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RESULTS OF THE LARGE-SCALE BIODEGRADABLE FAD EXPERIMENT IN THE EASTERN PACIFIC OCEAN

Marlon Román, Jon Lopez, Jon Uranga[1], Martín Hall, Francisco Robayo, Nick Vogel, José Luis García[2], Miguel Herrera[3], and Alexandre Aires-da-Silva

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[1] AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Basque Country, Spain.
[2] Tuna Conservation Group – TUNACONS
[3] Association of Large Tuna Freezers – AGAC

1. SUMMARY

Purse-seine effort on the fish-aggregating device (FAD) fishery in the EPO has steadily increased since the early 1990s due to its efficiency in capturing tropical tunas that aggregate under FADs. However, as with most fishing methods, FADs can have negative effects on associated species and ecosystems, such as entanglement of vulnerable species like sea turtles or sharks, accumulation of marine debris and pollution, and stranding events in vulnerable habitats (e.g., coastal nursery areas). Therefore, the IATTC required scientific recommendations to transition from traditional to biodegradable FADs that would reduce these impacts.

A total of 780 biodegradable FADs, known as NEDs (non-entangling degradable FADs) (114 prototype 1; 395 prototype 2; 271 prototype 3) were deployed along with their corresponding traditional FAD controls for a total of 1,544 experimental FADs. Results showed similar catch per set values between NEDs and traditional FAD controls (NEDs = 33.6 mt/set, traditional control FADs = 31.7 mt/set). Prototype 1 was found to be in good and very good condition after a minimum of two months at sea, while prototype 2 materials were from good to fair condition for at least three months. The NED design of prototype 3 was the least durable, but some modifications made in collaboration with the fleet improved its durability and were found to be in good to excellent condition during longer periods of soak time (at least two-three months).

Satellite buoys were used to determine the lifespan (i.e., 'operational' life) of the experimental FADs, with traditional FADs having a lifespan of 854 days and NED prototypes 1,2, and 3 having maximum lifespans of 790, 379 and 686 days, respectively. Comparisons of drifting trajectories showed that pairs with similar drifting patterns had lower differences in speed, while pairs with divergent trajectories had greater separation distances. Tuna biomass aggregation analyses using echo-sounder information of satellite buoys showed similar biomass index values for both traditional FADs and NEDs, with a consistent increasing trend up to 80 days for traditional FADs and up to 50-60 days for NEDs.

The IATTC staff's conclusions, future actions, challenges and lessons learnt from positively engaging with the industry and fishers are also described. This study suggests that starting a transition to biodegradable FADs to reduce negative impacts on the associated species and ecosystems may be possible without compromising the effectiveness of the fishing method.

2. INTRODUCTION

Fishers have been capitalizing on the aggregative behavior of tunas around floating objects for decades (Watters 1999; Hall and Román 2013). The use of fish-aggregating devices (FADs), which are artificial drifting objects designed to attract tunas, began in the 1980s by the tropical tuna purse-seine fleet in the eastern Pacific Ocean (EPO). By the early 1990s, the FAD fishery had significantly expanded and had become the most effective method for catching tropical tunas in the region (Lennert-Cody and Hall 1999; IATTC 2019; Hall and Román 2013). Over recent decades, the use of satellite-linked echo-sounder buoys to remotely monitor the location and biomass levels of tunas has made FAD fishing an extremely efficient method (e.g., minimal search time, low number of null sets) (Lopez et al. 2014; Lopez et al. 2016; Cillari et al. 2018). It is worth noting that FAD fishing is not exclusive to the EPO; presently, the majority of the global commercial tuna catches are obtained from FADs (ISSF, 2022).

FADs are typically constructed in two segments: a surface part and a submerged part. The surface component provides buoyancy to the FAD, and is usually made with bamboo wrapped in old, recycled fishing nets. Plastic floats or PVC frames have been added to enhance the FAD's floatability (Hall and Román 2013). The floatability component is typically made with dark-colored materials to prevent detection by other vessels and is expected to keep the FAD afloat typically for 6-12 months, depending on the environmental conditions where the fishery operates. While the fishing season in some areas (e.g., Peru) is restricted to 4-5 months and FADs that last up to 6 months are acceptable by the industry, in other regions (e.g., west of 110°W), fishers prefer FADs that can last for at least 9-12 months (Moreno et al., 2016).

