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# Using endemic-plant distribution, geology and geomorphology in biogeography: the case of Sardinia (Mediterranean Basin)

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## Research Article

# Using endemic-plant distribution, geology and geomorphology in biogeography: the case of Sardinia (Mediterranean Basin)

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The importance of robust systems for classifying biogeographical patterns has been emphasized for its usefulness in designing conservation strategies. For such purposes, the distribution patterns of the endemic flora have often been used. Several studies have identified phytogeographical units within Sardinia (western Mediterranean); however, the main part of the island remains unstudied. Thus, the aim of this study is to lay out a comprehensive biogeographical scheme for Sardinia based on endemic vascular plant distributions, together with geological and geomorphological units. We georeferenced, in a 1-km$^2$ grid cell, the presence of 290 vascular endemic taxa from the literature, herbarium specimens and field investigators' research. Sardinia was subdivided into 31 homogeneous units through the integration of geological and geomorphological maps and, subsequently, a presence–absence matrix of endemic taxa in each unit was built. Hierarchical cluster analysis was performed to define two levels of biogeographical units (i.e. sectors and subsectors). For each unit the exclusive and differential endemic taxa were identified. For sectors, indicator species were explored by the Indicator Value (Ind Val) analysis and relationships were analysed by quantitative interaction web. A total of six sectors and 22 subsectors were identified. The highest endemic plant richness was found in the Campidanese-Turritano, Sulcitano-Iglesiente and Supramontano sectors, and in the Gennargenteo, Barbaricino, Iglesiente and Sulcitano subsectors. All sectors were characterized by the presence of exclusive, differential and indicator taxa. The interaction analysis showed the highest uniqueness in endemic flora in the Supramontano and Sulcitano-Iglesiente sectors, which hosted a high number of exclusive endemic species. Mostly mountainous sectors/subsectors had higher endemic-species richness compared with lowland ones. The study showed the relevance of geology and geomorphology, together with accurate data on endemic distribution, to define consistent phytogeographical units. Furthermore, the biogeographical scheme presented here helps to define area-based conservation strategies in Sardinia.

**Keywords**: conservation, continental island, endemic plant richness, geology, geomorphology, Mediterranean vascular flora

## Introduction

Biogeography is a comparative science that attempts to describe and explain spatial patterns of biological diversity on Earth, with respect to its geological history and how these patterns change over time (Lomolino *et al.*, 2006; Parenti & Ebach, 2009). In recent years, the importance of robust systems seeking to classify biogeographical patterns has been emphasized (Whittaker *et al.*, 2005; Mackey *et al.*, 2008; Kreft & Jetz, 2010) for their usefulness in conservation planning (e.g. Mackey *et al.*, 2008 and references therein; Luna-Vega *et al.*, 2013). In this sense, distribution patterns of the vascular flora (e.g. Rivas-Martínez *et al.*, 2002; Moreno Saiz & Lobo, 2008; Moreno Saiz *et al.*, 2013), and in particular of endemic flora (e.g. Rivas Martínez *et al.*, 1997; García Barros *et al.*, 2002; Santa Anna Del Conde *et al.*, 2009; Medina-Cazorla *et al.*, 2010; González-Orozco *et al.*, 2013) has often been used to describe biogeographical schemes.

The spatial distribution of endemic species is not random (e.g. Laffan & Crisp 2003; Tribsch, 2004; Casazza *et al.*, 2008; Essl *et al.*, 2009); but is uneven across the world's land areas, with endemic species often being concentrated in specific regions or habitats (Trigas *et al.*, 2012). Several factors shape endemic distribution patterns, such as area, biotic interactions, stochastic events, habitat diversity, isolation and human impact (e.g. Lobo *et al.*, 2001; Willerslev *et al.*, 2002; MacMaster, 2005; Panitsa *et al.*, 2006; Casazza *et al.*, 2008; Duarte *et al.*, 2008). In addition, the current distribution of endemic species on continental Mediterranean

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islands is related to the fact that palaeogeography is the product of colonization events from the mainland during temporary land connections, followed by *in situ* diversification (e.g. Mansion *et al.*, 2008; Salvo *et al.*, 2010). Furthermore, geology and geomorphology are important factors determining endemic distribution patterns (e.g. Tribsch & Schönswetter, 2003; Valente & Vargas, 2013); indeed, bedrock chemistry has been shown to be significant for the delimitation of biogeographical units in several studies on mountain plants of south-eastern France (Médail & Verlaque, 1997), southern Spain (Mota *et al.*, 2002) and the Swiss Alps (Wohlgemuth, 2002), among others.

The Mediterranean Basin hosts an especially diverse flora due to its particular palaeogeography, climatic conditions, habitat heterogeneity and the varying origins of the flora itself (e.g. Médail & Quézel, 1997; Thompson, 2005; Blondel & Médail, 2009; Trigas *et al.*, 2012). Specifically, Mediterranean islands and islets are not only singular for their species richness, but also for the high endemicity rates (Rosselló *et al.*, 2009).

Sardinia and its *c.* 300 circum-Sardinian islands (including four archipelagos), covering 24 090 km$^2$, are situated in the western Mediterranean basin. The Sardinian flora consists of 2408 taxa (Conti *et al.*, 2005), 171 of which are exclusively endemic (Bacchetta *et al.*, 2012*b*), the particular geological history of the island being a determining factor of the floristic peculiarities. Thus, before the early Oligocene, Sardinia (and Corsica) was situated adjacent to current southern France, forming a continuous geological entity (part of the so-called Hercynian massif) which subsequently fragmented into microplates that dispersed throughout the western Mediterranean (Alvarez *et al.*, 1974). The tectonic separation of Sardinia from Corsica (which shared great floristic affinity, with 90 Sardo-Corsican endemic taxa; Bacchetta *et al.*, 2012*a*) began at 15 Ma and was complete by 9 Ma (Cherchi & Montadert, 1982), although episodic contacts occurred (Lambeck & Purcell, 2005; Gover *et al.*, 2009; Salvo *et al.*, 2010). The prolonged isolation and high geological diversity created a wide range of habitats, with high numbers of endemic species, especially on its mountain massifs (Médail & Quézel, 1997).

