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Temporal increase in the extent of Sardinian pine formations

G. Calvia[1] · G. Bonari[2] · C. Angiolini[3] · E. Farris[4] · G. Fenu[1] · G. Bacchetta[1]

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Abstract

Temporal changes in the distribution range of plant communities and habitats should be considered for optimal conservation. However, this information is often lacking. In this research, we investigated the changes in the spatial distribution pattern of the plant communities characterised by the presence of three Mediterranean pines considered native or putative native to Sardinia (Italy), namely *Pinus halepensis*, *P. pinaster*, and *P. pinea*. We analysed historical and current aerial photographs to prepare maps of the past and current distribution of natural pine formations, complemented with the aid of pine-related toponymy maps and interviews with local people. We calculated how the surface of natural pine formations varied across time, and found a high rate of recovery during the last decades. This rate is doubled when compared to the average extent of other Sardinian woody formations in the same period. Among the three pine species, the area of *P. halepensis* and *P. pinaster* formations increased the most. We also found that about 90% of pine formations fall within protected areas. More than 128 ha of natural pine formations are included in the priority habitat 2270, while those included in habitat 9540 cover 1100 ha. Our study provides a complete survey of the distribution of natural Sardinian pine formations, along with the quantification of their increase in the last decades, thus highlighting the importance of diachronic analyses for monitoring spatial changes in plant communities. We suggest considering the trends in the extent of vegetation formations and habitats for conservation purposes.

Keywords EU habitat · Land-use change · Mediterranean forest · *Pinus* · Phyto-toponym · Vegetation map

1 Introduction

The Mediterranean Basin is characterised by a long history of interactions between the environment and the humans (Thompson 2020). Humans have shaped this region since the beginning of agriculture, nearly 10,000 years ago (Quézel et al. 1999; Blondel et al. 2010; Marignani et al. 2017), though in many areas the human impact increased in the last 4000 years (Jalut et al. 2009; Sadori et al. 2011; Fyfe et al. 2017; Roberts et al. 2019). Pine tree species are an important part of the woody component of this geographical area, where 10 pine species are considered native (Barbero et al. 1998; Médail et al. 2019; Euro+Med 2020). However, the pine species that can be considered strictly Mediterranean in terms of ecological requirements and distribution are four: *Pinus brutia* Ten., *P. halepensis* Mill., *P. pinaster* Aiton, and *P. pinea* L. (Barbero et al. 1998; Bonari et al. 2021). These species characterise two habitats of community interest, according to the Habitats Directive 92/43/EEC (European Commission 1992): (i) the priority habitat 2270—"Wooded dunes with *Pinus pinea* and/or *P. pinaster*, including

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✉ G. Bonari
gianmaria.bonari@unibz.it

[1] Department of Life and Environmental Sciences, Centre for Conservation of Biodiversity (CCB), University of Cagliari, Viale Sant'Ignazio da Laconi 13, 09123 Cagliari, Italy

[2] Faculty of Science and Technology, Free University of Bozen-Bolzano, Piazza Università 5, 39100 Bolzano, Italy

[3] Department of Life Sciences, University of Siena, Via Mattioli 4, 53100 Siena, Italy

[4] Department of Chemistry and Pharmacy, University of Sassari, Via Piandanna 4, 07100 Sassari, Italy

old-established pine plantations on dune contexts" (Biondi et al. 2010), and (ii) the habitat 9540—"Mediterranean pine forests with endemic Mesogean pines" (Biondi et al. 2010). In the EUNIS system, Mediterranean pine woodlands are classified under the codes N1G—"Mediterranean coniferous dune forests", and T3A—"Mediterranean lowland to submontane *Pinus* forests" (Chytrý et al. 2020). From the syntaxomical point of view, pine-dominated Mediterranean formations are classified in the class *Pinetea halepensis* Bonari et Chytrý in Bonari et al. (2021).

Manifold are the tools that can support, implement, or refine the comprehension of species distribution. Aerial photographs can help in measuring temporal changes in canopy cover as a proxy for woody formation extent and its relation to land-use changes (e.g., Kozak et al. 2007; Wezyk et al. 2018) but changes in species distribution across time can be inferred from interviews with local people (Spampinato et al. 2017) and from the study of phyto-toponyms (Fagúndez and Izco 2016; Signorini et al. 2016; Pasta et al. 2020). This type of information has proven to be an important tool for understanding distributional traits and changes of different species (Bacchetta et al. 2000, 2007; Pinna et al. 2017).

