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Review

Can we preserve and restore overlooked macroalgal forests?

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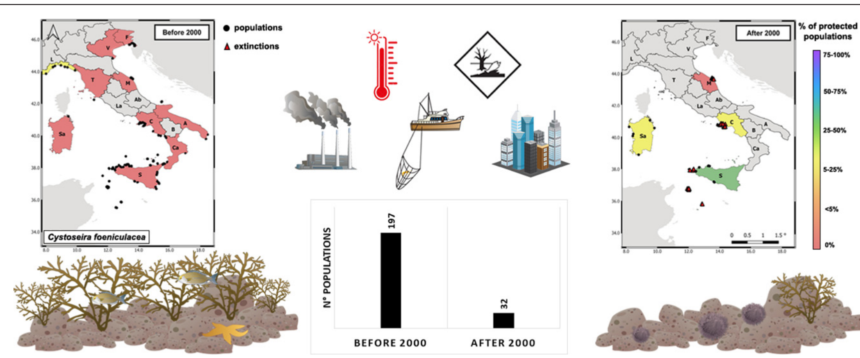
HIGHLIGHTS

- Macroalgal forests deserve prompt conservation and restoration efforts worldwide.
- *Cystoseira s.l.* forests severely declined along Italian coasts due to human impacts.
- Unknown drivers of extinction and poor monitoring prevent efficient conservation.
- Current protection measures may not be adequate.

GRAPHICAL ABSTRACT



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ABSTRACT

Habitat degradation and loss are severely affecting macroalgal forests worldwide, and their successful mitigation depends on the identification of the drivers of loss and the implementation of effective conservation and restoration actions.

We made an extensive literature review 1- to document the historical (1789–1999) and recent (2000—2020) occurrence of the genus *Cystoseira*, *Ericaria* and *Gongolaria* reported in the literature along the 8000 km of the coasts of Italy, 2- to assess their decline and patterns of extinction, 3- to ascertain the drivers responsible for these changes, 4- to highlight the existence of success stories in their conservation and natural recovery. In the last twenty years, overall information on the distribution of *Cystoseira s.l.* exponentially increased, although research focused almost exclusively on intertidal reefs. Despite the lack of systematic monitoring programs, the local extinction of 371 populations of 19 different species of *Cystoseira s.l.* was documented across several regions, since 2000. Coastal engineering and poor quality of waters due to urban, agricultural or industrial activities were often documented as leading causes of habitat loss. However, the drivers of extinction were actually unknown for the majority of the populations and cause-effects relationships are scarcely documented. Although the proportion of protected populations increased to 77.8%, Marine Protected Areas are unlikely to guarantee adequate conservation efficacy, possibly also for the widespread lack of management and monitoring plans dealing specifically with *Cystoseira s.l.* species, and few evidences of natural recovery were observed.

Our review shows the dramatic lack of baseline information for macroalgal forests, highlighting the urgent need for the monitoring of less accessible habitats, the collection of long-term data to unveil drivers of loss, and an updated reporting about the conservation status of the species of interest to plan future interventions.

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Contents

1. Introduction

Habitat degradation and destruction are recognized among the most serious threats to biodiversity and functioning of ecosystems, both in terrestrial (Hoekstra et al., 2005) and marine realms (Crain et al., 2009). Coastal marine ecosystems are particularly affected by this global phenomenon, due to increasing population density and multitude of human activities disturbing these systems (Micheli et al., 2013; Airoldi et al., 2020). Some habitats are entirely lost as a direct effect of coastal engineering, while others are exposed to the compound effect of multiple stressors, driving the shift from complex, diverse habitats to simpler and less productive ones (Airoldi et al., 2008; Claudet and Fraschetti, 2010).

Despite the efforts to contrast habitat destruction through the mitigation of human pressures or the implementation of conservation measures, the natural recovery of coastal habitats is rare, even when the proximate drivers of loss are removed (Lotze et al., 2011; Colletti et al., 2020). The onset of feedback mechanisms favors the persistence of degraded habitats and impairs the recovery ability of the system (Scheffer et al., 2001). In addition, recovery potential may be compromised by a scarce connectivity among degraded and healthy ecosystems, acting as vital sources of propagules (Duarte et al., 2013).

In this scenario, restoration is growingly acknowledged as a convenient strategy to actively trigger or accelerate the recovery of degraded coastal habitats (Abelson et al., 2020), as also recognized by the recently announced UN Decade on Ecosystem Restoration (2021−2030). Although restoration is less advanced in marine compared to terrestrial ecosystems, significant progress has been made for several coastal habitats, including seagrasses, saltmarshes, oyster reefs, mangroves, kelp forests, and coral reefs (Bayraktarov et al., 2016).

Yet, to make restoration interventions consistently successful, a detailed knowledge of present and past distribution of lost habitats, the individuation of donor populations, and the identification of the stressors that caused their decline or disappearance together with the evaluation of their mitigation state, should be considered prerequisites to select putative restoration sites (Gann et al., 2019).

Habitat formers are common targets of marine ecosystem restoration, intended not only to reverse species' local decline, but also to improve and provide habitat for other species of commercial value. However, recent analyses show that only a minority of the restored marine species for conservation purposes are actually of international conservation concern (Swan et al., 2016), and baseline knowledge is generally very limited to plan cost effective restoration interventions

(Bayraktarov et al., 2016). Macroalgal forests formed by fucalean algae (*Cystoseira* sensu *latu*, including the genera *Cystoseira*, *Ericaria* and *Gongolaria*; Molinari and Guiry, 2020) are critical habitats of intertidal and subtidal reefs in the Mediterranean Sea (Sala et al., 2012) and an excellent case study to show gaps strongly limiting restoration interventions. They host highly diverse assemblages, providing food and shelter for associated organisms and representing privileged nursery habitats for fish assemblages of commercial interest (Cheminée et al., 2013, 2017). Their presence enhances coastal primary productivity, and their primary role in maintaining high biodiversity and the functioning of rocky habitats have long been recognized. As a consequence, several species (*C. sedoides*, *E. amentacea* var. *stricta*, *E. mediterranea*, *E. zosteroides*, *G. montagnei*) have been protected since 1982, with the enforcement of the Bern Convention (1979). In 2009, an amendment of the Mediterranean Action Plan (Annex IV, SPA/BD Protocol - United Nations Environment Programme) adopted within the framework of the Barcelona Convention (1976), identified the conservation of all but one (*C. compressa*) Mediterranean *Cystoseira s.l.* species as a priority. Despite the robust legislative framework, specific conservation measures for the protection of these habitat-forming species have never been implemented (Fraschetti et al., 2011). For example, the selection of marine sites deserving protection under the Natura 2000 Sites network (https://ec.europa.eu/environment/nature/natura2000/index_en.htm) in the Mediterranean is generally based on the presence of *Posidonia oceanica* meadows, while the presence of *Cystoseira s.l.* is only incidental, as brown macroalgal forests are not listed in the Habitat Directive annexes (Directive 92/43 EEC).

Cystoseira s.l. are highly vulnerable to several human disturbances, which caused their regression in many regions of the Mediterranean Sea (Thibaut et al., 2005, 2014; Airoldi and Beck, 2007), and their natural recovery has rarely been observed (Perkol-Finkel and Airoldi, 2010). Restoration has been proposed as a promising approach to halt their decline (Gianni et al., 2013), and several European projects (e.g., MERCES, http://www.merces-project.eu/ and AFRIMED, http://afrimed-project.eu/) developed and tested new techniques to reintroduce *Cystoseira s. l.* species after local extinction, regenerating self-sustaining populations (Verdura et al., 2018).

At present, despite the interest of the European Community in the conservation and restoration of macroalgal forests and the growing attention of the scientific community, most of these questions risk to be hardly addressed for most Mediterranean regions. Here, we assess knowledge and gaps challenging the restoration of macroalgal forests with an extensive literature review that dates back to 1789, using Italian shores as a case study. The aims are i) documenting the historical and recent occurrence of *Cystoseira s.l.* species reported in the literature along the coasts of Italy; ii) assessing the current knowledge on the extent of decline and extinction of *Cystoseira s.l.* populations and on the drivers responsible for these changes; iii) exploring whether the present network of protected areas is efficiently contributing to the conservation of brown macroalgal forests.

2. Methods

Data on the historical and current distribution of brown fucalean forests in Italian coastal waters were collected from: 1) published literature, 2) grey literature, 3) monitoring programs, 4) unpublished data from experts and ongoing projects (e.g., AFRIMED). Herbarium specimens were included only when reported in published and grey literature.

The research of published literature was conducted using two databases (ISI Web of Science and Scopus) for the 1985–2020 time-frame. The systematic literature screening was carried out by searching in the “Title,” “Abstract,” and “Keyword” fields the following combination of terms: (“*Cystoseira*” OR “*Cystoseira* canopies” OR “Fucales” OR “brown algae” OR “macroalgal forest*” OR “habitat form*”) AND (“distribution” OR “occurrence” OR “presence” OR “shift” OR “habitat loss” OR “decline”) AND “Mediterranean”. Grey literature, dating back to 1883, included publications on national journals edited by national associations or institutions (e.g., Italian Society of Marine Biology, Italian Botanical Society, Gioenia Academy of Catania), books, unpublished Ph.D. theses and conference proceedings. We also searched the citation lists of the selected articles for further publications of interest. In addition, nearly 670 records of *Cystoseira* spp. were acquired from the monitoring program CARLIT (CARtography of LITtoral and upper-sublittoral benthic communities, Ballesteros et al., 2007). The full list of publications included in the analysis is reported in the Supplementary material. In terms of algal classification and nomenclature, we followed the current taxonomic arrangement of AlgaeBase (Guiry and Guiry, 2021).

We collected all the information about the georeferenced occurrence of *Cystoseira s.l.* populations along Italian coasts and classified it according to the region and basin (Supplementary Fig. S1). The geographic location of brown fucalean populations was digitized as shapefile points or polylines in order to be associated with a map, using the Open Source QGIS software (QGIS Development Team, 2018). In addition, for each geographical record, we noted the identity and number of *Cystoseira s. l.* species observed, the sampling method adopted (e.g., visual estimate, destructive sample, herbarium specimens), the year, season, and depth of observation, the extent of the population (when available, expressed as linear coastal extent or mapped area), the eventual certification of the disappearance or decline of a population and the drivers advocated as causes of decline. The localization of each population (encoded by single or multiple points or polylines, according to the source data) inside areas characterized by different protection regimes (i.e., national parks, natural marine reserves, underwater parks, Marine Protected Areas - MPA, Natura 2000 Sites of Community Importance - SCI or Specially protected areas - SPA, established on the Habitats Directive, Specially Protected Areas of Mediterranean Importance - SPAMI, defined in the Barcelona Convention) at the time of the biological sampling was assessed by using a modified shapefile from MAPAMED (2017) (https://medpan.org/main_activities/mapamed/), a database on sites of interest for the conservation of marine environment in the Mediterranean Sea.

