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Jaws from the deep: biological and ecological insights on the kitefin shark *Dalatias licha* from the Mediterranean Sea

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Due to their late maturation, extreme longevity, low fecundity and slow growth rates, deep-sea Chondrichthyes are extremely vulnerable to human impacts. Moreover, assessing the impact of deep-sea fisheries is difficult, as many species (including sharks) are part of the bycatch and are often discarded at sea, and/or landed under generic commercial-species codes. The lack of this information on fishery data sets and the limited availability of species-specific life history data make challenging the management of deep-sea Chondrichthyes. The kitefin shark *Dalatias licha* is a cosmopolitan elasmobranch, mainly found on continental and insular shelf-breaks and slopes in warm-temperate and tropical waters. This species is a common by-catch of the deep-sea trawling, considered as "Endangered" by the IUCN Red List for all European waters, Mediterranean Sea included. Here we present the results of a study based on a total of 78 specimens of kitefin shark collected over 3 years in the Ligurian Sea (NW Mediterranean) as by-catch from deep-water fisheries. Total length ranged from 380 to 1164 mm, and individual weight ranged from 198 to 8000 g. Immature and mature individuals showed a sex ratio dominated by males. Adult males were observed throughout the year, while mature females were observed only in spring-summer. These data lead to hypothesise a spatial segregation between genders. The kitefin shark diet was dominated by bony

fish (mainly Macrouridae) and other small sharks (e.g., *Galeus melastomus* and *Etmopterus spinax*), but their gut included plastic items and parasites. Data reported here underline the rarity, complex ecology and the threat for this shark species and support the urgency of promoting initiatives for their monitoring and conservation.

KEYWORDS

Chondrichthyes, conservation, deep-sea fisheries, life traits, Mediterranean Sea

1 Introduction

In the last four decades, human impacts (particularly bottom-contact fisheries) and other multiple stressors have expanded also to the deep-sea (i.e., >200 m depth; Danovaro et al., 2017), and if not adequately managed, can threaten several deep-sea species, with cascade effects on the functioning of deep-sea ecosystems (Pusceddu et al., 2014; Clark et al., 2016; Caddell, 2020).

Marine fisheries worldwide have operated at increasing depths since the 1970s, coinciding with declines in shallow-water stocks (Roberts, 2002; Norse et al., 2012; Mejjad and Rovere, 2021). Deep-sea fisheries, in fact, catch species generally characterized by long lifespans, slow growth rates and late maturity (Watson and Morato, 2013). In addition, for most mesopelagic and deep-sea species is very difficult to gather quantitative data to assess their stocks and conservation status (*sensu* International Union for Conservation of Nature) (Devine et al., 2006). In 2009, the Food and Agriculture Organization (FAO) launched the “International Guidelines for the Management of Deep-sea Fisheries in the High Seas” (FAO, 2009), to recommend the adoption of an ecosystem-based approach for the exploitation of the deep-sea species to States and to Regional Fishery Management Organisations (RFMOs), able to prevent significant adverse impacts on vulnerable marine ecosystems (VMEs).

Chondrichthyes are among the most vulnerable deep-sea taxa due to their extremely long-life histories and limited reproductive potential (Simpfendorfer and Kyne, 2009); in recent years, major declines in shark populations have been observed for several species and maritime sectors (Anderson and Ahmed, 1993; White and Kyne, 2010; Graham et al., 2011; Norse et al., 2012; Barbier et al., 2014; Pacoureaux et al., 2021).

Although approximately half of Chondrichthyes species live in the deep-sea, information on the biology and ecology of deep species is extremely limited (Cotton and Grubbs, 2015). This is due to the inherent difficulty associated with investigating deep-sea habitats, and the limited commercial interest for these species (Brooks et al., 2015). Given the apparent rarity of deep-sea species, the lack of sufficient data raises concerns for the sustainability of deep-sea fisheries for the chondrichthyans populations (Shipley et al., 2017).

In the deep Mediterranean Sea, one the most threatened maritime regions for overfishing (Walls and Dulvy, 2021), 21

species (out of total 73) of cartilaginous fishes are present (Serena, 2005). Among these only the blackmouth catshark is considered a non vulnerable species (according to IUCN), while the rest are defined “strongly threatened” or “lack enough data for classification” (Dulvy et al., 2016). The kitefin shark *Dalatias licha* is listed on IUCN Red List (IUCN, 2020) and classified as “Near Threatened” (NT) at global level and “Endangered” (EN) in European and Mediterranean waters (Nieto et al., 2015; Dulvy et al., 2016). It is widely distributed over continental shelves and slopes in either warm temperate and tropical areas, down to 1800 m (Compagno, 1984). In the Mediterranean Sea, the kitefin shark is the second most important top predator inhabiting the deep-sea after the six-gill shark *Hexanchus griseus* (Serena, 2005). This species is mostly reported from the Western Basin, but it is also present in the Eastern basin (Bradai et al., 2012; Guallart and Walls, 2016; Martin and Mallefet, 2022). It is frequently included in the by-catch of deep-sea fisheries, mainly bottom trawling targeting the shrimps *Aristeus antennatus* and *Aristaeomorpha foliacea* (Serena, 2005).