The debate about the original distribution of widely planted species such as the three pine species here studied, and especially *P. pinea*, is long-lasting and difficult to solve (Martínez and Montero 2004). These authors demonstrated, through the help of archaeological, palaeobotanical and palynological evidence, that the species is now to be considered native in areas where the species was previously considered non-native (i.e., south-western Spain). Further, genetic analyses confirmed the presence of a glacial refugium for this species in southern Spain (Mutke et al. 2019). Similarly, in Italy, *P. pinea* was reported as native (Martínez and Montero 2004; Abad Viñas et al. 2016b; Farjon 2017) and an archaeophyte species (Galasso et al. 2018). Currently, *P. pinea* is considered native in Sicily based on palaeobotanical findings (Zodda 1902; Brullo et al. 2002).

In Sardinia, three of the four Mediterranean pine species have been considered native or putative native (Arrigoni 2006; Camarda and Valsecchi 2008; Bacchetta et al. 2009; Pignatti et al. 2017), while *P. brutia* occurs only in reforestation (Arrigoni 2006).

Detailed knowledge of the distribution of vegetation types and habitats is crucial to understand land-use changes at the local and broader scales and to inform conservation practitioners (Puddu et al. 2012; Vilà-Cabrera et al. 2012; Preislerová et al. 2022). Historical data, referring to past centuries, suggest a broader diffusion of the pine natural formations on the island of Sardinia (e.g., Angius 1851; De Marco and Mossa 1980). Cuttings and wildfires caused a significant reduction in their distribution during the nineteenth century and the first 60 years of the twentieth century (Desole 1960, 1964; Arrigoni 1967; De Marco and Mossa 1980; Camarda and Valsecchi 2008). Because of habitat depletion, reforestation has been carried out, typically to combat soil erosion and strengthen dune stability (Pavari 1935; D'Autilia et al. 1967a). Additionally, thousands of hectares of pine afforestation in many areas of the island have been planted, rarely using local material (D'Autilia et al. 1967b; Brigaglia 1994; Calvia and Ruggero 2020). During the twentieth century, research on the distribution (Desole 1960, 1964; Arrigoni 1967; Mossa 1990) and phytosociological interpretation (De Marco and Mossa 1980) of Sardinian pine formations were published. These papers often described landscapes affected by decades of overexploitation and fire (Desole 1960; De Marco and Mossa 1980), whereas the distributional trends that were the result of land-use changes that occurred during the last decades have not been investigated yet. Accordingly, the creation of maps of the present distribution of Sardinian pine communities, and the quantification of the pine formations temporal extent variation is needed.

With this study, we aim at defining the present and past distribution of pine formations in Sardinia. We aimed at: (i) creating the first detailed distribution maps of native pine formations of Sardinia; (ii) quantifying their distribution changes across the second half of the twentieth century and the first two decades of the twenty-first century; and (iii) evaluating the found extent trends in a conservation perspective.

2 Material and methods

2.1 Study area

Sardinia has an area of c. 24,090 km^2, including smaller islands and islets. Sardinian coasts are about 1900 km long, three-quarters of which are rocky and the remaining sandy (Bacchetta et al. 2009). From a geological point of view, Sardinia is highly diversified. The granitic substrates dominate most of the eastern half of the island, while effusive substrates predominate on the western side. Nonetheless, metamorphic rocks and sedimentary carbonate reliefs are present in many parts of Sardinia (Carmignani et al. 2016).

The climate of Sardinia is predominantly Mediterranean, only locally temperate, with a sub-Mediterranean variant, in mountain areas of the northern and eastern parts of the island. It is characterised by a typical seasonality, with mild-wet winters and dry-hot summers (Bacchetta et al. 2009; Canu et al. 2015).

From the biogeographical point of view, Sardinia falls in the Italo-Tyrrhenian biogeographic Superprovince (Ladero Álvarez 1987; Bacchetta et al. 2013) and belongs to the Sardinian-Corsican province, together with the Tuscan

Archipelago (Bacchetta et al. 2012, 2013). The island is in turn divided into six biogeographic sectors and 22 subsectors, according to floristic and endemism rates (Fenu et al. 2014).

2.2 Pine species

Pinus halepensis (Aleppo pine) is a circum-Mediterranean species (Barbero et al. 1998; Bonari et al. 2021). It occurs at an elevation range from the sea level up to 1700 m a.s.l. in Morocco (Farjon 2017). At least in Sardinia, the species is indifferent to the substrate, although often reported with a preference for marls and limestones in different areas (Barbero et al. 1998; Mauri et al. 2016; Farjon 2017). This species is thermophilous and xerophilous, growing in areas with an annual average rainfall of 350–700 mm (Barbero et al. 1998; Mauri et al. 2016). The formations dominated by this species cover more than 3.5 million ha, and they are concentrated mainly in the western part of the Mediterranean Basin, while they are more scattered in the eastern (Pesaresi et al. 2017). In Italy, *P. halepensis* is considered a native species in many administrative regions, including the islands of Sicily and Sardinia (Bartolucci et al. 2018, 2020).

