



# Unravelling the deep: Assessing the bycatch of deep-sea elasmobranchs in crustacean bottom trawl fisheries in Portugal

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## ABSTRACT

Deep-sea elasmobranchs (DSE) play a crucial role in marine ecosystems. However, they are poorly studied and face threats from overfishing, emphasizing an urgent need for improved scientific information, monitoring, and management strategies to reduce their bycatch. This study aimed to assess DSE bycatch from crustacean bottom trawling in southern Portugal, considering depths above and below 800 m (Regulation 2016/2336). Potential bycatch of deep-sea sharks was evaluated using *in situ* observations from the months of February and March and extrapolated for the fishing ban period (2017–2022). A total of 1559 specimens belonging to 18 DSE species were collected from 77 hauls between June 2020 and May 2022. Despite trawlers preferences for fishing above 800 m in the South, fishing below 800 m in the Southwest resulted in increased bycatch of DSE, including protected, uncommon, and endangered species such as *Deania calceus*, *Mitsukurina owstoni*, and *Centroscymnus coelolepis*. Furthermore, the areas and depth strata occupied by species like *Galeus melastomus* and *Scymnodon ringens*, suggested habitat flexibility, while others showed an apparent preference for specific depths and areas. These findings highlight the complexity of managing DSE populations amidst fishing pressures and depth restrictions. Despite the ban imposed to fishing below 800 m, bottom trawling persisted, leading to a potential elevated bycatch of deep-sea sharks for the months of February and March. This study emphasizes the urgency for improved enforcement of regulations in Portuguese waters and calls for the implementation of effective bycatch mitigation and fisheries management practices to safeguard DSE populations.

## 1. Introduction

Elasmobranchs (sharks, skates and rays) constitute an ancient group within marine ecosystems, boasting a remarkable evolutionary history spanning over 400 million years [14]. They play a pivotal role in shaping marine communities by influencing the mortality rates and behaviour of various organisms (e.g., [54,65,73]). Their life history characteristics, including late maturity, long lifespans, extended gestation periods, and low offspring production, makes them highly susceptible to anthropogenic disturbances such as fishing pressure even at low levels [1,32,36,58,64,98]. As a result, global elasmobranchs populations are experiencing fast declines [77]. A recent reassessment of 1147 elasmobranch

species [38] showed an alarming increase in the percentage of threatened species since the first assessment in 2014 [37]. Overfishing is one of the main threats to elasmobranchs' populations, which includes industrial fishing bycatch [38,60] – i.e., the unintentional catch of non-targeted species that is either unused or unmanaged [35]. Industrial fisheries, such as bottom trawling, exert significant impacts by physically altering the seafloor, leading to habitat destruction, and sediment resuspension (e.g., [47,29,21]). These activities also affect sediment biogeochemistry [8] and result in the removal of substantial amounts of fish and biomass [97,104]. Moreover, bottom trawling accounts for over a third of discarded bycatch worldwide [66,78], with crustacean bottom trawling having the highest impact, followed by fish bottom trawling [8,

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86]. In the International Council for the Exploration of the Sea (ICES) ecoregions, bottom trawling stood out as the fishing activity responsible for some of the highest bycatch values of elasmobranch species (e.g., [105,17]).

Elasmobranchs bycatch is a worrying issue in the bottom trawling fishery due to the net poor selectivity and high at-vessel and post-release mortality rates [39,7,87,91], which, associated with their low resilience to fishing pressures, presents conservation concerns. Since bottom trawlers do not specifically target elasmobranchs, the bycatch rate is anticipated to be irregular and variable over time, even when using the same fishing gear and within the same country and subregion [10,102,85,9,92]. The bycatch of elasmobranchs, contrarily to that of seabirds, marine mammals, and chelonians (with some exceptions) may be retained if the captured species is of commercial interest and has no regulatory concern. However, in European Union waters, species that do not meet these criteria, such as deep-sea elasmobranchs (DSE), must be discarded back at sea (Regulation 2024/257). The DSE group, is characterized by sharks and skates that generally inhabit depths below 200 m, mainly below 500 m (e.g., [22,56,76]) and are meso-top predators, important for the balance of local food webs [20,30,52]. According to the European legislation, deep-sea sharks are prohibited from being targeted by commercial fisheries (Regulation 2018/2025), and since 2010, their Total Allowable Catch (TAC) has been set to zero (Regulation 1225/2010). Despite these regulations, they continue to be caught as bycatch in significant numbers and discarded by various fisheries [8,96], especially by bottom trawlers [11,56], leading to a reduction in their abundance and diversity [42,93]. This highlights the need for improved monitoring and management strategies to reduce the bycatch and protect these species.

Regionally, at the southern of mainland Portugal, crustacean bottom trawling is a socioeconomic important fishery [13,18,8,80,81]. The southern coast, which includes the South and Southwest subareas, is a crucial area for the bottom trawl fishery due to widening of the continental shelf and more uniform bathymetry that increase the access to greater depths [43]. Since 1970s this region is the most important fishing ground for crustaceans in Portugal, mainly targeting the rose shrimp *Parapenaeus longirostris* and the Norway lobster *Nephrops norvegicus* which are found in areas on the continental shelf and upper slope down to 500–600 m [89]. In the 1980s, technological advancements allowed expanding this fishery to greater depths, targeting species that were previously considered unimportant, such as the shrimps *Aristeus antennatus*, *Aristaeomorpha foliacea*, and *Aristeopsis edwardsiana* [15]. However, a significant portion of the catch of *A. edwardsiana* (currently highly valued) originates from fishing grounds that are well beyond the 800 m depth permitted by law in EU waters where bottom trawlers are banned from fishing in the NE Atlantic since 2017 (Regulation 2016/2336; [15]). Furthermore, DSE, especially uncommon and endangered sharks, are often captured in waters surpassing 500 m depth [44,56,69,84]. In fact, deep-sea sharks' species such as *Deania calceus*, *Centroselachus crepidater*, and *Centrophorus granulosus* rank among the top 20 most landed species associated with deep-sea trawling activities at depths above 800 m in southern Portugal [15]. While several studies delved into the bycatch of DSE (e.g., [8,67,24,25,31,69,15]), to our knowledge, none has provided information on the discarded bycatch of DSE by species and métier at depths below 800 m in this area. This hinders our understanding of the extent of its impact on DSE populations especially if fishers maintain this activity at non-permitted depths. Hence, the present study aimed to evaluate the fishing effort and bycatch of DSE in the crustacean bottom trawl fishery along the South (at depths above 800 m) and Southwest (at depths above and below 800 m) coasts of Portugal, between the period 2020–2022 (*in situ* data). This was achieved by determining the prevalence and diversity of DSE species in relation to the fishing effort among the studied subareas and depth stratum. It was also examined whether fishing activities conducted at depths exceeding the regulated limit (below 800 m), primarily targeting economically valuable deep-sea shrimps (i.e., *A. antennatus*,

*A. foliacea*, *A. edwardsiana*), could result in increased DSE bycatch (which is compulsorily discarded) in relation to the total catch. Furthermore, the potential bycatch of deep-sea sharks below 800 m after the fishing ban (2017–2021) was estimated using extrapolated data from shark counts and weights in the Southwest subarea. This estimation focused on the months of February and March, aligning with the periods when *in situ* data was collected—specifically February 2018 [52] and March 2021. The analysis incorporated fishing effort data from bottom trawlers operating in the same subareas, obtained from the Global Fishing Watch website (GFW; <https://globalfishingwatch.org>), using the Automatic Identification System (AIS).

## 2. Materials and Methods

### 2.1. *In situ* data collection

The study was conducted off the southern Portuguese coast and for the analysis's purposes, it was divided in two subareas: South (37°–36°N; 9°–7.5°W) and Southwest (39°–37°N; 9°–11°W, Fig. 2). Detailed catch data was collected between June 2020 and May 2022 onboard a commercial crustacean bottom trawler. Ten fishing trips were opportunistically conducted, totalling 77 hauls, 351 h of fishing effort in approximately 35 days (Table 1). The vessel presents two bottom-trawl nets with a codend diamond mesh of 55 and 70 mm for targeting shrimps/prawns, and Norway lobster, respectively. The fishing speed varied between 1.5 and 3.7 nm/h and the duration of the fishing hauls varied between 2.3 and 8.6 h at depths of 96–810 m in the South and 403–1244 m in the Southwest (excluding depths of 800–1200 m where no sampling was conducted given the opportunistic nature of the data collection).

The fishing effort unit corresponds to the fishing haul duration (in hours), and it was calculated from the moment the net reached the bottom of the ocean until the moment it started to be lifted. The fishing effort and depth (m) were registered using the Electronic Logbook (eLog) Olrac Dynamic Data logger (Olrac DDL®) and a mini DST-CTD logic® Star-Oddi® attached to the net, respectively. Geographic coordinates were registered using a GPS at the beginning and end of each fishing haul. The target species were divided into the following categories: shrimp (*A. foliacea* and *A. antennatus* in the South and *A. foliacea*, *A. antennatus*, and *A. edwardsiana* in the Southwest), Norway lobster (*N. norvegicus*), prawn (*P. longirostris* and *P. monodon*). For each fishing haul, the total weight of the catch inside the net (in kg) was visually estimated by the skipper.

After the end of each fishing haul, DSE specimens were immediately collected from the sorting table, identified [65,28], measured [total length from the tip of the snout to the tip of the caudal fin (0.5 cm)], and weighed (to the nearest 0.5 kg). The information was registered in the Olrac DDL® eLog for further analysis. All the DSE were discarded by fishers.

