



Research Article

A new plant association of the alliance *Saxifragion australis* described by drone-based phytosociology in northeastern Sicily (Peloritani Mountains)*

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Abstract

Although the chasmophytic vegetation of Sicily has been examined previously, it remains insufficiently explored due to the formidable challenges associated with accessing vertical cliff habitats. This study employed drone-based surveys combined with Braun-Blanquet methodology to investigate cliff vegetation in the Peloritani and Madonie Mountains. High-resolution aerial imagery enabled species identification and cover estimation on inaccessible rock faces. Twenty-three new relevés were combined with 33 literature records for multivariate analysis. Cluster analysis and DCA revealed floristic differentiation between Peloritani and Madonie phytocoenoses, contrasting with communities from Apennines that we used as an outgroup. We describe *Athamanto siculae-Saxifragetum australis* for the calcareous cliffs of Rocca Salvatesta (Peloritani), characterized by *Athamanta sicula*, *Hypochaeris laevigata*, and *Saxifraga callosa* subsp. *australis*. Additionally, we propose to change the name *Asperuletum gussonei* to *Cynanchicetum gussonei* for the high-elevation vegetation of the Madonie dominated by *Cynanchica gussonei*. Drone methodology proved effective for documenting cliff vegetation, offering a safe and replicable approach for advancing phytosociological knowledge in extreme habitats. This research contributes to the syntaxonomic revision of Mediterranean chasmophytic vegetation within the alliance *Saxifragion australis*.

Keywords

Chasmophytic vegetation, drone surveys, Mediterranean cliff vegetation, phytosociology, *Saxifragion australis*, UAV methodology

Introduction

Phytosociological research based on the Braun-Blanquet approach has provided the foundation for understanding and classifying plant communities across Europe for more than a century, enabling the development of hierarchical syntaxonomic systems that integrate floristic composition, ecological conditions, and biogeographical patterns (Westhoff and van der Maarel 1978; Mucina et al. 2016). This methodology has proven particularly valuable for documenting and conserving the vegetation

of extreme habitats, such as chasmophytic communities colonizing vertical rock faces and cliff systems, where specialized plant assemblages develop under conditions of severe substrate limitation, extreme drought stress, and high exposure to solar radiation (Larson et al. 2000). In the Mediterranean region, cliff vegetation represents a biodiversity hotspot characterized by high levels of endemism and ecological specialization, hosting relict taxa that have persisted in these refugial habitats since the Tertiary and early Quaternary (Médail and Quézel 1999; Thompson 2020).

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Despite their ecological and conservation significance, chasmophytic plant communities remain among the least studied vegetation types, primarily due to the extreme difficulty and safety risks associated with accessing vertical or near-vertical substrates using conventional field survey methods (Larson et al. 2000; Strumia et al. 2020). Traditional approaches relying on rope-access techniques or distant observation with binoculars and telephoto lenses are time-consuming, labor-intensive, and often yield incomplete floristic inventories, particularly for species growing in deep fissures or on overhanging surfaces (Alfaro-Saiz et al. 2019; La Vigne et al. 2022). These methodological limitations have created notable gaps in our understanding of the distribution, floristic composition, and syntaxonomic classification of cliff vegetation across many Mediterranean mountain systems, limiting both basic ecological understanding and the implementation of effective conservation strategies for threatened chasmophytic species. Recent advances in unmanned aerial vehicle (UAV) technology have opened new possibilities for surveying plant communities in inaccessible habitats, offering a safe, efficient, and non-invasive alternative to traditional field methods (Kaneko and Nohara 2014; Dash et al. 2019). High-resolution drone imagery enables botanists to identify dominant and diagnostic species, estimate cover values according to the Braun-Blanquet scale, and compile complete phytosociological relevés from vertical cliff faces without physical contact (Anderson and Gaston 2013; Li et al. 2022). This approach has demonstrated value for documenting rare and endangered cliff-dwelling species, facilitating their rediscovery in historical localities and enabling population monitoring in fragile habitats where human disturbance must be minimized, as well as discovering new species for science (Nyberg et al. 2024; Porrovecchio et al. 2024; Wagner et al. 2024). Furthermore, drone-based surveys generate permanent photographic archives that can be revisited for verification, shared among researchers, and integrated with spatial analysis tools for habitat mapping and long-term monitoring (Manfreda et al. 2018; Tavilla et al. 2024).

The chasmophytic vegetation of Sicily has been examined using a phytosociological approach (Brullo and Marcenò 1979; Brullo 1983; Raimondo 1983; Brullo et al. 2004); however, it remains incompletely studied, primarily owing to the considerable challenge of accessing the habitats found on the high vertical cliffs. The high-elevation chasmophytic vegetation of the principal mountain massifs, including the Madonie, Nebrodi, Monti Sicani (Rocca Busambra), and Peloritani ranges, harbors a diverse endemic flora comprising several species of conservation concern that are threatened (Raimondo 1983; Giardina et al. 2007; Raimondo et al. 2011; Gianguzzi et al. 2015). Early phytosociological investigations by Brullo (1983) and Raimondo (1983) described distinct phytosociological associations within the alliance *Saxifragion australis* for the Madonie Mountains, documenting assemblages dominated by *Saxifraga callosa* subsp. *australis*, *Cynanchica gussonei*, and *Potentilla caulescens* subsp.

nebrodensis. However, equivalent systematic surveys of cliff vegetation in the Peloritani Mountains have remained largely absent from the phytosociological literature, despite anecdotal historical reports of *Saxifraga callosa* subsp. *australis* from only one locality in this mountain chain (Nicotra 1880). The Rocca Salvatesta massif, located in the Peloritani Mountains near the Strait of Messina, presents a particularly challenging case study for vegetation research. Its summit and upper cliff systems, rising abruptly to 1340 m above steep slopes, have remained virtually inaccessible to botanists for more than a century, resulting in uncertainty regarding the current status of historical floristic records and the composition of potential chasmophytic communities at this site (Porrovecchio et al. 2024; Tavilla et al. 2024). Recent drone-based surveys conducted as part of a broader floristic investigation of the Rocca di Novara massif confirmed the presence of *Saxifraga callosa* subsp. *australis* on the high cliffs of Rocca Salvatesta, thus representing a rediscovery of this taxon after approximately 140 years and opening the possibility for phytosociological characterization of previously unstudied cliff vegetation in the Peloritani range (Tavilla et al. 2024).

The present study aims to integrate drone-based phytosociological surveys with traditional field methods to (1) describe and classify the chasmophytic vegetation dominated by *Saxifraga callosa* subsp. *australis* of Rocca Salvatesta in the Peloritani Mountains, comparing its floristic composition and ecological characteristics with previously documented associations from the Madonie region (both in Sicily); (2) evaluate the syntaxonomic position of these communities within the alliance *Saxifragion australis* and assess their biogeographical relationships with similar vegetation in central and southern Italy (Apennines); and (3) demonstrate the methodological utility of UAV technology for collecting standardized phytosociological data in cliff habitats, supporting both the advancement of syntaxonomic knowledge and the conservation monitoring of rare chasmophytic species. By combining cutting-edge remote sensing approaches with rigorous phytosociological classification, this research contributes to filling critical knowledge gaps in Peloritani Mountains cliff vegetation while providing a replicable methodological framework for future studies in similarly inaccessible environments.