From a biogeographical standpoint, Rivas-Martínez *et al.* (2002) considered Sardinia to be a subprovince that, together with Corsican and Tuscano-Calabrian subprovinces, constitutes the Italo-Tyrrhenian province. However, owing to the many similarities, other authors have suggested the rank of biogeographical province for Sardinia and Corsica, within an Italo-Tyrrhenian superprovince, which extends over the western coast of the Italian Peninsula, from Liguria to Calabria (Ladero Alvarez *et al.*, 1987; Bacchetta & Pontecorvo, 2005). More recently, Bacchetta *et al.* (2012*a*) proposed to consider Sardinia, Corsica and the Tuscan Archipelago as an independent biogeographical province.

Based on vascular endemic flora, several studies have identified biogeographical units (sector, subsectors and districts) within the island of Sardinia (e.g. Bacchetta & Pontecorvo, 2005; Bacchetta, 2006; Fenu & Bacchetta, 2008; Angius & Bacchetta, 2009; Fenu *et al.*, 2010; Bacchetta *et al.*, 2013); however, the main part of the island (*c.* 85% of the total surface) still lacks a detailed biogeographical study.

Thus, the aim of the present work was to lay out a comprehensive biogeographical scheme for Sardinia based on a spatially detailed and comprehensive dataset of endemic vascular plant distributions, together with geological and geomorphological units. Additionally, we aim to identify the most endemic-rich areas and to explore the relationships among the biogeographical units.

# Materials and methods

## Floristic data

The checklist of Sardinian endemic vascular plants was taken from Bacchetta *et al.* (2012*a*, *b*) by selecting the 290 endemic taxa (Appendix S1, see online supplemental material, which is available from the article's Taylor & Francis Online page at http://dx.doi.org/10.1080/14772000.2014.894592), which were Sardinian (183 taxa, including 12 new endemic taxa described in Sardinia in the last years) and Sardo-Corsican (90 taxa), as well as taxa also present in the Tuscan Archipelago (17 taxa). We georeferenced the presence of endemic taxa from the available literature (105 studies with 3980 records on 216 taxa), as well as from herbarium specimens conserved in several botanical museums (CAG, CAT, FI, RO, SASSA, SS, TO) and from the Sardinian Germplasm Bank (BG-SAR) database (1158 records on 171 taxa). Finally, 53 450 records on 139 taxa, from the authors' field research (including unpublished data), were incorporated into the database. The final dataset included 2431 records (on 106 taxa) accurately georeferenced, as well as 51 019 records georeferenced to 1-km$^2$ grid cells (of 43 widespread endemics). All records were checked for plausibility by the authors.

## Definition of biogeographical units

Initially, a presence–absence matrix was built by ascribing the georeferenced data of endemic taxa to geological units of Sardinia (60 171 units; Carmignani *et al.*, 2001). Afterwards, we removed duplicate taxon records in each unit. Preliminary hierarchical clustering showed that considering each geological unit independently led to uninterpretable results with regard to geographical coherence, as reported in previous studies (e.g. Reyjol *et al.*, 2007). Accordingly, basic geological units were grouped into homogeneous polygons through the integration of geological (Carmignani *et al.*, 2001) and geomorphological maps of Sardinia (Ulzega, 1988), with a minimum surface area of 780 km$^2$; some limits were adjusted using elevation or other cartographic sources (e.g. hydrographic and land-use maps). Thus, small units were grouped according to similar or identical geological substrates being part of a common structure, regarding origin or topographical features (e.g. mountain range, valley), using a GIS software. Subsequently, a new presence–absence data matrix was built from the total 31 polygons and the 59 232 records on endemic taxa (31 polygons × 1566 records, after removing duplicates). Spatial information was processed using QGIS 1.7.4 (Quantum GIS Development Team, 2012).

The data matrix was analysed by a hierarchical cluster analysis using 'hclust' function, included in the R vegan package (Oksanen *et al.*, 2012). Euclidean distance and arithmetic averages were used as clustering options, since they provided interpretable results. This analysis was performed following the procedure successfully tested by other authors (Reyjol *et al.*, 2007; Reygondeau *et al.*, 2012), by selecting two cut-off levels to define two levels of biogeographical units (sectors and subsectors hereafter). The resulting units were named in relation to local toponymy, according to the system proposed by Rivas Martínez *et al.* (1997).

The indicator species of the identified sectors were explored by the IndVal (Indicator Value) procedure (Dufrêne & Legendre, 1997), using the 'indval' function, which is included in the R labdsv package (Roberts, 2012). This function identifies the most characteristic taxa of each unit, i.e. taxa found mostly in a single unit and present in the majority of sites belonging to that unit. In addition, the endemic taxa that were mostly but not entirely restricted to a sector or subsector, i.e. a species might be found in one or two non-adjacent geological units outside its primary sector, were identified (differential taxa hereafter) following a similar approach used in previous studies (e.g. Laffan *et al.*, 2013).

Finally, to show relationships among Sardinian endemics and sectors, a graphic quantitative interaction web was produced using the R bipartite package (Dormann *et al.*, 2009). All statistical analyses were performed using the R statistical package (R Development Core Team, 2012).

## Results

A total of six biogeographical sectors and 22 biogeographical subsectors were identified (Figs 1–2). Only in the Gennargenteo sector was no subsector identified.

Although the surface area varied among units (for sectors as well as subsectors; Table 1), the highest endemic plant richness was found in the Campidanese-Turritano (166 taxa), Sulcitano-Iglesiente (129 taxa), Supramontano (117 taxa) and Gennargenteo (116 taxa) sectors. At the subsector level, the highest endemic plant richness was found in the Gennargenteo (116 taxa), Barbaricino (98 taxa), Iglesiente (83 taxa), Sulcitano (82 taxa) and Supramontano (79 taxa) subsectors. An exceptionally high number of endemic taxa in relation to its small surface area was found in the Tavolarino subsector (44 taxa in a surface area of *c.* 9 km$^2$; Table 1).

