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Original Article

Reproductive biology of the silky shark *Carcharhinus falciformis* (Müller & Henle, 1839) in waters off Côte d'Ivoire (West Africa)

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Abstract
Since 2008, the quantity and size of silky shark, *Carcharhinus falciformis* decrease drastically in catches of artisanal driftnet fishery operating in the coastal waters off Côte d'Ivoire. The objective of this study was to describe the reproductive biology of this species, based on 336 specimens (162 males and 174 females). The total length (TL) of males and female ranged from 81–242 and 79–254 cm respectively. The sex ratio was 0.89:1 (M:F) and 0.93:1 (M:F) in embryos and adults respectively. Males of >180 cm had calcified clasper (17–35 cm) whereas females of >190 cm had oviduct gland length of 18–47 mm. The estimated length at first maturity was 182.8 cm for males and 195.2 cm for females. The range in litter size of three gravid females was 7–9, with an average of 8 embryos of 52–54.5 cm TL were collected in August and December. However, the absence of neonates and scars on females' body, as well as ovulating and differentiating females in catches does not allow a clear determination of its reproductive period in Ivorian waters and therefore, additional research including histological analysis is necessary to better understand the process of spawning of silky shark.

Keywords: Atlantic Ocean; Côte d'Ivoire; fecundity; reproduction; sex ratio; silky shark

1 | INTRODUCTION

The silky shark, *Carcharhinus falciformis* (Müller & Henle, 1839) is an oceanic and coastal species found along the edge of the continental shelf, spending more time in the first 100 metres and diving to depths greater than 300 m (Curnick *et al.* 2020). This species is one of shark species frequently caught as by-catch in most longline and gillnet fisheries targeting swordfish and/or tunas in the western and central Pacific Ocean (Forselledo *et al.* 2022) and the north and southwest Atlantic Ocean (Campana *et al.* 2009; Lezama-Ochoa *et al.* 2018; Escalle *et al.* 2019; Clavareau *et al.* 2020). In Côte d'Ivoire, it is mainly caught by the artisanal driftnet fishery, which is very active in the Exclusive Economic Zone (EEZ; Konan *et al.* 2014). The gradual decreases in size of individuals caught since 1995 in Atlantic Ocean (Rigby *et al.* 2017), seem to indicate that silky shark populations are declining due to overfishing (Cortés *et al.* 2007; IOTC 2013). Its top ranking in terms of vulnerability to longline fishing (Cortés *et al.* 2010), prompting the International Union for the Conservation of Nature (IUCN) to re-evaluate its conservation status from "Least concern" to "Near threatened" in 2007. The development of management plans for its sustainable use requires reliable data on life-history. However, the implementation of these fisheries management plans is difficult due to the lack of adequate biological data.

Published information on the biology of *C. falciformis* are available in the Gulf of Mexico (Hoyos-Padilla *et al.* 2012; Galván-Tirado *et al.* 2015) and in the Pacific Ocean (Oshitani *et al.* 2003; Joung *et al.* 2008). In the Atlantic Ocean, despite its noticed abundance in catches, no published works exist on its reproductive biology in the central eastern region where studies have been limited to the northwest (Bonfil 2008) and equatorial regions (Hazin *et al.* 2007; Lana 2012). In Côte d'Ivoire, available works are restricted to those of N'Goran and Amon-Kothias (2002), N'Goran *et al.* (2005) and Konan *et al.* (2014) on abundance and catch composition. The present study aims to provide a description of the reproductive biology as biological input parameters for further evaluation of the silky shark stock.

2 | METHODOLOGY

2.1 Study area

Silky shark data were collected at the fishing harbour of Abidjan from the artisanal driftnet fishery targeting tuna species, which operated in the EEZ of Côte d'Ivoire (Figure 1). According to Morlière and Rébert (1972), the marine hydroclimate of this area includes four main seasons with two warm seasons (March – June and November – December) and two cold seasons (July – October and January – February). The surface seawater temperature of both years shows the same pattern, with two peaks separated by a period of low value. Temperatures are generally low between July and September (25.03 – 25.83°C) and high in January – June and October – December, with values ranging from 27.0 – 30.6°C (Figure 2). The concentration of chlorophyll–*a* also showed the same trend than that of temperature in both years. The values were relatively low (< 1 mg m^{-3}) in November – April, followed by an increase in concentration from June, peaking in July 2019 (2.62 mg m^{-3}) and 2020 (3.28 mg m^{-3}) (Figure 3).