### 2.2. Data analysis

To understand if the fishing occurring at depths below 800 m was contributing to increasing DSE bycatch, the proportion of DSE relatively to the total catch (in weight) was determined by subareas and depth stratum (i.e., at < 800 m and > 800 m) in the Southwest; in the South there was no bottom trawling conducted below 800 m depth.

The total DSE bycatch in number (n) and weight (kg) per fishing effort (hour) were calculated in each subarea and by depth stratum and are further denoted as CPUE n (given in n/h), CPUE kg (given in kg/h), respectively. The number of DSE species (diversity), and the CPUE n (abundance) and CPUE kg (biomass) by species, were also determined by subarea and depth stratum and were given for all the DSE species caught during this study.

To compare the CPUE n and CPUE kg between species in a given subarea, a Kruskal-Wallis followed by a Dunn-test (using p-adjusted

**Table 1**

For each reported subarea (South and Southwest) and depths (< 800 m and > 800 m), the targets of the crustacean bottom trawl fishery were Norway lobster (NL), prawn (P) and shrimp (SR). The number of hauls is also given by subarea and depth stratum as well as the number of deep-sea elasmobranchs (DSE) species. The fishing effort in hours, and the capture per unit effort of the number and weight of DSE specimens (CPUE n and CPUE kg, respectively) are reported as the median with the range of values in parenthesis. No fishing activity occurred below 800 m in the South, during the sampling period.

| Subarea    | South     |            | Southwest      |              |        |              |
|------------|-----------|------------|----------------|--------------|--------|--------------|
|            | < 800     |            | < 800          | > 800        |        |              |
| Seasons    | All       |            | Summer, Winter |              | Winter |              |
| Targets    | NL, P, SR |            | NL, P, SR      |              | SR     |              |
| Hauls (n)  | 61        |            | 10             |              | 6      |              |
| DSE spp.   | 14        |            | 12             |              | 14     |              |
| Effort (h) | 4.0       | (2.7–6.3)  | 4.7            | (2.9–5.6)    | 7.7    | (7.3–8.6)    |
| CPUE n     | 0.9       | (0 – 55.4) | 2.6            | (0.2 – 11.8) | 3.3    | (2.2 – 6.0)  |
| CPUE kg    | 0.3       | (0 – 11.6) | 4.2            | (0.3 – 9.3)  | 11.5   | (6.2 – 18.5) |

Bonferroni) were conducted. The CPUE n and CPUE kg values were compared between subareas and within species at depths above 800 m using a Mann-Whitney test. Only species that presented five or more CPUE observations were included in these analyses. These tests were done after checking for the assumptions of normality and homoscedasticity of residuals.

### 2.3. Shark bycatch estimation below 800 m after the ban

To estimate the bycatch (counts and weight) of deep-sea sharks at depths below 800 m in the Southwest since the fishing ban in 2017, we followed the methodology outlined by Mucientes et al. [72]. The approach used *in situ* CPUE data on deep-sea sharks and fishing effort retrieved from the open-source GFW website. The *in situ* CPUE n and kg of deep-sea sharks, was collected in February 2018, where five hauls totalling ca. 25 h of fishing effort were conducted within the coordinates 37°50'45''N to 38°9'44''N and 9°35'12''W to 9°23'15''W [52], and in March 2021, with six hauls totalling ca. 47 h of fishing effort within the coordinates 37°12'41''N to 37°41'28''N and 9°35'21''W to 9°28'26''W (present study). The commercial vessel used for this purpose provides a good representation of the crustacean bottom trawlers that fish at depths below 800 m in the Southwest subarea. This is a small fleet of ten vessels (ca. 40 % of the Portuguese crustacean bottom trawlers) with an average length of 22.5 ± 2.93 m and average gross tonnage of 145.5 ± 53.77 tons (GFW). To obtain fleetwide fishing effort for the same areas and months from the post-ban period (i.e. 2017–2021), AIS data was retrieved from the GFW website. First, the period was selected for February and March 2017–2021. Second, to select only AIS data from Portuguese trawling vessels, the following filters were applied: “Flags = Portugal” and “Gear types = Trawlers”. Zooming in to the relevant location using the above mentioned *in situ* coordinates, fishing effort in hours and the number of vessels operating in the area were extracted from each cell. Then, the total hours (mean ± S.D.) of fishing effort were computed for each month. Finally, to estimate the potential bycatch of deep-sea sharks in numbers and weight for the studied subareas and the years following the prohibition, we multiplied the *in situ* CPUE n and kg by the corresponding fleetwide fishing effort total hours (mean ± S.D.) of the obtained from GFW.

All statistical analyses were conducted with the open-source statistical language R [82].

## 3. Results

### 3.1. *In situ* data

The fishing effort was approximately three times higher in the South (259 h) than in the Southwest (92 h), covering all seasons of the year in the South, whilst in the Southwest sampling was only conducted in the Summer (< 800 m) and Winter (< 800 m and > 800 m). A rough comparison of the fishing effort only at depths above 800 m, showed that effort was ca. six times higher in the South than in the Southwest

(Table 1). Hauls at depths above 800 m primarily targeted Norway lobster (*N. norvegicus*), prawn (*P. longirostris* and *P. monodon*), and shrimp (*A. foliacea* and *A. antennatus*), while those at depths below 800 m focused primarily on shrimps (*A. foliacea*, *A. antennatus* and *A. edwardsiana*; Table 1).

A total of 1559 specimens of DSE were caught, belonging to 18 species (5 orders and 9 families): 15 sharks and three skates. Most of the specimens were collected at depths below 500 m. Within the Southwest subarea, shallower depths (< 800 m) contained a lower diversity in relation to deeper areas (> 800 m, Table 1). The proportion of hauls catching DSE was 71 % in the South and 100 % in the Southwest. The weight of discarded DSE in relation to the total catch varied between 0 – 47 % (median 1.05) above 800 m in the South, whilst for the Southwest values varied between 1 – 34 % (median 12.21) above 800 m and 25 – 58 % (median 33.37) below 800 m (Fig. 1).

In the South the highest CPUE n (median: 0.88, IQR: 3.32) was observed between 500 and 800 m depth mostly between the cities of Portimão and Sagres and within and surrounding the Portimão canyon (Fig. 2.a). The CPUE kg in the South (median: 0.25, IQR: 0.99) followed the overall pattern of the CPUE n. However, higher CPUE kg was found nearby the Portimão canyon (~800 m), when compared to the other depths above 800 m (Fig. 2.b). At the Southwest, CPUE n and CPUE kg values were the highest at depths below 800 m (median: 6.27, IQR: 5.36; Fig. 2.b).

*Galeus melastomus* and *S. ringens* are both small to medium-sized species of least concern conservation status (Table 2). *Galeus melastomus* showed the highest CPUE n and CPUE kg in the South and were commonly caught in groups across both subareas and depth stratum in the Southwest (Table 2). It exhibited peak CPUE n at 500–600 m in the South and higher CPUE kg above 800 m in the Southwest (Fig. 2). In the South it presented significantly higher CPUE n (median: 1.2, IQR: 1.74) and CPUE kg (median: 0.19, IQR: 0.45) compared to *D. oxyrinchus* (median: 0.28, IQR: 0.25) and *E. spinax* (median: 0.07, IQR: 0.07) respectively (Table A2); however, the CPUE n and CPUE kg of this species between subareas at depths above 800 m were not significantly different (Table A1). *Scymnodon ringens* presented the highest CPUE n and second-highest CPUE kg in the Southwest, also commonly caught in groups across both subareas and depth stratum (Fig. 2; Table 2). It showed peak CPUE n around 800 m in the Portimão canyon and below 800 m in the Southwest (Fig. 2). Exhibited significantly greater CPUE kg (median: 0.32, IQR: 0.94) than *E. spinax* and *Galeus atlanticus* (median: 0.03, IQR: 0.06) (Table A2) in the Southwest. The other least concern species were exclusively caught in specific areas. The skate *N. iberica*, was exclusively caught in the South with some of the lowest CPUE n values (Table 2). *Centroselachus crepidater*, was exclusively caught in the Southwest, below 800 m depth and in groups. It presented high CPUE n values despite being limited to one subarea and depth stratum (Fig. 2; Table 2).

*Etmopterus spinax*, *D. nidarosiensis*, *D. oxyrinchus*, and *G. atlanticus* are classified as near threatened (Table 2). *Etmopterus spinax*, a small-sized species, showed the second-highest CPUE n in the South, peaking at

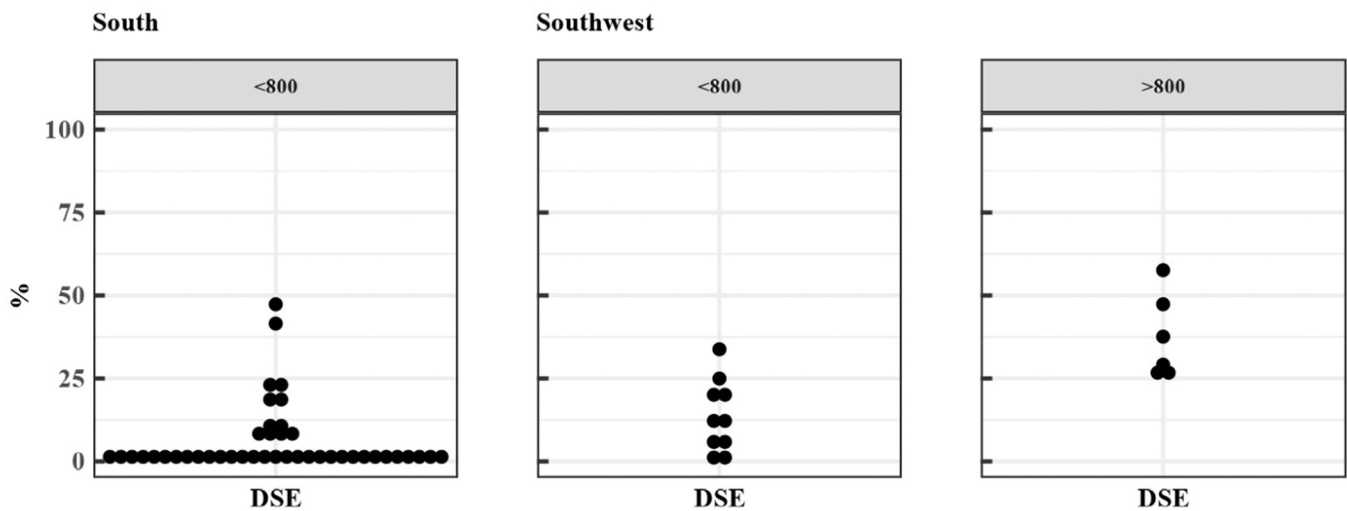


Fig. 1. Proportion (%) of the discarded bycatch weight of deep-sea elasmobranchs (DSE) in relation to the total catch weight of a crustacean bottom trawler in the South and Southwest coasts of Portugal at different depths (< 800 m and > 800 m). Each point corresponds to a fishing haul.

