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Posted Date: 30 May 2024

doi: 10.20944/preprints202405.2055.v1

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Preliminary Insights on the Habitat Use and Vertical Movements of Pelagic Stingray (*Pteroplatytrygon violacea*) in the Western Mediterranean Sea

François Poisson [1],*, Jim R. Ellis [2] and Sophy R. McCully Phillips [2]

[1] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France
[2] Centre for Environment, Fisheries and Aquaculture Science, Pakefield Road, Lowestoft, Suffolk. NR33 0HT. UK; jim.ellis@cefas.gov.uk (J.R.E.); sophy.phillips@cefas.gov.uk (S.R.M.P.)
* Correspondence: francois.poisson@ifremer.fr

Abstract: Pelagic stingray (*Pteroplatytrygon violacea*) is the only species of stingray (Dasyatidae) that utilizes both pelagic and demersal habitats. It is the main bycatch species in pelagic longline fisheries targeting bluefin tuna in the Gulf of Lions. In the Mediterranean Sea, their stock structure, behavioural ecology and movements are unknown. For the first time in the Mediterranean, 17 individuals (39 to 60 cm disc width) were tagged with pop-up satellite archival transmitting tags using a novel method of tag attachment, to investigate horizontal and vertical movements. The tags were attached for between two and 60 days. Between the months of July and October, pelagic stingray occupied a temperature range of 12.5 to 26.6°C, and a depth range extending from the surface to 480 m. Monthly trends in catch-per-unit-effort (CPUE) of pelagic stingray peaked in August and decreased by late autumn. Pelagic stingray may aggregate on the continental shelf during summer, and move southwards in early autumn, and this movement pattern is considered in relation to the reproductive cycle and overwintering. Future work and options for bycatch mitigation are discussed.

Keywords: bycatch; Dasyatidae; discard mortality; Gulf of Lions; mitigation; movements; pelagic longline; tagging methods; vertical distribution

Key Contribution: This work presents the first investigation horizontal and vertical movements of pelagic stingray (*Pteroplatytrygon violacea*) in the Mediterranean Sea using pop-up satellite archival transmitting tags and a novel method of tag attachment. Overall, pelagic stingray occupied a temperature range of 12.5 to 26.6°C, and a depth range extending from the surface to 480 m between the months of July to October. Individuals seemed to aggregate on the continental shelf during summer, moving southwards in early autumn, which may correspond with their spawning behaviour and overwintering.

1. Introduction

Pelagic stingray (*Pteroplatytrygon violacea*) is the only species from the family Dasyatidae known to utilize both pelagic and demersal habitats and inhabit the open ocean [1,2]. There is limited information on possible migrations of this medium-sized ray, which attains a disc width (DW) of up to 80 cm [3–6] and typically occurs in oceanic areas far from the coast [7,8]. They feed on highly mobile, pelagic prey including teleost fish and squid, but also crustaceans near the seafloor, and they seem to adapt their prey choice according to geographical location [9,10], presumably in relation to prey availability. Pelagic stingray can be found from the surface to at least 600 m in the open ocean [3].

In the Mediterranean Sea, and indeed globally, pelagic stingray is caught by various fishing gears operating over a range of depths, with pelagic longlines being the main capture method [11–13] followed by trawls and nets [4,14]. With no commercial value, pelagic stingray constitute an economic loss to the fishery [15] and are systematically discarded after capture. There are currently no reliable estimates of the quantities caught and discarded by fisheries, although it is known to be a frequent bycatch species in the French pelagic longline fishery targeting Atlantic bluefin tuna (*Thunnus thynnus*) in the Gulf of Lions (GoL; [13]). The incidental capture of pelagic stingray is a problem for fishers, as they interact with the bait which can be ingested partially or wholly, thus reducing the effectiveness of the gear by reducing the number of hooks available for commercial fish, and the handling of the stingrays is time-consuming (hook retrieval can reduce active fishing time). Furthermore, fishers risk injury from the venomous spines [16].

The migrations of pelagic stingray have been well evidenced [5], but the drivers for such movements are less defined. The thermal tolerance of this cosmopolitan species is relatively large, and it utilises tropical to warm temperate seas worldwide [2,17], and thus seasonal movements alone may not be described fully by temperature. Mollet (2002) indicated that in the eastern Pacific warm waters are utilised for pupping followed by a migration to higher latitudes, while in the Mediterranean Sea (Bay of Naples), pupping occurred before a migration to warmer waters [18,19]. In both the Mediterranean Sea [12] and Pacific Ocean [8], geographic position has been identified as a significant explanatory variable to presence. Wang et al. (2023) also found that comparatively lower salinity (33.0–34.5 psu), high chlorophyll concentrations and warmer water all had a positive correlation to abundance.

Pelagic stingray is one of the more productive elasmobranchs in oceanic ecosystems [20]. Females may produce two litters of 4–13 pups per year and may have a gestation time of 2–3 months, and so it may be the shortest gestation time of any shark or ray species [2,18]. Due to this high reproductive rate and declines of larger sharks (the major predators and competitors of the species) in the Mediterranean Sea [21], population increases in the Mediterranean pelagic stingray stock are conceivable.

Pelagic stingray is assessed as Least Concern globally [22] on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, due to their widespread occurrence and apparent resilience to fishing, although an earlier study suggested it was Near Threatened in the Mediterranean Sea [23]. Due to their frequency in catch records, they are often assumed to have high post-release survival rates after capture in longline fisheries [24].

Further research for this species is required to collect information on its biology, ecology and population dynamics, and appropriate monitoring of incidental catches is also required [4]. It is also crucial to understand the interactions between species and the fishing gears to develop and implement suitable mitigation measures [25]. Conservation strategies may include measures to minimise interactions through a greater understanding of spatial-temporal geographic distribution, and fishing gear modifications to reduce the capture or facilitate escapement of individuals. Much of our understanding of the seasonal distribution, movements, and abundance of pelagic stingray in the Mediterranean Sea are unclear, owing in part to the fishing season of the GoL longline fishery being limited mostly to the period from late spring to autumn [26].

The development of satellite telemetry and bio-logging technologies has allowed scientists to obtain accurate information on the free-ranging movements, population connectivity, and habitat preferences of elasmobranchs around the world [27]. Studies on the movements, migrations and habitat use of pelagic stingray, such as can be derived from using pop-up satellite archival transmitting tags (PSATs), are limited (Weidner et al., 2023). The latter study was based on just four individuals fitted with PSATs for 13-days in the western North Atlantic and Gulf of Mexico, and its habitat use was found to differ according to oceanographic conditions . The paucity of electronic tagging studies on pelagic stingray may be due to its more limited commercial and conservation interest (compared to some other elasmobranchs), the risk of stinging when handling stingrays, , and problems associated with tag attachment. Tags or sensors are usually attached to the wings of skates and rays [28,29] or sutured to the base of the tail [30].

The main aims of the present study were to (1) develop a new tag attachment method to avoid disruption to the ray's natural movements of the pectoral fins, (2) investigate the vertical (and horizontal) behaviour of individuals in the water column on important longline fishing grounds, as this knowledge is thought crucial to develop avoidance strategies such as deploying gear at depths or temperatures less likely to interact with unwanted species [31,32], and (3) evaluate interactions with the pelagic longline fishery, including information on catch rates, at-vessel mortality (AVM) and post-release mortality (PRM). These findings of the study, which were achieved through the deployment of archival tags and the collection of both fishery-dependent and biological data, are discussed in relation to the spatial ecology of pelagic stingray, and fisheries management and conservation strategies for this bycatch species.

