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Vulnerability of elasmobranchs caught as bycatch in the grouper longline fishery in the Gulf of Gabès, Tunisia

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Abstract

The present study aims to quantify the effect of the grouper demersal longline fishery to elasmobranchs in the Gulf of Gabès to support future conservation actions for the most vulnerable species. Data from 162 demersal longline sets carried out during the grouper fishing seasons in 2016 and 2017 were analyzed. At least 17 elasmobranch species were caught, representing about 50% of the total catch in number which exceeded the target catch of groupers *Epinephelus* spp. (44.15%). Elasmobranchs were present in 139 (85.80%) out of the 162 examined sets, while the frequency of occurrence per set varied greatly depending on the species. The nominal Catches Per Unit Effort of all species combined was 3.07 specimens per 1,000 hooks/hour of fishing. Sharks and batoids contributed equally to the total elasmobranch catch, comprising 51.84% and 48.16% in terms of number, respectively. *Mustelus mustelus*, *Carcharhinus plumbeus* and *Squalus* spp. were the most abundant species, representing 45.65% of the total elasmobranch catch, whereas the remaining shark species were rarely caught (6.19%). Batoids were dominated by *Glaucostegus cemiculus*, which represented 19.07% of the total elasmobranch catch in number, followed by *Dasyatis* spp. (8.91%), *Raja clavata* (7.1%) and *Taeniura grabata* (4.59%). The elasmobranchs discarded due to their low commercial value and/or small size represented 11.34% of the total catch in number. According to the results of the Productivity and Susceptibility Analysis, the coastal viviparous elasmobranch species in the study area are highly vulnerable to the grouper longline fishery activity and should be carefully managed to reduce the likelihood of overfishing.

Keywords: bycatch; demersal longline; elasmobranchs; Mediterranean Sea; vulnerability.

Introduction

Elasmobranchs are exploited worldwide either as targeted species of specific fisheries or, more often, as bycatch of fisheries targeting other commercial resources (Stevens *et al*., 2000; Worm *et al*., 2013; Carpentieri *et al*., 2021). The impact of fisheries on elasmobranchs is an increasingly prominent international concern considering their high population decline rates (Camhi *et al*., 2009; Dulvy *et al*., 2014). Although the Mediterranean Sea hosts the world's highest proportion of threatened elasmobranch species due to unregulated fishing (Dulvy *et al*., 2014), few quantitative assessments about the impact of fishing on their populations have been conducted in this region (Carpentieri *et al*., 2021). In this area, elasmobranchs have suffered significant declines in abundance and diversity, attributed to the combined effects of the high fishing pressure, pollution and habitat degradation (Ferretti *et al*., 2008, 2013; Maynou *et al*., 2011; Barausse *et al*., 2014; Colloca *et al*., 2017; Bradai *et al*., 2018). Furthermore, the low economic value historically assigned to elasmobranchs has led to a paucity of studies focusing on their fisheries, life histories and stock assessments (Bradai *et al*., 2012).

Management efforts to improve the sustainability of elasmobranch captures in the Mediterranean Sea are hampered by the lack of information on their fisheries, biology, and species-specific landing statistics (Bradai *et al*., 2018; Cashion *et al*., 2019). Moreover, conservation actions are complicated largely by the prevalence of small-scale fisheries, which are ubiquitous throughout the coastal waters, unmonitored and unmanaged. Small-scale fisheries use a wide variety of fishing gears, including trammel nets, gillnets and longlines, which all have the potential to severely impact elasmobranchs (Echwikhi *et al*., 2013; Saidi *et al*., 2016; Tiralongo *et al*., 2018; Lloret *et al*., 2020; Bousquet *et al*., 2022). These fisheries may be among the largest current threats to elasmobranchs because of the considerable spatial overlap in fishing activity and several shark and batoid species distributions

(Moore *et al*., 2010; Alfaro-Shigueto *et al*., 2011; Saidi *et al*., 2016; Lloret *et al*., 2020). Nevertheless, most studies about the effect of fisheries on the elasmobranch bycatch in the Mediterranean Sea focus on pelagic longline and trawl fisheries, resulting in a scarcity of information on the elasmobranch bycatch in small-scale fisheries (Saidi *et al*., 2016; Lloret *et al*., 2020).

In the Gulf of Gabès, 27 shark and 21 batoid species have been recorded till present, most of them found in favorable conditions to reproduce and develop (Bradai *et al*., 2005; Enajjar *et al*., 2015). Although this area is the most heavily impacted fishing area along the Tunisian coasts due to the intense fishing activities, which have been proven to threaten elasmobranch species (Bradai *et al*., 2006; Echwikhi *et al*., 2013, 2014; Saidi *et al*., 2016, 2019; Béjaoui *et al*., 2019), the fishery impacts on elasmobranchs have received little attention (Saidi *et al*., 2016). It has been reported that demersal longlines targeting groupers *Epinephelus* spp. in the Gulf of Gabès also caught threatened species such as sea turtles and elasmobranchs because of the high degree of spatial overlap between the fishing grounds and the habitats of these species (Jribi *et al*., 2008; Echwikhi *et al*., 2014). Thus, assessing the effect of demersal longline fisheries on elasmobranch populations is essential for their conservation.

Available information from the Gulf of Gabès indicates that elasmobranch landings have been declining since the late 2000s under intense fishing pressure (Echwikhi *et al*., 2013; Saidi *et al*., 2019). However, the vulnerability of these species is unknown. Added to that, there are no management strategies to ensure the sustainability of their populations. Given the need for improving data collection about these species to enhance management, the purpose of this study is to determine the elasmobranch composition in the demersal longline fishery, and to estimate their Catch Per Unit of Effort (CPUE) and length-frequency structure by species. Additionally, a Productivity and Susceptibility Analysis (PSA) is conducted to identify which species are most vulnerable to the grouper longline fishery considering the available biological and fishery information.

Material and Methods

Study area

The study area is located in the central Mediterranean Sea, and specifically in the southern Tunisian coast between 33°-35°N and 10°-12.5°E (Fig. 1). The Gulf of Gabès is known for its wide and shallow topographical continental shelf; 60 m depth occurs at 110 km distance from the coast. It is the most important fishing area that comprises about 50% of the Tunisian fishing fleet and contributes to almost 50% of the national fish production (Béjaoui *et al*., 2019). The Gulf of Gabès is recognized as an elasmobranch biodiversity “hotspot” within the Mediterranean Sea (Bradai *et al*., 2006; Enajjar *et al*., 2015).

