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Ecology and Phenology of the Subtidal Brown Alga *Sargassum furcatum* (Ochrophyta, Fucales), a Likely Non-Indigenous Species from the Mediterranean Sea

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Abstract: This study provides new insights regarding the ecology and phenology of the likely non-indigenous canopy-forming species *Sargassum furcatum* on the central-eastern coast of Sicily (Italy, Central Mediterranean). This species was described for St. Thomas (Virgin Islands), and it was reported for the first time in the Mediterranean in 1995 in the Chafarinas islands (Spain, western Mediterranean). After the first report, this species was found in 2021 in several sites located along the eastern coast of Sicily (Italy), along the French Mediterranean coastline, in Corsica, and recently also in the Aeolian Islands (Italy). No phenological studies on this species have been ever carried out in the Mediterranean Sea. To conduct this study, a visual census activity was performed in three sites along the Ionian coast of Sicily throughout 2023, during which the length of the main axis of *S. furcatum* specimens was measured and the frequency of findings of the species during the year was noted. In this study, it was observed that *S. furcatum* shows a wide adaptability in terms of range of depth, temperature, light exposure, and type of substrate. Since the distribution of this species is mostly centralized in the western Atlantic Ocean, it is likely that *S. furcatum* entered the Mediterranean through the Gibraltar Strait. Consequently, the entrance of this species in this Basin could be further proof of the ongoing seawater warming and tropicalization of Mediterranean waters. From this point of view, it is important to keep monitoring the dynamics of *S. furcatum* in the Mediterranean Sea in order to understand its putative impacts on autochthonous communities.

Keywords: canopy-forming species; community shift; non-indigenous species; seawater warming; tropicalization

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1. Introduction

Along the temperate rocky coasts, the canopy-forming species of the order Fucales represent dominant keystone species in unpolluted marine habitats [1–3]. They are ecosystem engineers, which thanks to the structural tridimensionality of their frond, offer shelter, food, and nurseries for a wide range of species [4]. Moreover, being crucial primary producers, they support diversified functional compartments and trophic levels [2,3,5].

In the Mediterranean Sea, fucoid species are mainly represented by the genera *Cystoseira sensu lato* (*s.l.*) (i.e., *Cystoseira* C. Agardh *sensu stricto*, *Ericaria* Stackhouse, and *Gongolaria* Boehmer) and *Sargassum* C. Agardh. Although *Sargassum* species contribute with the *Cystoseira* complex to the elevated photophilic layer of the macrophytobenthos, so far in the Mediterranean, most studies have focused on *Cystoseira s.l.* species, while *Sargassum* species have been scarcely studied, mostly due to the difficulties in identifying these species, in the absence of all diacritical characters (e.g., receptacles, aerocysts, foliose branches) [4].

Species of this genus are perennial (rarely annual) canopy-forming macroalgae [4], which develop fronds with receptacles that bear reproductive conceptacles. *Sargassum* species can be monoecious or dioecious, and conceptacles are unisexual or hermaphrodite. Fertilization normally occurs externally on or near parent plants, and zygotes develop still attached to the outside part of receptacles by a mucilage envelope or mucilage stalks [3].

