Have Non-entangling DFAD reduced ghost fishing in the Indian Ocean?

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ABSTRACT

In the last decade, Drifting Fish Aggregating Devices (DFAD) constructed with open wide mesh panels traditionally used by tropical tuna purse seine fisheries have been replaced by new designs and materials that minimize entanglement. This change was partially driven by a key scientific publication by Filmalter et al. (2013) that revealed a much larger scale of shark ghost fishing in the Indian Ocean by DFAD than previously thought. However, since 2012, when lower-risk entanglement DFAD designs where deployed following industry-based initiatives, and more recently in 2020 when IOTC mandates the exclusive use of non-entangling DFADs in the Indian Ocean, no comparable studies of ghost fishing have been conducted to evaluate their potential ecological impact. Using a similar methodology than the one used by Filmalter et al. (2013), combining underwater DFAD surveys with shark satellite tagging data and adding observer data to the analysis, this study reevaluates shark ghost fishing in the Indian Ocean a decade after. Our study indicates that the DFADs currently deployed in the Indian Ocean exhibit a daily shark entanglement rate of 0.00095. In contrast, Filmalter et al. (2013) reported a daily entanglement probability of 0.35 ± 0.08 per DFAD, highlighting a substantial reduction in shark ghost fishing associated with the transition to non-entangling DFADs. We estimate a total of 3,830 shark entanglements considering the number of active DFADs of the entire purse seine fleet in 2023, which results in 125 to 250 times lower than that reported in 2013 (i.e. between 480,000 and 960,000 sharks were estimated to be entangled annually in 2012 fishing scenario in the Indian Ocean). The shift to fully non-entangling DFADs, combined with the reduction in the number of active DFADs per vessel in recent years resulting from regulatory limits, has contributed to lowering entanglement levels. Industry-based initiatives and conservation measures, supported by scientific evidence, are helping resolve DFAD ghost fishing issues globally.

Keywords: ghost fishing, shark, Fish Aggregating Devices, purse seine, tuna fisheries, bycatch mitigation measures, tagging

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1. Introduction

Tropical tunas are among the most important seafood commodities globally, with annual catches averaging 5 million tonnes (ISSF, 2025). In terms of catch volume for this fishery, skipjack tuna (*Katsuwonus pelamis*) constitutes the principal species where purse seiners using drifting Fish Aggregating Devices (DFAD) are the main fishery (Murua et al., 2021; Pons et al., 2023). Historically, fishers have taken advantage of the aggregative behaviour of fish towards floating objects, both natural (e.g., logs, seaweed pats) and human-made (e.g., DFAD) to increase their catches (Castro et al., 2002; Girard et al., 2004). In the early days of the tropical tuna purse seine fishery, most sets were conducted on free-swimming tuna schools and few on natural logs (Fonteneau et al., 2013). However, with the emergence of tracking technologies, fishers began increasingly deploying human-made DFAD with radio-buoys attached to enhance opportunities for finding tunas (Moreno et al., 2007; Lopez et al., 2014). The use of DFAD rapidly increased from the mid-1990s onwards, with advances in geolocation tracking and echosounder buoy technology providing accurate real-time position and fish biomass estimation, respectively (Lopez et al., 2014; Torres-Irineo et al., 2014; Maufroy et al., 2017; Tidd et al., 2023). A study conducted in the mid-2010s estimated that 100,000 DFAD were deployed annually worldwide (Gershman et al., 2015). Recent conservation measures by tuna Regional Fisheries Management Organizations (tRMFOs) involving active buoy DFAD limits and buoy purchase limits may have reduced their number (Escalle et al., 2021).

Generally, DFAD consist of a floating or semi-submerged part (referred to as "raft"), and a submerged part ("tail") hanging underneath to provide an attractive mesohabitat for fish to gather around (Zudaire et al, 2023) and to provide slow drift (Moreno et al., 2016, 2023). DFAD models have progressively evolved over time, with designs being adjusted in response to oceanographic conditions that vary by season and geographic location. To build DFAD, purse seine fishers traditionally employed materials that were readily available onboard, including old net corks for flotation and wide-mesh purse seine net panels (e.g., 4.5-5.5 inches or 11-14 cm) to wrap the raft and to make the underwater tail (Escalle et al., 2023; Zudaire et al., 2023). In addition to target tuna species, a variety of non-target species can also be found associated with DFAD, mostly finfish species such as smaller neritic tuna species (e.g., *Auxis* sp., *Euthynnus* sp.), mahi mahi (*Coryphaena hippurus*), rainbow runner (*Elagatis bipinnulata*) and triggerfish (*Balistes* sp.), followed by sharks and, to a lesser extent, rays and sea turtles (Taquet et al., 2007; Gaertner et al., 2008; Filmalter et al., 2015; Tolotti et al., 2020; Murua et al., 2021; Acebedo-Iglesias et al., 2025). In the Indian Ocean, the estimated bycatch on DFAD sets during active fishing operations by the tropical tuna purse fishery represents 3% of the total catch weight, with neritic tunas accounting for 1.7%, other finfish for 1.0%, and sharks for 0.3% (Murua et al., 2021). Therefore, in tuna purse seiners, the bycatch rate, measured as a proportion of total catch volume from active fishing (i.e., non-target species accidentally caught in the purse seine net during a fishing set), is relatively low compared to other less selective gears such as longlines and driftnets (Kelleher, 2005; Davies et al., 2009; Oliver et al., 2015). Sharks observed at DFAD are mostly silky sharks (*Carcharhinus falciformis*) (~ 90%), (Hall and Roman, 2013; Mannocci et al., 2020; Acebedo-Iglesias et al., 2025). The aggregative behaviour of silky sharks around DFAD has been documented in all oceans (Filmalter et al., 2015; Forget et al., 2015; Lezama-Ochoa et al., 2016; Lopez et al., 2020). One hypothesis explaining the presence of sharks around DFAD is the increased probability of encountering and capturing prey in oligotrophic oceanic areas (Duffy et al., 2015; Filmalter et al., 2017). Many of these prey species occur in close proximity to the DFAD often within just few meters (Freon and Dagorn, 2000; Taquet et al., 2007). It seems plausible that sharks chasing prey in such proximity to the DFAD could swim across its submerged structure and accidentally become enmeshed if it is constructed with entangling materials.

