







## Article

# Outstanding Aggregation of the Atlantic Brisingid *Hymenodiscus coronata* (Sars, 1871) (Echinodermata: Asteroidea) in the Strait of Sicily

Margherita Toma<sup>1,2,\*</sup> , Antonio Giova<sup>3,4</sup> , Marzia Bo<sup>1,2,5</sup> , Simonepietro Canese<sup>3</sup> , Francesco Enrichetti<sup>1,2</sup>, Teresa Romeo<sup>6,7</sup>, Eva Salvati<sup>3</sup>  and Silvestro Greco<sup>8</sup> 

- <sup>1</sup> Dipartimento di Scienze della Terra dell'Ambiente e della Vita (DISTAV), Università di Genova, 16132 Genova, Italy; marzia.bo@unige.it (M.B.); francesco.enrichetti@edu.unige.it (F.E.)
  - <sup>2</sup> National Biodiversity Future Center (NBFC), 90133 Palermo, Italy
  - <sup>3</sup> Department of Integrative Marine Ecology, Stazione Zoologica Anton Dohrn, 00189 Rome, Italy; antonio.giova@studenti.unime.it (A.G.); simonepietro.canese@szn.it (S.C.); eva.salvati@szn.it (E.S.)
  - <sup>4</sup> Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, University of Messina, 98166 Messina, Italy
  - <sup>5</sup> Consorzio Nazionale Interuniversitario per le Scienze del Mare (CoNISMa), 00196 Rome, Italy
  - <sup>6</sup> Department of Biology and Evolution of Marine Organisms, Stazione Zoologica Anton Dohrn, Sicily Marine Centre, 98057 Milazzo, Italy; terese.romeo@szn.it
  - <sup>7</sup> ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale), National Institute for Protection and Environmental Research, 98057 Milazzo, Italy
  - <sup>8</sup> Department of Integrative Marine Ecology, Stazione Zoologica Anton Dohrn, Calabria Marine Centre, 87071 Amendolara, Italy; silvestro.greco@szn.it
- \* Correspondence: margherita.toma@edu.unige.it

**Abstract:** The sea star *Hymenodiscus coronata* is the only Mediterranean representative of the deep-sea order Brisingida. In the North-eastern Atlantic Ocean, this species is known to create dense aggregations, while, in the Mediterranean basin, it is generally reported as scattered individuals. Through the analysis of the video footage obtained from an extensive ROV campaign carried out in the northern Strait of Sicily in 2021, over 2850 specimens were counted. The specimens, observed between 310 m and 714 m depth, showed a large variability in size and number of arms. It was noted that 17% of the specimens displayed the peculiar “sail position”, with all the arms extended vertically in the water column, possibly increasing the filtration rate. Almost the totality of the individuals was noted on soft bottoms, in accordance with the ecological preferences of the species. The density of *H. coronata* in each site varied between 0.01 and 0.81 individuals m<sup>-2</sup>, with the highest densities reported in sites characterized by large muddy areas among rocky outcrops and turbulent hydrodynamic conditions. Although the trawling areas exploited in 2021 did not seem to interfere with the presence of *H. coronata* in the study area, a precautionary approach should be assumed to protect the largest ever reported Mediterranean aggregation of this poorly known species.

**Keywords:** sea star; population density; ecology; ROV; Sicily Channel



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## 1. Introduction

Mediterranean echinoderms represent 2.2% of the global echinoderm diversity, with 154 species recorded until 2010 [1]. Most of the known species reside in shallow environments, while there is still a substantial knowledge gap of deep-sea echinoderms species, especially in the southern and eastern regions of the basin [1–3]. The recent expansion in scientific interest and sampling efforts in deep-sea environments, coupled with advancements in the technologies involved in the explorations, has led to a continuous increase in our understanding of the biodiversity and ecology of deep-sea communities, including the echinoderm fauna [3,4].

The spatial distribution pattern of echinoderms can vary depending on several factors, including the environmental conditions, intra- and inter-specific interactions, the life cycle, and the availability of trophic resources [5]. While many echinoderms tend to occur as scattered individuals, some species can form extended populations with high abundances [3,6,7], which can have a significant impact on the structure and function of both shallow and deep environments [8,9]. In addition, temporary aggregative behavior can occur in the case of a localized high abundance of food or to increase fertilization success during breeding periods [10–12].

The sea stars of the order Brisingida Fisher, 1928 typically inhabit deep-sea ecosystems, from tropical waters to polar regions, both living solitarily or forming dense aggregations at favorable conditions [13,14]. Brisingids are characterized by a small circular disk and multiple slender arms equipped with spines for catching food particles from the water column, resembling the morphology of some ophiuroids and crinoids [13–15]. The Atlantic Ocean hosts twenty-three species of Brisingida [16], among which *Hymenodiscus coronata* (Sars, 1871) is the only one reported in the Mediterranean Sea. This species is present on the muddy plains of the basin from around 70 m up to a 2904 m depth [1,2,17,18]. It is characterized by 9–12 orange to reddish arms, up to 30 cm long [2]. The first description of the species was based on a specimen collected between a 200 and 300 m depth off Vestfjord (Norway), classified as *Brisinga coronata* by Sars (1871) [19]. Fisher (1917) re-assessed the diagnostic features reported in the original description, including the species in a new genus, *Brisingella* [20]. At the end of the century, Mah conducted a cladistic analysis on the order Brisingida, leading to a synonymizing of the genera *Brisingella* and *Hymenodiscus* Perrier, 1884, and, consequently, located the species to its final taxonomic position [21].