Sargassum species present the highest biodiversity at tropical latitudes [6], where they form extensive beds in subtidal coastal environments [7]. The genus *Sargassum* comprises 537 species worldwide, of which 356 are taxonomically accepted [8]. Indeed, within this genus, there is an extensive intra- and interspecific morphological variation [9] that has led to the description of many morphology-based species and infra-species taxa [10]. Nevertheless, recent molecular-based systematic studies have shown that the actual species diversity is smaller than previously believed [11]. In the Mediterranean Sea, only nine species were reported [12,13]: *Sargassum acinarium* (Linnaeus) Setchell, *S. desfontainesii* (Turner) C. Agardh, *S. flavifolium* Kützing, *S. furcatum* Kützing, *S. hornschuchii* C. Agardh, *S. muticum* (Yendo) Fensholt, *S. ramentaceum* Zarmouth and Nizamuddin, *S. trichocarpum* J. Agardh and *S. vulgare* C. Agardh nom. illeg. Nevertheless, the validity and taxonomic status of some of these species are still uncertain due to the lack of molecular data [13]. Hitherto, *S. hornschuchii*, *S. ramentaceum* and *S. trichocarpum* are considered Mediterranean endemic species; *S. acinarium*, *S. desfontainesii*, and *S. flavifolium* are species with distribution in both the Mediterranean and the Atlantic; *S. vulgare* is a cosmopolitan species; *S. muticum* is a non-indigenous species native of Japan, which was introduced via oyster aquaculture in western Europe and the Mediterranean Sea; and finally, *S. furcatum* is a species that was recently found in the Mediterranean Sea and is present in both the western Atlantic and the Pacific Ocean [8,13,14]. This species was described for St. Thomas, Virgin Islands [15], and it was reported for the first time in the Mediterranean in 1995 in the Chafarinas islands (Spain, western Mediterranean) at 12 m of depth by Flores-Moya and Conde [16]. After the first report, this species was found in 2021 in several sites located along the eastern coast of Sicily (Italy, Central Mediterranean): Acque Fredde, Scalo Pennisi, and Santa Maria La Scala (Acireale, Catania) [14]. Moreover, it was reported in two sites along the French Mediterranean coastline and Corsica [17], and recently, its occurrence was documented also in the Aeolian Islands [18].

Considering the provenance of this species, as well as the fact that it was recently found for the first time in areas widely studied in the past (e.g., Italy and France), it might be assumed that the species is non-indigenous [18]. Moreover, due to its distribution mostly in the Atlantic Ocean, it is likely that *S. furcatum* entered the Mediterranean through the Strait of Gibraltar, and it was transported to the abovementioned areas by drifting through the currents or by anthropogenic vectors (e.g., ballast waters). Along the eastern coast of Sicily, this species appears to have an expanding trend. Indeed, the finding of fertile individuals both along the Ionian coasts of Sicily and in the Aeolian Archipelago could demonstrate that *S. furcatum* is establishing reproductive and, possibly, self-sustaining populations in the Mediterranean Sea [14,18]. However, the putative impact of *S. furcatum* on the autochthonous benthonic communities has not yet been evaluated.

As concerns the ecology of this species, there is only scant information in the literature. In the native area, this species was frequently observed in shallow waters on rocky or sandy substrates. In the Mediterranean, this species has been found in both shallow and deep waters, but always on rocky and sandy seabed (Table 1).

Even more limited are the data regarding the phenology of *S. furcatum*. Indeed, the sole study that reported phenological information on this species is that by Godoy and Coutinho [19], who stated that in Brazil, this fucoid has a gradual increase in the average length from spring to late summer, and minimum height values during the winter months. In the Mediterranean, no phenological studies on *S. furcatum* have been ever carried out, but they are needed to understand the potential impact of this non-native species on native ecosystems.

The aim of this study is to provide new insights regarding the ecology of *S. furcatum* and its phenological variations in terms of the average length of the main axis, frequency, and reproductive period during the year, along the eastern coast of Sicily, where this species was previously reported.

Table 1. Areas, range of depth and type of substrate, where the presence of *Sargassum furcatum* was reported.

Locality	Depth (m)	Substrate	Reference
Atlantic Ocean			
Virgin Islands and Antilles	-	-	[20]
Venezuela	-	-	[21]
Salvage Islands	-	-	[22]
Cuba	2–4	Rocky	[9,23]
Brazil	1–5	Sandy	[19,24,25]
Trinidad and Tobago	-	-	[26]
Mexico	-	-	[27,28]
Canary Islands	-	-	[29]
Madeira	-	-	[30]
Costa Rica	0–1.5	Rocky and sandy	[31]
Azores	-	-	[32]
Puerto Rico	Up to 17	-	[33]
Pacific Ocean			
Philippines	-	-	[34]
Mediterranean Sea			
Spain	12	-	[16]
Italy	4–28	Rocky and sandy	[14,18]
France and Corsica	Upper and medium infralittoral	-	[17]