All sectors were characterized by the presence of exclusive endemic taxa, ranging from two to 33 taxa, as well as by differential endemic taxa, ranging from two to 23 taxa (Table 1). The sector with the highest number of exclusive species was the Sulcitano-Iglesiente (33 taxa), followed by the Campidanese-Turritano (31 taxa) and Supramontano (14 taxa) sectors. Also, exclusive taxa were present in all subsectors, except in Nuorese and Ogliastrino (Table 1), reaching a maximum of six (Sulcitano, Turritano and Marghino-Logudorese), seven (Iglesiente and Maddalenino) or eight taxa (Gennargenteo).

By applying indicator-species analysis, we found that some species had a significant preferential distribution in some sectors (Table 1). Specifically, four sectors included at least seven indicator species (Barbaricino, Sulcitano-Iglesiente, Supramontano and Gennargenteo), while Goceano-Logudorese and Campidanese-Turritano were characterized by only one taxon (Table 1).

The quantitative interaction web between sectors and endemic taxa is presented (Fig. 3). The black bar width is proportional to Sardinian endemic richness of the sectors (left bars) or to the frequency of endemic taxa in the sectors (right bars). This graph shows the floristic relationships among sectors; in particular the Sulcitano-Iglesiente and the Supramontano are the most different from each other (maximum distance), with the greatest endemic uniqueness. In addition, this analysis highlights that all sectors were characterized by the presence of exclusive and differential endemic taxa (see Table 1 for details), whereas species such as *Vinca sardoa*, *Oenanthe lisae*, *Quercus ichnusae*, *Santolina insularis* and *Dianthus sardous* were among the most frequent in the sectors (Fig. 3).

## Discussion

The study showed the relevance of geology and geomorphology to define consistent phytogeographical units, since the identified units hosted both exclusive and shared endemic taxa. In particular, six biogeographical sectors and 22 subsectors were defined for Sardinia and the circum-Sardinian small islands (including four archipelagos). This is the first study available to define biogeographical units at a small scale on a Mediterranean islands system, based on accurate distribution pattern of endemic vascular flora.

The biogeographical scheme identified in this study, on the basis of all the Sardinian endemics, was congruent

**Table 1.** Main characteristics of the biogeographical units identified for Sardinia. Abbreviations: No. end. = Number of endemic *taxa*; Prob. = Probability.

| Sector | Area (km$^{2}$) | No. end. | Subsector | Area (km$^{2}$) | No. end. | Exclusive species ($^{*}$) | Differential species ($^{*}$) | Indicator species | Ind_Val | Prob. |
|---|---|---|---|---|---|---|---|---|---|---|
| Gennargenteo | 721 | 116 | | | | *Armeria sardoa*. ssp. *genargentea*; *Centaurea magistrorum*; *Cynoglossum barbaricinum*; *Dianthus genargenteus*; *Genista pichi-sermolliana*; *Lamyropsis microcephala*; *Orobanche denudata*; *Ruta lamarmorae* | *Phalaris rotgesii*, *Trisetaria gracile* | *Hieracium soleirolianum* | 0.6667 | 0.0093 |
| | | | | | | | | *Potentilla rupestris* ssp. *corsica* | 0.6667 | 0.0075 |
| | | | | | | | | *Romulea revelieri* | 0.6349 | 0.0052 |
| | | | | | | | | *Myosotis soleirolii* | 0.5490 | 0.0130 |
| | | | | | | | | *Ranunculus cordiger* ssp. *cordiger* | 0.5000 | 0.0050 |
| | | | | | | | | *Festuca morisiana* | 0.4058 | 0.0370 |
| | | | | | | | | *Trisetaria gracile* | 0.3889 | 0.0193 |
| Goceano-Logudorese | 8643 | 104 | Nuorese (a) | 3894 | 58 | *Dianthus ichnusae* ssp. *ichnusae*$^{c}$; *Dianthus ichnusae* ssp. *toddei*$^{c}$; *Limonium acutifolium* ssp. *bosanum*$^{c}$; *Limonium acutifolium* ssp. *cornusianum*$^{c}$; *Lavatera plazzae*$^{c}$; *Romulea limbarae*$^{b}$; *Rubus arrigonii*$^{c}$; *Rubus limbarae*$^{b}$ | *Genista salzmannii*; *Phalaris rotgesii*$^{b}$; *Potentilla crassinervia*$^{b}$; *Trisetaria gracile*$^{b}$; *Anthyllis hermanniae* ssp. *ichnusae*$^{c}$; *Sagina pilifera*$^{c}$ | *Portulaca sardoa* | 0.3363 | 0.0455 |
| | | | Gallurese (b) | 1887 | 58 | | | | | |
| | | | Marghino-Logudorese (c) | 2954 | 66 | | | | | |
| Sulcitano-Iglesiente | 2897 | 129 | Sulcitano (a) | 1371 | 82 | *Anchusa formosa*$^{a}$; *Anchusa littorea*$^{c}$; *Anchusa montelinasana*; *Armeria sulcitana*; *Astragalus maritimus*$^{b}$; *Astragalus tegulensis*; *Astragalus verrucosus*$^{c}$;*Bellium crassifolium* var. *canescens*$^{d}$; *Cephalaria bigazzii*$^{d}$; *Charybdis glaucophylla*; *Dianthus morisianus*$^{c}$; *Genista arbusensis*; *Genista bocchierii*$^{a;}$ *Genista insularis* ssp. *fodinae*$^{d}$; *Genista insularis* ssp. *insularis*$^{a}$; *Genista ovina*$^{c}$; *Genista sulcitana*$^{e}$; *Genista valsecchiae*; *Helichrysum montelinasanum*; *Lavatera* | *Borago morisiana*; *Echium anchusoides*; *Galium corsicum*; *Genista salzmannii*; *Iberis integerrima*; *Polygala sardoa*; *Santolina corsica*; *Silene morisiana*; *Dianthus mossanus*$^{a,e}$; *Linaria arcusangeli*$^{a}$; *Orobanche australis*$^{a}$; *Phalaris rotgesii*$^{a}$; *Carduus fasciculiflorus*$^{b}$; *Filago tyrrhenica*$^{b,e}$; *Stachys salisii*$^{b}$; *Phleum sardoum*$^{c}$; *Buphthalmum inuloides*$^{d}$; | *Genista valsecchiae* | 0.7143 | 0.0069 |