Most of the information on the distribution of this species comes from trawling surveys. It has been documented from the North-eastern Atlantic Ocean, from Norway to the Canary Islands [22,23], and throughout the Mediterranean Sea, both in the western and the eastern basins [2,24–29].

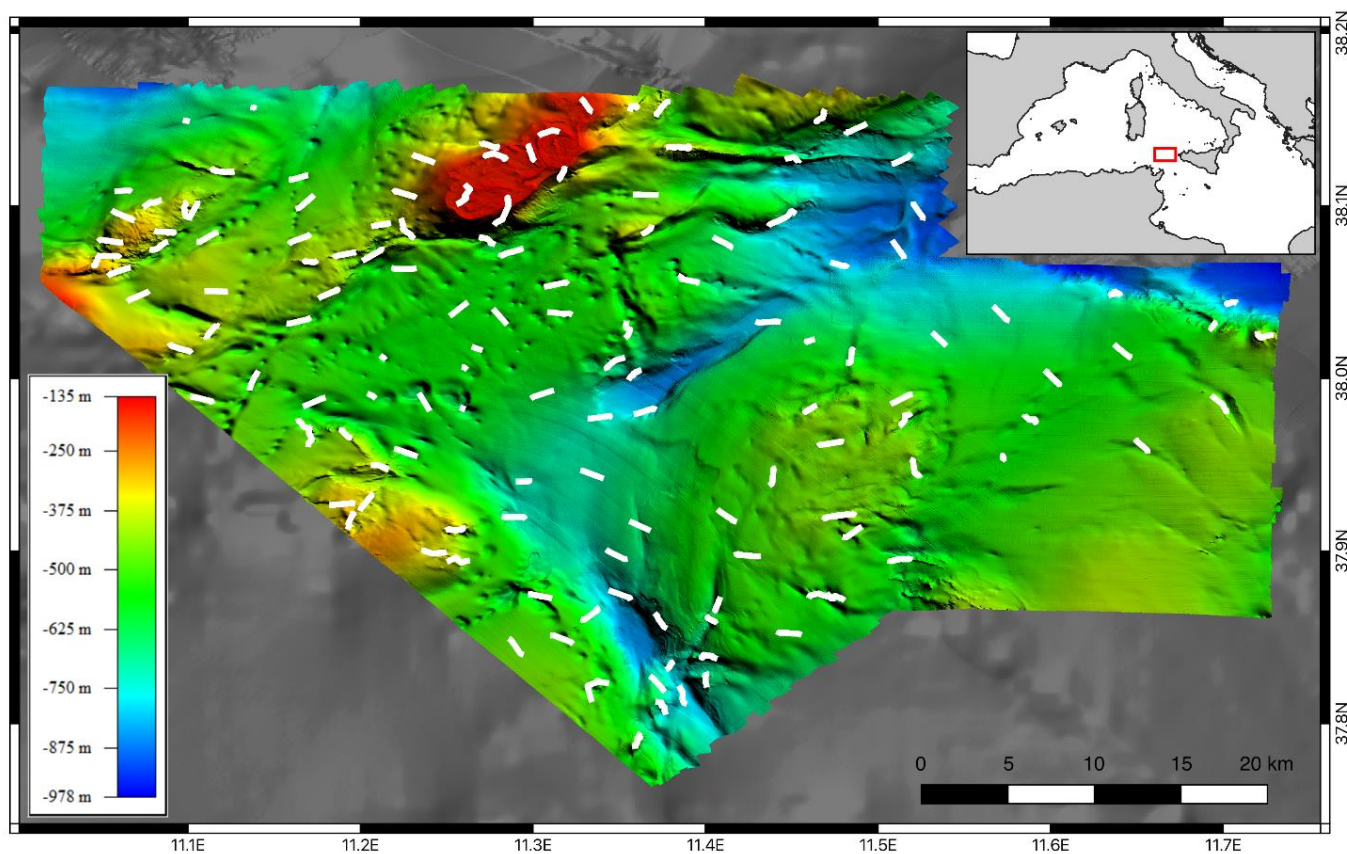
The species reaches the maximum densities in the Norwegian fjords, where populations of up to 3 individuals m<sup>-2</sup> have been reported [30], while, in the Mediterranean Sea, it usually occurs as scattered individuals [2,3,24,28,31]. Nevertheless, Massi and Titone reported the species as characteristic (*sensu* Pérès and Picard, 1964) in the trawling bycatch of the Strait of Sicily, even if the abundance values were never indicated in the reports [26,32,33]. This area constitutes an important crossroad between the western and eastern Mediterranean basins, playing a crucial role in the bi-directional flow of water masses and marine species [34,35]. The thermohaline circulation strongly influences the Strait of Sicily, with the eastward flow of the Modified Atlantic Water (MAW) in the upper layer (<200 m depth) and the westward flow of the deeper layers consisting of Levantine Intermediate Water (LIW) and a vein of the transitional Eastern Mediterranean Deep Water (tEMDW) [36,37]. The complex seabed morphology, including ridges, plateaus, canyons, and seamounts, further affects the current flow by causing upwelling and shallow mesoscale eddy structures [38,39]. These geological and hydrodynamic features lead to a high ecological diversity, making the Strait of Sicily one of the most significant biodiversity hotspots in the Mediterranean Sea [40].