Material and methods

Study area

The study was conducted at three localities in northern Sicily: (1) Rocca Salvatesta in the Peloritani Mountains and (2) Piano dei Cervi and (3) Monte Quacella in the Madonie Mountains (Figure 1). Rocca Salvatesta (also known as Rocca di Novara; 37°59'40"N, 15°08'50"E; ca. 1340 m a.s.l.) is situated in the municipality of Novara di Sicilia and represents the second-highest peak of the Peloritani Mountains. The Peloritani Mountains form part of the Calabria–Peloritani Arc, a tectono-metamorphic edifice recording

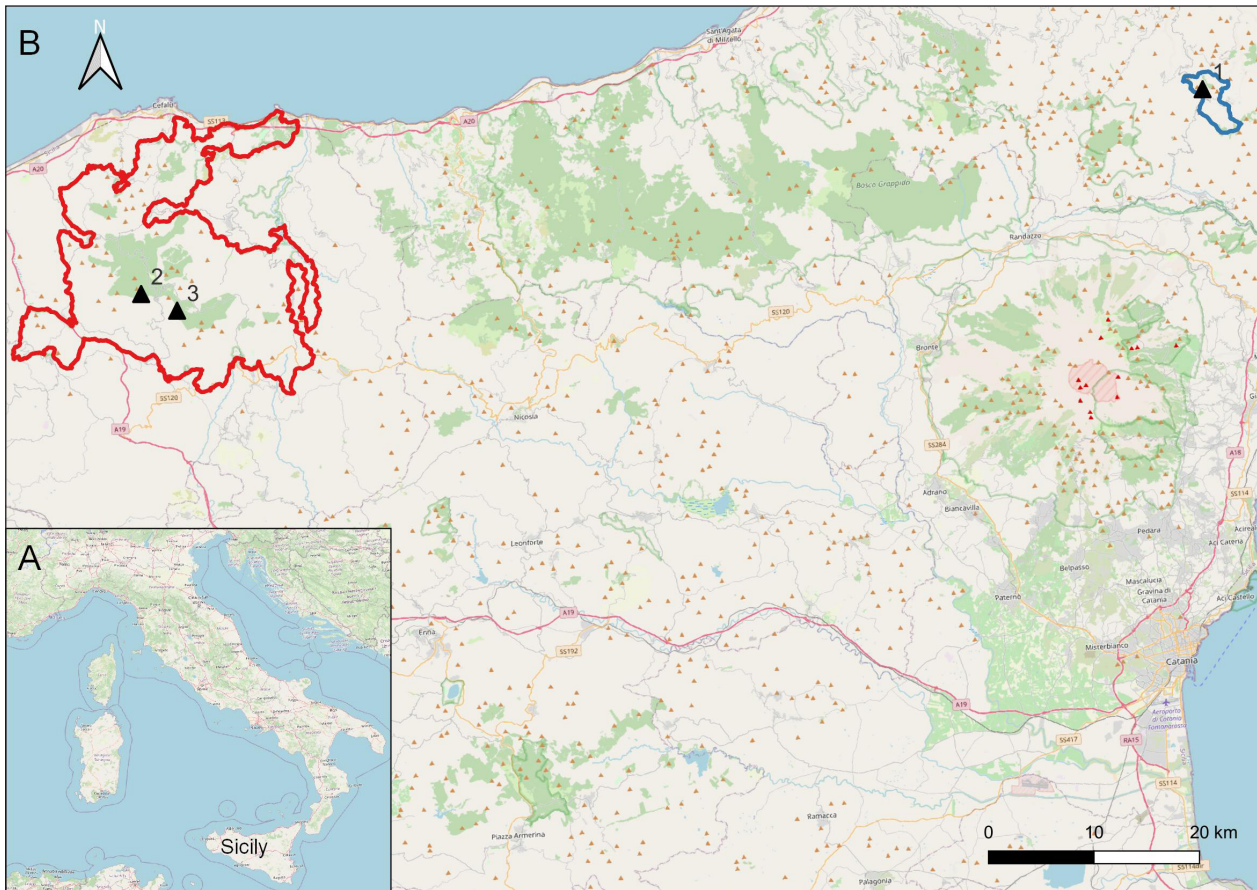


Figure 1. A Geographical position of Sicily; B Geographical distribution of the surveyed study areas. Blue boundaries indicate the Special Area of Conservation ITA030006 “Rocca di Novara”, and red boundaries indicate the Madonie Regional Park. Black triangles mark the locations of the investigated sites: 1, Rocca Salvatesta; 2, Piano dei Cervi; and 3, Monte Quacella (basemap: modified OpenStreetMap).

the subduction–exhumation cycle during Tertiary convergence between the African and European plates (Vignaroli et al. 2008; Catalano et al. 2018). The local geology consists predominantly of calcarenites of the Floresta Formation, developed over a crystalline-metamorphic basement.

According to bioclimatic data from Pesaresi et al. (2017), Rocca Salvatesta is characterized by a lower supra-mediterranean thermotype (Compensated thermicity index, $I_{tc} = 169.4$, mean annual temperature ca. 14°C) and a lower humid ombrotype (annual rainfall ca. 898 mm), with marked summer drought (Figure 2).

The other study areas are Piano dei Cervi (ca. 1500 m a.s.l.) and Monte Quacella (ca. 1680 m a.s.l.) in the Madonie Regional Natural Park (Gianguzzi et al. 2015). The Madonie are formed predominantly of Mesozoic carbonate platform sequences, including massive limestones and dolostones (Barreca 2014). The central massif around Piano dei Cervi is characterized by extensive karst topography, with dolines, sinkholes, and cave systems developed in these platform carbonates. Bioclimatically, both Piano dei Cervi and Monte Quacella fall within the upper supra-mediterranean thermotype ($I_{tc} = 179.0\text{--}180.2$) and lower humid ombrotype (annual rainfall 893–974 mm) according to Pesaresi et al. (2017), reflecting cooler and more mesic conditions than the Peloritani site.

Drone surveys

UAV surveys were conducted using a DJI Mavic 3 equipped with a 20 MP camera, with image geotagging provided by the on-board GNSS receiver (WGS84) stored in the EXIF metadata. Flights were carried out manually on 21st and 29th May and 26th June 2022 at Rocca Salvatesta, and on 10th July 2022 at Piano dei Cervi, under stable meteorological conditions suitable for photogrammetry (no precipitation; low wind; good visibility). Because the target surfaces were vertical to subvertical cliffs, image acquisition was performed by flying the UAV along the cliff front while maintaining a near-constant stand-off distance from the rock face, with a minimum stand-off distance ≥ 0.5 m. The camera axis was kept orthogonal to the wall using the gimbal. The imaging rate was set to acquire photographs at fixed time intervals (every 2 s), and the flight geometry was planned to ensure high overlap between consecutive images ($\geq 80\%$ forward overlap and $\geq 70\%$ side overlap). Each flight was kept within safe battery margins using the DJI Mavic 3 Intelligent Flight Battery (5000 mAh).