2. Materials and Methods

2.1. Tagging

Four different types of pop-up satellite archival transmitting tags (PSATs) from two manufacturers were deployed on pelagic stingray between 2016 and 2019 in the western Mediterranean Sea, mainly in the GoL and one from Corsica Island. Seventeen stingrays were tagged from July 2015 to October 2019 with MiniPAT (n = 1), Mark-report PAT (mrPAT; n=10) and survival PAT (sPAT; n=2) - all from Wildlife Computers, Inc., Redmond, Washington, USA. The remaining four tags were SeaTag-3D, from Desert Star, Marina, California, USA (Table 1).

Table 1. Summary of the 17 satellite tags deployed and reported data for pelagic stingray tagged in the Gulf of Lions (GoL) and Corsica Island (Cor), * Data not recoverable.

Site	Tag type	#	Tagging date	Sex	DW (cm)	Distance (km)	Days at liberty (d)	Mortality	Last tagging transmission	Remarks
GoL	SeaTag-3D	151713	2015-08-27	F	49	418	35	-	2015-09-26	Short period of transmission
GoL		151717	2015-08-03	F	60	25	2	No		Captured by a French gillnetter
GoL		151719*	2015-08-27	F	53	-	-	-		Failure
GoL		151720*	2015-08-05	M	46	-	-	-		Failure
GoL	MrPAT	149829	2015-08-03	F	52	94	60	No	2015-10-02	
GoL		149834	2015-07-15	F	47	303	60	No	2015-09-13	
GoL		149835	2015-07-21	F	50	97	60	No	2015-09-19	
GoL		149837	2015-08-05	F	47	217	60	No	2015-10-04	
GoL		149836*	2015-08-05	F	51	-	-	-		Failure
GoL		149833*	2015-08-27	M	43	-	-	-		Failure
GoL		149832*	2015-08-03	F	48	-	-	-		Failure
GoL		149828*	2015-08-27	F	55	-	-	-		Failure
GoL		149830*	2015-08-03	F	49	-	-	-		Failure
GoL		149831*	2015-08-27	M	39	-	-	-		Failure
GoL	sPAT	14P0099	2016-09-23	F	55	245	25	Unknown	2016-10-17	
GoL		13P0381	2016-08-04	F	45	73	27	Unknown	2016-08-30	Sighted and filmed close to shore 5 days after tagging
Cor	miniPAT	138296	2019-09-10	F	54	89	8	Yes	2016-09-17	Caught by the wing

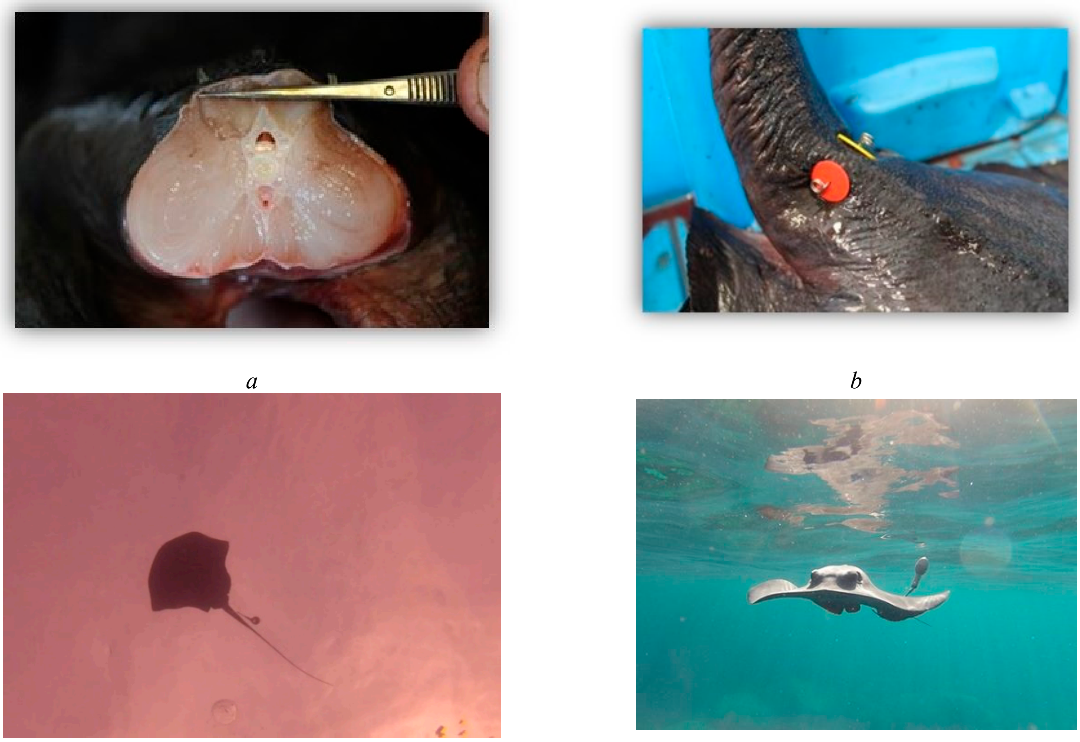
The mark-report pop-up archival tag (mrPAT; Tagware Version: 1.00a-3649), which was the smallest archival tag on the market at the time of the study (weighing 44 g), can record daily minimum and maximum temperature and the daily difference between the minimum and maximum tilt data. These tags, which were developed for large-scale studies of horizontal movements, were pre-programmed to detach from individual stingrays and provide a pop-up location after 60 days. The survival pop-up archival tag (sPAT), which weighs 61 g, can only transmit daily maximum and minimum values for depth and temperature.

The MiniPAT is designed to track the large-scale horizontal and vertical movements of fish able to record depth, temperature, and light-level data. All the tagging data were stored on the Wildlife Computers Data Portal (http://my.wildlifecomputers.com/data/). It was pre-programmed to collect these data at 150 second intervals for 30 days. The track of the stingray tagged with a MiniPAT was estimated using the WC-GPE3 algorithm, a software provided by the manufacturer using twilight, sea surface temperature, and dive depth data recorded by the tag to estimate the tracks [33]. These three tag types were programmed to detach after the recording period. They can also be set to automatically release when the animal is dead.

The SeaTag-3D can record light intensity, depth and temperature and provided locational data when surfacing.

2.2. *Tag Attachment*

The tagging method employed consisted of inserting a stainless-steel wire of 1.5 mm diameter transversely through the base of the tail above the spine (avoiding the vertebrae and artery), where the skin is thickest (Figure 1a). This location was selected (*cf*. the pectoral fins) following preliminary attachment testing on cadavers, in a bid to limit the impact of tagging on natural body movements, as stingrays use undulatory movements of the pectoral fins for forward locomotion. The wire was pre-coiled at one end, with a sharpened point which acted as a needle to drive through the tail at the other end. The pre-coiled end was pre-fitted with a Petersen disc which sat flush against the skin. Once fed through the tail base, the other end was also fitted with a Petersen disc, the point cut off, and then manually coiled with pliers, so as to be secured (Figure 1b). These two coils then served as attachment points for the PSAT, using monofilament line and crimps. The pin and the material used to affix tags were cleaned with ethanol beforehand. The wire was wrapped in a transparent silicon sheath to avoid abrasion of the skin.



a *b*

c *d*

Figure 1. Tag attachment for pelagic stingray, showing (a) cross section of the tail base, with the vertebrae and the artery; (b) Peterson disc tags in place showing the coils used to anchor the PSAT tag; (c); (d-e) pelagic stingray # 13P0381 swimming close to shore 5 days after its tagging.

All stingrays tagged were captured during trips on commercial vessels participating in the pelagic longline fishery. Tagged individuals were sexed, the disc was width measured to the centimetre below, and specimens tagged if they were active and without external injuries. During the tagging operation, the individuals were maintained on a waxed canvas mat, with a seawater hose

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used to keep them damp and to irrigate their gills. A person wearing hardware gloves would hold the tail with a damp cloth to steady the attachment site and prevent the scientist attaching the tag from being injured by the barbed spine. Hooks were removed before release.