Pinus pinaster s.l. (Maritime pine) has a west-Mediterranean Atlantic distribution, being naturally spread from the Tyrrhenian coasts of Italy to Portugal and from North-Africa to the Atlantic coasts of Spain and France (Barbero et al. 1998; Farjon 2017). The taxon grows from sea level up to 1600 m a.s.l. in Spain and Corsica, reaching 2000 m a.s.l. in Morocco (Abad Viñas et al. 2016a; Farjon 2017). It is considered a heliophilous and xerophilous species, that requires a climate with oceanic influence and a minimum annual average rainfall of about 600 mm (Mazza et al. 2014). From the edaphic point of view, it thrives mostly on siliceous substrates (Barbero et al. 1998; Abad Viñas et al. 2016a). In Italy, *P. pinaster* is native to the administrative regions of Liguria, Tuscany, Sicily, and Sardinia (Bartolucci et al. 2018).

Pinus pinea (Stone pine) is a Mediterranean species, though its native distribution is unclear due to the historical presence of human plantations across wide areas of the Mediterranean Basin (Bonari et al. 2017). This species grows in coastal areas or inland, reaching elevations up to 600 m a.s.l. (Farjon 2017). *P. pinea* is heliophilous, xerophilous, and thermophilous, with an optimum rainfall of 600 mm per year, and prefers sandy, siliceous substrates (Abad Viñas et al. 2016b; Bonari et al. 2020). In Italy, it grows in the peninsular administrative regions, Sicily, and Sardinia, and it is often cultivated (Pignatti et al. 2017).

2.3 Current distribution of native pine formations of Sardinia

To define the present distribution of natural Sardinian pine formations, delimiting their extension, and updating the data available, we collected information from cartographic (maps issued by the Istituto Geografico Militare Italiano—IGMI, scale 1:25,000 maps) and bibliographic sources (Arrigoni 1967; De Marco and Mossa 1980 for *P. halepensis*; Desole 1960, 1964; Veri and Bruno 1974; Brigaglia 1994 for *P. pinaster*; Arrigoni 1967; Mossa 1990 for *P. pinea*). In addition, to refine the data, we carried out 60 field excursions across the entire island of Sardinia in the years 2017–2019. These surveys concerned the localities known from the literature and the new ones we retrieved. To define the perimeter and the area of each pine formation, a ©Garmin GPS62st was used.

To map the present distribution of each pine formation, we considered three canopy cover categories, defined as followed: (i) areas where the dominant pine species had a < 1% of the canopy cover (including isolated trees, used for defining the distribution of the species in Sardinia); (ii) areas where the species had a higher canopy threshold, i.e., 1–35% of the canopy cover; and iii) areas where the species had > 35% of the canopy cover. We considered the third category as pine-dominated formations (i.e., communities where pine species are dominant or co-dominant). Then, we calculated the area of extent of each species and calculated the extent of the woody formations based on the third category.

2.4 Diachronic analysis of the distribution of the pine formations in Sardinia

To understand the changes in the distribution of the pine formations during the last decades, we used cartographic data, literature, and toponyms. The historical digitalised aerial photographs, referring to four different years of aerial surveys (1954, 1977, 1998, 2019), allowed us to create a multitemporal series of cartographic data. We retrieved these data from the Sardegna Geoportale website (2020). After aerial photograph interpretation, we delimited all pine formations undoubtedly referring to each pine species for the different years examined. Then, we calculated the area of extent of different pine formations for each available year and compared these measures with the current distribution maps obtained before (see methods described in Sect. 2.3).

2.5 Interviews

To complement previously obtained information on past distribution, we performed non-structured interviews. During the years 2016–2020, we interviewed 30 people, between the ages of 40–90 years, living and/or working in the municipalities relevant to this study. Most of the interviewed people worked as foresters (15), followed by shepherds (7), touristic guides (4), naturalists (2), and historians (2). Eight of these people had a university degree, 10 had a high school degree, 10 had a middle school diploma, and 2 had elementary education. We asked them to respond to questions about their knowledge of present and past existing pine formations or even isolated trees in specific areas where pines still exist or were previously known, information related to the eventual local disappearance of some formations, information about the reforestation and the used material, and confirmation and/or explanation of some toponyms.

2.6 Collection and interpretation of the pine-related toponyms of Sardinia

To better understand a likely past distribution of the pines, we also searched for toponyms that included "pine" in the name. Primarily, we recognised all the vernacular pine names through the consultation of Sardinian dictionaries (Wagner 1960; Congia 1998; Casu 2003; Martelli 2006; Rubattu 2006): *campingiu*, *compingiu*, *cumpingiu*, *obinu*, *op(p)inu*, *pinu*. Secondarily, we inspected all of the maps of Sardinia issued by the Istituto Geografico Militare Italiano (IGMI, scale 1:25,000 maps), and consulted the Sardegna Geoportale website (2019). Then, we searched for localities reported in the literature (e.g., Angius 1851; Desole 1960; Bacchetta 2006). Biogeographical and historical information helped in attributing every toponym to each pine species.

