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Vascular flora of the isthmus of Feniglia (southern Tuscany, Italy)

Tiberio Fiaschi[1], Gianmaria Bonari[1,2], Flavio Frignani[1], Gina Gizzi[3], Marco Landi[1,4], Sara Magrini[5], Giovanni Quilghini[6], Emilia Pafumi[1,2], Anna Scoppola[7], Claudia Angiolini[1,2]

1 *Dipartimento di Scienze della Vita, Università di Siena, Via P.A. Mattioli 4, 53100 Siena, Italy* **2** *NBFC, National Biodiversity Future Center, 90133 Palermo, Italy* **3** *Department of Science and Technology, University of Sannio, Via F. de Sanctis, snc, 82100 Benevento, Italy* **4** *Reparto Carabinieri Biodiversità di Siena, Via Cassia Nord 7, 53100 Siena, Italy* **5** *Department of Ecological and Biological Sciences, Tuscia University, largo dell'Università s.n.c., 01100 Viterbo, Italy* **6** *Reparto Carabinieri Biodiversità di Follonica, Via Bicocchi 2, 58020 Follonica, Italy* **7** *Department of Agricultural and Forestry Sciences (DAFNE), Tuscia University, Via S. Camillo de Lellis, 01100 Viterbo, Italy*

Corresponding author: Gianmaria Bonari (gianmaria.bonari@unisi.it)

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Abstract

We studied the vascular flora of the isthmus of Feniglia, a Nature Reserve in southern Tuscany stretching between the Italian Peninsula and Mt. Argentario. Since the nineteenth century, the area has undergone significant environmental modifications due to intensive grazing and deforestation. Later, rehabilitation interventions were carried out, including reforestation and planting of dune species, making it an interesting protected area to study for its botanical aspects. Therefore, we aim to compile the floristic inventory of this distinctive Mediterranean area by integrating old and new data. The checklist comprises 502 specific and subspecific taxa of vascular plants. The life-form spectrum shows a predominance of therophytes, followed by hemicryptophytes. The chorological spectrum highlights the dominance of Mediterranean species, followed by Euromediterranean and Eurasian species. The presence of 15 species of regional importance, 3 species of the Italian red list and 3 Italian endemics (*Ornithogalum exscapum* Ten., *Limonium multiforme* Pignatti, *Linaria purpurea* (L.) Mill.) is noteworthy. Despite the environmental changes undergone in this area, our study reports the presence of remarkable species, including rare ones such as *Atriplex littoralis* L., *Ruppia spiralis* L. ex Dumort., and species at their distribution margin in the Italian Peninsula, such as *Staphisagria macrosperma* Spach, *Juncus sorrentinoi* Parl. and *Maresia nana* (DC.) Batt. Additionally the presence of 26 alien species, of which 15 are invasive, 9 naturalized and 2 casual, indicates a relatively low

presence of alien species. Notwithstanding the significant environmental changes that the Feniglia isthmus has experienced in the last century and the high tourist pressure during the summer, the presence of the protected area suggested the effectiveness and benefits of such a form of protection for plant diversity.

Keywords
Coastal biodiversity, conservation, dune, flora, lagoon, Mediterranean, pine forest, protected area

Introduction

Floristic research stands as a baseline for pursuing biodiversity conservation. Acquiring this knowledge demands, however, substantial effort, including field and herbarium surveys, and plant determination endeavours. Unfortunately, these time-demanding tasks are leading to a significant decline, despite their fundamental importance in understanding and conserving our natural heritage (Prather et al. 2004).

Here, we studied the flora of the isthmus of Feniglia, a Nature Reserve in southern Tuscany stretching between the Italian Peninsula and Mt. Argentario. The area encompasses different macrohabitats, including pine forest, dune and lagoon. A well-represented macrohabitat in the study area is the pine forest, a forest type of artificial origin common along the Tuscan coasts. Pine forests line the sandy coastal regions of the Italian peninsula, spanning from the initial backdunes to the innermost settled dune environments. The coastal pine forest vegetation is primarily composed of *Pinus pinea* L. Initially serving as protective barriers shielding farmland from sea spray, these forests historically played a key role in producing pine nuts, timber, and resin. Planted predominantly from the latter half of the 20th century onwards, they were aimed at defending coastlines from water ingress and erosion (Bonari et al. 2017a). Dune systems are among the most threatened coastal ecosystems in Europe (Janssen et al. 2016). These are transitional ecosystems between marine and terrestrial environments, hosting exclusive species and habitats, and with a strong natural dynamics (Costa et al. 1996; Van der Meulen and Udo de Haes 1996; Bertacchi 2017; Gigante et al. 2018). Such dynamism is often negatively affected by urban sprawl, agriculture, reforestation, industry and human recreation activities (Schlacher et al. 2007; Malavasi et al. 2013; Sarmati et al. 2019). These anthropogenic pressures depend heavily on the surrounding landscape. For example, the presence of bathing facilities, cities and industrial and agricultural areas contributes negatively to the degradation of this ecosystem (Garcia-Lozano et al. 2018; Sarmati et al. 2019). The dunes of the Mediterranean region are, however, not always found in man-made settings. They are often surrounded by a more natural landscape such as forests, meadows or wetlands. This latter case, meaning dunes with proximity to wetlands, are somewhat rare. Coastal wetlands encompass river deltas, coastal lakes, marshes, temporary ponds and lagoons. According to Perez-Ruzafa et al. (2011), only 54 main coastal lagoons exist in the Mediterranean Basin. It turns out that coastal dunes are rarely in contact with coastal lagoons. Usually, these lagoons are dominated by shrubs and/or herbs, without forest vegetation or hosting

only sparse trees. One of these particular coastal areas is the isthmus of Feniglia, which is currently a State Nature Reserve. The isthmus of Feniglia hosts noteworthy vegetation types and species. For this reason, it was recognised as a protected biotope (Selvi and Stefanini 2005). Furthermore, it was identified as a distinctive biotope of the Mediterranean Macchia by the Nature Conservation Commission, as designated by the C.N.R. (Selvi and Stefanini 2005).

In the early 1800s, the isthmus of Feniglia was sold by the municipality of Orbetello to private owners who used it to largely exploit it for grazing and logging. This land-use change has led to several major environmental changes that have endangered the lagoon. For this reason, in 1911 a rehabilitation project started, with reforestation and planting of species typical of the Mediterranean coastal areas (Landi et al. 2012). It is likely the oldest ecological rehabilitation operation settled in Europe (Bonari et al. 2021).

The area encompassing the Duna Feniglia State Nature Reserve has been the subject of numerous botanical surveys aimed at assessing the conservation status of the dune ecosystem and devising potential intervention strategies (Bellarosa et al. 1989, 1996; Landi et al. 2012; Bonari et al. 2021). Additionally, studies of a more focused floristic and vegetation nature have been conducted (Gellini and Grossoni 1982; Celletti 1991–1992; Angiolini et al. 2013; Bonari et al. 2017b). A comprehensive analysis of the vascular flora of the isthmus of Feniglia, however, is still lacking. Accordingly, the aims of this work, undertaken more than a century after the ecological rehabilitation of the area, are twofold: firstly, to establish a comprehensive understanding of the vascular flora within the aforementioned Nature Reserve by compiling a dedicated floristic inventory. This is achieved through direct field surveys supplemented by bibliographic resources and herbarium records. Secondly, the study aims to highlight the presence of plant species with significant conservation and phytogeographic value.

