

Classification of the Sardinian pine woodlands

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Abstract. Mediterranean pine woodlands are one of the most common wooded vegetation types across the Mediterranean Basin and are included in two habitats of European interest as they have great conservation importance. We studied the woodlands of the class *Pinetea halepensis* dominated by *Pinus halepensis*, *P. pinaster*, and *P. pinea* in Sardinia (Italy) with the aim to clarify their syntaxonomic position. We compiled a dataset of 66 original vegetation relevés, complemented with the holotypes of similar vegetation types formerly described for Italy and Corsica (France). We classified *P. halepensis* woodlands, native to the Island of San Pietro, to the association *Erico arboreae-Pinetum halepensis*. We classified *P. halepensis* woodlands growing on limestones of the south-western coast of Sardinia to the new association *Smilaco asperae-Pinetum halepensis* and woodlands typical of coastal dunes to the new association *Asparago horridi-Pinetum halepensis*. We also described the northeastern Sardinia *P. pinaster* woodlands as the new association *Arbuto unedonis-Pinetum pinastri*, of which we recognised two new subassociations, *typicum* and *cephalantheretosum longifoliae*, ecologically distinguished by the xerophilous and mesophilous conditions, respectively. Furthermore, we classified *P. pinea* woodlands, putatively native only to stabilised sand dunes of south-western Sardinia, in the new association *Quercus calliprini-Pinetum pineae*. This study represents the first complete survey and classification of Sardinian pine woodlands, allowing a better understanding of their ecology, floristic composition and differences from other Mediterranean pine woodlands.

Keywords: Mediterranean Basin, phytosociology, *Pinetea halepensis*, *Pinus halepensis*, *Pinus pinaster*, *Pinus pinea*, Sardinia, syntaxonomy, vegetation.

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Introduction

Mediterranean pine woodlands are one of the most common wooded vegetation types across the Mediterranean Basin (Barbéro *et al.*, 1998). Many studies have analysed these plant communities, with increasing ecological and phytosociological attention in the last decade (Biondi & Vagge, 2015; Pesaresi *et al.*, 2017; Bonari *et al.*, 2018; Sarmati *et al.*, 2019; Bonari *et al.*, 2021). Recently, the new class *Pinetea halepensis* Bonari et Chytrý in Bonari *et al.* 2021 has been proposed. This class is physiognomically and compositionally different from the Mediterranean oak woodlands of the class *Quercetea ilicis* Br.-Bl. ex A. Bolòs et O. de Bolòs in A. Bolòs y Vayreda 1950 and comprehends pine woodlands dominated by *Pinus brutia* Ten., *P. halepensis* Mill., *P. pinaster* Ait. and *P. pinea* L. (Bonari *et al.*, 2021). A large amount of information previously scattered among tens of local studies has been recently integrated in a specific electronic vegetation database (*CircumMed Forest Database*, Bonari *et al.*, 2019). Nonetheless, a gap for lower levels

of the syntaxonomic knowledge of these natural formations in some areas of the Mediterranean Basin remains. In this respect, the island of Sardinia results of crucial importance, being placed at the centre of the Tyrrhenian Sea and hosting three Mediterranean pine species (*Pinus halepensis*, *P. pinaster*, and *P. pinea*) with an indigenous status, though putative indigenous in the case of *P. pinea* (Arrigoni, 2006; Pignatti *et al.*, 2017–2019).

From the phytosociological point of view, early studies about *P. halepensis* communities in Italy started in the second half of the 20th century (Agostini, 1964; De Marco & Mossa, 1980; De Marco & Caneva, 1984; De Marco *et al.*, 1984). More recently, the phytosociological aspects of *P. halepensis* woodlands of the central-eastern Mediterranean area were reviewed (Pesaresi *et al.*, 2017). The authors recognised five alliances and 25 associations, 15 of them present in Italy, while others occurring in France, Croatia, Albania, and Greece (Pesaresi *et al.*, 2017).

A few studies focused on *Pinus pinaster* woodlands in recent decades in Italy. These works considered

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P. pinaster woodlands of the Island Pantelleria in Sicily (Brullo *et al.*, 1977; Gianguzzi, 1999) and the communities of Liguria and Tuscany in north-western Italy (Biondi & Vagge, 2015). While contributions exist for the nearby island of Corsica (France), where these woodlands have been classified at the syntaxonomic rank of subassociation in the *Pulicario odorae-Arbutetum umedonis* Allier et Lacoste 1980 *pinetosum hamiltonii* Gamisans 1975 (Gamisans, 1977; Reymann *et al.*, 2016), phytosociological analyses of *P. pinaster* woodlands are currently lacking for Sardinia (Bacchetta *et al.*, 2009).

Italian studies regarding the phytosociological aspects of *P. pinea* woodlands are generally scarce. This is primarily linked to the fact that many woodlands have been planted. The natural communities are classified in two associations described for Sicily (Bartolo *et al.*, 1994; Brullo *et al.*, 2002). In Sardinia, the only putative native *P. pinea* population, firstly reported by Moris (1827), was studied by Mossa (1990), who provided a phytosociological table, without describing any association.

Mediterranean pine woodlands are included in two habitats of European interest (Habitats Directive 92/43/EEC) and they have great conservation importance (Bonari *et al.*, 2020). In coastal dunes, the habitat with Mediterranean and Atlantic thermophilous pines (*Pinus pinea*, *P. pinaster* and *P. halepensis*), including old-established plantations within their natural distribution range, is identified with the priority code 2270* - wooded dunes with *Pinus pinea* and/or *P. pinaster* (European Commission, 2013), while the other habitat of Mediterranean pines is identified with the code 9540 - Mediterranean pine forests with endemic Mesogean pines (European Commission, 2013). Mediterranean pine woodlands are also classified under the code T3A in the EUNIS classification system (Chytrý *et al.*, 2020).

In this study, we aim at describing the natural pine woodlands of Sardinia. Our specific aims were: (i) to test the differences of Sardinian relevés from previously described syntaxa from the Italian Peninsula, including Sicily, and Corsica, and (ii) to build an updated syntaxonomic scheme of Sardinian native pine woodlands.

Material and Methods

Study area

Sardinia, with an area of 24,090 km², including numerous smaller islands and islets, is the second-largest island of the Mediterranean Basin, after Sicily. The Hercynian granitic basement characterises the eastern half of the island, while effusive rocks are dominant in the western part. Other important geologic formations are represented by metamorphic rocks, and sedimentary carbonate reliefs, which are present in many parts of the island from north to south with a patchy distribution (Carmignani *et al.*, 2016).

The climate of Sardinia is characterised by a typical Mediterranean seasonality, with mild-wet winters, and

dry-hot summers. Mean annual temperature ranges between 11.6°C and 18°C, while annual rainfall ranges from 441 mm to 1,134 mm (Bacchetta *et al.*, 2009). Overall, two macro-bioclimates (*sensu* Rivas-Martínez *et al.*, 2002), seven thermotype belts, and 43 iso-bioclimates have been identified and mapped (Canu *et al.*, 2015).

In the framework of the Italo-Tyrrhenian biogeographic super-province (Ladero-Alvarez, 1987; Rivas-Martínez *et al.* 2002; Bacchetta *et al.*, 2012), Sardinia falls in the context of the Sardinian-Corsican biogeographic province (Bacchetta *et al.*, 2012), having a complex biogeography (Fenu *et al.*, 2014).

Pine species of interest

Pinus halepensis (Aleppo pine) is a Circum-Mediterranean species (Fady *et al.*, 2003; Mauri *et al.*, 2016; Farjon, 2017; Pesaresi *et al.*, 2017). It is considered native to Spain, Balearic Islands, France, Italy, Sardinia, Sicily, Bosnia and Herzegovina, Croatia, Montenegro, Albania, Greece, Turkey, Lebanon, Syria, Jordan, Israel, Morocco, Algeria, Tunisia, and Libya, while it is doubtful native to the Greek islands, Crete, and Cyprus (Euro+Med, 2006-2021). In Italy, *P. halepensis* is native to many regions, including Sicily and Sardinia, while it is absent in Piedmont and Val d'Aosta, and accidentally introduced in Lombardy, Veneto, and Friuli-Venezia Giulia (Pignatti *et al.*, 2017-2019; Bartolucci *et al.*, 2020). Its elevation range is normally limited to lowlands, but it can reach 1,600 m asl in Spain (López González, 2004), and 1,700 m asl in Morocco (Farjon, 2017). The species occurs on various substrates, but its optimum is on marls and limestones (Mauri *et al.*, 2016). It is a thermophilous and drought-resistant plant, therefore preferring semi-arid to sub-humid ombrotypes (*sensu* Rivas-Martínez *et al.*, 2002), with an annual average rainfall comprised between 350 and 700 mm (Barbéro *et al.*, 1998; Mauri *et al.*, 2016). The woodlands dominated by this species are concentrated mainly in the western half of the Mediterranean Basin, while they are more scattered in the eastern half (Pesaresi *et al.*, 2017). These woodlands have a typical open canopy and are frequently reported as aspects of garrigue or scrubland vegetation with scattered pines (Mauri *et al.*, 2016).

