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SHORT COMMUNICATION

The collapse of marine forests: drastic reduction in populations of the family Sargassaceae in Madeira Island (NE Atlantic)

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Abstract

Species of the genera *Cystoseira*, *Ericaria*, *Gongolaria*, and *Sargassum* (family Sargassaceae) are key components of the Mediterranean-Atlantic marine forests, essential for biodiversity and ecosystem functioning. Populations of these foundational species are particularly vulnerable to anthropogenic impacts, likely to be intensified under future scenarios of climate change. The decline and even disappearance of these species have been reported in different areas of the world. At Madeira Island (NE Atlantic), populations of *Gongolaria abies-marina*, *Ericaria selaginoides*, *Sargassum vulgare*, and *Sargassum filipendula*, the most ecologically relevant species in Macaronesian marine forests, have been suffering a drastic decline during the last decades, especially on the southern coast of the island, where anthropogenic pressure is higher than on the north coast. The lack of sufficient temporal coverage on qualitative and quantitative studies of Sargassaceae communities in Madeira poses a challenge to establish a specific period for this decline. Consulting qualitative studies and historical records, we have set for the first time a timeline that shows an evident decrease in Sargassaceae populations in the last 20 years on Madeira Island. Following this timeline, we pinpoint the start of this decline in the first decade of the 2000s. This can be particularly confirmed for places like Funchal and Reis Magos, with significantly higher historical records. Currently, most benthic communities on shallow subtidal rocky reefs along the south coast are dominated by sea urchins and crustose coralline algae, the so-called sea urchin barrens. However, in some cases, they are entirely covered by a layer of sediment. We discuss the possible factors contributing to these drastic changes, bringing Madeira's marine forests to a dramatic decline. As many animal species rely on marine forests, the decline of Sargassaceae populations represents an invaluable ecological loss for the coastal ecosystem of the island.

Keywords Marine forests · Anthropogenic pressures · *Cystoseira* · *Ericaria* · *Gongolaria* · *Sargassum* · Madeira · Macaronesia

Introduction

Macroalgal forests (order Laminariales Migula, 1909, and order Fucales Bory, 1827) represent one of the most productive habitats along temperate rocky coasts worldwide (Dayton 1985). These marine forests alter the physical, chemical, and biological conditions of the environment (Ballesteros 1992; Hoffmann et al. 1992; Ballesteros et al. 1998; Hirsh et al. 2020) with their high rates of primary productivity and by providing complex biogenic habitat, shelter, food, and nurseries for numerous species (Boudouresque 2004; Fraschetti et al. 2011; Giakoumi et al. 2012; Smale et al. 2013). Moreover, they are considered biological indicators of water and ecosystem quality (Gros 1978; Panayotidis et al. 1999; Pinedo et al. 2006).

Fucoids (Fucales, Ochrophyta) are "engineering species" (*sensu* Jones et al. 1997), present along rocky shores of

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temperate and subtropical areas. In pristine environments, these key species may become dominant (Schiel and Foster 2006), forming large canopies essential for biodiversity and ecosystem functioning (Bermejo et al. 2018 and references therein). The decline of fucoids (as well as kelp, mainly in the orders Laminariales and Tilopteridales, Ochrophyta) is a global tendency directly or indirectly induced by human activities (Wernberg et al. 2011; Franco et al. 2015). In recent decades, studies have detected the decline and even the disappearance of entire populations of the family Sargassaceae, across European waters, due to different human pressures, namely habitat destruction, overgrazing, sedimentation, invasive species, pollution, and ocean warming (Soltan et al. 2001; Airoldi 2003; Hill et al. 2003; Tuya et al. 2004; Clemente 2007; Roleda and Dethleff 2011; Scherner et al. 2013; Gianni et al. 2017). As a result, these marine forests are replaced by simple and less productive communities dominated by opportunistic taxa, such as turfs or barrens, in many areas worldwide (Vergés et al. 2014; Valdazo et al. 2017; Verdura et al. 2018).

A noticeable regression of marine forests has been described along some temperate and subtropical rocky shores, including the Mediterranean Sea and the Canary Islands (Thibaut et al. 2005; Bonaviri et al. 2011; Valdazo et al. 2017; Verdura et al. 2018). The archipelagos of the Azores, Madeira, Canary Islands and Cabo Verde are distributed along a latitudinal gradient in the Atlantic Ocean, with differences in climate and water temperature (Freitas et al. 2019). Nevertheless, all of them have recently experienced significant alterations in their coastal ecosystems and macroalgae formations (Sangil et al. 2018). In the last few decades, a severe decline in the populations of *Gongolaria abies-marina* (S.G.Gmelin) C.Agardh 1820 has been extensively documented in Gran Canaria Island (Valdazo et al. 2017).

