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Consumption of Post-Larval Swordfish (*Xiphias gladius*) by Dolphinfish (*Coryphaena hippurus*): New Ecological Insights into both Species in the Tyrrhenian Sea

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Abstract: Knowledge of post-larval swordfish (*Xiphias gladius*) ecology in the world's oceans is incomplete as they are rarely found in ichthyoplankton samplings or commercial catches and individuals are difficult to observe in the marine ecosystem. Analyses of stomach contents of apex predators can provide otherwise unobtainable ecological insights. Two well-preserved bills of post-larval swordfish were identified among the partially digested stomach contents of an adult male dolphinfish (*Coryphaena hippurus*) caught in the northern Tyrrhenian Sea. The lower jaw to fork lengths of the two predated swordfish were estimated at respectively, 18 and 22 cm, corresponding to 81- and 99-day-old swordfish hatched in the 2022 spawning season. This analysis and recent information on the reproductive dynamics of swordfish in the same area reported in the literature shed light not only on the early stages of swordfish growth but also on dolphinfish ecology in the Tyrrhenian Sea. The two species share the same habitat and are both caught with commercial pelagic surface longlines. Environmental shifts associated with climate change could unpredictably modify the reproduction dynamics, growth, recruitment and distribution of both species. This knowledge is important for the sustainable management of regional fisheries.

Keywords: dolphinfish; mediterranean sea; post-larvae; stomach contents; swordfish; tyrrhenian sea

1. Introduction

The dolphinfish (*Coryphaena hippurus*) and the broadbill swordfish (*Xiphias gladius*) are two large pelagic and highly migratory apex predators which share the same habitat in the western Mediterranean and are caught by surface longline vessels [1-3]. Swordfish is a high market value pelagic fish that is heavily fished in the Mediterranean Sea by at least 27 countries using different types of fishing gear [4,5]. Female swordfish are multiple spawners with asynchronous oocyte development, able to spawn every 2.3 to-3 days during the spawning period [6-8]. Based on the distribution of larvae and eggs, the presumed spawning grounds match the 24°C surface isotherm of the summer season in temperate areas, although in tropical waters, spawning can take place almost all year round. Swordfish swimming in pairs and displaying courtship behaviours are also mainly observed at temperatures above 24°C [9].

A considerable amount of literature is devoted to swordfish reproduction in the Mediterranean Sea [10]. The Straits of Messina and the southern Tyrrhenian Sea have been identified as the main swordfish spawning grounds, based on observations of eggs, larvae and mature females [11-13]. In the Ligurian Sea, that is part of the north-western Mediterranean, spawning takes place between June and September with a peak in July [14]. It is likely that the potential breeding area in the Mediterranean basin is relatively larger than the breeding are in the Atlantic [15,16]. New spawning areas for this species have been reported in the Levantine Basin [17], and other similar areas may exist in the Ionian Sea and the Levantine [4]. Since the 20th century [18], swordfish eggs and larvae are abundant only in July[19]. Recently observed seasonal variations in the sex ratio, as well as in the occurrence of females with running eggs confirm that spawning occurs off both sides of the island of Corsica[20].

Swordfish eggs and the earliest development stages of the fish have been described in detail based on individuals sampled in the wild [11,12,21-25] or on eggs hatched in the laboratory [12,25].

Despite the high commercial importance of this species, knowledge of the post larval swordfish ecology in the ocean is still incomplete [18,26]. Swordfish larval development is complex [12,27,28]. Larvae are generally associated with sea surface temperatures (SST) between 24° C and 29° C. Swordfish retain larval characters until their standard length, i.e. from the tip of the snout to the end of the middle caudal fin rays (SL) is at least 188 mm[21]. Knowledge of the ecology of post-larval swordfish in the ocean is incomplete due to the difficulty involved in observing these individuals in the marine ecosystem as they are rarely present in ichthyoplankton samplings and in catches.

Information on the spatial distribution of all swordfish life stages, from eggs to pre-adults, and on how environmental factors affect reproduction, spatial distribution, growth rate and recruitment of swordfish in the Mediterranean is lacking.

Swordfish is a fast-growing species, particularly in its first year. Juveniles entering the recruitment phase are caught near the coast in the last three months of the year. It is consequently assumed that coastal waters serve as a nursery habitat [29-31]. Positive SST anomalies could favour recruitment [32] while lower temperatures could delay the spawning season and slow down the growth rate of juveniles [33].