Fishery description

In the Gulf of Gabès, the demersal longline fleet consists of small wooden vessels ranging from 8 to 15 m in length, including 4 to 5 crew members each. This artisanal fleet is very heterogeneous and switches between gears according to the season, the economic profit, and/or the competition with other vessels. The demersal long-

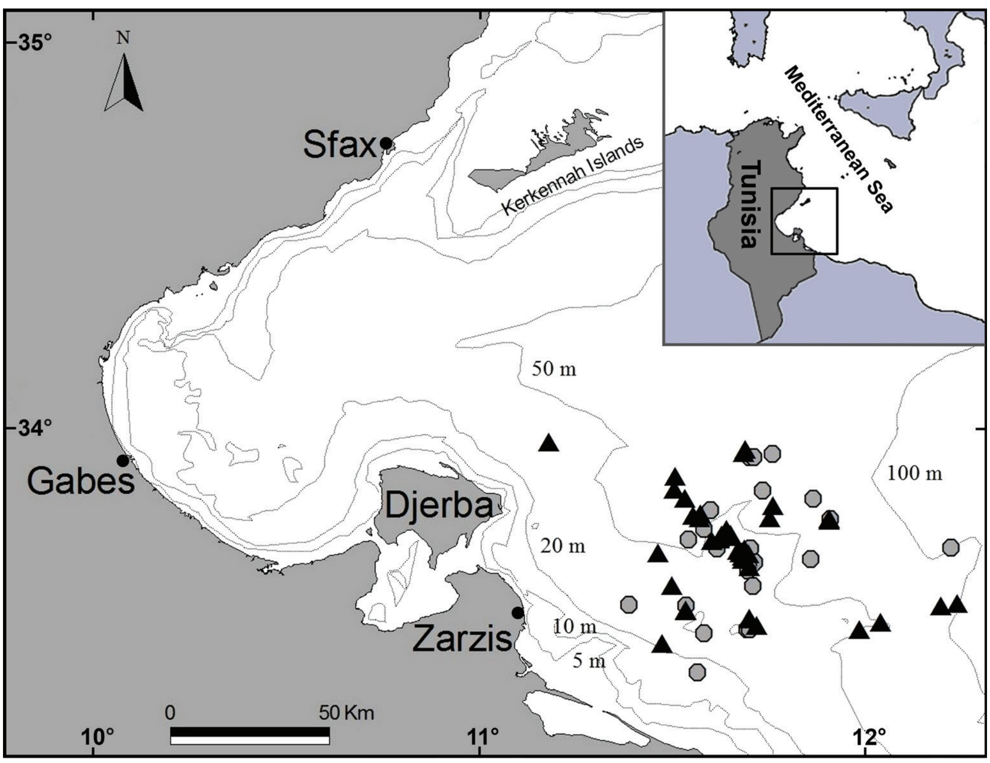

Fig. 1: Map showing the location of the grouper demersal longline sets surveyed during 2016 (▲) and 2017 (●) in the Gulf of Gabès.

line targets groupers (*Epinephelus* spp.) during summer. In other seasons, fishers target other species or switch longlines to other gears such as trammel nets.

The demersal longline consists of 7 to 15 km of braided polyamide mainline anchored to the bottom and suspended by a series of single nylon monofilament branchlines separated by a distance of about 6 m. Each branchline is 1-1.5 m long and 1.4 mm in diameter, which ends with a single baited J hook. Each fishing boat uses from 1,000 to 2,500 hooks, contained in 3 to 5 boxes. The hooks used to target groupers are 78 mm long and 41 mm wide (size 04). Sets are performed during daylight hours and their duration varies from 2 to 4 hours. The bait used usually is the round sardinella *Sardinella aurita* Valenciennes, 1847.

Data collection

Data were collected by observers on board fishing vessels recognized as part of the demersal longline fleet during the two consecutive fishing periods of 2016 and 2017. The boats were chosen randomly among vessels of the port of Zarzis (south of the Gulf of Gabès) where the majority of longliners targeting groupers are based. To obtain accurate information, observers were trained to collect information on gear characteristics, and to identify and record species, sex and size of all captured individuals. Observers had no influence on the choice of the fishing location and the organization of the fishing operations.

Observers collected information about each longline set including the setting position, the time of gear deployment and retrieval, the type of bait and the number of hooks deployed. The catch composition was recorded for all target and non-target species. For each set, elasmobranch specimens were identified to the lowest possible taxon (Supplementary Figure S1), enumerated, sexed and measured to the nearest mm. Standard measurements included the total length (TL) for sharks and disc width (DW) for batoids. Considering the taxonomic uncertainties within the genera *Dasyatis* and *Squalus* (Saadaoui *et al*., 2016; Kousteni *et al*., 2016, 2021; Ebert & Dando, 2020; Serena *et al*., 2020; Ferrari *et al*., 2021), two groupings were used: the brown stingray *Bathytoshia lata* (Garman, 1880), the common stingray *Dasyatis pastinaca* (Linnaeus, 1758) and the Tortonese's stingray *Dasyatis tortonesei* Capapé, 1975 were grouped into the species complex *Dasyatis* spp. while the longnose spurdog *Squalus blainville* (Risso, 1827) and the shortnose spurdog *Squalus megalops* (MacLeay, 1881) were grouped into the species complex *Squalus* spp. Finally, for each species, observers recorded if the specimens were landed, used for bait, released alive or discarded dead.

Data analysis

The nominal Catch Per Unit Effort (CPUE) was expressed as number of fish caught per 1,000 hooks per hour of fishing (individuals/1,000h/hour). CPUEs were calculated for each species in each fishing set (including sets with zero catches) and those values were used to calculate the mean CPUE with the respective confidence interval (C.I.).

The frequency of each species occurrence was calculated as the number of sets with the presence of at least one specimen in the catch out of the total number of sets. The data obtained served to quantify the interaction between demersal longline fishery and elasmobranch species.

In order to examine the impact of the demersal longline fishery on different life stages, examined specimens of each elasmobranch species were classified as neonate, juvenile or adult based on the available information about the species reproductive parameters in the area (Supplementary Table S1).