Although previous studies have mentioned a possible decline in the populations of the family *Sargassaceae* in Madeira (Bianchi et al. 1998; Sangil et al. 2018), none has examined the magnitude and scale of this loss, probably due to the lack of data for these populations in the past. To properly document this collapse, we compile the available historical knowledge reporting the regression of macroalgal populations from intertidal and subtidal coastal areas of Madeira.

From marine forests to collapse: the case of Madeira

The island of Madeira (32.7° N, −17° E), which together with Porto Santo and the uninhabited islands of Desertas forms the Madeira Archipelago, has a mainly rocky coastline (Alves et al. 2001), made up of platforms and boulders. Sea surface-water temperatures usually range between 17.0 and 23.5°C (Abreu and Biscoito 1998; Schäfer et al. 2019). Our study concentrates on the strongly human-influenced southeast coast of the island, from Calheta to Baia d'Abra, covering a shoreline of approximately 70 km. The southeast shore of Madeira has been the most studied part of the island over decades due to higher accessibility and better oceanic conditions throughout the year.

Before and during the 1980s, the south coast of Madeira was characterized by large habitat-forming species, mainly *Cystoseira* spp., *Gongolaria* spp., *Ericaria* spp., and *Sargassum* spp. (Levring et al., 1974; Canning-Clode, Wirtz, Kaufmann pers. obs; Bianchi et al. 1998). The brown algae *Gongolaria abies-marina* was the dominant algal species on the rocky coasts, generally distributed from the infralittoral to the upper circalittoral zone (Levring 1974; Augier 1985; Wildpret et al. 1987; Bianchi et al. 1998; Tuya and Haroun 2006). Other relevant species such as *Ericaria selaginoides* (Linnaeus) Molinari & Guiry 2020, *Cystoseira humilis* Schousboe, *Cystoseira foeniculacea* (Linnaeus) Greville 1830, *Sargassum vulgare* C.Agardh, and *Sargassum filipendula* C.Agardh were also abundant in shallow rocky sublittoral and intertidal exposed areas decades ago (Levring 1974; Augier 1985; Bianchi et al. 1998). Most of the species mentioned above were present in great abundance in Funchal, Garajau, Reis Magos, Machico, and Caniçal, highlighting *G. abies-marina* as the dominant species (Table 1). Especially in Funchal, the most studied location, from 1974 to 1998, *E. selaginoides*, *G. abies-marina*, *S. vulgare*, and *S. filipendula* were dominant species. The same appears to be true for less studied locations in the past: photographs from the 1990s (Fig. 1) show the presence of marine forests at the south coast of Madeira, at least from Baia d'Abra (Fig. 1A) to Calheta (Fig. 1E), passing through other sites such as Machico (Fig. 1B), Santa Cruz (Fig. 1C), and Reis Magos (Fig. 1D). In later studies (2008–2009), our target species were classified as occasional, rare, or even absent (Freitas Ferreira 2011; Alves et al. 2019). A more recent study evaluating the coast of Madeira almost completely (Friedlander et al. 2017) indicates that canopy-forming species are absent on the southeast coast. In those few areas where they were still present, their coverage never exceeded 15%. The bottoms were dominated by coralline crustose algae (CCA) and turfs up to 20 m depth (Friedlander et al. 2017). Sangil et al. (2018) found only *Sargassum vulgare*, in an extremely low coverage in the island (0.002 ± 0.002%); the other species of the family were absent. In a recent habitat mapping study of the Cabo Girão natural marine park, located on the south coast of Madeira, marine forests were not reported and species of the family Sargassaceae were totally absent from the species list for the area (Ribeiro and Neves 2020). Nowadays, benthic rocky bottoms are dominated by CCA or turfs and barrens, generally with a layer of sediment covering the benthos (Fig. 1). Currently, species of the family Sargassaceae are rare to find at the southeastern coast and seem to be restricted to intertidal