(*continued*)

**Table 1.** (*Continued*)

| Sector | Area (km$^{2}$) | No. end. | Subsector | Area (km$^{2}$) | No. end. | Exclusive species ($^{*}$) | Differential species ($^{*}$) | Indicator species | Ind_Val | Prob. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *triloba* ssp. *pallescens*$^{d}$; *Limonium carisae*; *Limonium insulare*$^{b}$; *Limonium malfatanicum*$^{a}$; *Limonium merxmuelleri* ssp. *merxmuelleri*$^{d}$; *Limonium sulcitanum*; *Limonium tigulianum*$^{a}$; *Linum muelleri*$^{d}$; *Ophrys normanii*; *Ophrys scolopax* ssp. *sardoa*; *Orchis sardoa*; *Sesleria insularis* ssp. *morisiana*$^{d}$; *Silene martinolii*; *Verbascum plantagineum* | *Clinopodium sandalioticum*$^{d}$; *Dianthus insularis*$^{d}$; *Genista sardoa*$^{d}$; *Leucojum roseum*$^{d}$; *Veronica verna*$^{e}$; *Viola corsica* ssp. *limbarae*$^{e}$ | | | |
| | | | Antioco–Carlofortino (b) | 415 | 47 | | | *Genista morisii* | 0.7108 | 0.0001 |
| | | | Guspinese-Arburese (c) | 339 | 59 | | | *Bellium crassifolium* | 0.6599 | 0.0121 |
| | | | Iglesiente (d) | 321 | 83 | | | *Plagius flosculosus* | 0.5728 | 0.0212 |
| | | | Linisico (e) | 361 | 56 | | | *Verbascum plantagineum* | 0.5714 | 0.0092 |
| | | | | | | | | *Charybdis glaucophylla* | 0.5714 | 0.0079 |
| | | | | | | | | *Bryonia marmorata* | 0.4864 | 0.0227 |
| | | | | | | | | *Genista sulcitana* | 0.4286 | 0.0169 |
| | | | | | | | | *Limonium tigulianum* | 0.4286 | 0.0194 |
| | | | | | | | | *Helichrysum montelinasanum* | 0.4286 | 0.0175 |
| | | | | | | | | *Armeria sulcitana* | 0.4286 | 0.0181 |
| | | | | | | | | *Limonium sulcitanum* | 0.4286 | 0.0178 |
| | | | | | | | | *Stachys corsica* var. *micrantha* | 0.3710 | 0.0284 |
| Campidanese-Turritano | 9365 | 166 | Ogliastrino (a) | 775 | 49 | *Anchusa crispa* ssp. *maritima*$^{c}$; *Anchusa sardoa*$^{g}$; *Asperula deficens*$^{b}$ *Astragalus thermensis*$^{c}$; *Centaurea corensis*$^{c}$; *Centaurea forsythiana*$^{b}$; *Colchicum arenasii*; *Colchicum verlaqueae*$^{e}$; *Genista ephedroides*$^{e}$; *Limonium acutifolium* ssp. *nymphaeum*$^{g}$; *Limonium acutifolium* ssp. *tharrosianum*$^{h}$; *Limonium ampuriense*$^{c}$; *Limonium capitis-eliae*$^{f}$; *Limonium capitis-marci*$^{h}$; *Limonium gallurense*$^{e}$; *Limonium lausianum*$^{h}$ | *Alyssum tavolarae*; *Limonium contortirameum*$^{a}$; *Centaurea horrida*$^{b,g}$; *Clinopodium sandalioticum*$^{b}$; *Dianthus insularis*$^{b,c}$; *Phleum sardoum*$^{c}$; *Salvia desoleana*$^{c}$ *Barbarea rupicola*$^{d}$; *Carduus fasciculiflorus*$^{d,e}$; *Dianthus mossanus*$^{d}$; *Hypericum annulatum*$^{d}$; *Linaria arcusangeli*$^{d}$; *Narcissus supramontanus* ssp. | *Erodium corsicum* | 0.3529 | 0.0352 |

(*continued*)