Results of the review are reported in Figs. 1–7, Supplementary Figs. S1–S8, and summarized in Tables 1, 2. We selected the 2000 as the break year between historical and recent assessments, as the decline and loss of brown fucalean forests has been reported in the literature

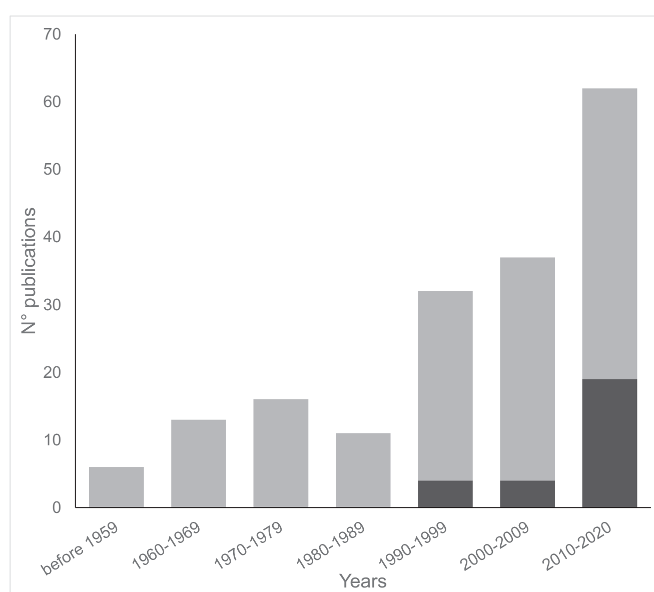

Fig. 1. Temporal trend of publications including georeferenced data on *Cystoseira s.l.* species distribution. Grey bars represent descriptive studies, black bars show experimental studies.

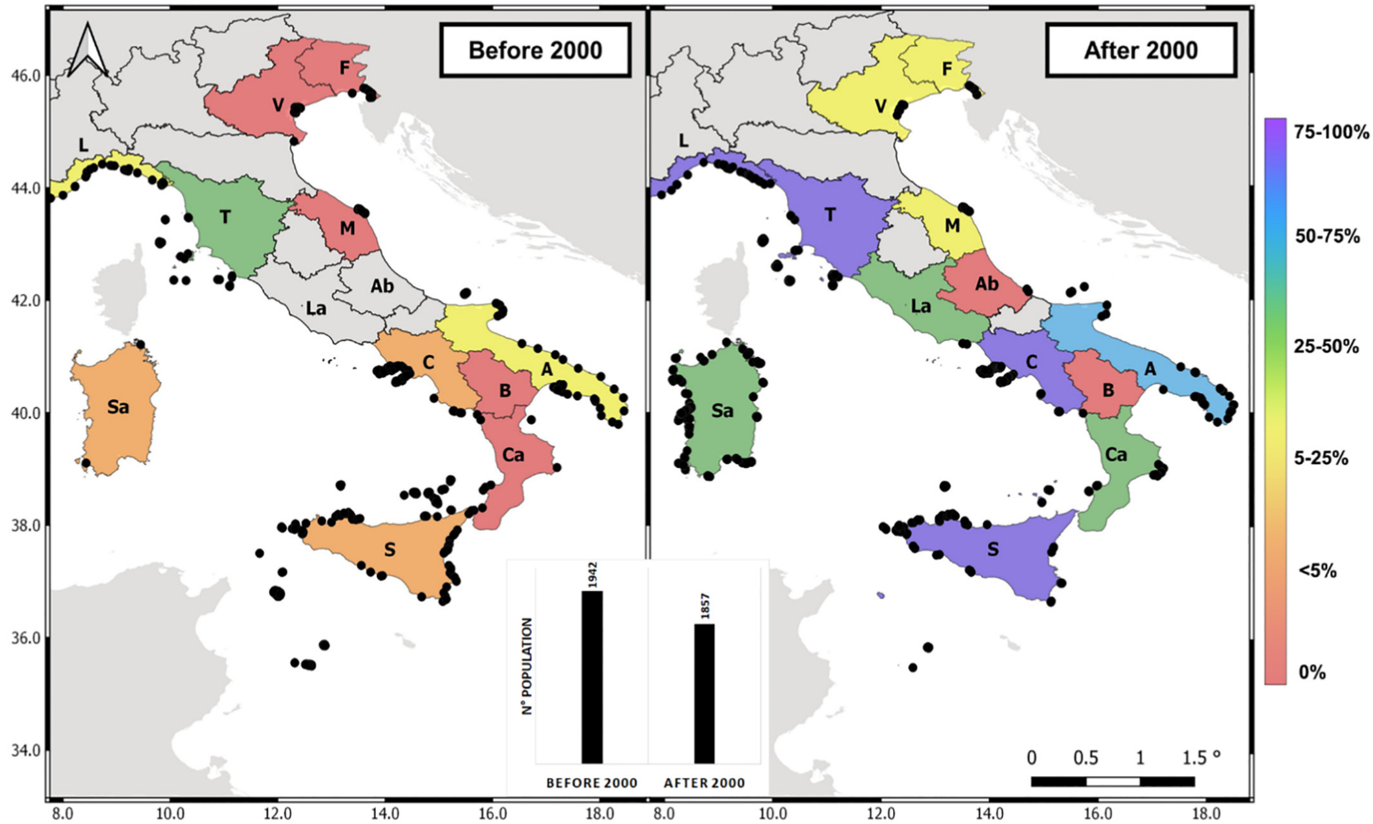

Fig. 2. Historical and recent distribution of *Cystoseira s.l.* along Italian coasts. Black dots and lines indicate the presence of the species. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

since the 2000s, and local extinctions were mostly documented around 2000 (27.6% and 65% respectively in the '90s and 2000s).

3. Results

3.1. Research of temporal trends and focus of interest

The review included 169 articles, books, and PhD theses. The number of publications reporting information on the distribution of *Cystoseira s.l.* increased during the '60s, showing an exponential growth in the last three decades, when experimental studies added to descriptive ones (Fig. 1). Before 1990, all published articles were represented by floristic/phytosociological studies reporting the description of algal assemblages in different regions, or taxonomic studies including morphological descriptions of the species (De Toni, 1895; Gerloff and Nizamuddin, 1976; Battiato et al., 1979; Giaccone, 1985; Cormaci and Furnari, 1988). Few studies focused on the description of assemblages associated to *Cystoseira s.l.* (Campisi et al., 1973; Pastore, 1981), and only two studies related the local regression of *Cystoseira s.l.* to anthropogenic impacts (i.e., eutrophication, water turbidity, industrial pollution, urbanization; Giaccone, 1974; Sfriso, 1987).

During the '90s, the literature was still dominated by phytosociological and taxonomic studies (e.g., Alongi et al., 1999a), although a growing interest was dedicated to phenological studies (e.g., Benedetti-Cecchi and Cinelli, 1993; Alongi et al., 1999b; Verlaque et al., 1999) and to the investigation of ecological interactions with the extant assemblage (Benedetti-Cecchi and Cinelli, 1992a,b, 1995; Benedetti-Cecchi et al., 1996). In recent years, *Cystoseira s.l.* was also the focus of new research fields, including ecotoxicology (Conti et al., 2010; Renzi et al., 2011; Conti et al., 2015), genetics (Buonomo, 2017; Buonomo et al., 2017), and microbiology of associated bacterial communities (Mancuso et al., 2016; Buonomo, 2017).

3.2. Human threats on macroalgal forests

Since the 2000s, brown algal forests have been perceived as habitats threatened by humans: researchers investigated patterns of local extinction (Curiel et al., 2001; Catra et al., 2006; Serio et al., 2006) and the major drivers of decline (e.g., urbanization, Benedetti-Cecchi et al., 2001; Mangialajo et al., 2008; human trampling, Milazzo et al., 2002, 2004; climate change, Schiaparelli et al., 2007; water pollution, Drago et al., 2004). In the last decade, efforts concentrated on investigating global and local drivers of forests decline (e.g., Porzio et al., 2011; Baggini, 2014; Mancuso, 2016; Buosi and Sfriso, 2017; Mancuso et al., 2018), among which overgrazing by herbivores emerged as a relevant threat (e.g., Agnetta et al., 2015; Gianni, 2016; Ferrario et al., 2016; Piazzi and Ceccherelli, 2019; Tamburello et al., 2019).

3.3. Protection and restoration of macroalgal forests

The efficacy of MPAs in preserving forests (Mangialajo et al., 2004; Ceccherelli et al., 2005; Cecere et al., 2005) and the effect of their loss for associated assemblages (Benedetti-Cecchi et al., 2001; Maggi et al., 2009) have been also studied since the 2000s. The role of *Cystoseira s.l.* as habitat formers was examined for several faunal groups (e.g., hydroids, Fraschetti et al., 2006; molluscs, Milazzo et al., 2000; Chemello and Milazzo, 2002; Gianguzza et al., 2005; Chiarore et al., 2019; fish assemblages, Fiorin et al., 2008; Riccato et al., 2008; Cheminée et al., 2013). In addition to habitat protection inside MPAs (Fraschetti et al., 2012; Sala et al., 2012; Gianni, 2016; Guarnieri et al., 2016) restoration was presented as a new, promising approach to contrast the loss of macroalgal forests (Perkol-Finkel and Airoldi, 2010; Perkol-Finkel et al., 2012; Ferrario, 2013; Gianni, 2016; Gianni and Mangialajo, 2016).

3.4. A zoom at species level: historical and recent distribution of Cystoseira s.l. species along the coasts of Italy

The historical (1789–1999) and recent (2000–2020) distribution of 11 species of the genus *Cystoseira*, 8 species of the genus *Ericaria*, and 7 species of the genus *Gongolaria* are reported in Table 1 and Figs. 3–9, S2–S8. The subdivision of Italian seas into sectors adopted in the present study is reported in the Supplementary material (Fig. S1). Overall, 674 records have been listed for the historical period and 3238 for recent years. Populations occurring in intertidal and subtidal habitats were almost equally frequent in historical data (respectively 487 and 468 observations), while the majority of information was on the intertidal habitat after 2000 (respectively 1301 and 353 observations).

Since the 2000s, the local extinction of 371 populations of 19 different species of *Cystoseira s.l.* was documented across 8 Italian regions. Yet, drivers of extinctions were largely unknown for many populations (108 out of 371, Fig. 10). Fig. 2 reports the percentage of *Cystoseira s.l.* populations protected by MPAs, National and Underwater Parks, Natura 2000 Sites and SPAMIs in each region. Only 51 out of the 1942 populations reported by historical data were protected, while populations protected after 2000 were 1445 out of 1857, concurrently with an increase of protected coastline from 3840 km to 5025 km in the last two decades. In Table 2, the presence of *Cystoseira s.l.* inside MPAs, National and Underwater Parks is reported, specifying whether it has been documented before or after the institution of a protected area.

3.4.1. Cystoseira compressa (Esper) Gerloff & Nizamuddin - intertidal, subtidal

Historical data reported 303 populations in 9 Italian regions across all seas (Fig. 3, Table 1). At the time of sampling, 5.3% of the populations were protected by MPAs, National Parks and Natura 2000 SCIs (Tables 1, 2).

After 2000, 721 populations were reported across all seas in 12 regions. The majority of the populations were located inside protected areas under different regulations: 49.9% were protected by MPAs or national parks, while 32.9% were located inside Natura 2000 Sites and SPAMIs. The local extinction of 39 populations has been documented in 1979–1984 in Veneto (Lido island) as a consequence of eutrophication (Sfriso, 1987) and in 2013–2016 in Campania (Gulf of Naples, Procida, Ischia and Capri). A reduction in nutrient loads of the Venice lagoon favored the natural recovery of populations located in Lido island by 2006–2008 (Sfriso and Facca, 2011).