Table 1 Presence/absence of different species of Sargassaceae family from 1974 to the present in different localities on the southeast coast of Madeira (from Calheta to Baia d'Abra). The presence has been quantified in 4 levels according to the descriptions of the consulted sources: dominant, abundant, occasional, present, and absent

Year	Taxa	SW <> SE								
		Calheta	**Ribeira Brava**	**Funchal**	**Garajau**	**Reis Magos**	**Santa Cruz**	**Machico**	**Caniçal**	**Baia' dAbra**
1974	**Levring, 1974**									
	C. humilis			●		●				
	C. foeniculacea			●●						
	E. selaginoides			●						
	G. abies-marina			●●●●		●●●●		●●●●	●●●●	
	S. vulgare			●●●	●●●	●●●			●●●	
1985	**Augier, 1985**									
	C. humilis			●●						
	E. selaginoides			●●●●						
	G. abies-marina			●●●●						
	S. vulgare			●●●						
1991	**Reed & Serrão (Per. Obs.)**									
	G. abies-marina									●●●
	Sargassum sp.									●●●
1995	**Wirtz (Per. Obs.)**									
	C. humilis						●●●			
	G. abies-marina			●●●		●●●				
	S. filipendula	●●●						●●●		
1998	**Bianchi, 1998**									
	G. abies-marina			●●●●						
	S. filipendula			●●●●						
2000	**Haroun et al., 2003**									
	C. humilis					●				
	C. foeniculacea					●				
	G. abies-marina					●				
	S. filipendula					●				
2007	**Canning-Clode (Per. Obs.)**									
	G. abies-marina								●	
2008	**Alves et al., 2019**									
	Cystoseira sp.			○	○	○		○		
	E. selaginoides			○	○	○		○		
	G. abies-marina			○	○	○		○		
	Sargassum sp.			●	○	○		○		
2009	**Ferreira, 2009**									
	Cystoseira sp.		●●	●		●●				
	E. selaginoides									
	G. abies-marina		●●	●						
	Sargassum sp.									
	S. filipendula					●●●				
2016	**Friedlander et al., 2017**									
	G. abies-marina	○	○	○	○	○	○	○	○	○
	Sargassum sp.	○	○	●	○	●	●	○	●	○
	Sargassum vulgare	○	○	●	○	○	○	○	○	○
2020	**Bernal-Ibáñez (Per. Obs.)**									
	C. humilis	○		●	●	●		●	○	●
	C. foeniculacea	○		●	●	●		●	●	○
	E. selaginoides	○		○	○	○		○	○	○
	G. abies-marina	○		●	○	○		○	○	○
	Sargassum sp.	○		●	●	○		●	○	○
2021	**Bernal-Ibáñez et al. (in prep.)**									
	C. humilis	○	○	●	●	○	○	●	○	●
	C. foeniculacea	○	○	●	●	●	○	●	●	○
	E. selaginoides	○	○	○	○	○	○	○	○	○
	G. abies-marina	○	○	○	○	○	○	○	○	○
	Sargassum sp.	○	○	●	●	●	○	○	○	○