Pinus pinaster s.l. (Maritime pine) is a western Mediterranean species (Abad Viñas *et al.*, 2016a). It is native to Portugal, Spain, Balearic Islands, France, Corsica, Italy, Sardinia, Sicily, Morocco, Algeria, and Tunisia (Euro+Med, 2006-2021). In Italy, *P. pinaster* is native to Piedmont, Liguria, Tuscany, Umbria, Latium, Sicily (Pantelleria), and Sardinia (Pignatti *et al.*, 2017-2019). This species grows in a broad elevation range, from the sea level to 1,600 m asl in Spain and Corsica but can reach 2,000 m asl in Morocco (Abad Viñas *et al.*, 2016a). It is usually a heliophilous, thermophilous species, preferring a climate with oceanic influence, and a minimum annual average rainfall of about 600 mm. Geologically, it usually thrives on siliceous substrates, rarely growing on limestones (Abad Viñas

et al., 2016a). The woodlands dominated by *P. pinaster* have an open canopy. They can be either mixed with oaks or monospecific, with a greater or lesser thick understorey of sclerophyllous shrubs (Farjon, 2017).

Pinus pinea (Stone pine) is a typical Mediterranean species, although its native distribution remains controversial due to old-established plantations (Bonari et al., 2017). This species grows in many Mediterranean countries, such as Portugal, Spain, Balearic Islands, France, Italy, Sardinia, Sicily, Croatia, Montenegro, Greece, Cyprus, Turkey, Syria, and Lebanon (Euro+Med, 2006–2021). In Italy, it is present in the peninsular regions, in Sicily and Sardinia, but is often widely planted (Pignatti et al., 2017–2019). In Sicily, fossil *P. pinea* cones from Pliocene sediments near Messina suggest the autochthony of the species (Zodda, 1902). On the other hand, for Sardinia there is no palaeobotanical evidence of its native status but some palynological findings to be deepened (Del Rio & Pittau, 1974). In Italy, it is primarily a species of coastal areas, while in Spain, Portugal, and Anatolia it also grows inland (Abad Viñas et al., 2016b; Bonari et al., 2020), and can reach elevations up to 1,000 m asl (Bonari et al., 2021). This species has been defined as a heliophilous, xerophilous, and thermophilous plant, having an optimum of 600 mm of rain per year (Abad Viñas et al., 2016b). In natural or semi-natural conditions, *P. pinea* forms woodlands with an open canopy and a shrub layer that, when present, varies in thickness. Normally, *P. pinea* is taller than the other co-occurring trees, sometimes forming mixed woodlands with other pines or oaks, e.g. *Quercus ilex* L. (Farjon, 2017).

Data collection

To obtain an update of the distribution of Sardinian natural pine woodlands, we initially retrieved references related to the natural distribution of the three pine species in Sardinia from local literature (Moris, 1827; Desole, 1960; 1964; Arrigoni, 1967; De Marco & Mossa, 1980; Mossa, 1990; Bacchetta, 2006; Bacchetta et al., 2009; Calvia & Ruggero, 2020). Then, during the years 2017–2019, we undertook a survey of the natural woodlands growing in Sardinia, mainly based on the available cartography, but also making use of the local knowledge. We carried out vegetation relevés on natural formations dominated by each pine species in the whole of Sardinia and collected environmental features, including elevation, slope, and aspect.

All the phytosociological sampling was carried out following the Zürich-Montpellier method (Braun-Blanquet, 1965; Rivas-Martínez, 2005). We followed the fourth edition of the International Code of Phytosociological Nomenclature (ICPN; Theurillat et al., 2021) for phytosociological nomenclature. Higher syntaxonomic ranks of pine woodlands follow Bonari et al. (2021). Other names of syntaxa in the text are according to Mucina et al. (2016). We identified all plant species using Arrigoni (2006–2015), Jeanmonod & Gamisans (2013) and Pignatti et al. (2017–2019). The plant names follow Euro+Med PlantBase (Euro+Med, 2006–2021) and Bartolucci et al. (2018).

Data preparation and analyses

To investigate the differences in species composition in each of the three Sardinian pine woodland types, we used the original 66 relevés of our survey contrasted with all the type relevés published for Italy and Corsica (see the list of associations in Appendix S1, Brullo et al., 1977; De Marco et al., 1984; De Marco & Caneva, 1984; Bartolo et al., 1994; Brullo et al., 2002; Biondi & Vagge, 2015; Pesaresi et al., 2017) obtained from *CircumMed Forest Database* (Bonari et al., 2019). Based on the assumption that the relevé type represents, in most cases, the barycentre of the compositional variability of a given association, the use of type relevés allowed us to better interpret the (dis-)similarities of the Sardinian communities with the other pine woodland types from the central Mediterranean area. Overall, we used 14 relevés for *P. halepensis* woodlands from Italy, and one from France (Corsica), four for *P. pinaster* woodlands from Italy and two for *P. pinea* woodlands from Italy (Sicily). The datasets included 39 relevés × 171 species for *P. halepensis* woodlands (24 original relevés, and 48 species are reported in Table S1), 36 relevés × 107 species for *P. pinaster* woodlands (32 original relevés, and 83 species are reported in Table S2) and 12 relevés × 70 species for *P. pinea* woodlands (10 original relevés, and 50 species are reported in Table S3). The decision of using three separated datasets for each dominant pine species was driven by the physiognomic approach recently adopted for Mediterranean pine forests (Bonari et al., 2021). Before the analysis, we combined the cover values of the same species present in different layers in a single layer. It was calculated under the assumption that covers can overlap and that they do so independently of each other (see Tichý & Holt, 2006).

We used TWINSpan (Hill, 1979) to classify the phytosociological relevés of the three datasets, setting the parameters of three pseudospecies cut levels (the “pseudospecies cut levels” value is the number of cut levels, while “values of cut levels” are the percentages corresponding to each cut level; Tichý & Holt, 2006), species percentage cover (0, 10, 25%) and minimum group size of two plots. We obtained eight, six, and two clusters for *P. halepensis*, *P. pinaster*, and *P. pinea*, respectively. We interpreted all the TWINSpan clusters by comparing species composition, ecological characteristics, and literature data, subsequently merging clusters in case of no substantial dissimilarities between them.

We defined diagnostic species for the clusters obtained by TWINSpan, and used the phi coefficient of association as fidelity measure calculated for equalised size of clusters following Tichý & Chytrý (2006). We defined diagnostic species as those with phi coefficient ≥ 0.3 and Fisher’s exact test value of the probability of the given concentration of species occurrences within the cluster < 0.05 . We defined constant species those with a percentage occurrence frequency $> 20\%$, and dominant species those occurring with a cover $> 20\%$.

Table 1. Synoptic table of the percentage constancies of the diagnostic, constant and dominant species for the vegetation plots dominated by *Pinus halepensis*. Species are sorted by decreasing values of the phi coefficient (Φ) for each association; only species with $\Phi > 0.3$ and $p < 0.05$ (based on Fisher's exact test) are shown.

<i>Smilaco asperae-Pinetum halepensis</i>	%	<i>Asparago horridi-Pinetum halepensis</i>	%	<i>Erico arboreae-Pinetum halepensis</i>	%
Number of relevés: 6		Number of relevés: 8		Number of relevés: 10	
Diagnostic species		Diagnostic species		Diagnostic species	
<i>Smilax aspera</i>	100.0	<i>Juniperus macrocarpa</i>	100.0	<i>Erica arborea</i>	100.0
<i>Arisarum vulgare</i>	66.6	<i>Tolpis virgata</i>	90.7	<i>Myrtus communis</i>	85.3
<i>Quercus calliprinos</i>	63.2	<i>Asparagus horridus</i>	81.6	<i>Arbutus unedo</i>	78.0
<i>Stachys major</i>	47.4	<i>Pancreatum maritimum</i>	75.0	<i>Lonicera implexa</i>	78.0
Constant species		<i>Silene canescens</i>	72.5	<i>Salvia rosmarinus</i>	66.7
<i>Pinus halepensis</i>	100.0	<i>Sixalix atropurpurea</i>	63.2	<i>Cistus monspeliensis</i>	55.5
<i>Pistacia lentiscus</i>	100.0	<i>Asphodelus ramosus</i>	46.3	Constant species	
<i>Juniperus turbinata</i>	100.0	Constant species		<i>Pinus halepensis</i>	100.0
<i>Phillyrea angustifolia</i>	100.0	<i>Pinus halepensis</i>	100.0	<i>Phillyrea angustifolia</i>	100.0
<i>Asparagus acutifolius</i>	100.0	<i>Juniperus macrocarpa</i>	100.0	<i>Pistacia lentiscus</i>	100.0
<i>Rubia peregrina</i>	100.0	<i>Asparagus acutifolius</i>	100.0	<i>Erica arborea</i>	100.0
<i>Smilax aspera</i>	100.0	<i>Pistacia lentiscus</i>	100.0	<i>Myrtus communis</i>	80.0
<i>Arisarum vulgare</i>	67.0	<i>Rubia peregrina</i>	100.0	<i>Salvia rosmarinus</i>	80.0
<i>Stachys major</i>	67.0	<i>Juniperus turbinata</i>	75.0	<i>Arbutus unedo</i>	70.0
<i>Quercus calliprinos</i>	50.0	<i>Asparagus horridus</i>	75.0	<i>Lonicera implexa</i>	70.0
<i>Carex distachya</i>	33.0	<i>Tolpis virgata</i>	88.0	<i>Juniperus turbinata</i>	50.0
<i>Asphodelus ramosus</i>	33.0	<i>Pancreatum maritimum</i>	62.0	<i>Asparagus acutifolius</i>	50.0
<i>Piptatherum miliaceum</i>	33.0	<i>Silene canescens</i>	62.0	<i>Cistus monspeliensis</i>	40.0
Dominant species		<i>Asphodelus ramosus</i>	62.0	<i>Rubia peregrina</i>	40.0
<i>Pinus halepensis</i>	100.0	<i>Phillyrea angustifolia</i>	50.0	Dominant species	
<i>Juniperus turbinata</i>	33.0	<i>Rhamnus alaternus</i>	50.0	<i>Pinus halepensis</i>	100.0
<i>Pistacia lentiscus</i>	33.0	<i>Sixalix atropurpurea</i>	50.0	<i>Phillyrea angustifolia</i>	40.0
<i>Phillyrea angustifolia</i>	17.0	<i>Stachys major</i>	38.0	<i>Erica arborea</i>	20.0
		<i>Cistus salviifolius</i>	25.0	<i>Arbutus unedo</i>	10.0
		<i>Crucianella maritima</i>	25.0	<i>Pistacia lentiscus</i>	10.0
		<i>Lobularia maritima</i>	25.0	<i>Quercus ilex</i>	10.0
		<i>Piptatherum miliaceum</i>	25.0		
		<i>Salvia rosmarinus</i>	25.0		
		<i>Romulea ligustica</i>	25.0		
		Dominant species			
		<i>Pinus halepensis</i>	100.0		
		<i>Juniperus macrocarpa</i>	62.0		
		<i>Juniperus turbinata</i>	12.0		

The analyses were performed using the JUICE software (Tichý, 2002). To display the relative position of our 66 vegetation relevés compared to the holotypes of the previously described vegetation types, we plotted the relevés in three DCA ordinations (Hill & Gauch, 1980), computed with presence/absence species data and down-weighting of rare species in each dataset using the *vegan* package (v. 1.17-9; Oksanen *et al.*, 2019) in R (v. 3.4.2; R Core Team, 2019).