We conducted 10 flights between May and June 2022, and each session lasted up to 30 min. Photogrammetric processing was carried out in WebODM (v2.4.2) to

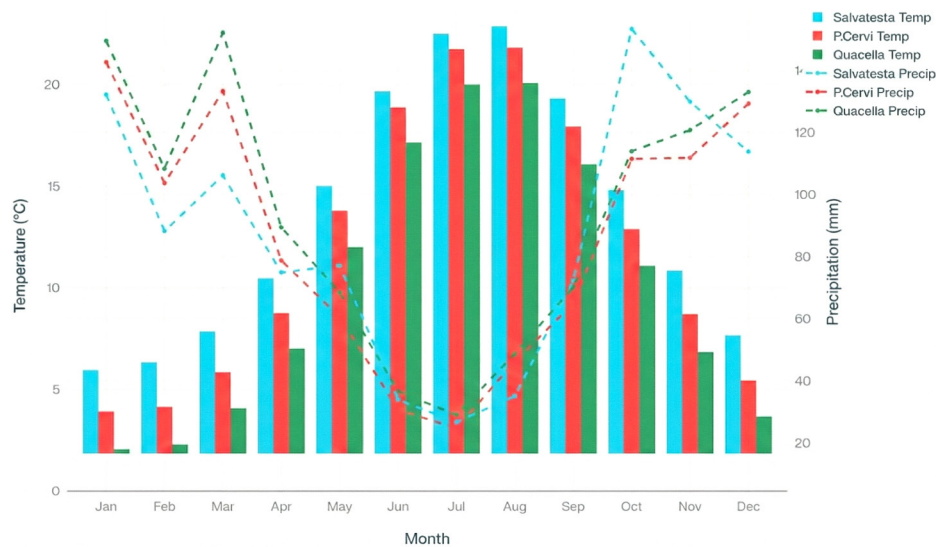


Figure 2. Climatic diagrams showing mean monthly temperature (bars) and precipitation (dashed lines) for Rocca Salvatesta (Peloritani Mountains), Piano dei Cervi, and Monte Quacella (data from Pesaresi et al. 2017).

generate a dense point cloud and a textured 3D mesh. In WebODM, the following options were selected: auto-boundary: true, mesh-octree-depth: 12, use-3dmesh: true, pc-quality: high, mesh-size: 300,000. To minimize perspective distortion on vertical surfaces, cover was not estimated on raw oblique photographs; instead, virtual square plots were delineated on the 3D reconstruction and cover was estimated within these plots. The effective spatial resolution was quantified as Ground Sample Distance (GSD; cm pixel⁻¹), with a final GSD of 0.63 cm. Ground control points (GCPs) were not deployed because the surveyed cliff faces were inaccessible; therefore, absolute georeferencing relied on the UAV's on-board GNSS tags.

Vegetation sampling and statistical analysis

Phytosociological surveys were conducted in inaccessible cliff areas using a DJI Mavic 3, which enabled the acquisition of high-resolution images that allowed plant species identification and cover estimation according to the Braun-Blanquet method (Braun-Blanquet 1964). This drone-based methodology overcomes the limitations of physical accessibility to rock faces while ensuring the precision typical of traditional phytosociological surveys. Photos and drone surveys were personally conducted by the authors at Rocca Salvatesta and Piano dei Cervi, while for Monte Quacella, they relied on relevés from literature (Brullo 1983). Additionally, other relevés from Brullo (1983) conducted in the central Apennines were used as an outgroup to assess biogeographical relationships with similar vegetation in the Italian Peninsula. Thus, the final dataset was composed of 23 unpublished relevés (square plots of 15 m²) and 33 relevés from the literature (Brullo 1983, Suppl. material: table S1). We focused only on vascular plants. Their nomenclature follows Pignatti et al. (2017–2019), Bartolucci et al. (2024), and subsequent updates reported on the Portal to the Flora of Italy (2025),

except for *Saxifraga callosa* subsp. *australis*, for which we adopted the nomenclatural treatment proposed by Tavilla and Del Guacchio (2023). Syntaxonomic nomenclature and classification adhere to Mucina et al. (2016), while the nomenclatural rules and typification procedures for syntaxa follow the International Code of Phytosociological Nomenclature (Theurillat et al. 2021).

Data analysis was performed using JUICE.NET software version 2025, the latest release of the JUICE program developed for vegetation analysis (Tichý 2002). Prior to statistical analysis, ordinal cover values from the 6-step Braun-Blanquet scale were converted to percentage values (+ = 0.1%; 1 = 5%; 2 = 17.5%; 3 = 37.5%; 4 = 62.5%; 5 = 87.5%). This transformation is necessary for applying numerical methods, reducing the inflation error associated with the use of ordinal scales (Tichý et al. 2020; Dengler and Dembicz 2023).

The resulting dataset was subjected to a sequential double transformation: first, a square-root transformation was applied, followed by the Hellinger transformation (Legendre and Gallagher 2001). The first transformation reduces the influence of extreme cover values, while the Hellinger transformation standardizes species abundances relative to the totals of each survey, making the data suitable for ordination methods based on Euclidean distance and reducing the effect of the double-zero problem typical of phytosociological data (Legendre and De Cáceres 2013; Legendre and Borcard 2018). This combination of transformations is particularly appropriate for compositional data such as plant community data, where the focus is on relative rather than absolute abundances (Legendre and Gallagher 2001; McNellie et al. 2019). Hierarchical classification analysis was performed using Ward's method with Euclidean dissimilarity measure (Ward 1963). Ward's method, based on the minimum variance criterion, minimizes the increment of within-group sum of squares at each step of hierarchical fusion, and is particularly effective in identifying compact

and well-separated clusters in ecological data (Murtagh and Legendre 2014). The use of Euclidean distance on Hellinger-transformed data is methodologically appropriate because the combination of these two procedures produces a Hellinger distance, which is not sensitive to the double-zero problem and differences in total abundance among surveys (Legendre and Gallagher 2001). We evaluated cluster quality using the generalized silhouette width (GSW), which extends the silhouette approach by using a generalized mean controlled by a parameter (p), thereby allowing different emphasis on compactness versus connectedness in potentially heterogeneous or gradient-like vegetation clusters. GSW was computed in R with the function `gensilwidth` (package `optpart`) on the same dissimilarity matrix used for the hierarchical classification, and mean GSW was reported for ($p = 0$) (geometric mean) and ($p = -1$) (harmonic mean) (Lengyel and Botta-Dukát 2019). We used the phi coefficient to assess fidelity and identify diagnostic species for each group, assigning zero fidelity to species not statistically significant ($p > 0.001$), and standardized all groups to equal sample sizes (Chytrý et al. 2002).