Materials and methods

Study area

The study area (42°25.14132'N, 11°24.2731'E) located in southern Tuscany (Grosseto, Italy; Fig. 1) is a dune system that stretches for 6 km in length and 1 km in width, covering an area of approximately 4.92 km^2 and reaching a maximum height of 14 meters above sea level (Angiolini et al. 2013). The Feniglia isthmus connects the Mt. Argentario promontory with the peninsular Tuscany coastline. Together with another sandy strip, it isolates the Orbetello lagoon from the surrounding Mediterranean Sea. The area covers the entire Duna Feniglia State Nature Reserve (EUAP0123) and includes the Special Protection Area (SPA) “Duna di Feniglia” (IT51A0028), a sandy strip that marks the southern end of the Orbetello lagoon. Furthermore, a portion of the Duna Feniglia, facing the lagoon, is part of the “Laguna di Orbetello” (IT51A0026), which is both a SPA and a Special Area of Conservation (SAC). The area also enters within

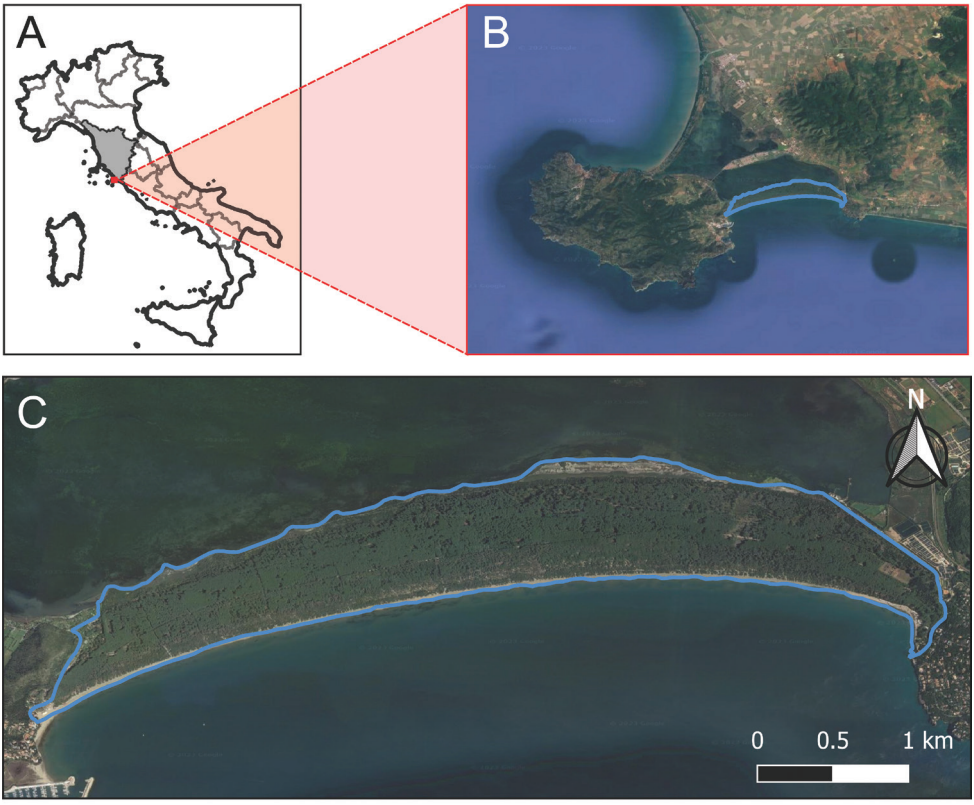

Figure 1. A location of the study area in Italy and Tuscany **B** close up on the study area and surrounding landscape **C** borders of the study area (blue line) Image source: Google Earth 2024.

the geotope of regional importance "Laguna di Orbetello" and borders the "Monte Argentario, Isolotto di Porto Ercole e Argentarola" (SPA and SAC; IT51A0025), while the part facing the sea borders the "Pelagos Sanctuary for the Conservation of Marine Mammals" (EUAP1174) a Specially Protected Area of Mediterranean Importance (SPAMI). Though not adjacent to the study area, there is also a RAMSAR site "Laguna di Orbetello" (AR_GR04), State Nature Reserve "Laguna di Orbetello di Ponente (EUAP0127) and Regional Nature Reserve "Laguna di Orbetello" (EUAP1030). The bioclimate of the study area can be classified as Pluviseasonal oceanic (Mediterranean); the thermotype is Lower mesomediterranean and the ombrotype is Upper dry, while regarding continentality, the climate is Weak Euoceanic (Pesaresi et al. 2014, 2017). The data of a thermopluviometric station located in the municipality of Orbetello (0 m a.s.l.), 2 km apart, reported, in the period 2000–2023, an average temperature of 24.8 °C in the hottest month (August), and 8.9 °C in the coldest month (January)and an average annual rainfall of 551 mm distributed in 55 days, with a peak during the late autumn period and a minimum during the summer (www.sir.toscana.it).

Landscape transformations and history of the isthmus of Feniglia

The isthmus of Feniglia was formed during the late Quaternary period through the accumulation of sandy or sandy-clay sediments eroded from Mt. Argentario (Mancini 1953). These deposits mainly consist of sand rich in carbonates, influenced by strong southwest winds and transported by sea waves (Mancini 1953; Carmignani and Lazzarotto 2004). With the formation of Feniglia, Mt. Argentario, once an island in the Tuscan Archipelago, turned into a promontory. Given the presence of endemic animals and plants, its biogeographical significance is remarkable (Manganelli et al. 2017; Barbato et al. 2018). In the early 1800s, the Orbetello municipality sold the dune to private property that used it for grazing and wood. Deforestation caused sand to fill the Orbetello lagoon, creating shallow marshes and increasing the risk of malaria. This sand influx also harmed fishing, a vital economic activity. To improve water circulation, authorities built canals linking the lagoon to the sea. Reforestation plans in 1900 aimed to control sand movement, delayed until 1910 due to landowners' opposition. Eventually, a law in 1910 designated all of Feniglia as public land (Bellarosa et al. 1996). In 1911, a project was initiated for the consolidation and reforestation, mainly using *Pinus pinaster* Aiton subsp. *pinaster* and *P. pinea* L. as forest species, of the Isthmus of Feniglia to prevent the lagoon from silting up (Fig. 2). The project also included the planting of species typical of Mediterranean dune grassland and shrubland formations along the coast such as *Calamagrostis arenaria* (L.) Roth subsp. *arundinacea* (Husn.) Banfi, Galasso & Bartolucci, *Cakile maritima* Scop. subsp. *maritima*, *Juniperus macrocarpa* Sm., *Euphorbia paralias* L. and *Medicago marina* L. (Landi et al. 2012). The reforestation works were carried out on about 360 hectares until 1925 when the dune became part of the Azienda Forestali Demaniali (Ciabatti et al. 2009). In the same period, an experiment was carried out to introduce non-native species such as *Pinus radiata* D.Don, *Hesperocyparis macrocarpa* (Hartw. ex Gordon) Bartel, *Robinia pseudoacacia* L. and other alien species (Selvi et al. 2006), some of which are still found in the area. In the following decades, the reforested area, namely a pine forest, reached approximately 460 hectares.