The hypothesis of parity in the sex-ratio was tested with chi-square (χ^2) statistics at a 95% confidence level. For species with specimens ≥10, the size composition by sex was evaluated for normality (Shapiro-Wilk test) and compared by using *t*-test or Mann-Whitney U test. The statistical significance was set at $P<0.05$.

Productivity and Susceptibility Analysis (PSA)

In order to assess the relative vulnerability of elasmobranch species captured by the demersal longline fishery in the study area, a Productivity Susceptibility Analysis (PSA) was conducted by species, following the framework described by Patrick *et al.* (2010) and modified by Duffy & Griffiths (2019) to avoid redundancy in the attributes.

Vulnerability (V) is expressed as a function of: (1) productivity (P) characterized by the life-history traits of each species (Hobday *et al*., 2011) and (2) susceptibility (S) characterized by how species are likely to be affected by the fishery in question (Patrick *et al*., 2010). Both parameters are combined to produce a single score that determines the stock status (Cortés *et al*., 2015). The values of P and S of each species were calculated by scoring a set of standardized attributes for each factor in a range of three-point scales, indicating low (1), medium (2) and high (3) values (Patrick *et al*., 2010). For P attributes, 1 indicates a relatively low productivity and high risk, and 3 indicates a relatively high productivity and low risk. Conversely, for S attributes, 3 points to relatively high susceptibility and high risk, and 1 indicates relatively low susceptibility and low risk (Patrick *et al*., 2010; Hobday *et al*., 2011).

A smaller list of attributes was used to facilitate the scoring of all species because basic information on several attributes is lacking for some species (Martínez -Candelas *et al*., 2020). Productivity was scored using six attributes (Table 1) to better distinguish between the life-history strategies of elasmobranchs (Osio *et al*., 2015; Furlong-Estrada *et al*., 2017). Duffy & Griffiths (2019) suggested the use of either size-based or age-based attributes, but not both of them to avoid redundancy as a

Table 1. Productivity (Hobday *et al*., 2011) and susceptibility (Patrick *et al*., 2010) attributes used to assess the vulnerability of elasmobranchs to the grouper longline fishery in the Gulf of Gabès.

Productivity	High (3)	Moderate (2)	Low (1)
Maximum size	<100 cm	100-200 cm	>200 cm
Growth coefficient (k)	>0.25	0.1-0.25	<0.1
Fecundity	>66 pups	34-66 pups	<34 pups
Maturity size ratio	<50 %	50-70%	>70%
Reproductive cycle	Biannual	Annual	Biennial
Average trophic level	<2.5	2.5-3.5	>3.5
Susceptibility	**Low (1)**	**Moderate (2)**	**High (3)**
Spatial overlap	<25% of stock present in the area fished.	25-50% of the stock present in the area fished.	>50% of stock present in the area fished.
Geographic concentration	Stock is concentrated in >50% of its total range.	Stock is concentrated in 25-50% of its total range.	Stock is concentrated in <25% of its total range.
Vertical overlap	<25% of stock present at the depth fished.	25-50% of the stock present at the depth fished.	>50% of stock present at the depth fished.
Management strategy	Catch limits and other measures for target populations. Non-target species are monitored.	Catch limits and other measures for target populations.	Target and incidental populations are not managed or monitored.
Seasonal migrations	Migrations decrease the fishery-species interaction.	Migrations do not affect the fishery-species interaction.	Migrations increase the fishery-species interaction.
Schooling and aggregation	Aggregations decrease the fishery-species interaction.	Aggregations do not affect the fishery-species interaction.	Aggregations increase the fishery-species interaction.
Species morphology	Species show low susceptibility to gear selectivity.	Species show moderate susceptibility to gear selectivity.	Species shows high susceptibility to gear selectivity.
Species value	Low or none	Moderate	High
Impact on essential fish habitats	Minimal or non-existent	High, but mitigated	High, but not mitigated

result of the correlation between attributes. In the present study, size-based attributes were chosen due to the availability of scientific information for most of the assessed species (Bradai *et al*., 2012; Tsikliras & Stergiou, 2014). All attributes were given equal weight to achieve parsimony (Duffy & Griffiths, 2019).

The values of P and S were plotted on an XY graph and the V value equaled the Euclidean distance between the origin and the coordinates of P and S (Patrick *et al*., 2010) according to the following formula:

$$V = \sqrt{(P - X_0)^2 + (S - Y_0)^2}$$

where X_0 and Y_0 are the (x, y) origin coordinates.

The PSA was conducted using the software PSA v.1.4 developed by NOAA and included in the Stock Assessment Toolbox (NOAA, 2010).

The overall P and S scores were divided into three categories (independently from the V scores): low (1-1.6), medium (1.6-2.2) and high (2.2-3). The V scores were divided into three categories: V≥2 for species with high vulnerability, 1.8≤ V<2.0 for species with medium vulnerability, and V<1.8 for species with low vulnerability (Cope *et al*., 2011).

PSA was performed only for the species represented by >7 individuals. Life-history information on the reproductive traits of each species was obtained from the studies conducted in the study area (Bradai *et al*., 2012) and other locations in the Mediterranean (Tsikliras & Stergiou, 2014, 2015).

Results

Fishing effort, Catch composition and Catch Per Unit Effort (CPUE)

The number of longline vessels fishing each year ranged from 20 to 30. During 2016 and 2017, observers were onboard for 45 trips and monitored 162 sets corresponding to 325,550 hooks and 327.5 hours of effective fishing aboard 19 vessels. A total of 97 and 65 sets were sampled during 2016 and 2017 which represents 11.66% and 8.68% of the sets estimated deployed by the entire fleet for the area and periods, respectively.

At least 17 species of sharks and batoids were identified as the component of the longline captures (Table 2). Ten of the captured elasmobranch species are characterized as threatened (Vulnerable, Endangered, and Critically Endangered) while two of them are Data Deficient and one is Not Evaluated in the Mediterranean according to the IUCN Red List of Threatened Species (Table 2).

Elasmobranchs constituted 49.30% of the total catches in terms of number, which exceeded the target catch

Table 2. Species composition, number of individuals caught (N), percentage of the catch in total and by elasmobranch species, frequency of occurrence and nominal Catch Per Unit Effort (CPUE, individuals/ 1,000 hooks/hour ± C.I) by species for the grouper demersal longline fishery in the Gulf of Gabès during 2016 and 2017. IUCN status in the Mediterranean Sea taken from the IUCN Red List of Threatened Species (Website: http://www.iucnredlist.org/ (Accessed on 19 October 2022; NE= Not Evaluated; LC = Least Concern, NT = Near Threatened, VU = Vulnerable, EN = Endangered, CR = Critically Endangered).