3.4.2. Cystoseira corniculata (Turner) Zanardini - subtidal

The species was observed for the first time in 1889 in Sardinia. During the '60s and '70, 17 populations were recorded along the coasts of the Northern Ionian Sea (Capo Rizzuto in Calabria and Santa Maria di Leuca in Apulia) and in the Central Adriatic Sea (Gargano Promontory, Tremiti islands) (Fig. S2, Table 1). None of them was included inside protected areas. After 2000, no populations of the species have been observed, and its local extinction has been documented in the Gargano Promontory (Apulia) in 1997, although no specific cause of disappearance has been identified (Cecere et al., 2000).

3.4.3. Cystoseira crinitophylla Ercegovic – intertidal, subtidal

Between 1958 and 1997, 16 populations were recorded in several locations of the Sicilian region, and in the central Adriatic Sea at the

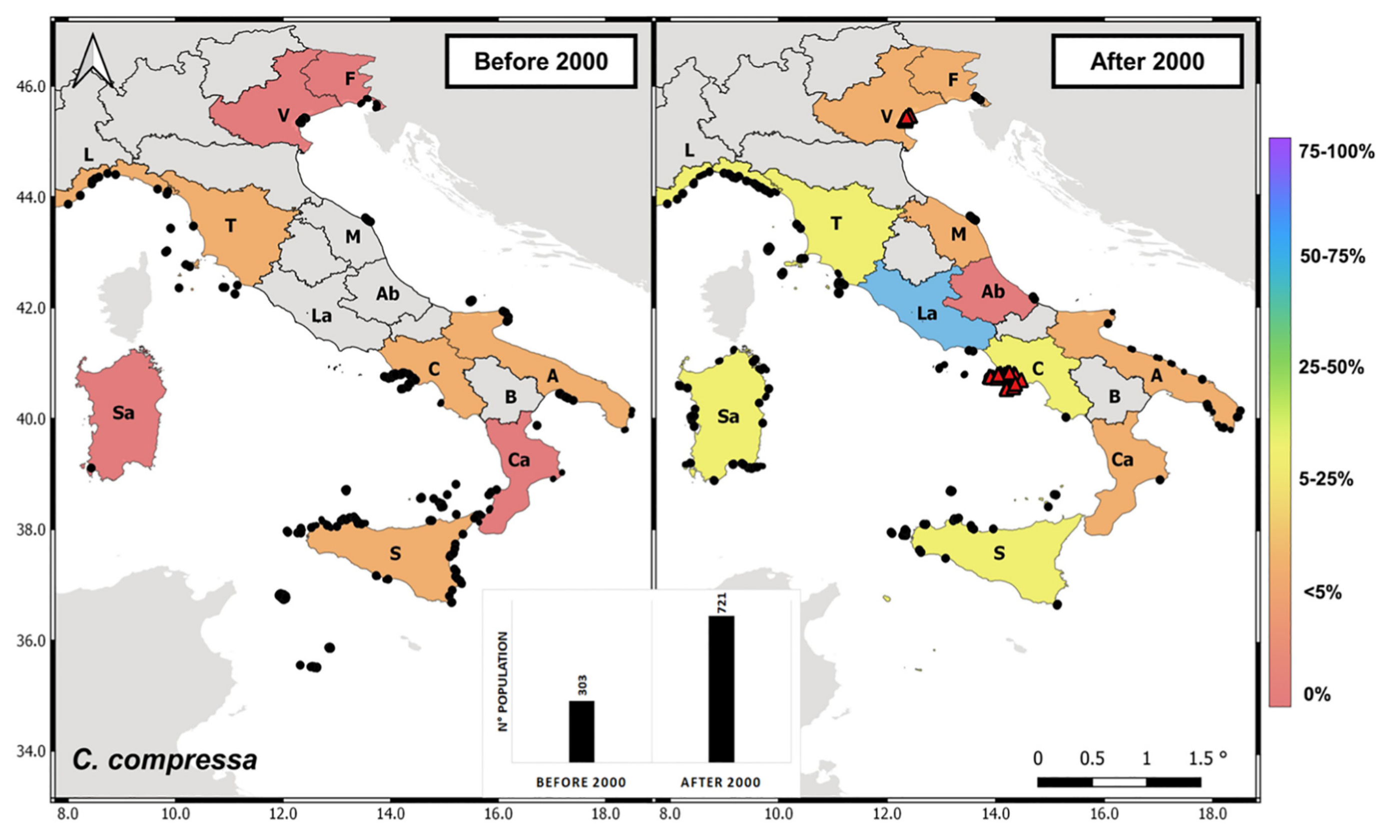

Fig. 3. Historical and recent distribution of *Cystoseira compressa* along Italian coasts. Black dots and lines indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

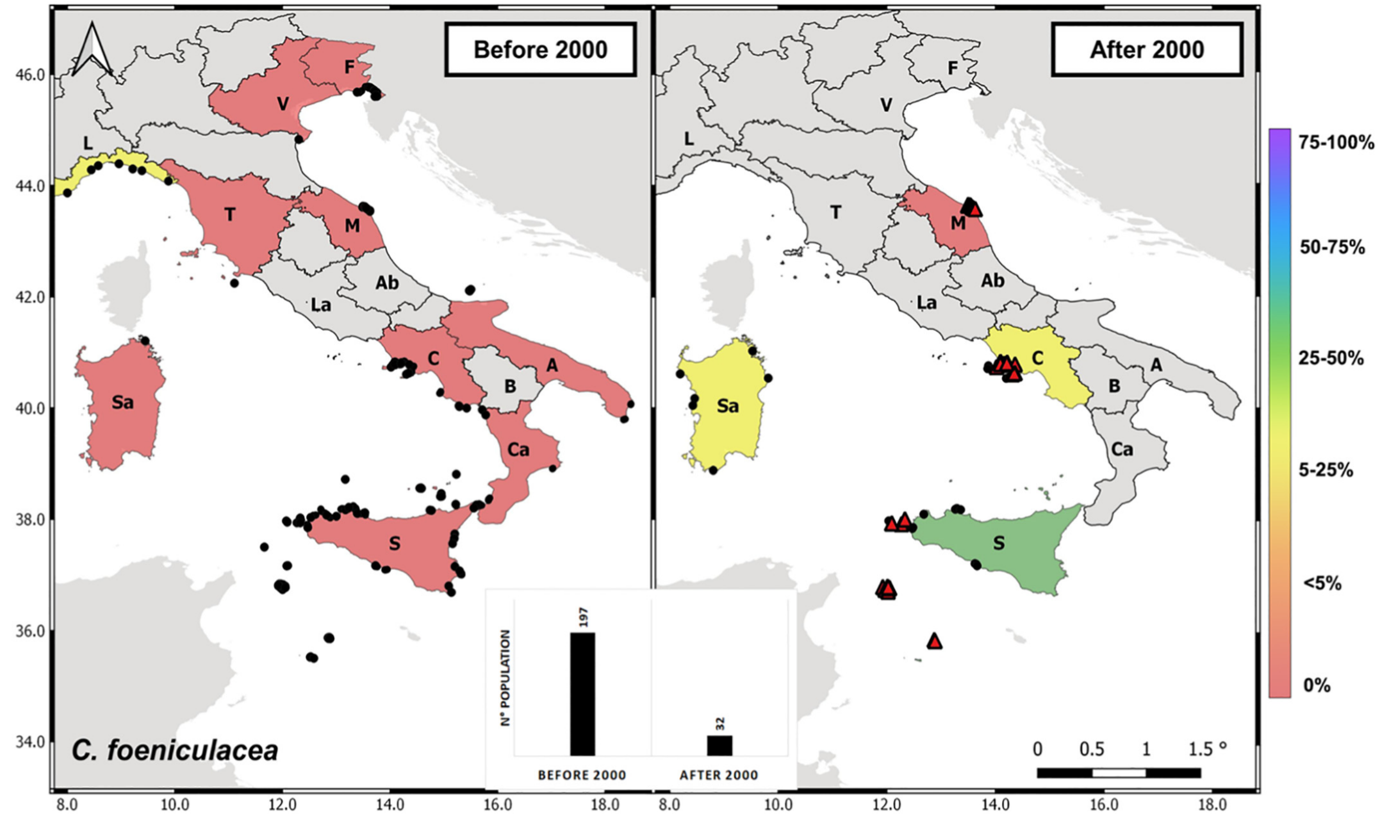

Fig. 4. Historical and recent distribution of *Cystoseira foeniculacea* along Italian coasts. Black dots and lines indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

Tremiti islands (Apulia) (Fig. S2, Table 1). Only the population censused in 1997 was protected by the MPA of the Tremiti islands (Table 2). No populations of the species have been censused after 2000, and its local extinction in Linosa was documented in 1999. The disappearance of *C. crinitophylla* and of several other *Cystoseira s.l.* species (*C. foeniculacea*, *C. humilis*, *E. brachycarpa*, *E. zosteroides*, *G. elegans*, and *G. sauvageauana*) from the island was attributed to sea water warming, in the absence of other local stressors, such as water turbidity, eutrophication, overgrazing by sea urchins, fishing activities or anchoring (Serio et al., 2006).

3.4.4. Cystoseira dubia Valiante - subtidal

Early records of *C. dubia* along Italian coasts date back to 1880–1930, when seven populations were censused in the Gulf of Naples (Campania) and on the Amendolara sea-mount (Calabria) (Fig. S2, Table 1). Between the '70s and '80s, ten further populations were recorded in Campania, Sicily, and the presence of the species on the Amendolara sea-mount (Calabria) was confirmed in 1982. None of the 17 populations recorded was protected. Two populations of the species were individuated after 2000 in the Sicilian MPA of Capo Gallo – Isola delle Femmine (Table 2), while the re-examination of algal assemblages in the Gulf of Naples (2013–2016) and on Favignana island in the Aegadian Archipelago (2001) documented the local disappearance of 5 populations in the last twenty years.

3.4.5. Cystoseira foeniculacea (Linnaeus) Greville - intertidal, subtidal

Historical data reported 197 populations in 10 Italian regions across all seas except the Northern Tyrrhenian (Fig. 4, Table 1). No populations were protected at the time of observation.

After 2000, only 32 populations were recorded in Tuscany, Sardinia, Campania, and Sicily. 46.9% of them were protected by MPAs (Capo Caccia – Isola Piana, Regno di Nettuno, Isole Egadi, Capo Gallo – Isola delle Femmine) and Natura 2000 Sites and SPAs (Table 2). The local extinction of 38 populations has been documented in 1999–2001 in Sicily (Linosa island and several locations in the Aegadian islands), in 2013–2016 in Campania (Gulf of Naples, Procida), and in 2020 along the Conero Riviera (Marche).

3.4.6. Cystoseira humilis Schousboe ex Kutzing - intertidal, subtidal

Between the '40s and the '90s, 52 populations of the species were recorded along the Conero Riviera (Marche) and in all seas surrounding Sicily and its archipelagos, including Pantelleria, Aeolian, Aegadian and Pelagian islands (Fig. S3, Table 1). Between 1994 and 1997, one population of *C. humilis* was recorded in Tuscany. None of the populations was located within protected zones.