2. Materials and Methods

This study was performed throughout 2023 in three areas located along the eastern coast of Sicily (Figure 1A): Santa Maria La Scala (37°36′46.5″ N–15°10′31.4″ E), Acque Fredde (37°38′15.7″ N–15°10′52.1″ E) and Scalo Pennisi (37°38′23.2″ N–15°11′04.6″ E). These areas are located in the northern sector of the Ionian coast of Sicily (Figure 1B). The first site, Santa Maria La Scala, is located in the Timpa Nature Reserve, a protected area extending on the emerged part of the Acireale (Catania) coastal strip. The Timpa Nature Reserve encompasses a coastal slope that extends for 6 km. The sea floor of Santa Maria La Scala resembles the morphology of the Timpa, being a rocky steep slope extending to a depth range of 20–30 m [35]. Acque Fredde and Scalo Pennisi are two nearby areas, which are characterized by a similar bottom topography with a rocky slope that begins at a 10–15 m depth and ends at about 30 m [36]. The sea bottom of these areas consists of basaltic bedrock locally covered with large volcanic blocks and hosts the Biocoenosis of the Infralittoral Algae (IA) [36]. In these areas, *Sargassum furcatum* is distributed as isolated specimens or small patches of 3–4 individuals.

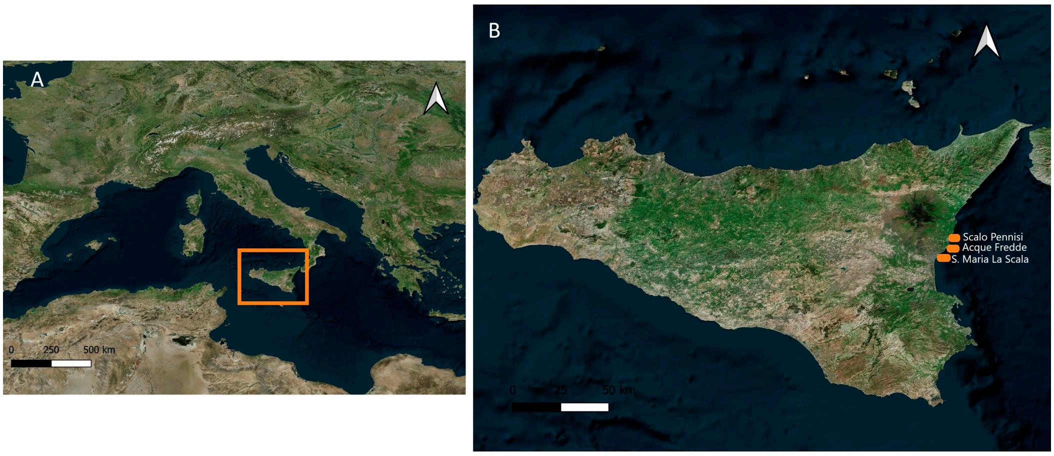

Figure 1. Geographical location of the study area in the Mediterranean Sea: (**A**) Sicily (Italy); (**B**) investigated sites located along the central-eastern coast of Sicily.

This study was performed through an underwater visual census viz. random courses [37] conducted by taking photos of the encountered specimens of *S. furcatum* during scuba dives. The dives, lasting one hour and a half, were performed in a range of depth of 0–30 m (according to the seabed geomorphology) once a month, always following the same pathway. Each specimen of *S. furcatum* encountered was photographed with an Olympus TG-6 underwater camera. For each month, the length of the main axis of five specimens was measured using a ruler for a total of n = 15 individuals for the three sites. Moreover, at the end of each dive, the total number of the found specimens was counted in order to estimate their frequency during the year. Moreover, the depth and temperature were recorded where specimens were found, and the occurrence or not of receptacles was noted.

A two-way ANOVA design was applied to evaluate the differences in the average length of the main axis (cm) and frequency of findings of *S. furcatum* throughout the year among the study areas. The frequency was expressed as the number of individuals per dive. The most significant terms ($p < 0.05$) were examined through Tukey's pairwise post hoc test. Moreover, the Chi-Square (χ^2) test of independence was used to check whether there was a significant association between the size distribution frequencies and the study areas.

Statistical analyses were performed using Jamovi version 2.3.