Field surveys and data analysis

For the compilation of the floristic inventory of the isthmus of Feniglia, we first retrieve all past botanical research conducted entirely or partly in our study area (Caruel 1860; Sommier 1902), including those done shortly after the start of the reforestation project (Sforzi et al. 1914; Liguori 1928) and those 70–80 years after reforestation (Géhu et al. 1984; Bellarosa et al. 1996; Vagge and Biondi 1999). We also considered data present in theses (Celletti 1991–1992; Sturba 2012–2013; Gizzi 2017–2018) and more recent studies (Landi et al. 2012; Angiolini et al. 2013; Ciccarelli et al. 2015; Bonari et al. 2017b). We complemented our data mining with several floristic surveys in 2023. We excluded from the analyses the species found before the reforestation (Caruel 1860; Levier and Sommier 1891; Sommier 1902; Baroni 1908) and those reported in the

Figure 2. The Feniglia Dune in 1911, before the reforestation work began (**A**) and how it looks at present (**B**). Photo credits: A. Liguori, 1928 (**A**) and G. Bonari, 2017 (**B**).

theses but identified as errors. The species used in reforestation were included in the flora only if they were naturalised, while the others were excluded. These species are listed in the Suppl. material 1.

The collected specimens are kept in the herbarium of Siena (SIENA) and Viterbo (UTV). The codes of the herbaria follow Thiers (2020 onwards).

The species were mainly identified according to Pignatti (1982), Tison and De Foucault (2014) and Pignatti et al. (2017–2019) but additional texts were also used (Castroviejo et al. 1984–2005; Arrigoni 2016–2021). The nomenclature of the taxa follows Bartolucci et al. (2024) and Galasso et al. (2024). Chorotypes were simplified as follows: Alien, Atlantic, Boreal, Endemic, Eurasiatic, Euromediterranean, Mediterranean, Orophilous and Wide distribution. Life forms and chorotypes were attributed according to Pignatti et al. (2017–2019). Ecological indicators (Ellenberg 1974) adapted to the flora of Italy were taken from Pignatti et al. (2005) or their updates, when available (Guarino et al. 2012; Domina et al. 2018). Our ecological indicator values had different scales. Light (L), Temperature (T) and Continentality (C) ranged between 1–12, Soil reaction (R), Moisture (U) and Nitrogen (N) ranged between 1–9, while Salinity (S) ranged between 0–7. Furthermore, to help interpret the ecological preferences of confirmed species, we classified each taxon into one or more of the following preferential macrohabitats: F = forest; D = dune; L = lagoon. When no evident preference was detected for a given species, the category other (O) was applied. This classification was later used in analysis. To verify the conservation status of each taxon, we checked the Tuscan attention list and the Italian Red List of vascular plants (Sposimo and Castelli 2005; Orsenigo et al. 2020). We used the data available on WikiplantbaseToscana (Peruzzi and Bedini 2013 onwards) as a proxy for the regional distribution and rarity of the species. For the national distribution and the status of occurrence (i.e. archaeophyte and neophyte, at both regional and Italian levels), we used the data available on Portal of the Flora of Italy (from 2023 onwards) as a proxy. For the distribution of woody species, we also consulted Roma-Marzio et al. (2016). We also calculated the H/T ratio as a bioclimatic index (Sabato and Valenziano 1975; Cannucci et al. 2019). We conducted the analyses for the whole flora and separated them by macrohabitats.

Finally, we computed the expected number of species based on the extent of the study area using the Species-Area Relationship (SAR) formula proposed by D'Antraccoli et al. (2019) along with the constants provided for Italy by D'Antraccoli et al. (2023). We performed the analysis for the whole flora and separately for native and alien taxa.

The analyses and graphs were done using R Studio v. 4.3.0 (R Core Team 2023).

Results

Floristic inventory

The floristic inventory of the isthmus of Feniglia includes 502 taxa (species and subspecies). These taxa are distributed across 80 families and 279 genera (Fig. 3). The most represented families are Poaceae (72 taxa), Asteraceae (54), Fabaceae (52), Caryophyllaceae (24), Brassicaceae (17), Lamiaceae (15) and Amaranthaceae (15). The genera with more taxa are *Trifolium* (16 taxa), *Euphorbia* (9), *Medicago* (8), *Carex* (7),

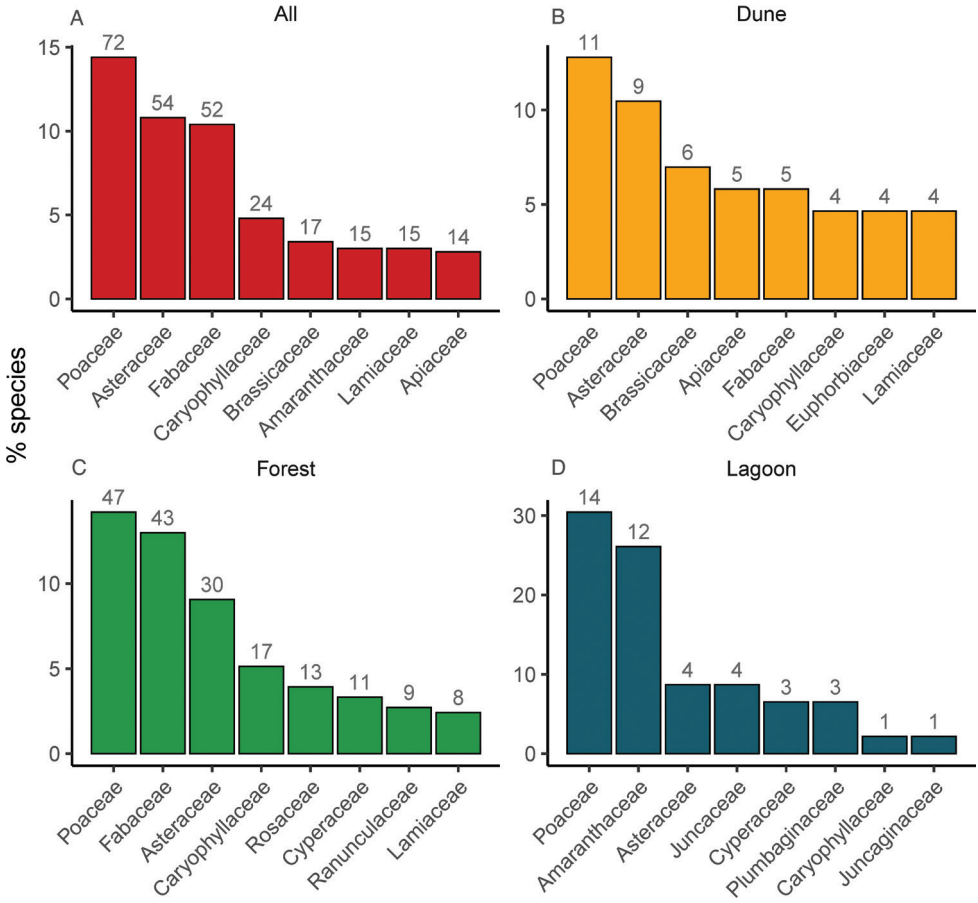

Figure 3. Bar plot of the 8 most represented families (percentages) across the inventoried flora (**A**) and divided as per macrohabitats of dune (**B**), forest (**C**) and lagoon (**D**).