After 2000, only five populations have been described inside the MPAs of Capo Gallo and in the Aegadian islands, and the presence of the species in Tuscany was confirmed in 2018 (Table 2). The local disappearance of the species from Pelagian islands was documented in 1999.

3.4.7. Cystoseira hyblaea Giaccone - intertidal

The species was described only in 1985 at Punta d'Aliga (Ragusa), in southern Sicily (Giaccone, 1985; Giaccone et al., 1985) (Fig. S3, Table 1). *C. hyblaea* was not protected, nor was its presence documented in recent years.

3.4.8. Cystoseira pelagosae Ercegovic - subtidal

Only two populations of the species were described in 1985 in Sicily and Ustica island (Giaccone et al., 1985) (Fig. S3, Table 1). The species was not protected, nor was its presence documented in recent years.

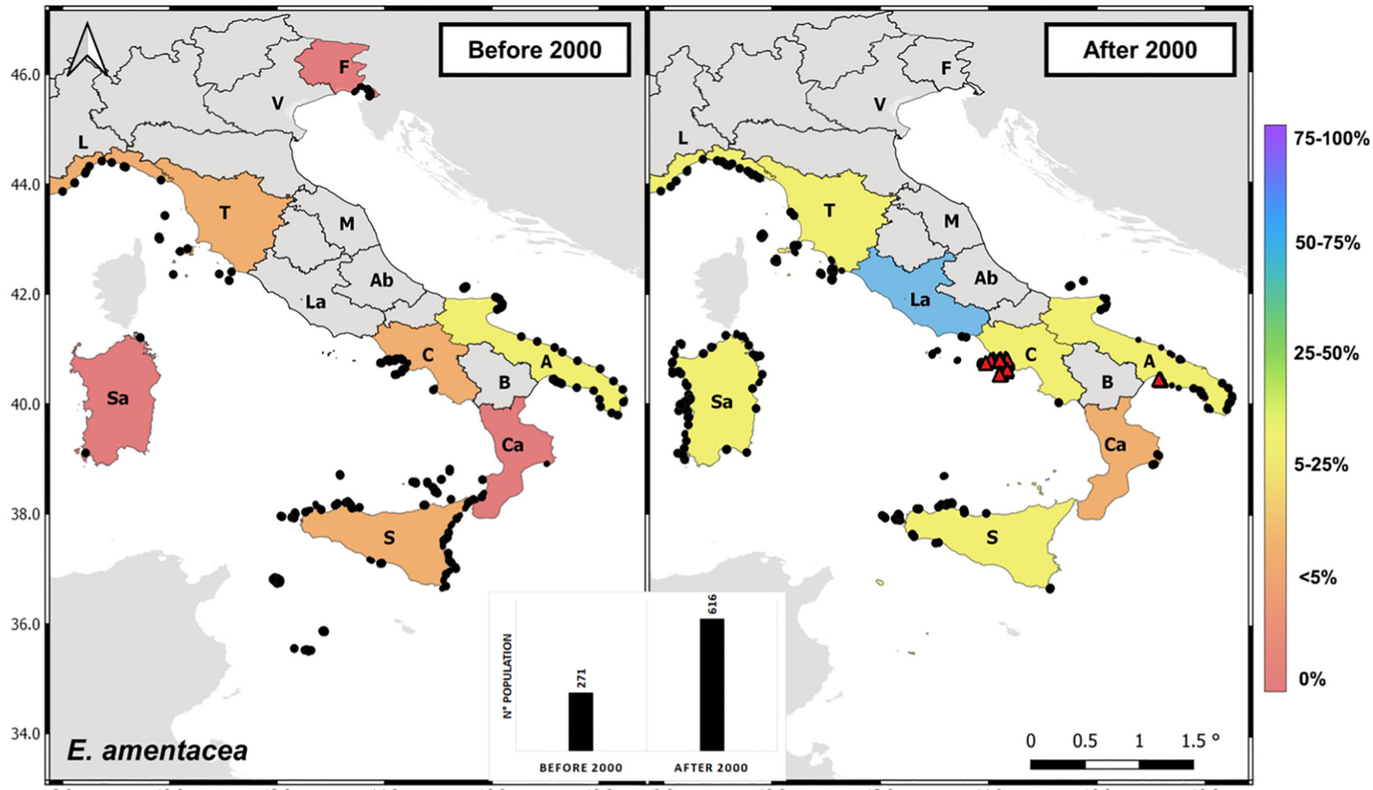

Fig. 5. Historical and recent distribution of *Ericaria amentacea* along Italian coasts. Black dots and lines indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

3.4.9. Cystoseira platyclada Sauvageau - subtidal

Between 1971 and 1985, 17 populations of the species were recorded in the Strait of Sicily in Pantelleria, Aegadian and Pelagian islands and on shallow rocky banks (Pantelleria, Talbot) (Fig. S4, Table 1). None of the populations was protected, and their presence has never been reassessed after 2000. In 2001, the local disappearance of the species from Favignana island was documented.

3.4.10. Cystoseira schiffneri Hamel - subtidal

Between 1923 and 1999, 27 populations were recorded in the Sicilian islands of the Southern Tyrrhenian Sea (Ustica and all Aeolian islands) and in Apulia (Cheradi islands, Tremiti islands and the Gargano promontory) (Fig. S4, Table 1). A single population in the MPA of Ustica was protected at the time of observation (Table 2). The local extinction of the populations of Filicudi and Cheradi islands was documented respectively in 1991 and 1992, while the species was not censused any longer along the Gargano promontory or in Tremiti islands in 1997. In the Cheradi islands, the degradation of algal assemblages and the local disappearance of *C. schiffneri* and several other *Cystoseira s.l.* species (*E. amentacea*, *E. crinita*, *G. montagnei*, *G. sauvageauana*) were attributed to pollution and illegal fishing of the date mussel *Litophaga litophaga* (Cecere et al., 1996; Colletti et al., 2020). In the Tremiti islands, the disappearance of the species and of *E. crinita* and *G. montagnei* was attributed to water turbidity due to terrigenous sediment, possibly associated to the presence of pollutants (Cormaci et al., 2001). No records of the species were provided after 2000.

3.4.11. Cystoseira sedoides (Desfontaines) C. Agardh - intertidal, subtidal

The species was recorded along the coasts of Pantelleria island (Sicily) in 1970–1971, and its distribution along the island coasts was confirmed by studies in 1985 and 1999 (Fig. S4, Table 1). None of the 19 populations of the species was protected, and no information on its distribution in recent years is available.

3.4.12. Ericaria amentacea (C. Agardh) Molinari & Guiry - intertidal

Historical data reported the distribution of 271 populations in 9 regions and across all Italian seas (Fig. 5 Table 1). 8.9% of the populations were located inside protected areas (the MPAs of Portofino, Punta Campanella, Ciclopi islands, Tremiti islands, and Porto Cesareo, the national park of the Tuscan Archipelago, and several Natura 2000 SCIs) (Table 2).

After 2000, 616 populations were recorded in 8 regions across all seas except the Northern Adriatic. Among them, 75% of the populations were protected: 49.8% were located inside MPAs, national and underwater parks, while 25.2% were located inside SPAMIs, and Natura 2000 – SCIs. The local disappearance of 27 populations has been reported by the end of the 19th century in Liguria, in 1992 in Apulia (Cheradi islands), and in 2013–2016 in Campania.

3.4.13. Ericaria barbatula (Kutzing) Molinari & Guiry - intertidal, subtidal

During the '90s, 5 populations of the species were recorded in the Strait of Sicily, on the islands of Pantelleria and Lampedusa (Fig. S5, Table 1). In 2002, the presence of the species was confirmed in a single location of Lampedusa island. None of the populations was protected at the time of observation.

3.4.14. Ericaria brachycarpa (J. Agardh) Molinari & Guiry - intertidal, subtidal

Historical data reported 107 populations of *E. brachycarpa* distributed in 6 regions along the Ligurian, Tyrrhenian, Sardinian, Ionian Sea

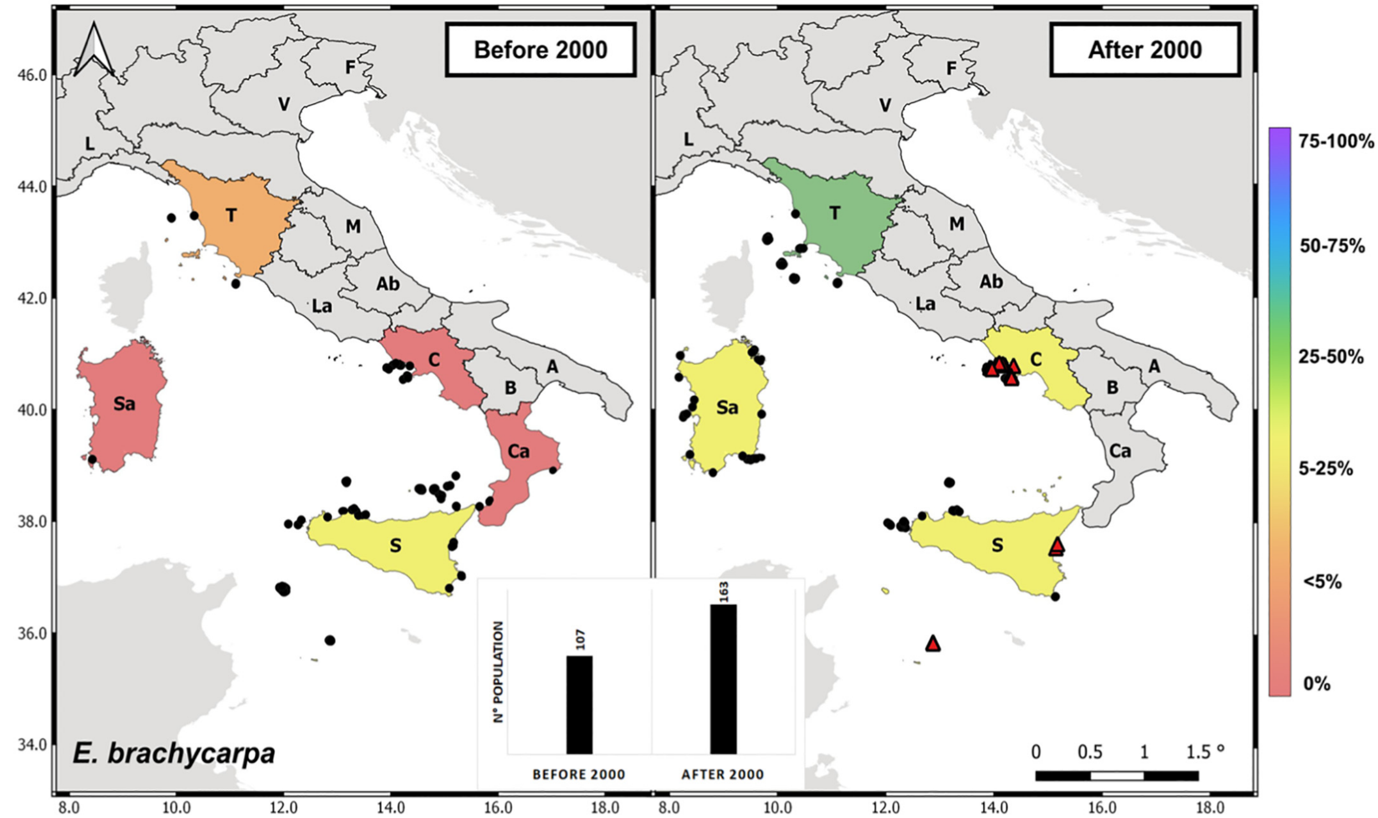

Fig. 6. Historical and recent distribution of *Ericaria brachycarpa* along Italian coasts. Black dots indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

and the Strait of Sicily (Fig. 6, Table 1). At the time of observation, only 5 populations were protected by the MPAs of Ustica and Ciclopi islands, in Sicily (Table 2).