2.3. Fishery Data

Between 2012 and 2023, qualified observers under the Data Collection Framework (DCF; Regulation (EU) 2017/1004) and scientists on board pelagic longliners operating in the GoL monitored fishing operations and collected catch data. For each set, they recorded operational parameters, including geographical coordinates (latitude and longitude) of the setting and hauling locations, hook and bait types, target catch (species and number), and bycatch data (species, number; sometimes these were measured and sexed). Additional data from volunteer fishers were also collated. In total, data from 382 longline fishing operations were obtained, with 175 sets from the DCF program. The 251 sets which occurred in the GoL were used to estimate the CPUE of pelagic stingray, blue shark (*Prionace glauca*), and bluefin tuna. An initial estimate of at-vessel mortality was established on the basis of information recorded in the logbooks filled in by the fishers and collected by scientists.

2.4. Data Analysis

Data analysis was conducted in R (R Core Team, 2021). The packages ‘RchivalTag’ and ’oceanmap’ [34,35] were used to analyse the MiniPAT archived data.

3. Results

3.1. Tag Deployments

Detailed information on the 17 satellite tags deployed on pelagic stingray is presented in Table 1. Fourteen tags were deployed on female pelagic stingray (45–60 cm DW), with the remaining three attached to males (39–46 cm DW). All specimens were tagged during the summer (July: n = 2; August: n = 13; September: n = 2). Of the 10 mrPAT deployed, four popped off on time and provided accurate data while the other six failed to report. Off the four SeaTag-3D deployed, only one reported several locations daily, and limited temperature and depth data were reported. Hence, these data were not considered usable. The successful tags remained attached for between two to 60 days, and yielded a total of 313 days of data.

3.2. Movements

3.2.1. Depth Profiles

The overall vertical ranges were obtained from two female stingrays tagged with sPATs (13P0381 and 14P0099; Figure 2) on the continental shelf in the GoL and from one female tagged with a miniPAT (138296) on the continental shelf to the northwest of Corsica (Figure 3).

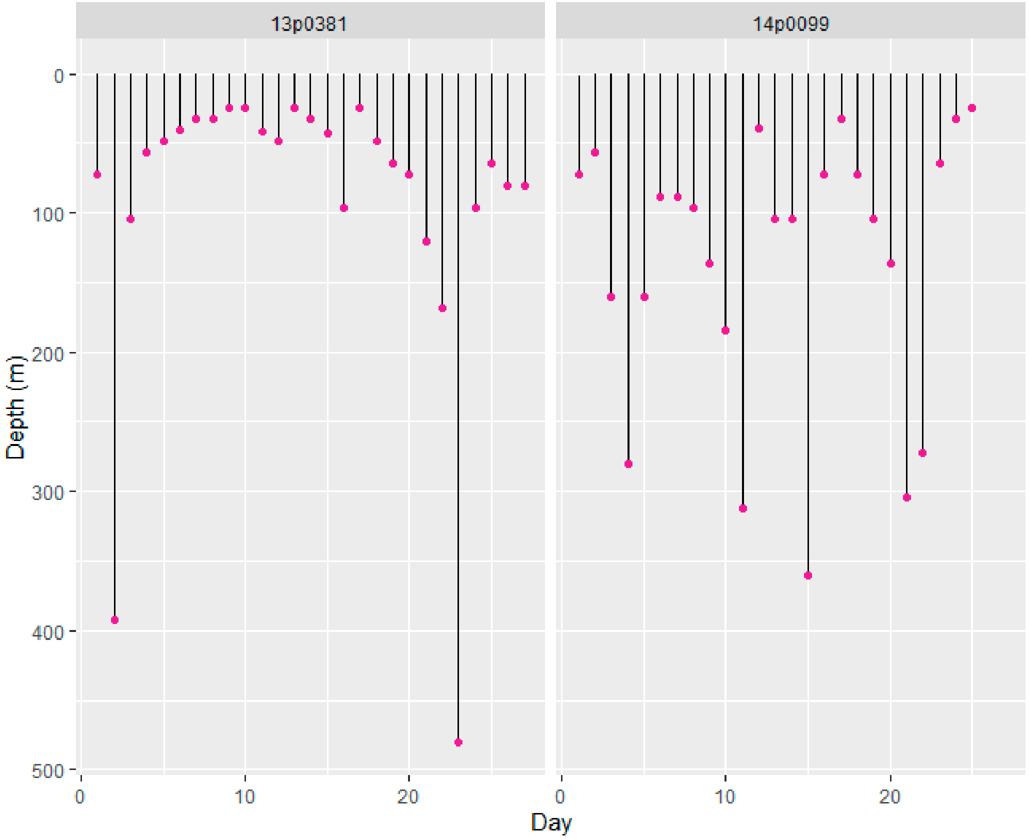
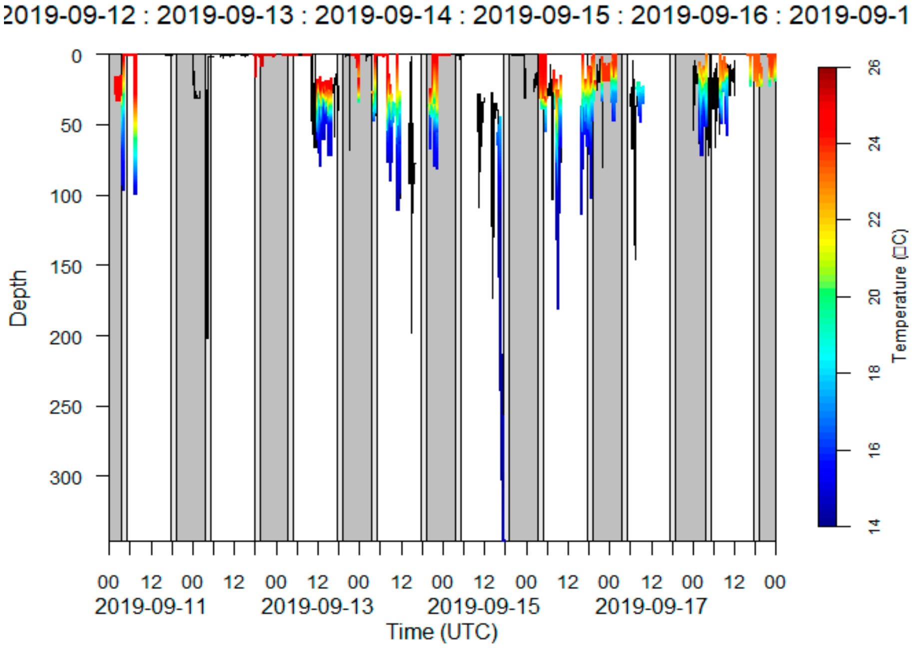
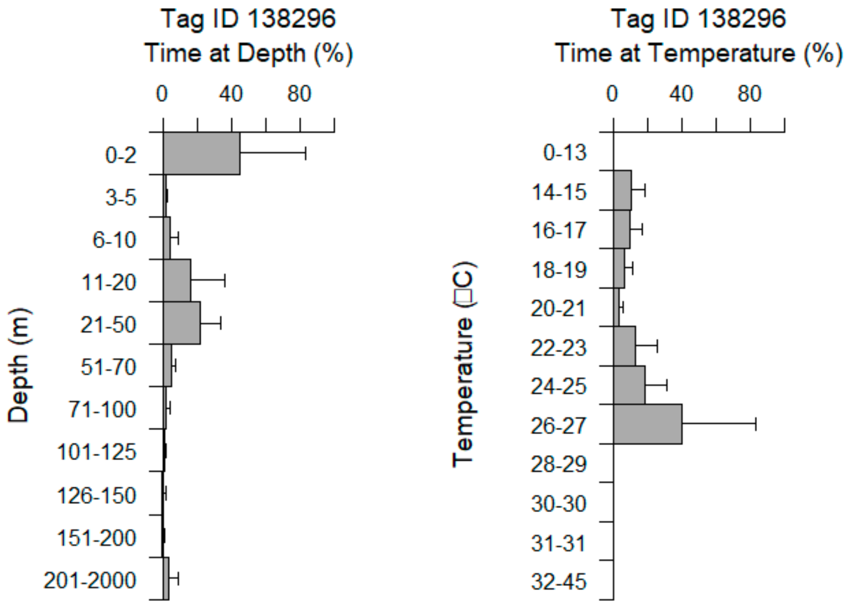


Figure 2. Daily minimum and maximum depths recorded by two pelagic stingrays tagged with sPATs over a period of 27 days (13p0381) and 25 days (14p0099). See Table 1 for further information..