Species	N	Total catch (%)	Elasmobranch catch (%)	Sets with catch (%)	CPUE	Retained (%)	Discarded (%)	IUCN category (References)
Epinephelus spp.	1,287	44.15			1.50±0.36	100		
Other teleosts	191	6.55			0.31±0.13	100		
Teleosts (total)	**1,478**	**50.70**			**1.81±0.38**	100		
Carcharhinus brevipinna	7	0.24	0.49	4.32	0.02±0.01	100		NE
Carcharhinus plumbeus	140	4.80	9.74	21.60	0.33±0.13	100		EN (Ferretti *et al*., 2016)
Carcharodon carcharias	1	0.03	0.07	0.62	$0.01\ 10^{-4}$	100		CR (Soldo *et al*., 2016a)
Heptranchias perlo	37	1.27	2.57	3.70	0.07±0.06	100		DD (Soldo & Bariche. 2016)
Mustelus mustelus	280	9.61	19.49	40.12	0.53 ±0.17	100		VU (Farrell *et al*., 2016)
Mustelus punctulatus	27	0.93	1.88	6.17	0.13±0.12	100		VU (Dulvy *et al*., 2016)
Scyliorhinus canicula	17	0.58	1.18	5.55	0.07±0.05		100	LC (Serena *et al*., 2015)
Squalus spp.	236	8.10	16.42	7.41	0.25±0.21	100		DD (Soldo *et al*., 2016b)
***Sharks* (total)**	**745**	**25.56**	**51.84**	**52.47**	**1.39±0.33**	**97.72**	**2.28**	
Aetomylaeus bovinus	44	1.51	3.06	8.02	0.15±0.11	100		CR (Walls & Buscher. 2016)
Dasyatis spp.	128	4.39	8.91	25.31	0.20±0.08	88.20	11.80	VU (Serena *et al*., 2016a)
Glaucostegus cemiculus	274	9.40	19.07	20.37	0.52±0.23	100		EN (Notarbartolo di Sciara *et al*., 2016)
Gymnura altavela	10	0.34	0.70	3.70	0.01±0.01	100		CR (Walls *et al*., 2016)
Myliobatis aquila	1	0.03	0.07	0.62	$0.03\ 10^{-2}$	100		VU (Serena *et al*., 2016b)
Raja clavata	102	3.50	7.10	14.20	0.42±0.22	38.24	61.76	NT (Ellis *et al*., 2016)
Raja miraletus	3	0.10	0.21	1.85	0.01±0.01		100	LC (Dulvy *et al*., 2020)
Raja radula	64	2.20	4.45	9.88	0.17±0.10		100	EN (Mancusi *et al*., 2016)
Taeniura grabata	66	2.26	4.59	19.14	0.19±0.09	100		DD (Jung & Buscher. 2016)
***Batoids* (total)**	**692**	**23.74**	**48.16**	**46.90**	**1.68±0.40**	**79.05**	**20.95**	
***Elasmobranchs* (total)**	**1,437**	**49.30**	**100**	**85.80**	**3.07±0.57**	**88.73**	**11.27**	

of groupers *Epinephelus* spp. (44.15%). Elasmobranchs were present in 139 (85.80%) out of the 162 sets examined, whereas the frequency of occurrence varied greatly by set depending on species. Sharks and batoids comprised 51.84% and 48.16% of the elasmobranch catch in terms of number, respectively. Among sharks, the smooth-hound shark *Mustelus mustelus* (Linnaeus, 1758) was the primary species captured, accounting for 19.49% of the entire elasmobranch catch in number and occurring in 40.12% of the sets. The dogfishes *Squalus* spp. (16.42%) ranked second in the observed catch followed by the sandbar shark *Carcharhinus plumbeus* (Nardo, 1827) (9.74%) while the latter showed a higher frequency of occurrence than the former. The catch of batoids was dominated by the blackchin guitarfish *Glaucostegus cemiculus* (Geoffroy Saint-Hilaire, 1817) that represented 19.07% of the elasmobranch catch in number. The stingrays *Dasyatis* spp. ranked second (8.91%), the thornback ray *Raja clavata* Linnaeus, 1758 ranked third (7.10%), and the round stingray *Taeniura grabata* (Geoffroy Saint-Hilaire, 1817) ranked fourth (4.59%). These species were followed by the rough skate *Raja radula* Delaroche, 1809 (4.45%) and the bull ray *Aetomylaeus bovinus* (Geoffroy Saint-Hilaire, 1817) (3.06%). Nevertheless, the stingrays were the most frequently caught by set (25.31%) followed by *G. cemiculus* (20.37%), *T. grabata* (19.14%), *R. clavata* (14.20%) and *R. radula* (9.88%). The remaining elasmobranch species were rarely caught accounting all together 7.17% of the entire elasmobranch catch in number (Table 2).

The number of individuals captured per 1000 hooks/hour of fishing ranged from 0 to 20 (mean 3.07±0.57individuals/1000 hooks/hour). Among sets in which elasmobranchs were present, 57.14% had CPUE of 1-3 individuals/1000 hooks/hour, 17.14% had CPUE of 4-5 individuals, 18.57% had CPUE of 6-9 individuals, and 5.71% had CPUE >10 individuals. As regards CPUE, the primary captured species was *M. mustelus,* followed by *G. cemiculus*, representing together 38.56% of the elasmobranch catch in number. These two species were followed by three species with CPUEs higher than 0.2 individual per 1,000 hooks/hour, namely *C. plumbeus* (0.33), *Squalus* spp. (0.25) and *R. clavata* (0.42) (Table 2).

The elasmobranch catch in the demersal longline was incidental, but the main fraction of elasmobranchs (88.72% in number) was retained and landed for first-sale auctions (Table 2). Small-sized species such as the lesser spotted dogfish *Scyliorhinus canicula* (Linnaeus, 1758), the brown ray *Raja miraletus* Linnaeus, 1758 and *R. radula* were systematically discarded. Individuals of the remaining species were discarded back into the sea because of their low commercial value (90.18%) or their small size (9.82%).