Juncus (7), *Quercus* (7) and *Vicia* (7). In the dune macrohabitat, the most represented families are Poaceae (11 taxa), Asteraceae (9), Brassicaceae (6), Apiaceae (5) and Fabaceae (5). In the forest macrohabitat, the most represented families are Poaceae (47), Fabaceae (43), Asteraceae (30), Caryophyllaceae (17) and Rosaceae (163). In the lagoon macrohabitat, the most represented families are Poaceae (14), Amaranthaceae (12), Juncaceae (4), Asteraceae (4) Cyperaceae (3) and Plumbaginaceae (3). The species excluded from the floristic list are 46 and are divided into 31 species not recently found, 10 erroneous species reported in theses, and 5 species used in reforestation but not self-maintaining.

As results from the SAR analysis, the observed number of taxa exceeds the expected value of 377 by +33.16%. For native species, we found +27.35% taxa compared to the expected value of 373, while for alien species we found +42.11% taxa compared to the expected value of 19.

Life-form spectrum

The life-form spectrum shows that the most represented species are therophytes (223 taxa), hemicryptophytes (120) and phanerophytes (60; Fig. 4A). The H/T ratio is 0.54. In the dune macrohabitat, the most represented species are therophytes (29), chamaephytes (15) and phanerophytes (15; Fig. 4B). In the forest macrohabitat, the most represented species are therophytes (139), hemicryptophytes (76) and phanerophytes (56; Fig. 4C). In the lagoon macrohabitat, the most represented are therophytes (16), hemicryptophytes and chamaephytes (9; Fig. 4D).

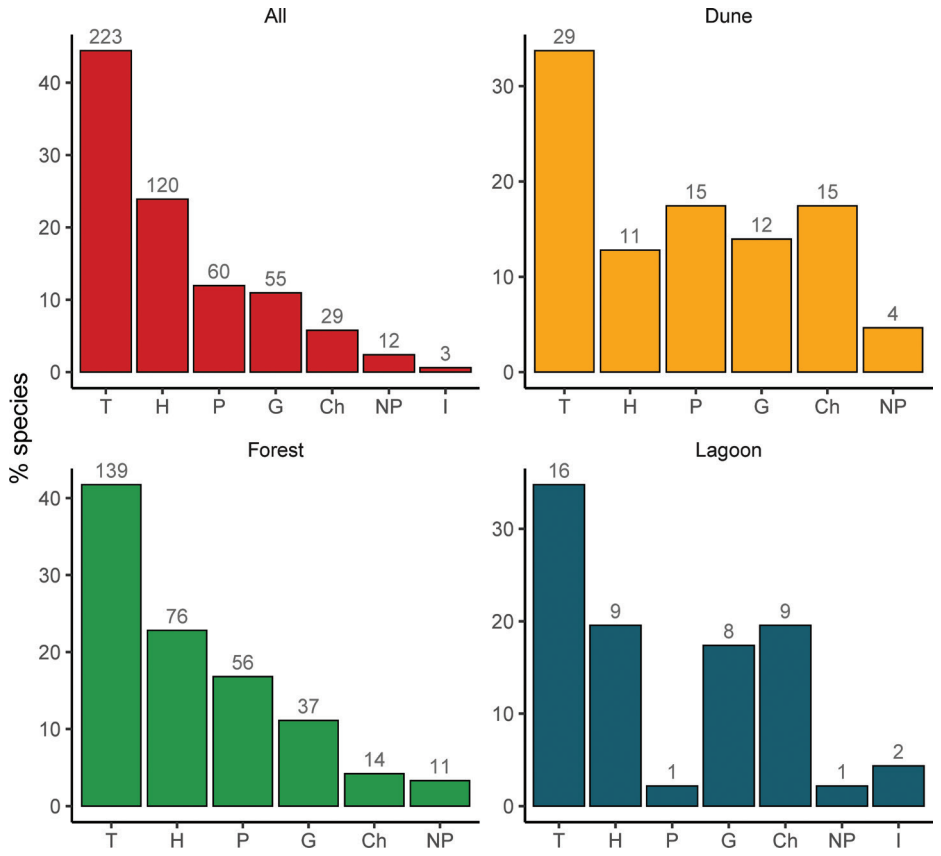

Figure 4. Bar plot graph of the life-form spectrum of the whole flora (**A**) and divided as per macrohabitat of dune (**B**), forest (**C**) and lagoon (**D**). T = Therophytes; H = Hemicryptophytes; P = Phanerophytes; G = Geophytes; Ch = Chamaephytes; NP = Nano-phanerophytes; I = Hydrophytes.

Chorological spectrum

The chorological spectrum shows that the most represented species have Mediterranean (157 taxa), Euromediterranean (115) and Eurasiatic distribution (91; Fig. 5A). In the dune macrohabitat, the most represented species have Mediterranean (43), Euromediter-

