.

S. sediforme showed an oscillating growth rate from October to January and there was a significant increase in growth in February.

S. spurium cf. 'Coccineum' was the species with the lowest growth. In the second period, there was a non-significant increase in its area. In April, it had a new increase similar to that of October. The growth of *S. spurium* cf. 'Summer Glory' had this same growth pattern but in this case, the second growth period was statistically significant and started in February.

Across the species, the largest increase in area percentage occurred in October and February (Figure 5). Regarding the increase in area when compared to the initial values (Figure 6), the same two trends which were observed in area evolution (Figure 4) can be seen again: significantly higher growth rates in *S. album, S. sediforme* and *S. sexangulare* as compared to the rates recorded in the two *S. spurium* varieties. It must be highlighted that there were no statistically significant differences in the initial area (in June) among the species. In the first 2 months, *S. album, S. sediforme* and *S. sexangulare* showed a gradual increase (between 12% and 56%) in their initial cover area while the most important increase in their average area occurred in October (240 % in all three cases). However, in the case of *S. spurium* cf. 'Coccineum' and *S. spurium* cf. 'Summer Glory', the first two months decreased their area by 42% and 23%, respectively. This loss of area was progressively recovered until February.

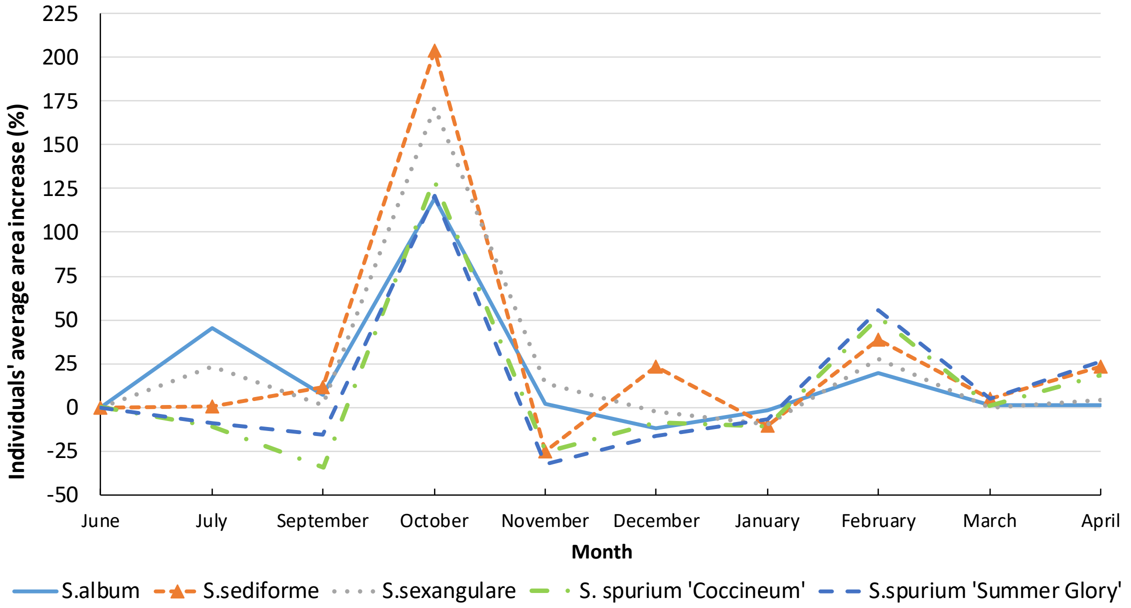

Figure 5: Evolution of the monthly individuals' average area increase (in %) in each studied species since the beginning of the experiment (June).