Biological information

The size range of the elasmobranch species caught in the grouper longline fishery varied among species (Table 3). Demersal longline caught a broad size range of both *C. plumbeus* and *M. mustelus* including all life stages (Table.3). Although demersal longline catches contained a wide size range of the other species, they did not include the newborns of these species (Table.3). The size range revealed that the percentage of juveniles was the highest for most of the captured shark species, except *Squalus* spp. Conversely, apart from *G. cemiculus*, the captured size range of batoids included mainly adults (Table 3). In demersal longline, most adult females, mainly those of *C. plumbeus*, *M. mustelus* and *G. cemiculus* were pregnant carrying near term embryos or post-partum.

Most of the captured batoid species did not show significant sex-specific differences in terms of size distribution (Mann-Whitney U-test, $P>0.05$). On the contrary, the size composition of females and males differed significantly for the most common shark species, including *C. plumbeus*, *M. muselus* and *Squalus* spp. (Mann-Whitney U-test, $P < 0.05$) (Table 3).

Furthermore, for the majority of species, sex ratio did not differ significantly from the parity (χ^2 test, d.f. = 1, $P>0.05$). However, more females than males were recorded for the most abundant species *M. muselus*, *Squalus* spp., *Dasyatis* spp. and *G. cemiculus* (χ^2 test, $P<0.05$) (Table 3).

Productivity and Susceptibility Analysis (PSA)

Based on the available data, the vulnerability of the elasmobranch species caught in demersal longline fisheries is presented in Figure 2. A wide range of productivity (P=1.17-2.17) and susceptibility (S=1.44-2.44) scores was observed (Table 4, Fig. 2).

The P scores clearly separated the oviparous elasmobranch species (*S. canicula, R. clavata* and *R. radula*) having medium values (P=1.83-2.17) from the remaining viviparous species (Fig. 2). All viviparous species were grouped towards the lowest end of the P scale (P=1.17-1.67).

Considering the S scores, coastal species were more susceptible to the demersal_longline fishery, although most species were intermediately susceptible (Table 4, Fig. 2). High S scores were obtained for the common coastal species *C. plumbeus*, the blackspotted smooth-hound *Mustelus punctulatus* Risso, 1827, *M. mustelus*, *Dasyatis* spp., *A. bovinus* and *G. cemiculus*, which were the major bycatch species of the demersal longline fishery in the Gulf of Gabès, representing more than 60% of the elasmobranch catches in terms of number (Table 2). Nevertheless, 50% of the species received moderate S scores (Table 4, Fig. 2).

Five out of the 14 species involved in the PSA analysis were classified as having the lowest vulnerability, 3 of them were identified with moderate vulnerability and 6 showed the highest vulnerability (Fig. 2, Table 4). The group with high vulnerability to the demersal longline fishery included two large coastal shark species belonging to the genus *Carcharhinus*, one small coastal shark (*M. mustelus*), and three batoid species, *G. cemiculus*, *A bovinus* and *T. grabata* (Table 4). The medium-vulnera-

Table 3. Number of individuals by sex, mean total length for sharks and disc width for batoids with size range, sex ratio and percentage of each life stage of main elasmobranch species captured in grouper demersal longline fishery in the Gulf of Gabès during 2016 and 2017. Significant values (P<0.05) are indicated in bold

Species	Sex	N	Mean length; Range (cm)	Mann-Whitney U-test	Sex ratio	Life stages in catch (%)		
						Newborns	Juveniles	Adults
Carcharhinus brevipinna	F	3	146.37; 103-206	-	χ^2=0.14; p>0.05	0	66.67	33.33
	M	4	151.38; 124-184			0	75.00	25.00
Carcharhinus plumbeus	F	81	125.43; 65-214	**U=1402.50; p<0.05**	χ^2=3.46; p>0.05	5.94	70.60	23.46
	M	59	99.73; 59-173			10.17	83.05	6.78
Heptranchias perlo	F	28	95.08; 74-109	U=51.5; p>0.05	**χ^2=9.76; p<0.05**	0	53.57	46.43
	M	9	94.25; 84-108			0	44.44	55.56
Mustelus mustelus	F	179	94.10; 50-160	**U=731; p<0.05**	**χ^2=21.73; p<0.05**	7.92	74.26	17.82
	M	101	73.24; 45-137			4.47	56.42	39.11
Mustelus punctulatus	F	15	98.67; 60-120	**U=9; p<0.05**	χ^2=0.33; p>0.05	0	13.33	86.67
	M	12	86.75; 70-100			0	16.67	83.33
Scyliorhinus canicula	F	6	34.67; 19-40	U=22.5; p>0.05	χ^2=1.47; p>0.05	0	66.67	33.33
	M	11	30.82; 21-38			0	36.36	63.64
Squalus spp.	F	150	73.23; 60-92	**U=61.5; p<0.05**	**χ^2=17.36; p<0.05**	0	8.00	92.00
	M	86	58.52; 48-67			0	3.57	96.43
Aetomylaeus bovinus	F	31	110.00; 40-148	U=474; p>0.05	χ^2=7.36; p<0.05	0	22.58	77.42
	M	13	91.20; 59-153			0	38.46	61.54
Dasyatis spp.	F	89	49.64; 25-70	U=389.5; p>0.05	**χ^2=19.53; p<0.05**	0	37.93	62.07
	M	39	40.22; 20-60			0	40.54	59.46
Glaucostegus cemiculus	F	154	119.62; 54-180	U=4147.5; p>0.05	**χ^2=4.22; p<0.05**	0	70.13	29.87
	M	120	103.23; 55-161			0	42.50	57.50
Gymnura altavela	F	4	120.00; 108-142	**U=2; p<0.05**	χ^2=0.40; p>0.05	0	0	100
	M	6	96.00; 87-116			0	0	100
Raja clavata	F	63	43.82; 30-66	U=601.5; p>0.05	**χ^2=5.65; p<0.05**	0	42.86	57.14
	M	39	39.12; 25-56			0	35.90	64.10
Raja radula	F	38	42.39; 20-50	U=213.5; p>0.05	χ^2=2.25; p>0.05	0	13.16	86.84
	M	26	38.95; 20-50			0	24.00	76.00
Taeniura grabata	F	36	66.58; 38-134	U=474; p>0.05	χ^2=0.55; p>0.05	not available		
	M	30	63.97; 35-102					