Results and Discussion

Diagnostic, constant, and dominant species for each syntaxon are reported in Tables 1–3. For *Pinus halepensis* woodlands, we interpreted the TWINSpan clusters at the third hierarchical level of division (see Figure S1).

The first division separated the calcifuge and calcicolous pine communities. The second division separated the communities growing on dunes from the others. At the third level, the Sardinian woodlands (Porto Pino promontory and the island of San Pietro) were separated from the peninsular and continental ones on the basis of substantial poverty of species.

For *Pinus pinaster* woodlands, we interpreted TWINSpan clusters at the third hierarchical level (see Figure S1). The first hierarchical division separated the submediterranean and Mediterranean *P. pinaster* types. The division at the second level separated the thermophilous and mesophilous Mediterranean communities. The third hierarchical level divided the Sardinian thermophilous communities from the Sicilian ones.

Finally, for *Pinus pinea* communities we interpreted TWINSPAN clusters at the first hierarchical level, where the Sardinian inland dune community and the Sicilian ones on rocky places were separated (see Figure S1).

DCA ordinations allowed us to show four communities clearly distinct from those previously described, a partial confirmation of a previously described association, and two further subassociations (Figure 1). We are aware that using the relevé type as the barycentre of the compositional variability of a given association might represent a limitation as part of the variability could not be expressed there. However, we believe that the information retrieved by contrasting the new data with the published data, i.e. the type relevés, represents a good practice as it allows to better interpret the data.

Pinus halepensis communities

The analysis of *P. halepensis* communities shows the presence of three groups, in agreement with the DCA (Figure 2), related to different ecological and edaphic conditions. The clear floristic and ecological characterisation justifies the presence of three associations, of which two are new.

Smilaco asperae-Pinetum halepensis Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. *ass. nova* Table S1, rels. 1–6 (Figures 1B, S1A).

Holotypus:

Pinus halepensis L. 4, *Juniperus turbinata* Guss. 2, *Phillyrea angustifolia* L. 2, *Pistacia lentiscus* L. 2, *Quercus calliprinos* Webb 2, *Rubia peregrina* L. 1, *Asparagus acutifolius* L. +, *Arisarum vulgare* L. +, *Asphodelus ramosus* L. +, *Rhamnus alaternus* L. +, *Smilax aspera* L. +, *Stachys major* (L.) Bartolucci & Peruzzi +. Area: 200 m²; elevation: 29 m asl; aspect: NE; slope: 2°; locality: Pineta Candiani, Sant'Anna Arresi (Italy); 31 May 2018; coordinates: WGS84, 38.960650° N, 8.590086° W.

Diagnostic species: *Arisarum vulgare*, *Quercus calliprinos*, *Smilax aspera*, *Stachys major* (Table 1).

Structure: open woodlands, dominated by *Pinus halepensis*, from (2)10 to 12 m tall, represented by a dense understorey of sclerophyllous shrubs, with a rich presence of lianas and almost total absence of the herb layer. The understorey is mainly dominated by *Phillyrea angustifolia* and *Pistacia lentiscus*, with a relevant presence of *Juniperus turbinata* and *Quercus calliprinos*. Some geophytes are present in the herb layer, such as *Arisarum vulgare* and *Asparagus acutifolius*. Vines are common and often diagnostic and/or constant, such as *Rubia peregrina* and *Smilax aspera*.

Synecology: this association is found in coastal areas, mainly on calcareous substrates, from the sea level to 40 m asl. They are the typical formations of Pleistocene conglomerates, mud deposits, and limestones of the Porto Pino promontory. Bioclimatically, they thrive in the MPO bioclimate, the lower thermo-Mediterranean thermotype, and lower dry ombrotype (Bacchetta, 2006; Canu *et al.*, 2015).

Syndynamics: this association is in series with the thermophilous shrub communities of the alliance *Oleo-Ceratonion siliquae* Br.-Bl. ex Guinochet et Drouineau 1944, and the garrigues of the class *Ononido-Rosmarinetea* Br.-Bl. in A. Bolòs y Vayreda 1950 class (Bacchetta *et al.*, 2007). Herb communities linked to the natural potential vegetation here described are the annual pioneer communities of the order *Brachypodietalia distachyi* Rivas-Mart. 1978. The association is in catenal contact with the associations *Rusco aculeati-Quercetum calliprini* Mossa 1990 and *Pistacio lentisci-Juniperetum macrocarpae* Caneva, De Marco et Mossa 1981 (Bacchetta *et al.*, 2009).

Syntaxonomy: this new association belongs to the order *Pinetalia halepensis* Biondi, Blasi, Galdenzi, Pesaresi et Vagge 2014, the alliance *Pistacio lentisci-Pinion halepensis* Biondi, Blasi, Galdenzi, Pesaresi et Vagge 2014, and the sub-alliance *Pistacio lentisci-Pinenion halepensis* Biondi et Pesaresi 2017.

Synchorology: this association describes the endemic *P. halepensis* woodlands growing in coastal SW Sardinia, more specifically in the Sulcitano-Iglesiente biogeographic sector, and Sulcitano biogeographic sub-sector (Fenu *et al.*, 2014).

EUNIS code: T3A - Mediterranean lowland to submontane pine forests.

Habitats Directive code: 9540 - subtype no. 42.845.

Asparago horridi-Pinetum halepensis Calvia, Bonari, Angiolini, Farris, Fenu et Bacchetta *ass. nova hoc loco* Table S1, rels. 7–14 (Figures 1C, S1A).

Holotypus:

Pinus halepensis L. 5, *Juniperus macrocarpa* Sm. 2, *Pistacia lentiscus* L. 2, *Juniperus turbinata* Guss. 1, *Pancratium maritimum* L. 1, *Asparagus acutifolius* L. 1, *Asparagus horridus* L. +, *Asphodelus ramosus* L. +, *Cistus salvifolius* L. +, *Rubia peregrina* L. +, *Silene canescens* Ten. +, *Sixalix atropurpurea* (L.) Greuter & Burdet +, *Stachys major* (L.) Bartolucci & Peruzzi +, *Sonchus bulbosus* (L.) N.Kilian & Greuter +, *Tolpis virgata* (Desf.) Bertol. +. Area: 200 m²; elevation: 4 m asl; aspect: NE; slope: 3°; locality: Porto Pino, Sant'Anna Arresi (Italy); 31 May 2018; coordinates: WGS84, 38.961832° N, 8.608536° W.