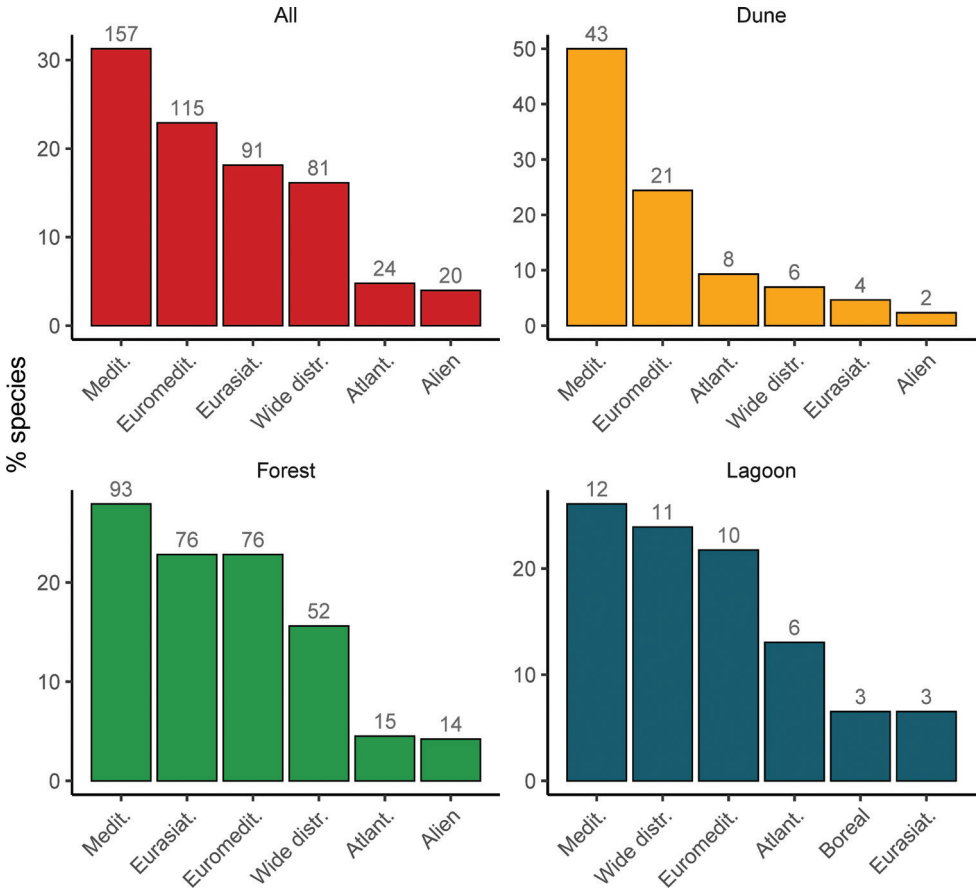

Figure 5. Bar plot graph of the 6 main chorological spectra of the whole flora (**A**) and divided as per macrohabitat of dune (**B**), forest (**C**) and lagoon (**D**). Medit. = Mediterranean; Euromedit = Euromediterranean; Euroasiat = Euroasiatic; Wide distr. = Wide distribution; Atlant. = Atlantic.

ranean (21) and Atlantic distributions (8; Fig. 5B). In the forest macrohabitat, the most represented species have Mediterranean (93), Eurasiatic (76) and Euromediterranean distributions (76; Fig. 5C). In the lagoon macrohabitat, the most represented species have a Mediterranean (12), Wide (11) and Euromediterranean distributions (10; Fig. D).

Ecological indicators

The median Ecological indicators for the whole flora (Fig. 6A) are light (8), temperature (8), soil reaction (6), continentality (5), moisture (3), nitrogen (3) and salinity (0). In the dune macrohabitat (Fig. 6B), heliophilous species are the most represented (11). In the forest macrohabitat (Fig. 6C), heliophilous and light-demanding species (8), while in the lagoon (Fig. 6D) light is the highest indicator value (9.5).

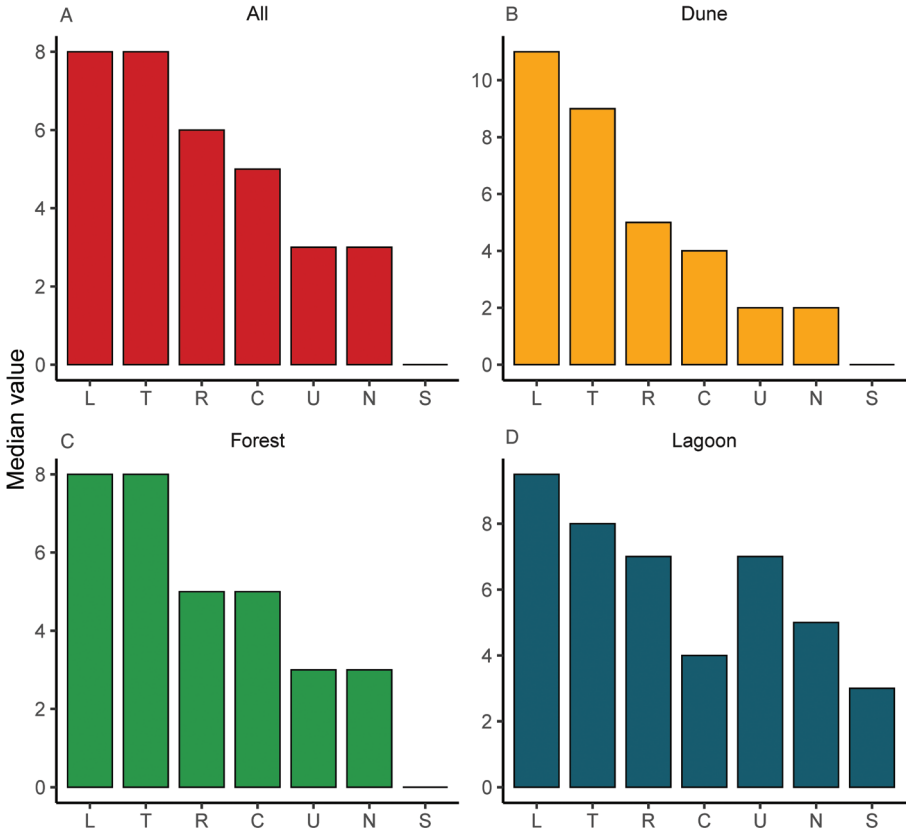

Figure 6. Bar plot graph of the Ecological indicators (median values) for the whole flora (**A**) and divided as per macrohabitat of the dune (**B**), forest (**C**) and lagoon (**D**). L = Light; T = Temperature; R = Soil Reaction; C = Continentality; U = Soil Moisture; N = Soil Nutrients; S = Salinity.

Species of attention lists and alien species

In total, we found 15 species of the Tuscan Attention List and 3 species of the Italian Red List (Table 1).

We found 16 species considered rare in Tuscany such as *Atriplex littoralis* L., *Brachypodium phoenicoides* (L.) Roem. & Schult., *Catapodium hemipoa* (Delile ex Spreng.) M.Laínz, *Clypeola jonthlaspi* L., *Daucus guttatus* Sm., *Euphorbia terracina* L., *Juncus sorrentinoi* Parl., *J. subulatus* Forssk., *Maresia nana* (DC.) Batt., *Nanozostera noltei* (Hornem.) Toml. & Posl., *Plumbago europaea* L., *Puccinellia festuciformis* (Host) Parl. subsp. *lagascana* M.A.Juliá & J.M.Monts., *Rostraria hispida* (Savi) Doğan, *Ruppia spiralis* L. ex Dumort., *Sphenopus divaricatus* (Gouan) Rchb. subsp. *divaricatus*, *Thinopyrum elongatum* (Host) D.R.Dewey., *Vicia segetalis* Thuill. We found 3 species new for the province of Grosseto. They are *Cucurbita maxima* Duchesne subsp. *maxima*, *Dichondra micrantha* Urb. and *Vicia segetalis* Thuill. We found 4 species at the northern distribu-

Table 1. Species included in the Tuscan Attention List (TOS) and Italian Red List (ITA), DD = Data Deficient; NT = Near Threatened; VU = Vulnerable; EN = Endangered; CR = Critically Endangered.