After 2000, 163 populations were recorded in 4 regions along the Ligurian, Tyrrhenian, Sardinian, Southern Ionian Sea and the Strait of Sicily. The majority of them (88.3%) were protected by 11 MPAs, National Parks (Tuscan Archipelago, Maddalena Archipelago), Natura 2000 sites, and SPAMIs. Between 1994 and 2016, the local disappearance of 17 populations was documented in Campania (Gulf of Naples, Ischia) and Sicily (mainland and Linosa). The extinction of *E. brachycarpa* forests from the eastern coasts of Sicily was attributed to increase in water turbidity, sediment deposition and overgrazing by sea urchins (Catra et al., 2019).

3.4.15. *Ericaria crinita (Duby) Molinari & Guiry - intertidal, subtidal*

Historical data recorded 119 populations in 8 Italian regions across all seas except the Northern Tyrrhenian and the Southern Adriatic Sea (Fig. 7, Table 1). None of the populations was protected.

After 2000, 83 populations were reported in 6 Italian regions along the Tyrrhenian, Sardinian, Northern and Southern Adriatic Sea, and the Strait of Sicily. 69.9% of the populations were protected, being located inside 8 MPAs, National Parks (Tuscan and Maddalena Archipelagos), Natura 2000 sites, and SPAMIs (Tables 1, 2). Between 1992 and 2016, the local extinction of 36 populations was documented in Campania, Sicily (Filicudi, Aegadian islands) and Apulia (mainland, Cheradi and Tremiti islands).

3.4.16. *Ericaria funkii (Schiffner ex Gerloff & Nizamuddin) Molinari & Guiry - subtidal*

Between 1909 and 1959, three populations of the species were documented on the Sorrento Peninsula in the Gulf of Naples (Campania) (Fig. S5, Table 1). Eleven further populations were recorded along Ionian Sicilian coasts, Pantelleria, Aeolian and Aegadian islands between 1974 and 1991. The presence of the species in the MPA of the Aegadian islands (instituted in 1991) was confirmed in 2001 (Table 2). The local extinction of the species was documented in 1999 in Pantelleria (Sicily) and in 2013–2016 in the Gulf of Naples (Campania).

3.4.17. *Ericaria mediterranea (Sauvageau) Molinari & Guiry - intertidal*

Historical data reported 48 populations of *E. mediterranea* in Southern Italy across Campania, Calabria, and Sicily (Fig. S6, Table 1). No population was protected at the time of observation. In recent years, only 7 populations located in Campania and Sicily were described, and 6 of them were protected inside the MPAs Regno di Nettuno and Capo Gallo, and in the Natura 2000 - SCI & SPA of Punta Campanella - Capri island (Table 2). The local extinction of 10 populations across Campania and Sicily (Marettimo) was documented between 2001 and 2016.

3.4.18. *Ericaria selaginoides (Linnaeus) Molinari & Guiry - subtidal*

Between 1883 and 1999, 41 populations were recorded across Campania, Calabria, Sicily, and Apulia (Fig. S6, Table 1). None of them was protected. No populations of the species have been censused after 2000, and the local extinction of all the populations in Campania was verified in 2013–2016.

3.4.19. *Ericaria zosteroides (C. Agardh) Molinari & Guiry - subtidal*

99 populations of the species were recorded between 1883 and 1999 in 6 regions across the Ligurian, Central and Southern Tyrrhenian, Sardinian, Ionian Sea and Strait of Sicily (Fig. S6, Table 1). None of them was protected at the time of observation.

After 2000, only 10 populations have been recorded across Liguria, Tuscany, Sardinia, Campania, and Sicily. All of them were located inside

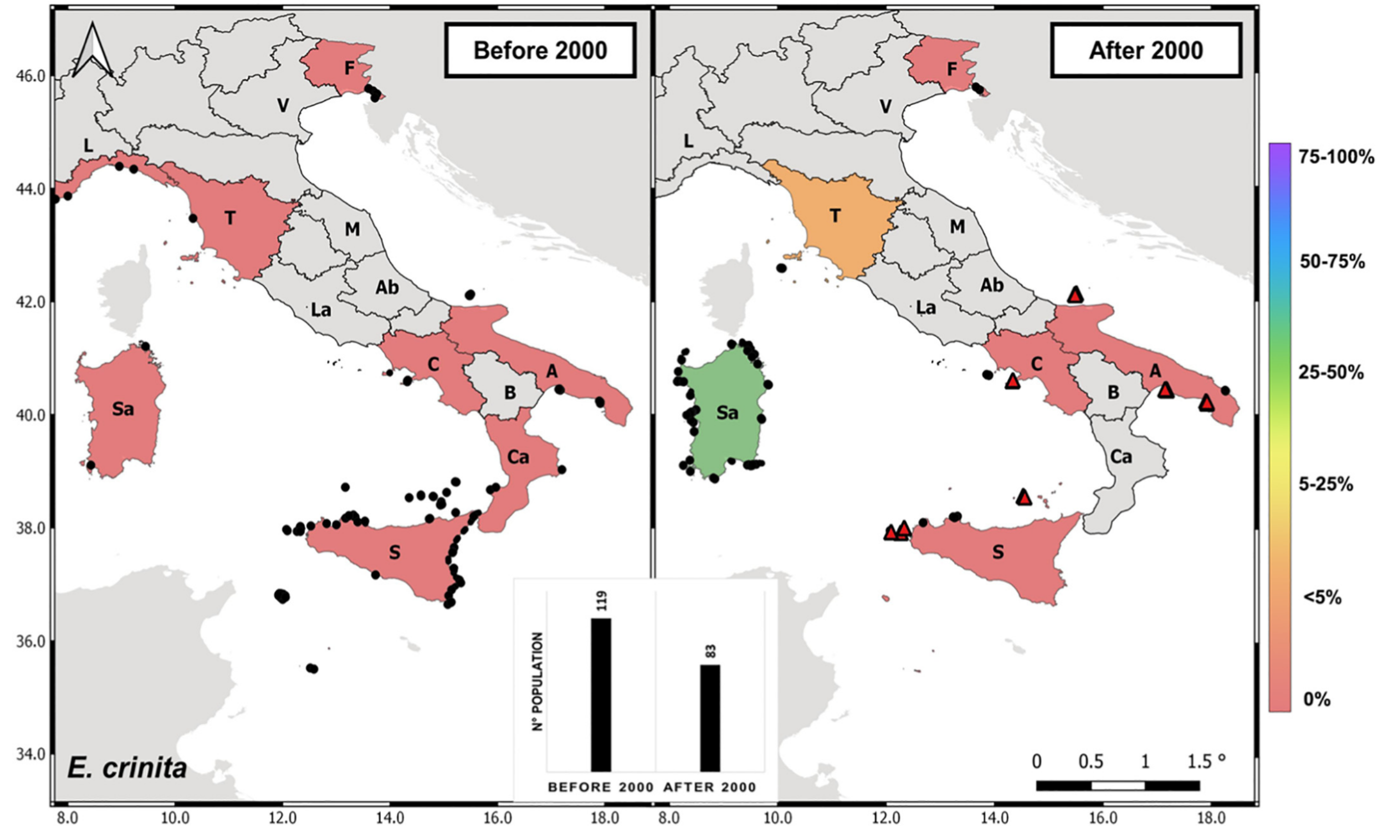

Fig. 7. Historical and recent distribution of *Ericaria crinita* along Italian coasts. Black dots indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

MPAs or Natura 2000 sites (Table 2). The local extinction of 21 populations has been documented between 1991 and 1999 in Sicilian islands (Filicudi, Marettimo, Pantelleria, Linosa), in 2013–2016 in Campania (Capri and Ischia, Gulf of Naples), and between 2009 and 2016 in the Natura 2000 SCI of Gallinara island (Liguria).

3.4.20. Gongolaria barbata (Stackhouse) Kuntze - intertidal, subtidal

Between 1879 and 1999, 187 populations of the species were censused in 10 regions across all seas (Fig. 8, Table 1). None of the populations was protected at the time of observation.

107 populations have been recorded in recent years in 6 Italian regions across Central and Southern Tyrrhenian, Sardinian, Adriatic and Northern Ionian Sea. 53.3% of them were located inside different types of protected areas (7 MPAs, the National Park of the Maddalena Archipelago, Natura 2000 SCIs and SPAs, and SPAMIs) (Table 2). Local extinctions of the species have been documented between 1979 and 2013–2016 for 40 populations across several regions, including Campania, Apulia, Sicily, Marche and Veneto. Yet, populations in Venice and Lido island, which were considered as extinct respectively in 1996 and 1979–1984, naturally recovered by 2000–2008 due to reduced nutrient load and improved water quality (Curiel et al., 2001, 2002; Marzocchi et al., 2003; Sfriso and Facca, 2011). A regression of the species along the Conero Riviera (Marche) was reported by Perkol-Finkel and Airoldi (2010), who invoked as main cause a combination of local disturbances (rock mining, beach nourishment) along with extreme storm events. In the practice, the species is still well represented and abundant at some sites (Rindi et al., 2020; Rindi, personal observation), although its distribution is patchy due to the particular nature of the substrate in this area. Trampling and swimming due to summer tourism is a major threat for the species at several sites of the Conero Riviera (Rindi, personal observation).

3.4.21. Gongolaria elegans (Sauvageau) Molinari & Guiry intertidal, subtidal

Between 1961 and 1985, 50 populations of the species were recorded in Tuscany, Marche, the Ionian coasts of Apulia, and Sicily (Fig. S7, Table 1). The distribution in Sicily comprised several islands and archipelagos, in addition to vast extensions of the coasts in the Southern Ionian Sea, Southern Tyrrhenian Sea and Strait of Sicily. The population of Capo Passero island was located inside a Natura 2000 SCI.

After 2000, only 7 populations were censused in Sardinia and Liguria. The Ligurian population was located in the Natura 2000 SCI of Gallinara island, and one of the Sardinian populations was protected by the MPA of Capo Caccia - Isola Piana (Table 2). In 2000–2001, the local extinction of the species was documented in three locations of Apulia and three Sicilian islands (Marettimo, Linosa and Pantelleria).

3.4.22. Gongolaria montagnei (J. Agardh) Kuntze - subtidal

Historical studies reported the presence of the species in all sectors of Italian seas, describing 213 populations across 10 regions (Fig. 9, Table 1). Two populations were protected by the MPA of Ustica and the Natura 2000 - SCIs of Gallinara island (Tables 1, 2).