An ROV-based exploration conducted in 2021 in the northern sector of the Strait of Sicily reported a large population of the Atlantic brisingid *H. coronata*, providing a rare opportunity to study this kind of aggregation. The present study aims to provide a detailed characterization of this population, assessing its geographic and bathymetric distribution, morphological variability, ecological preferences, and vulnerability.

## 2. Materials and Methods

A total of 140 ROV transects (each corresponding to a different site) were carried out in the northern part of the Strait of Sicily between 135 and 885 m depth (Figure 1). The surveys were performed from 15 September to 15 November 2021, by the MainportGeo vessel with a Tomahawk ROV Light Work Class. The ROV was equipped with two standard definition

cameras (for rear and frontal view), a high-definition camera, a ZCAM E2-F6 (EF) Full Frame 6 K Cinema with a Canon EF 16–35 mm f/2.8 L III USM lens (Z CAM, Shenzhen, China), two lights, two laser beams (20 cm-distanced), a Sonardyne Ranger 2 USBL underwater acoustic system (Sonardyne International Ltd, Yateley, United Kingdom), a multiparameter probe Seabird MicroCAT SBE 37 (Sea-Bird Scientific, Washington, DC, USA), and two hydraulic arms. The length of each transect was variable (ranging from 50 m to 2050 m; average length:  $929 \pm 257$  m), for a total of 129.5 km explored in about 406 h. The data-logging software OFOP (Ocean Floor Observation Protocol) (Version n° 11, License purchased 20 July 2021) [41] was used on board to record each observation with its corresponding information (date, time, geographic co-ordinates, and depth). The frequency of occurrence was defined considering the sites in which the species was reported with respect to the total. The depths at which each specimen was observed were used to create a boxplot to investigate the bathymetric distribution of the species. Multi-beam maps of the study area were obtained using a multi-beam echosounder Kongsberg EM2040 in shallower waters (from 150 to 300 m) and a Kongsberg EM710-MK2 in deeper waters (from 300 to 1000 m) (Kongsberg Discovery Simrad Bergen, Bergen, Norway).



**Figure 1.** Study area. Multi-beam bathymetric model (5 m resolution) of the explored area (Strait of Sicily, Central Mediterranean Sea, inset, red rectangle), with the 140 ROV transects (white lines).

At a later time, videos were analyzed using Apple’s Final Cut Pro X software (version 10.4) to collect more detailed information about the target species in each transect, namely, the size of the specimens (divided into three categories: small (smaller than 15 cm in diameter), medium (16–30 cm diameter), and large (>30 cm diameter)), the number of intact arms and the position on the seabed (divided into three categories: Plain (flat on the seafloor), Claw (with the arms partially lifted), and Sail (with the arms completely lifted to resemble a sail)), the type of substrate on which *H. coronata* were laying (in the categories: mud, coral rubble, and rock, including outcropping rocks and rocks constituted

by agglomerated white corals skeletons), and its inclination (horizontal ( $0^{\circ}$ – $20^{\circ}$ ), sloping ( $21^{\circ}$ – $80^{\circ}$ ), or vertical ( $81^{\circ}$ – $90^{\circ}$ )).

The possible differences among the three size groups and the position in which they were observed were verified by a Chi<sup>2</sup> test (Degrees of freedom = 4). All statistical analyses were performed using PAST Software version 4.03 [42].

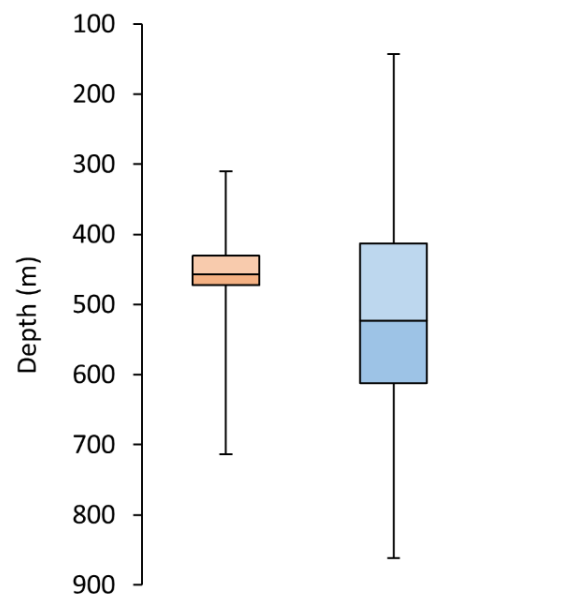
To determine the density of the populations and highlight the possible aggregations along the explored paths, the exact number of specimens in each transect was counted, and densities were calculated by dividing the transects into a string of adjacent 100 m<sup>2</sup> sampling units (SU).

To evaluate the possible impact of the fishing vessels operating in the considered area, data from the Automatic Identification System (AIS) regarding trawling efforts in 2021 were collected from the Global Fishing Watch free database (<https://globalfishingwatch.org>; accessed on 10 March 2024). The resulting raster of 1 km<sup>2</sup> resolution was cropped according to the area's footprint and processed to identify the fishing zones with at least one hour of trawling activity for 2021.

Finally, any interesting observation on the relationship of the target species with other benthic taxa has been noted.