●●●● Dominant, ●●● Abundant, ●● Ocasional, ● Present, ○ Absent

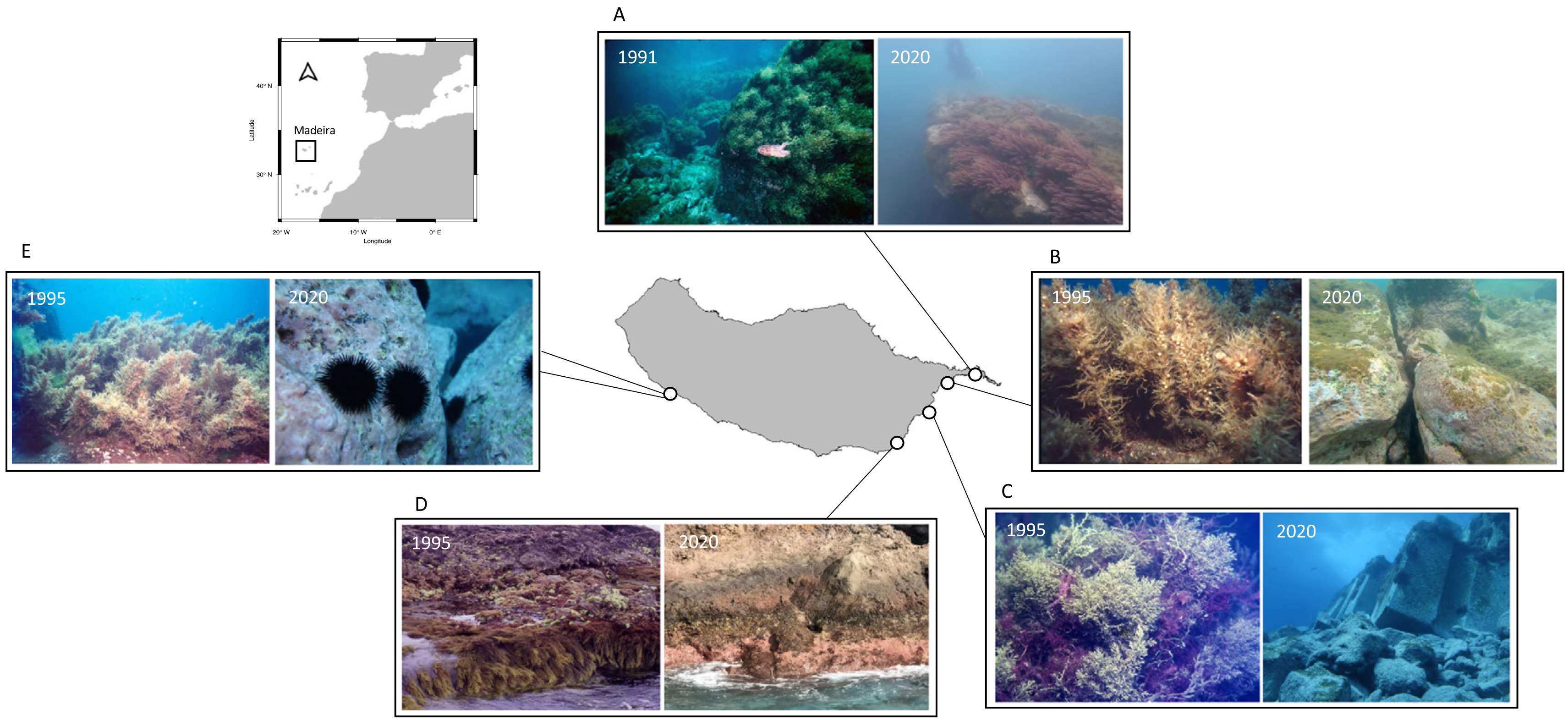

Fig. 1 Different places of Madeira showing photographs of areas dominated by *Cystoseira* and *Sargassum* in the past and currently dominated by coralline crustose algae, turf, sediments, bare rock, and the sea urchin *D. africanum*. **A** Baia d'Abra (1991: *Sargassum* sp. by J. Reed and E. Serrão; 2020: rocky bottom covered by *A. taxiformis* and sediments), **B** Machico (1995: *S. filipendula* by P. Wirtz; 2020: barren), **C** Santa Cruz (1995: *C. humilis* by P. Wirtz; 2020: barren and concrete structures), **D** Reis Magos (1995: *G. abies-marina* belts by P. Wirtz; 2020: barren), and **E** Calheta (1995: *S. filipendula* by P. Wirtz; 2020: *D. africanum* over coralline crustose coralline algae)

rockpools in specific locations. The only macroalgae found covering larger areas nowadays are *Asparagopsis taxiformis* (Delile) Trevisan, *Padina pavonica* (Linnaeus) Thivy, and other Dictyotales (Friedlander et al. 2017; Sangil et al. 2018).

Marine forests in Madeira have gone from dominating large rocky areas to being replaced by a simple and less productive system with a high presence of CCA and filamentous algae (Friedlander et al. 2017; Sangil et al. 2018). Everything seems to indicate that this phase change began in the first decade of the 2000s, at least in the vicinity of Funchal bay, a date very similar to that provided by similar studies in the Canary Islands (Valdazo et al. 2017). This is most evident at Funchal (the area most studied), where Sargassaceae species went from being dominant to rare in less than 10 years (Table 1). Other places along the SE coast of Madeira seem to follow the same pattern. Despite the lack of time-series data for these populations in Madeira, the scenario appears to be very similar to the one in the Canary Islands, where *G. abies-marina* populations declined 99% (Valdazo et al. 2017).

