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On the influence of plant morphology in the extensive green roof cover: A case study in Mediterranean area

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ABSTRACT

The success of green roofs in Mediterranean areas requires the selection of fast development plant species, able to grow in a shallow soilless substrate also under dry climatic conditions. In this context, the exploitation of native species from marginal sites characterized by limited availability of nutrients and water could be a strategy to select plants. In this work, various species, belonging to the Crassulaceae family from Central Mediterranean and sub-tropical regions, have been evaluated for their growth performance on extensive green roofs outdoor in Central Italy in mono and mixed culture. The morphology, i.e. branched or rosette type, resulted a fundamental trait for the coverage and species with prostrate branches, presented higher plant cover in the first year after transplant respect to the "rosette" type in monoculture. In particular, the Mediterranean native branched species *S. album, S. rupestre, S. sediforme* and the "rosette" *Sempervivum tectorum* presented a good performance under the seasonal variations, with high cover ability or biomass production after 15 months. In the mixed cultures, these species presented a different performance. *S. album* resulted highly competitive and "aggressive spreaders" respect to the other *Sedums* and may be suitable for monoculture or in combination with low covering shrub species. Among the "rosette" species, the allochthonous subtropical *Aeonium castello paivae* Bolle presented a good surface coverage and biomass production respect to the branched species while the native *Sempervivum tectorum* (Griseb. & Schenk) L. presented low covering ability in all the combinations. However, the introduction of "rosette" species in combination with "branched" ones (Sedums) could increase the diversity and aesthetic appearance of the roof.

1. Introduction

Today, the implementation of nature-based solutions (NBSs) in urban environments could be a valuable solution for their positive environmental effects other than for their aesthetic value (Calfapietra and Cherubini, 2019; Randrup et al., 2020; Raymond et al., 2017), as also suggested by United Nations (UN Climate Action Summit, 2019). In this context, the installations of green roofs on urban buildings are gaining interest since they can have a positive impact on the microclimate with mitigation of the urban heat island by plant shading and evapotranspiration (Susca et al., 2011; MacIvor et al., 2016; Saiz Alcazar et al., 2016; van der Kolk et al., 2020). Moreover, green roofs can improve air quality by CO_2 sequestering and adsorbing particulate on the leaf surfaces (Agra et al., 2017; Viecco et al., 2018). From an ecological point of view, green roofs could host a variety of arthropods, gastropods, reptiles, and birds since they can serve as stopovers for migratory organisms as ecological corridors in fragmented habitats, by improving and preserving the biodiversity (Brenneisen, 2006; MacIvor and Lundhomm, 2010; Salman and Blaustein, 2018; Passaseo et al., 2020). Additional effects could be the reduction of the noise and the mitigation of the storm water runoff (Nagase and Dunnett, 2010; Yang et al., 2012; Aloisio et al., 2016; Beaugeard et al., 2021) but the

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magnitude of these effects depend on plant species (Kemp et al., 2019). Green roofs could be classified as “intensive” with substrate of 20–50 cm depth or more and semiextensive and extensive if substrate is 8–20 cm depth (FLL, 2018; ANCV, 2019). Intensive roofs can support a larger number of species such as forbs, sedges, shrubs, and small trees while extensive roofs can host a limited range of plant species, usually herbaceous succulent plants with prostrate growth and grasses (Berardi et al., 2014; Nektarios et al., 2016; Tassoula et al., 2021; Varela-Stasinopoulou et al., 2023;). Substrates for these green infrastructures are usually a mix of soilless lightweight materials of different origin (e.g. sand, perlite, pumice, lapillus, zeolite, and expanded clay) added with organic matter (e.g. peat, coconut fibre, bark). Semi- and extensive green roofs are more frequently installed because of their light weight, low cost, reduced impact on the structure, and their capability to support vegetation with minimal requirement of maintenance.

The selection of suitable plant species is a critical factor in ensuring the long-term functionality and aesthetic appeal of green roofs. The choice of the plant species is not so often to be obvious and deserves to be explored taking into account various unstandardized parameters. The selection of plants adapted to shallow substrates and the variability of climatic conditions of the green roof has been the object of some investigations (Papafotiou et al., 2013; Tran et al., 2018; Cao et al., 2019; Liu et al., 2019). The installation of a community of species as well the use of native plants is recommended strategies to ensure the endurance, the aesthetic appearance, and the conservation of urban biodiversity (Dvorak and Volder, 2010; Nagase and Dunnett, 2010; Tran et al., 2018; Cao et al., 2019; Liu et al., 2019; Calheiros and Stefanakis, 2021). For this matter, studies have to be performed in order to exploit the best plant species and composition for each situation and to achieve coverage targets in all the climatic regions in compliance with standard regulations (i.e. UNI 11235:2015, 2025). The green roofs are frequently installed in the Northern regions of Europe and America but are still rare in Mediterranean areas, where the climatic conditions characterized by thermal day-night variations, high light radiation, and prolonged drought represent a threat for the plant survival. Thanks to its habitat variety and diversity in climatic zones, the Mediterranean region hosts a great number of native plants characterized by resistance to drought, heat, ability to colonize marginal sites and that could have a good performance in green roofs (Caneva et al., 2013; Van Mechelen et al., 2015). In this context, the Crassulaceae family could be of interest because it includes succulent plants with low water requirement. Some species belonging to Crassulaceae family, in particular to *Sedum* genus, are characterized by prostrate growth, coverage ability, and development of the root system on the surface. *Sedum* plants have a photosynthetic Crassulacean Acid Metabolism (CAM) that allows the closure of the stomata in daytime and the gas exchange during the night, reducing the transpiration and conferring resistance to the drought (Starry et al., 2014; Cao et al., 2019). *Sedum* genus includes 500 species mostly native of subtropical and temperate areas of the Northern hemisphere and in Europe it occurs predominantly in the Mediterranean region (Hart, 1991). Some *Sedum* species have been already evaluated for their performance on green roofs in continental climatic conditions (Emilsson, 2008; Getter and Rowe, 2009; Dvorak and Volder, 2010; Olszewski et al., 2010; Rowe et al., 2012; Zheng and Clark, 2013; Lundholm, 2015). To date, only few outdoor experiments have been performed in Mediterranean environment and only recently published. Summarizing, the evaluation of native *Sedums* for green roof in Mediterranean regions has reported good traits *for S. album* and *S. sediforme* in zones classified as Bsk (cold semi-arid) and Csa (hot summer) according to the Köppen climate classification (Beck et al., 2018) while *S. sexangulare* was reported in zone Bsk and *S. rupestre* in zone Csa (Benvenuti and Bacci, 2010; Nektarios et al., 2016; Tuttolomondo et al., 2018; Azeñas et al., 2018, 2019; Schlinder et al., 2019; Aprile et al., 2019; Pérez et al., 2020).