Swordfish management in the Mediterranean is under the control of the International Commission for the Conservation of Atlantic Tunas (ICCAT). As the high percentage of juveniles caught could have a negative impact on the spawning biomass per recruit, a closure period for longliners has been implemented. The most recent assessment in 2020 estimated biomass to be at its lowest level since 1950 [5]. As a result, a 15-year recovery plan was implemented [34]. It is prohibited to have on board, land, transport, store and sell swordfish measuring less than 100 cm LJFL (Lower Jaw to Fork Length) even though at-haulback mortality is thought to be as high as in the Atlantic (ranging between 78% and88%) and hence the same for the post-release mortality [5]. Countries are encouraged to find ways to reduce the capture of undersized swordfish [35]. The dolphinfish, a large tropical/subtropical migratory species, is an opportunistic predator which forages on epipelagic prey and is known to be associated with floating objects (FOBs) [36]. Acoustic telemetry data have shown that when associated with FOBs, dolphinfish can spend more than 95% of their time in the first ten meters below the sea surface [37] but that when not associated with FOBs and undertake daily vertical migrations, they swim down to a depth of 160 metres [38].

In the Mediterranean Sea, dolphinfish are targeted by the artisanal fisheries that use anchored fish aggregating devices (FADs) as well as by the recreational fisheries [39,40]. Commercial captures have increased steadily over time and it is assumed that climate conditions in March and April affect the catch rates of dolphinfish longline fisheries in September and October [2].

When early stages are cryptic, which is the case of swordfish post-larval stages, of stomach contents analysis of apex predators can provide otherwise unobtainable ecological information. A rare predation event on two swordfish larvae by a dolphinfish in the Tyrrhenian Sea, thus provides new insights into the ecology of both species in the area. The abnormally high SSTs recorded in 2022 in the area and the ecologically negative implications of dolphinfish predation are discussed.

2. Materials and methods

2.1. Sampling

Gonad samplings were conducted in the vicinity of the island of Corsica, in collaboration with domestic longline swordfish fisheries, from 2019 to 2021 in the framework of the GEN&REC project (European Maritime and Fisheries Fund-EMFF). The aim of the research is to fill the knowledge gap concerning swordfish reproduction biology in the north Tyrrhenian Sea and is in line with research conducted by (ICCAT)[41]. Five females with running eggs were caught between 2019 and 2021[20] (Table 1), and were measured and sexed during sampling at sea.

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Table 1. Date of capture, location, length, estimated batch and relative fecundity, and the gonadal index (GI) of five female swordfish (*X. gladius*) caught in the sea off the east coast (Tyrrhenian Sea, Tyrr) and off the west coast (South West Corsica, SWC) of the island of Corsica per month[20]. .

Date	Latitude	Longitude	Location	LJFL (cm)	Batch fecundity	Relative fecundity	GI
23 June 2021	41°52′N	9°45′E	Tyrr	184	1797321	22.29	8.30
27 June 2019	42°40.55′N	9°42.43′E	Tyrr	174	1983009	29.41	7.92
28 June 2021	42°N	9°33′E	Tyrr	209	4129165	37.24	10.34
15 July 2019	41°46.998′N	8°33.414′E	SWC	142	1108420	31.92	9.99
18 August 2019	41°46′N	9°43′E	Tyrr	135	675414	24.41	6.35

On the 23rd of September, 2022, a ripe male dolphinfish with a 97 cm fork length (FL) was caught by a drifting longline baited with *Illex sp*. (13-18 cm mantle length) at ca. 41° 49′ 684″ N; 9° 29′ 562″ E (Figure 1). It was caught alive at 14:10 UTC and rapidly gutted. The stomach of this specimen was opened on the deck. A visual inspection of the fragments of the digested fishes revealed two well-preserved pointed, depressed rostrums identified as swordfish bills. The hard parts were isolated and preserved in 90% ethanol for further examination together with the other tissues collected.

2.2. Estimated specimen size, age and spawning time

Age was estimated based on the results of a swordfish growth study conducted in the eastern Mediterranean [30] and the spawning times back-calculated integrating the swordfish egg incubation period proposed by Yasuda et al. [12].