We created a table containing all of the pine-related toponyms we found in different sources. We report the list of the phyto-toponyms for each pine species, their translation into English, municipality (province), biogeographical sector and subsector, coordinates, elevation, current status (extant or extinct), and original sources. Then, we prepared a distribution map with all phyto-toponyms related to natural formations found and compared them with the current Sardinian pine species distribution.

Problematic cases included confusion with personal names and the name of the species. In the Italian and Sardinian languages, "Pino" is used as an abbreviation of the name Giuseppe—Joseph. All the toponyms that we recognised as referring to confirmed planted pines as well as personal names were not included in the map nor considered in our analyses.

We prepared the past and present distribution maps, and we geo-referenced the phyto-toponyms using the Open-Source Geographic Information System Quantum GIS (QGIS 2.18).

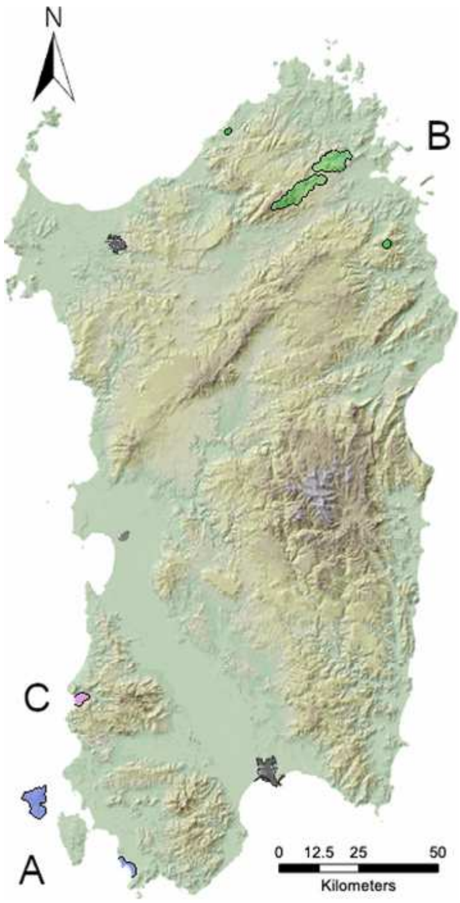

Fig. 1 Map of Sardinia showing the distribution of the three pine species on the island. **A** (blue) = *Pinus halepensis* area; **B** (green) = *P. pinaster* area; **C** (purple) = *P. pinea* area. Urban settlements of the main cities of Sardinia are reported in grey (colour figure online)

Table 1 Comparison of the current extents in hectares of different canopy covers for the three wood canopy categories of the different pine species formations

Species	Canopy cover (ha)		
	< 1%	1–35%	> 35%
Pinus halepensis	994	3100	770
Pinus pinaster	2903	2550	454
Pinus pinea	464	60	58

Aerial photographs were taken from RAS (Regione Autonoma della Sardegna) (2019)

3 Results

3.1 Current distribution of the pine species in Sardinia

The distribution of the three pine species is reported in Fig. 1. *Pinus halepensis* is currently distributed in an area of about 4864 ha in south-western Sardinia (Fig. 1, Table 1; Supplementary materials: S1A). Scattered trees (< 1% of the total pine canopy) represent about 20.4%. Intermediate canopy cover distribution areas (1–35% of the total pine canopy cover) are 63.7%. Finally, the areas where *P. halepensis* cover is > 35% of the canopy cover are 15.9%.

Pinus pinaster is currently distributed in north-eastern Sardinia over an area of approximately 5907 ha. The area with scattered pines is 49.1% of the total cover (Fig. 1, Table 1; Supplementary materials: S1B). Mixed formations with intermediate *P. pinaster* cover (canopy cover 1–35%) are 43.1%. Then, dense *P. pinaster* formations (estimated canopy cover > 35%) occupy 7.8%.

Pinus pinea distribution is about 582 ha in the south-western Sardinia (Fig. 1, Table 1; Supplementary materials: S1C). The area with scattered pines is 79.7%, while that of intermediate cover formations (canopy cover 1–35%) is 10.3%. Finally, the pine formations of *P. pinea* with high cover (canopy cover > 35%) are found in an area of about 10% (Table 1).