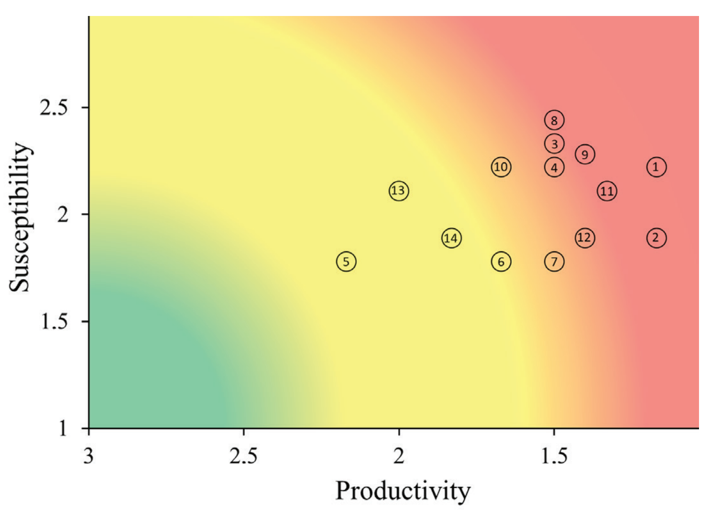

Fig. 2: Productivity, susceptibility and vulnerability scores of elasmobranch species caught by the grouper demersal longline fishery in the Gulf of Gabès. Numbers correspond to elasmobranch species as listed in Table 4. The colors represent the relative vulnerability: the green areas being the lowest, the yellow ones being the moderate and the red areas being the highest.

Table 4. Productivity (P), Susceptibility (S) and Vulnerability (V) values for the elasmobranch bycatch of the grouper demersal longline fishery in the Gulf of Gabès. Information about the mode of reproduction and habitat preference for each species is included.

	Species	Reproductive mode	Habitats	P	S	V
1	*Carcharhinus plumbeus*	Placental viviparous	Pelagic on coastal and oceanic zones	1.17	2.22	2.20
2	*Carcharhinus brevipinna*	Placental viviparous	Pelagic on coastal and oceanic zones	1.17	1.89	2.03
3	*Mustelus mustelus*	Placental viviparous	Demersal on coastal zone	1.50	2.33	2.00
4	*Mustelus punctulatus*	Placental viviparous	Demersal on coastal zone	1.50	2.22	1.93
5	*Scyliorhinus canicula*	Oviparous	Demersal on coastal zone	2.17	1.78	1.14
6	*Squalus* spp.	Aplacental viviparous	Demersal on coastal and oceanic zones	1.67	1.78	1.54
7	*Heptranchias perlo*	Aplacental viviparous	Epibenthic on oceanic zone	1.50	1.78	1.69
8	*Glaucostegus cemiculus*	Aplacental viviparous	Benthic on coastal zone	1.50	2.44	2.08
9	*Aetomylaeus bovinus*	Aplacental viviparous	Benthopelagic on coastal zone	1.40	2.28	2.05
10	*Dasyatis* spp.	Aplacental viviparous	Demersal on coastal zone	1.67	2.22	1.80
11	*Taeniura grabata*	Aplacental viviparous	Demersal on coastal zone	1.33	2.11	2.01
12	*Gymnura altavela*	Aplacental viviparous	Demersal on coastal zone	1.40	1.89	1.83
13	*Raja clavata*	Oviparous	Demersal on coastal to bathyal zone	2.00	2.11	1.49
14	*Raja radula*	Oviparous	Demersal on coastal zone	1.83	1.89	1.47

bility group included primarily species with low productivity, but with intermediate to high susceptibility to the longline fishery (Table 4).

Discussion

The incidental capture of non-target species during fishing operations constitutes a major threat to elasmobranchs worldwide. Nevertheless, qualitative and quantitative data about the bycatch of these species in the Mediterranean Sea is still limited (Bradai *et al*., 2018; Carpentieri *et al*., 2021). Furthermore, in the Mediterranean Sea, most studies on bycatch of elasmobranch species focus on trawl and pelagic longline fisheries, leaving a gap in studies on the bycatch composition of small-scale fisheries (Saidi *et al*., 2016; Tiralongo *et al*., 2018; Lloret *et al*., 2020), which have recently represented an important cause of mortality for marine vertebrates (Moore *et al*., 2010; Mancusi *et al*., 2020). Small-scale fisheries, operating in coastal waters worldwide, have direct impacts on elasmobranchs since numerous species utilize shallow water environments as birthing, nursery and/or feeding grounds (Peckham *et al*., 2007; Speed *et al*., 2010; Dulvy *et al*., 2014; Saidi *et al*., 2016). The present study provides an evaluation of the bycatch effect on different elasmobranch species in relation to the demersal longline fishery targeting groupers in the Gulf of Gabès, an elasmobranch biodiversity "hotspot" in the Mediterranean Sea.

The investigation revealed that at least 17 elasmobranch species were caught by this type of fishery, accounting for more than 38.6% of the species diversity reported in the study area (Bradai *et al*., 2006). Among these species, only 6, *C. plumbeus*, the spinner shark *Carcharhinus brevipinna* (Valenciennes, 1839), *M. mustelus, M. punctulatus, G. cemiculus* and *R. radula,* were recorded during the inspection of the same type of fishery during 2007 and 2008 (Echwikhi *et al*., 2014). Additionally, the number of captured species is greater than those reported in other demersal longline fisheries in the Mediterranean Sea (Table 5): 6 species were caught in Cycladic waters, southern Aegean Sea (Stergiou *et al*., 2002), 3 species were caught in the Gökova Bay, south-eastern Aegean Sea (Gülşahin & Soykan, 2017), 3 species were captured in the Izmir Bay, eastern Aegean Sea (Ceyhan *et al*., 2010), and 7 shark species were caught off the Catalan coasts (Nuez *et al*., 2021). In a similar way, studies in the Adriatic Sea reported lower diversity of elasmobranch species captured by the demersal longline fisheries ranging between 4 and 6 sharks and rays (Ungaro *et al*., 2005; Carluccio *et al*., 2021). Elsewhere in the north-western Ionian Sea, 8 species were collected by means of an experimental study of bottom longline (Carluccio *et al*., 2021). Furthermore, at least 15 species were caught by demersal longlines off the Lebanese coasts (Lteif, 2015). The differences in species diversity could be related to the species biology (e.g., distribution, reproductive periodicity), the positioning and depth of the species in the water, fishing technique and strategy, the environmental conditions and fishing grounds as well as to dissimilar fishing efforts between areas (Rincón-Sandoval *et al*., 2019).