### 3. Results

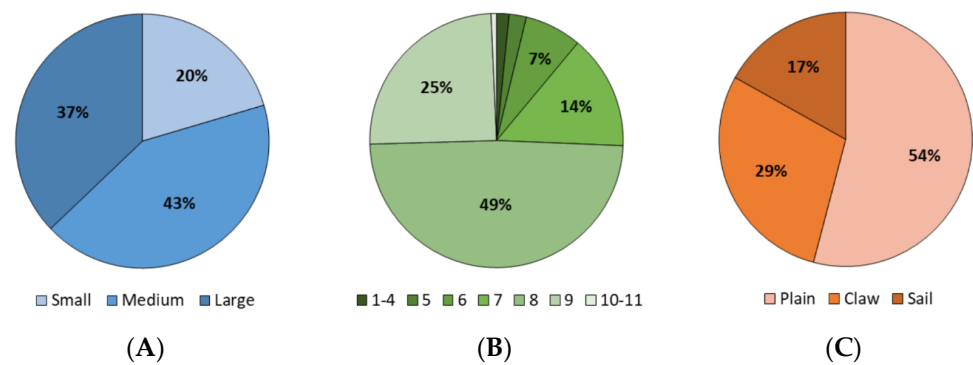
*Hymenodiscus coronata* was frequently encountered in the study area, being present in 34.3% of the explored sites, with 2852 specimens counted. Most of the specimens observed were reported in the northernmost part of the investigated area, occurring in a wide bathymetric range (310–714 m); however, maximum abundance was restricted to a narrower range, spanning from 431 m to 472 m (Figure 2).



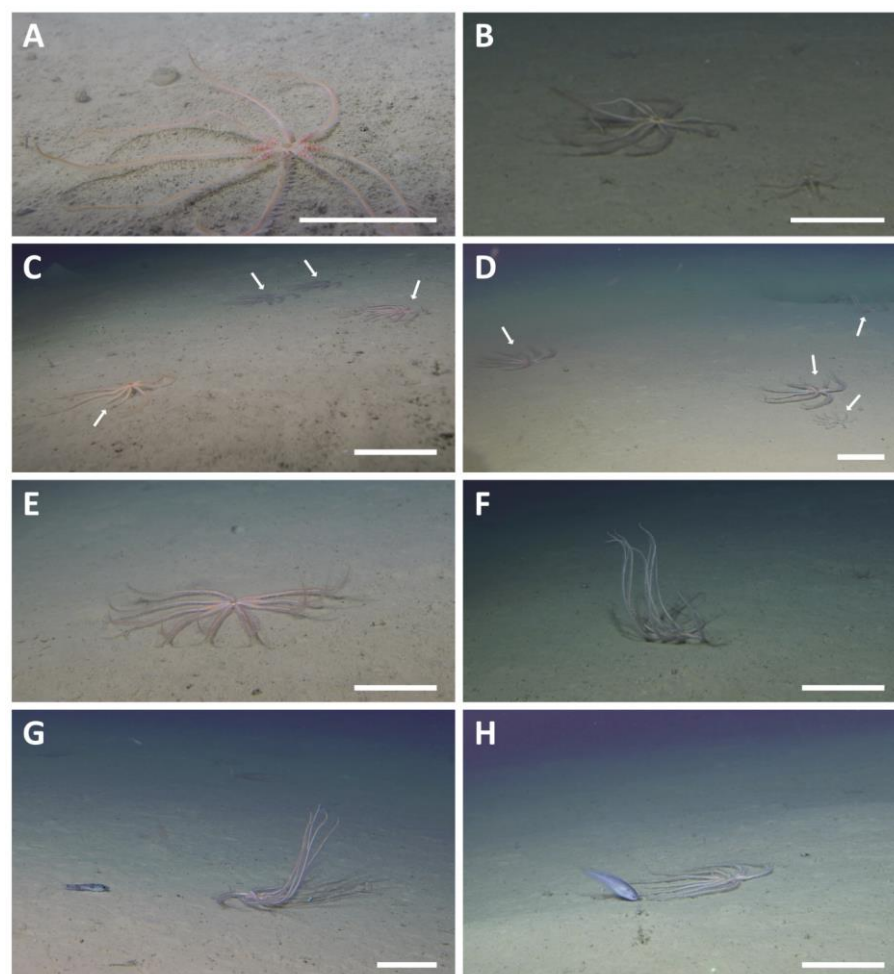
**Figure 2.** Bathymetric distribution. Boxplot of the bathymetric distribution of *Hymenodiscus coronata* in the present work (left, orange) and of the 140 ROV transects performed (right, blue).

The size varied between around 10 and 50 cm, with over 79% of the observed brisingids being larger than 15 cm in diameter (Figure 3A). The number of intact arms was highly variable, from one to eleven, even if almost 50% of the specimens had eight arms (Figures 3B and 4A,B). Moreover, many specimens showed arms of different sizes (Figure 4C).





**Figure 3.** Morphology. Frequency (%) of the target sea star *H. coronata* in terms of (A) size (Small, <15 cm; Medium, 16–30 cm; and Large, >30 cm), (B) number of intact arms, and (C) position on the seafloor.