500–600 m depth (Fig. 2; Table 2). It was commonly caught in groups, but only above 800 m at both subareas (Table 2). *Dipturus nidarosiensis*, a large-bodied skate, was caught individually, in pairs, or groups across both subareas and depth stratum in the Southwest (Table 2). It presented low CPUE n but higher CPUE kg at both subareas in comparison with the other species, with the highest CPUE kg in the Southwest (Fig. 2; Table 2). In fact, in the Southwest, it presented the highest CPUE kg (median: 3.13, IQR: 0.72) among species, significantly higher than *D. profundorum* (median: 0.09, IQR: 0.03), *E. pusillus* (median: 0.08, IQR: 0.07), *G. atlanticus* (median: 0.04, IQR: 0.1), and *G. melastomus* (median: 0.17, IQR: 0.47) (Table A1). *Dipturus oxyrinchus*, a medium-sized skate, was caught in various group sizes across both subareas and depth stratum in the Southwest, primarily above 800 m (Table 2). *Galeus atlanticus*, a small-sized species, was commonly caught in groups at both subareas but it was not present below 800 m in the Southwest (Table 2). The statistical comparisons performed on the CPUE n and CPUE kg values of this species between the studied subareas at depths above 800 m did not show significant differences (Table A1).

*Deania profundorum* and *E. pusillus* are both data deficient, small-sized species (Table 2). *Deania profundorum* showed high CPUE n in both subareas and was commonly caught in groups (Table 2). In the South, its highest CPUE n was around 500–600 m and 800 m in the Portimão Canyon, with heavier specimens above 800 m in the Southwest (Fig. 2). *Etmopterus pusillus* was also commonly caught in groups across both subareas and depth stratum in the Southwest, primarily above 800 m with peak CPUE n around 500–600 m in the South (Fig. 2; Table 2).

*Deania calceus*, *Centroscymnus coelolepis*, *Dalatias licha*, and *Centrophorus squamosus* are classified as endangered (Table 2). *Deania calceus* showed low CPUE n and CPUE kg in the South but high values in the Southwest and was commonly caught in groups below 800 m (Fig. 2; Table 2). *Centroscymnus coelolepis* presented low CPUE n and CPUE kg, was caught individually or in pairs only below 800 m in the Southwest (Table 2). *Dalatias licha* was caught in groups with different sizes across both subareas and depth stratum in the Southwest, with higher CPUE kg around 500 m depth in the South and 800 m in the Southwest (Fig. 2; Table 2). *Centrophorus squamosus* was caught individually at both subareas, appearing only below 800 m in the Southwest, with higher CPUE kg around 800 m depth in the South (Fig. 2; Table 2).

*Centrophorus granulosus*, a critically endangered species, was exclusively caught in the South (Table 2). Despite generally low CPUE n, it showed high CPUE n and some of the highest CPUE kg around 800 m depth in the Portimão canyon (Fig. 2).

*Chlamydoselachus anguineus*, *M. owstoni*, and *O. paradoxus* are rare species however the first two are listed as least concern and *O. paradoxus* is data deficient (Table 2). They were exclusively caught in the Southwest, mainly or exclusively below 800 m depth, generally individually (Table 2). While they presented some of the lowest CPUE n and CPUE kg values, *M. owstoni* showed relatively high CPUE kg values (Fig. 2; Table 2).

### 3.2. Shark bycatch estimation below 800 m after the ban

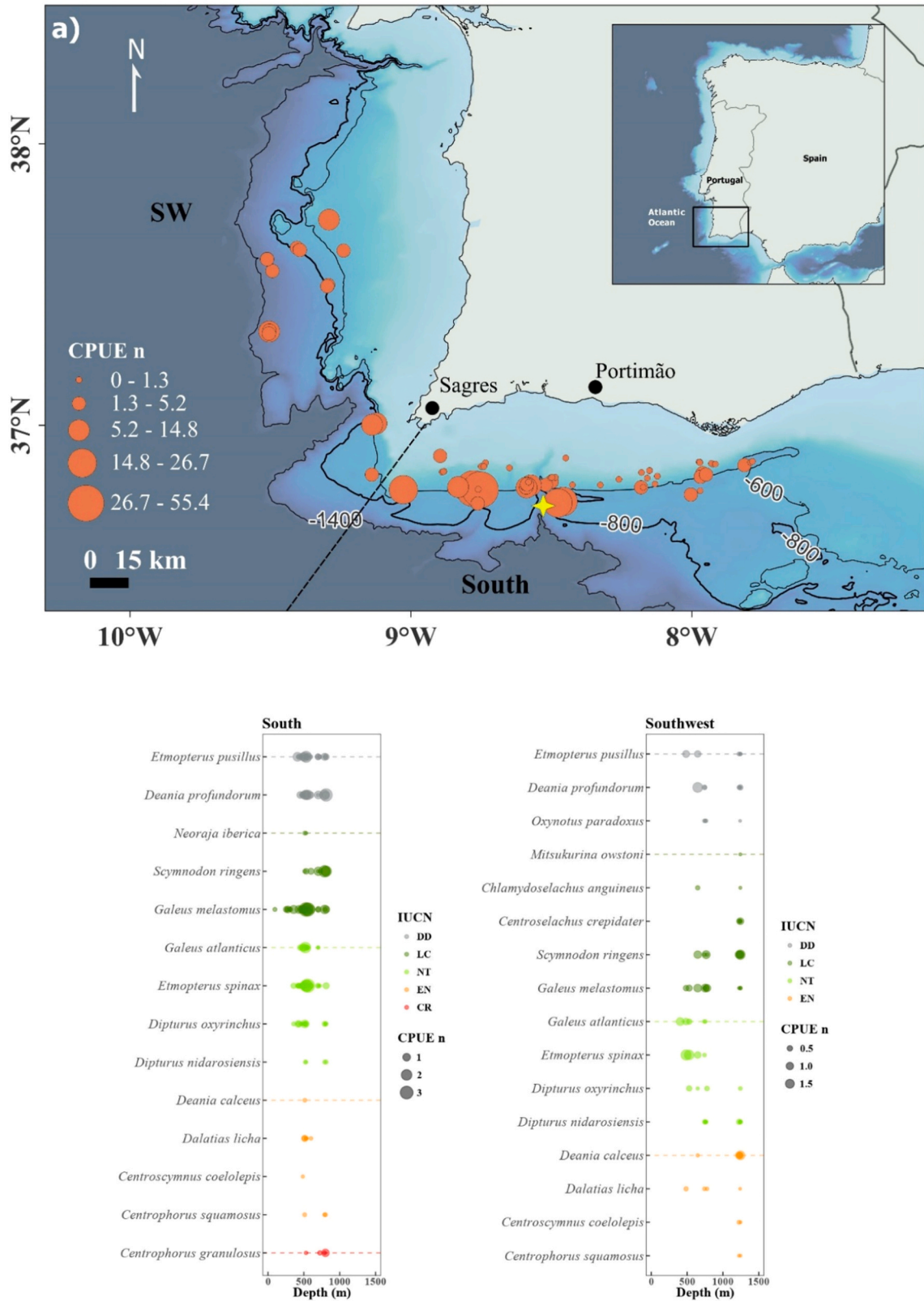
*In situ* CPUE n and CPUE kg for deep-sea sharks in February 2018 were 1.58 and 2.43 respectively. For March 2021 *in situ* CPUE n and CPUE kg were 3.77 and 9.48 respectively. The fishing effort data collected using the GFW website, for the months of February 2017–2021 was conducted by one to three bottom trawlers at depths varying between 1132 and 1447 m. For the month of March only 2017, 2019, and 2021 presented fishing effort data below 800 m, with fishing conducted by one to three trawling vessels, at depths varying between 1236 and 1369 m. February presented the highest fishing effort in comparison with March, hence it also presented the highest estimates in numbers and weight of deep-sea sharks (Table 3).