2.2 Data collection and laboratory examination

A total of 336 specimens were collected monthly at the fishing harbour of Abidjan, between April 2019 and December 2020. Sex was determined for each individual and the body weight was recorded to the nearest kg. The total length (TL) was measured in a straight line from the snout tip to the end of the upper tail to the nearest cm below. For females, the ovary, the uterus and oviducal glands (OG), as well as the diameter of the largest oocytes were weighted or measured. The presence of fertilised eggs, the number and the sex of embryos extracted into uterine of the pregnant females were recorded. The total length of the embryos was measured in cm. For males, the testes were weighted and the clasper length (from cloaca posterior edge to clasper distal tip) was measured to the nearest cm using callipers. Testes and ovaries were removed and preserved in 10% neutral formalin for later analysis.

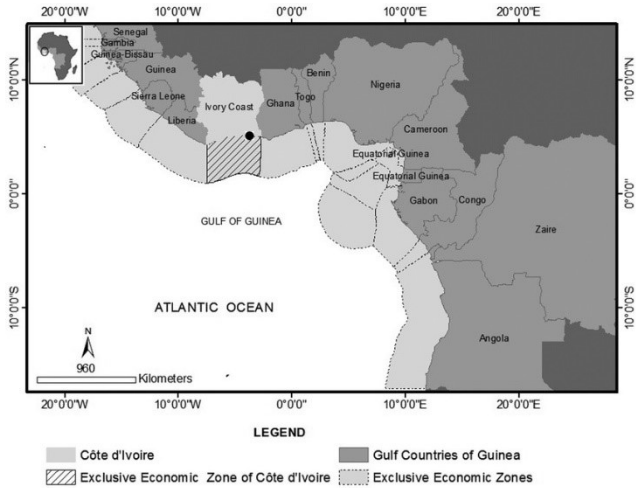

FIGURE 1 Study map showing landing (●) and sampling areas for silky sharks, *Carcharhinus falciformis*.

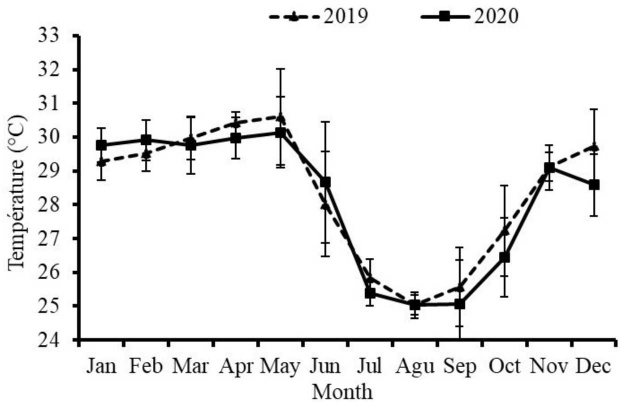

FIGURE 2 Monthly variation of temperature in the coastal waters of Côte d'Ivoire f between 2019 and 2020. (http://podaac-ftp.jpl.nasa.gov/allData/modis/L3/aqua).

2.3 Observation of gonads and sex ratio

To estimate sexual maturity, morphometric and morphological indicators of reproductive organs were regarded according to the scale of Sthemann (2002). For males, the following characteristics were recorded: Stage 1 (immature) – claspers undeveloped, shorter than posterior tips of pelvic fin lobes, small whitish testis, sperm ducts straight and thread-like; Stage 2 (maturing) – claspers partially calcified and longer than posterior tips of pelvic fin; their tips (glans) becoming structured. The sperm ducts beginning to coil; Stage 3 (mature) – claspers fully calcified and longer than pelvic fin; the sperm ducts coiled and well filled with sperm (a white liquid extruded from a cross-sectional cut through the thick caudal portion of the kidney, where the ampullae are situated); Stage 4 (mature active) – claspers fully calcified, clasper glans often dilated and swollen; the sperm present in the clasper grooves flows under pressure.