2.3. Climatology

SSTs were extracted from the MODIS-Aqua dataset (2002-present) at 4 km resolution (available at https://oceancolor.gsfc.nasa.gov/data/aqua/) and compiled by month. These data were used to represent the monthly SST mean in three areas, the Ligurian Sea, the northern Tyrrhenian Sea and the Mediterranean Sea off the south-west coast of Corsica.

3. Results

3.1. Identification, size and hatching day

The stomach contents were identified visually to the lowest taxonomic level. The contents mainly consisted of small fishes digested to varying degrees, plus two larger specimens. The identification was straightforward, with no confusion possible because the shape of the swordfish bill, a pronounced extension of the upper jaw, is unique[42] (Figure 1a,b) while the six billfishes that occur in the Mediterranean: the Mediterranean spearfish (*Tetrapturus belone*) an endemic species, the white marlin (*Tetrapturus albidus*), the Atlantic sailfish (*Istiophorus albicans*), the Atlantic white marlin (*Kajikia albida*), the roundscale spearfish (*Tetrapturus georgii*) and the sailfish (*Istiophorus platypterus*), a lessepsian species[23,24,43] all have a bill with a round cross-section.

Back in the laboratory, the body fragments, tentatively identified as juvenile swordfish were assembled and their LJFL estimated at respectively 18 and 22 cm.

Based on a growth rate of 2.3 mm day -1, the two sizes corresponded to 81- and 99-day-old swordfish, theoretically hatched on respectively, 16 June and 5 July 2022.

The shape of the two specimens observed resembles to the drawing published by Fowler (1924) and the picture of a juvenile with a LJFL 23 cm caught in the Aegean Sea (Greece) (Figure 1c).

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(**a**)

(**b**)

(c)

Figure 1. Swordfish bills collected from the stomach of a dolphinfish in the Tyrrhenian Sea in September 2022 (scale: 17 cm). 1b: Remains of two swordfish bills and body fragments taken from the stomach of a dolphinfish caught in the Tyrrhenian Sea in September 2022 (scale: 10 cm). c- Photo of a juvenile swordfish with a LJFL of 23 cm caught in the Aegean Sea (scale: 10 cm). Source: Dr Nota Peristeraki at the Hellenic Centre for Marine Research (HCMR).

3.2. Swordfish spawning events and oceanographic features

In both 2019 and 2021, the earliest spawning females were sampled in the Tyrrhenian Sea at the end of June whereas the first female at the same stage of maturity was sampled off the SW coast of

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Corsica in August. The maps showing the locations where three females ready to spawn were captured are shown overlapping the SST values to highlight the difference in temperature in the two areas (Figure 2). This variation could explain the difference between the beginning of the spawning period in the two areas.