To assess significant differences in ecological characteristics among the identified plant communities, we applied the Wilcoxon test and the Kolmogorov-Smirnov test. The Wilcoxon test is a robust non-parametric test used to compare distributions of continuous variables between pairs of groups when normality cannot be assumed, while the Kolmogorov-Smirnov test evaluates whether two samples come from the same continuous distribution by comparing their empirical cumulative distribution functions (Legendre and Legendre 2012). These tests are particularly appropriate for ecological data that often show asymmetric distributions and the presence of outliers. Ordination analysis was conducted using Detrended Correspondence Analysis (DCA; Hill and Gauch 1980). DCA is preferable when ecological gradients are long, a situation typical of phytosociological data where species show unimodal distributions along environmental gradients rather than linear responses (Hill and Gauch 1980; Lepš and Šmilauer 2003). The statistical robustness of the ordination was evaluated through three approaches implemented in R environment (version 4.5; R Core Team 2025) using the `vegan` package (Oksanen et al. 2020): (i) bootstrap analysis with 999 permutations to test the stability of ordination axes and calculate 95% confidence intervals of eigenvalues; (ii) comparison with the broken-stick model to determine the number of significant axes (Jackson 1993), where an observed eigenvalue greater than the broken-stick value indicates that the axis explains more variance than expected by chance; (iii) evaluation of gradient lengths to confirm the appropriateness of the unimodal method, where values greater than 4.0 SD support the use of DCA (Lepš and Šmilauer 2003). These combined approaches provide a comprehensive assessment of the quality and reliability of the ordination analysis, crucial aspects for the ecological interpretation of vegetation patterns.

Results

The hierarchical cluster analysis (Figure 3) combined with DCA ordination revealed three distinct vegetation groups. Based on the generalized silhouette width, the cluster showed mean GSW values of 0.24 for ($p = 0$) and 0.26 for ($p = -1$), while the standard ASW ($p = 1$) was 0.23, indicating weak-to-moderate cluster support and being consistent with retaining three groups.

In particular, phytosociological relevés from Sicily (Cluster 1 and 2) were compared using relevés from the Apennines as an outgroup (Cluster 3). Cluster 1 comprised 15 relevés (Table 1), Cluster 2 included 24 relevés, and Cluster 3 contained 14 relevés. The statistical comparison between Clusters 1 and 2 (the Sicilian plant communities) using both Wilcoxon and Kolmogorov-Smirnov tests yielded highly significant differences ($p < 0.001$), supporting their distinct floristic identities. In addition, a synoptic table was compiled (Table 2), including all relevés.

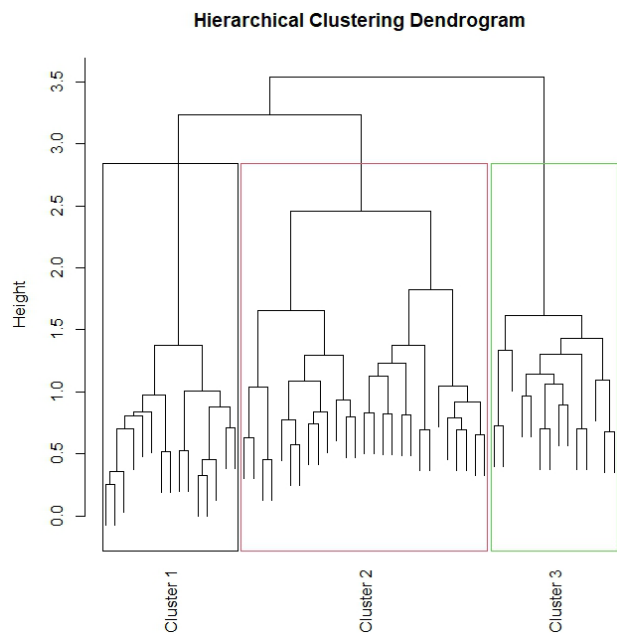


Figure 3. Hierarchical clustering dendrogram obtained using Ward's method with Euclidean distance. Relevés from Peloritani Mountains (Cluster 1), relevés from Madonie Mountains (Cluster 2), and relevés from Central Apennines (Cluster 3).

The DCA (Figure 4) ordination effectively captured the main ecological gradients structuring the vegetation patterns across the study area. The first two DCA axes explained a substantial proportion of the total floristic variance: DCA1 accounted for 44.02% (eigenvalue: 0.7969) and DCA2 for 28.13% (eigenvalue: 0.5092), together explaining 72.15% of the cumulative variance. The ordination diagram separated the three clusters along the primary gradient (DCA1), with Clusters 1 and 2 (the two Sicilian associations) positioned on the left side of the ordination space, while Cluster 3 (the outgroup from the Apennines) occupied a distinct position on the right side. The DCA2 axis further distinguished Clusters 1 and

2, reflecting ecological differentiation within the Sicilian chasmophytic communities. The use of Cluster 3 as an outgroup in the present analysis effectively highlighted the biogeographic and ecological distinctiveness of the two newly characterized Sicilian associations, demonstrating a floristic separation along the primary DCA axis.

The species-score DCA (Suppl. material: figure S1) highlights the position of diagnostic taxa in ordination space: Group 1 and Group 2 diagnostic species cluster on the negative side of DCA1, whereas Group 3 diagnostic species are concentrated on the positive side of DCA1.

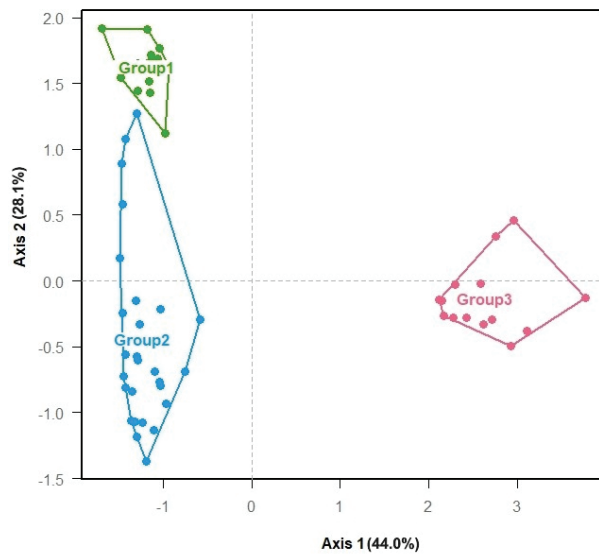


Figure 4. Ordination diagram of the relevés based on Detrended Correspondence Analysis (DCA) of species composition data. Each point represents a sampling site, color-coded and grouped according to the three main vegetation clusters identified in the hierarchical analysis. *Athamanto siculae-Saxifragetum australis* (Group 1), *Cynanchicetum gussonei* (Group 2), *Saxifraga australis-Trisetetum bertolonii* (Group 3).