**Table 1.** (*Continued*)

| Sector | Area (km$^2$) | No. end. | Subsector | Area (km$^2$) | No. end. | Exclusive species (*) | Differential species (*) | Indicator species | Ind_Val | Prob. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Tavolarino (b)<br>Turritano (c)<br>Sarrabense (d)<br>Maddalenino (e)<br>Campidanese (f)<br>Nurrense (g)<br>Sinisico (h) | 9<br>1703<br>645<br>362<br>5031<br>685<br>81 | 44<br>52<br>44<br>54<br>68<br>41<br>29 | *Limonium merxmuelleri* ssp. *oristanum*$^{f}$; *Limonium multifurcatum*$^{e}$ *Limonium pseudolaetum*$^{h}$; *Limonium pulviniforme*$^{e}$; *Limonium racemosum*$^{c}$; *Limonium retirameum* ssp. *caralitanum*$^{f}$; *Limonium tibulatium*$^{e}$; *Limonium ursanum*$^{e}$; *Limonium viniolae*$^{c}$; *Medicago intertexta* var. *tuberculata*$^{h}$; *Polygala sinisica*$^{h}$; *Romulea bocchierii*$^{d}$; *Scrophularia morisii*$^{c}$; *Senecio vulgaris* var. *tyrrhenum*$^{e}$; *Silene ichnusae*$^{g}$ | *cunicularium*$^{d,e}$; *Silene valsecchiae*$^{d,e}$; *Stachys salisii*$^{e}$ *Genista sardoa*$^{g}$; *Limonium laetum*$^{g}$; *Orobanche australis*$^{g}$ | | | |
| Barbaricino | 1294 | 116 | Sarcidanense (a) | 489 | 67 | *Anchusa capellii*$^{b}$; *Helianthemum morisianum*$^{a}$ | *Orobanche australis*$^{a}$; *Sagina pilifera*$^{b}$ | *Helianthemum morisianum* | 1.000 | 0.0008 |
| | | | Barbaricino (b) | 806 | 98 | | | *Solenopsis minuta* ssp. *corsica* | 1.000 | 0.0012 |
| | | | | | | | | *Ophrys ortuabis* | 0.8750 | 0.0032 |
| | | | | | | | | *Colchium gonarei* | 0.8750 | 0.0030 |
| | | | | | | | | *Ophrys funerea* | 0.7933 | 0.0025 |
| | | | | | | | | *Hypericum scruglii* | 0.7640 | 0.0058 |
| | | | | | | | | *Iberis integerrima* | 0.7636 | 0.0051 |
| | | | | | | | | *Dianthus insularis* | 0.7580 | 0.0024 |
| | | | | | | | | *Aquilegia nugorensis* | 0.7500 | 0.0061 |
| | | | | | | | | *Cymbalaria muelleri* | 0.7059 | 0.0056 |
| | | | | | | | | *Galium glaucophyllum* | 0.6269 | 0.0135 |
| | | | | | | | | *Ranunculus cymbalarifolius* | 0.5793 | 0.0195 |
| | | | | | | | | *Helichrysum saxatile* ssp. *saxatile* | 0.5285 | 0.0235 |
| | | | | | | | | *Anchusa capellii* | 0.5000 | 0.0480 |
| | | | | | | | | *Crepis caespitosa* | 0.5000 | 0.0467 |
| | | | | | | | | *Cistus creticus* var. *corsicus* | 0.4972 | 0.0353 |
| | | | | | | | | *Campanula forsythii* | 0.4668 | 0.0377 |
| | | | | | | | | *Borago pygmaea* | 0.4548 | 0.0190 |

(*continued*)

**Table 1.** (*Continued*)

| Sector | Area (km$^2$) | No. end. | Subsector | Area (km$^2$) | No. end. | Exclusive species (*) | Differential species (*) | Indicator species | Ind_Val | Prob. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | *Biscutella morisiana* | 0.4546 | 0.0387 |
| | | | | | | | | *Limonium morisianum* | 0.4138 | 0.0495 |
| | | | | | | | | *Romulea requienii* | 0.2884 | 0.0420 |
| Supramontano | 1348 | 117 | Supramontano (a) | 162 | 79 | *Aquilegia cremnophila*$^{a}$; *Aquilegia nuragica*$^{b}$; *Astragalus gennarii*$^{c}$; *Brassica tyrrhena*; *Centaurea filiformis* ssp. *ferulacea*$^{b}$; *Centranthus amazonum*; *Festuca alfrediana* ssp. *alfrediana*$^{a}$; *Genista cadasonensis*$^{b}$; *Genista toluensis*; *Lactuca longidentata*; *Limonium coralliforme*$^{c}$; *Narcissus supramontanus* ssp. *supramontanus*$^{a}$; *Nepeta foliosa*$^{a}$; *Ribes sardoum*$^{a}$ | *Hypericum scruglii*$^{a}$; *Stachys corsica* var. *micrantha*$^{b}$; *Carduus fasciculiflorus*$^{c}$ | *Lactuca longidentata* | 0.6955 | 0.0070 |
| | | | Oroseino (b) | 240 | 61 | | | *Anthyllis hermanniae* ssp. *ichnusae* | 0.5877 | 0.0193 |
| | | | Baronico (c) | 946 | 73 | | | *Centranthus amazonum* | 0.5000 | 0.0068 |
| | | | | | | | | *Genista toluensis* | 0.5000 | 0.0082 |
| | | | | | | | | *Brassica tyrrhena* | 0.5000 | 0.0094 |
| | | | | | | | | *Colchicum actupii* | 0.5000 | 0.0063 |
| | | | | | | | | *Ophrys panattensis* | 0.4500 | 0.0069 |
| | | | | | | | | *Micromeria cordata* | 0.4298 | 0.0171 |
| | | | | | | | | *Limonium protohermaeum* | 0.4048 | 0.0198 |
| | | | | | | | | *Cerastium supramontanum* | 0.3971 | 0.0182 |
| | | | | | | | | *Limonium hermaeum* | 0.3696 | 0.0262 |

(*) Different letters indicate that this taxon is exclusive or differential of the correspondent subsector.