## 4. Discussion

### 4.1. *In situ* data

In the present study it was noted that a greater fishing effort was conducted in the South than in the Southwest and that, within the Southwest, the fishing effort was nearly equal between depth stratum (i. e. < 800 m and > 800 m). This does not necessarily indicate a preference for fishing in the South. Sampling was opportunistic and some impediments were imposed by Covid-19 lockdowns. It could simply indicate that when the researchers were allowed to board the vessel, the environmental conditions favoured fishing in the South rather than in the Southwest. However, studies conducted with the crustacean trawling fleet off southern Portugal indicate that

crustacean bottom trawlers based in the South indeed often exploit nearby shrimp grounds at depths above 800 m targeting Norway lobsters (*N. norvegicus*) and prawns (*P. longirostris* and *P. monodon*) [13,8]. Since prawns and Norway lobster are readily available near their home ports, trawlers based in the South venture to Southwest waters if the weather is favourable and if the economic benefits outweigh the costs of the longer journey, hence targeting more lucrative crustacean species



**Fig. 2.** Capture per unit effort of the number of deep-sea elasmobranchs CPUE n (a) and weight CPUE kg (b) in the South and Southwest subareas of Portugal mainland. Each data point in the map represents the start of each fishing haul conducted by a crustacean bottom trawler. The dashed black line indicates the limits between the subareas South and Southwest. The yellow cross indicates the Portimão canyon. Isobaths lines represented in the map are of 600 m, 800 m (thicker line), and 1400 m depth. For each map, a density graph for the deep-sea elasmobranchs found in each subarea was also provided for the CPUE n (log-transformed values) and CPUE kg. Species are grouped according with the categories outlined by the International Union for Conservation of Nature and Natural Resources (IUCN; [75]), where DD-data deficient, LC-least concern, NT-near threatened, EN-endangered, and CR-critically endangered. In the South, depth range of collection is from 96 to 810 m and in Southwest from 400 to 1400 m, but there is a data gap between 800 and 1200 m where no fishing was conducted..

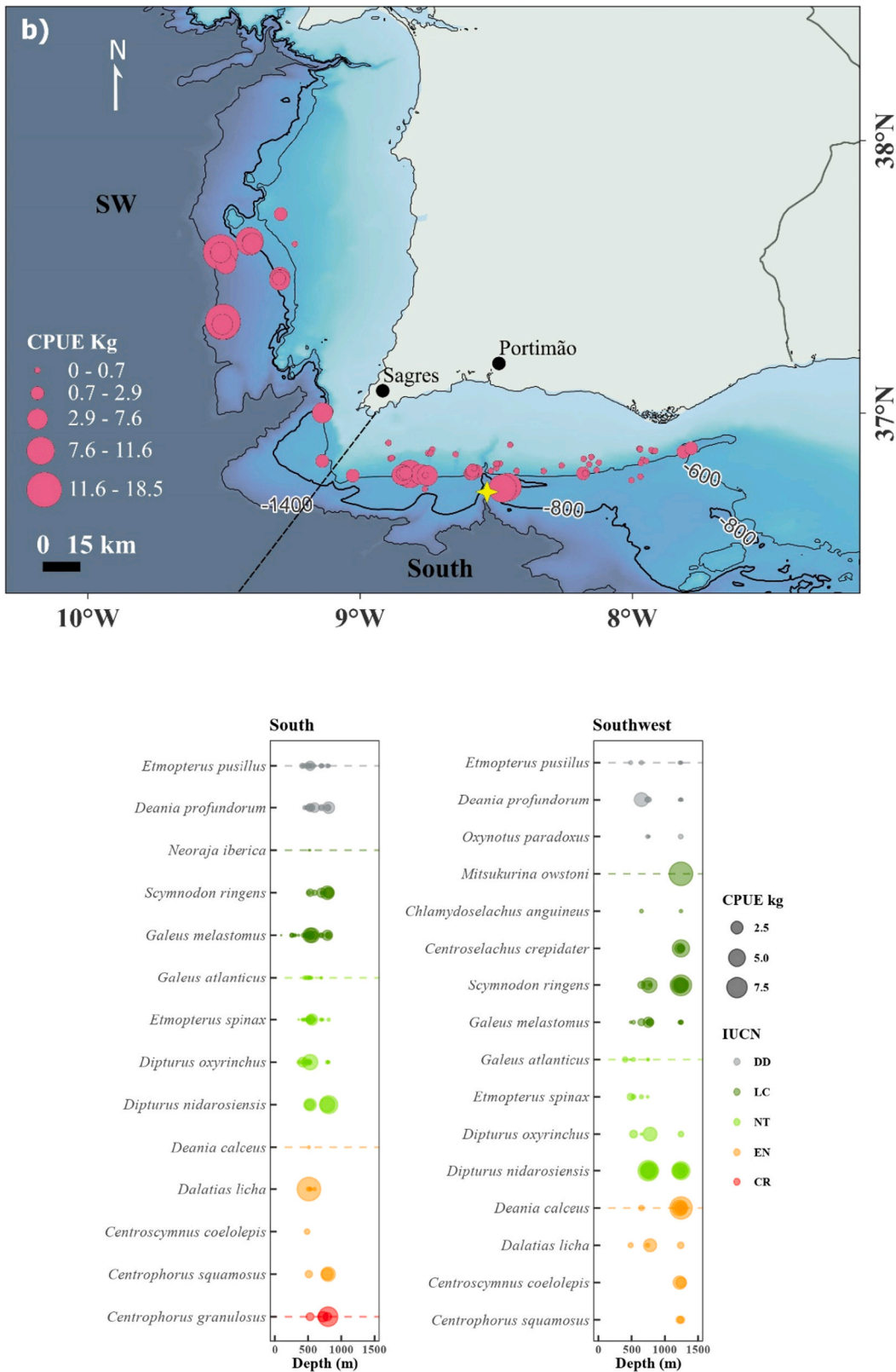


Fig. 2. (continued).

like the scarlet shrimp *A. edwardsiana*. This species is responsible for 16% of the total sales for crustacean bottom trawlers reaching an average 1 M € per year [15]. Despite its great economic value, a significant portion of the catch of *A. edwardsiana* originates from a relatively narrow area parallel to the Southwest coast between 1100 and

1400 m depth [15], well below the 800 m depth line permitted by law in EU waters (Regulation 2016/2336). Hence, the implementation of the depth ban in 2017, could have presented an economic impact for trawlers operating in the area, especially for those obtaining most of their revenues from this fishery [15]. Nonetheless, when looking at AIS

**Table 2**

Deep-sea elasmobranchs (DSE) species bycatch by subarea (South and Southwest), with the number of specimens per depth stratum (< 800 and > 800 m), total number of hauls (mean specimens per haul), total CPUE n and CPUE kg for each subarea and range of sizes (cm) for each species per subarea. European conservation status of the DSE is given in accordance with the European Red List from the International Union for Conservation of Nature and Natural Resources [75] where DD-data deficient, LC-least concern, NT-near threatened, EN-endangered, and CR-critically endangered.

| DSE Species                        | Subarea   | Depth (m) |       | Hauls<br>(n) | CPUE  |        | Size<br>(cm) | IUCN<br>Europe |
|------------------------------------|-----------|-----------|-------|--------------|-------|--------|--------------|----------------|
|                                    |           | < 800     | > 800 |              | n     | kg     |              |                |
| <i>Etmopterus pusillus</i>         | South     | 115       |       | 25 (4.6)     | 0.44  | 0.07   | 19–50        | DD             |
|                                    | Southwest | 10        | 6     | 6 (2.7)      | 0.17  | 0.04   | 17.5–46      |                |
| <i>Deania profundorum</i>          | South     | 167       |       | 18 (9.3)     | 0.64  | 0.12   | 23–92        | DD             |
|                                    | Southwest | 32        | 9     | 9 (4.6)      | 0.45  | 0.29   | 27–87        |                |
| <i>Oxyrinchus paradoxus*</i>       | South     |           |       |              |       |        |              | DD             |
|                                    | Southwest | 3         | 1     | 4 (1)        | 0.04  | 0.03   | 24–65        |                |
| <i>Mitsukurina owstoni</i>         | South     |           |       |              |       |        |              | LC             |
|                                    | Southwest |           | 1     | 1 (1)        | 0.01  | 0.77   | 250          |                |
| <i>Chlamydoselachus anguineus*</i> | South     |           |       |              |       |        |              | LC             |
|                                    | Southwest | 2         | 1     | 2 (1.5)      | 0.03  | 0.01   | 55.5–65      |                |
| <i>Centroselachus crepidater*</i>  | South     |           |       |              |       |        |              | LC             |
|                                    | Southwest |           | 17    | 6 (2.8)      | 0.18  | 0.63   | 64–116       |                |
| <i>Neoraja iberica</i>             | South     | 2         |       | 2 (1)        | 0.01  | 0.0001 | 18–19        | LC             |
|                                    | Southwest |           |       |              |       |        |              |                |
| <i>Scymnodon ringens*</i>          | South     | 101       |       | 11 (9.18)    | 0.39  | 0.14   | 30.4–70      | LC             |
|                                    | Southwest | 22        | 75    | 12 (8.1)     | 1.05  | 1.81   | 32–100       |                |
| <i>Galeus melastomus</i>           | South     | 450       |       | 28 (15.9)    | 1.74  | 0.24   | 12.4–65      | LC             |
|                                    | Southwest | 40        | 4     | 9 (4.4)      | 0.48  | 0.23   | 18–74        |                |
| <i>Galeus atlanticus</i>           | South     | 47        |       | 10 (4.7)     | 0.18  | 0.01   | 14–44        | NT             |
|                                    | Southwest | 17        |       | 7 (2.4)      | 0.18  | 0.03   | 13–45        |                |
| <i>Etmopterus spinax*</i>          | South     | 264       |       | 23 (11.5)    | 1.02  | 0.08   | 7–43.5       | NT             |
|                                    | Southwest | 39        |       | 4 (9.8)      | 0.42  | 0.04   | 16.5–44      |                |
| <i>Dipturus oxyrinchus</i>         | South     | 30        |       | 17 (1.77)    | 0.12  | 0.13   | 18.5–120     | NT             |
|                                    | Southwest | 5         | 2     | 4 (1.75)     | 0.08  | 0.22   | 38–113       |                |
| <i>Dipturus nidarosiensis</i>      | South     | 4         |       | 4 (1)        | 0.02  | 0.20   | 99–163       | NT             |
|                                    | Southwest | 5         | 10    | 9 (1.7)      | 0.16  | 1.99   | 97–172       |                |
| <i>Deania calceus*</i>             | South     | 1         |       | 1 (1)        | 0.004 | 0.0008 | 40.5         | EN             |
|                                    | Southwest | 1         | 44    | 6 (7.5)      | 0.49  | 1.30   | 67–101       |                |
| <i>Dalatias licha*</i>             | South     | 9         |       | 5 (1.8)      | 0.03  | 0.16   | 37.5–145     | EN             |
|                                    | Southwest | 3         | 1     | 4 (1)        | 0.04  | 0.20   | 54–127       |                |
| <i>Centroscyms coelolepis*</i>     | South     | 1         |       | 1 (1)        | 0.004 | 0.01   | 149          | EN             |
|                                    | Southwest |           | 3     | 2 (1.5)      | 0.03  | 0.34   | 100–112      |                |
| <i>Centrophorus squamosus*</i>     | South     | 3         |       | 3 (1)        | 0.01  | 0.09   | 80–126       | EN             |
|                                    | Southwest |           | 2     | 2 (1)        | 0.02  | 0.11   | 92–92.5      |                |
| <i>Centrophorus granulosus*</i>    | South     | 10        |       | 4 (2.5)      | 0.04  | 0.15   | 84–92        | CR             |
|                                    | Southwest |           |       |              |       |        |              |                |