Furthemore, there are also other Crassulaceae that could be of interest for green roof cover in the Boreal zone (Dvorak and Volder, 2010) that have not been tested yet outdoor in green roof condition. In this work, we evaluated and compare the outdoor growth of a group of Crassulaceae, including native species collected from the Mediterranean region and allochthonous sub-tropical species of different origin, in modular trays for green roofs under the climatic conditions of Central Italy. A particular focus is placed on comparing the adaptability and functional contributions of rosette and branched species. Through monoculture and mixed-culture experiments, we explore how these morphological traits influence roof coverage, biomass production, and long-term plant survival. We hypothesize that the ability to thrive and provide effective coverage is influenced by plant growth form (plant phyllotaxis), offering insights into optimal species combinations for Mediterranean extensive green roofs.

2. Materials and methods

2.1. Plant material and experimental set up conditions

All native accessions were collected in Mediterranean natural rocky habitats characterized by limited availability of nutrient and water or in interstitial spaces of ancient stone walls, in semi-natural or marginal sunny sites. All the species were perennials, characterized by vegetative self-propagation. The list of all plant species evaluated in this study is reported in Table 1.

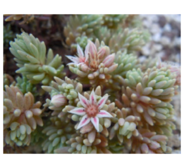
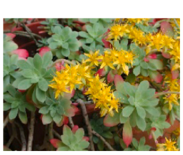
Briefly, *Sedum sexangulare* L., *Sedum album* L., and *Sedum rupestre* L. were collected on the Slovenian and Croatian coast; *Sedum acre* L., *Sedum hispanicum* L., and *Sempervivum tectorum* (Griseb. & Schenk) L. were collected in Central Italy at 850 m height; *Sedum sediforme* (Jacq.) Pau was collected by sampling plants growing on the interstitial spaces of the ancient Viterbo wall (Italy); *Sedum* sp. was collected in a marginal site closed to Viterbo (Italy); *Sedum spurium* M. Bieb and *Aeonium castello-paivae* Bolle were acquired by Viterbo Botanical Garden and originated from Italian Prealps and Canary Islands, respectively. *Sedum nussbaumerianum* Bitter was provided by a private collection and originated from Mexico. Albani and Ruggeri srl nursery (Viterbo, Italy) provided *Sedum palmeri S. Watson*, *Sedum reflexum* L., and another *Sedum acre* L. Considering the morphological traits, all these species could be divided in two distinct groups. Plants from the first group had an apical elongation or ramification of the succulent prostrate branches with small lanceolate leaves and could be called “branched” (BR). The group included eight native *Sedums*. The second group was characterized by succulent large leaves grouped on the top of the stem and the emission of basal shoots. Species belonging this group could be called “rosette” (RO) for their characteristic shape in the leaf arrangement resembling a rose. This group included *Sempervivum tectorum* (Griseb. & Schenk) L., *Aeonium castello-paivae* Bolle, and *Sedum nussmbaumerianum* Bitter.

Before experiments, all plant accessions were propagated in greenhouse on soilless substrates made of Agrilit 3:Agriterram TVS™ 1:1 v v^{-1}, both purchased at Perlite Italiana srl (Milan, Italy) before to start the experiment in order to have sufficient material. In particular, Agrilit 3 is made of perlite (Ø = 2–5 mm) while Agriterram TVS ™ is a mix of lapillus, pumice, zeolite, peat. The substrates were supplied with slow release fertilizer (16 N-24P-12 K; 1.0 kg·m^{-3}). This substrate mix was then used also for the outdoor experiments.

2.2. Monoculture set up and evaluations

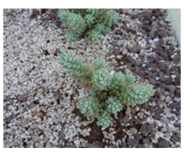
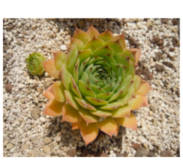
An experiment was conducted in styrofoam rectangular trays of 880 cm^2 with bottom holes for drainage, lined with a water permeable non-woven fabric (Geoplast, Padova, Italy) to prevent substrate dispersion. The Agrilit 3:Agriterram TVS™ 1:1 v v^{-1} substrate was added reaching 6 cm depth since the operational condition were set the most similar to real green roof substrate set up here in Mediterranean condition following the UNI 11235:2015, 2025 standard regulation. Four plants of about 2 cm height (single shoots) were transferred in each tray and three replicate trays for each species was adopted. Transplant was performed

Table 1
Species, origin, ecological traits, and morphology (branched, BR; rosette, RO) of plants used for experiments.