Recent studies have described some life traits of this deep-sea shark, yet the biology and ecology remain unknown, making the development of effective management and conservation actions difficult (Capapé et al., 2008; Navarro et al., 2014; Barria et al., 2015; de Loyola Fernández et al., 2017; Barria et al., 2018; Booth et al., 2020; Mulas et al., 2021).

Here we explored several life traits of the kitefin shark *D. licha* from the Ligurian Sea through the morphometric analyses, sexual features, and stomach contents to contribute to fill existing gaps on the biology and ecology of this deep-sea species, and to provide insights enabling the development of future conservation initiatives.

2 Materials and methods

2.1 Sampling

Overall, 78 specimens of *Dalatias licha* (Figure 1) were collected from June 2001 to September 2003 during activity of monitoring of bottom trawl fishery in the Ligurian sea (NW Mediterranean Sea). The specimens were caught as by-catch by a single professional deep bottom trawler targeting red shrimps and operating on a single



FIGURE 1
Adult male specimen of kitefin shark (*Dalatias licha*) sampled in the study area.

fishing ground, between Genoa and Sestri Levante at 600 - 800 m depth (Figure 2).

2.2 Biometric and gravimetric investigations

After landing, all specimens were immediately analysed in the laboratory, or frozen at -28°C until subsequent analysis. In the laboratory, the specimens were identified to species level according to Serena (2005), photographed and examined for the estimation of the following morphometric and gravimetric variables: total length (TL); standard length (SL); clasper length (CIL); total weight (TW); somatic weight (SW); liver weight (LW); gonadal weight (GW) and sex. Meristic characteristics were also collected following the keys reported by Serena (2005).

2.3 Sexual and reproductive variables

Specimens were sexed and the maturity stages were determined following the scales for viviparous Elasmobranchs used in MEDITS project protocol (MEDITS, 2017). The two-sample Kolmogorov-Smirnov (KS) test was used to assess for significant differences in the length frequencies by sex. Sex-Ratio (SR, female to male abundance ratio) was estimated for the whole population. The significance of deviation from the 1:1 null hypothesis was tested by the χ^2 test.

2.4 Stomach content analysis

Stomach contents (both individuals, moults and fragments) were identified to the lowest classification level (to the species level whenever possible) to gather information on the shark preys. The eyes' number, mouth parts, telsons or other anatomical portions were traced and referred to single specimens (Hyslop, 1980). The diet and relative importance of each food item was assessed by the:

- percentage frequency of occurrence ($F\% = \text{number of stomachs containing prey } i \text{ item} / \text{total number of non-empty stomachs} \times 100$);
- percentage abundance ($N\% = \text{number of individuals of prey } i \text{ item} / \text{total number of all prey items} \times 100$).

Based on the null hypothesis (i.e., there are no differences in the diet of *D. licha* among seasons nor among size classes, a PERMANOVA (Permutational Multivariate Analysis of Variance; Anderson, 2001) was performed. Abundance data of stomach content composition (N) was used to obtain a similarity matrix

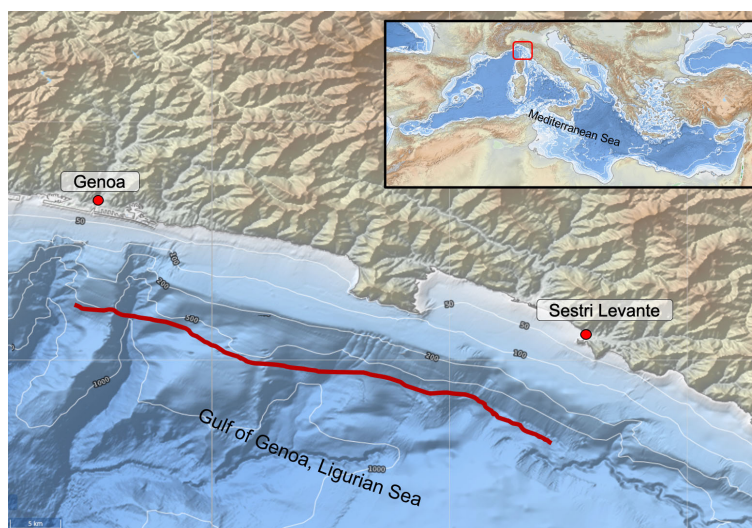


FIGURE 2
Study area where sampling effort (in red) took place.

based on a square root transformation using modified Bray-Curtis similarity. The model of analysis included two factors:

1. season, fixed with 3 levels (Spring, Summer and Autumn (no guts useful were found in winter);
2. size classes, fixed and orthogonal with 2 levels (<500 mm; > 500 mm).