(a)



(b)

Figure 3. Depth and temperature profiles of a pelagic stingray tagged with the MiniPAT (138296) in Corsican waters showing (a) vertical profiles during the day (white), night (grey), and dawn and dusk periods (light grey), and (b) histogram showing the average daily percentage of time spent at depth (m) and temperature (°C).

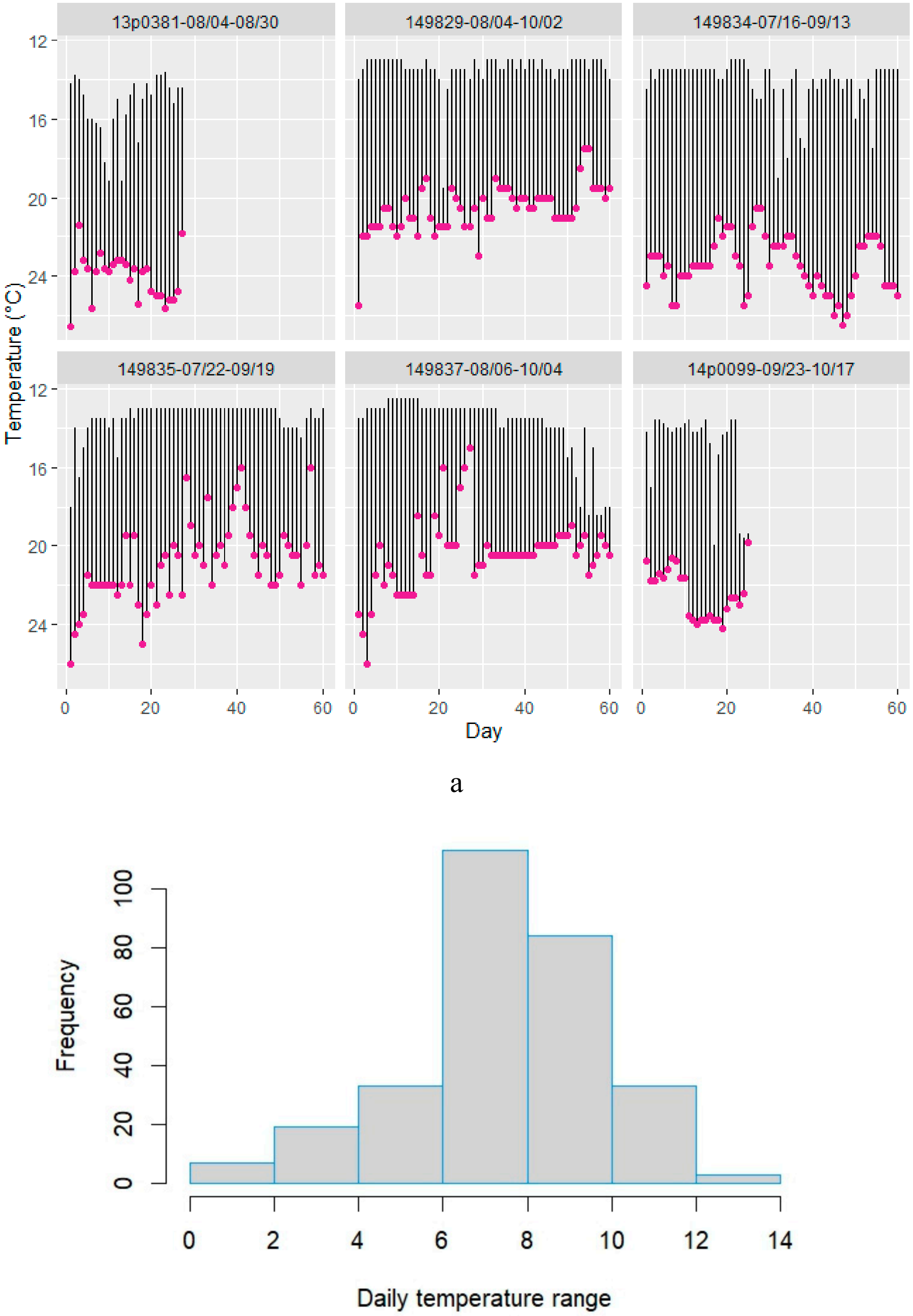
Data from the sPATs (Figure 2) showed that the minimum and maximum depths recorded daily over the 25- and 27-day periods were 0–360 m (14P0099) and 0–480 m (13P0381). Despite some behavioural differences, both individuals utilized much of the water column and surfaced daily. Individual 14P0099 was no longer on the continental shelf four days after tagging, with the maximum depths recorded exceeding 250 m. This was also evident for individual 13p0381, which exploited depths just less than 400 m two days post-tagging. However, this individual was also sighted and filmed close to the shore 5-days post-tagging by a speargun diver at just 10 m depth, around 26 km northwest from the tagging location. The footage showed the stingray coming from the bottom to swim around and close to the diver then it moved away, seemingly in a healthy condition (Figure 1c–d). This corresponded to the shallow depth values observed before the individual returned to offshore, to waters where the deepest depths (480 m) were recorded. The lack of vertical profile data for these two individuals after the 25–27-day period indicated that these animals may have suffered mortality with the tags remaining attached (with the automatic mortality detachment protocol failing to action).

Depth data for sPATs, which are summarised by daily minimum and maximum depths, limits analyses of vertical diving behaviours during day-night cycles, or the time spent by depth strata. However, these data confirmed that these individuals came to the surface every day, and spent much of their time (40%) between 0 and 2 meters, and utilized much of the water column between the surface and 70 m.

The single miniPAT tag deployed provided continuous data for both temperature and depth (Figure 3). The individual seemed to stay in deeper waters during the day, and shallower waters during the night. The two deepest dives (to 100–200 and 346 m) occurred at dawn on 12 September and almost at the end of the day on the 15 September 2019, respectively.