Species	Site characteristics	Collection site	USDA Hardiness Zone	Chorological types	Growth form
Aeonium castello-paivae Bolle 	Botanical Garden	Viterbo, Italy	9–11	Canary Islands	RO
Sedum acre L. 	at 850 m, on top of a dry-stone wall	Campobasso, Italy	7–10	Europe Caucasus	BR
Sedum acre L. 	purchased at Albani and Ruggeri srl nursery	Viterbo, Italy	7–10	Europe Caucasus	BR
Sedum album L. 	coastal rock with sand	Cres Island, Croatia	7–10	Euro-Mediterranean	BR
Sedum hispanicum L. 	at 850 m, on top of a dry-stone wall	Campobasso, Italy	6–10	South East Europe	BR
Sedum nussbaumerianum Bitter 	private collection	Viterbo, Italy	10–11	Mexico and Central America	RO
Sedum palmeri S. Watson 	purchased at Albani and Ruggeri srl nursery	Viterbo, Italy	8–10	Central America	BR
Sedum reflexum L.	purchased at Albani and Ruggeri srl nursery	Viterbo, Italy	8–10	West Central Europe	BR

(*continued on next page*)

Table 1 (*continued*)

Species	Site characteristics	Collection site	USDA Hardiness Zone	Chorological types	Growth form
 *Sedum rupestre* L.	interstitial spaces in a coastal stone wall	Losinj Island, Croatia	8–10	West Central Europe	BR
 *Sedum sediforme* (Jacq.) Pau	at 400 m, interstitial spaces in the ancient tuff wall	Viterbo, Italy	7–9	Steno-Mediterranean	BR
 *Sedum sexangulare* L.	coast, near salt pans	Piran, Slovenia	6–10	Central Europe	BR
 *Sedum* sp.	at 400 m, marginal sites along a country road	Viterbo, Italy	unknown	unknown	BR
 *Sedum spurium* M. Bieb	Botanical Garden	Viterbo, Italy	6–9	Europe Caucasus	BR
 *Sempervivum tectorum* (Griseb. & Schenk) L.	at 850 m, limestone land with rocks	Campobasso, Italy	5–10	South Europe	RO
					

on 5th May 2016 and the experiment was conducted for 452 days after transplanting (DAT), i.e. for fifteen months. All experiments described in this work were carried out outdoor, on a concrete-tile-paved terrace completely exposed to solar radiation, at the third floor of a building at ENEA Casaccia Research Center (Rome, Italy; 42°04′ N, 12°30′ E). The site is classified as Csa (dry summer Mediterranean) according to the Köppen climate classification. The air temperature was recorded at the experimental site by a climatic station connected to a datalogger (Campbell Scientific Inc., USA) and values were hourly averaged. For the studied period, the mean temperature was 15.7 °C (mean min, 10.8 °C; mean max, 23.8 °C) and the total rain was 992.8 mm. During the summertime the average maximum and minimum temperature was 32.2 °C and 15.0 °C, respectively, while during wintertime was 18.9 °C and 2.5 °C, respectively. In the hot periods (May–September), irrigation was provided twice a week for 10 min with a sprinkler (mean flow rate of 115 ml min^{-1}) and the structure of the containers allowed the drainage of the water in excess. At the initial stage of development, the number of plant shoots (at 15 DAT and 30 DAT) and the height of the highest shoot (at 75 DAT) was recorded to evaluate plant adaptability to substrate, as described by Nagase and Dunnett (2010). Moreover, for all the species flowering period and percentage of plants with flowers was recorded for both first and second year. During the experiment, the surface coverage for each monoculture was evaluated nine times using Emilsson's method (Emilsson, 2008) for both branched and "rosette" species. Briefly, a grid 1 × 1 cm was posed on the top of each container and the number of branches of each plant intercepting the square was recorded. Data were then analysed separately for the "branched" and "rosette" groups in order to highlight the valuable traits of each accession. At the end of experiment (452 DAT; end of the growing season), the aerial parts of the plants were harvested and immediately weighted (fresh weight; FW). Finally, dry weights (DW) were obtained by drying samples in oven at 65 °C until constant weight.

2.3. Mixed culture experiment and plant growth evaluations

The experiment was conducted on platforms of 1.5 m × 3.5 m in a structure obtained by the assemblage of Drainroof™ polypropylene modules (Geoplast, Padova, Italy), lined with a non-woven fabric and filled with the substrate mix. The surface was divided in 50 cm-squares and in each square five different species were transplanted in order to have a plant species in the center and four other ones in the corners. Species were selected for the diversity of morphological traits (branched or rosette) and initial performances in the monocultures and they were "mixed" with the commercial ones (*Sedum acre* L., *Sedum reflexum* L., and *Sedum palmeri S. Watson*). The experiment tested three combinations as reported in Fig. 1 replicated three times. Thus, the experiment was conducted on nine platforms (three for each combination) that served of replications with replications of 50 cm-squares inside (i.e. replications of the same combination were allocated in the same platform). The nine platforms were randomized by ensuring minimization of biases. The experiment started on 4th July 2016 and finished after 700 DAT (23 months). For the studied period, the mean temperature was 16.8 °C (mean min, 10.46 °C; mean max, 23.13 °C) and the total rain was 1676.4 mm. As for the monoculture experiments, in the period May–September irrigation was provided by sprinklers twice a week for 10 min (mean flow rate of 115 ml min^{-1}). After 2 years, the surface coverage and the weight of the aerial part of the plants were evaluated as previously described for monocultures.

2.4. Statistical analysis

One-way analysis of variance (ANOVA) was performed on evaluated parameters to assess plant performances and the effect of the different species combinations. In the case of percentage values, they were transformed to arcsin values prior to the statistical analysis. In the mixed culture experiment, platform effects were accounted for as blocking factors in ANOVA to eventually take into account platform effects. The differences among means were evaluated by the Duncan-Waller test, a multiple comparison procedure that combines elements of Duncan's multiple range test (which is less conservative) with Waller's more stringent approach, emphasizing control of Type I and Type II errors. For these calculations, SPSS software (package: statistics 20.0; SPSS Inc., Chicago, USA) has been used. While this method inherently incorporates adjustments for multiple comparisons, explicit *p*-value corrections can still be applied for stricter control. For this reason, a Bonferroni correction was calculated in a spreadsheet.

3. Results

3.1. Evaluation of accessions in monoculture

All species had a good rooting ability and an excellent initial colonization of the substrates (Table 2).