The submerged component of FADs consists of materials that hang in the water column, often including old fishing nets or other webbing materials. This component is believed to increase the attractive nature of the object and impact drifting speeds (Minami et al. 2007; Satoh et al. 2007; Lennert-Cody et al. 2008; Hall and Román 2013). In recent years, the depth of the submerged part seems to have increased, particularly in some areas of the EPO, where depths of 70-90 m have been reported (FAD-05-INF-A, FAD-06-01, FAD-07-01), although typically, this component reaches a depth of 30-40 m (Franco et al. 2012; Hall and Román 2013).

FADs are usually made from non-biodegradable materials, and their use is often associated with several potential ecological impacts. Studies from other oceans suggest that some sharks and sea turtles may become entangled in the FAD's submerged webbing material (Franco et al. 2009; Hall and Román 2013; Filmalter et al. 2013), and lost, abandoned, or damaged FADs can generate marine debris and pollution, potentially causing habitat impacts through stranding events in coastal areas, including beaching (Maufroy et al. 2015; Sinopoli et al. 2020). Additionally, fishing on FADs may increase bycatch and catches rates of small-sized tunas, including juveniles.

However, conservation measures for tropical tunas have been established (e.g., Resolution C-21-04) and several projects aimed at reducing the impact on non-target species and undersized tunas are currently underway (IATTC-93-06a; SAC-14-01). These projects include experiments on the effectiveness of sorting grids (Document IATTC-94-04; Project M.1.b), and the dynamic ocean management project, which explores the efficiency of near real time spatial management to make the fishery more selective (SAC-10 INF-D, Project J.2.a).

Initiatives to assess and reduce the impacts of non-biodegradable FADs are relatively recent, both locally and globally. For instance, the first attempts at producing non-entangling objects were carried out in the Indian Ocean, consisting of a submerged tubular structure made of synthetic sailcloth (Delgado de Molina et al. 2006) and later suggestions were made to use non-netting materials for the submerged part or to roll the netting into sausage-like bundles to reduce the risk of shark entanglement (Dagorn et al. 2012). Although shark entanglements are seldom observed in the EPO, no dedicated experiment has yet been conducted to quantify these events. In contrast, turtle entanglement in FADs has been frequently recorded by observers, but mortality rates are negligible, and the crew is required to promptly release turtles alive when possible (see Resolutions C-03-08 and C-07-03). In 2013, experimental FAD designs that prevent both turtle and shark entanglements and minimize environmental impacts (pollutants, non-degradable debris) were tested by t-RFMOs (ICCAT-13-01; IOTC-13/08; IATTC C-13-04).

To minimize the risk of entanglements of vulnerable species in FADs, the IATTC established guidelines effective from January 1, 2019. Specifically, any net used to cover the surface component of the FAD must have stretched mesh size of less than 7 cm. For the submerged component, net mesh should be avoided, but if used, mesh size must also be less than 7 cm. If the mesh size exceeds 7 cm, it must be rolled in coils or 'sausages' (see the Annex II of IATTC Resolutions C-18-05 and C-19-01).

Recently, various regional initiatives have been conducted or are still underway to test biodegradable FADs on a large scale under real-fishing conditions (ISSF 2020; Zudaire et al. 2021). For example, in the EPO, the Tuna Conservation Group (TUNACONS)—a consortium of Ecuadorian tuna fishing companies - conducted trials with natural fibers in controlled conditions and tested tens of these FADs under real fishing conditions (TUNACONS, 2018). Since 2021, 20% (+1,000) of FADs deployed by the TUNACONS fleet have been voluntarily constructed with biodegradable materials (TUNACONS-EcoFADs). Similarly, an EU consortium deployed around 1,000 biodegradable FADs in the Indian Ocean, and other initiatives are in place in the Atlantic and Western and Central Pacific Oceans (Zudaire et al. 2018; Moreno et al. 2018a-c; ISSF 2020; Zudaire et al. 2021).

Moreover, new non-entangling, degradable, innovative and simplistic FAD initiatives have been tested with promising results in different oceans. These initiatives aim to extend the durability of FAD components by reducing drifting speed, and avoiding wind and wave surface dragging (Moreno et al. 2021, Moreno et al. 2023).

Another objective of these initiatives is to develop guidelines on what should be considered a biodegradable FAD, including standards for materials and construction, since the use of biodegradable materials may be subject to certain requirements and specifications (Zudaire et al. 2018). In this regard, Zudaire et al., (2021) suggested that a standardized definition of biodegradable FADs should consider, among others, the international standards, the regulatory framework, the minimum requirement conditions for materials, and whether the term "biodegradable" should be applied to the materials themselves or to the final product (i.e., the FAD as a whole). Currently no harmonized definition exists among t-RFMOs, although interim definitions have been proposed by the IATTC staff and the *ad hoc* Working Group on FADs that take into account the aforementioned elements (see FAD-06-02 and IATTC-100-03-ADD, for details).