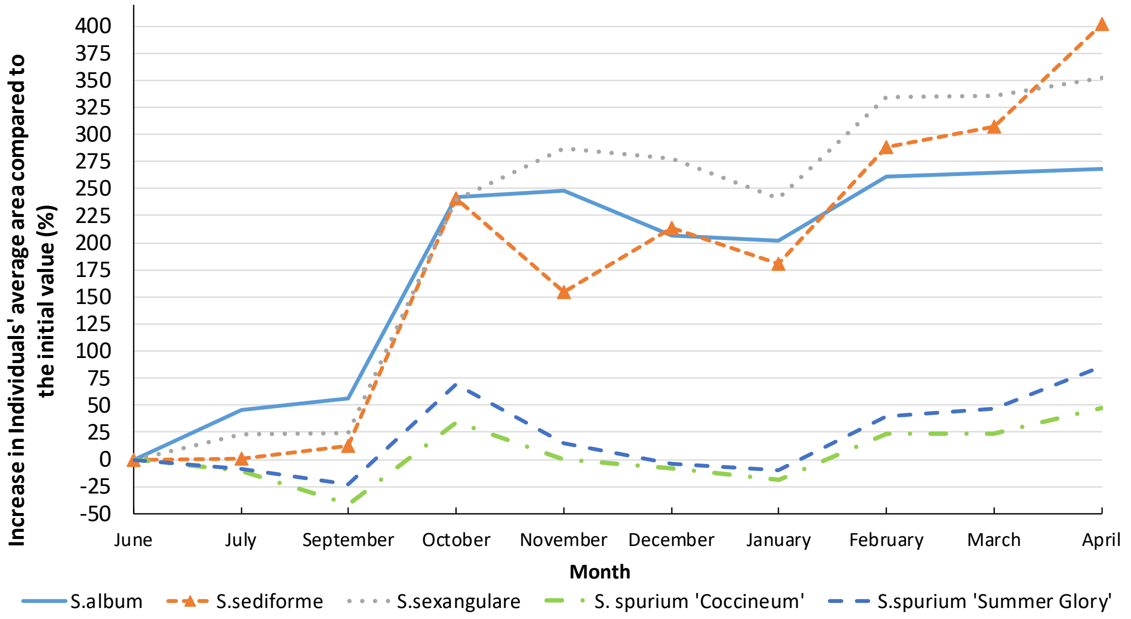

Figure 6. Evolution of the increase in individuals' average area compared to the initial individuals' average area, by species.

3.3 Shape Index (SI)

Figure 7 shows the evolution of shape index (SI). At the beginning of the study all species had approximately irregular forms, such as dendritic, sinuous or elongated shapes (SI values above 2), particularly *S. sediforme*. During the first summer (from June to September), these complex forms maintained an average value of SI above 3. However, in the second growth period, from October to January, all the species, except *S. spurium* cf. 'Coccineum', simplified their shapes, achieving average values of SI close to 2. The species that came closest to a circular form was *S. album*, especially from October to April. The trend of *S. spurium* cf. 'Coccineum', which increased its complex shape throughout the growth period, is completely different from the rest of the species.

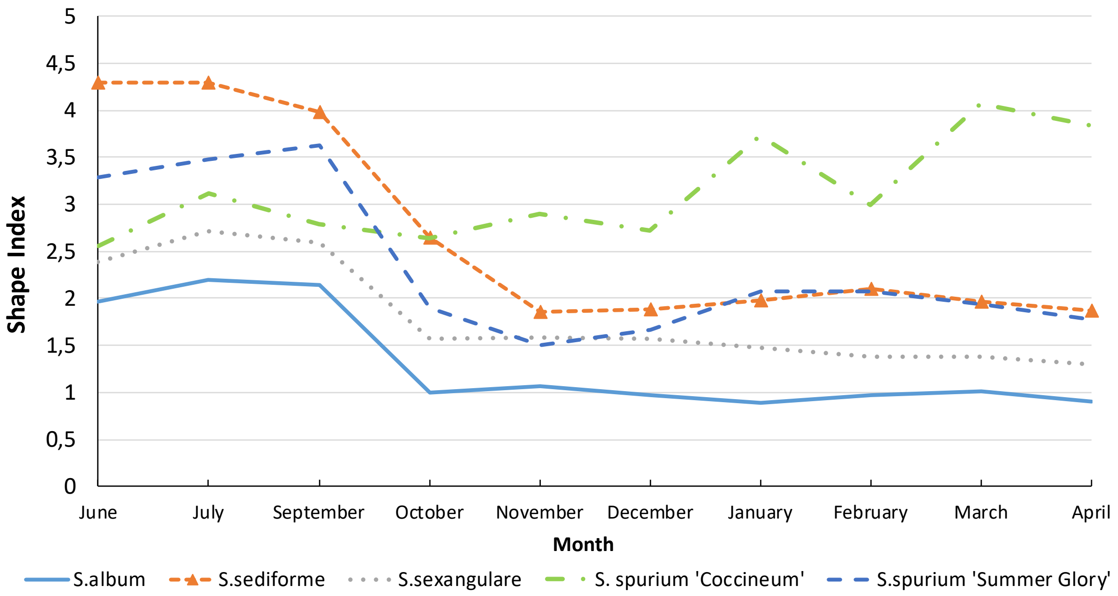

Figure 7. Evolution of the average shape index (SI) of each studied species

4 Discussion

4.1 Suitability of the studied species for their use in extensive green roofs in a continental Mediterranean climate

From the results of the study, it can be clearly observed that under Mediterranean climate conditions not all species traditionally used in green roofs are optimal for achieving the objectives of an extensive approach, i.e. short and soft roots, low maintenance, ability to withstand drought conditions, rapid multiplication, and of the self-generative type to achieve good ground coverage.