A high percentage of Sardinian pine formations falls within protected areas (Table 2). *P. halepensis* natural habitats are almost totally included in Special Areas of Conservation and Special Protection Areas (SAC ITB040027—"Isola di San Pietro"; SPA ITB043035—"Costa ed entroterra tra Punta Cannoni e Punta delle Oche"; and SAC ITB040025—"Promontorio, dune e zone umide di Porto Pino"). Only a part of *P. pinaster* formations are included in protected areas by the Habitats Directive (SAC ITB011109—"Monte Limbara"; and SAC ITB012211—"Isola Rossa-Costa Paradiso"), while about 20% of these formations are not included in SACs neither in Regional Forests. On the contrary, only 34% of the *P. pinea* formations fall within a protected area (SAC ITB042247—"Is Compinxius, Campo dunale Buggerru, Portixeddu"), though all the natural forests are included there and recognised as priority habitat 2270*.

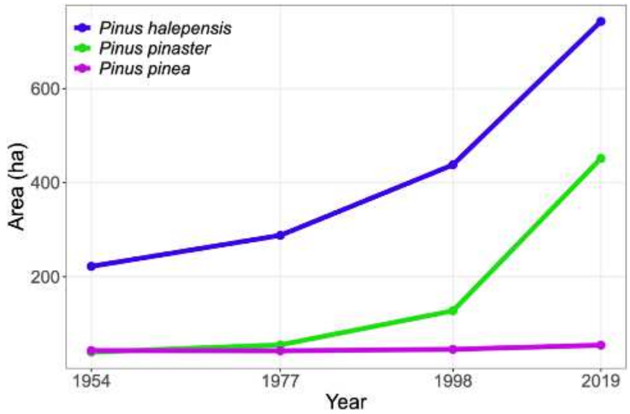

Fig. 2 Estimated hectares of native Sardinian pine formations (> 35% pine canopy cover) between 1954 and 2019, according to the interpretation of aerial photographs at intervals of about 20 years. Aerial photographs of 1954, 1977, 1998, and 2019 were taken from RAS (Regione Autonoma della Sardegna) (2019)

3.2 Diachronic analysis of the distribution of natural pine formations in Sardinia (1954–2019)

We recorded a significant expansion of the three pine formations of Sardinia during the last 60 years. This increase is + 1043% for *Pinus pinaster*, + 235% for *P. halepensis*, and + 27% for *P. pinea*.

The increase in the extent of *P. halepensis* formations appears to be constant between 1954 and 2019. The minimum extent was reached in 1954 (Fig. 2), with an area of about 222 ha. The first increase was in 1977, with 288 ha. In 1998, there was a further increase, reaching 438 ha. In 2019, the canopy cover was 770 ha (Supplementary materials: Figure S2).

The increase in the extent of *P. pinaster* formations appears to be rather constant between 1954 and 2019. The minimum extent was reached in 1954 (Fig. 2) when their extent was 39.5 ha. In 1977, the total *P. pinaster* formations extent in Sardinia slightly grew to 55 ha. A further increase in the extent was reached in 1998 when *P. pinaster* formations reached 127.5 ha. The current extent of *P. pinaster*

Table 2 Comparison of the extents in hectares of the three pine species distribution within protected areas (SACs, Forestry Agency managed areas), matching the two habitats 2270* and 9540 of the Habitats Directive

Species	Pine formations included in PA % (ha)	Out of PA % (ha)	Habitat 2270* (ha) (past)	Habitat 2270* (ha) (present)	Habitat 9540 (ha) (past)	Habitat 9540 (ha) (present)
Pinus halepensis	99.7 (4848)	0.3 (16)	28.8	77	710.2	666
Pinus pinaster	80.3 (4732)	19.7 (1162)	0	0	166.2	454
Pinus pinea	33 (193)	67 (389)	167.7	58	0	0