3.2.2. Temperature Profiles

The daily vertical distribution (minimum and maximum) temperature profiles were obtained from the same two female stingrays tagged with sPATs, along with an additional four mrPAT tags (Figure 4a). The range of temperatures experienced were quite similar due to the extensive vertical movements each day and the seasonal nature of the tag deployments (August to September). Individuals moved throughout the water column, and the minimum and maximum temperatures recorded across all individuals were 13.0°C and 26.6°C, respectively. The daily variation in temperatures experienced ranged from 2.5 to 13.5°C differences over a 24-hour period. The range of daily temperatures experienced by pelagic stingray was bell-shaped, with a peak between 6 and 10°C, indicating that rays undergo significant diel vertical migrations and associated range of water temperatures (Figure 4b).



a

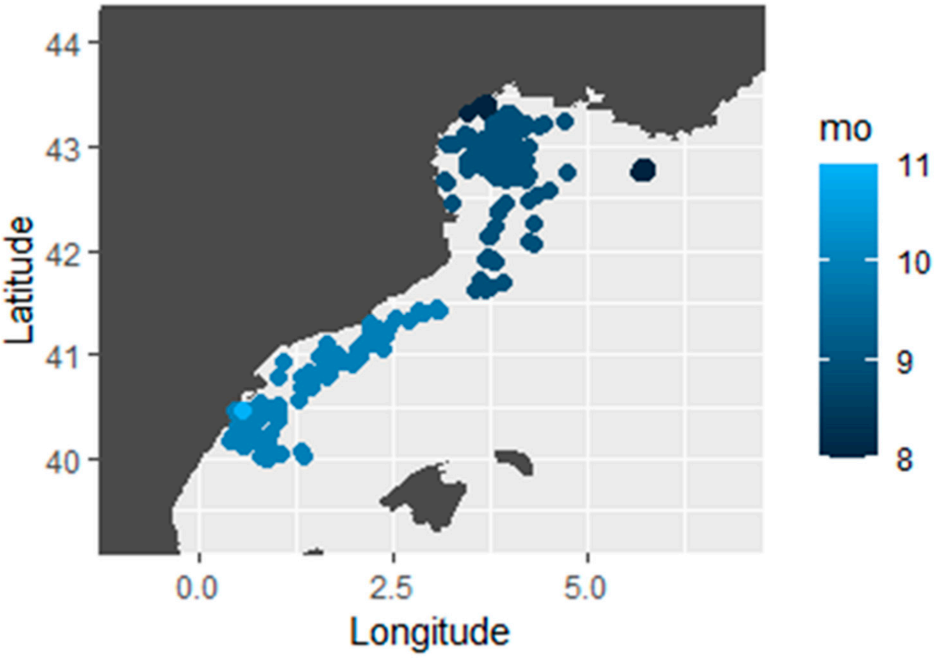
b

Figure 4. Water temperatures experienced by pelagic stingray showing (a) the daily minimum and maximum temperature recorded for six individual pelagic stingrays tagged with mrPAT or sPAT

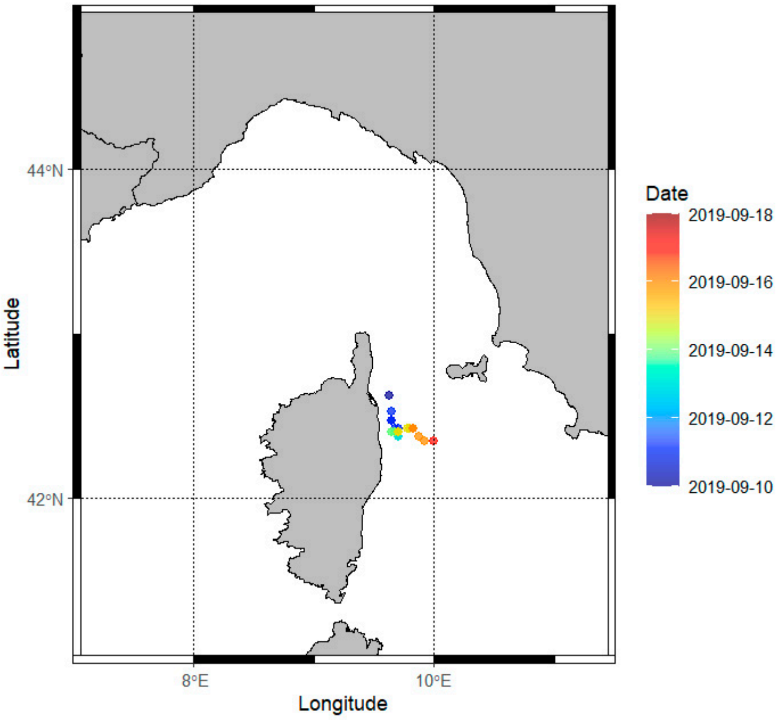
over periods of 25 to 60 days, and (b) a histogram showing the daily temperature ranges experienced aggregated across all individuals.

3.2.3. Horizontal Movements

Detailed data on horizontal movements were limited to two individuals (SeaTag-3D 151713 and miniPAT 138296). The former, which provided detailed location and track data for 35 days, was tagged in the open sea on the 27 August 2015, and headed straight towards the shelf on the 5 September where it stayed for 20 days. By the 26 September it started to move southwest along the edge of the continental shelf crossing the national jurisdiction border and reached the Spanish coast between Barcelona and Valencia by early November (Figure 5a). The tagging and tag release locations, or the loss of signal in the case of the SeaTag-3D tag, were mapped to provide the minimum theoretical, straight-line distances, and showed that pelagic stingray can carry out long distance movements (range 25 – 418 km; Figure 6). Female 151713 covered at least 418 km in 35 days, equating to 11.9 km.day^{-1} (horizontally).



A



B

Figure 5. Tracks of pelagic stingray showing (a) estimated path of pelagic stingray (SeaTag-3D tag 151713; 49 cm DW female that travelled an estimated 1531 km (straight-line distance 418 km) and (b) estimated path of pelagic stingray 138296 (a 54 cm DW female) tagged off the east coast of Corsica.

The specimen tagged off Corsica (138296) moved southwards along the coastline before moving offshore, although detailed track data were only available for eight days (Figure 5b).

Whilst detailed movements were lacking for other tags, six tags allowed for estimation of theoretical straight-line movements (Figure 6). Stingray # 13P0381, which was tagged on the outer edge of the GoL headed to the inshore waters of the GoL in August after its release (with an excursion to the shallow waters of Toulon where it was filmed). All the rays tagged in the inshore water of the GoL moved offshore, with four of them moving south-west. Five stingrays were off the shelf edge by the time of their last transmission times in either September (# 149834, #149835) or October (#14P0099, # 149829, #149837) (Figure 6; Table 1).