Cluster 1 – *Athamanto siculae-Saxifragetum australis* Tavilla, Minissale et Cambria ass. nov.

Typus: Table 1, relevé 7, holotypus.

Diagnostic species: *Athamanta sicula*, *Hypochaeris laevigata*.

Dominant species: *Saxifraga callosa* subsp. *australis*, *Hypochaeris laevigata*, *Athamanta sicula*, *Festuca marginata* subsp. *marginata*.

Constant species: *Saxifraga callosa* subsp. *australis*, *Festuca marginata* subsp. *marginata*.

Ecology: This association colonizes rocky crevices of vertical to subvertical carbonate cliffs at Rocca Salvatesta (Peloritani Mountains, NE Sicily) (Figure 5). The communities develop on steep limestone substrates with moderate to deep fissures that accumulate sufficient soil for establishment of the characteristic species. The assemblage occupies exposed to semi-shaded habitats where microclimate conditions are influenced by aspect and fissure

dimensions. This association represents the most thermophilous aspect of the phytocoenosis dominated by *S. callosa* subsp. *australis* in Sicily. The presence of *Athamanta sicula* as a diagnostic taxon together with *Saxifraga callosa* subsp. *australis*, defines this association as a distinct chasmophytic community referable to the alliance *Saxifragion australis* Biondi et Ballelli ex S. Brullo 1984.

Structure and composition: The vegetation structure is characterized by a sparse to moderate cover of chasmophytic perennials occupying rock fissures and ledges. *Saxifraga callosa* subsp. *australis* forms compact cushions that achieve the highest constancy and dominance values within the community, establishing it as the physiognomic dominant. Floristically, the association is characterized by the presence of *Athamanta sicula* and *Hypochaeris laevigata*. The floristic composition is enriched by *Festuca marginata* subsp. *marginata*, a constant companion species threading through interstices and contributing appreciably to structure and biomass. The species assemblage reflects adaptation to extreme environmental conditions, including limited water availability, strong insolation, and substrate instability characteristic of limestone cliffs in Rocca Salvatesta (Peloritani Mountains).

Cluster 2 – *Cynanchicetum gussonei* Brullo 1983 mut. Tavilla, Minissale et Cambria nom. mut. nov.

Synonyms: *Asperuletum gussonei* Brullo 1983 (Brullo 1983: 371)

Authoritative taxonomic treatments that use the name *Cynanchica gussonei*: Del Guacchio and Caputo (2020), Bartolucci et al. (2024).

Diagnostic species: *Cynanchica gussonei*, *Silene saxifraga*, *Anthemis cupaniana*, *Iberis semperflorens*.

Dominant species: *Silene saxifraga* subsp. *lojaconoi*, *Potentilla caulescens* subsp. *nebrodensis*, *Iberis semperflorens*, *Anthemis cupaniana*.

Constant species: *Saxifraga callosa* subsp. *australis*, *Galium lucidum*, *Edraianthus graminifolius* subsp. *siculus*.

Ecology: This association occupies high-elevation (more than 1600 m a.s.l.) calcareous rock faces in the Sicilian Mountain of Madonie, particularly in areas characterized by intense solar radiation and pronounced xericity. This community colonizes limestone cliffs with the presence of several endemic species. In fact, the distinctive occurrence of *Cynanchica gussonei* characterizes this association and differentiates it from related communities in the central Apennines and eastern Sicily. Moreover, this plant community is characterized by the dominance of *Potentilla caulescens* subsp. *nebrodensis*, *Anthemis cupaniana*, *Silene saxifraga* subsp. *lojaconoi* and *Iberis semperflorens*. This floristic assemblage, together with the environmental conditions to which it is subject, renders this association endemic to the Madonie, where it is replaced in the surrounding area by another, markedly more thermophilous association, namely the *Anthemido cupaniana-Centaureetum busambarensis* Brullo et Marcenò ex Terzi, Jasprica et Caković 2017.

Table 1. Phytosociological table of the *Athamanta siculae-Saxifragetum australis* Tavilla, Minissale et Cambria ass. nov. [Rocca Salvatoresta (Novara di Sicilia, Sicily): rels. 1–2 (21.05.2022), rels. 3–10 (29.05.2022), rels. 11–15 (26.06.2022)].

Relevé number	1	2	3	4	5	6	7*	8	9	10	11	12	13	14	15
Surface (m ²)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Elevation (m a.s.l.)	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260
Total cover (%)	25	25	30	30	20	20	20	25	25	20	20	25	20	20	20
Diagnostic species															
<i>Hypochaeris laevigata</i>	2	2	1	2	1	1	2	3	2	1	+	+	+	1	1
<i>Athamanta sicula</i>	3	2	3	4	1	+	1	1	+	+	+	1	+	.	+
Characteristic of <i>Saxifragion australis</i>															
<i>Saxifraga callosa</i> subsp. <i>australis</i>	4	3	2	+	3	2	2	4	4	3	3	1	1	1	1
<i>Edraianthus graminifolius</i> subsp. <i>siculus</i>	.	.	+	.	.	.	+	+	.	+	.	.	.	+	.
Characteristic of <i>Asplenietea trichomanis</i>															
<i>Sedum dasyphyllum</i>	+	.	.	.	.	.	+	1	.	+	.	.	.	.	.
<i>Asplenium ceterach</i>	.	.	+	.	.	.	+	.	.	.	.	.	.	.	.
Other species															
<i>Festuca marginata</i> subsp. <i>marginata</i>	.	.	1	.	.	.	+	1	3	1	2	+	+	+	+
<i>Dianthus arrostoi</i>	.	.	.	1	+	1	.	.	.	.	.	.	+	.	.
<i>Aubrieta columnae</i> subsp. <i>sicula</i>	.	+	.	.	.	.	.	.	+	.	.	.	.	.	+
<i>Poa bivonae</i>	.	+	.	+	+	.	+	.	.	.	1	.	.	.	.
<i>Helianthemum croceum</i>	.	.	.	.	.	.	1	.	.	.	.	.	+	.	.
<i>Lomelosia crenata</i>	.	.	.	.	.	.	+	.	.	.	1	.	.	1	.
<i>Galium pallidum</i>	.	.	.	+	+	+	1	1	.	.	+	.	+	.	.
<i>Arabis alpina</i> subsp. <i>caucasica</i>	.	.	+	.	.	.	.	+	.	.	.	.	.	+	.
<i>Dryopteris filix-mas</i>	.	.	1	.	.	.	.	1	.	.	.	.	.	.	.
<i>Sabulina tenuifolia</i> subsp. <i>tenuifolia</i>	.	.	.	+	.	.	1	.	.	.	.	.	+	+	.
<i>Saxifraga rotundifolia</i>	.	.	1	.	.	.	.	1	.	.	.	.	.	+	.