Past data refer to standard data forms or management plans of the SACs

PA protected areas

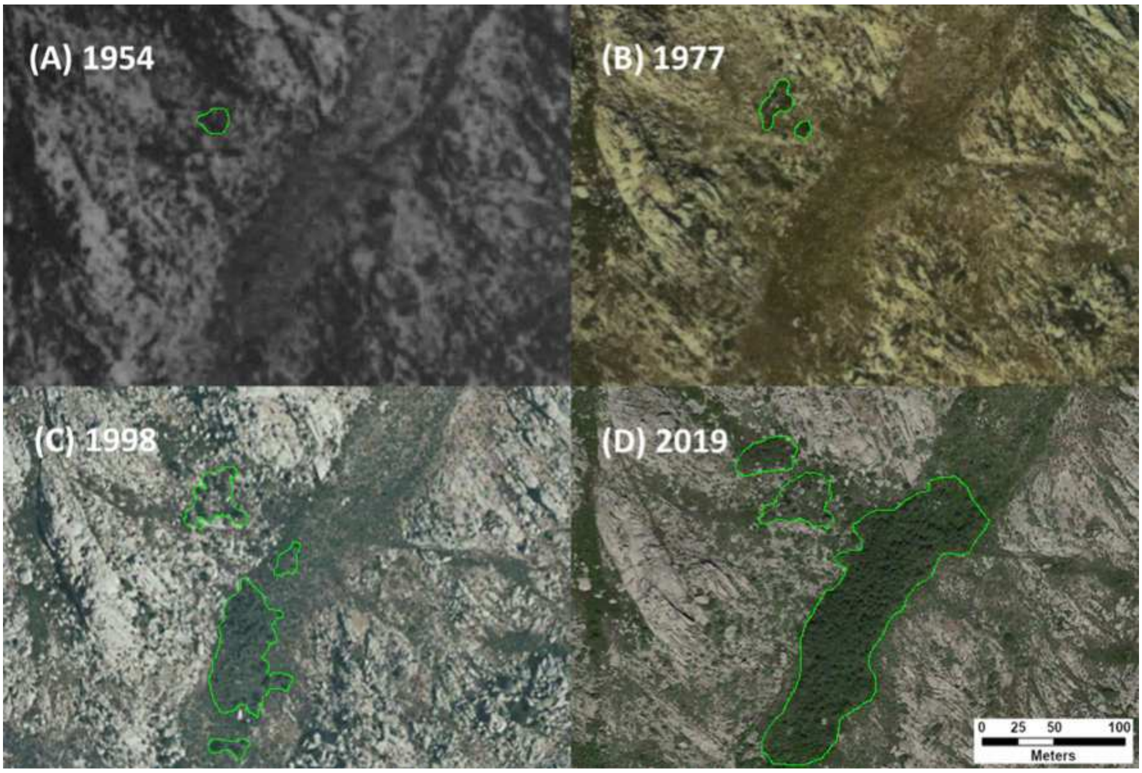

Fig. 3 Aerial photographs showing an example at the local scale of the increasing of Sardinian pine formations (at the centre of each photograph) in **A** 1954, **B** 1977, **C** 1998, and **D** 2019

formations reaches 454 ha (Supplementary materials: Figure S3).

There was only a small increase in extent of *P. pinea* formations between 1954 and 2019. The extent was rather constant during the last decades (Fig. 2), slightly fluctuating from 43 ha in 1954 to a minimum of 42.5 ha in 1977, then increasing again to 45.5 ha in 1998, and finally reaching the current 58 ha (Supplementary materials: Figure S4).

An example at the small scale of the recent pine formations increase is reported in Fig. 3. From these images, as representative of a wider phenomenon, is visible the difference in the extent between the past (especially visible in Fig. 3A and B) and more recent times (especially visible in Fig. 3C and D).

3.3 Pine-related toponyms

We found a total of 36 toponyms that can be attributed to native or putative native formations of the three pine species (Figure S5). The full list of toponyms is reported in Table S1, while the doubtful toponyms are reported in Table S2 of the Supplementary materials.

We found seven toponyms that may refer to *Pinus halepensis*. They are all concentrated in four municipalities of south-western Sardinia. Five toponyms fall in extant formations.

We found 26 toponyms that may refer to as *P. pinaster*, located in 15 municipalities of the north-eastern part of the island. Another toponym exists in the central-eastern part of Sardinia. Overall, five out of 27 toponyms fall in the current native pine distribution, while the others are long extinct.

We found two toponyms that may refer to as *P. pinea*. Both are in south-western Sardinia where this species still thrives.

We also found 11 toponyms that did not refer to native pine formations. Nine were recognised as related to planted pines since they indicate farms, private houses, or reforestation stands of the twentieth century, while two were referred to personal names (Table S2).

4 Discussion

4.1 Distribution of the three pine species in Sardinia: an update

We found an overall increase in the extent of all Sardinian pine species investigated and of their associated formations.

From 1954 to 2019, the average increase of the three species considered altogether shows an expansion of +310%. Noteworthy, *Pinus pinaster* formations currently cover an area more than 10 times larger than in 1954. *P. halepensis* formations currently cover an area that is about three times larger than in 1954. These trends mirror what is known for the whole woody formations of Sardinia (Puddu et al. 2012). These authors reported an increase in forests from less than 2000 km^2 in 1965 to 4927 km^2 in 2007, meaning their extent passed from a minimum of 7.9 to 20% of the Sardinian area. This translates into a woodland expansion of + 146% in 42 years, for the whole of Sardinia.

Sardinian *Pinus halepensis* native formations occur on different substrates and in some of the most arid zones of the island, in the thermo-Mediterranean thermotype. Since the nineteenth century, these pine formations have been reported in the areas of the south-western Sardinia where the species is currently present: the Island of San Pietro and the Gulf of Porto Pino (Moris 1827; Angius 1851). Previous authors did not quantify the total extent of the species but depicted mostly sparse thickets, small trees scattered within garrigues and scrublands (Arrigoni 1967; De Marco and Mossa 1980). All of the reported areas fall in the Sulcitano-Iglesiente sector and Antioco-Carlofortino subsector (Fenu et al. 2014).