Species	TOS	ITA
Daucus guttatus Sm.	NT	-
Euphorbia barrelieri Savi	-	EN
Isoëtes histrix Bory	VU	-
Juncus sorrentinoi Parl.	CR	DD
Juncus subulatus Forssk.	VU	-
Limonium multiforme Pignatti	NT	-
Marcus-kochia ramosissima (Desf.) Al-Shehbaz	EN	-
Maresia nana (DC.) Batt.	EN	-
Nanozostera noltei (Hornem.) Toml. & Posl.	EN	-
Ruppia spiralis L. ex Dumort.	VU	NT
Salicornia fruticosa (L.) L.	VU	-
Salicornia procumbens Sm.	VU	-
Sphenopus divaricatus (Gouan) Rchb. subsp. *divaricatus*	VU	-
Stachys maritima Gouan	EN	-
Staphisagria macrosperma Spach	VU	-
Suaeda vera J.F.Gmel.	VU	-
Triglochin barrelieri Loisel.	-	EN

tion limit: *Erodium laciniatum* (Cav.) Willd. subsp. *laciniatum*, *Juncus sorrentinoi* Parl., *Maresia nana* (DC.) Batt., *Staphisagria macrosperma* Spach and *Suaeda vera* J.F.Gmel.

We found 26 alien species at Italian level, of which 4 archaeophytes and 22 neophytes. The invasive status of these species in Italy is distributed into three categories: 15 species are invasive, 9 naturalised and 2 casual while we found 27 alien species for Tuscany divided as follows 9 invasive, 10 naturalised and 8 casual (*Ulmus laevis* Pall. is a regional alien species) (Table 2).

Discussion

The floristic inventory of the isthmus of Feniglia reveals the botanical diversity of the area, including rare and protected species, also due to its particular geography and geomorphological features, thus demonstrating relevant ecological and phytogeographical importance.

The proportion of species belonging to the Poaceae, Asteraceae and Fabaceae families is similar to the general pattern of the Italian flora, though the first two families are reversed. Similarly to the flora of the neighbouring Mt. Argentario (Baldini 1995) and Lake Burano (Angiolini et al. 2002), as well as the flora of Tuscan coastal dunes (Ciccarelli et al. 2015), the present study aligns with prior botanical findings. The high number of Poaceae is related to the presence of xerophilous and discontinuous small grasslands. These scattered grasslands can be attributed to a priority habitat according to Habitats Directive 92/43/EEC: Sub-steppe of annual grasses and plants of the Thero-Brachypodietea (Natura 2000 code: 6220; Biondi et al. 2009) that occurs as a mosaic in the pine forest understorey, especially in clearings (Bonari et al. 2018). As

Table 2. Alien species in Tuscany (TOS) and Italy (ITA), divided into Archaeophytes (A) and Neophytes (N), and their associated status (INV = Invasive; CAS = Casual; NAT = Naturalised).

Species	TOS	ITA
Carpobrotus acinaciformis (L.) L.Bolus	N INV	N INV
Citrullus lanatus (Thunb.) Matsum. & Nakai	A CAS	A CAS
Crepis sancta (L.) Bornm. subsp. *nemausensis* (P.Fourn.) Babc.	N INV	N INV
Cucurbita maxima Duchesne subsp. *maxima*	N CAS	N CAS
Cupressus sempervirens L.	A NAT	A NAT
Datura stramonium L.	N NAT	N INV
Dichondra micrantha Urb.	N NAT	N NAT
Erigeron bonariensis L.	N INV	N INV
Erigeron canadensis L.	N INV	N INV
Erigeron sumatrensis Retz.	N INV	N INV
Eucalyptus camaldulensis Dehnh. subsp. *camaldulensis*	N NAT	N INV
Eucalyptus globulus Labill. subsp. *globulus*	N NAT	N NAT
Euphorbia maculata L.	N INV	N INV
Hesperocyparis arizonica (Greene) Bartel	N NAT	N NAT
Hesperocyparis macrocarpa (Hartw. ex Gordon) Bartel	N CAS	N NAT
Malus domestica (Suckow) Borkh.	A CAS	A NAT
Opuntia stricta (Haw.) Haw.	N INV	N INV
Oxalis articulata Savigny	N NAT	N INV
Oxalis dillenii Jacq.	N NAT	N INV
Pinus pinea L.	A NAT	A NAT
Populus ×canadensis Moench	N CAS	N INV
Robinia pseudoacacia L.	N INV	N INV
Syringa vulgaris L.	N CAS	N NAT
Ulmus laevis Pall.	N CAS	-
Veronica peregrina L.	N CAS	N NAT
Xanthium orientale L.	N INV	N INV
Xanthium spinosum L.	N NAT	N INV

far as the other families are concerned, the flora of Feniglia follows the pattern of the Italian flora (Bartolucci et al. 2018; Galasso et al. 2018). Furthermore, it is noteworthy the abundance of Amaranthaceae and Cyperaceae species. The former, including genera associated with coastal salt marshes, make up the late summer-autumn flowering components (Piva and Scortegagna 1993). The latter family includes species linked to wet habitats, such as taxa of the genus *Carex*, as the isthmus encompasses part of the coastal lagoon and hosts freshwater wetlands in mosaic with the pine forest (Angiolini et al. 2013). The high number of species belonging to the genus *Trifolium* is noteworthy. The presence of sandy soils rich in silica and numerous dry grasslands with therophytes could justify the high presence of *Trifolium* sp. pl. (Scoppola at al. 2018). The natural presence of numerous species of the genus *Quercus* in such a limited area is noteworthy and would merit a specific study of these populations. Numerous species also belong to the genera *Euphorbia* and *Medicago*, some specialising in dune and back dune environments. Notably, vascular cryptogams are represented by only two species, *Isoëtes histrix* Bory and *Pteridium aquilinum* (L.) Kuhn subsp. *aquilinum*, playing a

minor role in this coastal area. The limited water availability during the summer season and the absence of rocky substrates appear to be limiting factors influencing the low presence of ferns in this area. Compared to the prediction based on SARs, the results show that the study area exhibits high floristic richness.