Bamboo has always been identified by both scientists and fishers as one of the main alternatives for an eco-friendly surface structure (Hall and Román 2013). Bamboo is abundant worldwide and non-polluting, and its durability at sea could be enhanced through natural treatments (Razak et al. 2005; 2008). Another biodegradable alternative that has been suggested in fishers' workshops is balsa wood (*Ochroma pyramidale*; Moreno et al., 2016). This type of wood is well known for its buoyancy properties, making it an ideal addition for the surface component. Moreover, it is readily available in most tropical regions of the EPO. For the submerged FAD component, several vegetal fibers distributed worldwide have been explored and tested either as a net-webbing substitute to avoid species' entanglement or to improve structure cohesion. The abaca fiber (*Musa textilis*) has been used for multiple purposes since the early 20th century (Saragih et al. 2018). In recent years, its potential as a bio-composite plastic substitute material or interaction material in composite systems traditionally using plastic fibers has been suggested due to its remarkably high tearing resistance (Saragih et al. 2018; Valášek et al. 2017; Karlsson 2007). The use of cotton fiber (*Gossypium spp*.) dates back centuries with multiple applications (Mwaikambo 2006). Its resistance from sea trials has been tested either alone or with other natural fibers, offering insights into its potential use in the EPO tuna purse-seine fishery (Lopez et al. 2019). Alternatively, bio-based biodegradable plastic materials may be an option to consider in the future, as long as they comply with regulatory marine biodegradation standards (Zudaire et al. 2021).

Efforts to reduce entanglements with FADs in the EPO have been significant. Promising potential has been shown by some biodegradable and non-entangling materials, as well as by initiatives testing materials of natural origin (TUNACONS, 2018; Lopez et al., 2019). However, no large-scale, scientifically monitored at-sea trials with FADs made entirely of bamboo, cotton, abaca, or other biodegradable materials have been conducted in the EPO.

In 2015, following Resolution C-15-03, the IATTC staff was required to provide recommendations on the use of biodegradable materials to mitigate species entanglement and reduce marine debris. Subsequently, the European Union granted funds (Grant EU-7592) to the IATTC for a two-phase project involving controlled and at-sea experiments with biodegradable non-entangling FADs. During Phase 1, experiments with biodegradable non-entangling FADs were conducted in a controlled environment, and the materials and designs for prototypes of non-entangling and biodegradable materials (NEDs) were determined for the next phase (Phase 2) (see designs in Figure 1).

The work plan for Phase 2 included several activities, such as the selection and construction of the definitive prototypes for NEDs, the identification of collaborators and participants, the development and agreement of an experimental design, the monitoring and tracking of the experimental FADs, as well as the data collection and analyses. Specific details of Phases 1 and 2 are indicated in documents SAC-11-11 and FAD-06-02.

3. OBJECTIVE

The phase 2 of the project described in this document focused on developing and testing NEDs at large-scale and current fishing conditions. The NEDs had to meet the following criteria:

- They must be durable enough to last for at least 6 to 12 months, while also degrading without causing harm to the environment.
- They must have the non-entangling construction characteristics that were achieved in Phase 1.
- They must perform similarly to traditional FADs in terms of attracting and retaining tunas, ensuring that fishing efficiency is maintained.
- They must be constructed with materials readily available in the region and the market, at reasonable costs.

4. WORK PLAN

The following activities were carried out in Phase 2 (see SAC-11-11 and FAD-06-02 for further details):

4.1. Prototype selection, identification of collaborators and experimental design

Three definitive NED prototypes were chosen in collaboration with fishers and fishing companies. Abaca was the primary natural fiber component for NED prototypes 1 and 2, while prototype 3's main natural fiber component was cotton (see Figure 2 for prototype dimensions and components). Companies and vessels willing to collaborate were identified through close cooperation with TUNACONS and AGAC, two tuna fishing organizations that consist of 8 and 9 groups of companies, respectively. A total of 31 TUNACONS and 14 AGAC vessels committed to participating in the project.

To ensure standardization of NED construction the manufacturing site was individualized and construction was programmed on a quarterly basis to minimize prolonged storage time and incorporate seasonality into the experimental design. A local coordinator regularly visited construction sites to ensure NEDs were constructed following the project's standards. To maximize the total number of NEDs used in the experiments, participating organizations agreed to cover half of the material costs associated with NED construction and the full costs of associated electronic equipment, such as satellite-linked echo-sounder buoys and data transfer fees (see Figure 3 for details).