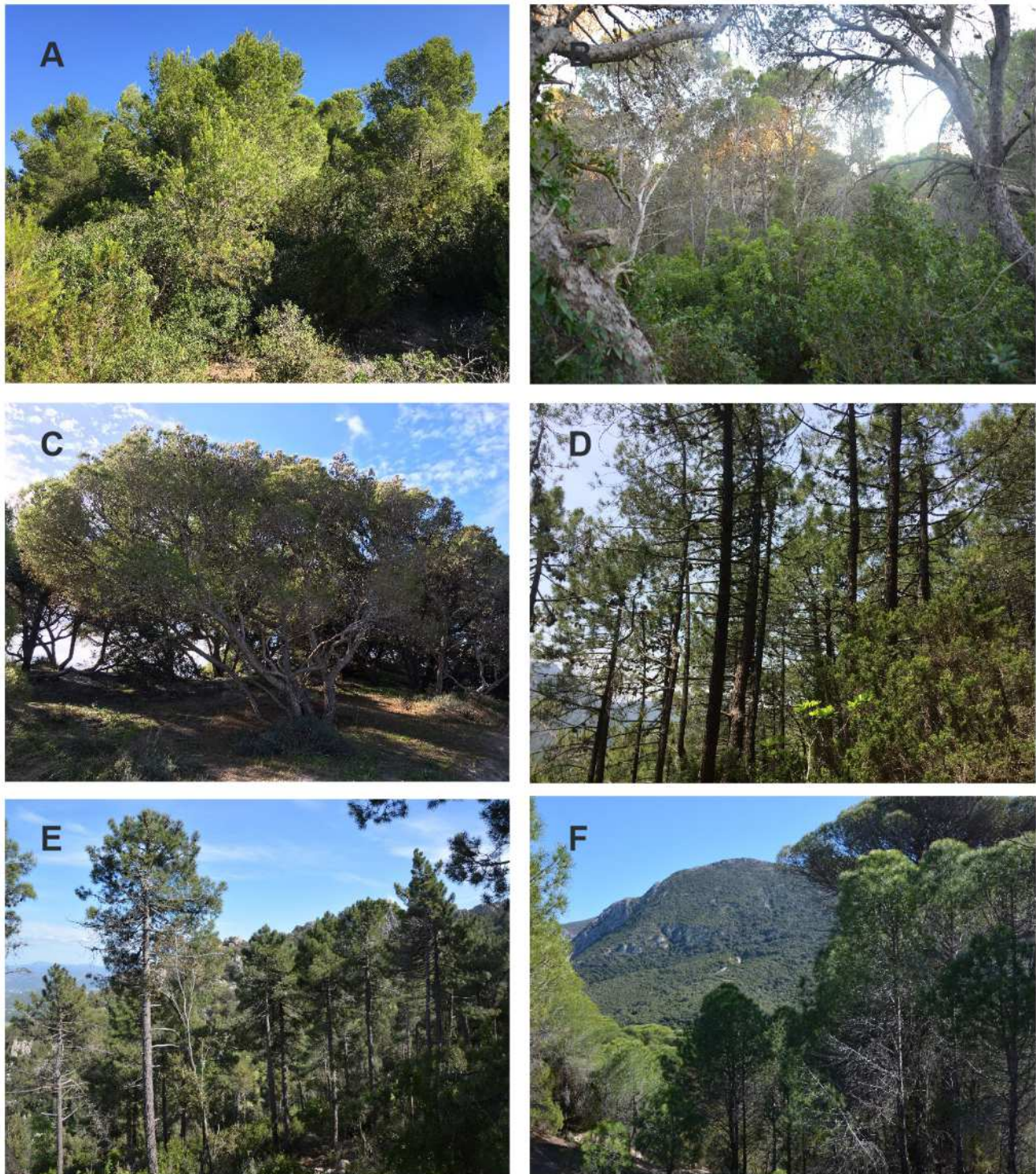


Figure 1. Typical pine associations and subassociations of Sardinia: A, *Erico arboreae*-*Pinetum halepensis*; B, *Smilaco asperae*-*Pinetum halepensis*; C, *Asparago horridi*-*Pinetum halepensis*; D, *Arbuto unedonis*-*Pinetum pinastri typicum*; E, *Arbuto unedonis*-*Pinetum pinastri cephalantheretosum longifoliae*; F, *Quercu calliprini*-*Pinetum pineae*.

Diagnostic species: *Asparagus horridus*, *Asphodelus ramosus*, *Juniperus macrocarpa*, *Pancratium maritimum*, *Silene canescens*, *Sixalix atropurpurea*, *Tolpis virgata* (Table 1).

Structure: open woodlands dominated by *Pinus halepensis*, 5 to 10 m tall, often characterised by sparse patches of small pine trees with *Juniperus macrocarpa*. The understorey is represented by geophytes (i.e. *Pancratium maritimum*, *Sonchus bulbosus*) and shrubs

(*Phillyrea angustifolia*, *Pistacia lentiscus*), with a rather dense presence of psammophilous hemicryptophytes and chamaephytes typical of coastal dunes, such as the species related to the alliance *Crucianellion maritimae* Rivas Goday et Rivas Mart. 1958 (i.e. *Crucianella maritima*, *Silene canescens*). *Asparagus horridus* often dominates the understorey and is locally substituted by *A. acutifolius*, mainly in low-light conditions.

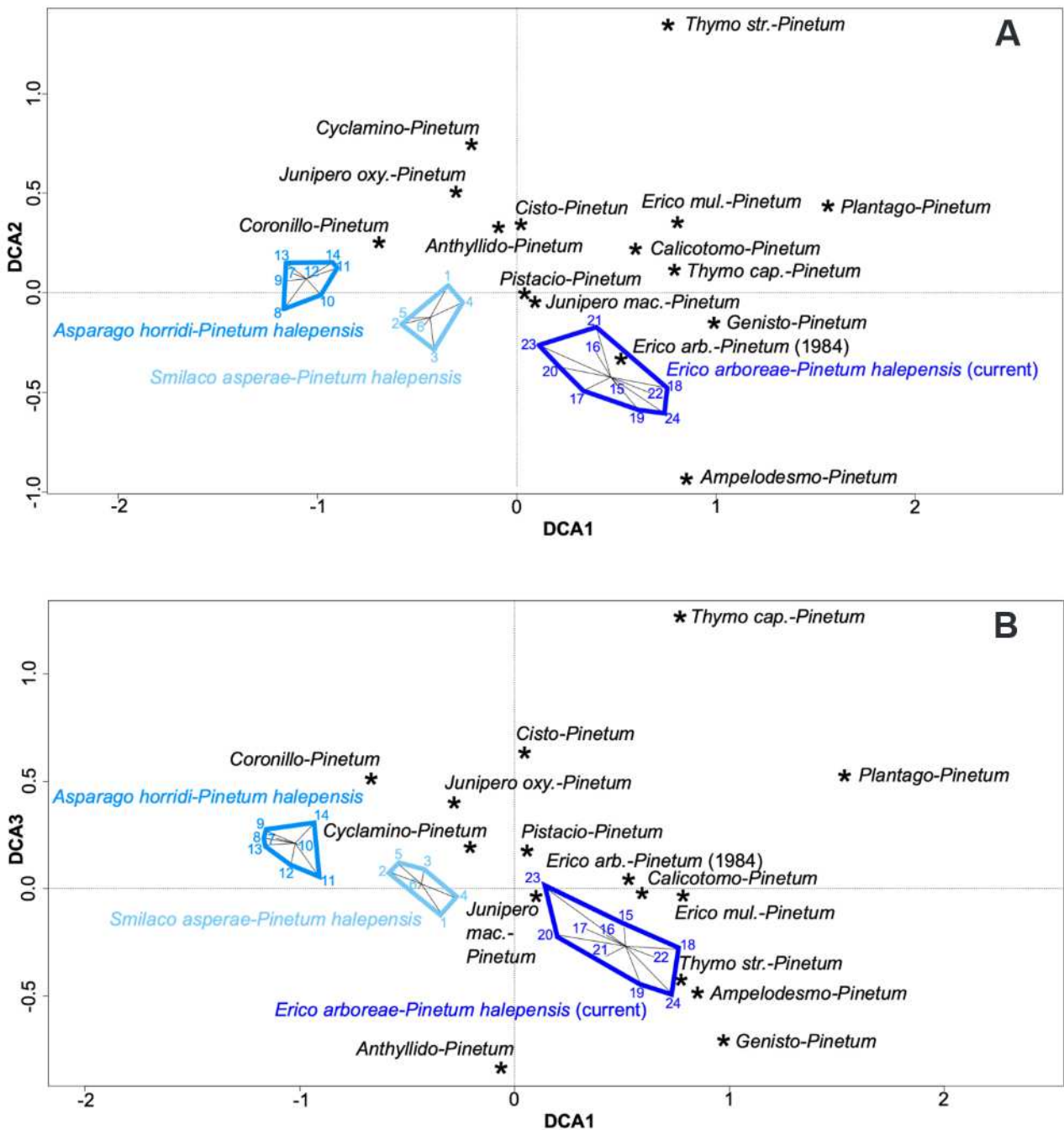


Figure 2. Ordination diagram of the Italian *Pinus halepensis* woodland associations; 2A, axes 1 and 2; 2B, axes 1 and 3. Coloured relevés are new data from Sardinia, while different shades of blue represent different clusters. Asterisks represent the type relevés of associations previously described. Full names of the syntaxa can be found in Appendix S1. 'Current', refers to the present status of this vegetation type. See results and discussion for further explanation.

Synecology: this association grows in aeolian sand dunes. It is present both in foredune and in inner dune systems as far as 700 m from the seashore, within the MPO bioclimate, the isobioclimate where the association thrives is a lower thermo-Mediterranean thermotype, lower dry ombrotype (Bacchetta, 2006; Canu *et al.*, 2015).

Syndynamics: the association is part of the Sardinian geosigmatum of coastal dune systems related to the association *Asparago acutifolii-Juniperetum macrocarpae*

R. et R. Molinier ex O. Bolòs 1962 (Bacchetta *et al.*, 2009). The chamaephyte communities are related to the association *Ephedro distachyae-Helichrysetum tyrrhenici* Vals. et Bagella 1991 *corr.*, while the herbaceous layer is represented by geophyte communities of the association *Sileno corsicae-Ammophiletum arenariae* Bartolo, Brullo, De Marco, Dinelli, Signorello et Spampinato 1992 and psammophilous therophytes belonging to the association *Sileno nummicae-Malcolmietum ramosissimae* Biondi et Bagella 2005. Locally, where these formations border the shores of the ponds, the association is in contact with the

series belonging to the class *Salicornietea fruticosae* Br.-Bl. et Tx. ex A. Bolòs et O. Bolòs 1950.

Syntaxonomy: this new association belongs to the order *Pinetalia halepensis*, the alliance *Pistacio lentisci-Pinion halepensis*, and the sub-alliance *Pistacio lentisci-Pinenion halepensis*.

Synchorology: the association occurs exclusively in south-western Sardinia, on coastal dunes of the Gulf of Porto Pino (SW Sardinia), and more specifically in the Sulcitano-Iglesiente biogeographic sector, and Sulcitano sub-sector (Fenu *et al.*, 2014).

EUNIS code: T3A - Mediterranean lowland to submontane pine forests.

Habitats Directive code: 2270*.

Erico arboreae-Pinetum halepensis De Marco et Caneva 1984

Table S1, rels. 7–14 (Figures 1A, S1A).