3 Results

3.1 Biometric and gravimetric results

In the present study, 62 males and 16 females were collected. They included both juveniles and adult individuals. The Length frequency distribution (Figure 3) shows a large number of males in the classes from 80 to 94 cm, with a mode in size class 85-89 cm. The length frequency analysis of females showed two main groups: I) from 35 to 54 cm (immature/juveniles) and II) from 95 to 119 cm (i.e., the largest specimens with pregnant sharks; Figure 3). The total length (TL) of *Dalatias licha* ranged from 34.5 to 116.4 cm (which is also the female range of distribution), while male length ranged from 36.9 to 95.5 cm. Body weight of females and males ranged from 150-187 g to 3591 g, respectively). As a result, significant differences were reported in size distribution between genders (Kolmogorov Smirnov, $D=0.4839$; $P<0.05$).

The analysis of the gonadosomatic index (GSI) highlighted a wide variability among adult individuals of both genders (Figures 4A, C).

The hepatosomatic index (HSI) shows an increase directly correlated to size for both the sexes; in particular, it is worth

noting higher values for male specimens rather than females among the adult individuals, (Figures 4B, D).

3.2 Sexual and reproductive information

The overall sex ratio (FF/FF*MM) was significantly biased towards males (0.20), as also pointed out by chi-square test ($\chi^2 = 27.128$ $P<0.05$).

The ratio between the length of the claspers and the total length of the male individuals allowed us to highlight the size at first maturity, which is around 70.5 cm (Figure 5).

Mature females occurred mainly in summer, when pregnant specimens with $LT > 980$ mm presented oviduct glands and uteri fully formed and rounded containing yolk matter (3b- Early pregnancy) or uteri well filled with visible segments and often small embryos (3c- Mid pregnancy) (Figure 6A). Males in the regressing stage were caught in May, June, and September (Figure 6B).

In June and August, females with enlarged, flaccid walled uteri and gonads with small follicles of different sizes (stage 4b - Regenerating) were reported (Figure 7).

Males showed a large reproductive period with respect to the female one (Figure 8). Mature males (stage 3a and 3b) were observed from May to December.

In Table 1, the mean size and weight of female and male *D. licha* for each maturity stage are represented. A progressive increase of both variables with the development of the maturity process of the gonads can be observed (Table 1).

Length and weight were significantly correlated as expected (the Student's t-test revealed a significant positive allometric growth for the species at $P < 0.01$) (Figure 9). The equation showed a value of

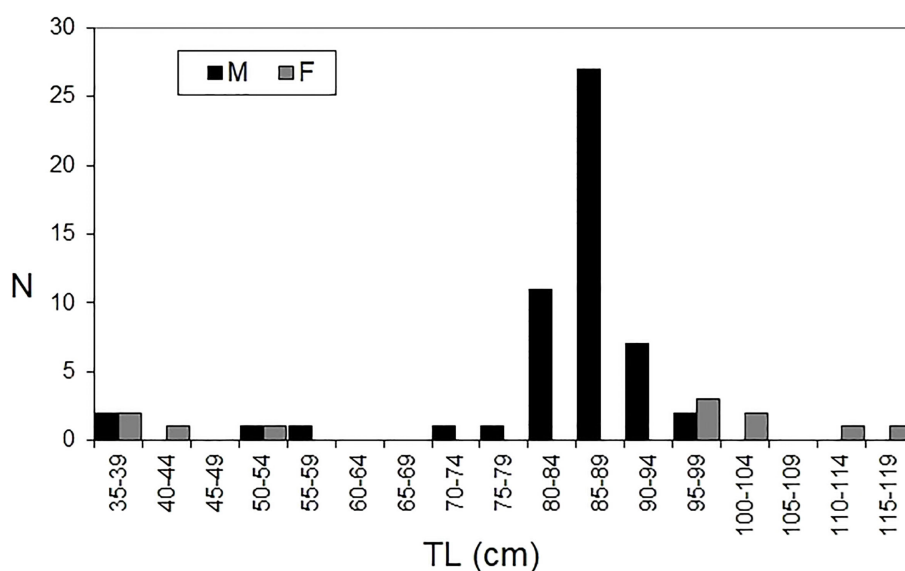


FIGURE 3
Length frequency distribution of kitefin shark *Dalatias licha*.