A total of 796 NEDs were targeted for the at-sea trials, with 199 per quarter. The number of NEDs deployed by each vessel was capacity-specific in metric tons (mt), as follows:

1. Vessels > 1200 mt: 20 NEDs/year, 5 per quarter;

2. Vessels <=1200 and >363mt: 16 NEDs/year, 4 per quarter;
3. Vessels <=363 and >182mt: 12 NEDs/year, 3 per quarter; and,
4. Vessels <=182 mt: 4 NEDs/year, 1 per quarter.

To evaluate the efficiency of the NEDs in terms of aggregating tuna against conventional FAD designs, each NED deployment was accompanied by the deployment of a traditional FAD. Green tags were attached to NEDs, and red tags were attached to traditional FADs for easy observer recordings. The attached buoys were also marked with corresponding tags (Figure 4). More information on the protocols followed on the deployment of experimental FADs can be found in document SAC-11-11 and FAD-06-02.

4.2. Monitoring and tracking of experimental FADs

To ensure effective monitoring and tracking of the experimental FADs, guidelines and visual material such as posters (Figure 18) were produced to train observers and project participants on the proper use of tags and satellite buoys during FAD interactions, including deployments and buoy replacements. To maintain consistency in comparisons, paired FADs had similar dimensions, and the satellite buoy make and model matched that of the NED as closely as possible. In the event of a satellite buoy replacement, the same brand and model was requested to maintain consistency, where possible. Metallic tags on the buoys and objects were always matched to ensure accurate tracking, and any buoy replacement was accompanied by a subsequent tag replacement.

Dedicated forms (Registro de objetos flotantes complementario- ROF-C; Figure 5) and instructions were developed for observers, skippers, and fishing crews of TRIMARINE's fleet (NPR-TS; Figure 6a), as well as for other fleets (RNC-NO; Figure 6b) when observers were absent. Additionally, a specific email address was created to receive data and questions from project participants. To ensure everyone involved in the project was familiar with the protocol and specific requirements, stakeholders and fishing organizations received documentation and posters detailing the project's methodology, objectives, expectations, and responsibilities. Observers were trained by the local coordinator and personnel from other regional field offices and workshops were conducted regularly with skippers to inform them of the project's progress and address any comments they may have had regarding the functionality, preliminary results, key concepts related to monitoring and tracking experimental objects, and durability estimates.

In addition to observer data, the project aimed to gather complementary information on the efficiency of the experimental FADs by collecting data on satellite buoys, including trajectories and biomass data, for both NEDs and control FADs (as detailed in MOUs signed with both fishing organizations). This information is key and provides insights into drifting patterns, lifespan, and biomass aggregated for both observed and unobserved experimental FADs.

4.2.1. Observer data collection

The condition and degradation of NEDs over time are recorded on a dedicated form called ROF-C (Figure 5). The form categorizes the condition of each NED component as excellent (1), very good (2), good (3), fair (4), poor (5), or very poor (6). Observers also note on the form when a particular component of the NED has been replaced.

Each NED recorded on the ROF-C form is unique and identified by a metallic tag and a combination of attributes such as the trip ID number, the floating-object ID number, and the number of times the NED was encountered. These attributes are also recorded on the main flotsam observer form (ROF; Figure 7) and are used to link both forms in the main IATTC observer database. The regular ROF provides additional information on the NED, such as date, time, location of the interaction, information on NED origin, catch of target and non-target species, and satellite buoy identification code. Once the fishing trip is complete, all data is incorporated into the "Experimental FADs-Observer" database after debriefing with the observer.

In rare cases where the observer was not present on board, skippers are expected to send all NED information to the IATTC scientific staff through a dedicated email address at the end of the fishing day. The information is checked for errors using computer routines.

Historically, the information collected by observers from national observer programs has been submitted to the IATTC annually, which would have caused significant delays in the data collection and analysis. To mitigate this, the local project coordinator interviews observers in person or coordinates with them via email/telephone to request copies of the ROF and ROF-C in advance (i.e., scanned copies, pictures). This information is added to the Experimental FADs-Observer database as soon as possible, along with reports from non-participating vessels. The information on the paired control FAD is recorded on the conventional flotsam form only (ROF) and is accessed and validated by the project coordinator through connections to the databases once the trip is finished.