3. Results

3.1. Description of the Studied Specimens

The specimens encountered during this study exhibited both a creeping and erect habit (Figure 2A,B). They usually showed a blue iridescence in situ (Figure 2C). Thalli were attached to the substrate by a basal disc, from which a short, smooth, or knotty axis took origin. Primary branches and secondary branches were cylindrical and knotty; they were usually arranged in a fan shape (Figure 2D). The apex was smooth and slightly prominent (Figure 2E). Primary and secondary branches brought foliose lanceolate or lobate branches with a pronounced central midrib, toothed or wavy margins, and an acute apex. The blades were dichotomously divided between one and four times, with the midrib following the bifurcation of the branches (Figure 3A). Aerocysts were rarely observed during this study. When present, they were spherical, smooth, borne on a short pedicel, and were distributed at the apical portion of the thallus (Figure 3B). Cryptostomata were usually sparse on both sides of the midrib. Receptacles were warty, cylindrical, and borne on a short pedicel. They were usually branched, forming a bunch at the axilla of the foliose branches (Figure 3C).

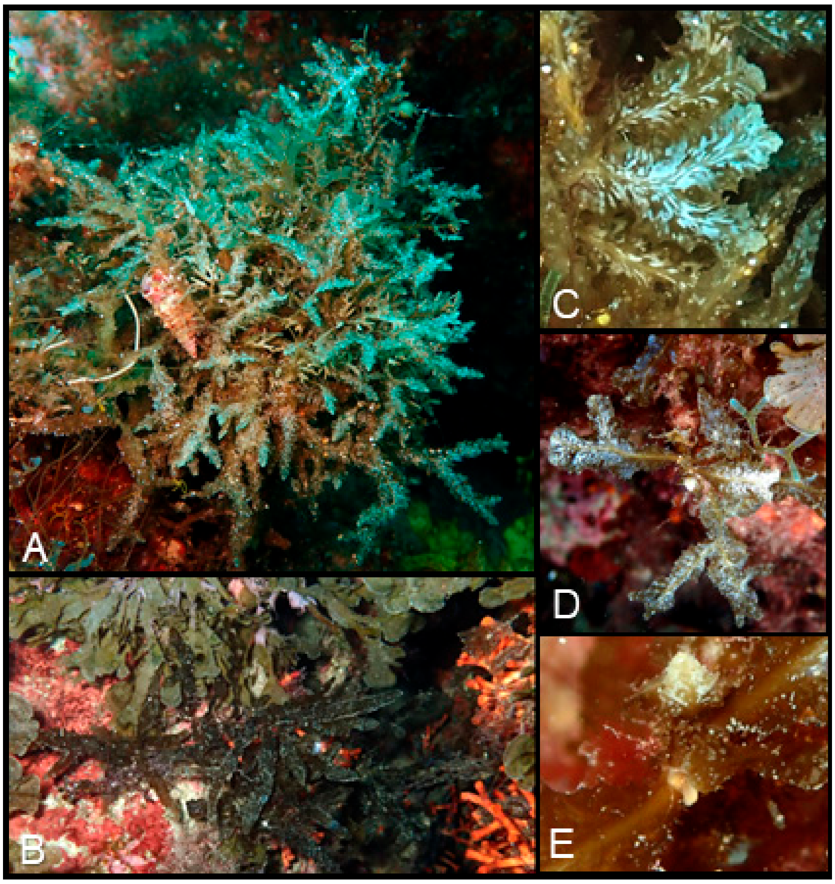

Figure 2. *Sargassum furcatum* in the study areas. (**A**) erect habit; (**B**) creeping habit; (**C**) iridescence on the foliose branches; (**D**) fan-shape arrangement of branches; (**E**) smooth apex.

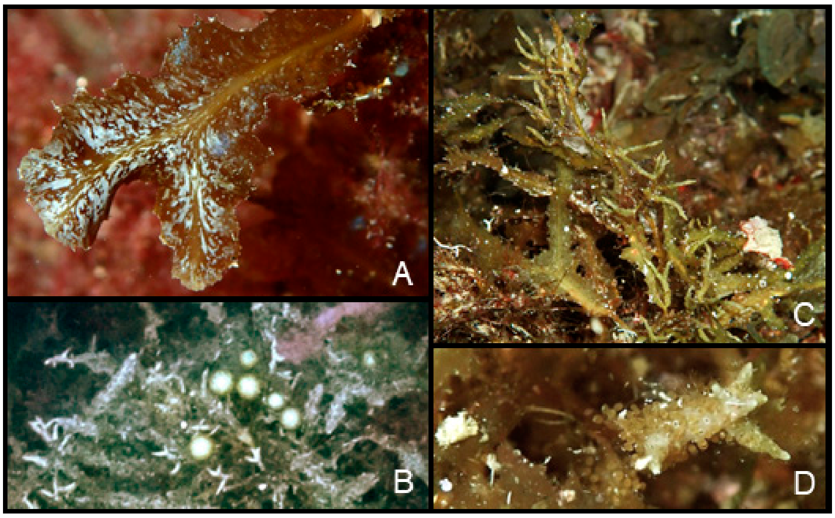

Figure 3. *Sargassum furcatum* in the study areas. (**A**) midrib that follows the bifurcation of the branches; (**B**) spherical aerocysts; (**C**) receptacles; (**D**) zygotes and embryos attached to the receptacles.