Structure and composition: The community exhibits a highly specialized floristic composition dominated by chasmophytic species adapted to rupicolous habitats. Unlike Cluster 1, this association shows more balanced dominance among multiple species. *Saxifraga callosa* subsp. *australis* maintains high constancy but lower dominance compared to the first association, indicating a more diverse structural arrangement (Figure 6). The diagnostic species *Cynanchica gussonei*, *Silene saxifraga* subsp. *lojaconoi*, *Anthemis cupaniana*, and *Iberis semperflorens* collectively define the floristic identity of this community. The constant presence of *Galium lucidum* and *Edraianthus graminifolius* subsp. *siculus* further enriches the species composition, contributing to the overall structure of these specialized rock-face communities. The vegetation structure reflects adaptation to more fragmented substrate conditions compared to Cluster 1, with species forming small, scattered patches rather than continuous cover.

Cluster 3 – *Saxifraga australis-Trisetetum bertolonii* Biondi et Ballelli 1982

Diagnostic species: *Trisetum bertolonii*, *Saxifraga paniculata* subsp. *stabiana*, *Edraianthus graminifolius* subsp. *graminifolius*, *Campanula tanfanii*, *Hieracium villosum*, *Sesleria juncifolia*, *Saxifraga oppositifolia*, *Potentilla apennina*, *Primula auricula*.

Dominant species: *Saxifraga callosa* subsp. *australis*, *Potentilla apennina*, *Saxifraga paniculata* subsp. *stabiana*, *Saxifraga exarata* subsp. *ampullacea*, *Carex kitaibeliana*.

Constant species: *Saxifraga callosa* subsp. *australis*.

Ecology: This association, originally described from the central Apennines, represents chasmophytic communities colonizing high-elevation calcareous cliffs in mountain ranges of central Italy. The communities occupy exposed to partially shaded rock faces at elevations typically ranging from 1500 to 2500 m a.s.l., where they experience alpine climatic conditions characterized by prolonged snow cover, intense frost action, and short growing seasons. The presence of characteristic Apennine endemic and orophilous species, including *Trisetum bertolonii*, and *Campanula tanfanii*, as well as *Potentilla apennina*, distinguishes this association from the Sicilian communities. The habitat is characterized by deeper rock fissures compared to the Sicilian associations, allowing establishment of a more diverse assemblage of hemicryptophytes alongside typical chasmophytes.

Structure and composition: The vegetation exhibits a relatively rich floristic composition with numerous diagnostic species reflecting the biogeographic affinities with central Apennine Mountain flora. *Saxifraga callosa* subsp. *australis* maintains high constancy and achieves moderate dominance, serving as a physiognomic element linking this association to the Sicilian communities of the alliance *Saxifragion australis*. However, the structural composition is enriched by the distinctive presence of *Trisetum bertolonii*, *Saxifraga paniculata* subsp. *stabiana*, and other Apennine endemic species that achieve high diagnostic values. The community represents a more mesophilous variant within the chasmophytic vegetation complex, as

Table 2. Shortened synoptic table of the associations analyzed; columns represent vegetation clusters and numbers indicate percentage constancy of species within each cluster; *Athamanto siculae-Saxifragetum australis* (cluster 1), *Cynanchicetum gussonei* (cluster 2), *Saxifraga australis-Trisetetum bertolonii* (cluster 3). The grey cells highlight the diagnostic species of each association.

No. cluster	1	2	3
No. relevés	15	24	14
Taxa			
<i>Hypochaeris laevigata</i>	100	52	.
<i>Athamanta sicula</i>	93	22	.
<i>Cynanchica gussonei</i>	.	67	.
<i>Silene saxifraga</i> subsp. <i>lojaconoi</i>	.	59	.
<i>Anthemis cupaniana</i>	.	56	.
<i>Iberis semperflorans</i>	.	52	.
<i>Trisetum bertolonii</i>	.	.	100
<i>Edraianthus graminifolius</i> subsp. <i>graminifolius</i>	.	.	86
<i>Saxifraga paniculata</i> subsp. <i>stabiana</i>	.	.	86
<i>Campanula tanfanii</i>	.	.	86
<i>Hieracium villosum</i>	.	.	71
<i>Sesleria juncifolia</i>	.	.	64
<i>Saxifraga oppositifolia</i>	.	.	57
<i>Potentilla apennina</i>	.	.	57
<i>Primula auricula</i>	.	.	50
Characteristic of alliance <i>Saxifragion australis</i>			
<i>Saxifraga callosa</i> subsp. <i>australis</i>	100	81	79
<i>Edraianthus graminifolius</i> subsp. <i>siculus</i>	33	63	.
<i>Draba aizoides</i>	.	37	.
<i>Potentilla caulescens</i> subsp. <i>nebrodensis</i>	.	37	50
<i>Saxifraga porophylla</i>	.	.	43
<i>Achillea barrelieri</i> subsp. <i>mucronulata</i>	.	.	14
Characteristic of order <i>Potentilletalia caulescentis</i>			
<i>Iberis violacea</i>	.	26	.
<i>Mcneillia rosanoi</i> subsp. <i>rosanoi</i>	.	4	21
<i>Armeria gracilis</i> subsp. <i>majellensis</i>	.	.	29
<i>Kerneria saxatilis</i>	.	.	21
<i>Grafia golaka</i>	.	.	21
<i>Robertia taraxacoides</i>	.	.	21
<i>Saxifraga exarata</i> subsp. <i>moschata</i>	.	.	14
<i>Saxifraga caesia</i>	.	.	7
Characteristic of class <i>Asplenetia trichomanis</i>			
<i>Sedum dasyphyllum</i>	20	56	57
<i>Cystopteris fragilis</i>	.	.	43
<i>Helichrysum pendulum</i>	.	37	.
<i>Hieracium symphytifolium</i>	.	33	.
<i>Draba aspera</i>	.	.	29
<i>Saxifraga exarata</i> subsp. <i>ampullacea</i>	.	.	29
<i>Asplenium trichomanes</i>	.	.	21
<i>Asplenium viride</i>	.	.	21
<i>Biscutella laevigata</i>	.	.	14
<i>Sedum magellense</i>	.	.	14
<i>Asplenium ceterach</i>	7	11	7
<i>Odontites bocconeii</i>	.	11	.
<i>Hieracium amplexicaule</i>	.	.	7

evidenced by the presence of species adapted to longer snow-lie periods and higher moisture availability compared to the Sicilian associations.

Discussion

The integration of drone-based phytosociological surveys with traditional field methods has enabled a comprehensive analysis of the chasmophytic vegetation of Sicilian mountains dominated by *Saxifraga callosa* subsp. *australis*, revealing a floristic and ecological pattern that support the recognition of a new association in the Peloritani Mountains. The cluster showed moderate support. Since generalized silhouettes reduce the preference for spherical clusters and vegetation patterns often vary continuously along gradients, some overlap among clusters is expected; therefore, groups are interpreted primarily using diagnostic species patterns (and their separation in ordination space). This methodological approach demonstrates the potential of unmanned aerial vehicles to overcome accessibility constraints typical of cliff habitats, while maintaining the rigor and detail required for phytosociological classification (Nyberg et al. 2024; Quattrini et al. 2025).