In the present study, the elasmobranch species composition of the bycatch reported from the demersal longline fisheries was typical for those inhabiting the continental

Table 5. List of elasmobranch species captured incidentally by demersal longlines in different areas of the Mediterranean Sea. Stingrays (*Bathytoshia lata*, *Dasyatis pastinaca* and *Dasyatis tortonesei*) were grouped into the species complex *Dasyatis* spp., and dogfish sharks (*Squalus megalops* and S*qualus blainville*) were grouped into the species complex *Squalus* spp.

Species	**Present study**	**South Aegean Sea (Stergiou *et al*., 2002)**	**Southern Adriatic Sea (Ungaro *et al*., 2005)**	**Eastern Aegean Sea (Ceyhan *et al*., 2010)**	**Southeastern Aegean Sea (Gülşahin & Soykan, 2017)**	**Lebanese coasts (Lteif, 2015)**	**Southern Adriatic Sea (Carluccio *et al*., 2021)**	**North-Western Ionian Sea (Carluccio *et al*., 2021)**	**Catalan coasts (Nuez *et al*., 2021)**
Aetomylaeus bovinus	+					+			
Alopias vulpinus									+
Carcharhinus brevipinna	+								
Carcharhinus plumbeus	+								
Carcharhinus obscurus						+			
Carcharodon carcharias	+								
Centrophorus granulosus						+	+	+	
Cetorhinus maximus									+
Dalatias licha							+		
Dasyatis spp.	+				+	+			
Dipturus oxyrinchus						+		+	
Etmopterus spinax							+	+	
Galeorhinus galeus									+
Galeus melastomus			+			+	+	+	
Glaucostegus cemiculus	+					+			
Gymnura altavela	+					+			
Heptranchias perlo	+								
Hexanchus griseus			+			+			+
Isurus oxyrinchus									+
Leucoraja circularis								+	
Leucoraja fullonica								+	
Mustelus mustelus	+	+	+	+	+	+			
Mustelus punctulatus	+								
Myliobatis aquila	+			+					
Prionace glauca								+	+
Pteroplatytrygon violacea						+	+	+	
Raja clavata	+	+		+	+				
Raja miraletus	+	+							
Raja radula	+	+							
Raja spp.			+						
Rhinobatos rhinobatos						+			
Scyliorhinus canicula	+	+					+		
Squalus acanthias									+
Squalus spp.	+					+			
Squatina oculata						+			
Taeniura grabata	+					+			
Torpedo marmorata		+				+			

shelf, including species typically demersal such as *Mustelus* spp., *Squalus* spp., *Dasyatis* spp., *Raja* spp. and *G. cemiculus* (Lteif, 2015; Gülşahin & Soykan, 2017; Carluccio *et al*., 2021; Bousquet *et al*., 2022). Although demersal longlines tend to catch more demersal species of elasmobranch, some sporadic catches of pelagic species were reported including the great white *Carcharodon carcharias* (Linnaeus, 1758) and the pelagic stingray *Pteroplatytrygon violacea* (Bonaparte, 1832) (Table 4). These captures could be related to the fact that these species conduct diel vertical migration cycles, which makes them susceptible to demersal longline (Speed *et al*., 2010; Andrzejaczek *et al.*, 2022). Moreover, these species could have been caught in the pelagic zone during setting or hauling operations.

Even though there is no demersal longline fishery targeting sharks or batoids in the Gulf of Gabès, it generates significant amounts of elasmobranch bycatch, which represented about 50% of the total catch in number. The highest proportion of elasmobranch bycatch is consistent with previous results obtained in the same area during 2007 and 2008 (Echwikhi *et al*., 2014). On the other hand, the amount of elasmobranchs caught by the demersal longline in the study area is quite high compared to other Mediterranean areas such as the Aegean Sea (Stergiou *et al*., 2002), the Gökova Bay (Gülşahin & Soykan, 2017), the Adriatic Sea (Ungaro *et al*., 2005; Carluccio *et al*., 2021), and Corsica (Bousquet *et al*., 2022). These differences could be related to several parameters including the environment, species abundance, configuration of the fishing gear, fishing ground, hook size, bait type and soak time (Rincón-Sandoval *et al*., 2019).

Although the bycatch was highly diverse, at least 6 species dominated the catch of the present study (*C. plumbeus*, *M. mustelus*, *Squalus* spp., *G. cemiculus*, *R. clavata* and *Dasyatis* spp.), comprising more than 80% of the total elasmobranch catches. The predominance of these species was consistent with the current knowledge about their distribution and abundance in the area studied (Bradai *et al*., 2006; Echwikhi *et al*., 2014; Enajjar *et al*., 2015). Additionally, *C. plumbeus*, *M. mustelus*, and *G. cemiculus* use the area as primary and secondary nursery grounds (Enajjar *et al*., 2015). Alternatively, this dominance could be ascribed to the selectivity of the gear, the configuration of the fishing gear and the hook depth (Pennino *et al*., 2016; Rincón-Sandoval *et al*., 2019).

There is no available long-term catch data that can be examined for changes in the catch rates of elasmobranch species in the Gulf of Gabès. However, the analysis of the historical series of shark and batoid landings in Zarzis showed that a significant decline followed the maximum of 2002 (Saidi *et al*., 2019). Furthermore, fishery-dependent data from pelagic longline surveys indicated nearly 40% decrease in catch rates of elasmobranchs over a decade in the same area (Saidi *et al*., 2019). The negative temporal trend for elasmobranch species in the Gulf of Gabès is in line with the general decrease in the Mediterranean population of sharks observed during the last 50 years (Ferretti *et al*., 2008, 2013; Colloca *et al*., 2017), perceived by the fishers (Maynou *et al*., 2011) and clearly correlated with the increasing trend regarding the fishing effort (Dell'Apa *et al*., 2012; Barausse *et al*., 2014). This could be attributed to the population declines in the Mediterranean species due to the regional fishing activity (Ferretti *et al*., 2008). Other factors that could explain these differences include variation in sampling methodology, fishing ground, and fishing effort.