Biological spectrum

The life-form spectrum shows a marked dominance of therophytes, represented by species with a short vegetative cycle and adapted to well-drained and nutrient-poor soils. The abundance of therophytes is in line with what has been reported for Mt. Argentario (Baldini 1995) and Lake Burano (Angiolini et al. 2002). Hemicryptophytes can be mostly found in mesophilic herbaceous communities of the understory (*Brachypodium sylvaticum* (Huds.) P.Beauv. subsp. *sylvaticum* and *Oloptum miliaceum* (L.) Röser & H.R.Hamasha) or in thermophilic grasslands (*Anthoxanthum odoratum* L. and *Ranunculus bulbosus* L.). The significant presence of nano-phanerophytes and phanerophytes, the latter being more abundant compared to the nearby Mt. Argentario (Baldini 1995) and Lake Burano (Angiolini et al. 2002), is linked to the presence of dynamic stages of natural dune vegetation, represented by maquis and holm oak formations, which establish themselves within the pine forest, especially where the pine cover thins out (Bonari et al. 2017a). Geophytes prevail in woodland environments (e.g. *Dioscorea communis* (L.) Caddick & Wilkin) and wetlands (e.g. *Isoëtes histrix* Bory) (Lattanzi et al. 2004); they are, however, present in lower percentages compared to the flora of neighbouring areas (Baldini 1998; Angiolini et al. 2002), probably due to the occurrence of ungulates that impact on this habitat by eating plant bulbs (Fattorini and Ferretti 2020). The relatively low presence of chamaephytes confirms the good state of the phanerophytes component in forest communities despite the storm of 2019 causing damages. Hydrophytes are represented by a few species: *Nanozostera noltei* (Hornem.) Toml. & Posl., *Posidonia oceanica* (L.) Delile and *Ruppia spiralis* L. ex Dumort. The limited presence of hydrophytes and helophytes in the flora of the isthmus of Feniglia can be attributed to the ephemeral presence of freshwater bodies. The hydrophytes present grow in saltwater or brackish waters. Even the permanent or semi-permanent ponds that form in the lagoon area are saline or brackish, thus providing unfavourable conditions for freshwater hydrophytes. The H/T ratio reflects a Mediterranean-type bioclimate; this result is similar to values reported for protected areas of the surroundings (Diaccia Botrona: 0.7; Sforzi and Selvi 1999; Lake Burano: 0.67; Angiolini et al. 2002), which indicates a mesomediterranean climate. In these areas, the climate is not typically thermomediterranean, possibly due to the mitigation effect of the brackish environment. Despite this, the H/T ratio of plain areas of the nearby Maremma Regional Park is significantly different (1.04; Arrigoni 2003). This difference is probably partly due to the much larger size of the area that includes environments that are not present in our study area, such as pastures and olive groves.

In all macrohabitats, therophytes are the most common biological form. This is in agreement with the Mediterranean climate and indicates that there is no life form

more suitable for thriving in this environment. The forest macrohabitat reflects the biological form distribution of the overall flora, except for the absence of hydrophytes. This is due to its large area and because it is the most heterogeneous environment, being transitional between dune and lagoon macrohabitats. In the dune macrohabitat, life forms are equally represented, except for nano-phanerophytes. These latter species are the least represented. In the lagoon environment, the limited presence of phanerophytes and nano-phanerophytes is due to various physico-chemical factors, including salinity, anaerobic and muddy substrate, along with fluctuations of water levels, which reduce their occurrence.

Chorological spectrum

The chorological analysis of the whole flora highlights the abundance of Mediterranean and Euromediterranean species. This confirms the picture outlined by the biological spectrum and agrees with the climate of the study area, in turn, consistent with the findings in other coastal areas of Tuscany such as Mt. Argentario (Baldini 1995), Diaccia Botrona (Sforzi and Selvi 1999) and Lake Burano (Angiolini et al. 2002). Eurasian species are well represented. Those with widespread distribution are scarce and primarily identified by cosmopolitan species associated with the Atlantic distribution. Similar values to the European ones are observed, with a less significant boreal component. While being an area with various environments, the flora of Mt. Argentario also has a significant component of Atlantic and Western European species (Baldini 1995). There are a few endemic species, such as *Linaria purpurea* (L.) Mill., widespread in central and southern Italy, excluding Sardinia; *Ornithogalum exscapum* Ten., found in the pine forest, that is endemic to central and southern Italy, excluding Sardinia and Marche regions, and *Limonium multiforme* Pignatti, an endemic species of the Tuscan coast, distributed along the entire rocky coastline from Livorno to the Ansedonia Promontory (Rizzotto 1999).

In all macrohabitats, Mediterranean species are dominant, in accordance with the overall flora. In the dune macrohabitat, they constitute half of the total flora. Many of them are species that have specialised to live in this environment and are often exclusive. The forest macrohabitat more faithfully reflects the composition of the total flora because it is the most widespread and heterogeneous environment that is in contact with both the dune and lagoon macrohabitats. In the lagoon macrohabitat, there are specialised species with a wide distribution chorotype, including many species from the northwest, such as Boreal and Atlantic species. In the lagoon, no alien species occur because they are often ruderal or escaped from gardens. The harsh ecological conditions of the lagoon environment are not favourable.

Ecological indicators

The Ecological indicators of the flora are in line with the values of the Italian flora, except for the values of Temperature, which are slightly higher, and the values of Soil

Moisture, which are significantly lower. These discrepancies stem from the geographical and ecological conditions of the isthmus of Feniglia. The forest macrohabitat is the most similar to the whole flora. This is because a large portion of species is found in this habitat and because it is the most extensive. The dune macrohabitat shows a higher value of light. This is due to the ecological conditions of the dune, where the flora is specialised to cope with high solar radiation. Specific chemical and physical conditions characterise the lagoon macrohabitat, and consequently, its flora profoundly differs. Soil moisture, soil nutrients and salinity values are higher compared to the values of the total flora due to the specialisation of the species present.

Species of attention lists and alien species

We list here the most interesting species in the study area.

Atriplex littoralis L. is an annual species that thrives in arid environments often characterised by marked salinity, alkalinity, and high nitrate content (Pignatti et al. 2017–2019). This species has been found in the lagoon area of Feniglia, within communities predominantly dominated by *Salicornia* spp. In Italy, the species is only present in Friuli Venezia Giulia, Veneto, Emilia-Romagna, Liguria and Tuscany regions; Feniglia, therefore, represents the southern distribution limit for the Italian populations. There are doubtful reports for other Italian regions and historical reports for Apulia (Portal of the Flora of Italy 2023). In Tuscany, only historical or undated records exist, thus making populations of Feniglia the only recent and certain ones.

Daucus guttatus Sm. is a rare annual species of the family Apiaceae reported in 1991 for the dune area of Lake Burano (Angiolini et al. 2002; Selvi 2010). It prefers uncultivated and abandoned clearings but is easily found in coastal environments with sandy soils (back dunes). Its distribution concerns central-southern Italy; it is reported for all the peninsular regions except for the Marche region (Portal of the Flora of Italy 2023). In the Tuscan Attention List, it is reported as 'Near Threatened' (NT) because, despite the strong alteration of its living environments, the population was known in a protected area. It is the overall fifth report of the species in Tuscany, but only the second recent one.

Juncus sorrentinoi Parl. is a species with a western Mediterranean distribution, of considerable conservation interest due to its rarity at the national level and ecological specialisation. In Italy, it is only present in Sardinia and Tuscany and historical reports for Sicily (Portal of the Flora of Italy 2023). It is a silicicolous species, living in ephemeral humid environments with a sandy-mineral substrate, such as small pools, drip sites and streams. This report represents the second record for Tuscany. The only previously known population was for Mt. Leoni (Selvi 1998), consisting of a few individuals in clearings of sparsely vegetated acidophilus shrubland at serious risk of fire and forest evolution (Selvi 2010). Listed in Annex A of Regional Law 56/2000, it is categorised as "Vulnerable" (VU) in Re.Na.To (Sposimo and Castelli 2005). The threats are represented by the evolution of evergreen shrub vegetation.