Among the five species studied, *S. album* and *S. sexangulare* were those with the best performance and adaptation to local conditions. This might mainly be a consequence of their superior surface coverage strategy, characterized not only by a high increase in area (bidimensional growth), but also a clear tendency toward growing in a spherical shape (a very compact form of tridimensional growth) (Fernández-Marín et al., 2017; Hernández et al., 2010; Medrano et al., 2008). It is known that different species survive and coexist using various functional strategies. Specifically, species' ability to respond to changes in water availability has been associated with morphological and physiological traits and constraints. In this context, drought-resistance plant traits have been synthesized into several functional classifications, on the basis of leaf habit, rooting structure, regeneration strategy or hydraulic traits, and drought architecture (Hernández et al., 2010).

On the other hand, *S. sediforme*, despite showing an increase in covered area similar to that expressed by *S. album* and *S. sexangulare*, does not generate an optimal surface coverage, since this increase was the consequence of its dispersion strategy by fragmentation, which leads to the establishment of new individuals from dispersed propagules (Lundholm et al. 2010; Lundholm et al. 2014; Dunnett et al., 2008). This specific strategy can also lie behind the oscillating growth rate showed by this species during the period from October to January.

It is worth highlighting that these three species were those which performed most successfully during the extremely limiting continental Mediterranean winter conditions. This behaviour is the result of the autochthonous component of *S. album* and *S. sediforme*, which are species well adapted to this climate and which can usually be found growing in exposed environments with thin soil layers and, consequently, subjected to freezing (Getter et al., 2007). On the other hand, *S. sexangulare* is native to central Europe, so it is well adapted to low winter temperatures (Getter et al., 2007).

Finally, the two tested varieties of *S. spurium* did not show any ability for optimal adaptation to the test conditions. Actually, these species did not significantly increase in coverage area and, in the case of *S. spurium* ‘Coccineum’, it tended to acquire very irregular shapes which were far from spherical form (Monterusso et al., 2005; Fernández-Marín et al., 2017; Hernández et al., 2010).

The red colour of *S. spurium* might also have affected its survival under continental Mediterranean conditions. According to some previous authors, leaf colour and chlorophyll content may affect canopy temperature and, indirectly, plant metabolism and dry matter production (Karageorgou and Manetas, 2006; Clark and Zheng, 2013). Although with controversial results, previous studies addressed the correlation between foliar anthocyanin content and resistance to biotic and abiotic agents, like fungi, herbivores, cold and excess of radiation (Karageorgou and Manetas, 2006). In studies conducted using *Sedum* spp. it was suggested that the occurrence of more yellow and red pigments might have been the result of resource reallocation during cold or drought stress periods (Clark and Zheng, 2013).

In this context, *S. spurium*, due to its red colour, may have had a lower photosynthetic rate and therefore be less competitive in a limited-resource and highly stressed environment, materialized as the lower covering rate which was recorded in the study.

4.2 Implications of the results in extensive green roof designs

After a year-long experiment in continental Mediterranean climate conditions, it can be stated that *S. album*, *S. sexangulare* and *S. sediforme* could be successful choices for the floristic palette of extensive green roofs. They comply with the requirements of these construction systems, i.e. minimal maintenance, self-generative typology, ability to withstand drought conditions, and achieve good surface coverage. Besides, *S. sediforme* ensures the valuable expansion of its populations through its high dispersion capacity.

In addition to their large development, in the case of *S. album* and *S. sexangulare* it is worth highlighting their spherical growth pattern. This spherical shape is common in natural habitats exposed to extreme climatic conditions (Macek et al., 2016), and provides more optimal coverage, as well as a compact and dense foliage layer (Box, 1996; Macek et al., 2016). Consequently, it could provide a better provision of the associated ecosystem services, such as the shadow effect, noise reduction, pollution absorption, etc. when compared to other kinds of development patterns that, with equal coverage area (2D), leave several spaces exposed (Figure 8).