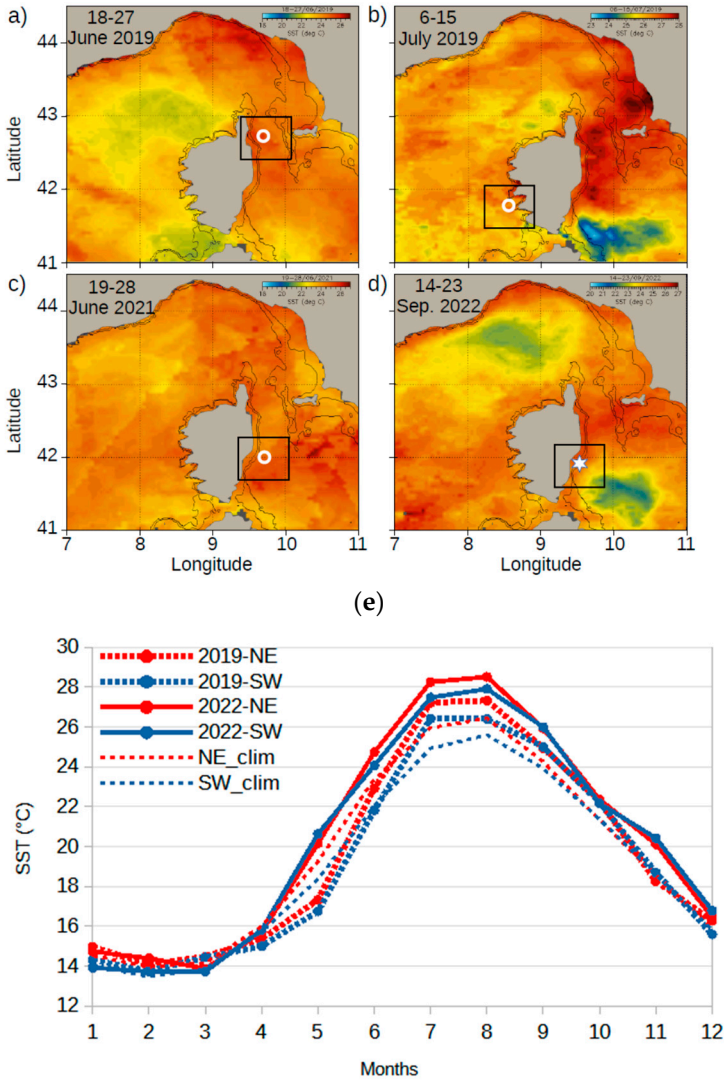

Figure 2. The locations of females ready to spawn (white circles) are shown overlapping the 10 days averaged sea surface temperature (SST) on map (a) samples taken on 23 June, 2019; map (b) samples taken on 15 July, 2019; map (c) samples taken on 15 June, 2021. The location where the dolphinfish was caught is marked by a white star (d). The black frames around the locations where spawning females were caught correspond to the spatial area where the SST data were extracted to calculate mean monthly SST trends. (e) Comparison of monthly SST trends in 2003 and 2018 (climatology/clim) on both sides of the island of Corsica - in the northern part of the Tyrrhenian Sea (NE) and off the south-west coast of Corsica (SW)- and the SST values for the years 2019 and 2022 in the same areas. .

Figure 2e shows the mean monthly SST trends for the period 2003-2018 (climatology) in two areas off the island of Corsica (in the northern part of the Tyrrhenian Sea (NE) and off the south-west coast of Corsica (SW)). The SST curve in the Tyrrhenian Sea is above the one for the south-west Corsica April onwards and the temperature gap of around 2 °C continues until August. In September, SSTs on both sides of Corsica are homogeneous.

The SST trends in the same areas in 2019 show that SST were higher than the climatology of 1° C from July to October.

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The trends of SST for the same areas as those shown for 2022 were higher than in 2019, underlining the fact that in 2022, SSTs were abnormally high from May to November and reached a difference of more than 2 °C in July.

4. Discussion

The location of spawning swordfish and the analysis of the stomach contents of dolphinfish contents provided valuable information concerning the spawning grounds, the geographic distribution and spatial aggregation patterns of juvenile swordfish and revealed particular oceanographic features that occurred in 2022.

4.1. A rare event

The size of male dolphinfish at first maturity in the western Mediterranean was estimated to be 61.8 cm and the mean trophic level for large individuals was estimated to be 4.5 ± 0.70 [44]. The dolphinfish is an opportunistic daytime predator that can use different foraging strategies depending on the prey availability [36].

A review of the literature on dolphinfish diet showed that both neritic and demersal finfish were among the stomach contents in all of the studies but that dolphinfish also consume crabs and epipelagic cephalopods. Global records of species identified in dolphinfish stomachs have previously not included young swordfish. Young juvenile swordfish were found in the stomach of 10 other predators including billfish, tuna and blue shark. Only one case of a 19.21 cm long swordfish found in the stomach of a dolphinfish captured on the trolling lines has been reported [45]. In the present study, the mature male observed was able to swallow two juvenile swordfish. Based on the scientific literature, these are the largest post larvae ingested ever reported.

It is of course difficult to know whether the fish were alive or dead when consumed. However, dolphinfish feed on the surface and are associated with FOBs. It is also difficult to explain how these two individuals could have died almost at the same time (as they were found in a similar stage of decomposition) apart from due to an attack by a predator. It is therefore, more likely that these are two cases of predation rather than consumption of dead animals.

In these circumstances, this event can be considered as rare and reflects the ability of adult dolphinfish to catch free swimming prey that are as long as the bait used by swordfish longliners. The presence of juvenile swordfish in the dolphin's stomach leads to the hypothesis that, at this early stage, swordfish that are more common in epipelagic waters, are associated with FOBs.

From the point of view of conservation, it is vital to determine, if post larval swordfish occur more frequently than previously assumed. This can be achieved by systematic sampling of the stomachs of top predator fish. This indirect would enable additional information to be inferred concerning pelagic communities [46].