In particular, the initial development and adaptability to the substrate, evaluated as number of shoots per plant at 15 DAT and 30 DAT, was significantly higher for the two branched species *S. acre* L. and *S. album* L. respect to the others in both dates. Rosette species [*A. castello-paivae* Bolle, *S. nussbaumerianum* Bitter and *S. tectorum* (Griseb. & Schenk) L.] did not show any visible increase in both dates. The height of plants after 10 weeks from transplanting was significantly different among the species and, in particular, *S. sexangulare* L. (BR), *Sempervivum tectorum* (Griseb. & Schenk) L. (RO), and *S. nussbaumerianum* Bitter (RO) presented the lower values (Table 2). Data reported in Table 2 showed diversity among accessions also on the flowering pattern. In the first summer after the transplant only *S. acre* L. (BR) and *S. hispanicum* L. (BR) presented flowers on 50 % and 60 % of plants, respectively. The second year all *S. acre* L. (BR) plants flowered in June while *S. hispanicum* L. (BR) had no flowers. In this second year, *S. album* L. (BR) and *S. rupestre* L. (BR) had the longest flowering period (from 4th June until 31st July) in 100 % of plants, while *S. sediforme* (Jacq.) Pau (BR), *S. sexangulare* L. (BR) and *S. spurium* M. Bieb (BR) presented a shorter flowering period on 100 %, 100 %, and 50 % of plants, respectively. The RO species, i.e. *A. castello-paivae* Bolle and *S. tectorum* (Griseb. & Schenk) L., presented a limited flowering period and flowered only in July, showing flowers on 50 % and 8 % of plants, respectively.

Surface coverage data for branched (Fig. 2) and rosette species (Fig. 3) revealed an overall increase in coverage for all species, with

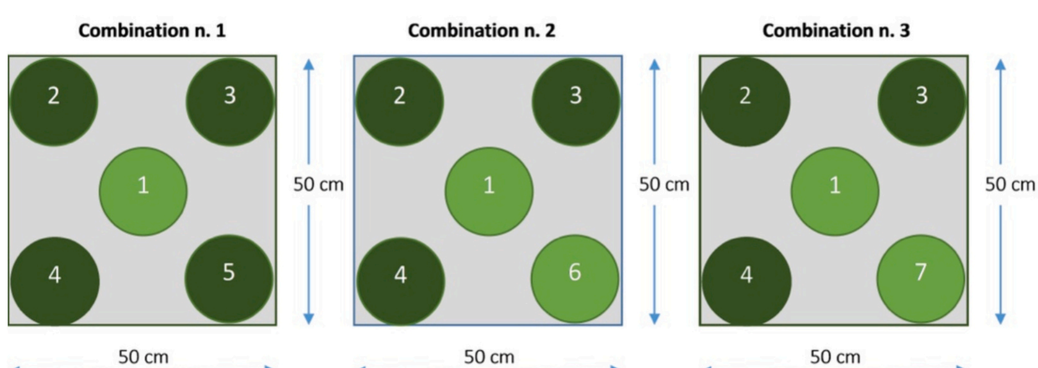
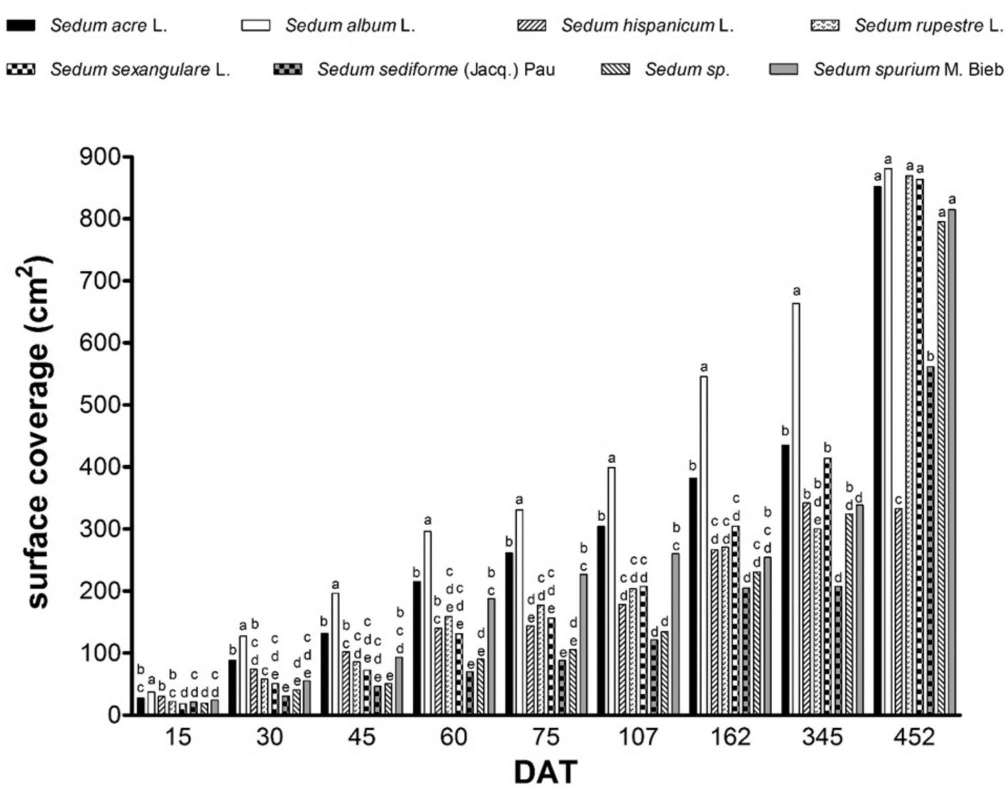


Fig. 1. Plant combinations in the outdoor mixed cultures. In dark green, branched (BR) species; in pale green, rosette (RO) species. 1) *Sempervivum tectorum* (Griseb. & Schenk) L. (RO)*;* 2) *Sedum acre* L. (BR); 3) *Sedum reflexum* L. (BR); 4) *S. palmeri S. Watson* (BR); 5) *Sedum album*, L. (BR); 6) *Sedum spurium* M. Bieb (BR); 7) *Aeonium castello-paivae* Bolle (RO). These combinations were replicated in the trays three times. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Number of plant shoots (at 15 and 30 days after transplanting or DAT) and height (the highest shoot; at 75 DAT), flowering period in the 1st and 2nd year, and % of plants with flowers (in bracket) of branched (BR) and rosette (RO) species in monoculture. In each column (same date) different letters indicate significantly different means among species ($p < 0.05$).