Maresia nana (DC.) Batt. is a psammophilous species that inhabits sandy coastal environments. In Italy, it has been reported in Lazio, Molise, Apulia, Abruzzo, Ba-

silicata, and Sicily, historical reports for Emilia-Romagna (Portal of the Flora of Italy 2023). Regarding Tuscany, past authors confirmed the presence of *M. nana* along the beaches of Follonica and Mt. Argentario (Fiori 1929). Only recently its presence has been confirmed on the beaches of the isthmus of Feniglia, which currently seems to be the only site where the species is known in Tuscany (Selvi and Stefanini 2005; Selvi 2007). In Re.Na.To. (Sposimo and Castelli 2005), it is reported as "Endangered" because dune habitats are threatened by human expansion.

Plumbago europaea L. is a Mediterranean chamaephyte that grows in uncultivated areas, roadside verges and walls (Pignatti et al. 2017–2019). In the isthmus of Feniglia, it is present in the lagoon, in communities dominated by *Salicornia* spp., in meadows, and the pine forest. In Italy, it is found in all the peninsular and insular regions, in Liguria, in Veneto, and in Emilia-Romagna. *P. europea* is considered alien in Emilia-Romagna, Veneto and Tuscany regions (Portal of the Flora of Italy 2023). In accordance with Arrigoni (2003) and Selvi (2010), who found *P. europea* in other areas of the Grosseto province, we consider the populations present in Feniglia to be native and therefore deem the alien status for the Tuscany region as incorrect.

Staphisagria macrosperma Spach is an annual helio-xerophilous species of considerable size, with a narrow Mediterranean distribution, typically found in arid fallow lands, olive groves and old ruins. In Italy, it is found in Marche, Lazio, Abruzzo, Apulia, Basilicata, Calabria, Sardinia and Sicily and historical reports for Campania (Portal of the Flora of Italy 2023). In Tuscany, it was collected over a century ago in three locations: on the hill of Ansedonia (Grosseto), near Suvereto (Livorno) and on the island of Elba near Porto Azzurro (Caruel 1860; Baroni 1897). In the early 2000s, it was rediscovered on the hill of Ansedonia within the excavation area of the Roman city of Cosa (Selvi 2002); in Re.Na.To. (Sposimo and Castelli 2005), it is reported as "Vulnerable". The population of the Feniglia is locally abundant near to the entrance to the reserve on the Ansedonia side (Peruzzi et al. 2015).

Suaeda vera J.F.Gmel. is a succulent, cosmopolitan species that prefers sunny coastal environments typically characterised by high salinity levels. The distribution in the Mediterranean basin has become, however, increasingly fragmented and reduced due to the alteration of coastal habitats. In Italy, it is found in Tuscany, Emilia-Romagna, Lazio, Veneto, Friuli Venezia Giulia, Abruzzo, Apulia, Basilicata, Calabria, Sardinia and Sicily and historical reports for Campania and Liguria (Portal of the Flora of Italy 2023). The designation of "Vulnerable" status in Re.Na.To. (Sposimo and Castelli 2005) to some extent reflects this issue and the limited extent of the area occupied.

Among the species reported in the past but not recently found, there are some included in the Italian Red List as Least Concern, *Allium chamaemoly* L. subsp. *chamaemoly*, *Ophrys tenthredinifera* Willd. (under the name *O. tenthredinifera* subsp. *neglecta* (Parl.) E.G.Camus) (Orsenigo et al. 2020). The reporting of a specimen from 1856 of *Polygala flavescens* DC. subsp. *maremmana* (Fiori) Arrigoni found in the Feniglia isthmus is particularly interesting (Arrigoni 2014). This species is endemic to Mt. Argentario (Arrigoni 2014; Peruzzi et al. 2019). It was likely present before reforestation efforts; however, it has not been rediscovered in the study area and has thus been excluded from the current floristic list.

Despite the SARs results, alien species presence is limited. Alien species present are generally rare, except for *Erigeron* spp., which often colonise the small patchy grasslands in the pine forest. Although *Pinus pinea* L., which is considered by some authors an alien species, along with *P. pinaster* Aiton. and *P. halepensis* Mill., it forms the priority habitat of Directive 2270*.

Despite that, previous studies have shown its relatively limited effect in shaping floristic composition in coastal areas. Dune species can, to some extent, still occur in the understory of this forest type according to a gradient of salinity (Bonari et al. 2017a). Furthermore, being a Mediterranean species, it can be considered alien only to a certain extent. Accordingly, not all authors agree in considering this species as alien in Italy (Calvia et al. 2022).

The ecological and geomorphological conditions have undoubtedly aided in the isolation of Feniglia, limiting the arrival of alien species, as evidenced by the low number of alien species present in the dune. Of the numerous alien species used in reforestation, very few have naturalised, and the majority are no longer present (Bonari et al. 2021). Among alien species, *Hesperocyparis macrocarpa* (Hartw. ex Gordon) Bartel is reported as new to Tuscany, while *Ulmus laevis* Pall. is reported as new to the Province of Grosseto. The discovery of this new phanerophyte is relevant in the context of the woody flora of Tuscany (Roma-Marzio et al. 2016). The lagoon environment, with its unique physicochemical characteristics and the absence of alien species, can be defined as a barrier that protects Feniglia.

Conclusions

The importance of floristic studies serves as a benchmark for future research, not only in botany but also in related fields. In this context, this work contributes to the knowledge of the vascular flora of the isthmus of Feniglia, an area that has witnessed significant changes in management and protection over the centuries. Feniglia has undergone important vegetation changes, transitioning from the dominance of shrublands to pastures, then dunes, and later forests. Reforestation was the most recent significant human intervention, after which no other significant interventions were carried out on the structure of the vegetation. There are species of particular conservation interest, many of them rare or found in Feniglia isthmus their geographical distribution limit. The low presence of alien species is an excellent indicator of naturalness, especially considering that the few alien species occur with very limited populations. From the biogeographical point of view, it is also important to highlight the role the area plays as an ecological corridor, connecting the Italian Peninsula to the former island of Argentario, while from a conservation perspective, the recognition of the isthmus of Feniglia as a protected area under different designation types (i.e. Nature Reserve, Special Protection Area and Special Area of Conservation), favoured its preservation.

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Supplementary material 1

Floristic list of the isthmus of Feniglia

Authors: Tiberio Fiaschi, Gianmaria Bonari, Flavio Frignani, Gina Gizzi, Marco Landi, Sara Magrini, Giovanni Quilghini, Emilia Pafumi, Anna Scoppola, Claudia Angiolini

Data type: docx

Explanation note: Floristic inventory of vascular flora of the isthmus of Feniglia (southern Tuscany, Italy)

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