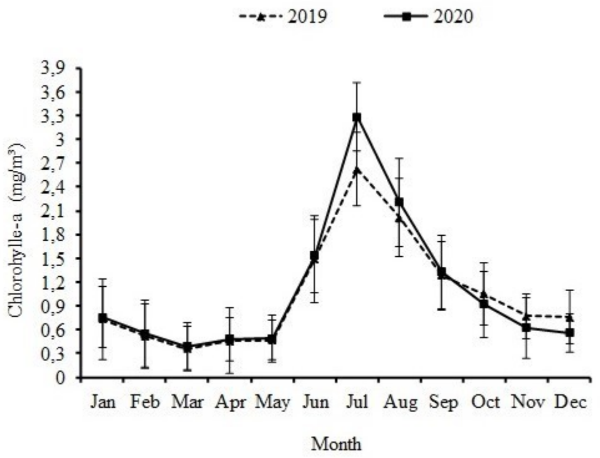

FIGURE 3 Monthly variation of chlorophyll-*a* concentration in the coastal waters of Côte d'Ivoire f between 2019 and 2020. (http://podaac-ftp.jpl.nasa.gov/allData/modis/L3/aqua).

For females, the following characteristics were recorded: Stage 1 (immature) – ovaries undeveloped, their internal structure gelatinous and no oocytes differentiated. Uteri narrow and thread-like; Stage 2 (maturing) – ovary, somewhat enlarged, has a transparent wall with translucent oocytes starting to differentiate. The oviducts are narrow and become to widen posteriorly (uterus); Stage 3 (preovulatory) – ovary with developing oocytes; some already large can easily be counted and measured. Uteri internal structure is spongy; Stage 4 (Ovulating) – oocytes sometimes un-ovulated from ovary are well enlarged and yellowish. Uteri widened contain fertilised eggs, no embryos are visible; Stage 5 (differentiating) – Uteri contain visible embryos but unpigmented; Stage 6 (expecting) – Uteri contain pigmented embryos; Stage 7 (postnatal) – ovaries at resting stage, similar to stage 1 or 2. Uteri empty but still widened considerably over their full length in contrast to stages 1 or 2. The sex ratio was defined as the relative proportion of the number of males to that of females in a population at a specific period.

2.4 Size at first sexual maturity

The size at first maturity (L_{50}), defined as the length at which 50% of the population is mature, was estimated using the following logistic equation, fitting a non-linear regression to the proportion of mature individuals taken in 10 cm TL intervals (Ghorbel *et al.* 1996). For both sexes, maturity stages 1 and 2 were considered immature, while stages 3 – 4 in males and 3 – 7 in females were considered mature.

$$P = \frac{e^{(\alpha + \beta TL)}}{1 + e^{(\alpha + \beta TL)}}$$

where P = percentage of mature fish and α and β = coefficients. This equation can be transformed into a logarithmic form as follows:

$$\frac{\ln P}{1 - P} = \alpha + \beta TL$$

The value of L_{50} was estimated as the negative ratio of the coefficient (-α / β), by substituting p = 0.5 in the second equation.

2.5 Fecundity

The fecundity could be estimated either oocytes (ovary) or embryos (uterus) counting. Uterine fecundity was regarded here by counting the embryo number collected in the pregnant female uteri (Pratt 1979). The largest oocytes in the ovary were also counted.

2.6 Data analysis

The Kolmogorov-Smirnov test (K-S), considering a significant level of 95%, was applied to compare the size-frequency distribution between sexes. The total number of males to females in both adults as embryos were analysed using a Chi-square test (χ^2) to determine whether there was a significant difference from the expected 1:1 ratio. The relationships between total length and clasper length for males, between total length and oviducal gland diameter as well as number of embryos for females were examined.

3 | RESULTS

3.1 Size distribution and sex ratio

A total of 336 specimens including 162 males and 174 females were sampled during the sampling period. The size distribution is continuous with a clear modal class (120 cm LT) observed for both sexes (Figure 4). The size-frequency distribution of males and females showed no significant difference (K–S test, D–stat = 0.079156306 < D19, 0.05 = 0.301). So, the data was a reasonably good fit with the normal distribution. Most of individuals caught were immature, representing up to 76% (n = 254) of catches vs. 24% (n = 82) of mature stages. The size of males ranged from 81 to 242 cm (134.18 ± 37.87 cm, TL) and females from 79 to 254 cm (132.66 ± 34.12 cm). Immature sharks occurred during throughout the year, except April (Table 1). Immature females were more numerous than males from November to June whereas immature males occurred mainly in September – October. However, the sex ratio was not statistically different from the theoretical 1:1 (M:F) ratio. Mature individuals were found in December, February and in May – October but the sex ratio did not differ significantly from parity (χ^2 = 0.78, p > 0.05; n = 82), except in July and September. Of the mature females collected, three were pregnant with

24 embryos (13 females and 11 males) in August and December. The sex ratio of embryos was 0.85:1 (M:F) and was not significantly different (χ^2 = 0.17; $p > 0.05$; n = 24).