The traditional DFAD characterized by tails constructed with open wide mesh purse seine netting (e.g., 5 inches or 15 cm), which are referred to as high entanglement risk DFAD (HERDFAD), created sufficiently large gaps for juvenile sharks to become accidentally enmeshed if swimming close enough. In 2010 to 2012 period, when only traditional HERDFAD were used in the Indian Ocean, Filmalter et al. (2013) examined shark entanglement rates by carrying out diving surveys on 51 DFAD, combined with the tagging of 29 silky sharks with satellite pop-up tags to monitor shark interactions with DFAD. Based on the inferred entanglement rates obtained and extrapolating them to the estimated number of DFAD in the Indian Ocean at that time (i.e. from 3,750 to 7,500 DFAD active on a daily basis), they estimated that between 480,000 and 960,000 sharks were entangled annually in this region. The work by Filmalter et al. (2013) importantly raised awareness on the potential large-scale ghost fishing caused by HERDFAD which led to the development of guidelines of DFAD designs to reduce shark and turtles entanglement risk by the International Seafood Sustainability Foundation (ISSF, 2015, 2019) and the implementation of the Code of Good Practices by the EU fleet (Grande et al., 2019).

In that scenario in 2012, the EU purse seine fleet voluntarily adopted DFAD designs to reduce the risk of entanglement. The first mandatory regulation on non-entangling DFAD (NEDFAD) adopted by a tRFMO was in 2013 by the Indian Ocean Tuna Commission (IOTC; Res. 13/08). This resolution required the removal of large open-mesh panels and a gradual transition to fully non-entangling designs. It was later reinforced by Res. 19/02, which prohibited the use of any mesh in DFAD construction starting in 2020. In other regions, such as the Pacific and Atlantic Oceans, traditional DFAD were constructed using similar materials (e.g., large-meshed purse seine net), leading to the assumption that shark entanglement events were also highly prevalent.

In these oceanic regions, non-entangling DFAD have also been progressively introduced, with full global implementation at tRFMO level achieved in 2025. In the last decade, DFAD materials and designs have globally undergone significant changes to minimize ghost fishing events. Vessels in the Indian Ocean have moved from HERDFAD to fully non-mesh non-entangling DFAD (NEDFAD) following the implementation of their voluntary Code of Good Practices, and the adoption of Resolution 13/08 and 19/02. Despite those resolutions and the implementation of fully NEDFAD, there were concerns about the potential high risk of entanglement of DFAD in the Indian Ocean because the Filmalter et al. (2013) shark entanglement rates were not updated following new IOTC resolutions. Therefore, we conducted underwater DFAD inspections, analysed observer data on entanglements, and tagged shark using satellite tags to estimate for 2023 the current shark entanglement rate in the Indian Ocean and the number of sharks entangled in the NEDFAD scenario.

2. Material & Methods

2.1. Drifting DFAD characteristics and their entanglement risk

All purse seine vessels from Spanish Purse Seine associations operating in the Indian Ocean are monitored since 2015 either by a human observer and/or an electronic monitoring system (EMS), which goes well beyond the IOTC requirements (i.e., 5% observer coverage). DFAD activities are recorded by observers upon arrival to and departure from each DFAD, whether in opportunistic encounters or in planned encounters to tracked DFAD. In all observations when DFAD are visible, the observers register the constituent materials (i.e., floating and submerged parts) and configuration (i.e., indicating whether they are constructed with mesh or non-mesh materials, including data on mesh size if present). If DFAD are not visible to the observer—either because they are underwater or too distant and indistinguishable—they are classified as non-visible. This study used data collected by observers in 2015 and 2023 to classify the DFAD into three categories based on their entanglement risk, as defined by the International Seafood Sustainability Foundation (ISSF, 2019): (a) non-entangling DFAD (NEDFAD) constructed without mesh material, (b) lower entanglement risk DFAD (LERDFAD) constructed with mesh material less than 7 cm mesh size or rolled into sausage-like bundles, and (c) high entanglement risk DFAD (HERDFAD) constructed with open netting of mesh size greater than 7 cm. DFAD that were not visible for observers or EMS were excluded from the analysis.

2.2. Shark entanglement assessment based on observer data

Shark entanglement events were determined by analysing visual records by onboard human observers and electronic monitoring. Both monitoring methods collected data on marine fauna entanglement events (i.e., presence/absence of entangled individuals), the number of specimens and species entangled in DFAD when lifted for observation. Based on the observer data collected in 2023 the entanglement rate was calculated for the Indian Ocean for 2023. DFAD that were not assessed or classified as non-visible by human observers and/or EMS were excluded from the analysis.