After 2000, 74 populations were mapped across 5 regions in the Ligurian, Central and Southern Tyrrhenian, Sardinian, Southern Ionian Sea and Strait of Sicily. Among them, 79.7% of the populations were protected, being located inside 10 MPAs, the National Park of La Maddalena Archipelago, Natura 2000 sites, and SPAMIs. Between 1992 and 1999, the local disappearance of the species was certified for 27 populations across the Gargano promontory and Tremiti islands (Apulia), Pantelleria (Sicily), and in Tuscany. The extinction of further 24

Table 1
Populations of *Cystoseira s.l.* recorded across Italian seas before and after 2000. For each species, the overall number of populations, the number of populations protected (divided in two categories: MPAs, National and Underwater Parks; or Natura 2000 SICs and SPAs, SPAMIs), the number of extinct populations, and the regional distribution in different seas, are reported. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

	Before 2000													
	n° populations	Ligurian	N Tyrrhenian	C Tyrrhenian	S Tyrrhenian	Sardinian	N Adriatic	C Adriatic	S Adriatic	N Ionian	S Ionian	Strait of Sicily	MPAs, National Parks	Natura 2000, SPAMI
Cystoseira														
compressa	303	L T	T	C	Cl S	Sa	V F	A	A	A Cl	S	S	13	2
corniculata	18					Sa		A		A Cl			–	–
crinitophylla	16				S			A				S	1	–
dubia	17			C	S					Cl	S	S	–	–
foeniculacea	197	L		C B	Cl S	Sa	V F	M A	A	A	Cl S	S	–	–
humilis	53	T			S			M			S	S	–	–
hyblaea	2											S	–	–
pelagosae	2				S								–	–
platyclada	17											S	–	–
schiffneri	27				S			A		A			1	–
sedoides	19											S	–	–
Ericaria														
amentacea	271	L T	T	C	Cl S	Sa	F	M A	A	A	S	S	24	–
barbatula	5											S	–	–
brachycarpa	107	T	T	C	Cl S	Sa				Cl	S	S	5	–
crinita	119	L T		C	Cl S	Sa	F	A		A Cl	S	S	–	–
funkii	14			C	S						S	S	–	–
mediterranea	48			C	Cl S						Cl	S	–	–
selaginoides	41			C	Cl S			A			S	S	–	–
zosteroides	99	L T		C	Cl S	Sa				A	Cl S	S	–	–
Gongolaria														
barbata	187	L	T	C	S	Sa	V F	M A	A	A Cl	Cl S	S	–	–
elegans	50	T			S			M		A	S	S	–	1
montagnei	213	L T	T	C B	Cl S	Sa	F	M A	A	A Cl	Cl S	S	1	1
sauvageauana	106			C	Cl S	Sa				A Cl	Cl S	S	2	–
squarrosa	9											S	–	–
susanensis	1										S		–	–
usneoides	1										S		–	–

populations was documented in 2009–2016 in the Natura 2000 SCI of Gallinara island (Liguria), and in 2013–2016 in Campania due to sewage outfalls.

3.4.23. Gongolaria sauvageauana (Hamel) Molinari & Guiry - intertidal, subtidal

Between 1879 and 1999, 106 populations of the species were censused in Southern Italy along the coasts of 5 regions (Fig. S7, Table 1). Two populations located inside the MPA of Ustica were protected (Table 2).

In recent years, 15 populations were recorded in Sicily, one population was censused in Tuscany, and three populations were still documented in the Gulf of Naples (Campania). 16 of them were protected, being located inside the MPAs of Ustica, Plemmirio, Punta Campanella, Regno di Nettuno, Tuscan Archipelago, and in Natura 2000 - SCIs. Between 1992 and 2016, the local extinction of the species has been documented for 31 populations across the Gulf of Naples (Campania), Amendolara Sea mount (Calabria), Cheradi islands (Apulia), Linosa, Pantelleria, Favignana and Marettimo islands in Sicily.

3.4.24. Gongolaria squarrosa (De Notaris) Kuntze - intertidal

In Linosa (Sicily), nine populations of the species were recorded in 1973 (Fig. S8, Table 1). At the time of observation, the island was not protected. After 2000, 7 populations of the species were censused in Sardinia, Sicily, and Apulia. Sardinian populations were located inside the Pelagos Sanctuary for the Conservation of Marine Mammals, which was instituted in 2001, while the Apulian and Sicilian populations were respectively protected by the Natura 2000 SCI Alimini and the Capo Gallo MPA (Tables 1, 2).

3.4.25. Gongolaria susanensis (Nizamuddin) Molinari & Guiry - intertidal

Between 1991 and 1995, a single population of the species was sampled in a non-protected location in eastern Sicily (Alongi et al., 1999a) (Fig. S8, Table 1). No further populations of the species have been censused.

3.4.26. Gongolaria usneoides (Linnaeus) Molinari & Guiry - subtidal

A single population of the species was described in 1985 in eastern Sicily (Giaccone et al., 1985) (Fig. S8, Table 1). The species was not protected, nor was its presence documented in recent years.

4. Discussion

4.1. Historical and recent distribution of Cystoseira s.l.: intertidal vs subtidal species

In the last twenty years, overall information on the distribution of *Cystoseira s.l.* exponentially increased, as a result of growing attention to the conservation and restoration of these priority habitat-forming species. Yet, due to easiness of sampling and monitoring, research has focused almost exclusively on intertidal reefs, improving the available information only for a few target species (mostly *C. compressa* and *E. amentacea*). Although the reassessment of their distribution by comparing historical and recent data revealed several local extinctions (Cecere et al., 1996; Grech, 2017; Rindi et al., 2020), the number of populations described in the last two decades has more than doubled, and these species appear still widespread across most of the Italian rocky shoreline. A contribution to the knowledge of their distribution has been provided by the implementation of the CARLIT monitoring (Ballesteros et al., 2007), regularly applied by Regional Agencies since 2007 to assess the Environmental Status according to the EU Water

After 2000														
n° populations	Ligurian	N Tyrrhenian	C Tyrrhenian	S Tyrrhenian	Sardinian	N Adriatic	C Adriatic	S Adriatic	N Ionian	S Ionian	Strait of Sicily	MPAs, National Parks	Natura 2000, SPAMI	Local extinctions
Cystoseira														
721	L T	T	Sa C La	Sa S	Sa	V F	A Ab M	A	A Cl	S	S	360	237	39
0												–	–	5
0												–	–	1
2				S								2	–	5
32		T	Sa C	S	Sa						S	15	6	38
6	T										S	4	1	11
0												–	–	0
0												–	–	0
0												–	–	1
0												–	–	22
0												–	–	0
Ericaria														
616	L T	T	Sa C La	S	Sa		A	A	A Cl	S	S	307	155	27
1											S	–	–	0
163	T	T	Sa C	Sa S	Sa					S	S	132	12	17
83		T	Sa C	Sa S	Sa	F		A			S	45	13	36
2											S	2	–	3
7			C	S								4	2	10
0												–	–	7
10	L	T	C		Sa						S	8	2	21
Gongolaria														
107			Sa	Sa S	Sa	V F	M	A	A			36	21	40
7	L		Sa		Sa							1	1	6
74	L	T	Sa C	S	Sa					S	S	48	11	51
19		T	C	S						S	S	14	2	31
7			Sa	S	Sa			A				1	3	0
0												–	–	0
0												–	–	0

Framework Directive (WFD, 2000/60/EC) (De La Fuente et al., 2018). The CARLIT index indicates *Cystoseira s.l.* assemblages as highly sensitive to environmental stresses, and associates their presence and healthy status (in terms of continuous distribution) to good environmental conditions. In addition, experimental studies, which generally focused on single species, privileged *C. compressa* and *E. amentacea* as target species (16 studies out of 27), thanks to their wide distribution (Crowe et al., 2013; Mancuso, 2016) and/or easiness of access for manipulative purposes (Maggi et al., 2009; Gianni, 2016; Rindi et al., 2017).

The scenario drawn by the available information is more heterogeneous for species inhabiting subtidal reefs. A relevant amount of recent information is concentrated on few species (i.e., *E. brachycarpa*, *E. crinita*, *G. barbata*, *G. montagnei*) inhabiting shallow waters. These species, once distributed across most Italian waters, showed a more jeopardized distribution in recent years. The description of numerous new populations of *E. brachycarpa* and *E. crinita* across Sardinia and the Tuscan Archipelago was counterbalanced by a loss of information across Calabrian and Sicilian waters. *G. barbata* and *G. montagnei*, once distributed across all basins, have drastically contracted their range of distribution, virtually disappearing from several regions, although new populations have been described in Liguria and Sardinia, which has been intensively sampled only in recent years (2 out of 829 records refer to samplings before 2000).

Inferences of extinctions based on comparison of historical and recent data must be drawn with great caution, as they are reliable only for well-studied areas that have been monitored continuously for a long time. In cases of temporally discontinuous investigations, such differences are likely to reflect a decrease in the information available on their distribution, rather than an actual decline. Even considering this, a declining trend for these species across Italian waters is strongly suggested by many local extinctions that have been reliably documented.

A second group of species (i.e., *C. foeniculacea*, *E. mediterranea*, *E. selaginoides*, *E. zosteroides*, *G. elegans*, *G. sauvageauana*), once widely distributed (3–9 regions) and frequently recorded across Italian waters, has rarely or ever been reported in recent studies. Cases of local extinction have been suggested for all these species, indicating that a declining trend combines with the contraction in the range of distribution observed by recent data. Lastly, a conspicuous group of rare species (i.e., *C. corniculata*, *C. crinitophylla*, *C. dubia*, *C. hyblaea*, *C. humilis*, *C. pelagosae*, *C. platyclada*, *C. schiffneri*, *C. sedoides*, *E. barbatula*, *E. funkii*, *G. squarrosa*, *G. susanensis*, *G. usneoides*), which were historically described in few locations (1–3 regions), appears to have virtually disappeared according to recent data. Local extinctions have been documented for most of them (i.e., *C. corniculata*, *C. crinitophylla*, *C. dubia*, *C. humilis*, *C. platyclada*, *C. schiffneri*, *E. funkii*), and very few populations have been censused in recent years (only for *C. humilis*, *E. barbatula*, *E. funkii*, *G. squarrosa*).

4.2. Decline, extinction of Cystoseira s.l. populations, and drivers responsible for these changes

Despite the overall increase in recent information (i.e., 3238 records after 2000 versus 674 before 2000), the comparison of historical and recent data highlighted a severe loss of information for most *Cystoseira s.l.* species, which may correspond to a declining trend for most species. Few studies were explicitly devoted to verify the persistence of species, by integrating historical and new data. Whenever this approach was adopted, a dramatic situation emerged: for instance, in different areas of the Gulf of Naples the loss of *Cystoseira s.l.* populations was estimated between 60 and 100%, with the disappearance of 7 out of 15 *Cystoseira s. l.* species previously reported in the area and a severe decline of the remaining species (Grech, 2017). A re-evaluation of algal assemblages of

Table 2
Populations of the different species of *Cystoseira s.l.* located inside Marine Protected Areas, Underwater, and National Parks. The presence of each species before and after the institution of protection is indicated. b = before, a = after, e = extinct.