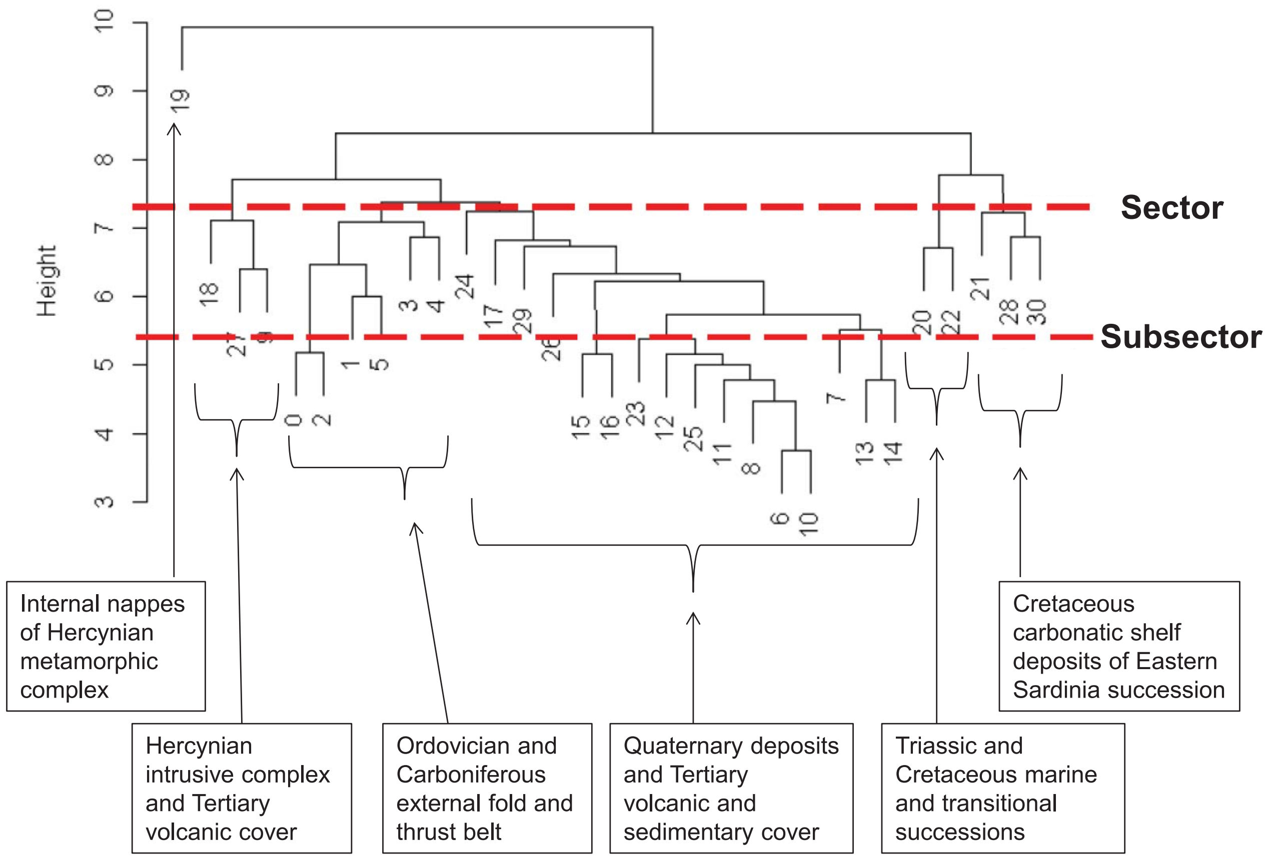

**Fig. 1.** Dendrogram derived from hierarchical cluster analysis showing two cut-off levels to define sectors and subsectors, as well as geological features. Characteristics of each geological unit, according to Carmignani *et al.* (2001): (0) Metalimestones and metasandstones of Lower Cambrian; (1) Oligocene-Miocene calcalkaline volcanic cycle; (2) Carboniferous quartzites and granites; (3) Coastal metalimestones and metasandstones of Lower Cambrian; (4) Ordovician-Carboniferous metasandstones and metasiltstones; (5) Coastal Ordovician metasandstones; (6) Quaternary conglomerates, sand and mud deposits; (7) Tertiary basalts and limestones; (8) Quaternary conglomerates, sand and mud deposits; (9) Oligocene-Miocene calcalkaline volcanic cycle; (10) Post Middle Eocene-Lower Miocene continental and marine deposits; (11) Cenozoic continental and marine deposits; (12) Basaltic plateaus and rhyolitic uplands of Pliocene lying on post Middle Eocene-Lower Miocene marls, sands and siltstones; (13) Triassic-Cretaceous carbonatic shelf deposits; (14): Palaeozoic paragneisses and alkaline metagabbroes; (15) Coastal granites; (16) Para-Sardinian islands of granitic origin; (17) Para-Sardinian island of dolomitic origin; (18) Hercynian granitic basement; (19) Hercynian metamorphic complex; (20) Upper Cretaceous dolomitic uplands; (21) Upper Cretaceous carbonatic mountains; (22) Upper Cretaceous dolomitic uplands with a Devonian-Carboniferous terrigenous basement; (23) Middle Cambrian-Lower Odovician micaceous metasandstones and quartzites; (24) Upper Carboniferous-Permian tonalitic granodiorites; (25) Metamorphic rocks of Ordovician-Carboniferous origin; (26) Upper Carboniferous-Permian tonalitic granodiorites; (27) Hercynian granitic mountains; (28) Upper Cretaceous carbonatic coast; (29) Oligo-Miocenic andesites and ignimbrites spaced out by Miocenic silty and sandy marls; (30) Paragneisses and Pliocenic rhyolite.

with the results of partial studies carried out in some floristic territories within the island (Bacchetta & Pontecorvo, 2005; Bacchetta, 2006; Fenu & Bacchetta, 2008; Angius & Bacchetta, 2009; Fenu *et al.*, 2010; Bacchetta *et al.*, 2013), although some minor differences at the subsector level were found.

Several units were well defined, not only because of the endemic flora that they shared, but also because they owned a high number of exclusive, differential and indicator endemic taxa. On the contrary, the definition of other units was less conclusive (i.e. the Campidanese-Turritano sector and their subsectors), since they are characterized by scarcity of exclusive or indicator endemic taxa. This result could be due to geology, geomorphology and historical constraints (e.g. Jansson, 2003; Casazza *et al.*, 2008), but also to be a territory with high level of anthropic alteration (which can cause the loss of endemic plants) or still not thoroughly investigated.