\* TAC Zero European Union (EU) list of deep-water sharks (Regulation 2024/257; 2023/194)

**Table 3**

Data presented for the months of February and March (2017–2021) on the fishing effort in hours (mean  $\pm$  S.D.) which was directly recovered from the Global Fishing Watch website from crustacean trawlers fishing below 800 m depth. Deep-sea sharks counts and weight were estimated using in situ capture per unit effort values.

|                          | February<br>(2017–2021)       | March (2017, 2019,<br>2021)  |
|--------------------------|-------------------------------|------------------------------|
| Fishing effort (h)       | 813.4<br>(162.7 $\pm$ 199.2)  | 80.2<br>(26.8 $\pm$ 13.8)    |
| Estimated counts (n)     | 1285.7<br>(256.3 $\pm$ 313.8) | 302.6<br>(100.9 $\pm$ 52.1)  |
| Estimated weight<br>(kg) | 1980.0<br>(396.0 $\pm$ 484.9) | 760.9<br>(253.7 $\pm$ 131.0) |

data on bottom trawlers' fishing effort on the website GFW (global-fishingwatch.org), for the years following the depth ban implementation (i.e. 2017–2021), it is notable that fishing below 800 m in the Southwest coast still occurred. Aside from the economic benefits, it is unclear why fishers were fishing at depths below 800 m during the studied period in opposition with the EU regulation in place. An extraordinary concession by the Portuguese Directorate-General for Natural Resources, Security and Maritime Services (Portuguese acronym DGRM) could have been conceded for some trawlers to operate in that area at those depths, however, no information is publicly available regarding this matter. The DGRM was contacted via email to clarify this situation but did not reply

until the date of the publication of this study.

According to results from the present study, fishing at depths below 800 m in the Southwest exhibited a notably higher proportion of DSE biomass, ranging from 25 % to 58 %, compared to hauls conducted above 800 m, which ranged from 0 % to 47 %. This highlights some of the highest bycatch values reported in the literature, which is predominantly focused on shallower Mediterranean depths. For example, around the Balearic Islands and in the Aegean Sea, elasmobranchs represent 5–8 % and 14 % respectively, of the total catch biomass [16, 33] while specific hotspots like the Alboran Sea, recorded high biomass of species such as *G. melastomus* which exceeded the target species *A. antennatus* [99]. Recently, in the Moroccan Mediterranean Sea (20 to ca. > 60 m depth), elasmobranchs constituted only 5–9 % of the total catch biomass in trawlers targeting cephalopods, teleosts, and crustaceans [62]. Similarly, in the northeastern Mediterranean, demersal elasmobranchs accounted for 23 % of the total fish biomass, with fishing efforts concentrated at depths from 0 to > 100 m [105]. On the Egyptian Mediterranean coast, species like *D. oxyrinchus* and *G. melastomus* were part of the bycatch retained by bottom trawlers, comprising up to 21 % of the total catch biomass, with discards including species like *E. spinax* and *Centrophorus* sp., contributing to 9 % of the biomass discarded at depths above 800 m [40]. Additionally, the current study reports DSE biomass values higher than those reported in earlier studies conducted in the same areas at depths above 800 m. For example, Monteiro et al. [67] recorded 15 % of chondrichthyan bycatch while Borges et al. [8] reported chondrichthyan bycatch values as high as 29 % for crustacean

trawlers, which included elasmobranch species not typically classified as deep-sea (e.g., *Torpedo nobiliana*, *Raja clavata*, and *Scyliorhinus canicula*) but excluding DSE that were present in great proportions in the present study (e.g., *S. ringens*, and *D. profundorum*). This suggests that, if all chondrichthyans caught in the present study were considered—including those not frequently observed in deep-sea environments—the bycatch values to report would be even higher. The disparity between the bycatch values presented in this study and in those above-mentioned, indicates a potential increase in elasmobranchs' bycatch values over time and/or a possible shift in the composition of the species encountered.

In the South, the abundance (CPUE n) and biomass (CPUE kg) values were lower than in the Southwest for the same depths (i.e., < 800 m), which could be a consequence of elevated fishing activity in the South [13,8] since abundance and biomass are negatively correlated with fishing effort [74,79,88]. This trend was also observed by Ferretti et al. [42]. Conversely, it could also be due to a patchy distribution of DSE in this subarea, but those assumptions require further investigations which were out of the scope of the present study, since the opportunistic nature of the sampling scheme did not allow to identify the drivers for the observed differences. Furthermore, in the South high CPUE n and CPUE kg of DSE were generally observed between 500 and 800 m depth, with variations among species. Species like *C. granulatus*, *D. profundorum*, and *S. ringens* exhibited higher values around 800 m depth in comparison with shallower areas. Notably, hauls in the vicinity and within the submarine Portimão Canyon (~800 m), revealed specimens of the critically endangered *C. granulatus*, endangered *C. squamosus*, and near-threatened *D. nidarosiensis*, along with a high CPUE n of smaller species like *D. profundorum* and *S. ringens* that were caught in groups. These findings underscore the ecological importance of the Portimão Canyon, a hotspot for biodiversity in the South subarea [51], due to the unique physical and oceanographic features characteristic of submarine canyons [41,90]. Morais et al. [68] studied the substrate and fauna at the head of the Portimão canyon (~200 m), identifying a dynamic ecosystem with notable shifts in species composition and trophic structures, likely impacted by intense trawling activity [8]. Although Scyliorhinidae sharks were observed, no other shark species were detected, potentially due to the relatively shallow depth at which images were captured [68]. Despite the fact that, in the present study, there were some hauls conducted within the canyon at greater depths than the ones addressed by Morais et al. [68] which obtained species of conservation concern, it is unclear if bottom trawlers consistently operate within this canyon or if they 'fly' the nets over the canyon [68]. A deeper understanding of the DSE assemblages that inhabit the canyon across various depths, and of the behaviour of trawling activities within this region, would help identify potential impacts of this activity within DSE inhabiting the Portimão canyon.

In the Southwest, high CPUE n but low CPUE kg were generally observed between 400 and 800 m. However, endangered species like *C. squamosus*, *C. coelolepis*, and *D. calceus*, along with the least concern species *C. crepidater* and *S. ringens*, were either found only at depths exceeding 1200 m or exhibited high CPUE n at those depths, in accordance with previous studies for the Portuguese coast [56,69,70]. Likewise, higher CPUE kg and lower CPUE n was found at depths below 1200 m. This suggests that immature or small DSE specimens inhabit shallower depths (< 800 m), whereas larger or mature specimens of uncommon and endangered sharks inhabit depths below 1200 m, a trend also noted by Ruiz-García et al. [88] in the western Mediterranean. It is known that depth plays a crucial role in shaping the composition of elasmobranch communities, with skates like *D. oxyrinchus* preferring the upper continental slope (200–500 m) and most sharks preferring the deepest part of the continental slope (> 500 m; [16,34,69,88]). Clarke et al. [23] recommended restricting bottom trawling to depths of 600 m instead of the current 800 m due to the potential negative ecological impacts on DSE which would outweigh the commercial benefits below 600 m. Because DSE exhibited higher CPUE n and CPUE kg starting

around 500 m in the South and 400 m in the Southwest, consistent with the literature from the Northeast Atlantic (e.g., [56,76]), that could indicate that the depth limits for bottom trawlers could be even less than the suggested 600 m to increase DSE protection. Furthermore, avoidance of depths below 800 m by bottom trawlers, seems to be beneficial not only to the protection of DSE communities but might as well benefit fishers economically, since at depths above 800 m the retained catch weight might be greater than the discarded weight given that DSE weight presented a median of 1.1 %. Yet, the assessment of the economic performance of this fishery was beyond the scope of the present study, but such analyses are encouraged for future research, considering the distribution of high valued shrimps at depths beyond the permitted by law. It is also important to recognize that the percentage of total weight attributed to DSE was calculated in relation to the total weight of the catch in the net codend, which includes both target and bycatch species, whether discarded or retained. The net codend weight was visually estimated by the skipper either when the net is lifted on top of deck, or when the catch is already inside the "pond" (an area below deck where the codend is offloaded). Visual estimate of the total catch is usually conducted by experienced observers or skippers, however, some bias could be introduced by under- or overestimating the weight, given that it is a visual estimation. Nonetheless, it is one of the recognized methodologies to estimate total catch weight and discards (e.g., [2,71]). The use of a codend weigher (which is basically a scale that weigh the codend as it is hauled aboard the vessel), along with information on the retained catch weight (that is daily recovered by fishers using onboard scales), could help estimate discards in a more precise way, hence assisting in reducing the level of discards in EU fisheries [19].