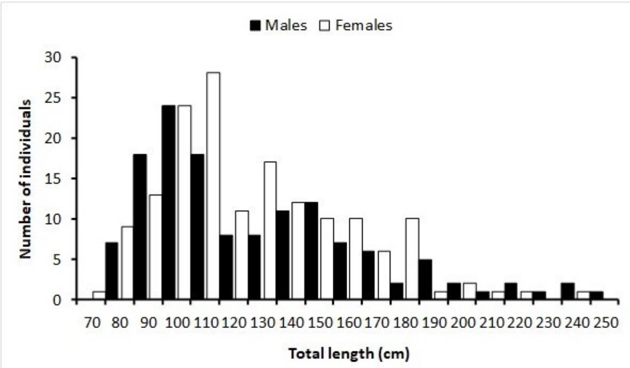

FIGURE 4 Size-frequency distribution of female and male silky sharks, *Carcharhinus falciformis*, caught off the coast of Côte d'Ivoire between April 2019 and December 2020.

3.2 Description of reproductive organs and size of sexual maturity

In males, the clasper length shows a proportional increase with body length. Individuals of size ranging between 80 and 180 cm TL were immature and possessed soft or partially calcified claspers with sizes of 3 – 16 cm (6.23 ± 2.38 cm, n = 117). In contrast, individuals measuring 182 cm TL or greater were mature, with elongated and fully calcified claspers of 17 – 35 cm (21.73 ± 5.22 cm, n = 45) (Figure 5). In female, all individuals smaller than 190 cm LT were immature with undeveloped ovaries contained translucent oocytes and oviducal glands varied from 0.61 to 2.00 cm in width. Females larger than 190 cm LT, with oviducal glands measuring between 2.00 and 4.20 cm were all mature (Figure 6). The estimated size at first sexual maturity was 182.8 cm TL for males and 195.2 cm for females (Figure 7).

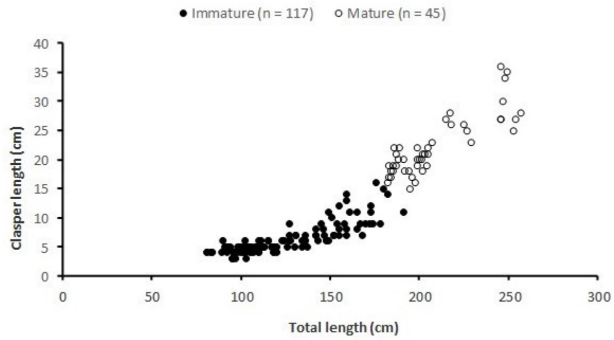

Figure 5 Relationship between total length and clasper length in silky shark, *Carcharhinus falciformis*, caught off the coast of Côte d'Ivoire between April 2019 and December 2020.

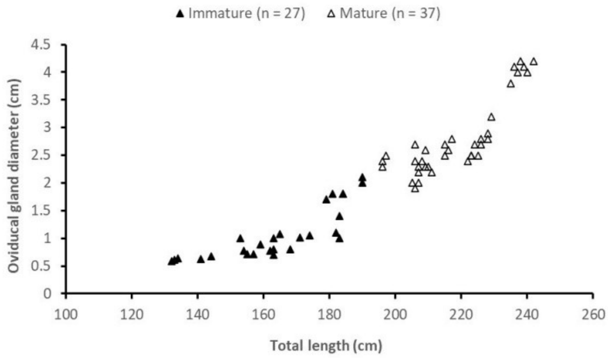

FIGURE 6 Relationship between total length and oviducal gland width in silky shark, *Carcharhinus falciformis*, caught off the coast of Côte d'Ivoire between April 2019 and December 2020.

TABLE 1 Monthly proportion of sexes and sex-ratio of silky shark *Carcharhinus falciformis* in the coastal waters of Côte d'Ivoire between April 2019 and December 2020.