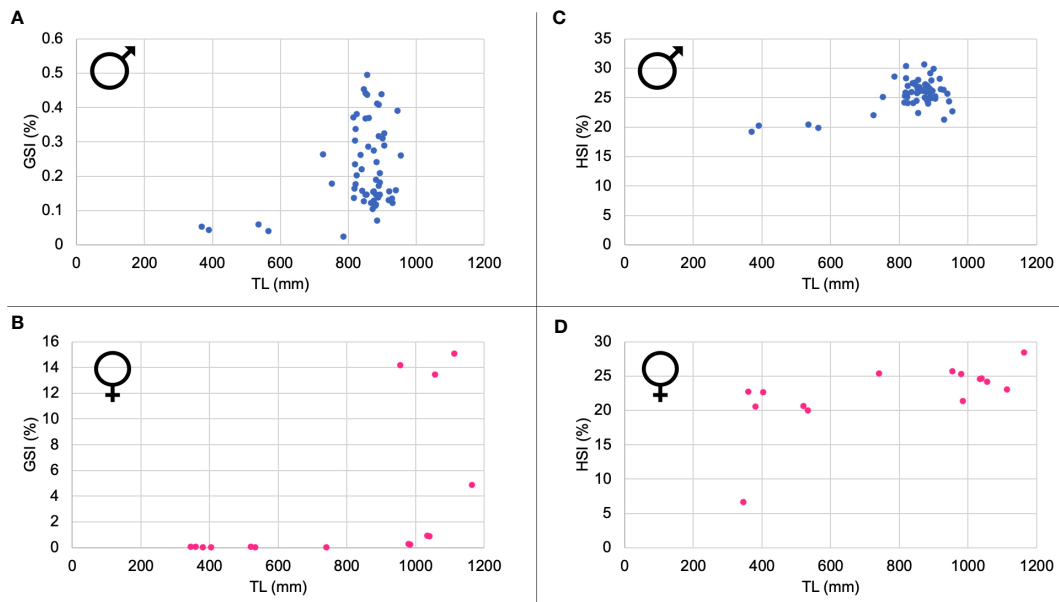


FIGURE 4 Gonadosomatic Index (GSI) for male (A) and female (B) specimens and Hepatosomatic Index (HSI) for male (C) and female (D).

$a=0.00045$ and 0.0156 respectively for female and male and $b= 3.42$ and $b= 3.14$ respectively for female and male.

3.3 Stomach content data

Gut content analysis (Table 2, Figure 10) reveals a vacuity index of 31.6%. Bony fish were the most abundant preys both in terms of frequency of occurrences (F%) and number (N%) (Table 1). Unidentified bony fish represented a large part (F%=30.2; N%=16.52) while macrourid fishes were the identified group more

represented (F%=7.5; N%= 3.5%). Sharks were the second group found in the stomach of kitefin shark (F%=37.0; N%=18.3): within this group the blackmouth catshark *Galeus melastomus* was the more present prey in terms of F% (9.4) and N% (4.3). Cephalopods and crustaceans were also present in the gut of *D. licha*, even if with lower values of F% (9.4; 57 respectively) and N% (6.1; 2.6 respectively). Many parasites (Cestode worms) were found (F%=60.4; N%=37.4) in the stomachs, along with the presence of plastic items.

PERMANOVA showed no significant differences associated with seasons and size classes in the diet of *D. licha* (Table 3).

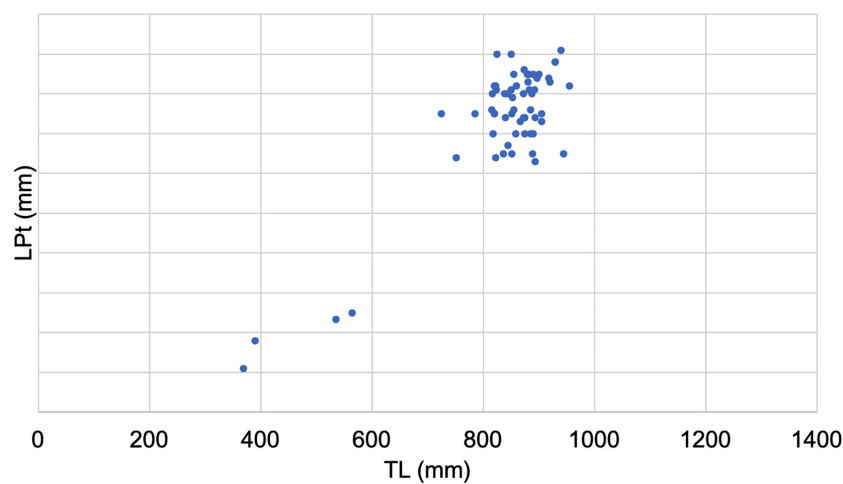


FIGURE 5 Relationship between the length of the claspers (LPt) and the total length (TL) of the male individuals.

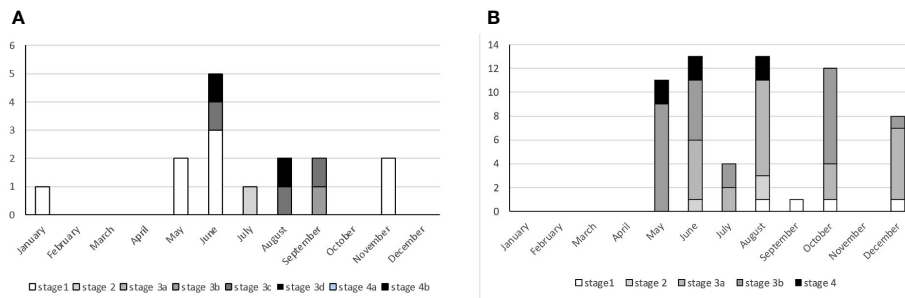


FIGURE 6 Seasonal distribution of *Dalatias licha* females (A) and males (B) at each gonadal phase during the sampling period.