2.3. Shark entanglement events based on underwater observations

Various underwater observation methods can be used to estimate the number of animals entangled in DFADs. Due to the time and safety constraints of conducting diving inspections at DFADs during commercial tuna purse seine fishing trips, a novel observation method was developed and validated under controlled conditions prior to its use aboard tuna vessels. The prototype developed consisted of 4 GoPro cameras, each housed in a submersible case, mounted on a square PVC frame with ropes for lightweight and easy assembly and transportation. The PVC frame was perforated to reduce its buoyancy, and a 2 kg weight was attached to the bottom end for faster sinking and improved stability. This structure was stable even in strong current or wave conditions, however, it could be subject to rotational movements that cannot be controlled by the operator. To avoid blind spots in the observation of DFADs, the 4 GoPro cameras were placed at 90-degree angles to each other (i.e., covering 360 degrees horizontally), but without the distortion typical of conventional fisheye lens videos (Fig. 1). The camera attachment to the base of the submergible gadget allows for (i) pitch adjustment (i.e., to film deeper, recording DFAD without the need to lower the camera to the end of the tail nor to direct the camera towards the water surface to record the sideway of the FAD) and (ii) roll adjustment (i.e., adjusting the camera angle due to currents). Hence, this configuration enabled the capture of high-quality images and video from a variety of angles, which is considered essential for detailed monitoring of DFAD shark activity.

Figure 1. Gadget used for underwater data collection

The prototype is divided into three parts (Fig 1): (i) a rope of sufficient length to film the entire submerged FAD structure, (ii) the framing device with the cameras, and (iii) the weight. The first and third parts were stored on the workboat (i.e., a speedboat used by fishers to check DFAD and tow them out of the net during fishing sets), while the frame with cameras was brought back to the purse seiner after each immersion for maintenance (i.e., desalination, storage in a cool shaded environment to prevent lenses fogging and battery overheating), and for media material download and storage.

Using this prototype, underwater DFAD inspections were conducted during two opportunistic research trips onboard a tuna purse seiner between January and May 2024 in the Indian Ocean (i.e. from January 21st to 12th February and from 10th April to 9th May). During these observations, the presence and number of entangled sharks were recorded. Additionally, information about the type of DFAD, including type of raft cover (e.g., canvas, mesh net), the presence or absence of the tail structure and its characteristics, and the types of attractors used (e.g., colorful ropes, sac strips, palm leaves) were recorded.

The protocol of recording the shark entanglement in DFAD was simple and easy to support the future implementation of fisher-based monitoring activities. The inspection process, once a DFAD was sighted, followed these steps: the speedboat was launched into the water with the pilot and the device operator. On the way to the DFAD, the operator mounted the rope with a carabiner to the top and the weight to the bottom of the frame device. While the pilot checked the DFAD's instrumented buoy or changed it, the operator turned on all four cameras and lowered the prototype to 50 m depth (using 5-meter markings on the rope as a depth reference) nearby the FAD to obtain a clear image of it and then began to slowly retrieve it at an approximate speed of 40 m/minute. Once the device was back at the sea surface, it was carefully extracted from the water and placed in the speedboat, where it was checked that all the cameras had functioned properly before being turned off. As mentioned above, the rope and weights were detached and remained in the workboat until the next inspection.

2.4. Shark entanglement assessment based on tagging data

The vertical movements of silky sharks tagged with pop-up archival transmitting satellite tags were also used to detect shark entanglement in DFADs or other fishing gears. sPAT and MiniPAT tags from Wildlife Computers (www.wildlifecomputers.com) were used. Data from 50 tagged sharks, collected between 2020 and 2024, were analysed to identify potential entanglement events. The tags stored light intensity, depth and temperature record every 3 seconds. Once they were detached from the shark and surfaced, they transmitted a summary of the recorded data to the ARGOS satellites. This data had a temporal sampling resolution of every 10 minutes throughout the entire monitoring period for MiniPATs, while for sPATs, this resolution was available only for the last four days of data collection. The sPAT tags were programmed to be released from the tagged animals within 60 days after tagging, except for one sPAT tag that was programmed for 30 days, while the MiniPATs were set for 180 days. Tags were programmed for release before the scheduled period if (i) the animal reached 1,400 meters (some of the tags were programmed at 1,700 meters instead) or (ii) remained at constant depths over 3 days, indicating the animal was death.

To estimate entanglement events, sharks captured as bycatch and released following best practices were tagged (Grande et al., 2019, Murua et al., 2023). Only those exhibiting normal behavior for more than 10 days were evaluated for detection of entangling events (i.e. 50 sharks), time threshold established to identify individuals that survive the fishing operation (Hutchinson et al., 2015). Vertical shark movements were assessed to differentiate entanglement events from natural shark behavior. From the time series provided by the tags, the mean depth and associated variance were estimated at 60-minute intervals. Periods of reduced vertical movement (RVM) were identified when the shark depth standard deviation in the 60-minute time interval was less than 2 meters (to include tide amplitude). Then RVMs periods that occurred just prior to tag release at depths deeper than 3 m (see Filmalter et al. 2013) were classified as potential entanglement, in those sharks that survive the fishing operation and tag release occurred before the stablished time-period setting.