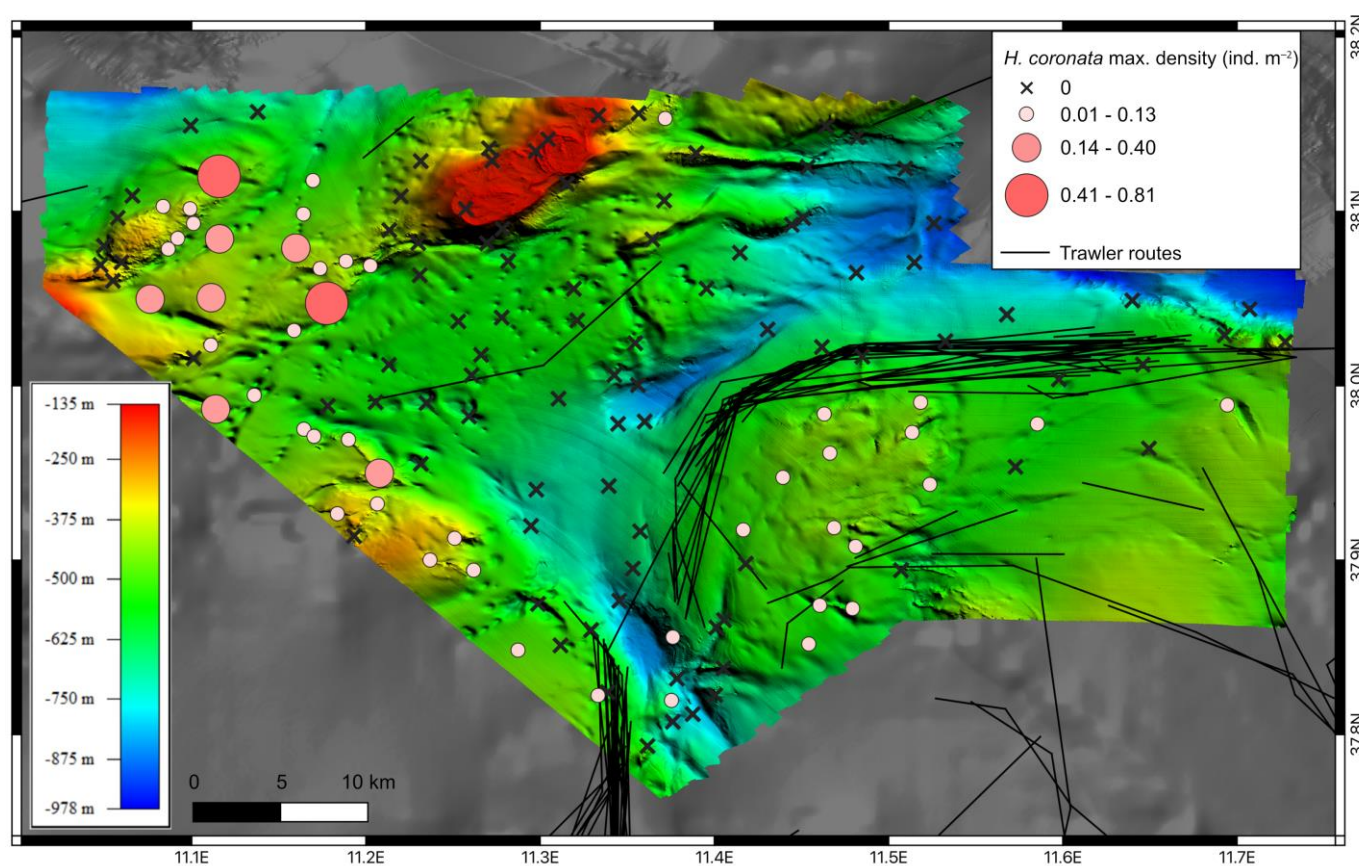
**Figure 4.** Morphology and ecology. ROV images of the sea star *H. coronata*: (A) close-up of a large specimen on mud, with well-visible spines on the eight slender arms and the gonads at the base of the arms; (B) two different-sized individuals with the arms slightly lifted; (C) several large specimens of *H. coronata* showing arms of different sizes flattened on the muddy bottom (white arrows); (D) close individuals of different size and number of arms (white arrows); (E) large specimen on the horizontal muddy substrate with the arms' tips lifted; and (F) *H. coronata* in the "sail position". (G,H) *Chlorophthalmus agassizi* and *Benthocometes robustus* are among the benthonektonic species frequently observed close to the target sea stars. Scale bar: 15 cm.

Most of the specimens were lying on the bottom with the arms flattened (54%), 29% had the arms partially risen, and 17% were observed with all the arms lifted in the "sail

position" (Figures 3C and 4D–F). Moreover, when considering the relationship between individual size and position, the percentages of specimens observed flat on the substrate or with the arms slightly lifted were very similar for the three considered size classes, varying between 52% and 62% and between 23% and 33%, for the "plain" and "claw" positions, respectively. On the other hand, the "sail pose" was performed by only 8% of the small-sized individuals against over 14% and 24% of the medium and large ones, respectively (result not shown). The relationship among size and position was statistically significant ( $\text{Chi}^2 = 93.7$ , degrees of freedom = 4,  $p = 0.0001$ ).