4 Discussion

The kitefin shark *Dalatias licha* is a deep-sea shark incidentally caught by bottom-contact fisheries down to 800 m depth at mid latitudes. According to the International Union for Conservation of Nature (IUCN) *D. licha* is an endangered species (Nieto et al., 2015; Dulvy et al., 2016). Recently the observations of this shark are becoming so rare that the European Council set a quota zero for certain European maritime sectors (EU, 2021).

Here we provide new insights on the biology and ecology of the shark *D. licha* from the Ligurian Sea. Specimens were collected at 600-800m depth, which represent the deepest depths recorded so far for this species in the Mediterranean Sea (Macpherson, 1980; Matallanas, 1982; Kabasakal and Kabasakal, 2002; Capapé et al., 2008). Previous investigations reported the presence of this species at high depths only in the southern Sardinian waters and the Gulf of Lion (Follesa et al., 2011; Navarro et al., 2014). This batymetric

range corresponds to the deepest depths of trawling in the Mediterranean Sea, but it cannot be excluded the presence of this shark at deeper depths.

Consistently with previous information available for this species, the maximum size observed here was larger for females than for males, yet the longest specimens remain considerably smaller than those reported in South Africa (maximum total length of 1820 mm; Compagno, 1984). However, we have insufficient information on this species to assess whether the smaller size in the Mediterranean Sea is due to the intensive by-catch on this species or the result of a miniaturization of the body size, as previously reported for another deep-sea sharks (*Centroscyminus coelolepis*) in the Mediterranean Sea (Catarino et al., 2015).

The allometric growth observed in the present study is consistent to values reported in previous studies and confirms that females show a significantly higher body weight compared to



FIGURE 7 Female of *Dalatias licha* in stage 3C – mid pregnancy with small embryo (above) and Stage 4b – resting (below).

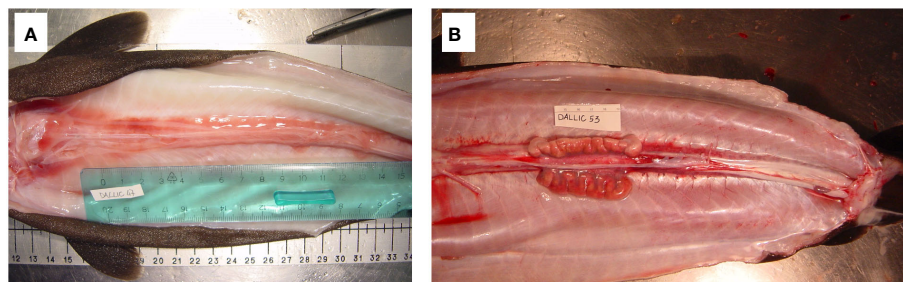


FIGURE 8
Male of *Dalatias licha* in stage 1 – immature (A) and Stage 3b – actively spawning (B).

males, which is a typical feature of elasmobranchs (Carrier et al., 2004; López Calero, 2013; Barría et al., 2015; de Loyola Fernández et al., 2017).

D. licha is a piscivorous predator species, specialised in hunting fast fish preys, either strictly demersal and benthopelagic (Navarro et al., 2014). The hepatosomatic index of this species shows significant higher values in smaller individuals, which could be related to a remarkable swimming capacity associated to the predatory behaviour (Martin and Mallefet, 2022). As observed in other deep-sea shark species, the slight increase in the gonadosomatic index reported in the present study for males could be related to their deeper bathymetric distribution than the females (Moura et al., 2014) and the lower values observed in mature females could be related to the vitellogenesis (Clarke et al., 2001).

The results of this study pointed out a sex ratio significantly shifted towards males. A similar unbalanced ratio was also reported in previous studies, but could be due to a sexually-driven spatial segregation between the two genders, possibly displacing females at depth beyond the trawling depths (Munoz-Chapuli, 1984; Yano and Tanaka, 1988; Wetherbee, 1996; Girard and Buit, 1999; Clarke et al., 2001; Jakobsdóttir, 2001; McLaughlin and Morrissey, 2005; Moura et al., 2014; Finucci et al., 2018). Such spatial segregation has been proposed as a mechanism to increase the efficiency of the reproductive effort, while minimising the risk of cannibalism and depredation of juveniles and sub-adults by mature individuals (Moura et al., 2014). Such spatial segregation would also explain the dominance of females at deeper depths in Sardinian waters, (Mulas et al., 2021).

The few female specimens investigated in the present study were juveniles or pregnant with embryos in the early stage of development. Previous studies conducted on *Centrophorus*

squamosus and *C. coelolepis* reported pregnant females in shallower and warmer waters, suggesting that this might be a common feature of several deep-sea shark species (Yano and Tanaka, 1988; Moura et al., 2014) and it could be explained by the fact that these conditions can satisfy specific requirements for embryonic development and/or trophic feedings of pregnant specimens (Robbins, 2007; Moura et al., 2014). The absence of females in later stages of pregnancy could suggest that this species moves to greater depths for the parturition, as observed in other elasmobranchs (Bansemmer and Bennett, 2009), to reduce the risk of predation on the new-born sharks.