Species	Growth form (RO/BR)	Plant shoots (number)		Height (cm)	Flowering period	
		15 DAT	30 DAT	75 DAT	1st year	2nd year
Aeonium castello-paivae Bolle	RO	1.08 g	1.17 d	4.83 ab	–	01 July-31 July (50 %)
Sedum acre L.	BR	18.66 a	44.75 a	4.29 abc	03 June-18 July (50 %)	01 June-30 June (100 %)
Sedum album L.	BR	14.83 b	46.5 a	3.67 c	–	04 June-31 July (100 %)
Sedum hispanicum L.	BR	9.00 c	26.92 b	4.00 bc	17 June-03 July (60 %)	–
Sedum nussbaumerianum Bitter	RO	1.00 g	1.00 d	2.00 d	–	–
Sedum rupestre L.	BR	5.83 de	17.83 c	5.25 a	–	04 June-31 July (100 %)
Sedum sediforme (Jacq.) Pau	BR	2.16 fg	5.17 d	4.75 abc	–	04 July-31 July (100 %)
Sedum sexangulare L.	BR	7.66 cd	21.08 bc	2.37 d	–	04 June-01 July (100 %)
Sedum sp.	BR	4.75 def	7.7 d	5.13 ab	–	–
Sedum spurium M. Bieb	BR	3.33 efg	6.25 d	5.04 ab	–	10 June-31 July (50 %)
Sempervivum tectorum (Griseb. & Schenk) L.	RO	1.17 g	1.17 d	2.66 d	–	30 July (8 %)

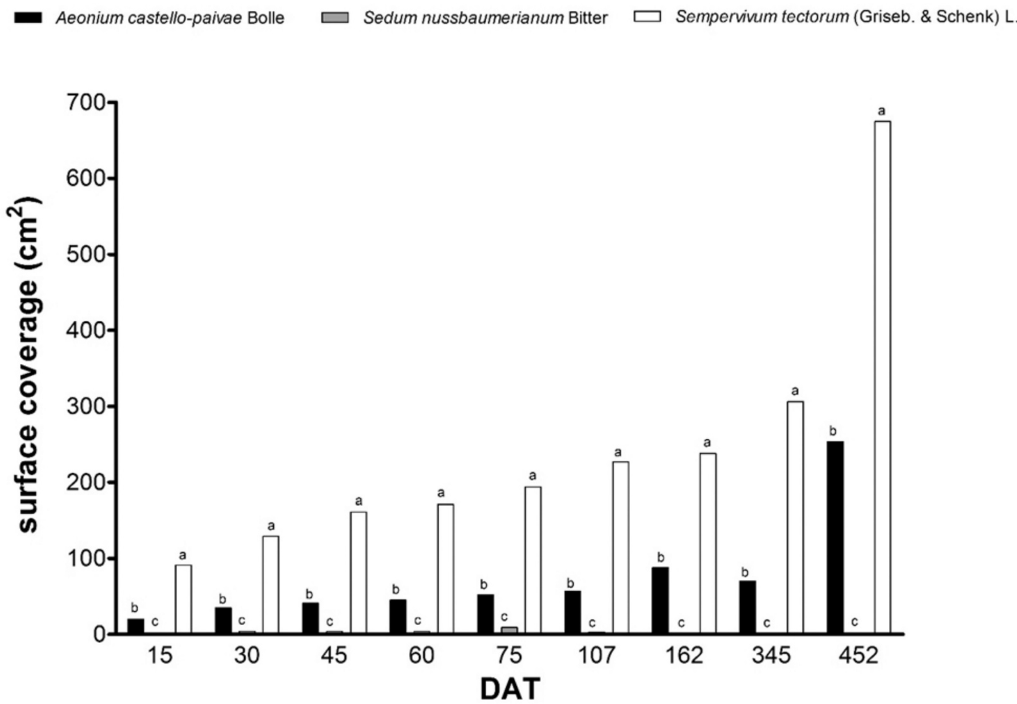


Growth rate									
Species	DAT								
	15	30	45	60	75	107	162	345	452
Sedum acre L.	9.22	29.44	43.89	71.67	87.11	101.33	144.89	127.44	283.86
Sedum album L.	12.44	42.33	65.44	98.67	110.33	133.00	181.78	221.22	293.75
Sedum hispanicum L.	10.00	24.67	34.11	46.78	48.00	59.44	88.89	114.00	110.89
Sedum rupestre L.	7.22	19.33	28.56	52.89	59.11	67.89	90.11	100.11	289.86
Sedum sediforme (Jacq.) Pau	7.00	10.22	15.44	23.33	29.33	40.44	68.22	69.22	187.08
Sedum sexangulare L.	6.00	16.89	24.11	43.78	52.11	69.22	101.56	138.11	287.88
Sedum sp.	6.44	13.44	16.89	30.00	35.22	44.78	77.00	108.11	265.13
Sedum spurium M. Bieb	8.00	18.44	31.11	62.67	75.78	86.67	112.89	84.67	271.53

Fig. 2. Mean surface coverage and growth rate (surface coverage of each evaluation/surface coverage of the first evaluation) of each branched species (monoculture) at 15, 30, 45, 60, 75, 107, 162, 345, and 452 days after transplanting. For each date, means with different letters are statistically different ($p < 0.05$).

statistically significant differences observed across dates for each species. The exception was *S. spurium* M. Bieb (BR), which showed minimal growth beyond the first summer (between 107 and 162 DAT).