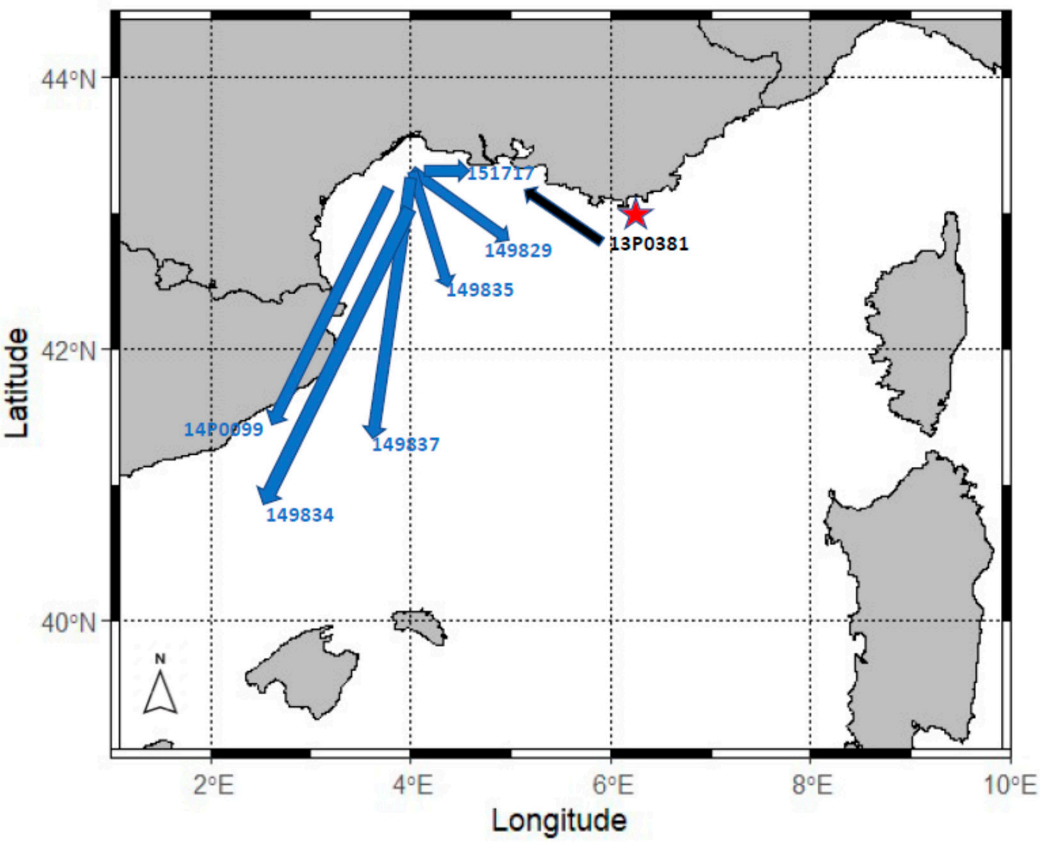


Figure 6. Release positions and theoretical straight-line distances travelled by seven other pelagic stingrays (sPAT tags 14P009 and 13P0381, SeaTag3D tag 151717, and MrPAT tags 149829, 149834, 149835 and 149837. The red star shows the location where stingray 13P0381 was filmed in the wild. See Table 1 for further details and Figure 5 for other movements.

3.3. Interactions with the Longline Fishery

Nominal catch-per-unit-effort (CPUE) data (ind./1000 hooks) were calculated for three species for the period April to December (Figure 7). The mean nominal CPUE for pelagic stingray on the continental shelf increased from June (1.3 ind./1000 hooks) to July (28.2 ind./1000 hooks), and peaked over late summer (July to September) before decreasing in October and subsequent months to levels comparable to those observed in the spring. A broadly similar CPUE trend was also seen for blue shark, for where the highest CPUE (4.3 ind./1000 hooks) was observed in the summer (June and July, albeit with higher variance) before decreasing over the autumn and winter, when the CPUE was <2 ind./1000 hooks. The CPUE of the target species, Atlantic bluefin tuna varied over the year. Whilst the highest monthly mean nominal CPUE was observed in April (17.1 ind./1000 hooks), this was based on a limited number of fishing trips and had a large variance, and the nominal CPUE in the mean fishing season (June to October) ranged from 1.2–11.3 ind./1000 hooks.

In total, 2984 pelagic stingrays were captured throughout the area fished by the fleet, with only two recorded as discarded dead (at-vessel mortality rate of 0.07%).

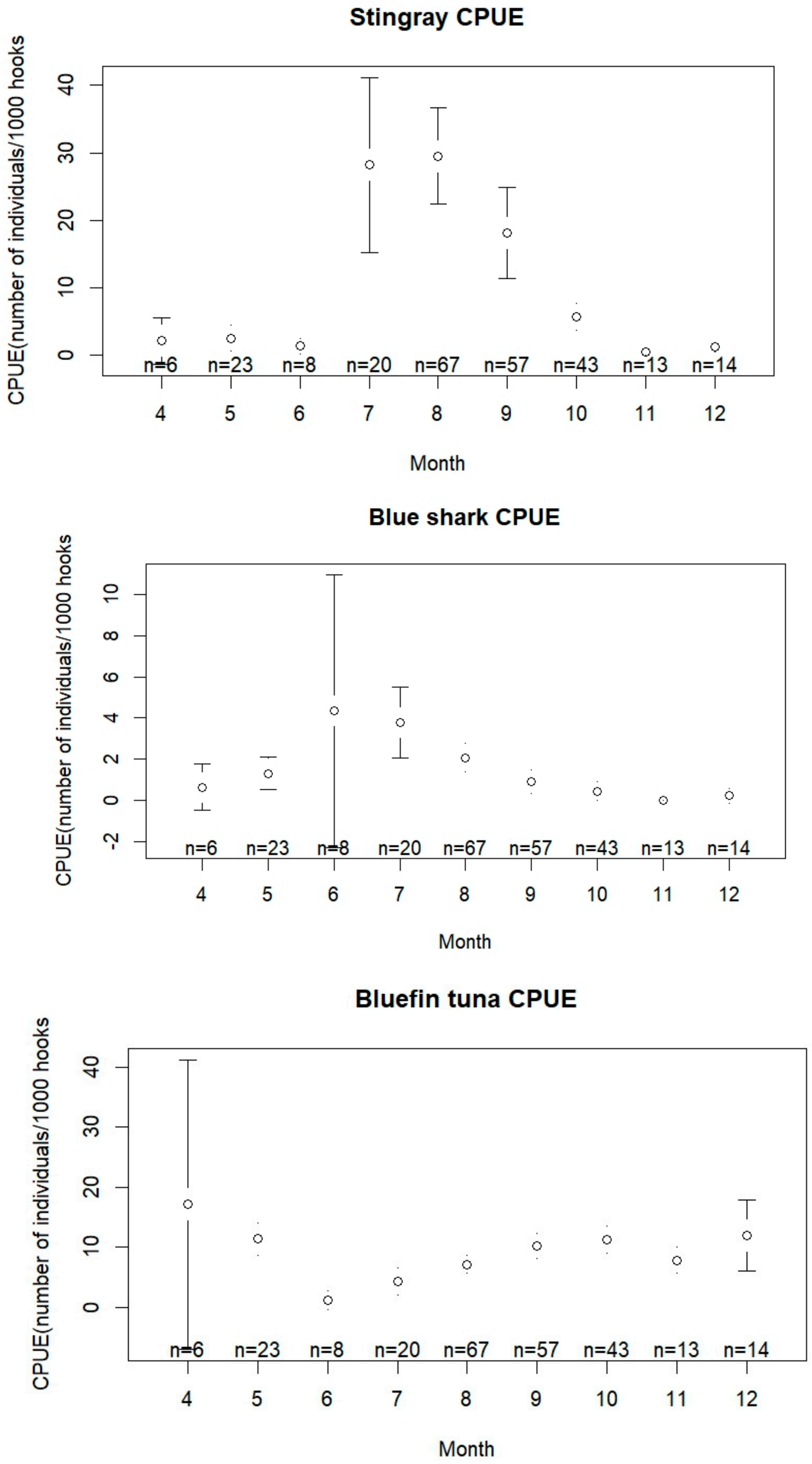


Figure 7. Monthly trends in the mean nominal CPUE (ind./1000 hooks) and SD for pelagic stingray, blue shark, and bluefin tuna caught in the Gulf of Lions pelagic longline fishery targeting bluefin tuna. Data collected from 2012 to 2023 and monthly data aggregated across all years. The number of trips for which data were available each month is also indicated.

doi:10.20944/preprints202405.2055.v1

4. Discussion

Determining the distributions and vertical and horizontal movements of bycatch species interacting with longline fisheries is an important element for considering spatial management and mitigation measures. For example, recent studies have examined the migratory patterns of blue shark in the western Mediterranean Sea [36]. Incidental capture of pelagic stingray during commercial fishing operations in the GoL is substantial and, whilst many are released alive, these interactions could pose a threat to this species. This has been highlighted by an evaluation of the bycatch of different elasmobranch species in relation to pelagic/midwater trawling in the northern central Adriatic Sea [4]. The present study is the first to provide some understanding of the vertical activity (and horizontal movements) of pelagic stingray in the Mediterranean Sea by using archival tags and fisheries data. We anticipate that knowledge obtained on habitat utilization and behaviour of this species could help inform options for mitigation measures for the species.