For sharks in which an entanglement was detected, the geographical position and evidence of the drifting pattern of DFAD in the area were analyzed to assess the potential cause of entanglement and explore whether the entanglement occurred in a DFAD or in another fishing gear.

2.5. Assessment of total shark entanglements in DFAD

The number of sharks entangled was estimated for 2023 integrating the entanglement events recorded by observers in 2023 and underwater observations relative to the number of DFAD examined. The number of sharks entangled is assumed to be proportional to the number of DFAD drifting in the water (Filmalter et al., 2013). The number of daily active buoys in 2023, as reported by the IOTC (IOTC, 2023), was used to estimate annual entanglement cases in the Indian Ocean. The daily operational buoys estimation for 2023 was extracted from data available at the IOTC Secretariat (i.e., in the large-scale purse seine fishery of the Indian Ocean a maximum of 11,055 buoys were daily monitored at sea during first semester of 2023) (IOTC, 2023). Alternatively, the information of shark entanglement based on tags was used to inform about the entanglement risk in a NEDFAD habitat.

3. Results

3.1. DFAD entanglement potential

Based on observed data collected from 28 purse seiners and 8 supply vessels belonging to the associations ANABAC and OPAGAC-AGAC from visits to DFAD (i.e. either tracked or un-tracked), the percentage of HERDFAD decreased considerably from 65.2% to 0.6% in the Indian Ocean from 2015 to 2023 (Fig. 2). Similarly, LERDFAD in 2023 accounted for 2.5% of DFAD at sea, whereas in 2015 they represented 14.4% of the monitored DFAD. NEDFAD prevailed in 2023 (i.e., 96.8% of the DFAD visited on arrival complied with non-mesh characteristics) reflecting the implementation of the new fully NEDFAD management measure which reduced DFAD entangling potential in the water.

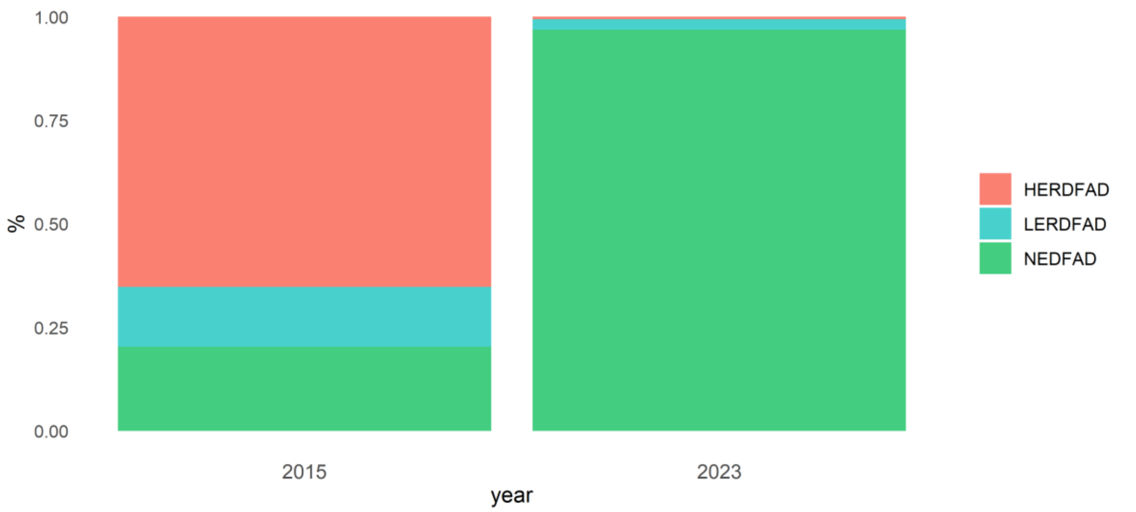

Figure 2. Entangling character of the DFAD of ANABAC and OPAGAC-AGAC (i.e. DFAD at arrival when a visit or a fishing set was carried out) in 2015 (before NEDFAD measure) and 2023 (after NEDFAD measure) in the Indian Ocean. DFAD are classified according to ISSF criteria of high entanglement risk FAD (HERDFAD), low entanglement risk FAD (LERDFAD) and non-entangling DFAD (NEDFAD).

3.2. Shark entanglement rate based on observer data

The observed entanglement rate, based on observer records (both human on-board and EMS) of the presence and/or number of entangled fauna, and where possible detailed species identification, showed one shark detected in 2,026 FAD visits in the Indian Ocean in 2023. The observer-based results showed that the estimated rate of entanglement in DFAD was 0.0005. Although only observed DFAD were considered, in certain cases, the complete structure of the DFAD might not be fully observable by human observers or EMS due to limited visibility of the submerged tail part (i.e., the FAD is not lifted completely out of the water or towed out over the purse seine net). Thus, the entangling rate in the absence of full underwater observations may be underestimated. Therefore, for the estimation of the entanglement rate the underwater observations were considered.

3.3. Shark entanglement events detected in underwater observations

Eighty-one floating objects were sampled between January and May 2024 in the western Indian Ocean. Over half were (52%, n=42) “cage” type (i.e. a submerge shallow cubical structure) DFAD (Fig. 3), 44% (n=36) were DFAD made with a grill with or without tails (the 30% had lost the tail due to the tail breaking off) (Fig. 3), three were marine debris resulting from human activity

(2 resulting from fishing activities or FALOG and one from non-fishing activity or HALOG (Gaertner et al., 2016; Grande et al., 2019). All DFAD displayed different kinds of attractors, commonly including colorful ropes and raffia bags.