Designation name	Year of institution	*C. compressa*	*C. corniculata*	*C. crinitophylla*	*C. dubia*	*C. foeniculacea*	*C. hyblaea*	*C. humilis*	*C. pelagosae*	*C. platyclada*	*C. schiffneri*	*C. sedoides*	*E. amentacea*
Isola di Bergeggi MPA	2007	b a											b a
Portofino MPA	1998	a				b							b a
Cinque Terre MPA	1997	b a											b
Arcipelago Toscano National Park	1996	b a				a							b a
Tavolara - Punta Coda Cavallo MPA	1997	a											a
Arcipelago della Maddalena National Park	1991	a	b			b							b a
Capo Testa - Punta Falcone MPA	2018	b											a
Isola dell'Asinara MPA	2002												a
Capo Caccia - Isola Piana MPA	2002	a				a							a
Penisola del Sinis - Isola Mal di Ventre MPA	1997	a											a
Capo Carbonara MPA	1999	a											a
Gaiola Underwater Park	2002	b a e				b e							b a e
Baia Underwater Park	2002	a				b e							
Regno di Nettuno MPA	2007	b a e			b e	b a e							b a e
Punta Campanella MPA	1997	b a e				b e							b a e
Santa Maria di Castellabate MPA	2009	b				b							b
Costa degli Infreschi e della Masseta MPA	2009					b							
Capo Rizzuto MPA	1991	b a	b			b							b a
Capo Gallo - Isola delle Femmine MPA	2002	b a			b a	b a		b a					b a
Isola di Ustica MPA	1986	b a				b			b		a		b a
Isole Egadi MPA	1991	b a			b e	b a e		b a		b e			b a
Isole Pelagie MPA	2002	b		b e		b e		b e		b			b
Plemmirio MPA	2004	b			b	b		b					b
Isole Ciclopi MPA	1989	b a			b	b							b a
Porto Cesareo MPA	1997	a											b a
Torre Guaceto MPA	1991	a											
Isole Tremiti MPA	1989	b a	b	a		b					b e		b a
Miramare MPA	1986	a				b							

the Cheradi islands after 30 years highlighted the extinction of 5 out of 7 *Cystoseira s.l.* species (Cecere et al., 1996), while in Linosa 7 out of 8 *Cystoseira s.l.* species disappeared (Serio et al., 2006), and in the Aegadian islands 9 out of 12 *Cystoseira s.l.* species locally extinguished (Catra et al., 2006). At least two species of *Cystoseira s.l.* have disappeared from the Conero Riviera (possibly more, due to taxonomic uncertainty of some unverifiable literature records; Rindi et al., 2020). This trend suggests that the phenomenon of local extinction of *Cystoseira s.l.* might be underestimated, and the lack of information on the distribution of the majority of *Cystoseira s.l.* species in recent years could mask a dramatic decline across Italian seas.

In addition, the decline in taxonomic expertise might have substantially compromised the ability of researchers to identify several *Cystoseira s.l.* species.

Despite the scientific interest for the decline of *Cystoseira s.l.* forests, the identification of the local drivers of loss is still a daunting task. Very few studies (13 out of 169) clearly identified the stressors affecting the canopies. When the information was provided, urbanization (e.g., sewage outfall, coastal development, harbor proximity; Mangialajo et al., 2008; Grech, 2017), agricultural or industrial activities (e.g., pollutants, eutrophication, water turbidity due to terrigenous sediments; Sfriso, 1987; Cecere et al., 1996; Cormaci et al., 2001; Grech, 2017; Catra et al., 2019), aquaculture or fisheries (Cecere et al., 1996; Grech, 2017) were identified (Fig. 10). In addition, overgrazing by sea urchins (Catra et al., 2019), sea water warming (Serio et al., 2006), and the combination of local stressors (i.e., rock mining and beach nourishments) and extreme storminess (Perkol-Finkel and Airoldi, 2010), were advocated as drivers of decline at the scale of populations. Other experimental studies investigated mechanisms that might compromise the resilience of brown algal forests, likely contributing to their fragmentation (e.g., human trampling, Milazzo et al., 2002, 2004; competition with invasive species, Bulleri et al., 2017). Hence, although the scientific community has agreed on the major threats for Mediterranean macroalgal forests (i.e., habitat loss due to coastal development, Airoldi and Beck, 2007; pollution, Munda, 1982; Soltan et al., 2001; heavy metals, Sales et al., 2011; de Caralt et al., 2020; eutrophication, Arevalo et al., 2007; outbreaks of grazer populations including sea urchins, salema fish and rabbitfish Sala et al., 1998, 2011; climate change, Bevilacqua et al., 2019; Verdura et al., 2021), a case-by-case identification of stressors is far from being reached (Fig. 10), although this step

E. barbatula	*E. brachycarpa*	*E. crinita*	*E. funkii*	*E. mediterranea*	*E. selaginoides*	*E. zosteroides*	*G. barbata*	*G. elegans*	*G. montagnei*	*G. sauvageauana*	*G. squarrosa*	*G. susanensis*	*G. usneoides*	Year of documented extinction
						a			a					
	b a	a				a	b	b	b a	a				
	a	a					a		a					
	a	b a					a		a					
		b					b		b					
		a					a		a					
	a	a					a	a						
	a	a				a	a		a					
	a	a					a							
														2013–2016
	b			b	b	b	b		b	b				
	e			e	e	e	e		e	e				
	b e								b e					2013–2016
														2013–2016
	b a	a		b a	b	b a	b		b a e	a				
	e	e		e			e							
	b a	b	b e	b		b a			b a	a				2013–2016
	e	e		e										
						b	b		b					
				b					b					
	b	b					b		b	b				
	b a	b a		b		b	b	b	b a	b	a			
	b a													
		b				b	a	b	b a	b a				
	b a	b a	b a	b		b a	b	b	b a	b				2001
		e		e		e	e	e		e				
b	b	b				b		b	b	b	b			1999
	e					e		e		e				
	b	b				b	b		b					
	b a e	b	b	b		b	b	b	b a	b a				2015–2016
		b e					a	b e						2000
		b e					b		b e					1997
		a					b							
							a							

represents a necessary requisite to plan local conservation interventions, or to identify putative sites for restoration purposes (Gann et al., 2019).

4.3. Success stories of natural recovery

Similar to the cases observed along the Catalan and Istrian coasts (Roca et al., 2015; Ivesa et al., 2016), the partial recovery of fucalean forests has been reported in Italian waters as a result of the mitigation of local stressors and amelioration of water quality due to the reduction of nutrient loads and water turbidity in the Venice lagoon (Marzocchi et al., 2003; Sfriso and Facca, 2011). Yet, the two species populating the lagoon, namely *G. barbata* and *C. compressa*, being provided with aerocysts that allow medium-distance dispersal of vegetative fragments, present a higher potential to naturally recolonize sites after local extinction compared to the majority of *Cystoseira s.l.* species, which are generally characterized by very low dispersion distance of the zygotes (Thibaut et al., 2014). For these species of *Cystoseira s.l.*, with virtually no connectivity with other populations, restoration emerges as the solely opportunity to contrast their decline. Yet, one of the key pieces of information for the planning of restoration interventions is the historical extent of the fucalean forests and an eventual estimation of the fragmentation or contraction of their distribution. Attention to this aspect would allow to operate prompt reforestation interventions before the populations are totally lost, eventually preventing the settlement and spread of organisms that might inhibit their future recovery (e.g., the invasive *Sargassum muticum*, Marzocchi et al., 2003; algal turfs or mussels, Perkol-Finkel and Airoldi, 2010). Yet, except for a few studies including mapping of *Cystoseira s.l.* populations to establish a baseline for selected locations (e.g., Calvo et al., 1980; Gianni, 2016; Grech, 2017), only the study by Perkol-Finkel and Airoldi (2010) provided an accurate estimate of the historical extent, severity of decline, and degree of fragmentation of the declining populations of *G. barbata* along the Conero promontory.

4.4. How much are censused Cystoseira s.l. populations protected?

Before 2000, a negligible proportion of *Cystoseira s.l.* populations were protected (2.6%). The proportion of protected populations has increased in recent years to 77.8%, with nearly two thirds of the

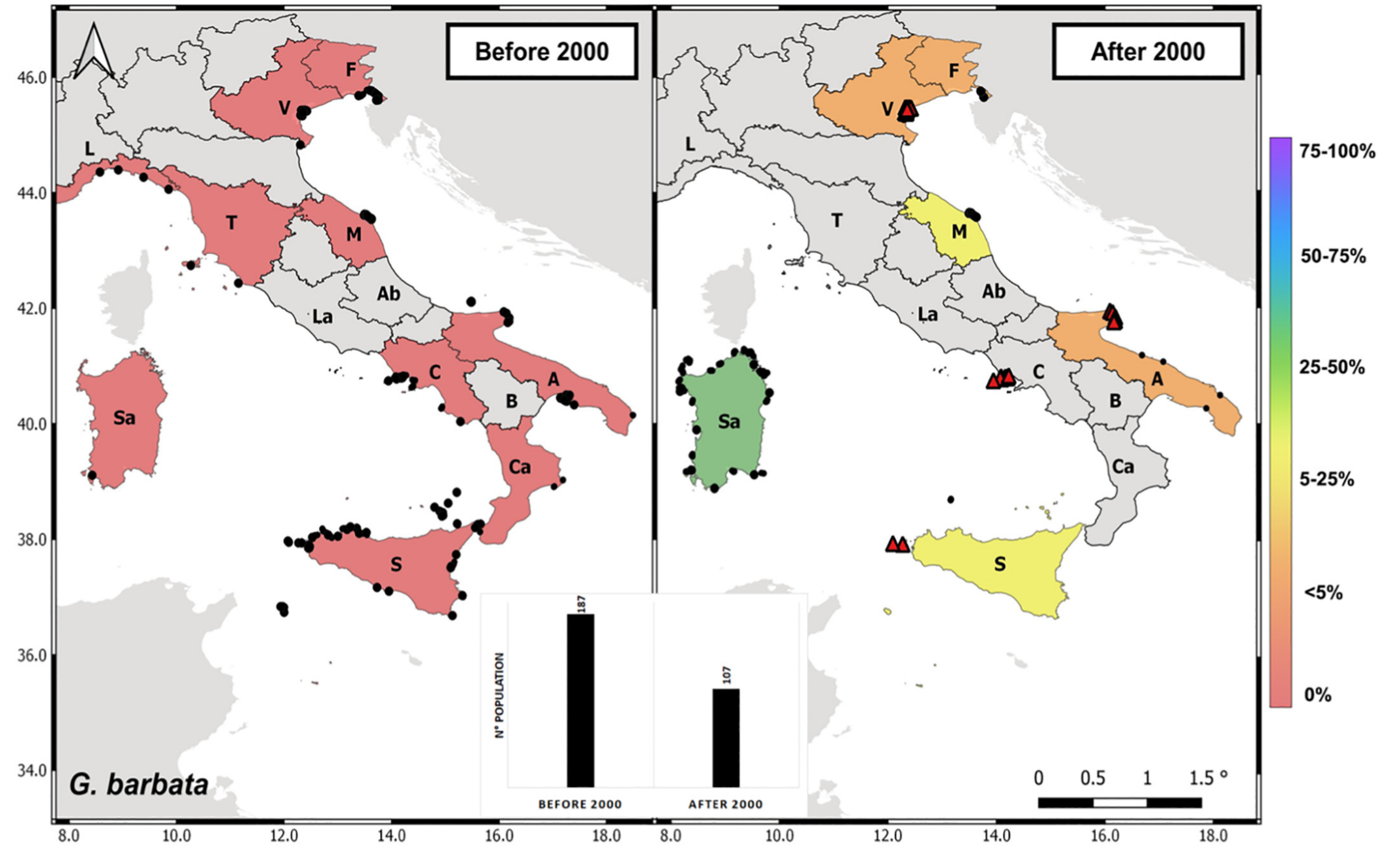

Fig. 8. Historical and recent distribution of *Gongolaria barbata* along Italian coasts. Black dots and lines indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