The cluster analysis and DCA ordination separated the two Sicilian associations from the Apennine vegetation, confirming distinct biogeographical patterns within the alliance *Saxifragion australis*. Moreover, the occurrence of *Asplenium ceterach* and *Sedum dasyphyllum* can allow its inclusion in the class *Asplenetia trichomanis* (Terzi and Di Pietro 2018). The alliance *Saxifragion australis* represents a specialized phytosociological unit of chasmophytic vegetation endemic to the central and southern Apennine Mountain system of Italy, functioning as a southern vicariant of the more widely distributed northern alliance *Potentillion caulescentis*. This alliance was originally indicated by Pedrotti in Pedrotti and Sanesi (1969) as *nomen nudum*, and later repropounded by Biondi and Ballelli (1982), encompassing specialized plant communities that colonize calcareous rock faces and fissures throughout the Umbrian-Marchean, central-southern Apennines and Sicily. The newly described *Athamanto siculae-Saxifragetum australis* is characterized by diagnostic taxa such as *Athamanta sicula* and *Hypochaeris laevigata*, which distinguish it from closely related associations of the Madonie Mountains (Brullo 1983). Indeed, to date, plant communities with *Saxifraga callosa* subsp. *australis* have been investigated only on the Madonie (Brullo 1983; Raimondo 1983). According to Brullo (1983), the *Cynanchicetum gussonei* is an association endemic to the Madonie. The nomenclatural correction of *Cynanchicetum gussonei* (syn. *Asperuletum gussonei*) reflects the taxonomic revision of *Asperula gussonei*, now correctly attributed to the genus *Cynanchica* (Del Guacchio and Caputo 2020). In our view, our results support treating these two syntaxa as distinct, based primarily on diagnostic species composition and bioclimatic differentiation, while acknowledging some overlap consistent with

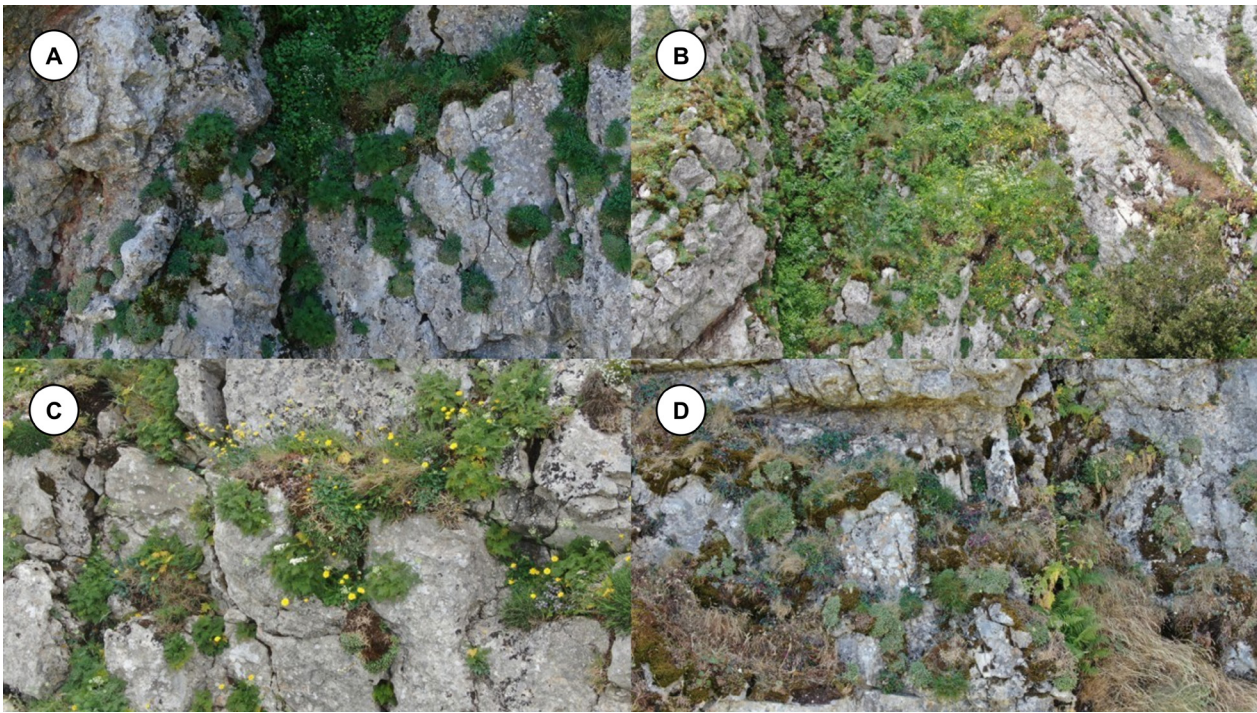


Figure 5. *Athamanto siculae-Saxifragetum australis* at Rocca Salvatesta (Peloritani Mountains). A. Image taken on May 21, 2022; B, C. Images taken on May 29, 2022; D. Image taken on June 26, 2022.

continuous vegetation gradients. The marked occurrence of several endemic species of the Nebrodi district in the *Cynanchicetum gussonei* helps distinguish it from the new association of the Peloritani. In the *Athamanto siculae-Saxifragetum australis*, the presence of *Athamanta sicula* is diagnostic and dominant, as is that of *Saxifraga callosa* subsp. *australis*. Moreover, the bioclimatic differences between the two associations likely act as environmental filters, selecting for distinct assemblages of chasmophytic specialists with differing cold-tolerance thresholds and phenological strategies, thereby explaining the floristic segregation between the two vegetation clusters and their respective diagnostic species pools (Scherrer and Körner 2011; Ciccarelli et al. 2016).

The use of the Apennine association *Saxifrago australis-Trisetetum bertolonii* as an outgroup in the analysis effectively highlighted the biogeographical distinctiveness of the Sicilian chasmophytic vegetation. The first DCA axis, accounting for 44% of the floristic variance, reflects a north-south gradient within the *Saxifragion australis*, with the Sicilian associations positioned distinctly from the Apennine reference group. The enrichment of the Sicilian associations with thermophilous Mediterranean elements, together with the presence of local endemics, suggests a longer history of isolation and in situ speciation compared to the more recently colonized Apennine mountains (Médail and Diadema 2009). The application of drone technology for vegetation sampling in inaccessible cliff habitats represents a significant methodological advancement for phytosociological research (Bertacchi et al. 2025; Quattrini et al. 2025). The drone equipped with high-resolution imaging systems enabled precise

species identification and cover estimation following the Braun-Blanquet method, while ensuring observer safety and reducing survey time (Tavilla et al. 2024). This approach proved particularly valuable for accessing vertical to subvertical rock faces where traditional ground-based surveys would be impractical or impossible.