Species of least concern (e.g., *G. melastomus* and *S. ringens*) generally exhibited higher CPUE values than the most imperilled, suggesting more stable and abundant populations. In contrast, the low CPUE values of endangered and critically endangered species (e.g., *C. coelolepis* and *C. granulatus*) reflect their high risk of population's depletion or even extinction. Near threatened and data deficient species (e.g. *D. oxyrinchus* and *E. pusillus*) exhibited intermediate CPUE values. Furthermore, the high abundance of *G. melastomus* could have masked the CPUE n contribution of other comparable species (i.e., species with number of specimens > 4; *D. oxyrinchus*, *D. licha*, *Etmopterus spp.*, and *G. atlanticus*) in the South subarea as previously seen in other studies (e.g., [93]); however, statistical analysis (Table A2), showed that CPUE n of *G. melastomus* was not significantly different than the other evaluated species, except for *D. oxyrinchus* which presented much lower abundance comparatively with *G. melastomus* (Table A2). *Galeus melastomus* is a prolific species [76,100], that seems to prefer depths above 800 m (e.g., [55,61,76]). It is probably the most well-known species among the studied DSE, with a fair number of studies in European waters, mostly for the Mediterranean Sea (e.g., [32,46,83,84,93,88]). In contrast, very little is known about *S. ringens* despite its common occurrence in the bycatch of deep-sea fisheries in Northeast Atlantic waters [27,49,56,61]; however, their presence seems to be more prominent at depths below 700 m [56,69,76]. *Galeus melastomus*, *S. ringens*, *E. pusillus*, and *D. profundorum*, appeared generally in groups (> 3 specimens per haul) at both studied subareas and depth stratum, which suggests some habitat flexibility. Species that generally appeared individually in the hauls, were uncommon and endangered species that occurred in only one of the studied subareas (*M. owstoni*, *O. paradoxus*, *C. anguineus*, and *C. granulatus*) or that occurred both in South and Southwest but at different depth strata (*D. licha*, *C. squamosus*, and *C. coelolepis*). Indeed, it is known that deep-sea sharks segregate in habitat by age, sex, and reproductive states (e.g., [5,59,63,103,106]). For example, *C. coelolepis* segregates by size, sex, and maturity stage [103] while *D. licha* shows different depth preferences in different areas [101,4,95]. However, practically all deep-sea sharks are threatened by bycatch even at low levels, which may prevent recovery given their low resilience to exploitation [38,45], especially those living at the deepest depths [94].

In EU waters, DSE are included in a few regulations like biannual

quotas (skates from the order Rajiformes) and zero TAC (Regulation 2024/257). The zero TAC imposed on deep-sea shark species is important to avoid targeted fisheries, but at the same time, has precluded the development of comprehensive stock assessments and spatial distribution models. This is because sharks are promptly discarded upon capture, with no monitoring or records of their bycatch in deep-sea fisheries [56]. Furthermore, this regulation does not avoid the bycatch of these species, as it was seen in the present study, where endangered species such as *C. squamosus*, *D. calceus*, *D. licha*, and *C. coelolepis*, exhibited some of the highest CPUE kg among species in the Southwest region below 800 m. Additionally, the Regulation 2024/257 does not ensure the survivorship of the specimens after discards. Mortality estimates of DSE are generally lacking for bottom trawling, but a recent study found that 85 %, 91 % and 88 % of the specimens from the species *D. oxyrinchus*, *G. melastomus* and *E. spinax* respectively, were either dead or inactive (i.e., not responsive but still breathing hence with extremely low chances of survival after discards; [91]). These numbers are extremely alarming and call for improved monitoring of the discards of the DSE in order to understand the impact of bottom trawling on the survivorship of DSE species of conservation concern.

The ecological implications of DSE elevated bycatch, combined with frequent discarding practices because of regulations or low commercial and with high mortality rates may be significant. Elasmobranchs, particularly deep-sea species, play essential roles in maintaining ecosystem balance, acting as apex or mesopredators [23]. Discarding these species without understanding their mortality rates and the potential consequences, can lead to disruptions in trophic dynamics and reduce biodiversity, impacting ecosystem health [94].

#### 4.2. Recommendations for the monitoring of bycatch and mitigation of impacts

Given the important but concerning findings from the present study several approaches could be followed to monitor DSE bycatch and discards and to mitigate the impacts of bottom trawling on these animals. For the monitoring, efforts should focus on improving fisheries technology to remotely identify specimens and maintain records of their population status for stock assessments and distribution patterns. Emerging technologies, such as electronic monitoring, are promising in addressing this challenge by enabling remote identification of DSE using video imagery. For instance, in a study conducted simultaneously to the present study [da Rocha et al. (unpublished results)] several DSE specimens were successfully identified up to the species level using images from an onboard camera in a crustacean bottom trawler; however, the complexity of distinguishing between congeneric species, such as *Etmopterus* spp. and *Deania* spp., often complicates precise species-level identification. While many studies group all sharks and all skates, sometimes even grouping by order [26,37,48,9], it is important to recognize that even congeneric species can differ significantly in their ecology and biology, requiring distinct regulatory measures. For example, *E. spinax* and *E. princeps*, along with *D. calceus*, are designated as zero TAC species, whereas *E. pusillus* and *D. profundorum* are not, and this could lead to enforcement constraints given their notorious physical similarities with congeners. Hence, the importance in identifying specimens up to species level calls for improvement on such monitoring tools not only to properly identify species, but to speed up the identification process by developing AI tools integrated with electronic monitoring at a fishery/fleet basis. However, since congeneric species like *Deania* spp. and *Etmopterus* spp. cannot currently be reliably distinguished via video imagery, implementing supplementary strategies, such as amalgamating congeneric species in the deep-sea shark list (Regulation 2024/257), would, at least for the time being, streamline the utilization of this accessible electronic monitoring tool to identify DSE, albeit limited to the genus level, thereby contributing to a better understanding of data poor groups like DSE.

To mitigate the impacts of bottom trawling on DSE, a set of measures

could be applied. First, efforts to reduce DSE bycatch should be prioritized. This can be achieved by identifying areas and seasons of high bycatch of DSE using fishery dependent or independent data (e.g. surveys conducted in fishing and in research vessels, or species distribution models), and limit fishing activities during a certain period or in certain areas. Additionally, testing the use of bycatch-reducing devices is crucial. Examples of such devices include the Nordmøre grid [57], which has been regarded as an efficient method to mitigate elasmobranch bycatch in various crustacean trawl fisheries globally, being mandatory in all shrimp fisheries inside the Norwegian EEZ. Furthermore, employing turtle excluder devices in nets [12,53,6], as well as electromagnetic exclusion devices, acoustic or light-based deterrents, were all proven successful and should be explored [56]. However, the effectiveness of such measures in reducing the bycatch of DSE specifically in the European crustacean bottom trawl fishery, requires further investigation. Second, if DSE's bycatch cannot be prevented, DSE should be immediately discarded and recorded in logbooks. This type of data is difficult to obtain but is to be done by skippers and onboard observers in deep-sea fisheries, ultimately with the aid of electronic monitoring by onboard video cameras, as previously explained. Recording of this data would allow collecting information on i) species composition, biomass and abundance; ii) spatial and temporal bycatch patterns and rates, which allows for comparisons among and within fishing gears and data reporting methods [3,107]; iii) potential breeding areas; iv) the effectiveness of different management measures, such as spatio-temporal closures, net restrictions, and the use of bycatch reduction devices for their discards. Third, best practices protocols for safe onboard handling and release of DSE should be developed to improve DSE discards survival [50,7].

#### 4.3. Sharks bycatch estimation below 800 m after the ban

Estimates of deep-sea sharks' bycatch in the Southwest, measured by both count and weight, suggest that substantial numbers of deep-sea sharks may have been caught, in the five years following the prohibition on bottom trawling at depths below 800 m in the Northeast Atlantic (Regulation 2016/2336). A comparison of February and March data provides insights into why shark capture estimates were higher in February than in March. Specifically, *in situ* data from February 2018 and March 2021, combined with GFW data for February and March across 2017–2021, indicate that seasonal fishing conditions and regulatory factors have influenced these estimates. A critical factor is the annual January fishing cessation mandated by Ordinance N° 43/2006, which requires crustacean trawlers with codend mesh sizes of 55–59 mm or larger to remain in port for that month. Because trawling ceases in the month preceding February's sampling, fishers have observed increased catches of commercially valuable crustaceans in the weeks immediately following this break (personal communications, March 2021). This increased crustacean availability likely attracts more sharks to the area, leading to higher shark concentrations for feeding purposes. Sharks in this region are known to feed on crustaceans [52], a behaviour that could heighten their susceptibility to capture in February.