All except one DFAD observed by underwater surveillance were categorized as NEDFAD, without mesh material. The exception was a HERDFAD with a typical NEDFAD cage-like structure, but with a large-mesh gillnet tangled into it**.**

One entangled shark was found during the underwater observation surveys, and it was associated with the HERDFAD that had the appended gillnet material previously mentioned. This entangled silky shark was identified in the video footage after downloading the data from the cameras, as it was not visible to the device operator from the speedboat (Fig. 4).

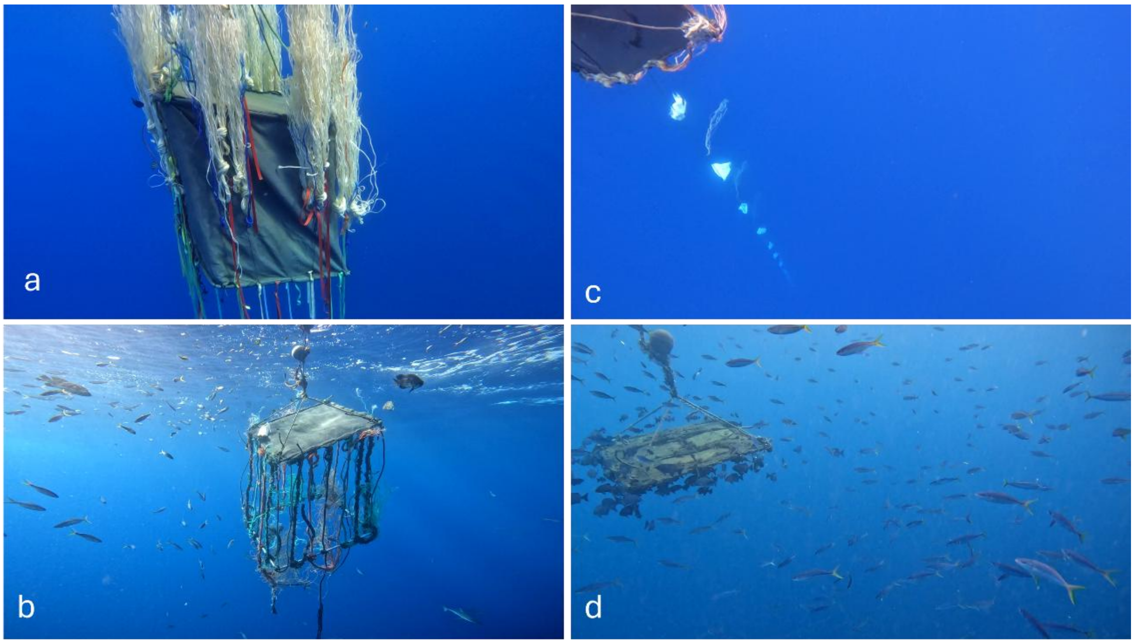

Figure 3. Different DFAD configurations: a) cages made with raffia; b) cage made with ropes, c) submerged rafts with tail and d) submerged raft without tail.

Figure 4. A silky shark entangled in a net affixed to a cage-type DFAD.

3.4. Shark entanglement events based on satellite tagging

Data from 50 tagged silky sharks (16 MiniPATs and 34 sPATs) that were released alive and survived the fishing operation in the Indian Ocean were evaluated for detecting entanglement events (Table 1 and 2).

Table 1. Details of the silky sharks tagged with MiniPATs

TT	Tag_Date	Size (TL)	Sex	Rel_Date	Reason	Days
204858	11/11/2020	134	Male	06/02/2021	Premature	87
205512	23/10/2020	110	Female	15/02/2021	Premature	115
225276	01/10/2021	144	Female	30/10/2021	Recaptured	30
225278	03/10/2021	198	male	01/04/2022	Interval	178
208252	05/10/2021	137	Female	05/02/2022	Recaptured	113
208254	06/10/2021	102	Male	08/11/2021	Too Deep	29
208255	07/10/2021	180	Female	01/01/2022	Premature	86
208256	07/10/2021	160	Male	07/12/2021	Floater	60
210668	08/10/2021	164	Male	31/12/2021	Premature	84
225279	08/10/2021	193	Female	06/04/2022	Interval	180
225277	08/10/2021	169	Female	06/04/2022	Interval	180
225280	09/10/2021	104	Male	07/04/2022	Interval	180
225283	10/10/2021	183	Female	08/04/2022	Interval	180
225284	10/10/2021	140	Male	08/04/2022	Interval	179
225285	10/10/2021	154	Female	17/11/2021	Recaptured	38
225287	11/10/2021	113	Female	02/02/2022	Premature	113

Fifty-four percent of the tags (n= 27) were released as scheduled, and 8% (n=4) of the tagged sharks were recaptured in during later fishing sets and brought on board in the brailing process. These results indicate that no entanglement in the DFAD structure occurred during the monitoring period. The remaining tags (38%, n=19) were released prematurely before the scheduled time (i.e. premature, floater or tags achieving the limited depth threshold), which indicated a potential entanglement and, thus, their RVM was evaluated.