The high-resolution imagery captured by drones allows botanists to identify dominant and diagnostic species with accuracy comparable to traditional field methods, while providing a permanent photographic archive for future reference and verification (Zhou et al. 2021; Nyberg et al. 2024). As proposed by Quattrini et al. (2025), given the growing interest in and the numerous phytosociological applications of UAVs, it is advisable to envisage future methods to standardize data acquisition through these platforms. Additionally, in rupicolous environments, which are more variable and whose rock faces can differ across territories, there still appear to be no proposals for standardized data-collection protocols.

However, certain limitations of drone-based surveys should be acknowledged. Small herbaceous species and non-vascular plants within the understory or in deep rock fissures may be difficult to detect from aerial imagery, potentially leading to incomplete species lists compared to direct field observations (Quattrini et al. 2025). Nevertheless, for characterizing and discriminating plant associations, the identification of dominant and diagnostic species, which are typically more conspicuous, is generally sufficient (Maciejewski et al. 2022). The chasmophytic vegetation of the Sicilian mountains is of high conservation value due to its richness in endemic and rare species, many of which are included in regional and

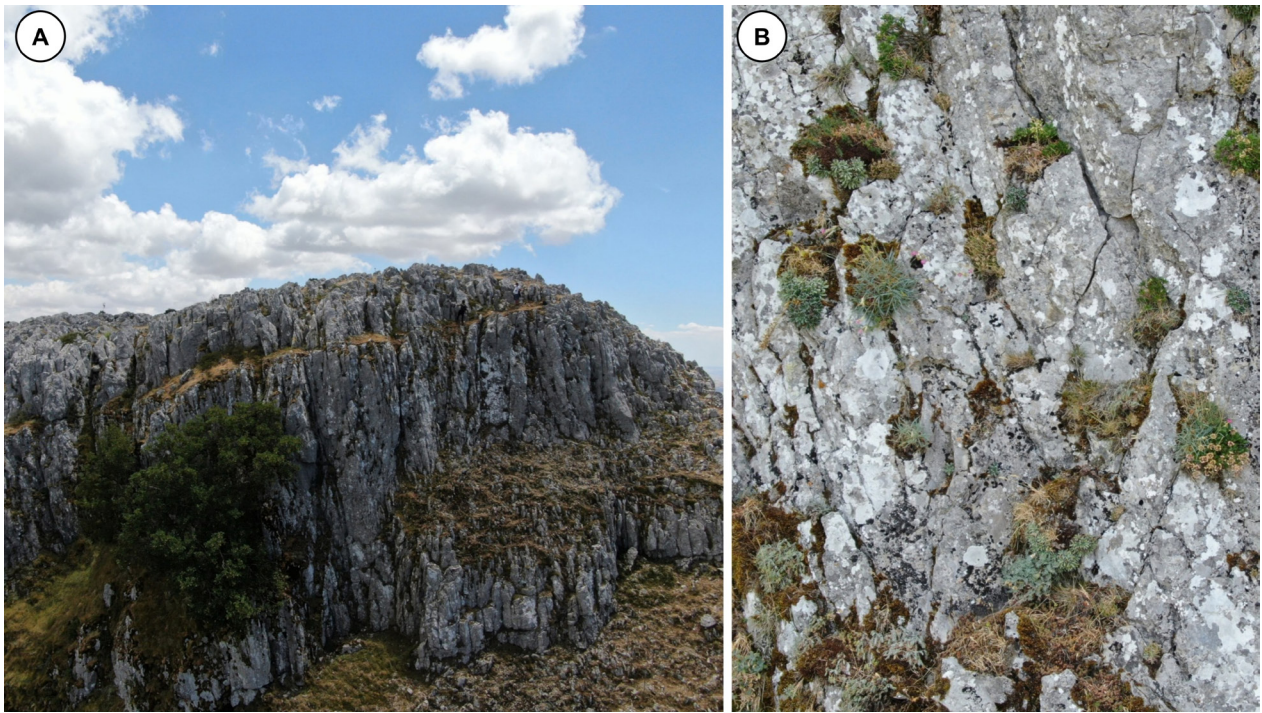


Figure 6. A. Cliffs at Piano dei Cervi (Madonie); B. Close-up of the cliffs with *Saxifraga callosa* subsp. *australis* (images taken on July 10, 2022).

national Red Lists (Orsenigo et al. 2018). The recognition of distinct associations with narrow geographical ranges enhances our understanding of biodiversity patterns and provides a scientific basis for targeted conservation strategies. Both *Athamanto siculae-Saxifragetum australis* and *Cynanchicetum gussonei* can be classified to the habitat 8210 “Calcareous rocky slopes with chasmophytic vegetation”, which is listed in Annex I of Directive 92/43/EEC.

The steep, inaccessible nature of these habitats provides natural protection against direct human disturbance, but they remain vulnerable to climate change impacts, particularly increased drought stress and altered fire regimes (March-Salas et al. 2023). The narrow climatic tolerance of many endemic chasmophytes makes them particularly sensitive to warming trends, which may cause upward range shifts and local extinctions at lower elevations (Pauli et al. 2012). Long-term monitoring using standardized drone-based protocols could provide valuable data on vegetation dynamics and help detect early signs of climate-driven changes.

Conclusions

This study contributes to the phytosociological knowledge of Sicilian chasmophytic vegetation dominated by *Saxifraga callosa* subsp. *australis*, while demonstrating the value of drone-based methods for investigating vegetation in inaccessible habitats. Future research should extend drone-based surveys to other poorly explored mountainous areas of Sicily and southern Italy, integrating such approaches to elucidate the structure of endemic rupicolous phytocenoses.

Syntaxonomic scheme

ASPLENIETEA TRICHOMANIS (Br.-Bl. in Meier et Br.-Bl. 1934) Oberd. 1977

POTENTILLETALIA CAULESCENTIS Br.-Bl. in Br.-Bl. et Jenny 1926

Saxifragium australis Biondi et Ballelli ex S. Brullo 1984
Athamanto siculae-Saxifragetum australis Tavilla, Minisale et Cambria ass. nov.

Cynanchicetum gussonei Brullo 1983 mut. Tavilla, Minisale et Cambria nom. mut. nov.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

The authors employed Gemini 3 Pro (Google) solely to enhance the phrasing and readability of text; the AI did not generate any content independently.

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Author contributions

Conceptualization: GT. Methodology: GT. Software: GT. Formal analysis: GT. Investigation: GT, PM, SC. Data curation: GT. Writing – original draft: GT. Writing – review and editing: GT, PM, SC. Supervision: GT, PM. Validation: GT, PM, SC.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary table S1

Authors: Gianmarco Tavilla, Pietro Minissale, Salvatore Cambria
Data type: xlsx

Explanation note: Phytosociological table of the analyzed relevés.

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Link: <https://doi.org/10.3897/ved.182223.suppl1>

Supplementary material 2

Supplementary figure S1

Authors: Gianmarco Tavilla, Pietro Minissale, Salvatore Cambria
Data type: docx

Explanation note: The supplementary file includes the DCA ordination diagram of species scores.

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