During the reproductive season, we observed receptacles frequently with a wrinkled aspect due to the high presence of zygotes and embryos, which remained attached to them (Figure 3D).

3.2. Habitat and Distribution

During this study, *Sargassum furcatum* was observed at depths from 4.6 to 29.3 m, but the most frequent depth range was 21–25 m (Figure 4). The range of temperature where this fucoid was observed is from 14 to 23 °C.

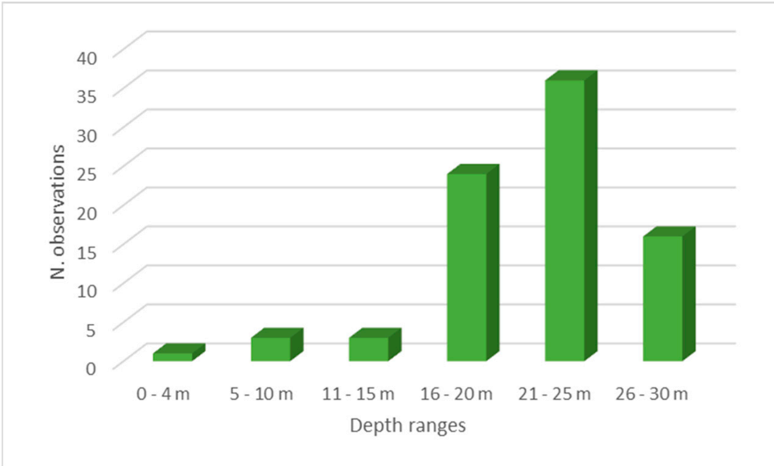

Figure 4. Frequency of observation of *Sargassum furcatum* in the different depth ranges.

During this study, this fucoid was found growing both in well-lit environments, on rocks exposed to light, and in more shaded areas (e.g., in crevices). In these last environments, specimens were more elongated and showed a few aerocysts in the apical portion (Figure 5A). *S. furcatum* specimens were more frequently distributed on hard substrates, but sometimes they were also encountered on sandy substrates (Figure 5B). The habitat where most of the specimens were observed was characterized by macroalgae of deep and shaded waters, e.g., *Zonaria tournefortii* (J. V. Lamouroux) Montagne (Figure 5C,D). In the study areas, *S. furcatum* was frequently associated with the canopy-forming species *Ericaria zosteroides* (C. Agardh) Molinari and Guiry (Figure 5D).

Figure 5. Habitat and distribution of *Sargassum furcatum* in the study areas. (**A**) a specimen in a low-light environment; (**B**) a specimen on sandy substrate; (**C**) a specimen with *Zonaria tournefortii*; (**D**) a specimen with *Ericaria zosteroides*.

3.3. Phenology of *Sargassum furcatum* during the Year

A two-way ANOVA analysis showed that there was a significant difference in the average length of the main axis according to the site ($p = 0.009$) and month ($p = 0.03$), but not according to the two crossed factors of site × month ($p = 0.1$). Tukey's post hoc test showed that the most significant differences were between Scalo Pennisi and S. Maria La Scala ($p = 0.009$) and Acque Fredde and S. Maria La Scala ($p = 0.02$). The site with the highest values for average length was Scalo Pennisi (5.51 ± 2.09 cm), followed by Acque Fredde (4.53 ± 2.04 cm) and S. Maria La Scala (2.81 ± 0.72 cm) (Figure 6A).