Males investigated in the present study included individuals with different sexual maturity stages during the four seasons suggesting that the investigated area is a mating area. Data reported here also suggest that mature males of *D. licha* might have an extended reproductive period (i.e., the lack of a seasonality for the reproductive period), similarly to what was reported for most deep-sea shark species (Girard and Buit, 1999) and for other ovoviviparous sharks (Kyne and Simpfendorfer, 2010).

The size of first maturity in Mediterranean males is around 70 cm (see also Capapé et al., 2008), yet this size is much lower than that reported from the Atlantic Ocean, as previously observed for the Mediterranean in the Portuguese dogfish *C. coelolepis* (Compagno, 2001; Serena, 2005; Catarino et al., 2015), suggesting that the oligotrophic conditions of the Deep Mediterranean Sea promote the dwarfism in deep shark species.

The analysis of the stomach contents of kitefin shark confirms that this species is a carnivorous predator, preferring fish and highly mobile animals (Macpherson, 1980; Matallanas, 1982; Kabasakal and Kabasakal, 2002; Capapé et al., 2008; Dunn et al., 2010; Dunn et al., 2013; Navarro et al., 2014; Mulas et al., 2021). The importance

TABLE 1 Mean total length and weight (\pm standard deviation) of *Dalatias licha* females and males in relation to the different gonad phase.

	stage1	stage 2	stage 3a	stage 3b	stage 3c	stage 3d	stage 4a	stage 4b
females TL (mm)	455 \pm 137	848 \pm 152	–	1139 \pm 36	1010 \pm 35	–	–	1010 \pm 42
females PT (g)	605 \pm 771	3896 \pm 2268	–	7900 \pm 141	7300 \pm 1273	–	–	6150 \pm 1202
males TL (mm)	465 \pm 99	775 \pm 71	870 \pm 39	866 \pm 41			862 \pm 51	
males PT (g)	458 \pm 288	2364 \pm 549	3090 \pm 415	3044 \pm 435			3015 \pm 461	

grey cells, Stage not included in the male maturity scale; - data not available.

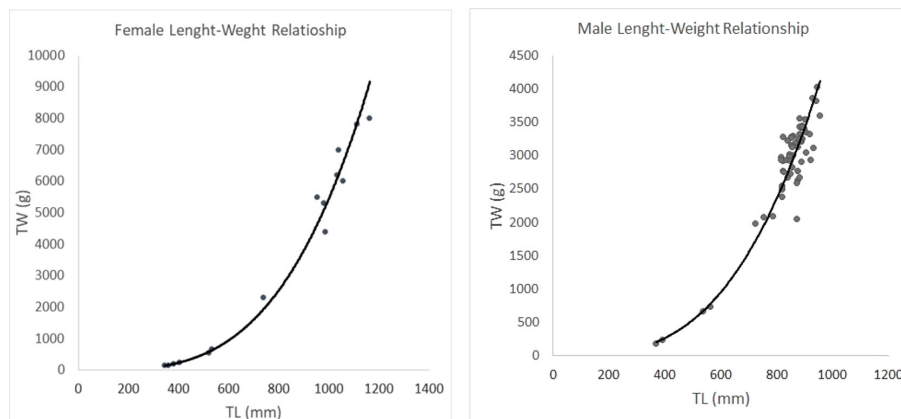


FIGURE 9
Length-Weight relationship of *Dalatias licha* caught during the study period. The equation showed a value of $a=0.00045$ and 0.0156 respectively for Female and Male and $b= 3.42$ and $b= 3.14$ respectively for female and male.

of bony fish (e.g., macrourids) in the diet of this species is confirmed by other studies conducted in other areas of the Mediterranean Sea (Macpherson, 1980; Matallanas, 1982; Capapé et al., 2008; Mulas et al., 2021) and reflects the common availability of these preys

TABLE 2 Gut content analysis of *Dalatias licha*. Frequency of occurrence (F%) and percent number (N%) of prey items are reported.

Prey Items	F%	N%
Parasites	60,4	37,4
Cephalopods Unidentified	9,4	6,1
Crustacean unidentified	3,8	1,7
<i>Nephrops norvegicus</i>	1,9	0,9
Crustaceans total	5,7	2,6
Osteichthyes unidentified	30,2	16,5
<i>Antias antias</i>	3,8	1,7
<i>Epigonus telescopus</i>	3,8	1,7
Macruridae ind.	7,5	3,5
<i>Hymenocephalus italicus</i>	1,9	0,9
<i>Nezumia sclerorhynchus</i>	3,8	1,7
<i>Trachyrincus scabrus</i>	1,9	0,9
Bony fish Total	52,8	27,0
Sharks unidentified	15,0	6,9
<i>Scyliorhinus</i> sp	3,8	1,7
<i>Galeus melastomus</i>	9,4	4,3
<i>Etmopterus spinax</i>	1,9	0,9
egg-case	7,5	4,3
Sharks total	37,7	18,3
Plastic Fragments	5,7	3,5
Unidentified Items	7,6	7