The periods of *in situ* data collection in February 2018 (the first year of the fishing prohibition) and March 2021 (four years into the prohibition, with Covid-19 lockdowns) may explain variations in fishing effort and shark capture rates. In February 2018, fishing effort may have remained consistent as fishers did not immediately alter their practices in response to the new depth restrictions. By March 2021, while the prohibition was well established, Covid-19 restrictions introduced additional complications. The pandemic led to disrupted supply chains, restricted movement, and reduced crew availability, which could have caused disruptions in fishing activities. These combined factors likely contributed to lower effort, hence lower shark captures in March 2021, complicating comparisons between February and March and adding a layer of variability to long-term bycatch estimates.

It is also important to consider limitations in AIS data, as some vessels capable of fishing at these depths may not use AIS tracking. While GFW data is reliable for global fishing activity monitoring, challenges like intentional AIS disabling and occasional inaccuracies in vessel identification still exist. Additionally, while GFW's "Gear type = Trawler" filter includes various types of trawling vessels, specific vessel reviews confirm that all identified vessels in this area engage in crustacean bottom trawling activities, confirming the reliability of the fishing effort data collected.

However, it is crucial to highlight that the estimates provided are underestimating actual numbers of deep-sea sharks caught below 800 m depth in the Southwest of Portugal, since data collection was limited to February and March and included only one to three vessels in a specific subarea. So, if we were to extrapolate the analyses to the entire fishing area below 800 m and extend it throughout the year this would significantly increase those estimates, at least by tripling vessel counts to as many as ten according to GFW data - which corresponds to 40 % of the total number of crustacean trawlers of Portugal (personal communications DGRM, October 2024). This expansion would provide a fuller picture of fishing effort and shark bycatch, underscoring the potential impact of trawling on deep-sea shark populations.

Considering all the limitations presented, these results should be viewed as exploratory; but given that fishing took place at prohibited depths and resulted in large estimates of deep-sea sharks bycatch, the compliance and enforcement of the 800 m depth restriction is essential to reduce DSE bycatch effectively. Further studies on the ecology and biology of DSE would enhance our understanding of their vulnerability to fisheries and their distribution in this region.

## 5. Conclusion

In the present study it was seen that DSE represents a high proportion of the total catch biomass reaching up to 60 %, especially at depths below 800 m. Despite EU regulations restricting fishing below 800 m, bottom trawlers were observed operating at these depths during *in situ* data collection, corroborated by GFW data from 2017 to 2021. This activity led to some of the highest DSE bycatch rates recorded when compared to shallower depths within this study and to previous studies in the area and in EU waters. This is concerning given that they have very low chances of survival even if returned to the water alive, hence avoiding their capture in first place should be prioritized. Furthermore, it was highlighted the relevance of depth into shaping DSE communities in the study areas, with deeper areas hosting larger and endangered specimens. The presence of endangered and critically endangered DSE species in the submarine Portimão canyon is of concern and should be further investigated given the high trawling activity in the South of Portugal. Understanding long-term effects of trawling on DSE species composition and ecosystem dynamics is crucial for evaluating the ecological role of the studied areas and for shaping effective management strategies to protect biodiversity, especially of taxa of conservation concerns. Further studies are encouraged to help bring solutions tailored for crustacean trawlers operating in EU waters to avoid DSE bycatch. Nonetheless, the present study demonstrated that due to the high bycatch of DSE, immediate action is required to mitigate the impact of bottom trawling on DSE populations and fragile deep-sea ecosystems.

## Ethical standards

This study was conducted in accordance with the Guidelines of the European Union Council (86/609/EU) and Portuguese legislation for the use of animals and enforced by CCMAR. CCMAR staff are certified to house and conduct experiments with live animals, and their facilities are also certified in accordance with the three "R" policy, national and European legislation, and with guidelines defined by the ethical

committee ORBEA CCMAR-CBMR.

## Author Contributions

S.G.A., A.T. and E.D. conceived and designed the study. S.G.A., T.M., P.d.R. and E.D. collected and treated the data. S.G.A. performed the analysis and wrote the first version manuscript. N.Q. Global Fishing Watch data collection and analysis. S.G.A, A.T., A.B. and E.D. provided funding. All authors wrote the second version of the manuscript and gave final approval for publication.

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## Author statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs Signed by all authors.

## CRediT authorship contribution statement

**Ester Dias:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Sofia Graça Aranha:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alexandra Teodósio:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Pedro Pires da Rocha:** Writing – review & editing, Investigation, Data curation. **Nuno Queiroz:** Writing – review & editing, Methodology, Formal analysis. **Amos Barkai:** Writing – review & editing, Software, Funding acquisition. **Tiago Marsili:** Writing – review & editing, Investigation, Data curation.

## Declarations of Competing Interest

None.

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Appendices

Table A1

Kruskal Wallis (KW) and Mann-Whitney (MW) test results among deep-sea elasmobranch species' capture per unit effort of specimens (CPUE n) and weight (CPUE kg) in the South and Southwest coasts of Portugal from a crustacean bottom trawler.

| Subarea   | Source                            | Test | Test Stat | df | p-value  |
|-----------|-----------------------------------|------|-----------|----|----------|
| South     | Species x CPUE n                  | KW   | 17.25     | 7  | 0.016    |
| Southwest | Species x CPUE n                  | KW   | 12.21     | 7  | 0.094    |
| South     | Species x CPUE kg                 | KW   | 22.44     | 7  | 0.002    |
| Southwest | Species x CPUE kg                 | KW   | 36.38     | 7  | < 0.0001 |
| All       | <i>Galeus atlanticus</i> x CPUE n | MW   | 23        |    | 0.6612   |
| All       | <i>G. atlanticus</i> x CPUE kg    | MW   | 23        |    | 0.6612   |
| All       | <i>G. melastomus</i> x CPUE n     | MW   | 97        |    | 0.9337   |
| All       | <i>G. atlanticus</i> x CPUE kg    | MW   | 81        |    | 0.5877   |

Table A2

Post hoc Dunn test results between deep-sea elasmobranch species' (with n > 4) and their designated capture per unit effort of counts (CPUE n) and weight (CPUE kg) in the South and Southwest coasts of Portugal, from the crustacean bottom trawl fishery. p < 0.05 \* p < 0.005 \*\*