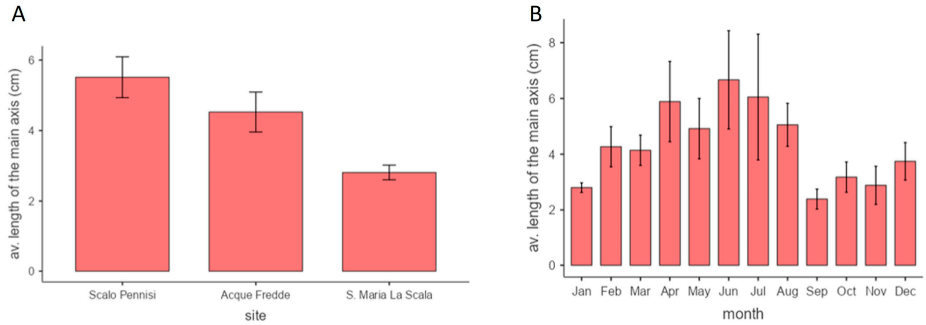

Figure 6. Average length of the main axis of *Sargassum furcatum* in the three sites (**A**) and throughout the year (**B**). Data are expressed as mean ± standard deviation.

As concerns the trend of the average length of the main axis during the year, the highest values were observed during the spring and summer months, while during autumn, there was a decrease, and at the beginning of winter, there was a new increase (Figure 6B).

In all the study areas, the reproductive period of *S. furcatum* was observed from June to August. In particular, July was the period with the highest fertility of the species; indeed, as abovementioned, it was possible to observe a high number of zygotes and embryos still attached to the receptacles (Figure 3D).

3.4. Frequency of *Sargassum furcatum* during the Year

As regards the frequency of finding, the ANOVA test showed a significant effect of site, month, and site × month on this parameter ($p < 0.001$). Tukey's post hoc test revealed significant differences among the sites ($p < 0.001$). The highest frequency of findings was observed at Scalo Pennisi (9.38 ± 5.9 individuals per dive), followed by Acque Fredde (4.88 ± 2.79 individuals per dive) and S. Maria La Scala (2.71 ± 2.16 individuals per dive) (Figure 7A). As concerns the frequency of findings during the year, the highest number of specimens per dive was observed from March to May; then, during the summer, there was a decline until the beginning of autumn, and from November, there was a slight growth (Figure 7B).

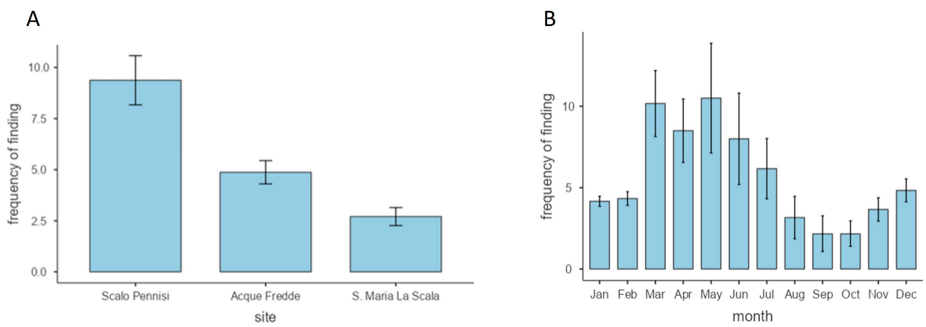

Figure 7. Frequency of finding of *Sargassum furcatum* in the three sites (**A**) and throughout the year (**B**). Data are expressed as mean ± standard deviation.

3.5. Size Distribution Frequencies

The Chi-Square test of independence revealed a significant association between the size distribution frequencies and the three study areas ($\chi^2 = 13.6$; $p = 0.001$). Indeed, contrary to the other sites, at Scalo Pennisi, larger sizes classes (e.g., 8 and 10 cm) were detected. Moreover, at Scalo Pennisi, the most frequent size class was 6 cm, while at Acque Fredde, it was 4 cm, and at S. Maria La Scala, it was 3 cm (Figure 8).

Figure 8. Size distribution frequencies of *Sargassum furcatum* in the study areas: Scalo Pennisi, Acque Fredde, S. Maria La Scala.