Table 2. Details of the silky sharks tagged with sPATs

TT	Tag_Date	Size (TL)	Sex	Rel_Date	Reason	Days
205441	24/10/2020	166	Female	07/12/2020	Premature	44
205443	24/10/2020	149	Male	26/11/2020	Premature	33
205445	25/10/2020	117	Female	24/12/2020	Interval	61
205446	25/10/2020	120	Female	24/12/2020	Interval	61
205447	25/10/2020	119	Female	24/12/2020	Interval	61
205448	27/10/2020	139	Female	26/12/2020	Interval	61
205444	27/10/2020	139	Female	26/12/2020	Interval	61
205454	29/10/2020	142	Male	30/11/2020	Premature	32
204896	29/10/2020	127	Male	28/12/2020	Interval	60
204897	02/11/2020	164	Female	01/01/2021	Interval	57
204898	02/11/2020	144	Female	25/11/2020	Floater	24
204900	05/11/2020	140	Male	04/01/2021	Interval	53
204902	07/11/2020	140	Female	06/01/2021	Interval	57
196530	11/11/2020	144	Female	11/12/2020	Interval	31
205457	11/11/2020	153	Male	11/01/2021	Interval	60
205451	16/11/2020	167	Male	12/01/2021	Interval	57
205456	13/11/2020	134	Male	13/01/2021	Interval	61
205453	14/11/2020	188	Female	13/01/2021	Interval	57
225376	04/10/2021	171	Female	29/10/2021	Recaptured	25
221596	05/10/2021	140	Female	05/12/2021	Interval	61
209073	07/10/2021	143	Male	07/12/2021	Interval	61
209077	10/10/2021	97	Female	12/11/2021	Premature	34
209075	10/10/2021	130	Male	09/12/2021	Interval	61
209076	11/10/2021	100	Male	11/12/2021	Interval	61
209080	11/10/2021	140	Female	11/12/2021	Interval	61
209079	13/10/2021	143	Male	12/12/2021	Interval	61
252214	31/01/2024	140	Male	19/02/2024	Too Deep	19
221601	31/01/2024	123	Female	01/03/2024	Premature	21
252197	08/02/2024	171	Male	23/02/2024	Too Deep	15
252185	08/02/2024	162	Female	27/02/2024	Premature	19
252195	08/02/2024	139	Female	28/02/2024	Too Deep	20
252191	08/02/2024	110	Female	23/02/2024	Too Deep	15
252204	09/02/2024	158	Male	09/04/2024	Interval	60
252206	09/02/2024	126	Female	04/03/2024	Too Deep	24

Based on the analysis of the periods of reduced vertical movement (RVM) of those tags (n=19), only one tag (205512) indicated a potential entanglement event. This tag showed an RVM for 3 days (from 2021-02-09 to 2021-02-12, Figure 5) before released at a depth of around 48 meters (Fig. 5), after which the tag surfaced at 1.66ºN and 81.66ºE (South Sri Lanka).

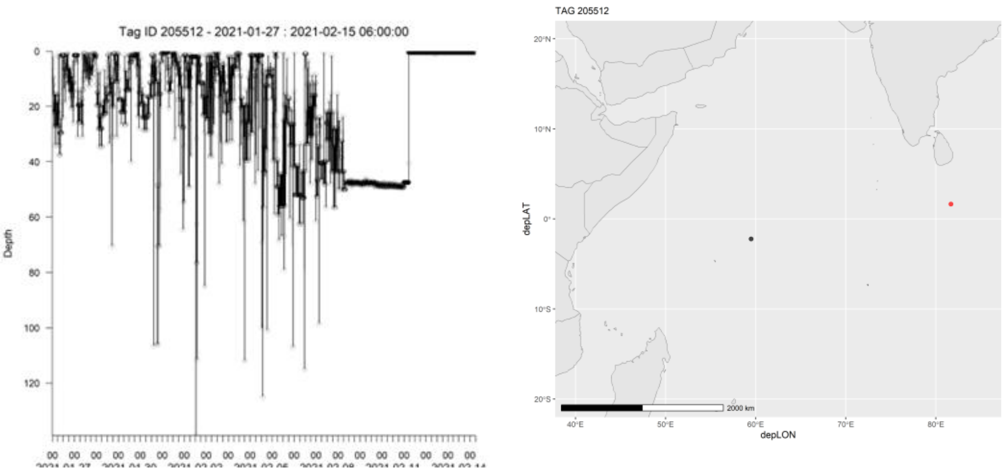

Figure 5. Vertical (left panel) and horizontal (right panel in which the black dot corresponds to deployment position and red dot to detachment position) data provided by the MiniPAT tag 205512, which showed a premature release. The vertical movement for the last 10 days before release is shown.

Considering the potential entanglement event showed by tag 205512, the DFAD drifting data for 2021 (i.e., the year when this tag was deployed) showed that the DFAD density is low in the area (Floch et al., 2022). There is an eastward DFAD drift that tend to concentrate DFAD around the Equator mainly at southern latitudes between 70ºE to 90ºE. In the area in which the entanglement was detected, the presence of gillnet, line and longline fisheries is relatively high while DFAD density is low (Floch et al., 2022; IOTC, 2024). Thus, it is not possible to elucidate in which gear the shark was entangled (DFAD or any other fishing gear commonly observed in that area).

Overall, in a total of 3,376 days monitored using tags, with a mean individual monitoring period of 68 days, there was one potential entanglement detected in a fishing gear.

3.5. Assessment of total entanglement events in DFAD

Total entanglement rate for all purse seiner DFAD activity in 2023, was estimated integrating on board monitoring (human and EMS) and underwater surveys. The underwater observations were added to the visual evaluations made by observers on board. In total, two sharks were identified in 2,107 observed DFAD (one by human observers and one by underwater monitoring), with a resulting entanglement rate of 0.00095 sharks by DFAD drifting at sea.