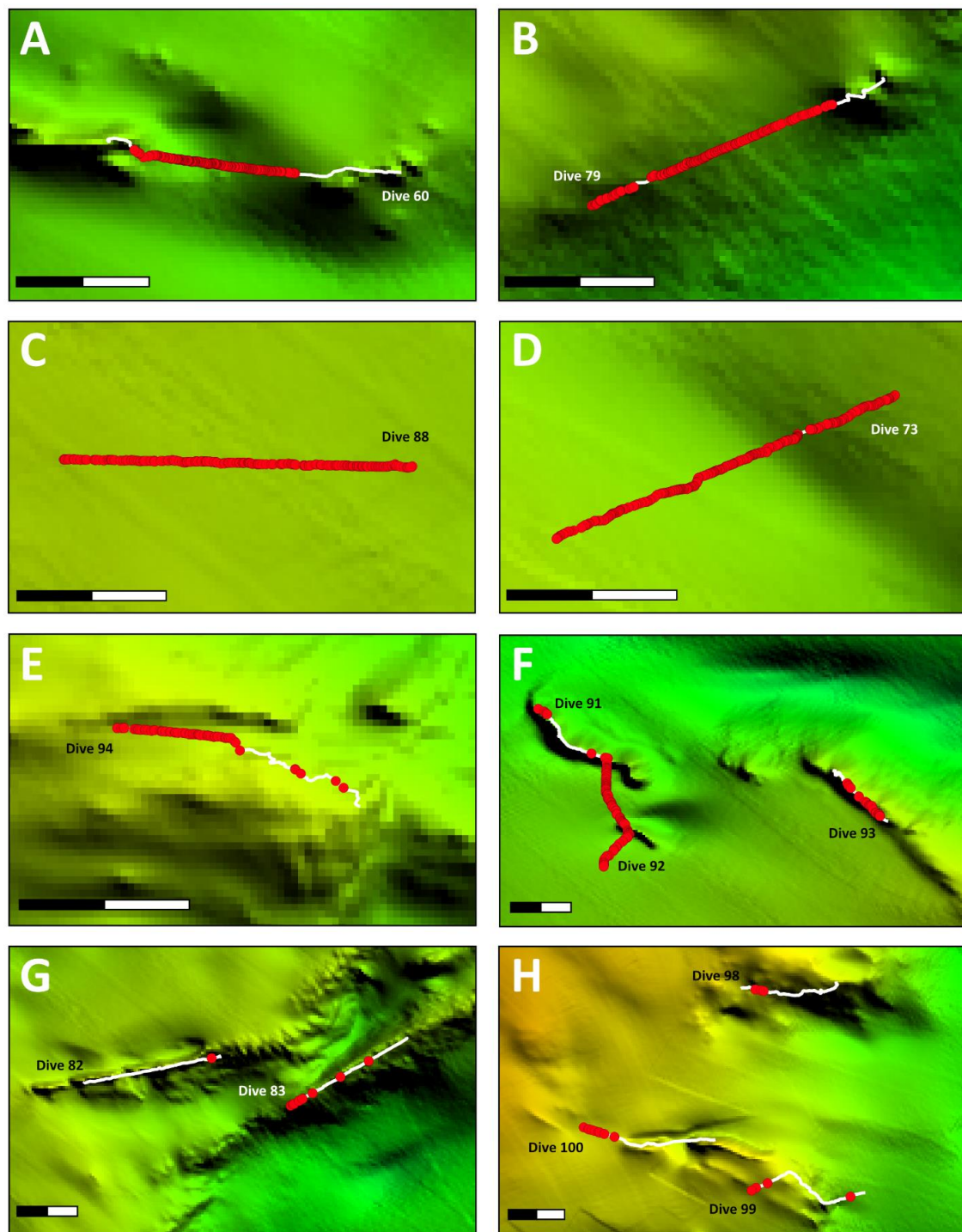
Regarding habitat preferences, almost all the individuals were observed on horizontal or moderately inclined muddy bottoms, on the flanks of small reliefs, or where the seafloor presented some roughness. In contrast, only ten individuals were reported on hard substrates, namely, coral rubble and silted rocks.

*H. coronata* occurred in 37.2% of the 1,001,100 m<sup>2</sup> SU delimited on the transects, with density varying between 0.01 and 0.81 individuals m<sup>-2</sup>. Considering only the SU where the asteroid was present, in 17%, the maximum density exceeded 0.14 individuals m<sup>-2</sup>. In eight SU (five in Dive 60, two in Dive 79, and one in Dive 73), it was higher than 0.4 individuals m<sup>-2</sup> (Figure 5).



**Figure 5.** Population density and fishing impact. Distribution of the transects in which *H. coronata* was observed, with the indication of the maximum density per sampling unit and the trawling areas exploited in 2021.