4.1. Satellite Tag Deployment

Studies on the movements, migrations, and habitat use of pelagic stingray are limited (Weidner et al., 2023), with the present study providing the first such data for this species in the Mediterranean Sea. The reasons for paucity of earlier studies may be related to several factors, including low commercial value, limited conservation interest, risk of injury when handling the species, difficulties in tag attachment and (often) more offshore distribution. The tag attachment method described here appeared to be effective and clearly did not restrict the movements of the tagged individuals, either vertically or horizontally, and thus would be supported as an appropriate method for future studies on species of stingray. The video footage obtained showed that the swimming action of the ray was fluid, with the oscillatory movements of the wings undisturbed. As a result, some individuals were able to cover great distances in a short duration.

The release system of the Desert Star tags did not function correctly, and none of them popped off as programmed. Nevertheless, daily geographic locations were recorded over the whole programmed tag duration when the stingray swam at the surface. The issues of reliability extend beyond the release system, with problems also encountered with data outliers, data transfer and analysis software malfunctions.

Similarly, reliability issues were encountered with the mrPAT tags, whereby six of the 10 deployed failed to report any data. The rationale of such a high failure rate is not clear. Although Chen et al., (2018) encountered an identical failure rate (60%) when applying mrPAT tags to Japanese eel (*Anguilla japonica*), many other studies have encountered far lower rates, ranging from 0% [37] to 9% [38], when deploying these tags on elasmobranchs [39].

4.2. Vertical Movements

The current study provided new insights into the vertical movements of pelagic stingray. It supports the view that individuals could utilise much of the water column, which would corroborate that this species can also feed on demersal species [40]. Individuals moving throughout the water column experienced daily temperature differences ranging from 2.5 to 13.5°C over a 24-hour period. The minimum water temperature recorded for all individuals was 13°C, which means that pelagic stingray can cross the thermocline and may range into cooler waters where light intensity and oxygen levels are lower. However, information suggests that 13°C was too cold for captive rays [19] (F. Bentivegna, personal communication; cited in Mollet, 2002). Whilst pelagic stingray can experience a wide range of water temperature over the course of the day (Figure 4a), the detailed time at temperature data available for individual 138296 (Figure 3, S1) indicated that very little time (ca. <10%) was spent at any temperature band <22°C, with the majority of the time (ca. 40%) spent in waters of 26–27°C. This individual also spent >40% of the time in the upper two metres of the water column, which may indicate that pelagic stingrays occupy surface waters as behavioural thermoregulation.

Whilst limited to a single tagged individual, visual examination of the two-dimensional dive time series allowed the identification of dive patterns which are reflective of pelagic fish [41–43]. The deepest dives could be identified as V-dive patterns (Figure S1), as also observed for blue shark [42]. No U-dive patterns, which are often viewed as corresponding to foraging behaviour, were noticeable. Further studies are required in order to determine whether these deeper dives are linked to behavioural thermoregulation, as shown in the case of bat ray *Myliobatis californica* [3,44] and/or foraging in the water column, from the surface to the thermocline. This hypothesis could be confirmed by additional tagging data profiles. In contrast, pelagic stingray tagged in the western North Atlantic Ocean did not spend much time at the surface [3].

Atlantic bluefin tuna is a key commercially-important fish that is present in the GoL for most of the year (but less abundant during the spawning season (May to July) [45], with tagging studies showing site fidelity from August to October [46]. When the waters of the GoL are stratified during the summer months, bluefin tuna exploit the surface waters, where they are targeted by the longline fisheries, but as the stratification breaks down from autumn to winter, bluefin tuna move into deeper waters [46,47]. This study has shown that pelagic stingray surface daily, and data from one tag indicated that >40% of time was spent at depths of 0–2 m (Figure 3b). Bauer et al., (2020) found that ~30–60% of time for bluefin tuna was between 0–10 m during the period April to September. Consequently, there will be high vertical overlap between pelagic stingray with the target bluefin tuna fishery, and therefore limits the feasibility of modifying the depth of longline setting to avoid this bycatch species.

4.3. Horizontal and Seasonal Movements

The GoL is thought to be a crucial area for a range of elasmobranch species [48], and may include important reproductive areas and nursery areas. Furthermore, the GoL is strongly influenced by the interannual freshwater discharge of the Rhone River, which is an important source of nutrients in the area, as well as strong coastal upwellings [49].

The 10-year fisheries data series examined in this study demonstrated that pelagic stingray is a common bycatch species. Bycatch events occurred in the middle of the GoL peaking from July to September. Blue shark is also caught on the shelf by the same fishery, mainly between June and July. The catch rates recorded for blue shark were lower than observed for both bluefin tuna and pelagic stingray, which may be due to blue sharks biting through the fishing line.

The elevated CPUE of pelagic stingray in the fishery from July to September could relate to seasonal aggregating behaviours during the spring and summer months, which may relate to the reproductive cycle. Females are likely to move into inshore waters for parturition and then migrate off the shelf. The elevated temperatures experienced in the surface waters of the GoL may also support the development and growth of embryos, given that parturition is thought to occur in late summer to early winter. In the Bay of Naples, for example, full term embryos were observed only in August–September [18,19,50], suggesting that parturition occurred before the stingrays migrated to warmer water, when the water in the Bay of Naples became too cold (Mollet 2002). Another study reported a female pelagic stingray that shed near-term pups in August (Gulf of Lions), and free-swimming neonates off the Tunisian coast in September and December [51]. Longline fishing activity in the GoL is often limited to the period from early summer to early autumn [43], which limits a full evaluation of the seasonal changes in the pelagic stingray population. Elsewhere in the world, it has been suggested that parturition could occur over much of the year in the south-western and equatorial Atlantic, probably with a rather short reproductive cycle (Veras et al. 2014). In the North Atlantic, pelagic stingrays give birth in August–September near the continental shelf, while in October, when the temperatures there dropped to 18.8°C, catches increased in the south close to the Gulf Stream waters, and no pregnant females and no small specimens were observed (Wilson and Beckett, 1970). . Overall, and as noted for the blue shark, the GoL could be an area used in the reproductive cycle of pelagic stingray in the Mediterranean [36] during the spring and summer. The tagging data align with the fisheries data highlighting a decline in catch rates at the end of the summer season, supporting the hypothesis of seasonal movements away from the GoL shelf environment.

4.4. Interactions with the Longline Fishery

In this study, the AVM of 0.07% was very low, a likely consequence of the reduced number of hooks deployed (400 to 900 hooks per set) and short soak times (less than 5 h) in the GoL longline fishery [13]. Low AVM rates (<2%) have also been observed in the Atlantic [52,53]. There is no study to our knowledge of the PRM for this species [54]. However, PRM could conceivably be high, as this species is often considered dangerous and of no value by fishers, thus pelagic stingrays are often discarded without any care, and often with the trailing gear remaining which could lead to mortality, as evidenced in sharks [55].

In terms of PRM, all individuals tagged and released in 2015 field studies, and for which sufficient data were reported, appeared to have survived 60 days post-tagging (n = 4), with no PRM. Subsequent studies indicated that one individual (that had been caught by the wing) probably died eight days post-release. A further two individuals might have died after 25 (14P0099) and 27 days (13P0381). Of these, one individual (14P0099; 55 cm disc width) covered a distance of 245 km in a southerly direction (a theoretical linear average of almost 10 km per day), while the second remained close to the tagging site. Most capture-induced mortality occurs within days of release [56], although thirty days have been considered to be the minimum deployment period required for estimating whether any ‘immediate’ fishery-induced PRM has occurred [57]. Depending on whether or not the individuals at liberty for 25–27 days had died due to PRM or other factors (e.g. predation) would result in PRM estimates of 14.3–42.9%. These values are, however, based on very few individuals and thus remains only indicative for individuals caught during short fishing operations, handled, tagged and released in the best possible conditions by scientists and cannot be extrapolated for the entire fleet. Further studies on PRM are, therefore, required in order to provide more accurate estimates.