within the distribution range of the kitefin shark (Sinopoli et al., 2012). Our results confirm also the importance of small sharks (such as *Galeus melastomus*) in the diet of *D. licha* (Macpherson, 1980; Matallanas, 1982; Kabasakal and Kabasakal, 2002; Capapé et al., 2008; Dunn et al., 2010; Dunn et al., 2013; Navarro et al., 2014; Mulas et al., 2021). There are various hypotheses to explain the relevance of these elasmobranchs in the kitefin shark diet: the first is that the high concentration of fatty acids in their livers can support the energetic requirements and the buoyancy of their predators (Corner et al., 1997; Navarro et al., 2014). The second is that preying upon other sharks reduces the interspecific competition for the common preys (e.g., macrourids; Lourenço et al., 2014). The predation among sharks remains an intriguing enigma in the scientific community (Cortés, 1999), and further studies are needed to elucidate these predation preferences (Lotze et al., 2006; Navarro et al., 2014). Finally, the large abundance of crustaceans and cephalopods in the diet of kitefin shark reflects the relative abundance of these preys in the deep-sea consistently with the optimal foraging theory (Pyke, 1984; Kabasakal and Kabasakal, 2002; Mulas et al., 2021) as reported in other shark species and in general for fish species (Valls et al., 2011; Sinopoli et al., 2012; Navarro et al., 2014; Martin and Mallefet, 2022).

The gut of kitefin sharks investigated in the present study contained a rich endoparasitic helminthofauna. The presence of other parasites, such as nematodes (*Anisakis simplex* and *Raphidascaris* sp.), has been previously reported in other Mediterranean kitefin sharks (Henderson et al., 2003) as well as the presence of Hexabothriids (Kheddami et al., 2016), monogeneans (*Septitrema licha* in nasal tissue; Kheddami et al., 2020), and digenean trematodes (*Otodistomum veliporum*; Sperone and Milazzo, 2018). However, this is the first study reporting the presence of flatworms as endoparasites of the kitefin shark.

We report here also that the gut of the *D. licha* contained plastic items. This result confirms that plastics are impacting also large predatory deep-sea species and point out the potential risk of this form of contamination for the conservation of this vulnerable species (Chiba et al., 2018; Valente et al., 2020).

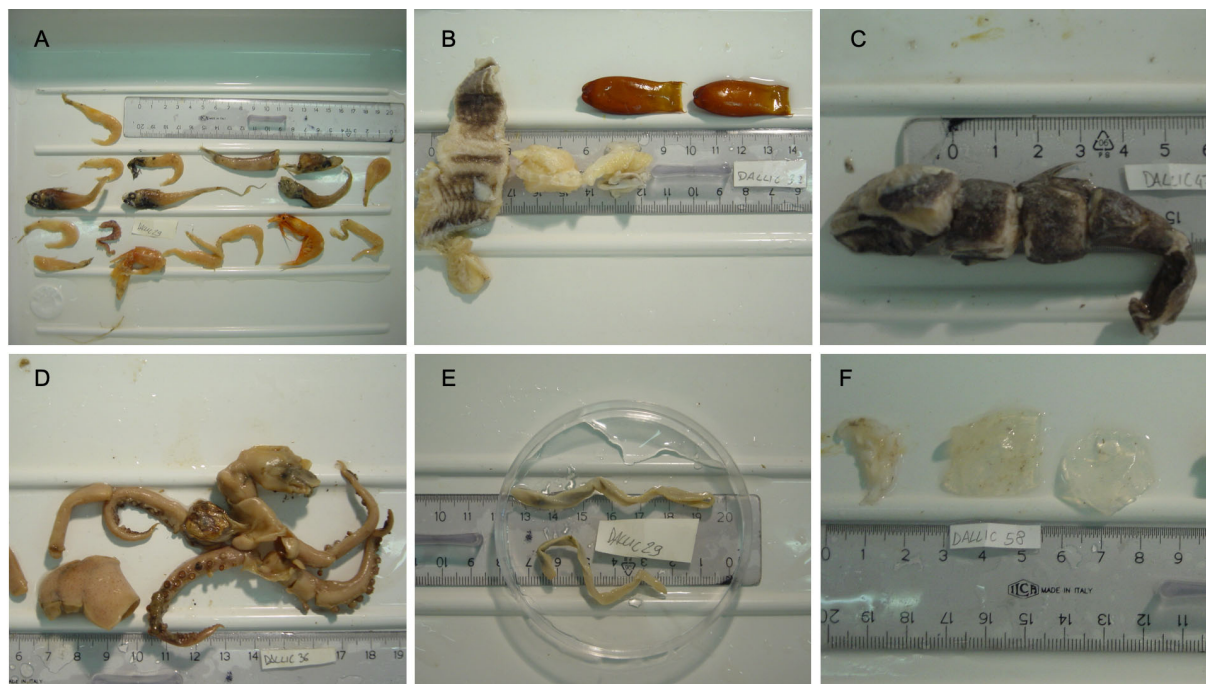


FIGURE 10

Images of preys found in the stomach contents of some specimens sampled in this study. (A) teleosts and shrimps (B) *Galeus melastomus* remains and egg capsules, (C) *Etmopterus spinax* remains (D) cephalopods remains, (E) parasites and (F) plastic fragments.