Sardinian *Pinus pinaster* formations are related to granitic rocks, ranging from 90 m up to about 1250 m a.s.l. in Mount Limbara, where the species reaches the temperate bioclimate in the sub-Mediterranean variant (Calvia and Ruggero 2020). Historical data, referring to the nineteenth century, showed a past distribution of *P. pinaster* wider than today, since Angius (1851) reported the species in sites that fall in three different Sardinian subsectors (Fenu et al. 2014): Gallurese, Baronico and Ogliastrino. Nowadays, of the 27 toponyms mentioning *P. pinaster*, only five preserve pine formations. However, we speculate the current species distribution is generally larger, if compared to what was depicted by Desole (1960, 1964) as this author reported *P. pinaster* in four areas of Gallura and 11 sites, mostly characterised by poor formations and isolated trees. We refined the current distribution of *P. pinaster* in Sardinia, which currently occurs in the same four areas cited above but in 57 main pine formations, plus several other minor sites. From the biogeographical point of view, all the extant pine formations fall within the Goceano-Logudorese sector and the Gallurese subsector (Fenu et al. 2014).

Sardinian *Pinus pinea* formations occur in only one area (Arrigoni 1967; Mossa 1990; Bacchetta et al. 2009). These pine formations, already cited by Moris (1827; 1837) and Angius (1851), can be considered the only natural *P. pinea* formations on coastal dunes in Italy (Pignatti et al. 2017). They grow mainly on Holocene sands of the wide dune system that extends from Portixeddu towards inland for about 3 km, reaching a maximum height of 202 m a.s.l., in the upper thermo-Mediterranean thermotype. Some more isolated trees grow up to 6 km inland, at the extreme border of the alluvial deposits. Our research showed the increased extent covered by these formations. We detected five main stands, while several scattered trees grow elsewhere and are mostly isolated in low dunes and scrublands. The total area of the *P. pinea* formations is about 582 ha. It is confined to the south-western coast between Fluminimaggiore and Buggerru, in the Sulcitano-Iglesiente sector and Iglesiente subsector (Fenu et al. 2014).

4.2 Pine woodland changes between the twentieth and twenty-first centuries reflect the land-use change

The results of our study shed light on the landscape transformations observed in Sardinia over the last 60 years. They can be summarised as a natural expansion of pine formations, also favoured by a reduction of human-generated disturbance such as wildfires and cuttings in many areas (Desole 1960; De Marco and Mossa 1980). In some places, this expansion might represent a threat to garrigues with endemic species (Calvia et al. 2022).

The total distribution of native pine formations in Sardinia, has been affected during the last centuries by strong human pressure (Angius 1851; Spano 1958; Desole 1960, 1964; Arrigoni 1967). The interpretation of aerial photographs suggested that the pine species formations were at their minimum in post-World War II and allowed us to estimate the increase in canopy cover that occurred during the last decades. This is in line with the increasing trend of wooded areas in Sardinia, Italy, and other European regions (Poyatos et al. 2003; Falcucci et al. 2007; Gehrig-Fasel et al. 2007; Puddu et al. 2012; Barbati et al. 2013; Smiraglia et al. 2015; Ferretti et al. 2018). All of the Sardinian areas where the expansion of *Pinus halepensis* and *P. pinaster* is higher are characterised by human depopulation, a decrease of livestock, and the disappearance of agricultural activities over the last 50–60 years. Therefore, in hilly and mountain areas, the traditional burning by shepherds to renew wild pastures (Desole 1960) and/or to combat rabbit expansion (De Marco and Mossa 1980) ceased. The recent pines expansion can be explained by the fact that pines are pioneer species and can therefore rapidly recolonise degraded lands (Barbero et al. 1998), even in the absence of fire (Wyse et al. 2019).

The first mention of *Pinus halepensis* in Sardinia dates back to 1737 in a historical document that specifically refers to the Island of San Pietro, which was then an uninhabited island and was described as rich in pine formations (Arrigoni 1967). After island colonisation, the pine formation surface was greatly reduced in a short time frame, mostly as a consequence of frequent wildfires (De Marco and Mossa 1980). In the recent decades, the constant increase of these pine formations has led to the current 770 ha.

Historical data reported *Pinus pinaster* in some places where it no longer occurs (Angius 1851; Desole 1960). The many toponyms found in north-eastern Sardinia, confirmed by interviews and by literature, helped in depicting a former distribution of *P. pinaster* with a larger extent compared to the current one. Conversely, the constant increase of *P. pinaster* formations during the last decades is primarily attributed to the reduction of agro-pastoral activities such as ploughing, the cutting of Mediterranean scrubland and, especially, the periodical burning of scrublands for creating cattle and goat pastures (Desole 1960; Piussi 2005; Mancino et al. 2014; Camarretta et al. 2018). The creation of vast protected areas also aided the recovery of more natural conditions. In addition, extended reforestation was locally planted with the use of autochthonous germplasm (Brigaglia 1994; Calvia and Ruggero 2020).