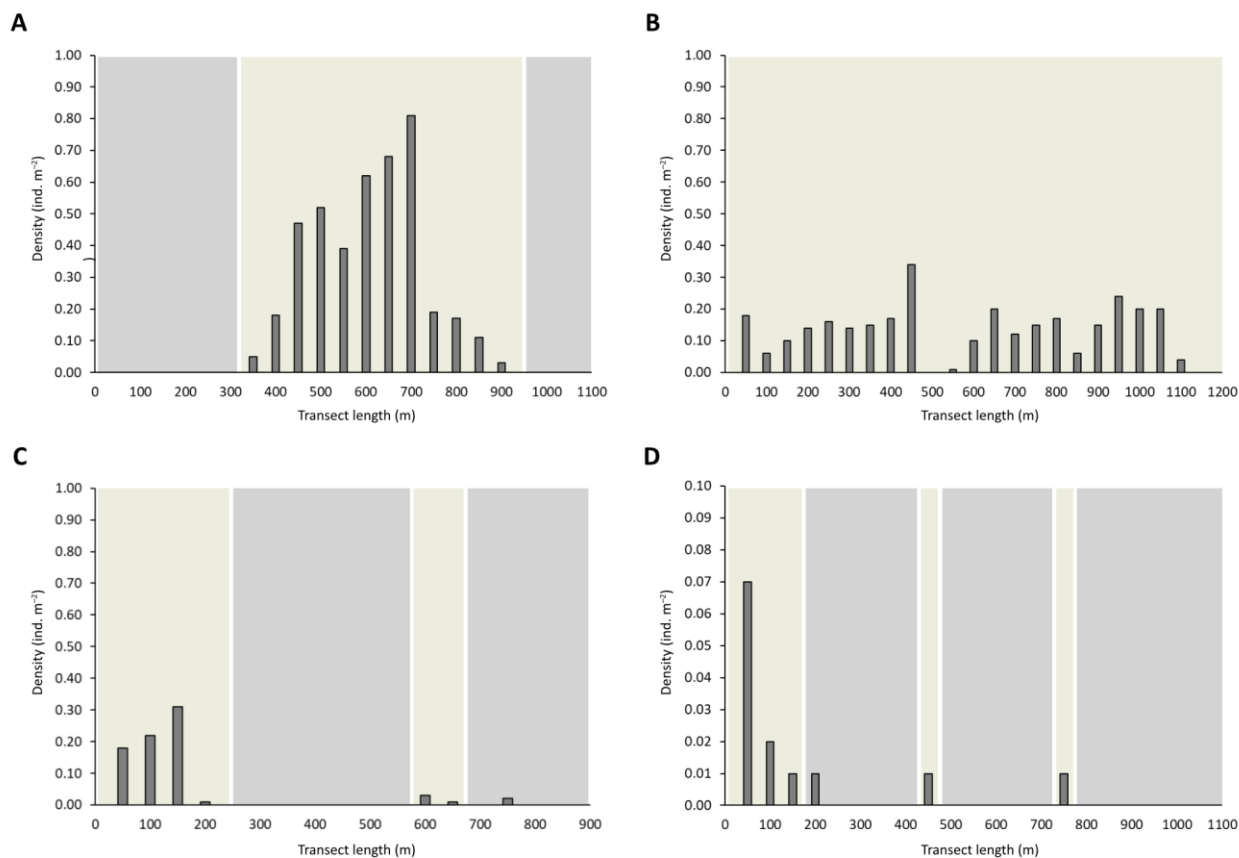
The highest density values were reported in sites dominated by large muddy areas among rocky outcrops (Figures 6A,B and 7A); on horizontal and sloping soft bottoms, the densities were high and homogeneous along the ROV transect (Figures 6C,D and 7B); and, finally, in sites characterized by a complex topography of the seafloor and located above a 300 m depth, the frequency of occurrence of *H. coronata* was markedly lower, with scattered individuals strictly confined to the small muddy patches interspersed among rocks or rarely settled on the silted cliffs (Figures 6E–H and 7C,D).



**Figure 6.** Population density and ecological preferences. Distribution of the specimens (red dots) along the transects (white lines) according to substrate type and inclination: (A–D) horizontal or slightly inclined muddy substrates with sparse rocks; and (E–H) sloping to vertical rocky outcrops with scattered muddy patches. Scale bar: 250 m.

Despite being very close, the trawler areas only partially overlapped with the sites in which the target species was present (Figure 5). They were located mainly in the central and southernmost part of the explored areas, on the flanks of a large deep creek between two wide rocky elevations (Figure 5).





**Figure 7.** Patchiness. Maximum density per sampling unit related to the substrate type (grey, outcropping rocks; and light yellow, mud) in four selected transects: (A) Dive 60; (B) Dive 88; (C) Dive 94; and (D) Dive 83.

Finally, several benthonektonic taxa were observed close of the target brisingid, namely, three crustaceans (*Penaeus kerathurus* (Forskål, 1775), *Plesionika giglioli* (Senna, 1902), and *Plesionika* sp.) and seven fish species (*Benthocometes robustus* (Goode & Bean, 1886), *Chlorophthalmus agassizi* Bonaparte, 1840, *Coelorinchus caelorhincus* (Risso, 1810), *Gadiculus argenteus* Guichenot, 1850, *Helicolenus dactylopterus* (Delaroché, 1809), *Hymenocephalus italicus* Giglioli, 1884, and *Synchiropus phaeton* (Günther, 1861)), among which *C. agassizi* and *C. caelorhincus* were the most frequent (Figure 4G,H).

#### 4. Discussion

The Atlantic brisingid *Hymenodiscus coronata* is a common encounter on the Mediterranean bathyal muds, e.g., [1,2,18,29], that has only been observed as scattered individuals or small groups of few specimens until now, e.g., [3,24,28,31]. This work reports, for the first time, in the Mediterranean Sea, the observation in situ of aggregations of this species in the Strait of Sicily, with novel information on its distribution, morphology, ecology, and vulnerability. Using the ROV-imaging technique, over 2850 specimens were observed, plausibly representing an underestimation due to the small size, pale cryptic colour, and partial sediment coverage of some individuals, making them undetectable through the ROV footage.

The species shows a large variability in terms of morphometry: in fact, the size varies from less than 15 cm to around 50 cm in diameter, and the number of intact arms is between 1 and 11. According to Sanchez, the number of arms in some Asteroidea groups is determined during ontogeny, so the starfishes with more than five arms tend to grow their extra arms in the first life stages, and the origin of new arms diminishes in frequency with increasing size (and age) [43]. The reduced number of arms observed



in many specimens may be related to several factors. First, it may be due to the fragility of the thin arms of the species, as already reported by several authors, e.g., [14,44,45]. It could also be due to the capacity of some asteroids to reproduce asexually by fissiparity. Fissiparity has been suggested for *H. coronata* by Sars and Sars 1872, but this observation is very speculative [46]. Another explanation may come from the predatory activity of other benthic taxa. In fact, during the investigations, a dozen fish and crustacean species were noted near the target brisingids. In this regard, Romeu et al. recently reported the echinoderms *Penilpidia ludwigi* (Marenzeller, 1893) and *H. coronata*, together with the polyps of the bamboo coral *Isidella elongata* (Esper, 1788), as the main components of the gut content of the deep-sea spiny eel *Notacanthus bonaparte* Risso, 1840 in the lower slope of the Balearic basin [47]. Our study did not observe the notacanthid near the target brisingid, although it was noted in the explored sites. However, most of the seven fish noted near the brisingids are generalist species [48–51], feeding on a large variety of benthic organisms and putatively on the thin arms of *H. coronata*.