populations included in MPAs, National and Underwater Parks, and one third protected by Natura 2000 sites or SPAMIs. The regulations and enforcement of MPAs and National Parks guarantee protection to *Cystoseira s.l.* by limiting coastal urbanization and overfishing, including the illegal and destructive practice of date mussel harvesting, which can foster the permanent shift from forested habitats to barrens (Colletti et al., 2020). In addition, limitations of the fishery pressure may indirectly safeguard *Cystoseira s.l.*, by allowing the recovery of high-level predators, which control herbivore populations avoiding overgrazing (Sala et al., 1998, 2012), or directly limiting the discard of abandoned fishing gears (Capdevila et al., 2016). Instead, Natura 2000 Sites and SPAMIs are characterized by more limited regulations, as they cannot forbid several human activities such as fishery or shipping, and lack no-take zones. In addition, limited enforcement and the lack of management and monitoring plans generally make their regulations poorly applied (Olsen et al., 2013). Hence, their efficacy in protecting brown macroalgal forests might be scarce. Yet, recent studies highlighted that even MPAs might have limited protection efficacy, since they cannot constrain regional- or basin-scale stressors such as eutrophication or water turbidity, nor mitigate global change effects (Gianni et al., 2013; Fraschetti et al., submitted). This is further supported by the extinction of several *Cystoseira s.l.* species (*C. compressa*, *C. dubia*, *C. foeniculacea*, *C. platyclada*, *E. amentacea*, *E. brachycarpa*, *E. crinita*, *E. mediterranea*, *E. zosteroides*, *G. barbata*, *G. elegans*, *G. sauvageauana*) located in the MPAs of Punta Campanella, Regno di Nettuno, Porto Cesareo, Aegadian, Pelagian, Ciclopi and Tremiti islands, documented in our study.

77.9% of the populations currently protected inhabit intertidal reefs, including the non-protected species *C. compressa* (41.3%), *E. amentacea* and *E. mediterranea*. Among species populating subtidal reefs, *E. brachycarpa* is the most frequently censused in protected areas, followed by *G. montagnei* and *E. crinita* (respectively 10%, 4.1%, and 4% of the protected populations). All the *Cystoseira s.l.* species for which the presence has been confirmed during the last twenty years are partially or totally protected, except for *E. barbatula*. However, due to the lack of monitoring programs dealing specifically with brown fucalean species, half of the MPAs did not collect any information after their institution, to confirm the presence or disappearance of species previously censused within their borders. Only about one third of the MPAs have an updated overview of the situation, generally corresponding to the disappearance of most *Cystoseira s.l.* species. A positive exception is represented by the MPAs located in the Sardinian region, for which the scarcity of historical data is compensated by a recent and widespread census activity.

5. Conclusions

With increasing recognition of the need to adopt restoration actions, several analyses have been carried out showing the challenges that restoration should tackle to be effective (Abelson et al., 2020; Fraschetti et al. submitted). The development of effective methods for restoration upscaling, the incorporation of innovative tools to promote the consideration of climate changes, and the integration of social and ecological restoration priorities, are among the most frequent issues emerging from these perspectives. Our review on the iconic macroalgal forests shows the dramatic lack of baseline information for a group of species which are presently the focus of many restoration interventions. In particular, we found three topics deserving specific attentions in the next future: the undervaluation of habitats less accessible to monitor, the

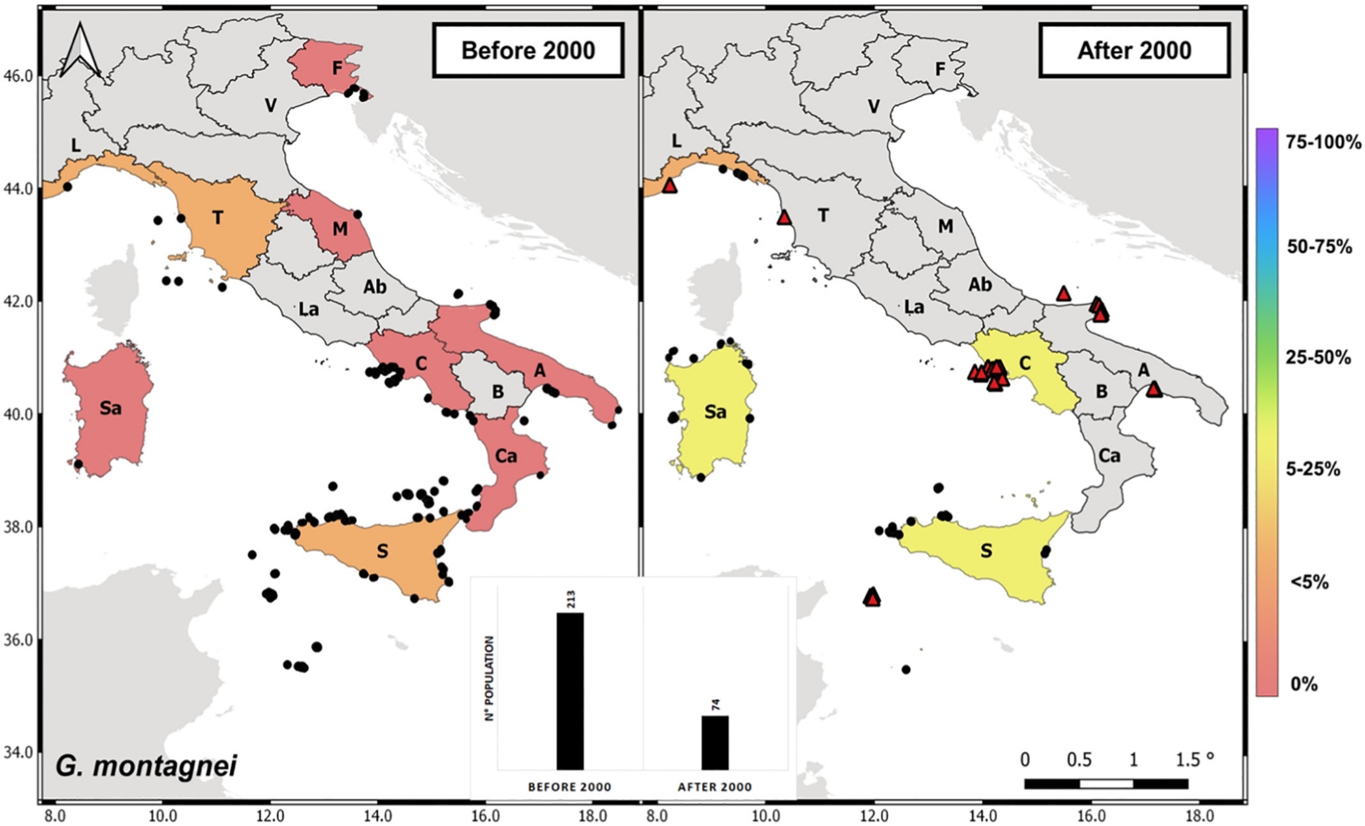

Fig. 9. Historical and recent distribution of *Gongolaria montagnei* along Italian coasts. Black dots and lines indicate the presence of the species, red triangles show documented local extinctions. The color of each region represents the percentage of populations protected by MPAs, national and underwater parks, Natura 2000 sites or SPAMIs within each region, grey regions indicate no population censused. A = Apulia, Ab = Abruzzo, B = Basilicata, C = Campania, Cl = Calabria, F = Friuli-Venezia Giulia, L = Liguria, La = Lazio, M = Marche, S = Sicily, Sa = Sardinia, T = Tuscany, V = Veneto.

lack of long-term data to unveil drivers of loss, and an updated reporting about the conservation status of the species of interest to plan future interventions.

Macroalgal forests are a paradigmatic example to document several limits that can compromise the recent effort from scientists, policy makers and stakeholders such as MPA managers to limit the observed shifts or plan restoration actions. Together with the challenges imposed by climate changes, data about historical presence, present occurrence and the conservation status of the target species/groups are critical to succeed in restoration actions. Our study documents a dramatic lack of information for most *Cystoseira s.l.* species, together with the state of their conservation, requiring timely interventions. Above all, there is

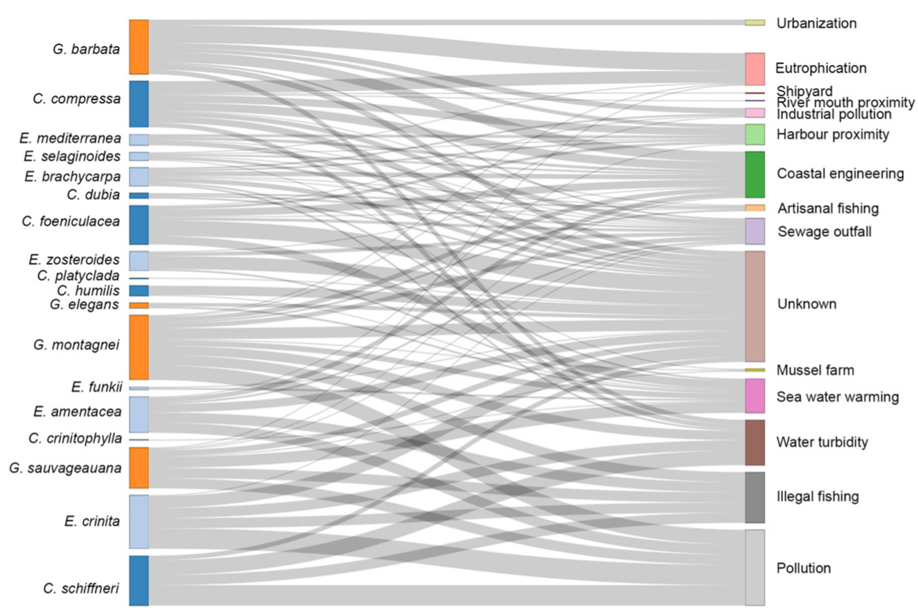

Fig. 10. Sankey diagram representing the putative drivers affecting populations of different *Cystoseira s.l.* species described in the literature. The width of the nodes and lines is proportional to the number of extinct populations attributed to each stressor. Multiple drivers might have been attributed to a single extinction event.

an urgent need to implement regular monitoring plans to update the knowledge on the distribution and status of *Cystoseira s.l.* populations within protected areas, representing preferential areas for restoration activities, given recovered environmental conditions and increased chances of restoration success (Medrano et al., 2020).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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