Holotypus: rel. 9, Table II (De Marco & Mossa, 1980).

Diagnostic species: *Arbutus unedo*, *Cistus monspeliensis*, *Erica arborea*, *Lonicera implexa*, *Myrtus communis*, *Salvia rosmarinus* (Table 1).

Structure: open to slightly open woodlands dominated by *Pinus halepensis*, from (4)8 to 10(14) m tall, with a dense understorey represented by sclerophyllous shrubs and a very poor herb layer, mainly with hemicryptophytes and geophytes. Moreover, there is a nearly total absence of typical garrigue elements (e.g. *Lotus dorycnium*, *Genista corsica*, and *G. valsecchiae*) that were considered characteristic and differential of the association (De Marco & Mossa, 1980). It is possible that those less evolved stages of vegetation are now present only as a variant in more degraded areas. The understorey of the community is rich in shrubs such as *Arbutus unedo*, *Erica arborea*, *Lonicera implexa*, *Myrtus communis*, *Phillyrea angustifolia* and *Pistacia lentiscus*. The presence of *Juniperus turbinata* is scarce. Other tree species, such as *Olea europaea* var. *sylvestris* and *Quercus ilex*, rarely occur in areas with deeper soils and northern aspect.

Synecology: the geology of the Island of San Pietro, where this association occurs, is represented by Miocene volcanic formations such as ignimbrites, comendites, rhyolites, quartzites, and Quaternary sediments, like sands, arenites, travertine, and alluvial soils (Garbarino *et al.*, 1985). Therefore, the association is calcifuge, typical of shallow soils and xeric conditions, and is present from the sea level up to 200 m asl. Bioclimatically, it thrives in the Mediterranean Pluviseasonal Oceanic (hereafter MPO) bioclimate, from lower thermo-Mediterranean, to upper thermo-Mediterranean thermotypes, and from lower dry to upper dry ombrotypes (Bacchetta, 2006; Canu *et al.*, 2015).

Syndynamics: the community represents an evolved stage of the previously described association *Erico arboreae-*

Pinetum halepensis (De Marco *et al.*, 1984; Pesaresi *et al.*, 2017). Successional stages of the series are determined by shrubs belonging to the alliance *Oleo-Ceratonion siliquae* Br.-Bl. ex Guinochet et Drouineau 1944, garrigues of the class *Cisto-Lavanduletea stoechadis* Br.-Bl. in Br.-Bl., Molinier et Wagner 1940, and therophytic dry grasslands of the alliance *Tuberarion guttatae* Br.-Bl. in Br.-Bl., Molinier et Wagner 1940 (Bacchetta *et al.*, 2007). Our analyses did not allow us to recognise the subassociations *pinetosum halepensis*, *quercetosum ilicis* and *juniperetosum turbinatae*, which represent catenal contacts with more xeric formations (*Erico arboreae-Juniperetum turbinatae* Arrigoni, Bruno, De Marco et Veri 1985) and the mixed holm oak woodlands characterising the areas with deeper soil.

Syntaxonomy: this association belongs to the order *Pinetalia halepensis* Biondi, Blasi, Galdenzi, Pesaresi et Vagge 2014, the alliance *Pistacio lentisci-Pinion halepensis*, and the sub-alliance *Pistacio lentisci-Pinenion halepensis* (Pesaresi *et al.*, 2017).

Synchorology: this association is distributed in many areas of the island of San Pietro (SW Sardinia), more specifically in the Sulcitano-Iglesiente biogeographic sector, and Antioco-Carlofortino biogeographic sub-sector (Fenu *et al.*, 2014), where it appears to be endemic (Pesaresi *et al.*, 2017).

EUNIS code: T3A - Mediterranean lowland to submontane pine forests.

Habitats Directive code: 9540 - subtype no. 42.845.

***Pinus pinaster* communities**

The analysis of *P. pinaster* communities shows the presence of two groups, in agreement with the DCA (Figure 3), that relates to different ecological conditions. The floristic and ecological characterisation justifies the presence of one new association, divided into two subassociations.

Arbuto unedonis-Pinetum pinastri Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. *ass. nova*
Table S2, rels. 1–32 (Figures 1D, S1B).

Holotypus:

Pinus pinaster Aiton 4, *Quercus ilex* L. 3, *Arbutus unedo* L. 2, *Erica arborea* L. 2, *Pistacia lentiscus* L. 2, *Smilax aspera* L. 2, *Bupleurum fruticosum* L. 1, *Lonicera implexa* Aiton 1, *Phillyrea angustifolia* L. 1, *Cistus creticus* L. subsp. *eriocephalus* (Viv.) Greuter & Burdet +, *Genista corsica* (Loisel.) DC. +, *Polypodium cambricum* L. +, *Rubia peregrina* L. +, *Salvia rosmarinus* Spenn. +, *Senecio lividus* L. +. Area: 200 m²; elevation: 210 m asl; aspect: S; slope: 18°; locality: Mount Lu Pinu, Trinità d'Agultu (Italy); 16 May 2018; coordinates: WGS84, 41.053647° N, 8.962651° W.

Diagnostic species: *Arbutus unedo*, *Bupleurum fruticosum*, *Erica arborea*, *Lonicera implexa*, *Phillyrea angustifolia*, *Pistacia lentiscus*, *Polypodium cambricum*, *Smilax aspera* (Table 2).

Structure: open to slightly open woodlands dominated by *Pinus pinaster*, (6)10 to 15(20) m tall, forming monospecific woodlands, sometimes with a lower tree layer characterised also by oaks (*Quercus ilex*, *Q. suber*). The understorey is dominated by sclerophyllous shrubs (e.g. *Arbutus unedo*, *Erica arborea*, *Myrtus communis*, *Phillyrea angustifolia*), and vines (e.g. *Lonicera implexa*, *Rubia peregrina*, *Smilax aspera*), while the herbaceous layer is not particularly rich (e.g. *Brachypodium retusum*, *Geranium purpureum*, *Pulicaria odora*, *Senecio lividus*, *Umbilicus rupestris*).

Synecology: the association thrives on igneous intrusive substrates, where it normally occupies poor soil and rocky places, often with a steep slope. It ranges from 90 to 1,150 m asl. The geology of the places where the association occurs is mostly related to evenly sized monzogranites and leucogranites, which are the most common, while in a very small portion of the northernmost locality (Costa Paradiso, Trinità d'Agultu) grows on sand and mud deposits dated to Pliocene-Pleistocene (Carmignani *et al.*, 2016). The bioclimate is preferentially MPO, ranging from upper thermo-Mediterranean, upper dry in the most coastal zone, to lower supra-temperate (in sub-Mediterranean variant), lower humid in the central areas of Mount Limbara, where the highest formations grow (Canu *et al.*, 2015).

Table 2. Synoptic table of the percentage constancies of the diagnostic, constant and dominant species for the vegetation plots dominated by *Pinus pinaster*. Species are sorted by decreasing values of the phi coefficient (Φ) for each subassociation; only species with $\Phi > 0.3$ and $p < 0.05$ (based on Fisher's exact test) are shown.

<i>Arbutus unedo</i> - <i>Pinetum pinastri</i> <i>typicum</i>	%	<i>Arbutus unedo</i> - <i>Pinetum pinastri</i> <i>cephalantheretosum longifoliae</i>	%
Number of relevés: 18		Number of relevés: 13	
Diagnostic species		Diagnostic species	
<i>Phillyrea angustifolia</i>	70.7	<i>Cephalanthera longifolia</i>	92.6
<i>Bupleurum fruticosum</i>	62.0	<i>Cytisus villosus</i>	85.6
<i>Lonicera implexa</i>	62.0	<i>Viola alba</i> subsp. <i>dehnhardtii</i>	60.7
<i>Pistacia lentiscus</i>	57.7	<i>Rubus ulmifolius</i>	53.1
<i>Smilax aspera</i>	52.1	<i>Fraxinus ornus</i>	46.4
<i>Polypodium cambricum</i>	49.1	<i>Pteridium aquilinum</i>	42.6
Constant species		Constant species	
<i>Pinus pinaster</i>	100.0	<i>Pinus pinaster</i>	100.0
<i>Arbutus unedo</i>	100.0	<i>Erica arborea</i>	100.0
<i>Erica arborea</i>	100.0	<i>Quercus ilex</i>	100.0
<i>Quercus ilex</i>	100.0	<i>Rubia peregrina</i>	100.0
<i>Rubia peregrina</i>	100.0	<i>Cephalanthera longifolia</i>	92.0
<i>Phillyrea angustifolia</i>	67.0	<i>Arbutus unedo</i>	85.0
<i>Smilax aspera</i>	67.0	<i>Cytisus villosus</i>	85.0
<i>Brachypodium retusum</i>	67.0	<i>Rubus ulmifolius</i>	69.0
<i>Lonicera implexa</i>	56.0	<i>Brachypodium retusum</i>	62.0
<i>Bupleurum fruticosum</i>	56.0	<i>Viola alba</i> subsp. <i>dehnhardtii</i>	54.0
<i>Pistacia lentiscus</i>	50.0	<i>Fraxinus ornus</i>	46.0
<i>Juniperus oxycedrus</i>	39.0	<i>Juniperus oxycedrus</i>	46.0
<i>Myrtus communis</i>	39.0	<i>Pulicaria odora</i>	46.0
<i>Senecio lividus</i>	39.0	<i>Pteridium aquilinum</i>	31.0
<i>Polypodium cambricum</i>	39.0	<i>Quercus suber</i>	23.0
<i>Quercus suber</i>	33.0	<i>Brimeura fastigiata</i>	23.0
<i>Lavandula stoechas</i>	28.0	<i>Melica minuta</i>	23.0
<i>Pulicaria odora</i>	28.0	Dominant species	
<i>Cistus salviifolius</i>	22.0	<i>Pinus pinaster</i>	100.0
<i>Daphne gnidium</i>	22.0	<i>Erica arborea</i>	69.0
<i>Genista corsica</i>	22.0	<i>Arbutus unedo</i>	15.0
<i>Salvia rosmarinus</i>	22.0		
<i>Umbilicus rupestris</i>	22.0		
Dominant species			
<i>Pinus pinaster</i>	100.0		
<i>Erica arborea</i>	44.0		
<i>Arbutus unedo</i>	22.0		
<i>Juniperus oxycedrus</i>	6.0		
<i>Myrtus communis</i>	6.0		
<i>Quercus ilex</i>	6.0		
<i>Quercus suber</i>	6.0		
<i>Brachypodium retusum</i>	6.0		