4.1 Possible management and conservation measures

Our study stresses that, besides the industrial fishery, also local-scale fisheries, as those utilised for the present study, can significantly impact this endangered deep-sea shark species, and underline the urgency of planning adequate and effective fishery management measures for its conservation (King and McFarlane, 2003; Young et al., 2006; McCluskey and Lewison, 2008).

In Mediterranean waters (as in the other European seas), deep-sea cartilaginous fishes are not primary fishing targets, but represent in most cases victims of the by-catch. Most of these species monitored by the International Union for Conservation of Nature (IUCN) are reported as endangered or data deficient (Nieto et al., 2015; Dulvy et al., 2016). The track record of European fisheries is clearly unsustainable also for deep-sea sharks (Villasante et al., 2012), as evident from the remarkable decline of the abundance of

deep-sea sharks (Danovaro et al., 2010; Eigaard et al., 2017). At the same time, in the last 30 years, some deep-sea sharks started having a commercial interest especially in the northeast Atlantic (Alves et al., 2020). The global market for elasmobranch products is also increasing and diversifying in different sectors: food, pharmaceutical, and even material (clothing), with industries now able of processing and selling meat, liver oil, cartilage, skin, and other shark related products (Dent and Clarke, 2015).

To mitigate the impact of the fisheries on deep-sea Chondrichthyes and on deep-sea biodiversity, the General Fisheries Commission for the Mediterranean (GFCM) in 2005 banned bottom trawling at depths beyond 1000 m. In addition, the European Union has restricted the total allowable catches (EU, 2021) announced the prohibition of bottom trawling in a large area of the North Atlantic (EU, 2022) and is planning further management efforts with the creation of Fisheries Restricted Areas (FRAs) for the deep-sea fisheries (EU, 2019).

TABLE 3 Multivariate Permutational Analysis of Variance performed of abundance of prey items.

Source	df	MS	Pseudo-F	P (perm)	perms
Seasons	2	4334,4	1,2636	0,251	ns
Size classes	1	6572,3	1,9161	0,078	ns
Season x Size classes	2	2975,3	0,8674	0,615	ns
Res	26	3430,1			
Total	31				

ns, not significant.

Despite all of these efforts, deep-sea sharks do not show signs of recovery, as their high mobility and migrations at shallower depths exposes these species to a significant risk of by catch (Musick and Cotton, 2015; Treberg and Speers-Roesch, 2016). In this regard, the obligation to release deep-sea Chondrichthyes incidentally caught is not always effective as many of these large animals do not survive once fished (Talwar et al., 2017). Extending no-fishing zones or marine protected areas from the shelf break down to the continental slopes (thus able to cover the whole bathymetric range of their movements across life stages and encompassing the spatial segregations between genders) could represent an important tool for conservation of these threatened species. However, enforcing the protection of marine areas is difficult, due to the conflicting economic interests (Hilborn et al., 2004; Botsford et al., 2009; Pérez-Ruzafa et al., 2017).

A complementary solution could be the active engagement of fishermen to endorse improved fishing practices (Ellis et al., 2017), and the use of devices able to reduce the by-catch (Brčić et al., 2015; Nuez et al., 2023). Currently, experimental trials the use by-catch reduction devices are showing remarkable positive effects, with a significant decrease of the incidental captures of deep-water elasmobranchs without negative effects on commercial yields (see the results of the LIFE ELIFE project).

Another solution is intensifying the controls against illegal fisheries that are often extending trawling beyond the depth limits (1000 m for the Mediterranean Sea) also using new technologies and satellite sensors (Clarke et al., 2015). Finally, a better fishers' knowledge of this deep-sea Chondrichthyes and the direct involvement of local fisheries for the use of low impact fishing gears may contribute significantly to preserve these vulnerable deep-sea Chondrichthyes.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Ethics statement

The animal study was reviewed and approved by Animal Welfare Body of SZN (OBA).

Author contributions

MB: conceptualization; acquisition, analysis and interpretation of data, drafting the work and revising the final version. MS: analysis and interpretation of data, drafting the work and revising the final version. IB: analysis and interpretation of data, drafting the work. MCF: analysis and interpretation of data, drafting the work. AC: analysis and interpretation of data. IC: acquisition and analysis of data. FS: analysis of data. ES: analysis and interpretation of data.

MV: conceptualization, revising the final version. LM: analysis of data. GC: analysis and interpretation of data and drafting the work. RD: conceptualization, interpretation of data, revising the final version. All the authors provide approval for publication of the content. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer MG declared a shared affiliation with the author MV to the handling editor at the time of review.

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