The daily monitored DFAD with active buoys at sea showed high variability and seasonality, as published by the IOTC Secretariat (IOTC, 2023). In 2023, the daily maximum number of monitored DFAD buoys at sea was estimated at 11,055 (IOTC, 2023) which was used as an indicator of the number of daily DFADs at sea. It is important to note that this number does not account for lost and/or discarded DFAD at sea. For the estimation of the total annual entanglement events, it is further assumed that the estimated entanglement rate represents the daily entanglement rate. The findings suggest that an estimated 3,830 shark entanglements may occur each year in the Indian Ocean.

4. Discussion

The implementation of non-mesh NEDFAD in the Indian Ocean has shown significant reductions in shark entanglements, as observed through a combination of underwater DFAD surveys, observer data and satellite pop-up tag data. The effectiveness of this change in DFAD materials is clearly reflected in the marked decrease in entanglement events, from Filmalter et al. 2013 (i.e. between 480,000 and 960,000 per year) when traditional HERDFAD were used, to our 2023 estimates after the introduction of conservation measures banning mesh materials to construct DFAD introduced in 2020 (i.e. 3,830 shark entanglements estimated in 2023). Even if the present survey's estimates may be underestimated due to limited underwater DFAD observations, as was also the case in Filmalter et al. (2013), the decrease of shark entanglements by two orders of magnitude is strongly indicative of the positive effect achieved by switching to NEDFAD. Regarding tagged sharks, one potential entangling in a fishing gear was detected from 50 individuals monitored (i.e. 2% of the tracked sharks), while in the case of Filmalter et al. (2013) 4 of the 29 were identified entangled (i.e. 13.8% of the tracked sharks). Efforts to increase sample sizes of tagged sharks and DFAD subsurface observations should continue to increase the robustness of entanglement rate estimates. In addition, it would be beneficial to conduct underwater surveys year-round to capture the spatio-temporal variability in shark abundance, including potential hotspots (Mannoci et al., 2021).

In the last decade, there have been drastic changes in the design and materials employed in DFAD construction in the Indian Ocean and other regions. Traditional DFAD with high entanglement risk characteristics (e.g., reused purse seine large mesh open panels), such as those examined by Filmalter et al. (2013), have been prohibited in all oceans for several years now while the prohibition of using netting in their construction was implemented in the IOTC in 2020 and since 2025 is mandatory in all oceans. The transition to NEDFAD in the Indian Ocean has followed a stepwise approach, commencing in 2012 with collaborative science-industry experimental trials using entanglement-minimizing designs and materials (e.g., LERDFAD), which were then voluntarily adopted by EU fleet associations worldwide, thereafter, supported by RFMO regulations. However, due to concerns with tied-up net bundles uncoiling and small mesh netting deteriorating overtime and creating larger gaps for marine fauna to accidentally enmesh, there has been a push to eliminate mesh materials in DFAD. The first tRFMO to apply a zero-mesh net policy was the IOTC starting in 2020, leading to the use of materials such as canvas and ropes to construct NEDFAD. In the Atlantic and Pacific Oceans tuna RFMOs (i.e, IATTC, WCPFC, and ICCAT) have also adopted the non-mesh net criteria from 2025 onwards and global industry players such as the International Seafood Sustainability Foundation (ISSF) will request, from April 2025 onwards, that their participating companies only conduct transactions with vessels using non-mesh NEDFAD.

In 2012, when Filmalter et al. (2013) experimental surveys were conducted, few DFAD conservation measures were in place in the Indian Ocean, and the impact of HERDFAD was likely at its peak. However, since then, not only have NEDFAD been instituted, but the IOTC has also been active in adopting other conservation measures, such as limits on the number of active DFAD per vessel since 2015 and a timeline for the implementation of fully biodegradable NEDFAD by 2030. These resolutions show how tRFMOs have taken a more active role in the management of DFAD over the last decade to mitigate their ecosystem impacts.

However, the adoption and implementation of any management measure should be evaluated to ensure that it achieves its goals. We observed that current NEDFAD designs would have significantly reduced ghost fishing compared to traditional HERDFAD, as reflected by the estimations (i.e. observed and underwater data records and tagging information) presented in this study. From the outcomes of observer data records, underwater surveys, and shark tagging data, it appears that few sharks become entangled with the new types of NEDFAD employed in the Indian Ocean. Nevertheless, even if isolated ghost fishing cases are still observed in DFAD (i.e., 2 case from 2,107 DFADs, one entanglement was recorded in 2,026 visual evaluations, and another in 81 underwater DFAD inspections) it is important to characterize the form of enmeshment to take preventive actions. For example, during the underwater observations, the entanglement in a DFAD was caused by a gillnet that had become tangled with it. Identification of causes of shark entanglement using observer data and underwater camera surveys can provide useful information to redesign NEDFAD to further reduce undesirable impacts. Furthermore, if fishers encounter DFAD with mesh, they should remove it after setting or replacing the buoy.