Syndynamics: the association appears to be edapho-xerophilous in those areas characterised by poor and scarcely evolved soils, often in rocky and degraded places. Normally, the successional stages of these woodlands are related to shrub communities of the alliance *Ericion arboreae* (Rivas-Mart. ex Rivas-Mart. et al. 1986) Rivas-Mart. 1987, while the garrigue stage is mostly related to the alliance *Teucrium mari* (Gamisans et Muracciole 1984) Biondi et Mossa 1992. Finally, the herbaceous stage is connected to the communities of the alliance *Tuberarion guttatae* (Bacchetta et al., 2007). Locally, it has catenal contacts with some associations of the class *Quercetea ilicis*, such as *Galio scabri-Quercetum suberis* Rivas-Mart., Biondi, Costa et Mossa 2003, *Galio scabri-Quercetum ilicis* Gamisans (1977) 1986 and, only on the mountain areas, *Saniculo europaeae-Quercetum ilicis* Bacch., Bagella, Biondi, Farris, Filigheddu et Mossa 2004.

Syntaxonomy: the association is classified in the order *Pinetalia halepensis* and in the alliance *Genisto pilosae-Pinion pinastri* Biondi et Vagge 2015, although we found some differences in species composition, which could suggest the existence of a different alliance.

Synchorology: this association includes *P. pinaster* endemic woodlands growing on granitic substrates of north-eastern Sardinia, in the Goceano-Logudorese biogeographic sector and the Gallurese sub-sector (Fenu et al., 2014), from sub-coastal to mountain environments.

Variability: based on local bioclimatic differences, we distinguished two subassociations that are characterised by a different species composition. The typical subassociation (typicum) is found in lowlands and hills with thermophilous and xerophilous species, e.g. *Bupleurum fruticosum*, *Lonicera implexa*, *Myrtus communis*, *Phillyrea angustifolia*, *Pistacia lentiscus*.

The subassociation *cephalantheretosum longifoliae* is more related to mountain environments, with more mesophilous species, such as *Cephalanthera longifolia*, *Cytisus villosus*, *Fraxinus ornus*, and *Viola alba* subsp. *dehnhardtii*. Our analyses evidenced one transitional relevé relatively poor in diagnostic species, isolated from the others (Figure 3B, rel. 6, Table 2). It was recorded in an old-growth pine stand, thus resulting transitional between the two subassociations.

EUNIS code: T3A - Mediterranean lowland to submontane pine forests.

Habitats Directive code: 9540 - subtype no. 42.825.

typicum

Table S2, rels. 1–5, 7–19 (Figures 1D, S1B).

Diagnostic species: the same of the association (Table 2).

Structure: open woodlands dominated by *Pinus pinaster*, (6)10 to 18(20) m tall, with a sparse to dense understorey, characterised by sclerophyllous shrubs and lianas. Physiognomically, the understorey is characterised by woody sclerophyllous species, such as *Arbutus unedo*, *Erica arborea*, *Myrtus communis*, *Phillyrea angustifolia*, *Quercus ilex*, *Q. suber*, *Rhamnus alaternus*, and *Viburnum tinus*. The suffrutescent species and dwarf shrubs characteristic of the class *Cisto-Lavanduletea* are often limited to marginal areas in the open patches, where they appear as remnants of previous garrigues colonised by pines.

Synecology: this subassociation is found at lower elevations, on granitic hills, ranging from 90 to 650 m asl. It thrives mainly on rocky places on the southern aspect, while its bioclimatic range varies from the upper thermo-Mediterranean, upper dry, to the lower meso-Mediterranean, lower sub-humid (Canu et al., 2015).

Syndynamics: the subassociation represents the potential natural vegetation of the edapho-xerophilous and calcifuge series, *sensu* Farris et al. (2010). It is sometimes in a catenal relation with the association *Galio scabri-Quercetum suberis*, and locally with the *Galio scabri-Quercetum ilicis*.

Synchorology: it has been recognised in the northern and central sides of Gallurese biogeographic sub-sector (Fenu et al., 2014) where it appears to be endemic, on the Monti Ultana chain, as well as in the restricted zone of Costa Paradiso (Trinità d'Agultu).

cephalantheretosum longifoliae Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. *subass. nova*
Table S2, rels. 20–32 (Figures 1E, S1B).

Holotypus:

Pinus pinaster Aiton 5, *Arbutus unedo* L. 2, *Fraxinus ornus* L. 2, *Quercus ilex* L. 2, *Cytisus villosus* Pourr. 1, *Erica arborea* L. 1, *Hedera helix* L. 1, *Juniperus oxycedrus* L. 1, *Brachypodium retusum* (Pers.) P.Beauv. +, *Brimeura fastigiata* (Viv.) Chouard +, *Cephalanthera longifolia* (L.) R.M.Fritsch +, *Daphne gnidium* L. +, *Hieracium bernardii* Rouy subsp. *gallurense* (Arrig.) Greuter +, *Pteridium aquilinum* (L.) Kuhn +, *Rubia peregrina* L. +, *Rubus ulmifolius* Schott +, *Senecio lividus* L. +, *Viola alba* Besser subsp. *dehnhardtii* (Ten.) W.Becker +. Area: 200 m²; elevation: 918 m asl; aspect: ENE; slope: 22°; locality: Mount Limbara, Carracana, Berchidda (Italy); 21 May 2018; coordinates: WGS84, 40.844410° N, 9.191817° W.

Diagnostic species: *Cephalanthera longifolia*, *Cytisus villosus*, *Fraxinus ornus*, *Pteridium aquilinum*, *Rubus ulmifolius*, *Viola alba* subsp. *dehnhardtii* (Table 2).

Structure: open woodlands dominated by *Pinus pinaster*, (8)10 to 15(18) m tall, with a rather thick understorey, represented by sclerophyllous shrubs and a scarce herbaceous layer, with rare therophytes and geophytes.

Synecology: this subassociation is found in mountain areas, mainly in the most edapho-xerophilous conditions, such as steep slopes and ridges, up to 1,150 m asl, thriving mainly on eastern aspects. In the mountain plateaus, it grows on very poor soil conditions dominated by garrigue species, because of the frequency of wildfires in the past. However, locally it can be found also on deeper soils of the mountain slopes of Mount Limbara, between 500 and 700 m asl.

Bioclimatically, this subassociation thrives in the upper meso-Mediterranean, upper sub-humid, to lower sub-temperate and lower humid belts (Canu *et al.*, 2015).

Syndynamics: in some of the most degraded areas, it represents the evolution of garrigues ascribed to the *Viola limbarae-Genistetum limbarae* Vals. 1994 *corr.* The subassociation is characterised by the presence of some species that are also part of the alliance *Genisto pilosae-Pinion pinastri*. Locally it appears to be in catenal contact with plant communities of the order *Quercetalia ilicis* Br.-Bl. ex Molinier 1934. In particular, the *Galio scabri-Quercetum ilicis* in the lower part of its range, and the *Saniculo europaeae-Quercetum ilicis* at higher elevations (Bacchetta *et al.*, 2009).

Synchorology: this subassociation is known in the inner part of Gallurese biogeographic sub-sector (Fenu *et al.*, 2014), where it appears to be endemic and characterises the north-eastern side of the Limbara massif.

Pinus pinea communities

The analysis of the *P. pinea* communities shows a high affinity between the relevés, therefore the presence of one group only, in agreement with the DCA (Figure 4). The floristic and ecological homogeneity justifies the existence of only one association.

Quercus calliprini-Pinetum pineae Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. *ass. nova* Table S3, rels. 1–10 (Figures 1F, S1C).

Holotypus:

Pinus pinea L. 5, *Juniperus macrocarpa* Sm. 3, *Quercus calliprinos* Webb 2, *Arbutus unedo* L. 2, *Rubia peregrina* L. 2, *Juniperus turbinata* Guss. 1, *Pistacia lentiscus* L. 1, *Rhamnus alaternus* L. 1, *Asparagus acutifolius* L. +, *Dianthus morisianus* Vals. +, *Smilax aspera* L. +, *Sonchus bulbosus* (L.) N.Kilian & Greuter +. Area: 200 m²; elevation: 148 m asl; aspect: N; slope: 25°; locality: Portixeddu dunes south, Buggerru (Italy); 10 March 2019; coordinates: WGS84, 39.428969° N, 8.430000° W.

Diagnostic species: *Juniperus macrocarpa*, *J. turbinata*, *Quercus calliprinos*, *Rubia peregrina* (Table 3).

Structure: open woodlands dominated by *Pinus pinea*, (8)10 to 18(20) m tall. The tree layer is normally formed by pines, with a relatively sparse understorey of sclerophyllous shrubs. The herbaceous layer is often rich in therophytes, with rarer hemicryptophytes and geophytes. It is characterised by thermo-Mediterranean elements, with a relevant presence of psammophilous species, such as *Dianthus morisianus*, *Juniperus macrocarpa*, *Silene canescens*.