The ‘vessel effect’ is considered to be a major factor for the survivorship of this species compared to other species. Even when trained in good handling practices [58], the motivation on board is low when a crew member has been injured in the past, or may drop rapidly when large numbers of stingrays are caught (with a concurrent decline in the catches of the target species). The capture of one individual without a tail indicates that it could have been cut by the crew before being discarded, this practice has been mentioned in other fisheries [59]. Moreover, while sharks with residual hooks in the jaw are commonly observed [60,61], this has seemingly never been reported for pelagic stingray. This indicates that pelagic stingrays may be discarded with trailing gear, by cutting the branch line, which is not always close to the hook.

4.5. Mitigation

Given the level of interactions between pelagic stingray and the surface longline fishery, the potential impact of large numbers being caught could have adverse ecological consequences [8], there is a need to consider mitigation measures.. The wide vertical movements of pelagic stingray on the GoL plateau indicates that they utilise both demersal and pelagic environments, which supports findings from dietary studies indicating that they can feed on both pelagic and benthic prey [40]. Pelagic stingray seemed very active at night, and their peak catches in the GoL also corresponded to the summer period, when fishing effort for bluefin tuna is high. Changing from shallow sets to deep daytime sets might reduce catch rates of pelagic stingray [62], but it is inconceivable to change the fishing strategy and the line fishing depth on the shelf of the GoL, as this would reduce catches of bluefin tuna, the target species. Furthermore, given that the tagging results show that stingrays caught in the GoL can undertake long journeys westwards into Spanish waters, where other fleets operate, they are also subject to fishing pressure throughout the year [12] and thus alternative mitigation options need to be considered.

The soak time for the longline fishery is very short in the GoL, as the fishing grounds (within the 20 nm limits) are shared with trawlers. Therefore, the longlines must be retrieved before the trawlers start their fishing. Consequently, the AVM was found to be very low. In the case of low AVM but possibly higher PRM, it is assumed that the discarding of pelagic stingray with hooks trailing gear, coupled with any other physical injuries, may lead to delayed mortality. This highlights the fact that developing and promoting appropriate release methods may be an important element of reducing the PRM of pelagic stingray. Fishers should be encouraged to follow guidelines to handle safely and release rays in good condition, by using pliers or de-hookers for removing hooks.

In the frame of a research project conducted in collaboration with the fishing sector [13], scientists went on-board commercial vessel to document the existing mitigation techniques developed by the crews. Several types of de-hookers were provided to skippers to be tested [26]. Combining scientific observations and empirical knowledge from skippers and crew, a manual providing appropriate handling practices to ensure crew safety and increase the odds of survival for released animals was developed [58] and disseminated. Handling should be minimised where possible, to preserve the safety of the crew and also facilitate a quick return to the water for the stingray. Thus, as a conservation measure which could reduce PRM, fishers should be strongly encouraged to remove hook and trailing fishing gear prior to release.

Pelagic stingray catch rates have been reported as being significantly higher when J-style hooks (*cf*. circle hooks) are used [63]. However, circle hook shedding rates are much longer and trailing gear could cause continuous necrosis without expulsion of the hook [13]. Sardines, used as bait by domestic longliners, are a size which allows for complete ingestion by pelagic stingray which can lead to gut hooking. Wide circle hooks seems to reduce pelagic stingray catch and at-vessel mortality rates [64]. Hence, larger, wider hooks baited with mackerel could be proposed as an adapted mitigation solution if the bluefin tuna catch rates were still demonstrably profitable [64,65].

Preliminary observations on captive pelagic stingrays feeding when strong magnets mainly composed of neodymium (26mm×11mm×12mm 0.885 T from Ingeniera Magnetica Aplicada, Barcelona, Spain) were placed close to the food should little or no effect of magnetic repellents [13], and such systems would be unlikely to reduce catch rates [66].

It would be desirable to improve the quality of the information provided by fishers in order to provide pragmatic bycatch mitigation solutions. A scientific observer program with a large coverage and appropriate survey design would be beneficial in providing robust bycatch estimates and to train and to assist fishers in data and information collection. This can be augmented with a phone application dedicated for fishers to record catch and bycatch data [26]. It had been proposed to provide users with maps to delineate bycatch hotspots that could then be avoided, although the quantity of data received was insufficient to provide such outputs. Anecdotal observations indicated that as pelagic stingray ‘rush’ to the bait, the “Management of offal and spend discharge” might be a useful mitigation measure, as it could reduce the risks of subsequent interactions with the fishing gear [67].

5. Conclusions

Despite a considerable number of pelagic stingrays bycaught by the French pelagic longline fisheries and other fleets across the Mediterranean Sea, the species has received little research attention. There are clear economic and conservation benefits in reducing the bycatch of this species. High pelagic stingray catch rates constitute an economic loss to the fishery and so it is important to find solutions to reduce and mitigate interactions with longline gears. Identifying critical habitats of vulnerable species like sharks and rays is of paramount importance in regional management and conservation strategies. Post-release mortality (PRM) rates are assumed to be variable and vessel dependent, as they are typically discarded without any particular care, and often with trailing fishing gear. This study has shown that pelagic stingrays are capable of crossing jurisdictional boundaries in less than a month. The vertical and horizontal movements of pelagic stingray in the GoL have been demonstrated, which contributes to better understand the role of this area in the life cycle of this species. The large vertical movements from the surface to the bottom might be associated with behavioural thermoregulation or foraging activity, since the species feeds on pelagic and demersal preys. The seasonal distribution, as inferred from fishing data, are consistent with these tagging data but would benefit from larger sample sizes of both sexes. Since very little is known on the ecology of pelagic stingray, further work is needed to understand the real impact of incidental capture on this species in the Mediterranean Sea. The use of circle hooks baited with mackerel should be investigated to determine whether catch rates of the target species are affected, as this could be a potential mitigation solution. Whilst handling time of pelagic stingray should be minimised for crew and animal welfare, the removal of hooks and trailing gear is important in maximising chances of post-release survival.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Conceptualization, F.P.; Data curation, F.P.; Formal analysis, F.P.; Investigation, F.P.; Methodology, F.P., J.E. and S.M.P.; Visualization, F.P.; Writing—original draft, F.P.; Writing—review & editing, F.P., J.E. and S.M.P. All authors have read and agreed to the published version of the manuscript.

Funding: The present study is the outcome of a project "RéPAST", funded by France Filière Pêche (FFP), IFREMER and the Regional councils of Hérault, Pyrénées-Oriental, Languedoc Roussillon (France), carried out in collaboration with the fishing sector: AMOP (Sathoan and OP du Sud) and CEPRALMAR.

Institutional Review Board Statement: Tagging operations took place under IFREMER Ethics Committee application E34-192-6.

Acknowledgments The authors are grateful to all the skippers of the fleet who took part of the programme and especially Christophe, Kevin and Dorian from the "Dochris" and Mr Ranc from the "Prince des mers" for facilitating the capture of pelagic stingrays. We thank the Stellaris association who funded 6 extra PATs and both aquariums' teams from the Seaquarium and Marineland who took care of the health of the rays in captivity. Catch and effort data were provided by DGAMPA (French government) and processed by Iframe- SIH (Système d'Informations Halieutiques). The results of the study are the sole responsibility of the authors.

Conflicts of Interest: The author declares no conflict of interest.

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