Possible causes and impacts

Changes in the distribution and extension of Sargassaceae species in Madeira in the last decades are evident and dramatic. Very few algal species in the world have been adequately evaluated over decades due to a lack of historical data (Blanfuné et al. 2016). Madeira is no exception; its remoteness, oceanic conditions, and cliff-lined coast have been a challenge for the development of phycological studies in the past. Despite the limitations of our study due to the lack of time series, our results are in agreement with studies published in the Canary Islands (Hernández et al. 2008a; Valdazo et al. 2017), in the Mediterranean Sea (Thibaut et al. 2005; Mangialajo et al. 2008; Thibaut et al. 2015), and in general for canopy-forming brown macroalgae around the world (Wahl et al. 2015). The area occupied by these species in the past could be underestimated due to the lack of techniques and procedures evaluating these communities over the years, including populations below 20 m depth. Despite this, we can assume these inaccuracies since the regression is evident, especially in the intertidal and shallow subtidal zones. This decline is a general pattern on the southeast coast of Madeira, regardless of levels of anthropogenic pressure or protection, because even in those protected areas (such as Garajau), it has been dramatic.

The decline of these species seems to have occurred in a period of greater urbanization and tourism development and, therefore, many local impacts, as has happened in the Canary Islands (Tuya et al. 2014; Ferrer-Valero et al. 2017). In recent decades, several human pressures, particularly coastal development on the shoreline of Madeira, have increased considerably, especially on the more heavily inhabited and accessible southeast coast. The numerous constructions that have taken place in recent decades (e.g., hotels, artificial pools, ports, marinas, private houses, and roads) are human activities with a clear impact on the coastal environment. These constructions are especially important in the Bay of Funchal, where the coastline has been intensively modified. Popular knowledge recognized that debris generated from the construction of new coastal infrastructure created a layer of mud on the bottom, impacting the habitats (Martínez-Escauriaza et al. 2020a). Intensive urbanization causes substantial seaweed species declines, particularly among Phaeophyceae, associated with habitat destruction and the degradation of water quality (Scherner et al. 2013; Cacabelos et al. 2016). After a monitoring program to assess the impact of urban wastewater discharges through submarine outfalls and to explain the processes that determine water quality in the south coast of Madeira Island, Campuzano et al. (2010) concluded that nutrient dynamics were mainly related to mesoscale events and land-based inputs are unlikely to play a strong role in the ecological processes of the region. The disappearance or modification of continuous coastal shores (or natural rocky platforms) can disable the normal development of macroalgal species and reduce the habitat available for recruitment and settlement (Steneck et al. 2020; Perkol-Finkel and Airoldi 2010; Blanfuné et al. 2016; Cacabelos et al. 2016; Ferrario et al. 2016). This can even have consequences at the genetic level. For example, the genus *Cystoseira*, *Ericaria*, and *Gongolaria* are species with low dispersion, and reproductive drifting thalli in floating rafts is the main mechanism of connectivity between populations (Susini et al. 2007). If connectivity is restricted, isolated small populations with poor gene pools are more vulnerable to possible impacts (Buonomo et al. 2017). In addition, modifications of the coastline can lead to changes in the light and turbidity regimes due to changes in hydrodynamics (Tuya et al. 2002). These stressors have been impacting the seagrass *Cymodocea nodosa* that has almost disappeared along the southern coast of Madeira, where it was already extremely reduced by coastal construction impact before 2007 (Cunha et al. 2013; Kaufmann and Maranhão 2017; Schäfer et al. 2020).

Another detrimental impact on canopy-forming algae may be a large amount of sediment loads from land after intense rainfalls, also affecting light availability and turbidity regimes. The mean annual precipitation varies between 600 and 800 mm on the south coast versus 1500–2000 mm on the north, reaching 3000 mm on top eastern mountains (Baioni et al. 2011) but sometimes leading to severe torrential rains, as occurred in February 2010 when rainfall attained 500 mm in a single day (Fragoso et al. 2012). The increase in floods is directly related to human activity on the south coast of Madeira (Baioni et al. 2011). Due to the loss of forest mass on the island, as a consequence of urbanization and agriculture (Baioni et al. 2011; Fernández-Palacios et al. 2016), the retention of sediments has been greatly diminished, increasing river sediment loads that reach the coast in greater quantities (Baioni et al. 2011; Quartau et al. 2018). During these events, the water turns brownish with high turbidity, contrasting with the typical crystalline waters of the island, and this can negatively affect photosynthetic organisms (Bernal-Ibáñez per. obs.; Kaufmann and Maranhão 2017). Moreover, these sediments end up deposited on the sea bed, which represents a mechanical impact for all sessile species and prevents the settlement of algae propagules (Schiel and Gunn 2019). The negative impact of turbidity and sedimentation on macroalgae has already been studied in other locations (Airoldi and Cinelli 1997; Airoldi 2003). Further research is necessary to evaluate the impact of turbidity and sediment deposition on the response of benthic communities in Madeira, as not only photosynthetic organisms can be affected (Kjelland et al. 2015).