Table 3. Synoptic table of the percentage constancies of the diagnostic, constant and dominant species for the vegetation plots dominated by *Pinus pinea*. Species are sorted by decreasing values of the phi coefficient (Φ) for the association; only species with $\Phi > 0.3$ and $p < 0.05$ (based on Fisher's exact test) are shown.

<i>Quercus calliprini-Pinetum pineae</i>	%
Number of relevés: 10	
Diagnostic species	
<i>Quercus calliprinos</i>	100.0
<i>Rubia peregrina</i>	100.0
<i>Juniperus macrocarpa</i>	90.0
Constant species	
<i>Pinus pinea</i>	100.0
<i>Pistacia lentiscus</i>	100.0
<i>Quercus calliprinos</i>	100.0
<i>Rubia peregrina</i>	100.0
<i>Juniperus macrocarpa</i>	90.0
<i>Juniperus turbinata</i>	80.0
<i>Phillyrea angustifolia</i>	80.0
<i>Geranium purpureum</i>	80.0
<i>Rhamnus alaternus</i>	60.0
<i>Smilax aspera</i>	60.0
<i>Cistus creticus</i>	60.0
<i>Lagurus ovatus</i>	60.0
<i>Cistus salviifolius</i>	50.0
<i>Dactylis glomerata</i>	50.0
<i>Aetheorhiza bulbosa</i>	50.0
<i>Asparagus acutifolius</i>	50.0
<i>Arbutus unedo</i>	40.0
<i>Dioscorea communis</i>	40.0
<i>Rumex bucephalophorus</i>	40.0
<i>Ruscus aculeatus</i>	40.0
<i>Torilis arvensis</i>	40.0
<i>Lobularia maritima</i>	30.0
<i>Ophrys fuciflora</i> subsp. <i>chestermanii</i>	30.0
<i>Dianthus morisianus</i>	30.0
<i>Asplenium onopteris</i>	30.0
<i>Prasium majus</i>	30.0
<i>Senecio leucanthemifolius</i>	30.0
<i>Silene canescens</i>	30.0
<i>Sixalix atropurpurea</i> subsp. <i>maritima</i>	30.0
Dominant species	
<i>Pinus pinea</i>	100.0
<i>Juniperus macrocarpa</i>	30.0
<i>Juniperus turbinata</i>	30.0
<i>Pistacia lentiscus</i>	10.0

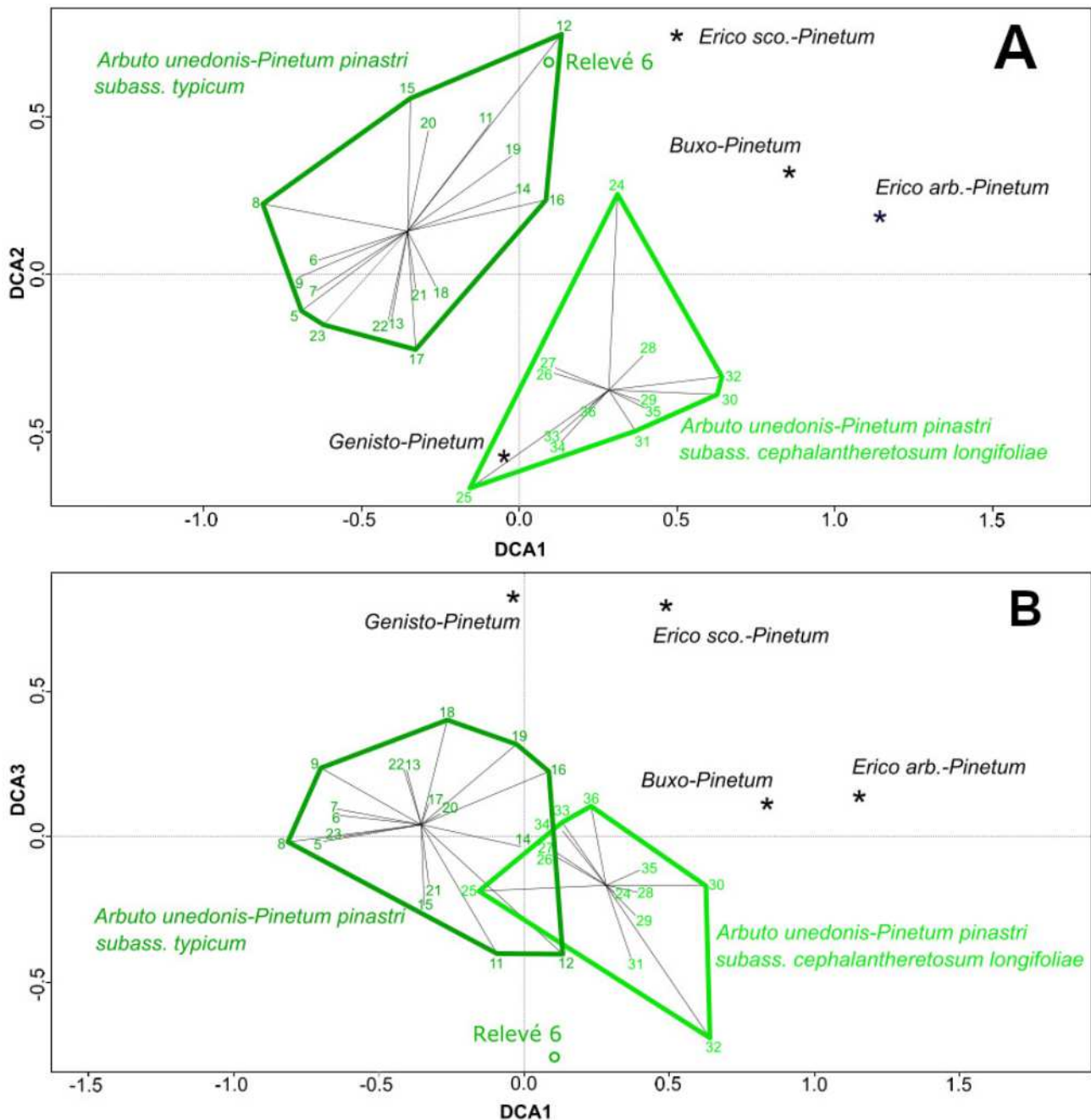


Figure 3. Ordination diagram of the Italian *Pinus pinaster* woodlands; A, axes 1 and 2; B, axes 1 and 3.

Coloured relevés are new data from Sardinia, while different shades of green represent different clusters.

Asterisks represent the type relevés of associations previously described. The circle indicates a single relevé placed at an intermediate position between the two subassociations. Full names of the syntaxa can be found in Appendix S1.

Synecology: the association thrives mainly on inner dune formations, between 10 and 200 m asl. The natural *P. pinea* communities of Sardinia grow on Holocene sands, rarely extending on Ordovician metaconglomerates. The bioclimate is MPO, with upper thermo-Mediterranean thermotype, and upper dry ombrotype (Canu *et al.*, 2015). The *P. pinea* formations grow mainly along ridges of the inner stabilised dunes, as well as on steep slopes facing both northern and southern exposures.

Syndynamics: the other stages related to this series are those of the *Pistacio lentisci-Juniperetum macrocarpae* Caneva, De Marco et Mossa 1981, the *Crucianelletum*

maritimae Br.-Bl. 1933 and the *Rusco aculeati-Quercetum calliprini* Mossa 1990 associations, of which it could represent a paraclimax (Mossa, 1990).

Syntaxonomy: this new association belongs to the order *Pinetalia halepensis*, and to the informal group of Mediterranean *Pinus pinea* woodlands, in agreement with Bonari *et al.* (2021).

Synchronology: this association is found only in the dune system of Portixeddu (Buggerru, SW Sardinia) more specifically in the Sulcitano-Iglesiente biogeographic sector and Iglesiasentino sub-sector (Fenu *et al.*, 2014), where it appears to be endemic.

EUNIS code: T3A - Mediterranean lowland to submontane pine forests.

Habitats Directive code: 2270*.

Our results allowed us to describe six new syntaxa, including four associations and two subassociations for the Sardinian pine woodlands. The analyses of the relevés dominated by *Pinus halepensis* evidenced a slight difference in composition with *Erico arboreae-Pinetum halepensis* described by De Marco *et al.* (1984). The understorey of the woodlands analysed in our study is richer in shrubs and poorer in chamaephytes, although in both

cases the relevés were species poor. Also, we did not find some of the diagnostic species highlighted by De Marco & Caneva (1984). This can be due to the fact that when the syntaxon was described the vegetation was perhaps not fully developed yet and more related to the first phase of land abandonment (De Marco & Mossa, 1980). For this reason, we believe there is no need to describe a new association. However, the floristic composition of our vegetation relevés highlights the relationship with the alliance *Pistacio lentisci-Pinion halepensis* (Pesaresi *et al.*, 2017; Bonari *et al.*, 2021).