The size range of most species reported in the present study showed that the demersal longline catches are mainly consisted of juvenile sharks and adult batoids. On the other hand, all life stages of *C. plumbeus* and *M. mustelus* were present in the continental shelf where longliners operated. Similar size and life stage characteristics for most shark and batoid species were observed during fishery-independent investigations conducted in the study area (Echwikhi *et al*., 2013, 2014; Saidi *et al*., 2019). The demersal longline fishery period overlaps with the parturition period of most species in the area (Bradai *et al*., 2012). Furthermore, the extremely wide continental shelf in the Gulf of Gabès provides an extended habitat that is used as a nursery area for some species (Bradai *et al*., 2005; Enajjar *et al*., 2015). This could explain the capture of all life-history stages in the case of *C. plumbeus* and *M. mustelus* and suggests that this type of fishery may opportunistically operate in breeding or nursery areas. As such, the demersal longline fishery may be among the greatest current threats to the elasmobranch populations in the Gulf of Gabès, and further monitoring is needed to avoid future stock depletion of such a vital resource.

Conventional stock assessment methods that normally allow a quantitative evaluation of fish stocks are difficult to be used for elasmobranch species because biological information is still insufficient (Furlong-Estrada *et al*., 2017). The PSA is a semi-quantitative method, which is particularly useful in data-poor situations. The PSA has been recommended to study elasmobranchs since it estimates vulnerability based on a simplified understanding of their biological characteristics and their interaction with fisheries (Gallagher *et al*., 2012; Furlong-Estrada *et al*., 2017; Clarke *et al*., 2018). Furthermore, the PSA estimates the relative vulnerability between species to a fishery with the scope to prioritize monitoring, assessment and management of stocks (Hobday *et al*., 2011).

The PSA on the elasmobranch bycatch of the grouper demersal longline fishery in the Gulf of Gabès showed that 9 species had high to intermediate vulnerability to this type of fishery (Table 4). These species shared common traits, including low fecundity, delayed maturity, high spatial overlap with fishing grounds, low mobility and bottom-dwelling habits. Furthermore, these species are known to approach the coast to breed during spring and summer, increasing their susceptibility. These observations are consistent with the results of the PSA conducted for the otter trawl fishery in the Mediterranean Sea, which also identified most elasmobranch species as highly vulnerable, while few species were found to be less vulnerable (Abella *et al*., 2011; Osio *et al*., 2015; Serena *et al*., 2018). In these studies, the demersal species were found to be most vulnerable primarily because of their high susceptibility to bottom-trawl fisheries (Abella *et al*., 2011; Osio *et al*., 2015; Serena *et al*., 2018). Sharks and batoids are fundamentally vulnerable due to their intrinsic life-history characteristics making them less resilient to fishing pressure (Stevens *et al*., 2000). These characteristics result in very low rates of population increase with little capacity to recover from overfishing, and habitat loss and degradation (Dulvy *et al*., 2014).

In the present study, the difference in vulnerability among species appears to be driven more by susceptibility than by productivity for the type of examined fishery. Indeed, species with significant susceptibility scores ranked higher in terms of overall vulnerability. The species classification as moderately and highly vulnerable resulted from their low reproductive potential and high susceptibility to the demersal longline fishery. These findings are in line with results of previous studies indicating that elasmobranchs are particularly vulnerable due to their high susceptibility to the fishing gear (Abella *et al*., 2011; Osio *et al*., 2015; Serena *et al*., 2018). Moreover, species with low vulnerability scores (*S. canicula*) were no longer abundant as bycatch, while species with medium to high vulnerability scores (*C. plumbeus*, *M. mustelus*, *G. cemiculus*) dominated in the elasmobranch bycatch. The dominant species in the longline fishery catch were mainly coastal. High susceptibility probably results from the fishing ground, which overlaps with the distribution of these species as they approach coasts to reproduce during warmer months (Enajjar *et al*., 2015). In addition, these species are inherently vulnerable due to their biological characteristics coupled with high market values (Bradai *et al*., 2018). As recent studies have shown that coastal species are more exposed to the combined threats of fishing and habitat degradation than those preferring deep-water ecosystems, thus facing a higher risk of extinction (Dulvy *et al*., 2014), their high susceptibility is to be considered in future management scenarios.

Most of the elasmobranch species recorded in the present study were also caught by other fishing gears operating in the same area (Hamdaoui, 2010; Saidi *et al*., 2016). Specifically, the small-sized elasmobranchs *M. mustelus*, *M. punctulatus*, and *Dasyatis* spp., and the large-sized sharks *C. plumbeus* and *C. brevipinna* were also recognized as by-catch in trawl and shrimp trammel nets (Hamdaoui, 2010; Saidi *et al*., 2016). Furthermore, the elasmobranch bycatch of the bottom-trawl fisheries in the Gulf of Gabès comprised of 14 sharks and 17 batoids species (Hamdaoui, 2010). However, the relative cumulative risk to species from multiple activities was not considered a method that could be extended to assess the cumulative risk associated with different gears (Micheli *et al*., 2014). The extension of PSA may provide a tool for evaluating the risk posed by overlapping fisheries within an ecosystem-based management framework that accounts for the full suite of extractive activities and their possible interactions (Micheli *et al*., 2014).

The results from this study indicate that the demersal longline fishery in the Gulf of Gabès catches incidentally a wide diversity of shark and ray species of different life stages. This type of fishery may particularly be detrimental to the elasmobranch fauna, considering that several species are found in coastal habitats, which are impacted by the combined effect of anthropogenic pressure and fishing operations. Thus, basic information on the distribution and habitat preferences of common species is essential for their management and protection. Furthermore, as elasmobranch susceptibility related to other fishing gears can be of minor or major importance, there is a great need to assess the impact of all gears used to catch the species in question. Therefore, successful conservation of these vulnerable taxa requires the introduction of scientific on-board observation programs to collect basic, but highly informative data on the spatial distribution of elasmobranchs with a special emphasis on the highly vulnerable species not only to the grouper longline fishery, but all gears operating in the area. Furthermore, spatial management requires an improved knowledge of population structure and habitat utilization including the location of important life-history stages such as nursery and pupping grounds (Kinney & Simpfendorfer, 2009).

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Supplementary Data

The following supplementary information is available online for the article:
***Fig. S1*:** Example of species captured in demersal longline fishery in the Gulf of Gabès.
Table S1: Basic size range of life stages used to determine percentage of newborns, juveniles and adults of main elasmobranch species captured in demersal longline fishery in the Gulf of Gabès.