| Subarea | Variable | Species 1                  | Species 2                  | n1 | n2 | statistic | p     | p-adjusted |
|---------|----------|----------------------------|----------------------------|----|----|-----------|-------|------------|
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Deania profundorum</i>  | 6  | 18 | 2.158     | 0.031 | 0.866      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Dipturus oxyrinchus</i> | 18 | 17 | -2.261    | 0.024 | 0.665      |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Dipturus oxyrinchus</i> | 6  | 17 | 0.532     | 0.595 | 1.000      |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Etmopterus pusillus</i> | 6  | 25 | 1.971     | 0.049 | 1.000      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Etmopterus pusillus</i> | 18 | 25 | -0.392    | 0.695 | 1.000      |
| South   | CPUE n   | <i>Dipturus oxyrinchus</i> | <i>Etmopterus pusillus</i> | 17 | 25 | 2.047     | 0.041 | 1.000      |
| South   | CPUE n   | <i>Dipturus oxyrinchus</i> | <i>Etmopterus spinax</i>   | 17 | 24 | 2.310     | 0.021 | 0.585      |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Etmopterus spinax</i>   | 6  | 24 | 2.158     | 0.031 | 0.866      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Etmopterus spinax</i>   | 18 | 24 | -0.104    | 0.917 | 1.000      |
| South   | CPUE n   | <i>Etmopterus pusillus</i> | <i>Etmopterus spinax</i>   | 25 | 24 | 0.311     | 0.756 | 1.000      |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Galeus atlanticus</i>   | 6  | 11 | 1.267     | 0.205 | 1.000      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Galeus atlanticus</i>   | 18 | 11 | -0.978    | 0.328 | 1.000      |
| South   | CPUE n   | <i>Dipturus oxyrinchus</i> | <i>Galeus atlanticus</i>   | 17 | 11 | 1.009     | 0.313 | 1.000      |
| South   | CPUE n   | <i>Etmopterus pusillus</i> | <i>Galeus atlanticus</i>   | 25 | 11 | -0.700    | 0.484 | 1.000      |
| South   | CPUE n   | <i>Etmopterus spinax</i>   | <i>Galeus atlanticus</i>   | 24 | 11 | -0.939    | 0.348 | 1.000      |
| South   | CPUE n   | <i>Dipturus oxyrinchus</i> | <i>Galeus melastomus</i>   | 17 | 29 | 3.371     | 0.001 | 0.021 *    |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Galeus melastomus</i>   | 6  | 29 | 2.859     | 0.004 | 0.119      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Galeus melastomus</i>   | 18 | 29 | 0.883     | 0.377 | 1.000      |
| South   | CPUE n   | <i>Etmopterus pusillus</i> | <i>Galeus melastomus</i>   | 25 | 29 | 1.415     | 0.157 | 1.000      |
| South   | CPUE n   | <i>Etmopterus spinax</i>   | <i>Galeus melastomus</i>   | 24 | 29 | 1.078     | 0.281 | 1.000      |
| South   | CPUE n   | <i>Galeus atlanticus</i>   | <i>Galeus melastomus</i>   | 11 | 29 | 1.805     | 0.071 | 1.000      |
| South   | CPUE n   | <i>Dalatias licha</i>      | <i>Scymnodon ringens</i>   | 6  | 11 | 1.778     | 0.075 | 1.000      |
| South   | CPUE n   | <i>Deania profundorum</i>  | <i>Scymnodon ringens</i>   | 18 | 11 | -0.301    | 0.764 | 1.000      |
| South   | CPUE n   | <i>Dipturus oxyrinchus</i> | <i>Scymnodon ringens</i>   | 17 | 11 | 1.679     | 0.093 | 1.000      |
| South   | CPUE n   | <i>Etmopterus pusillus</i> | <i>Scymnodon ringens</i>   | 25 | 11 | 0.017     | 0.986 | 1.000      |
| South   | CPUE n   | <i>Etmopterus spinax</i>   | <i>Scymnodon ringens</i>   | 24 | 11 | -0.227    | 0.821 | 1.000      |
| South   | CPUE n   | <i>Galeus atlanticus</i>   | <i>Scymnodon ringens</i>   | 11 | 11 | 0.608     | 0.543 | 1.000      |
| South   | CPUE n   | <i>Galeus melastomus</i>   | <i>Scymnodon ringens</i>   | 29 | 11 | -1.073    | 0.283 | 1.000      |
| South   | CPUE kg  | <i>Galeus atlanticus</i>   | <i>Scymnodon ringens</i>   | 11 | 11 | 3.173     | 0.002 | 0.042 *    |
| South   | CPUE kg  | <i>Etmopterus spinax</i>   | <i>Scymnodon ringens</i>   | 24 | 11 | 3.164     | 0.002 | 0.044 *    |
| South   | CPUE kg  | <i>Etmopterus spinax</i>   | <i>Galeus melastomus</i>   | 24 | 29 | 3.158     | 0.002 | 0.044 *    |
| South   | CPUE kg  | <i>Galeus atlanticus</i>   | <i>Galeus melastomus</i>   | 11 | 29 | 3.029     | 0.002 | 0.069      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Galeus atlanticus</i>   | 18 | 11 | -2.515    | 0.012 | 0.333      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Etmopterus spinax</i>   | 18 | 24 | -2.442    | 0.015 | 0.409      |
| South   | CPUE kg  | <i>Dipturus oxyrinchus</i> | <i>Scymnodon ringens</i>   | 17 | 11 | 2.338     | 0.019 | 0.544      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Deania profundorum</i>  | 6  | 18 | 0.401     | 0.688 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Dipturus oxyrinchus</i> | 6  | 17 | -0.684    | 0.494 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Etmopterus pusillus</i> | 6  | 25 | -0.244    | 0.807 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Etmopterus spinax</i>   | 6  | 24 | -1.254    | 0.210 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Galeus atlanticus</i>   | 6  | 11 | -1.524    | 0.128 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Galeus melastomus</i>   | 6  | 29 | 0.667     | 0.505 | 1.000      |
| South   | CPUE kg  | <i>Dalatias licha</i>      | <i>Scymnodon ringens</i>   | 6  | 11 | 1.142     | 0.253 | 1.000      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Dipturus oxyrinchus</i> | 18 | 17 | -1.519    | 0.129 | 1.000      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Etmopterus pusillus</i> | 18 | 25 | -0.971    | 0.331 | 1.000      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Galeus melastomus</i>   | 18 | 29 | 0.367     | 0.713 | 1.000      |
| South   | CPUE kg  | <i>Deania profundorum</i>  | <i>Scymnodon ringens</i>   | 18 | 11 | 1.021     | 0.307 | 1.000      |
| South   | CPUE kg  | <i>Dipturus oxyrinchus</i> | <i>Etmopterus pusillus</i> | 17 | 25 | 0.679     | 0.497 | 1.000      |
| South   | CPUE kg  | <i>Dipturus oxyrinchus</i> | <i>Etmopterus spinax</i>   | 17 | 24 | -0.781    | 0.435 | 1.000      |
| South   | CPUE kg  | <i>Dipturus oxyrinchus</i> | <i>Galeus atlanticus</i>   | 17 | 11 | -1.159    | 0.246 | 1.000      |
| South   | CPUE kg  | <i>Dipturus oxyrinchus</i> | <i>Galeus melastomus</i>   | 17 | 29 | 2.043     | 0.041 | 1.000      |
| South   | CPUE kg  | <i>Etmopterus pusillus</i> | <i>Etmopterus spinax</i>   | 25 | 24 | -1.614    | 0.107 | 1.000      |
| South   | CPUE kg  | <i>Etmopterus pusillus</i> | <i>Galeus atlanticus</i>   | 25 | 11 | -1.830    | 0.067 | 1.000      |

(continued on next page)

Table A2 (continued)

| Subarea   | Variable | Species 1                        | Species 2                     | n1 | n2 | statistic | p     | p-adjusted |
|-----------|----------|----------------------------------|-------------------------------|----|----|-----------|-------|------------|
| South     | CPUE kg  | <i>Etmopterus pusillus</i>       | <i>Galeus melastomus</i>      | 25 | 29 | 1.504     | 0.133 | 1.000      |
| South     | CPUE kg  | <i>Etmopterus pusillus</i>       | <i>Scymnodon ringens</i>      | 25 | 11 | 1.910     | 0.056 | 1.000      |
| South     | CPUE kg  | <i>Etmopterus spinax</i>         | <i>Galeus atlanticus</i>      | 24 | 11 | -0.552    | 0.581 | 1.000      |
| South     | CPUE kg  | <i>Galeus melastomus</i>         | <i>Scymnodon ringens</i>      | 29 | 11 | 0.792     | 0.428 | 1.000      |
| Southwest | CPUE kg  | <i>Dipturus nidarosiensis</i>    | <i>Etmopterus pusillus</i>    | 9  | 6  | -4.020    | 0.000 | 0.002 **   |
| Southwest | CPUE kg  | <i>Dipturus nidarosiensis</i>    | <i>Galeus atlanticus</i>      | 9  | 5  | -3.983    | 0.000 | 0.002 **   |
| Southwest | CPUE kg  | <i>Deania profundorum</i>        | <i>Dipturus nidarosiensis</i> | 9  | 9  | 3.731     | 0.000 | 0.005 **   |
| Southwest | CPUE kg  | <i>Etmopterus pusillus</i>       | <i>Scymnodon ringens</i>      | 6  | 10 | 3.367     | 0.001 | 0.021 *    |
| Southwest | CPUE kg  | <i>Galeus atlanticus</i>         | <i>Scymnodon ringens</i>      | 5  | 10 | 3.363     | 0.001 | 0.022 *    |
| Southwest | CPUE kg  | <i>Dipturus nidarosiensis</i>    | <i>Galeus melastomus</i>      | 9  | 10 | -3.303    | 0.001 | 0.027 *    |
| Southwest | CPUE kg  | <i>Deania profundorum</i>        | <i>Scymnodon ringens</i>      | 9  | 10 | 3.001     | 0.003 | 0.075      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Galeus atlanticus</i>      | 6  | 5  | -2.636    | 0.008 | 0.235      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Etmopterus pusillus</i>    | 6  | 6  | -2.585    | 0.010 | 0.272      |
| Southwest | CPUE kg  | <i>Galeus melastomus</i>         | <i>Scymnodon ringens</i>      | 10 | 10 | 2.544     | 0.011 | 0.307      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Galeus atlanticus</i>      | 6  | 5  | -2.450    | 0.014 | 0.400      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Etmopterus pusillus</i>    | 6  | 6  | -2.390    | 0.017 | 0.471      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Deania profundorum</i>     | 6  | 9  | -2.149    | 0.032 | 0.885      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Deania calceus</i>         | 6  | 6  | 0.195     | 0.845 | 1.000      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Deania profundorum</i>     | 6  | 9  | -1.936    | 0.053 | 1.000      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Dipturus nidarosiensis</i> | 6  | 9  | 1.401     | 0.161 | 1.000      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Galeus melastomus</i>      | 6  | 10 | -1.509    | 0.131 | 1.000      |
| Southwest | CPUE kg  | <i>Centroselachus crepidater</i> | <i>Scymnodon ringens</i>      | 6  | 10 | 0.694     | 0.487 | 1.000      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Dipturus nidarosiensis</i> | 6  | 9  | 1.188     | 0.235 | 1.000      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Galeus melastomus</i>      | 6  | 10 | -1.727    | 0.084 | 1.000      |
| Southwest | CPUE kg  | <i>Deania calceus</i>            | <i>Scymnodon ringens</i>      | 6  | 10 | 0.476     | 0.634 | 1.000      |
| Southwest | CPUE kg  | <i>Deania profundorum</i>        | <i>Etmopterus pusillus</i>    | 9  | 6  | -0.683    | 0.495 | 1.000      |
| Southwest | CPUE kg  | <i>Deania profundorum</i>        | <i>Galeus atlanticus</i>      | 9  | 5  | -0.830    | 0.406 | 1.000      |
| Southwest | CPUE kg  | <i>Deania profundorum</i>        | <i>Galeus melastomus</i>      | 9  | 10 | 0.524     | 0.600 | 1.000      |
| Southwest | CPUE kg  | <i>Dipturus nidarosiensis</i>    | <i>Scymnodon ringens</i>      | 9  | 10 | -0.827    | 0.408 | 1.000      |
| Southwest | CPUE kg  | <i>Etmopterus pusillus</i>       | <i>Galeus atlanticus</i>      | 6  | 5  | -0.171    | 0.865 | 1.000      |
| Southwest | CPUE kg  | <i>Etmopterus pusillus</i>       | <i>Galeus melastomus</i>      | 6  | 10 | 1.164     | 0.245 | 1.000      |
| Southwest | CPUE kg  | <i>Galeus atlanticus</i>         | <i>Galeus melastomus</i>      | 5  | 10 | 1.286     | 0.199 | 1.000      |

## Data availability

Data will be made available on request.

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