Presumably the use of no mesh in NEDFAD employed in other regions aside from the Indian Ocean should similarly result in a significant reduction in shark entanglement events. Despite different DFAD designs in the Indian Ocean and the other three regions (i.e., Atlantic, Eastern Pacific and Western and Central Pacific Oceans), which generally employ an appendage with underwater windows or sails to increase drag, the overall lack of mesh will greatly reduce the likelihood of accidentally entangled animals in all areas. However, it is recommended that similar studies be conducted in each tRFMO to verify the extent to which newly employed NEDFAD reduce ghost fishing impacts on sharks and other vulnerable fauna such as sea turtles. The submersible equipment employed in this study to examine underwater NEFAD appendages has proven very useful, affordable, and easy to replicate (i.e. a tethered frame with four submersible cameras) and could be deployed by the purse seiner's speedboat drivers when operating with DFAD. More sophisticated camera systems, even with real-time transmission to the purse seiner's bridge, could also be utilized to assess entanglement events. Even they could have the potential to detect shark presence at DFAD, but the effectiveness of these underwater camera systems on detecting presence and number of sharks swimming around DFAD is still being tested.

The limiting factor to examine the whole DFAD tail structure for shark entanglement with cameras, or divers, could be poor water visibility. For example, in nutrient rich waters with a shallow thermocline, such as upwelling regions off the coast of Peru in the Eastern Pacific Ocean or Gabon in the Atlantic Ocean, the complete examination of a DFAD tail, often extending below 60-meter depth, is more difficult. Nevertheless, in most oceanic areas, visibility is good, especially in the average depth range of sharks around DFAD which tend to concentrate near the surface (e.g., 0-30 m depth). In addition, in the specific case of the Indian Ocean the DFAD are shallower than in the Atlantic and Pacific case. Therefore, large numbers of underwater DFAD observations can be quickly acquired using the method described in the paper or with similar submersible cameras systems.

Furthermore, the combination of observations with pop-up tag data can help at least partially overcome the limitations of poor visibility in underwater surveys in certain regions. Satellite tags enable the tracking of sharks' vertical and horizontal movements around DFAD, regardless of visibility conditions, helping assess whether they exhibit normal swimming behavior. When sharks become entangled in DFAD their typical vertical movements cease, and the animal remains at a constant depth for several days, at which point the tag detaches and transmits the information. It is worth noting that not all entanglement events can be directly associated with DFAD, as entanglements in other gear types may also happen (e.g., sharks meshed in drifting gillnets or other gear) but at least can provide a clear indication of sharks not being entangled.

Due to the relatively high costs of pop-up satellite tags (2,000-4,000 USD), the sampling size using this technology would predictably be lower than with visual inspections. In recent years, silky shark satellite tagging studies in tuna purse seine DFAD fisheries have increased across all oceans, mostly employed for shark behavior and post-release survival studies (Poisson et al., 2014; Filmalter et al., 2015; Eddy et al., 2016; Hutchinson et al., 2015; Onandia et al., 2021; Grande et al., 2021; Grande et al., 2022; Murua et al., 2021). Data from past shark satellite tag studies, as well as others in the future, could be examined for indicators of whether sharks were likely entangled or not in DFADs. Building a database of shark satellite tag information in DFAD fisheries could be valuable to better evaluate entanglement rates and for filling knowledge gaps in the behavior of oceanic sharks.

This study demonstrates the importance of using scientific data to assess the efficiency of DFAD regulations adopted by fisheries management bodies. Evaluating whether conservation measures achieve their intended objectives or fall short is a crucial exercise necessary to determine its effectiveness and whether corrective actions are needed. In the case of NEDFADs, the intended goal of substantially reducing ghost fishing events appears to have been achieved.

We illustrate the importance of closely monitoring the effect of other DFAD mitigatory actions (e.g., transition to biodegradable DFAD, changes in FAD limits, FAD loss rates). Furthermore, this type of research should be conducted in each oceanic region, as multiple variables, including specific DFAD designs, oceanographic conditions, fish behavior or fleet operational strategies, can play important roles in the efficacy of environmental mitigation policies. The replacement of HERDFAD with NEDFAD in the Indian Ocean provides a prime example of how bottom-up approaches (i.e., fisher-scientist collaborations for entanglement-minimizing FAD designs and voluntary adoption by the industry), combined with top-down regulatory management measures to support their implementation, can yield significant improvements towards sustainable fishing practices.

While the transition to NEDFAD has significantly reduced shark mortality in the Indian Ocean purse seine fishery, the vulnerable status of these species calls for a holistic approach to ensure their conservation and proper management. Observer coverage in IOTC area should be increased to at least 20% across all gear types to enable robust estimates of bycatch mortality (Babcock et al., 2003; MSC, 2021). In addition, further research on ghost fishing should be conducted for all gear types, including lost and abandoned fishing gear and driftnets. The impact of other measures in reducing the fishing-induced mortality and species vulnerability, such as avoidance strategies and improved release practices, both from the net and from the deck, should be also assessed across all gear types (Gilman et al., 2024; Griffiths et al., 2024).

Finally, equally important is the continued outreach and engagement with fishers, whose collaboration has been instrumental in the successful transition to NEDFADs. Sustained awareness-raising, training, and dialogue will be necessary to encourage best practices, and ensure that conservation measures translate effectively into fishing operations.

Acknowledgements

We thank the tropical tuna purse seine fleets of ANABAC and OPAGAC-AGAC, for their collaboration and contribution in this study. This work has been supported by several funding sources including OPAGAC, ECHEBASTAR, SIOTI, Basque Government, Spanish Government, Bermeo Tuna World Capital and the International Seafood Sustainability Foundation (ISSF).

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