4. Discussion

Through this study, we investigated the ecology and phenology of *Sargassum furcatum* along the central-eastern coast of Sicily, where this species was reported for the first time in 2021. The visual census activity, performed throughout 2023, allowed us to follow the phenological variations of this species during the year. In particular, it was observed that the average length of the main axis grows from April to June. Then, it begins to decrease during the summer, and from October to March it remains almost stable. The highest number of specimens was observed from March to May, with a gradually decreasing number from June to October and a slight increase from November to February. As concerns the reproductive period, in the study areas, this species is fertile from June to August, with the maximum fertility observed in July. The reproductive period observed during this study aligns with that reported by Blanfuné et al. [17] for the same species in France and Corsica, and for other *Sargassum* species present in Sicily [18,38].

Among the study areas, the site that showed the highest values in the average length of the main axis and largest size classes was Scalo Pennisi, followed by Acque Fredde and S. Maria La Scala. Moreover, as concerns the frequency of *S. furcatum* during the year, the site that showed the highest number of specimens per dive was Scalo Pennisi. At this site, the most frequent size class was 6 cm, whereas at Acque Fredde it was 4 cm and at S. Maria La Scala it was 3 cm. Therefore, despite the proximity of the study areas, there is heterogeneity in both the distribution of size classes and the frequency of *S. furcatum* during the year. As observed for another deep fucoid species, *E. zosteroides*, this variability could be connected to different environmental factors, even at a small scale [39]. From a hydrogeological standpoint, the Ionian coast of Sicily is affected by the tidal currents of the Strait of Messina and the upwelling currents of the Ionian Sea. Moreover, the coastal morphology determines local variations in the general current regime, with multiple eddies characterized by marked directional instability [35]. As also observed for *E. zosteroides* populations present in the same sites [40], these factors create microhabitats. This could explain why *S. furcatum* shows a wide adaptability in the study areas, in terms of range of depth, temperature, light exposure, and type of substrate. Nevertheless, this fucoid seems to prefer deeper areas characterized by hard substrates and scarce light irradiance—a type of environment that is dominant at Scalo Pennisi, where *S. furcatum* reaches higher size classes and is more frequent during the year. Moreover, another possible reason for this difference in the size class distribution among the study areas could be related to the current's direction, which is southernly, deriving from the Strait of Messina [41]. This results in a decreasing size distribution frequency from north to south, as seen above. Furthermore, this current's direction could have determined the spread of *S. furcatum* from the northernmost site (Scalo Pennisi) to the southernmost site (S. Maria La Scala).

As for many other species of *Sargassum* recorded from the Mediterranean Sea [13], as well as for *S. furcatum*, molecular studies are necessary to confirm the correct identification of Mediterranean specimens. Indeed, there are other little-studied taxa that show similar morphological features, such as *Sargassum diversifolium* (Turner) C. Agardh, currently known only from the Red Sea [42]; it was described for Egypt by Turner as *Fucus diversifolius* Turner ([43], p. 103), without specifying whether it was present on the Mediterranean coast. Moreover, it should be noted that Blanfuné et al. [17] and Boudouresque et al. [44] erroneously reported for the Mediterranean also *Sargassum vulgare* f. *diversifolium* Grunow, a taxon described for the Canary Islands, the Azores Islands, and the Island of Madeira [45], based on not-documented records.

The apparent establishment in the Mediterranean Sea of *S. furcatum*, an Atlantic species with warm affinity (see Table 1), which entered the Mediterranean through the Straits of Gibraltar, could be further proof of ongoing seawater warming and the tropicalization of Mediterranean waters. The tropicalization process promotes the disappearance of temperate species and their substitution with tropical ones [46]. Moreover, the synergistic effects of global warming and anthropogenic pressures enhance regime shifts, compromising temperate benthic ecosystem structure [47]. From this point of view, *S. furcatum* could represent a possible threat to the autochthonouscanopy-forming species, which are currently in a regressing status [48]. The foreseen warming scenario could favor the expansion of many *Sargassum* species, and the possibility that they will become part of the temperate environments is most likely [49]. The replacement of the temperate canopy-forming species by tropical *Sargassum* species could cause a community shift (in terms of composition and structure) and produce new opportunities for the arrival of other non-indigenous species [49]. Nevertheless, these species could create new ecological niches and habitats, where canopy-forming species are completely lost, as in many Mediterranean areas. From this perspective, it is crucial to keep monitoring the dynamics of *S. furcatum* in the Mediterranean Sea, to deepen our knowledge of its potential expansion in view of the foreseen warming scenario and be able to understand its putative impacts on autochthonous communities.

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