Coverage data confirmed the greatest significant increase for *S. album* L. (BR) plants until the end of the experiment (452 DAT), when they covered completely the available surface. Taking into account the other BR species, at 452 DAT results showed significantly high values for all the branched species except for *S. hispanicum* L. and *S. sediforme* (Jacq.) Pau that presented the lowest coverage values (Fig. 2). All rosette species coverage increased until 162 DAT (14th October 2014; Fig. 3).



Growth rate									
Species	DAT								
	15	30	45	60	75	107	162	345	452
Aeonium castello-paivae Bolle	6.67	11.56	13.78	15.11	17.33	19.11	29.33	23.44	84.56
Sedum nussbaumerianum Bitter	1.33	1.33	1.33	1.33	3.00	0.89	0.00	0.00	0.00
Sempervivum tectorum (Griseb. & Schenk) L.	30.44	42.89	53.67	56.89	64.67	75.56	69.22	35.22	224.86

Fig. 3. Mean surface coverage and growth rate (surface coverage of each evaluation/surface coverage of the first evaluation) of each rosette species (monoculture) at 15, 30, 45, 60, 75, 107, 162, 345, and 452 days after transplanting. For each date, means with different letters are statistically different ($p < 0.05$).

After that date, only *A. castello paivae* Bolle and *S. tectorum* (Griseb. & Schenk) L. survived and presented an increase of the coverage until the end of the experiment (452 DAT). *S. tectorum* (Griseb. & Schenk) L. coverage was constantly the highest recorded among the rosette species.

At the end of the experiment (452 DAT), data of coverage was high for almost all the BR species reaching 100 % of coverage in *S. album* L. (BR) monoculture and a coverage major of 90 % in *S. acre* L., *S. rupestre* L., *S. sexangulare* L, *Sedum* sp., and *S. spurium* M. Bieb (Table 3).

Among branched species, *S. hispanicum* L. and *S. sediforme* (Jacq.) Pau presented the lowest values (37.75 % and 63.69 % of coverage, respectively), despite the good growth in the initial stage. The higher fresh weight was reported for *S. album* L., *S. rupestre* L., *Sedum* sp., and *S. sediforme* (Jacq.) Pau, while the higher dry weight was recorded for *Sedum* sp. Among the BR species, the ratio fresh weight/surface and dry weight/surface showed high values for *Sedum* sp., *S. sediforme* (Jacq.) Pau, and *S. rupestre* L. The surface coverage of the rosette species showed significantly higher values for *Sempervivum tectorum* (Griseb. & Schenk) L. respect to *A. castello-paivae* Bolle in all the evaluations while *S. nussbaumerianum* Bitter presented a slower growth and died after the sixth observation (Fig. 3; Table 3). Regarding the survival of rosette species, *S. tectorum* (Griseb. & Schenk) L. presented the highest coverage values of 76.55 % while *A. castello-paivae* Bolle coverage was lower than 30 %. The percentage of surface coverage of all the species after 15 months showed comparable values for *S. tectorum* (Griseb. & Schenk) L. and *A. castello paivae* Bolle respect to *S. sediforme* (Jacq.) Pau and *S. hispanicum* L. (Table 3). Finally, *S. tectorum* presented a weight

Table 3
Percentage of surface coverage relative to the total tray surface (880 cm^2), fresh and dry weight of plant aerial part, fresh and dry weight per surface of branched (BR) and rosette (RO) species after 452 days after transplanting in monoculture. In each column the means with different letters are statistically significant ($p < 0.05$).

Species	Growth form (RO/BR)	Surface coverage (%)	Fresh weight (g)	Fresh weight/surface ($g\bullet cm^{-2}$)	Dry weight (g)	Dry weight/surface ($g\bullet cm^{-2}$)
Aeonium castello-paivae Bolle	RO	28.79 d	195.75 fg	0.84	24.17 ef	0.10
Sedum acre L.	BR	96.63 ab	231.46 fg	0.27	26.01 de	0.03
Sedum album L.	BR	100.00 a	780.15 a	0.89	58.17 bc	0.07
Sedum hispanicum L.	BR	37.75 d	109.29 gh	0.33	11.78 e	0.04
Sedum nussbaumerianum Bitter	RO	–	–	–	–	–
Sedum rupestre L.	BR	98.68 ab	721.25 ab	0.83	71.26 ab	0.08
Sedum sediforme (Jacq.) Pau	BR	63.69 c	524.92 cd	0.94	46.40 cd	0.08
Sedum sexangulare L.	BR	98.00 ab	340.70 ef	0.39	41.11 cd	0.05
Sedum sp.	BR	90.26 b	610.33 bc	0.77	91.76 a	0.12
Sedum spurium M. Bieb	BR	92.44 b	417.76 de	0.51	38.57 cd	0.05
Sempervivum tectorum (Griseb. & Schenk) L.	RO	76.55 c	1843.26 a	3.0	244.90 a	0.39

significantly higher respect to all branched species.

3.2. Evaluation of mixed culture

Surface coverage of selected plant species grown in mixed cultures after 23 months are shown in Table 4. In this Table data on the absolute magnitude of plant coverage, particularly important for comparisons with other studies or for practical applications, and about the percentage, important for potential comparison across species or treatments, are reported.