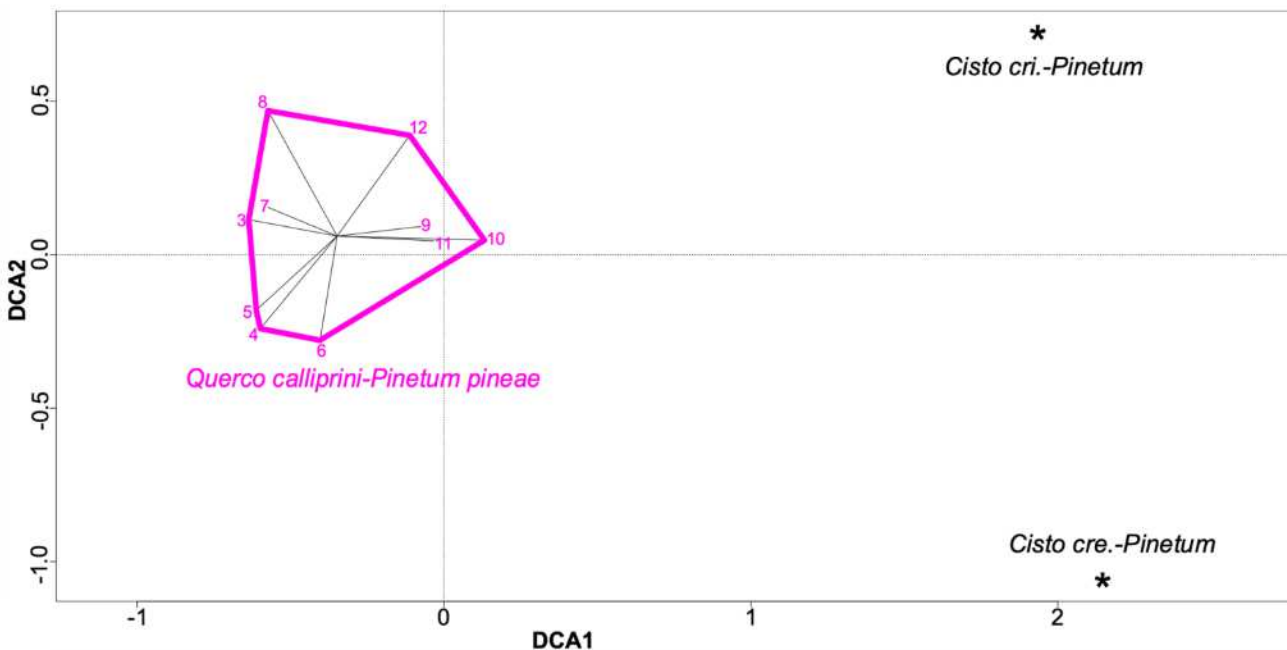


Figure 4. Ordination diagram of the Italian *Pinus pinea* woodlands, axes 1 and 2. Coloured relevés are new data from Sardinia. Asterisks represent the type relevés of associations previously described. Full names of the syntaxa can be found in Appendix S1.

The Porto Pino woodlands represent an association that, although poor in species, deserves to be described as new, in contrast with former authors (De Marco *et al.*, 1984). The new association *Smilaco asperae-Pinetum halepensis* differentiates mostly in terms of synecologic, syndynamic, and synchorologic features. The species composition is similar to that of the *Pistacio lentisci-Pinetum halepensis*, although the DCA showed a certain distance between the two syntaxa. However, this association is represented mainly by shrubs and lianas, while the herb layer, including chamaephytes, abundant in the *Pistacio-Pinetum halepensis*, is here often nearly absent, as well as many differential species.

The composition of the new association *Asparago horridi-Pinetum halepensis* allows us to classify it within the alliance *Pistacio lentisci-Pinion halepensis*. It is differentiated from other psammophilous associations, like *Junipero macrocarpae-Pinetum halepensis* Biondi, Pesaresi et Vagge 2017 of Corsica, characterised by a calcifuge species pool (i.e. *Arbutus unedo*, *Clematis flammula*, *Erica arborea*, *Myrtus communis*) that totally lacks in the Sardinian association. The dune systems between Porto Pino and Capo Teulada are made up of

the accumulation of sediments of organic origin, not by intrusive and metamorphic rocks, as in other areas. The DCA showed a floristic similarity with the association *Cyclamino repandi-Pinetum halepensis* Biondi, Casavecchia, Guerra, Medagli, Beccarisi et Zuccarello 2004 from which it differs for a richer presence of psammophilous species. According to the DCA, the most closely related syntaxon to the new association would be *Coronillo emeroidis-Pinetum halepensis* Allegrezza, Felici et Biondi 2006. However, the ecology, as well as the species composition of the two syntaxa, are substantially different. The latter is characterised by the presence of species of the class *Quercus roboris-Fagetea sylvaticae* Br.-Bl. et Vlieger 1937, which are absent in the Sardinian one.

Concerning the relevés dominated by *Pinus pinaster*, despite some differences in species composition, we classified the new association *Arbutus unedonis-Pinetum pinastri* in the alliance *Genisto pilosae-Pinion pinastri*, described by Biondi & Vagge (2015). This alliance was described for *P. pinaster* woodlands growing on acidic or decarbonated soils, rich in thermophilous evergreen species, occurring in the Ligurian-Provençal

sector. However, a broader analysis suggests that this alliance can grow on a variety of soils (Bonari *et al.*, 2021). The higher presence, frequency, and cover of West-Mediterranean and Circum-Mediterranean species of the Sardinian woodlands (e.g. *Brachypodium retusum*, *Myrtus communis*, *Phillyrea angustifolia*, *Quercus ilex*, *Q. suber*, *Rubia peregrina*), contrasts with the richer presence in Euro-Mediterranean species of the Ligurian-Provençal associations. The association *Arbuto unedonis-Pinetum pinastris* appears to be closer to the Sicilian association *Genisto aspalathoidis-Pinetum hamiltonii* Brullo, Di Martino et Marcenò 1977, from which, however, it differs for the higher presence of mesophilous elements. The Sicilian association is more xeric and differs from the Sardinian one in the characteristic species, as well as a remarkable presence of *Erica multiflora*, which in Sardinia is found on calcareous soils only.

Pinus pinea formations are included within the order *Pinetalia halepensis* and in the informal group of Mediterranean *P. pinea* woodlands. This informal group reflects the uncertainties at many Mediterranean sites about the origin of *P. pinea* woodlands (Bonari *et al.*, 2021). Despite that, we speculate that the Sardinian association *Quercus calliprini-Pinetum pineae* is probably the oldest *P. pinea* formation of Italy, known as a natural community for about 200 years (Moris, 1827). Based on our analysis the new association *Quercus calliprini-Pinetum pineae* is clearly separated from the previously described associations of Sicily (Brullo *et al.*, 1977; Bartolo *et al.*, 1994). The main difference is ecological, being that the Sardinian formations are characteristic of sand coastal dunes, while the Sicilian ones thrive inland and on rocky substrates. The floristic composition of Sardinian *P. pinea* woodlands is represented by several typical psammophilous species, which are lacking both in the *Cisto crispus-Pinetum pineae* Bartolo, Brullo et Pulvirenti 1994 and in the *Cisto cretici-Pinetum pineae* Brullo, Minissale, Siracusa, Scelsi et Spampinato 2002. The species belonging to the *Cisto-Lavanduletea* are nearly absent in the Sardinian *P. pinea* formations. Differently, Brullo *et al.* (2002) classified all the *P. pinea* associations described in Lebanon, Turkey, and Sicily, within the class *Cisto-Lavanduletea*, the order *Lavanduletalia stoechadis* Br.-Bl. in Br.-Bl. *et al.* 1940 and the alliance *Pinion pineae* Feinbrun 1959. We should recall that classifying a woodland syntaxon to an alliance of nanophanerophytes and chamaephytes is not optimal and might create problems in e.g. management (Bonari *et al.*, 2021).

Conclusions

We provided the first updated and comprehensive vegetation classification of natural pine woodlands of Sardinia, with seven different syntaxa dominated by Mediterranean pines, six of which are newly described. These syntaxa have an important chorological value within the Mediterranean context. Some of them have an extremely localised distribution range and have

distinctive ecological features. Particularly, the limited distribution of native *Pinus halepensis* and *P. pinea* woodlands in Sardinia has high conservation importance, as do the communities they form. For example, some of the syntaxa presented in this study are part of the priority habitat 2270* and they deserve to be protected, especially considering that they often grow in coastal environments threatened by human activities. This study provides the classification and description of the natural pine formations of Sardinia, thus allowing a better understanding of their ecology, floristic composition, and differences with other Mediterranean pine woodlands.

Syntaxonomic scheme

PINETEA HALEPENSIS Bonari et Chytrý 2021 in Bonari *et al.* 2021

Pinetalia halepensis Biondi, Blasi, Galdenzi, Pesaresi et Vagge 2014

Pistacio lentisci-Pinion halepensis Biondi, Blasi, Galdenzi, Pesaresi et Vagge 2014

Pistacio lentisci-Pinenion halepensis Pesaresi, Vagge, Galdenzi et Casavecchia 2017

Smilaco asperae-Pinetum halepensis Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. 2022

Asparago horridi-Pinetum halepensis Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. 2022

Erico arboreae-Pinetum halepensis De Marco et Caneva 1984

Genisto pilosae-Pinion pinastris Biondi et Vagge 2015

Arbuto unedonis-Pinetum pinastris Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. 2022
typicum

cephalanthetosum longifoliae Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. 2022

Mediterranean *Pinus pinea* woodlands (informal group)

Quercus calliprini-Pinetum pineae Calvia, Bonari, Angiolini, Farris, Fenu et Bacch. 2022

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Data availability

The data presented in this article are available in the *CircumMed Forest Database* (GIVD code: EU-00026).

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Supplementary material

Table S1. *Smilaco asperae-Pinetum halepensis* ass. nova; *Asparago horridi-Pinetum halepensis* ass. nova; *Erico arboreae-Pinetum halepensis* De Marco et Caneva 1984.

Table S2. *Arbuto unedonis-Pinetum pinastri* ass. nova; *cephalantheretosum longifoliae* subass. nova.

Table S3. *Querco calliprini-Pinetum pineae* ass. nova.

Figure S1. TWINSPLAN dendrogram up to the third hierarchical level of division.

Appendix S1. List of associations.