In Madeira, barrens are dominated by the sea urchin, *Diadema africanum* Rodríguez, Hernández, Clemente & Coppard, 2013, cited as the main driver of the variability in the shallow benthic communities (Hernández et al. 2008b), reaching densities of up to 6 ± 4.8 individuals/m^2 in the southeast coast (Alves et al. 2001, 2019; Gizzi et al. 2020). Overfishing is one of the main reasons underlying the displacement of large macroalgal formations by sea urchin barrens (Guidetti et al. 2005; Sangil et al. 2011). The intense coastal fishing activity promotes the capture of top predators in the systems, which can be direct predators of settling stages and juveniles of sea urchins. Subsequently, sea urchin populations flourish as more individuals are recruited, and they reach larger sizes. The high recreative fishing activity on the coast of Madeira has been studied (Martínez-Escauriaza et al. 2020a, 2020b) in addition to the effect of the predation of *D. africanum* on macroalgae (Alves et al. 2003). Other grazers, such as the sea urchins *Arbacia lixula* and herbivorous fishes (*Sparisoma cretense* and *Sarpa salpa*), also contribute to the consumption of Sargassaceae species (Verges et al. 2009).

In the current context of climate change, ocean warming implies a global impact on coastal benthic communities and especially on marine forests (Wernberg et al. 2013; Filbee-Dexter et al. 2020; Smale 2020), producing the decline of fucoids and their displacement to cold waters (Wernberg et al. 2011). Regional studies have shown the negative effect of warming on brown macroalgae (Sansón et al. 2013). In addition to rising temperatures, the role of extreme high-temperature events (marine heatwaves) also has a negative impact on fucoid populations (Vergés et al. 2014; Arafeh-Dalmau et al. 2020). As the magnitude and frequency of extreme events are expected to increase under climate change (Gaines and Denny 1993; Coumou and Rahmstorf 2012; Frölicher and Laufkötter 2018), this should be taken into consideration in future experiments testing their effects on canopy-forming algae in Madeira.

The degradation of the marine forests in Madeira appears to be the result of a set of drivers interacting across regional and local scales that have increased in frequency and magnitude in recent decades: increase of overgrazing (especially *D. africanum*) as a consequence of imbalanced food chains by overfishing, increase of turbidity and sedimentation, habitat loss and fragmentation, climate change effects, among others. All this has led to a considerable recession of the populations of family Sargassaceae, making them taxa that are very difficult to find nowadays. This ecological loss brings with it the invaluable loss of numerous associated species, as well as all the ecosystem services provided by these macroalgae, from which society benefits both directly and indirectly (Ballesteros et al. 1998; Boudouresque 2004; Buonomo et al. 2018). Marine forests represent a vital habitat for nesting, establishment, and development of numerous associated species (some of them of economic interest) threatened with the regression of their habitat. The associated loss of biodiversity is likely to have a negative effect on the ecosystem services produced by marine forests in Madeira.

It is time to assess and understand all the ecological mechanisms and processes involved in this recession, taking into account the different interacting human pressures and the resistance of remnant populations. More efforts should be made to protect Madeira's coastal systems, following successful examples from the region such as the MPA in La Palma Island (Sangil et al. 2012) or Selvagens Islands (Friedlander et al. 2017). These cases show the important effect of active protection over benthic beds, presenting well-preserved macroalgal communities and even recovering communities lost in the past in less than 4 years (Sangil et al. 2012).

This study highlights the need to monitor the remaining populations of the species belonging to the family Sargassaceae in Madeira. Their decline appears to be a general pattern in the Macaronesian region, especially in Madeira and the Canary Islands. It is obviously necessary to collect more data to monitor this decline and to evaluate the state of these populations in the coming years. The information provided in this study is a basis to evaluate the conservation of the family Sargassaceae on the island of Madeira.

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