S. album had the best surface coverage (about 40 % coverage of the available surface) respect to the other species. In contrast, *S. spurium* M. Bieb presented a limited competition ability, with a lower coverage respect to *S. acre* L., but similar to *S. reflexum* L. In the trial *A. castello-paivae* presented higher coverage ability not only respect to both rosette species *Sempervivum tectorum* (Griseb. & Schenk) L. and *S. palmeri S. Watson* but also to the branched *S. acre* L. and *S. reflexum* L. *Sempervivum tectorum* (Griseb. & Schenk) L., present in all combinations, had always a low competition ability with a coverage of only 10 % respect the available surface. A visual distinction of plants was possible for the evaluation of surface coverage in the two combinations containing three branched species, but the ramification and length of the herbaceous branches did not allow a complete separation of the plants for the evaluation of the biomass of each species. For this reason, fresh and dry weight of the plants were evaluated after two years only for the combination n. 3, i.e. with two branched and two rosette species. Data reported in Table 5 showed higher weight and weight/surface values for *A. castello-paivae* respect to the other species of the combination.

4. Discussion

A group of Crassulaceae collected in Mediterranean marginal sites or from semi-tropical areas have been evaluated for their suitable traits of colonization and development in a possible Mediterranean green roof. The horizontal growth conferring carpeting ability and the fresh and dry biomass production were the traits of selections. The evaluated species presented morphological diversity and have been divided in branched and rosette type. Their growth rate (ratio of each evaluation respect to the value of the first evaluation) showed a constant increase for almost all the selected species along the whole experimental period and it was an indication of tolerance to the cold season and could indirectly play a role as indicator in determining the performance of the tested species in the long time. Only *S. sediforme* (Jacq.) Pau and *Aeonium castello-paivae* Bolle, branched and rosette species respectively, presented a decline in the fall and winter (Fig. 2, Fig. 3) while *S. nussbaumerianum* Bitter did not survive to the winter. In this Mediterranean context, the native *S. album* L., *S. rupestre* L., and *S. sexangulare* L., all characterized by prostrate branches, presented the best performances in terms of coverage and adaptability confirmed also by the long flowering and abundant period that indicated their adaptation to the green roof conditions and added an aesthetic value to the plants and, eventually, to the roof.

The best initial adaptably of *S. album* L. has been confirmed by its coverage ability, in accord with Tuttolomondo et al. (2018) that have evaluated a local genotype of this species in Sicily (Csa Italian zone). Recently, also Pérez et al. (2020) have detected a good coverage performance of *S. album* L. in Lleida, Spain (zone Bsk). *S. album* presented higher coverage ability respect to the other species in agreement with Emilsson (2008) that reported a major expansion of *S. album* L. respect to *S. acre* L., also tested in this work, in different substrate mixes.

It is a matter of fact that the UNI 11235:2015 Italian regulation requires a coverage at least of 60 % of the substrate after one year from the installation of Sedums and some of the branched species of this study could satisfy this condition in extensive or mid-extensive Mediterranean green roofs. Moreover, our results showed that in some cases the high coverage ability was also related to the biomass production. *S. rupestre* L. presented high biomass production as well as good carpeting ability, in accord with studies that reported good growth and resistance to drought of this species in Central Italy, zone Csa (Benvenuti and Bacci, 2010; Provenzano et al., 2010). It confirmed that biomass is a "performance metric" rather than a functional trait per se. However, the accumulation of biomass reflected the interaction of multiple traits (e.g. growth rate) under specific environmental condition. If the biomass production for surface unit is considered a valuable trait, *S. sediforme* (Jacq.) Pau could be considered among the best performing species despite the low coverage respect to other selected species even because it is a drought-resistant species (as reported also by Nektarios et al. 2015 for Greece, zone Csa), it has got satisfactory aesthetic appearance as well as thermal regulation characteristics (as also reported by Azeñas et al., 2018, 2019, and Pérez et al., 2020 for Baleari Islands and Lleida, Spanish Bsk zone). In this study *S. spurium* M. Bieb presented a coverage performance similar to *S. acre* L. in contrast with some data of the literature (Getter and Rowe, 2009; Koźmińska et al., 2019). *S. tectorum* (Griseb. & Schenk) L. and *A. castello-paivae* Bolle with rosette morphology presented a low surface coverage in monoculture even if both had a high biomass production and the ratio fresh weight/surface and dry weight/surface was higher to all BR species, demonstrating strong drought resistance due to high fresh weight but exhibiting a vertical growth habit.

Table 4
Surface coverage in cm^2 of selected plant species grown in mixed cultures after 23 months (700 days after transplanting). Means in columns with different letters are significantly different ($p < 0.05$). Percentages are also calculated on the total area of each square (50 cm × 50 cm = 2500 cm^2). BR, branched species; RO, rosette species.

Species	Growth form (RO/BR)	Surface coverage in cm^2 *(%)*		
		Combination n. 1	Combination n. 2	Combination n. 3
Sedum album L.	BR	1166.67 a (*46.67 %*)		
Sedum spurium M. Bieb	BR		709.12 ab (*28.36 %*)	
Aeonium castello-paivae Bolle	RO			754.91 a (*30.20 %*)
Sempervivum tectorum (Griseb. & Schenk) L.	RO	41.67 c (*1.67 %*)	52.33 b (*2.09 %*)	32.71 c (*1.31 %*)
Sedum acre L.	BR	41.67 c (*1.67 %*)	1525.03 a (*61.00 %*)	340.67 bc (*13.63 %*)
Sedum reflexum L.	BR	708.33 b (*28.33 %*)	516.01 ab (*20.64 %*)	491.33 ab (*19.65 %*)
Sedum palmeri S. Watson	RO	333.33 bc (*13.33 %*)	66.98 b (*2.68 %*)	243.02 bc (*9.72 %*)

Table 5
Fresh, dry weight and plant fresh weigh/surface of the mixed culture containing *Aeonium castello-paivae* Bolle after 23 months (700 days after transplanting). Total surface of each square is 50 cm × 50 cm = 2500 cm^2. BR, branched species; RO, rosette species; fresh weight, FW; dry weight, DW.