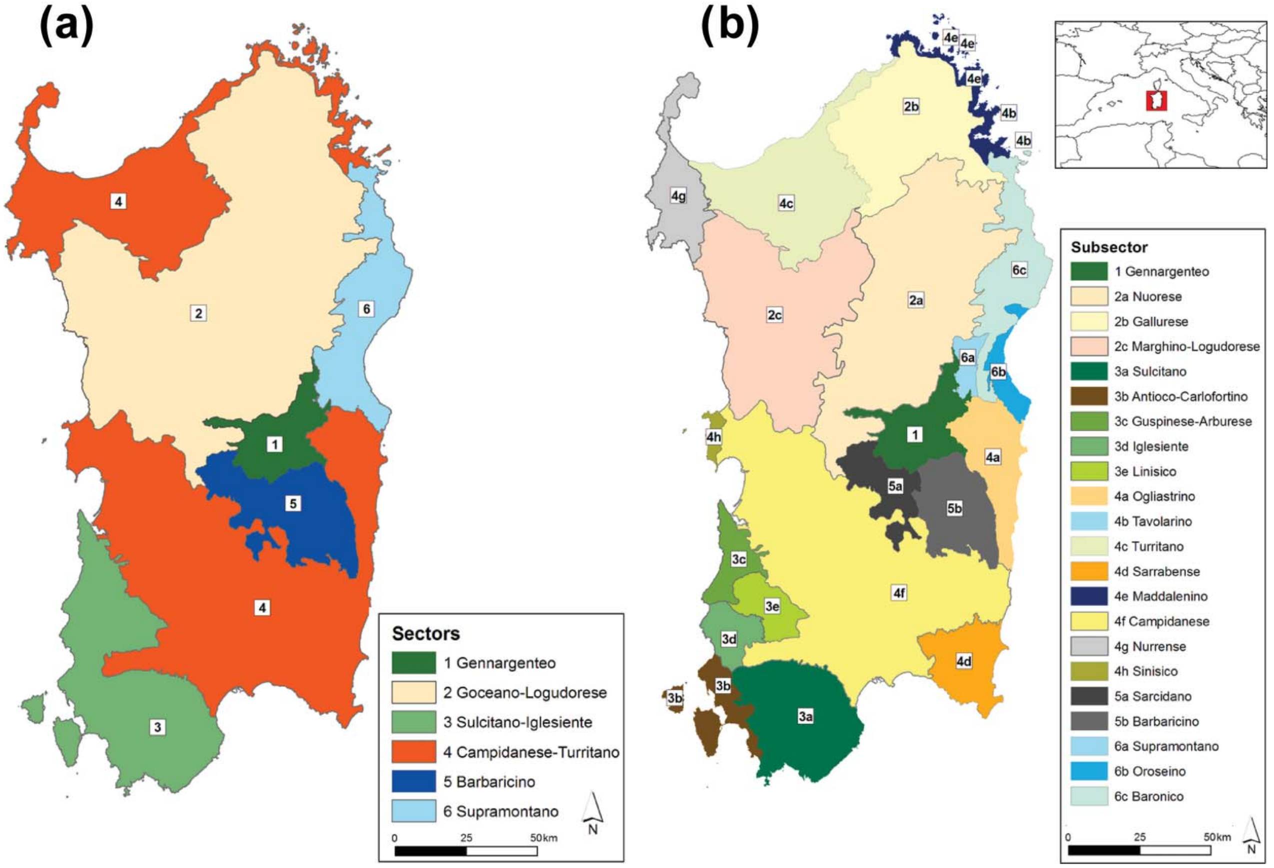

**Fig. 2.** Biogeographical regionalization in sectors (a) and subsectors (b) of Sardinia based on the distribution of endemic vascular plants.

Our results show that the mountainous subsectors maintain higher endemic species richness compared with lowland ones. Higher endemic-species richness in the mountainous areas could be attributed to increased ecological isolation, altitudinal range or higher habitat diversity (Médail & Quézel, 1997; Thompson, 2005; Fenu *et al.*, 2010; Trigas *et al.*, 2012; Bacchetta *et al.*, 2013; Cañadas *et al.*, 2014). In addition, these areas have a high level of naturalness and low human pressure.

Island geology has been recognized to be a strong determinant of species numbers (Kreft *et al.*, 2008). In this sense, for example, in the Sulcitano-Iglesiente sector the complex palaeogeography (these areas have constituted islands for long periods) and geological history (i.e. Palaeozoic limestones and dolomites in the Iglesiente subsector, Palaeozoic autochthonous siliceous rocks such as metapelites, metacalcites and metasiltites in the Sulcitano subsector; see Carmignani *et al.*, 2001), have played a key role in the evolution of endemic richness (Bacchetta, 2006).

In addition, the Sulcitano-Iglesiente, Gennargenteo and Supramontano sectors include several areas that were identified as Mediterranean putative refugia (*sensu* Médail & Diadema, 2009) with high endemic richness (Fenu *et al.*, 2010; Bacchetta *et al.*, 2013). The less drastic climate changes on large Mediterranean islands during the Quaternary could promote the local persistence of high plant richness and the co-existence of distinct genetic lineages (Valiente Banuet *et al.*, 2006; Medail & Diadema, 2009). The quantitative interaction graph separates, according to their endemic flora, the south-western part of Sardinia (Sulcitano-Iglesiente sector) from the central territories of the Island (Gennargenteo and Supramontano sectors). Thus, these sectors have a complex geological history and prolonged insularity and include several putative Mediterranean refugia.