Figure 8. ***Sedum sexangulare*** **and** ***S. sediforme,*** **two different growth strategies.**

The use of *S. spurium*, especially the ‘Coccineum’ variety, would not be recommended for use on extensive green roofs in this climate. However, *S. spurium* might have a chance on semi-intensive and intensive green roofs where thicker substrate layers allow for the retention of higher quantities of water and provide more physical support and nutrients to the plants. In these cases, although the effective cover of *S. spurium* would not increase, it may prove able to survive in adverse conditions, especially in winter with minimal maintenance, providing aesthetic and landscape services. In addition, the irregular growth pattern, far from spherical, of *S. spurium* would provide multiple niches for the spontaneous colonization or controlled planting of various other species. Due to the related nursery effect (Van Mechelen et al., 2014), the inclusion of these species would help improve the green roof’s design for aesthetic or landscaping purposes.

According to the European and Mediterranean Plant Protection Organization (EPPO), the use of autochthonous flora in gardening and botanical gardens is recommended (Heywood and Sharrock, 2013). The successful performance of *Sedum* species in extreme climates, such as the dry continental Mediterranean climate, has been evaluated in the present study. Its results would support the inclusion of autochthonous plants in green roof designs in accordance with EPPO recommendations, therefore optimizing roof sustainability and avoiding the use of exotic species in urban gardening.

4.3 Seasonal considerations of the results for green roof establishment

After planting in May, the plants faced the most stressful period of the year due to the high temperatures. The tested species of *Sedum* took about three months to completely adapt to its new location under continental Mediterranean conditions. This result has implications for the future design and implementation on *Sedum*-based extensive green roofs in Mediterranean environments, since depending on the planting date, adaptation timing may vary.

It has been proven that once the species have adapted to their new conditions, they are able to resist future periods of adversity, in this case, hard winter conditions. Hence, it indicates the importance of planning the dates of planting in new green roof projects in this climate (Getter and Rowe, 2008; Fioretti et al., 2010).

5 Conclusions

In the present study, five species of *Sedum* commonly used on extensive green roofs (*Sedum album* (White stonecrop)*, S. sediforme* (Pale stonecrop)*, S. sexangulare* (Tasteless Stonecrop)*. S. spurium* (Two-row stonecrop) cf. ‘Coccineum’ and *S. spurium* cf. ‘Summer Glory’ were studied for a more than one-year period with the aim of characterizing their growth and development patterns under dry continental Mediterranean climate conditions. The main purpose was to gain knowledge about their individual potential in contributing to plant coverage, green roof sustainability, and linked ecosystem services.

From the results, and taking the extensive conditions of study into account, it can be concluded that:

- *S. album. S. sexangulare. S. sediforme* perform suitably under the extreme climate conditions of a continental Mediterranean climate (Csa; warm temperate; dry summer; hot summer), showing a great capacity for colonization and coverage. Therefore, they can be recommended for use in this climate.

- On the other hand, both tested varieties of *Sedum spurium*, cf. ‘Coccineum’ and cf. ‘Summer Glory’ although seeming to have suitable characteristics for their use in green roofs, did not develop successfully in the extensive conditions of the study, especially the ‘Coccineum’ variety. Consequently, the recommendation might be to use these two species as part of a more complete palette of other more suitable ones, or in other, less extreme conditions (semi-intensive green roofs, irrigation systems to support the plants, etc.).

- The use of the Shape Index (SI) could be an adequate tool for decision-making in the selection of plant species in the design of green roofs, because it provides information not only about the shape and size but also on the growth strategy of each species, and therefore their performance relating to the coverage potential and green roof development.

This study is the first approach to the analysis of the growth and development of *Sedum* species that form part of extensive green roofs in Mediterranean conditions, and has yielded results of relevant significance. However, it is expected to be further optimized by increasing the space between individuals in order to delay the fusion of the species, allowing the growth dynamics to be rehearsed over longer periods and to obtain a more in-depth analysis of temporal variations on the perimeter of the species.

For further studies, the establishment of minimal irrigation support under maximum water stress conditions has been proposed in order to ensure the survival of less well-adapted species. This could offer new alternatives for the selection of extensive green roof species in situations where irrigation support might be possible.

Likewise, conducting studies on the three-dimensional structure of *Sedums,* and other species currently used on green roofs, is recommended in order to obtain more information on their actual behaviour. Such studies would also provide more insight into these species' contributions to suitable green roof development (degree of coverage, the nursery effect, etc.) and the provision of related ecosystem services (the cooling effect of evapotranspiration, the shadow effect, etc.).

Finally, further studies on the influence of *Sedum* pigmentation on the performance of these species and on the development of the whole green roof must be carried out. The differences in colour between species, the changes in pigmentation through development stages, as well as the seasonal changes due to the climate influence, are aspects that would be worth studying in an in-depth manner in the future. It would also be wise to consider the misinterpretations which this factor can provoke when determining the true type of *Sedum* used in every single project and the following consequences on green roof development and functionality.

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