4.2. Spawning and nursery grounds

The migratory nature of swordfish allows them to reach the favourable environmental spawning conditions needed to guarantee successful reproduction. Temperature is a crucial parameter in the distribution of swordfish in all the world's oceans [47]. In the present study, females ready to spawn were captured in three areas with contrasting oceanographic features and water mass circulation (currents and eddies) [20] where sea surface temperatures were above 24 °C, which could explain the short time lag before the beginning of the spawning season and its duration. Above this temperature threshold, growth rates are assumed to be high, consequently reducing the duration of the critical period of high mortality of larval and juvenile stages [48,49]. Poisson et al.[8] demonstrated that a simultaneous decrease in SST and an increase in the prevalence of females is an indicator of the end of the spawning season.

Reproduction in the Ligurian Sea is seasonal, with a peak in July–August and a tail in September, and all stages from post-larva to advanced ages have been found there [50-52]. In the vicinity of the island of Corsica, the spawning season has been inferred from the trend of the gonadal index, from

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histological studies of the gonads and observation of females with running eggs [20]. Spawning occurs in June and July off the coast on both sides of Corsica. The two swordfish found in the dolphinfish stomach were estimated to be hatched in the 2022 spawning season. Optimum temperatures and food availability influence the growth rate of fish larvae[49,53], and it is likely that both trophic and oceanographic conditions favour the development and growth of swordfish in their early life stages. Coastal waters off both sides of Corsica have been identified as nursery grounds for swordfish. The association with FOBs could facilitates the dispersal of juveniles along the coast. It can be assumed that young-of-the-year swordfish remain in the spawning grounds during the first year of their life. Yabe et al. [45] reported that swordfish can reach 50-60 cm in their first year, and then grow between 25 and 38 cm per year.

The smaller swordfish which was less than 90 cm long must have hatched the previous year. There is also evidence that the young of the year prefer coastal waters particularly during the winter months [47] .

4.3. Environmental factors and recruitment

Peristeraki et al. [33] demonstrated that successful recruitment is closely positively correlated with high ambient water temperatures, and that lower temperatures in particular can delay the spawning period and reduce the growth rate of juveniles. The year 1998, qualified as a warm year, was identified as an "exceptional" year for the recruitment of young individuals[32] . Due to the high SSTs recorded over an extended period, one would expect 2022 to be a good recruitment year for swordfish, as both the period of reproduction and its length could have been affected by changes in the SST.

Obtaining this information is critical because predation can affect recruitment. Spawning could have taken place earlier in the season and continued over an extended period.

Scenarios produced by CERES (Climate Change and European Fisheries and Aquaculture, H2020, EU 678193; https://ceresproject.eu/case-studies/ last accessed in May 2023) show that dolphinfish is a potential "winner" of climate change in the Mediterranean Sea as it will affect both the spawning season and location together with the growth rate of juveniles. Dolphinfish are predicted to be more frequent throughout the year and their size and total catches may vary in the near future [54].

5. Conclusions

Information on the early stages of development of the Mediterranean swordfish is currently limited as synoptic observations in marine ecosystems are difficult. The unusual and auspicious observation reported here describes a rare event involving two charismatic predators. This is the first evidence for consumption of young-of-the-year swordfish by dolphinfish thereby shedding light on swordfish predation by another apex predator species. It raises the question whether or not the expanding dolphinfish distribution is an indicator of potential impacts on swordfish stock abundance.

The influence this behaviour could have on the swordfish stock should not underestimated. Although it is impossible to draw conclusions based on the two larvae captured here, further large-scale dietary surveys of dolphinfish using DNA-based approaches are needed to clarify if changes have occurred in their foraging behaviour.

Investigating the post-larval stage is critical to understand larval mortality, to identify its drivers and which drivers could regulate recruitment. These questions are crucial for the management of the stock of Mediterranean swordfish. The spatial distribution and connectivity between swordfish spawning and putative nursery grounds during swordfish ontogeny also requires further investigation.

Climate experts have already indicated the direction research dolphinfish should take in the coming years. Additional investigations can be recommended: (1) into how climate change could affect environmental constraints to spawning and growth, the spawning season and extent, and fish

growth rates, but also (2) to discover if predation on swordfish is currently more frequent than previously and if so, will increased predation affect the level of swordfish recruitment.

Institutional Review Board Statement: No ethical parameters required as the gutted Dolphinfish [a marketable fish] used for the study was provided by skipper of the fishing boat.

Data Availability Statement: All data generated or analysed during this study are included in this published article.

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