The high endemic richness in the Tavolarino subsector deserves special attention. An anomalous species richness on smaller islands, in comparison with larger ones, has been identified and this phenomenon has been described as the 'small island effect' (Panitsa *et al.*, 2006). The debate over this effect is not yet resolved (Triantis *et al.*, 2012), although the case of the Tavolarino subsector could be useful to test whether the small islands deviate from the common pattern of species–area relationship (Panitsa *et al.*, 2006). In addition, the carbonate substrates and the

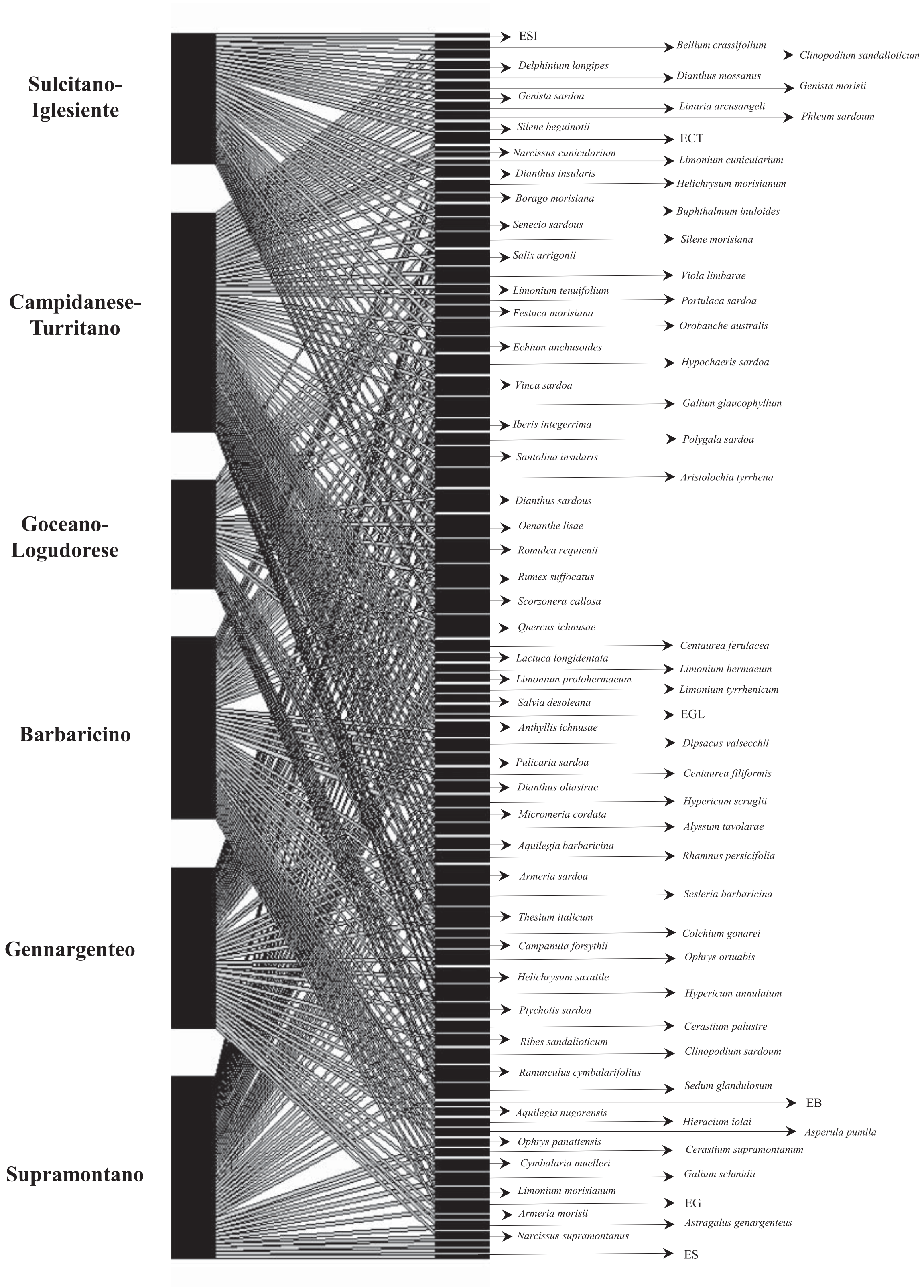

**Fig. 3.** Quantitative endemic-sector interaction web. Left bars represent sectors and right bars represent endemic taxa. Linkage width indicates the presence of each endemic taxon in each sector. Exclusive endemic taxa of each sector (given in Table 1) were grouped and showed using the following abbreviations: **ESI** (Exclusive of Sulcitano-Iglesiente sector), **ECT** (Exclusive of Campidanese-Turritano sector), **EGL** (Exclusive of Goceano-Logudorese sector), **EB** (Exclusive of Baronico sector), **EG** (Exclusive of Gennargenteo sector) and **ES** (Exclusive of Supramontano sector). Plant names are given in Appendix S1.

island altitude, higher than the other circum-Sardinian islands and comparable to the cliffs of Orosei Gulf, could strongly govern endemic richness. Similarly, the Sinisico subsector, consisting mainly of carbonate substrates, deserves particular attention because these substrates constitute an ecological island with a wide range of habitat variability (Fenu & Bacchetta, 2008).

The definition of biogeographical units on a fine scale, which is considered a fundamental step in biogeography in recent decades (Hengeveld, 1999; Di Virgilio *et al.*, 2013), gained key support from tools such as geographical information system (GIS). The GISs make possible the creation of geodatabases with detailed information on taxa distribution and other key variables in biogeographical studies, such as geology and geomorphology. Moreover, the use of different tools such as the Indval Analysis, which enable the identification of indicator taxa in geographical units (Casazza *et al.*, 2008; Casazza & Minuto, 2009), can help in biogeographical analysis. Similarly, the bipartite network diagram, showing the relationships among Sardinian endemic taxa and biogeographical sectors, used for the first time in this type of study, may represent a powerful tool to summarize the biogeographical scheme of a territory. These tools are a valuable help to obtain useful information for biogeographical units, identifying key taxa for conservation within the units. In fact, conservation guidelines have been improved over recent decades by applying biogeographical methods and principles (Whittaker *et al.*, 2005). Since the identification of priorities at finer scales is essential to ensure the implementation of conservation measures (e.g. Brooks *et al.*, 2006; Cañadas *et al.*, 2014), the biogeographical scheme presented here helps to identify area-based conservation strategies in a floristic hotspot such as Sardinia.

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