Month	Immature				Mature			
	Male (M)	Female (F)	Sex-ratio (F:M)	χ^2	Male (M)	Female (F)	Sex-ratio (F:M)	χ^2
Jan	3	10	1: 0.30	3.77	0	0	–	–
Feb	1	2	1: 0.50	0.33	6	8	1:0.75	0.29
Mar	4	8	1: 0.50	1.33	0	0	–	–
Apr	0	0	–	–	0	0	–	–
May	11	21	1: 0.52	3.13	16	11	1:1.45	0.92
Jun	12	18	1: 0.67	1.20	0	2	1:0	2.00
Jul	22	19	1: 1.16	0.22	6	0	–	6.00*
Aug	5	5	1: 1	0.00	7	7	1:1	0.00
Sep	17	13	1: 1.31	0.53	5	0	–	5.00*
Oct	32	21	1: 1.52	2.28	5	7	1:0.33	0.71
Nov	6	13	1: 0.46	2.59	0	0	–	–
Dec	3	6	1: 0.50	1.00	0	2	1:0	2.00
Total	117	137	1: 0.85	1.57	45	37	1: 0.82	0.78

* = Significant difference between mature males and females

3.3 Maturity stage frequency

The monthly frequency of sexual maturity stages of females was summarised in Figure 8. No specimen was recorded in April throughout the sampling period. The immature females (stages 1 and 2) were found abundantly (78.74%) throughout the year, except April. The proportion of preovulatory females (stage 3) increased gradually from September, peaked in February and then decreased until June. Gravid females (stage 6) with well pigmented embryos were sampled in August and December. Ovulating or early pregnancy Females (stage 4) and differentiating or full pregnancy (stage 5) were not encountered in catches.

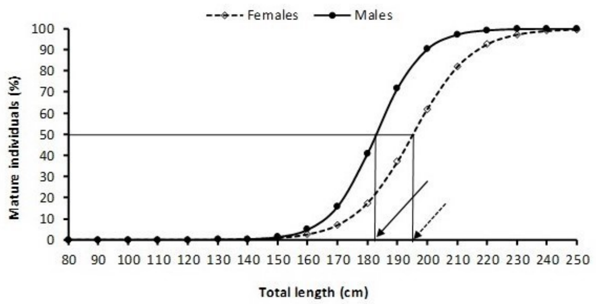

FIGURE 7 Length at first maturity of male and female silky sharks, *Carcharhinus falciformis* caught off the coast of Côte d'Ivoire between April 2019 and December 2020.

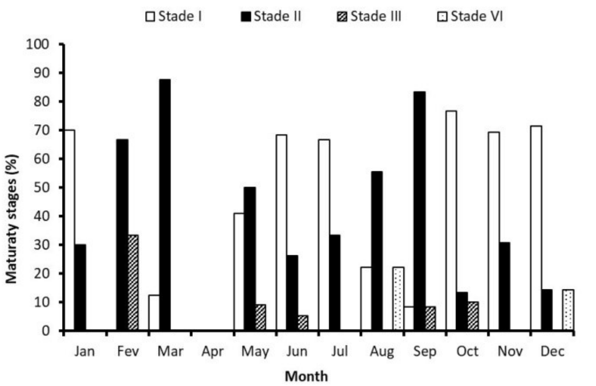

FIGURE 8 Relative frequencies of maturity stages for female silky sharks caught off the coast of Côte d'Ivoire between April 2019 and December 2020.

3.4 Uterine fecundity

Three gravid females were recorded and examined in detail in this study. Two of these gravid females, with sizes ranging from 235 to 239 cm TL were caught in August and had embryos of 49.50 – 51.00 cm TL (51.97 ± 1.85 cm TL). The last gravid female measuring 242 cm TL was caught in December. The total length of embryos ranged from 52.00 to 54.50 cm TL with a mean of 53.33 ± 0.81 cm TL. All embryos collected from gravid female uteri were already pigmented (Figure 9) even if those recorded in December were slightly larger than those observed in August. The range in litter size of three gravid females was 7 – 9, with an average of 8 embryos of 52 – 54.5 cm TL.

FIGURE 9 Silky shark embryos observed in the uteri of pregnant females caught off the coast of Côte d'Ivoire between August 2019 and December 2020.