Pinus pinea is the only species that, during the examined decades, maintained a rather constant distribution area in Sardinia. This is due to the isolation of the pine formations in some portions of a dune system that did not differ much, except for one afforestation started in 1958 around the historically known populations (Arrigoni 1967). A very small decrease was observed between 1955 and 1977. Since then, the main formations had a small increase, mainly in the innermost parts of the dune, i.e., those not affected by afforestation.

These formations are sometimes invaded by alien species. The *Pinus pinea* natural formations today are frequently in contact with an extensive old-established plantation of *P. pinea* trees, which began to be planted in 1958 (Arrigoni 1967), along with the invasive *Acacia saligna* (Labill.) H. L. Wendl. Planted pine trees currently cover approximately 224.5 ha, while *A. saligna* is colonising the understorey and the open areas of the dune system. Specifically, the current invasion by *A. saligna* could affect the natural woodland patches referred to in the EU priority habitat 2270* regions in the long term (Del Vecchio et al. 2013; Lozano et al. 2020). Similarly, several non-native species, such as *Abies cephalonica* Loudon, *Cedrus atlantica* (Endl.) G.Manetti ex Carrière, *Pinus nigra* J.F.Arnold subsp. *laricio* Palib. ex Maire, *P. radiata* D.Don, were also planted in reforestation, and their spread now affects different areas of the habitat 9540 in hilly and mountain areas (Calvia and Ruggero 2020). The other two factors limiting the expansion and quality of pine stands are related to urbanisation, likewise to the pressure of agro-pastoral activities.

Concerning the conservation status of the Sardinian pine formations, they mostly fall within protected areas. Concerning *Pinus halepensis*, all pine formations on the Island of San Pietro fall within the SAC ITB040027, "Isola di San Pietro". Almost all of the pine formations of the coastal zones of south-western Sardinia are included in the SAC ITB0400025, "Promontorio, dune e zona umida di Porto Pino". Only the southernmost fragment of the Porto Pino area is not included in any protected area. Moreover, this latter is part of the military polygon of Capo Teulada. Among Sardinian pines, *P. halepensis* is the only species whose formations fall in both habitat 2270* and habitat 9540 (Table 2).

About *Pinus pinaster* formations, the northernmost is included in the SAC ITB012211, "Isola Rossa—Costa Paradiso". The formations of Monte Limbara are part of the SAC ITB011109. At both sites, *P. pinaster* formations are within the community habitat 9450. On the other hand, the *P. pinaster* formations of Monti Ultana and Monte Nieddu are not part of any protected area but can be classified also within the habitat 9540.

Finally, *P. pinea* formations are included in the SAC ITB042247, "Is Compinxius—Campo dunale di Buggerru—Portixeddu". These natural pine formations are classified within the priority habitat 2270*, although without a clear distinction with pine plantations. Recent studies have clarified some ecological aspects of the priority habitat 2270*, mainly considering *P. pinea* formations of the Tyrrhenian shores of central Italy and partly those of the North Adriatic coast (Bonari et al. 2017; 2018; Sarmati et al. 2019). However, further studies are needed to clarify ecological features of this habitat in Sardinia, where only natural formations have been in the spotlight (Calvia et al. 2022).

5 Conclusions and implications for conservation

Our study contributes to a better understanding of the past and present distribution of *Pinus halepensis*, *P. pinaster* and *P. pinea* in Sardinia. The three species occur in the same areas where they were historically mentioned. However, the extent of the two most widely distributed pine species of Sardinia are experiencing a trend of expansion during the last decades, with a recovery pattern two times faster than the average overall forest formations of Sardinia. Accordingly, we found an important increase in the extent of *P. halepensis* and *P. pinaster* native formations, while the extent of *P. pinea* formations are rather stable. Nevertheless, especially *P. halepensis* and *P. pinaster* formations are still far from having occupied their potential distribution range (i.e., Potential Natural Vegetation, sensu Farris et al. 2010). The search of toponyms suggested an important loss of the formations compared to the past, specifically between the nineteenth and the first half of twentieth century. These temporal changes in distribution particularly affected *P. pinaster* formations, and to a lesser extent *P. halepensis*.

Our study highlights the importance of diachronic analyses for monitoring environmental changes. These analyses can be fruitfully combined with other approaches such as the study of phyto-toponyms and interviews with local people. In this respect, this study might support conservation measures for the two EU habitats physiognomically characterised by Mediterranean pines, i.e., 2270* and 9540 in Sardinia, including problematic aspects such as old-established plantations that are sometimes difficult to be distinguished from natural formations. We suggest considering the trends in the extent of vegetation formations and habitats for conservation purposes.

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