Species	Growth form (RO/BR)	FW (g)	FW/total surface ($g{\bullet}cm^{-2}$)	DW (g)	DW/total surface ($g{\bullet}cm^{-2}$)
Aeonium castello-paivae Bolle	RO	582.57 a	0.77 a	71.74 a	0.09 a
Sempervivum tectorum (Griseb. & Schenk) L.	RO	88.39 b	0.10 b	11.88 b	0.02 b
Sedum acre L.	BR	90.89 b	0.27 b	8.20 b	0.02 b
Sedum reflexum L.	BR	331.28 ab	0.45 ab	47.4 ab	0.06 ab
Sedum palmeri S. Watson	RO	135.11 b	0.55 b	16.51 b	0.06 b

Since the combination of species with physiological and morphological diversity is considered a strategy to ensure the resistance of the green roof to the climatic conditions, some of the species with the best performance in the first stages in monoculture were also tested in mixed cultures with commercial varieties in a two-year trial. The mixed culture allowed the evaluation of the competition demonstrating that some species presented a different performance in mixed cultures respect to the results obtained in monoculture. *S. album* L., with a cover of 40 % of the available surface, resulted more aggressive spreaders respect to the other species by affecting the diversity of a possible extensive roof. Conversely, it could be suitable in mid-extensive green roofs in combination with species characterized by low coverage as small shrubs. *S. album* L. is characterized by adventitious roots from the branches and forms a mat-similar dense coverage; for these reasons, it could be used as monoculture for green roofs, in accord with Domeneghini et al. (2013) that proposed the introduction of *S. album* L. in urban landscapes considering its morphological traits and the resistance to the drought. In the combination trial, *S. spurium* presented a lower surface coverage respect to the other branched species, in contrast with the good results presented in monoculture. *S. spurium* M. Bieb was not native of the experimental area. It was naturalized in Northern Italy and Giuliani et al. (2018) did not include it among the Mediterranean *Sedum* taxa. This may explain its poor competition respect to Sedums of the combination *S. acre, S. reflexum, S. palmeri* (here in this work, combination n. 2). In the combination trial, *Sempervivum Tectorum* (Griseb. & Schenk) L., that had a good surface coverage as rosette species in monoculture, did not compete with branched species in the mixed cultures and presented always a low coverage. On the other hand, *A. castello-paivae* Bolle, the other rosette species selected for the mixed cultures, after two years presented a higher coverage respect to the other species of the combination n. 3 (*Sempervivum tectorum* (Griseb. & Schenk) L., *Sedum acre* L., *Sedum reflexum* L., *S. palmeri S. Watson*). Following these results, both the rosette species should be included in mixed cultures with branched species in Mediterranean area considering the good ratio weigh/surface, the resistance to the environmental factors, and the aesthetic value of their morphological traits.

Of course, our study aimed to evaluate the adaptability and performance of plant species in green roof, including watering, to simulate optimal establishment phases. While this approach may not fully reflect the water-scarce conditions typical of green roofs in Mediterranean climates, it provides critical baseline data on species growth potential, coverage, and biomass production. This information is highly relevant for identifying candidate species that can subsequently be tested under reduced watering regimes or fully operational green roof setups. Furthermore, frequent watering during the establishment phase mirrors real-world practices where irrigation is often used to ensure initial plant survival before transitioning to minimal maintenance conditions. This step is particularly important in Mediterranean and semi-arid climates, where the early success of green roofs depends on careful plant establishment strategies. For this reason, the watering regime in our study may have influenced growth rates and species performance. Succulent and drought-tolerant species, which are well-suited for green roofs, may exhibit different growth dynamics under limited water availability. However, the observed differences among species in terms of surface coverage and biomass production remain valid indicators of their relative performance. To address this limitation, future studies should explore long-term evaluations under restricted watering to mimic real green roof conditions more closely. Nevertheless, the findings were a useful first step in screening species for their potential adaptability and functionality on green roofs in Mediterranean climates. The identified species that thrived under these watered conditions were promising candidates for further testing in less favourable scenarios, helping advance the adoption of green roofs in water-limited regions.

Finally, this study was a first attempt to evaluate system-level performance since, while our focus was on individual species' performance in mixtures, this is a preliminary step toward understanding their behaviour in more complex plant communities. For this reason, we would suggest future research explicitly targeting: 1) the dynamics of total coverage and species interactions in mixed green roof systems by exploring "neighbour effects" (e.g., competition, facilitation) in mixed plantings and their influence on community resilience and overall green roof performance; 2) the role of specific traits (e.g. stress tolerance) in determining the suitability of species for green roofs and additional traits (e.g. photosynthetic efficiency) to complement the current findings; and 3) how combinations of species contribute to ecosystem services, such as stormwater retention or biodiversity support, on green roofs.

5. Conclusions

In this study, some of the native species of *Sedums* characterized by prostrate branches presented useful traits for the establishment and colonization of green roofs in Mediterranean climatic conditions. The evaluation of the species has considered not only the carpeting ability but also the biomass production for surface unit since this trait could affect the competition ability in mixed cultures. Some of the native *Sedums* could be used in extensive green roofs in monoculture or in combination with species characterized by major aesthetic value and lower coverage ability, in order to satisfy the requirements of some regulations that require a coverage of 60 % of the substrate from the plants after one year from the installation (i.e. UNI 11235:2015 Italian regulation). Among the species with "rosette" morphology, the subtropical *A. castello-paivae* Bolle presented a good competition in a long-term mixed culture while the native *Sempervivum tectorum* presented low coverage. Since the installation of mixed cultures ensures the success of the roof, this study suggests that both the "rosette" species are suitable in combination with the branched *Sedums* in order to increase the resistance, diversity, and aesthetic traits of Mediterranean roofs in well-watering condition. Moreover, other studies are needed to assess how the combinations of these species contribute to ecosystem services.

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Germina Giagnacovo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Damiano Biagiotti:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Rita Di Bonito:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sara Di Lonardo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlo Alberto Campiotti:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this article. The authors have no relevant financial or non-financial interests to disclose.

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Data availability

Data will be made available on request.

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