4 | DISCUSSION

The present study provides a first estimate reproductive data for silky shark in the Gulf of Guinea. The size frequency indicated that landings consisted mainly of immature individuals of both sexes, representing up to 76% of catches. The maximum length recorded for this species in the present was 242 – 254 cm TL. This could be due to fishing operations being carried out close to the coast where juveniles and subadult are found more frequently and are more susceptible to fishing as reported by Galván–Tirado *et al.* (2015). The same trend has been reported by authors using data from tropical tuna purse seiners operating on high seas (Clarke *et al.* 2012; Grant *et al.* 2018; Hutchinson *et al.* 2019; Lopez *et al.* 2020; Chia *et al.* 2021). The assumption of gear influences and capture methods does not seem to be supported the fact that most of landings were composed of immature individuals. According to Kouamé *et al.* (2019), artisanal fishermen operate close to the coast using baited hooks associated to gillnets to attract sharks. So, if larger individuals were enough on fishing area, they would have been more numerous in catches. Previous studies (Heupel *et al.* 2007; Bonfil 2008; Tavares 2009) have highlighted that shallow and highly productive coastal areas are important habitats for the development of immature sharks. According to Chia *et al.* (2021), immature silky sharks are demersal and tend to remain in the nursery areas of continental shelf waters and deeper parts of continental and island shelves. Similarly, Hutchinson *et al.* (2019) reported that juvenile silky sharks spend almost of their time in warm shallow waters where temperatures vary between 24 and 29°C. Based on these findings, this would have repercussions on management strategies for this species, since selective capture could have an unfavourable impact on the population's ability to recover.

The sex ratio of embryos and immature sharks found in this study was close to 1:1 throughout the year. Similarly, the sex ratio of mature individuals was close to 1:1 year-round, except in July and September where no male was caught. Del Rosario (1998) and Ronquillo-Benıtez (1999) reported the same ratio for Guatemala and Chiapas respectively.

The length at sexual maturity estimated in this study was 182.8 cm for males TL and 195.2 cm for females, which represents the first estimated value for this area using a logistic model. These values were very similar to those reported by Galván–Tirado *et al.* (2015), of 180 cm TL for males and 190 cm for females in the southern Mexican Pacific and within the range of 180 – 187 cm TL for males and 193 – 200 cm for females proposed by Oshitani *et al.* (2003). However, the maturity sizes from this work were smaller than those found by Joung *et al.* (2008) who recorded 212.5 cm TL for males and 210 – 220 cm for females in northeast Taiwan. The variation of size at maturity might be related the latitude of sampling areas, as fish grows faster and matures earlier in tropical waters than fish do in temperate waters (Lombardi-Carlson *et al.* 2003; Hall *et al.* 2012). However, the actual mechanism needs to be investigated. The fact that size at first maturity was highest in females seems to be common for shark in general.

Besides the absence of mating, neonates and ovulating and differentiating females in catches, data on pregnant females and embryos length distribution were not enough to well-defined the reproductive cycle and determine the parturition period of silky shark. Although pigmented embryos with sizes of 52 – 54.5 cm TL have been recorded in the catches, parturition does not occur in the Gulf of Guinea as the birth size of this species was estimated to be to 75 cm TL by Compagno (1984). According to Hazin *et al.* (2007), the silky shark does not have a clearly established seasonal gestation cycle in equatorial Atlantic Ocean. The litter size was found to be 7 – 9 based on the observation of three litters, which was similar to that reported in northeastern Taiwan waters (8 – 10 embryos; Joung *et al.* 2008). This figure was quite different from that of 1 – 16 embryos from the Pacific Ocean (Oshitani *et al.* 2003), 4 – 15 embryos from equatorial Atlantic Ocean (Hazin *et al.* 2007) and 3 – 13 embryos from the central west Pacific (Grant *et al.* 2018).

5 | CONCLUSIONS

The present study provided important information on the reproductive biology of *C. falciformis* in the Ivorian EEZ. Results indicate that landings are mainly composed of immature individuals (76% for both sexes), constituting a real threat for the stock of *C. falciformis* in this area. Additional data are needed to clarify the structure of the stock before any management measures can be formulated, which should take into account the life history characteristics (slow growth, late maturation and limited offspring) of this species.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

KJK and OEE designed and coordinated the study. KCn collected field data. KCn, KJK, KYNK analysed the data and wrote the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request to the corresponding author.

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