The density of the brisingid results strictly related to the topographic characteristics of the explored sites, in particular, its bathymetry and the type and inclination of the substrate. The depth range in which *H. coronata* was recorded in the present work agrees with the known bathymetric distribution of the species, confirming its presence from the upper to the lower bathyal. Our observations support the preference of *H. coronata* for horizontal and moderately sloping soft bottoms. Most of the specimens were recorded on the flanks of small relieves and on seafloor irregularities, including artificial ones (i.e., trawl marks). Grinyó et al. recently reported a similar scenario in the Alboran Sea, where the trawl marks were colonized by megabenthic species, including *H. coronata* [31]. The specimens were observed on the edge of the fishing marks with their arms extended vertically in the water column. According to several authors, the position assumed by *H. coronata* seems to be related to its feeding activity: specimens flat on the sea floor are resting, while those with all the arms raised are capturing food in the water current, e.g., [13,14,30,31]. This habitus may explain the preference of the species, highlighted also in the present work, for areas exposed to the water flow, such as inclined substrates at the base of rocky cliffs, and muddy areas among rocky outcrops and trawl marks, to benefit from the accelerated flow over topographic highs to implement the feeding rates. Interestingly, the “sail pose” was displayed mainly by large individuals, suggesting that the filtering activity is more efficient in long-armed specimens. The highest densities are reported in areas characterized by large muddy patches among rocky elevations, probably because of the small-scale water turbulence created by the bottom roughness. The density is homogeneous when the environmental conditions are stable (i.e., on horizontal muddy planes). Finally, in sites with a complex seafloor topography (i.e., steep outcrops, vertical rocky walls, and biogenic coral reefs) or located at a shallower depth (<400 m depth), the density of *H. coronata* is significantly lower.

*Hymenodiscus coronata* exhibits a distribution pattern similar to other benthic species originating from the Atlantic Ocean and settling in the Strait of Sicily, e.g., [40,52–54]. In addition, the complex seafloor topography and turbulent hydrodynamic conditions of the Strait probably favor the largest aggregation of this species known for the Mediterranean Sea. Data on the density of the species in the Mediterranean Sea are scarce. Grinyó et al. and Mecho et al. counted 36 and 47 brisingids on the bathyal bottoms of the Alboran and Balearic seas in the western basin [2,31]. At the same time, Terribile et al. and Leonard et al. reported  $1.8 \times 10^{-6}$  and  $7.2 \times 10^{-5}$  individuals  $m^{-2}$ , respectively, in the deep waters around the Maltese Islands [2,28]. In the eastern basin, D’Onghia et al. reported  $1.5 \times 10^{-4}$  individuals  $m^{-2}$  in an area off Apulia (South-eastern Italy) between a 300 m and 700 m depth [24]. The density reported in the present study (up to 0.81 individuals  $m^{-2}$ ) was significantly higher, even if significantly lower than that reported in the Norwegian fjords [30]. It is possible to hypothesize that the population in the area may potentially account for more than 25 million individuals, considering an average density of 0.08 individuals  $m^{-2}$  and an extension of the optimal habitat of  $33 \times 10^7 m^2$  (based on the

multi-beam map, taking into account the preferred substrate type and inclination, and the depth range in which it was present).

Echinoderms in deep Mediterranean environments are highly susceptible to the destructive effects of bottom trawling, being unable to escape or withstand them, e.g., [55–57]. This may explain the very low densities of *H. coronata* reported in the available literature. Grinyó et al. showed evidence of the human impact on the megabenthic assemblages of bathyal sediments in the Alboran Sea, comparing the diversity and abundance of benthic species, including *H. coronata*, inside a marine protected area and in an adjacent site with no regulation [31]. Overall, megabenthic species densities in the trawled area were significantly lower than where fishing is prohibited. In the present study, the effects of bottom trawling on the *H. coronata* population are not clear. Bottom trawlers generally operate at depths greater than those where the highest densities of the target sea star were observed and prefer horizontal soft bottoms where their target species live (mainly aristeid and penaeid shrimps, red mullets, and European hakes) [58–60]. This allows for the avoiding of areas with scattered rocks and turbulent hydrodynamic conditions, preferred by *H. coronata*. Nevertheless, it cannot be excluded that the absence of individuals in the trawled areas may have been determined by the passage of the fishing vessels in the years preceding our monitoring. In favor of this hypothesis, Massi, and Massi and Titone frequently reported the species in the trawling bycatch of this area, supporting the impact of this activity on the brisingid *H. coronata*, e.g., [26,33,61–63].

For these reasons, a precautionary approach should be assumed in evaluating the effect of human activities on the benthic organisms present in this area, especially on those whose knowledge is still scarce, such as *H. coronata*. The aggregation reported in this study represents, at present, the largest ever reported in the Mediterranean Sea, so its protection may have a key role in the conservation of the species in the basin.

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