4.2.2. Satellite buoy data collection

To monitor drifting patterns, lifespan and aggregated biomass, the project requested a minimum of one position and biomass sample per day per buoy, or more frequently if possible, depending on the buoy make, model, and original sampling strategy decided by the fisher. Unnecessary data collection was minimized to avoid disrupting the fishing strategy. Data was transferred directly from buoy manufacturers to IATTC staff and stored in a local database at the La Jolla headquarters to ensure confidentiality. The data was reported with a 2-3 month delay, which has been proven to be an efficient reporting strategy for information reported under Resolutions C-17-02, C-20-06 and C-21-04, as well as other global initiatives (e.g. Zudaire et al. 2021).

5. DATA ANALYSIS

5.1. Interactions with experimental objects

To gain a better understanding of the spatial-temporal distribution and frequency of interactions with NEDs by prototype and the paired control FADs, the project analyzed object interactions using observer data, such as deployments, re-deployments, visits with no set involved (referred to as "visits"), and visits leading to a set (referred to as "sets"). NEDs that were attached to a floating object found at sea were excluded from the analysis to ensure each deployment was made in a newly deployed non-colonized (i.e., ‘virgin’) environment.

5.2. Catch per set

Similarly, the catch per set (i.e., the total amount of tuna caught per set, mt) of NEDs by prototype was compared to the catch of multiple sets on FADs closely related in time and space, including paired control FADs when possible. The analysis only included FAD sets conducted within a 1-degree (111 km) radius and seven days before or after the NED set to account for spatial and temporal variations. Unsuccessful sets (total tuna catch = 0) were not included in the analysis.

To ensure that the whole tuna aggregation was captured and to avoid potential influence of catch per set on the object, consecutive sets made on the same FAD over a short time period (such as 2 days) were summed and considered as a single set (fishers may set a FAD multiple times in consecutive days). Short-residence times of individual tunas and aggregations at FADs, varying by species (Schaefer and Fuller 2013, Travassos-Toloti et al. 2020; Tsukagoe 1981; Cayré 1991; Leroy et al. 2009; Matsumoto et al. 2006), where taken into consideration while applying this approach. For instance, bigeye tunas in the EPO have short residence times of 2-3 days while other residence times can last up to 24 days (Schaefer and Fuller 2013). Studies analyzing association dynamics of tunas with drifting FADs in the Atlantic Ocean report average continuous residence times of 9, 19, and 25 days for skipjack, yellowfin, and bigeye tuna, respectively (Travassos-Toloti et al. 2020). Baidai et al. (2019) estimated the residence time of a tuna aggregation around a drifting FAD to be about 6 days using echo-sounder buoys. Therefore, a conservative measure of two days was used to account for the variability in residence times in this study. The same methodology was applied to compare catch per set between paired control FADs and surrounding non-experimental objects. Additionally, the number of days between the set and deployment was estimated and compared for both NEDs and paired control FADs.

5.3. Condition of NEDs

To evaluate the degradation of materials and designs of NEDs at sea, the soak time for each NED interaction (e.g. sets, visits) was estimated, and the condition values recorded by the observers for the different components of the floating and submerged parts were extracted and analyzed for each prototype. Soak time refers to the duration each NEDs is at sea between deployment and retrieval or the last known record, and was grouped into four categories: 1-30 days, 31-60 days, 61-90 days, and over 90 days. Condition values for each component of the NEDs were averaged for each time period, with the soak time estimated using the minimum and maximum values, as well as the 25%, 50%, and 75% quantiles.

Data from 2019-2022, which included observer data from both the IATTC and national observer programs, was used to analyze activity and catch per set. However, for 2023 data, the analysis was based solely on data from the IATTC observer program.

5.4. Drifting patterns and biomass comparisons between experimental FADs

To evaluate the efficacy of the experimental FADs, georeferenced and acoustic information from echo-sounder buoys was utilized to analyze and compare their drifting patterns, lifespan, and biomass indicators. The drifting patterns and lifespan of NED and paired control FADs were analyzed by examining the position data collected by all available buoys (n = 1066), whereas some were excluded for the biomass analyses (n = 937; see section 5.4). The following steps were taken to analyze satellite buoy data, including trajectories and biomass.

5.4.1. Echo-sounder buoys database preparation

Following the methodology applied by Zudaire et al. (2021a) and Murua et al. (2023), an 'Echo-sounder buoy' database was created, which included information such as the date of buoy transmission, buoy position, buoy speed and acoustic signal (biomass information). This database was merged with the 'Experimental FADs-Observer' database by linking the buoy identification code present in both databases. The colored tags on the paired experimental FAD were used to identify the echo-sounder buoy data for each FADs.

5.4.2. Echo-sounder data filtering

To filter the data in this study, established protocols from previous studies were followed as outlined in Baidai et al. (2020) and Grande et al. (2019). To estimate the biomass of tuna aggregations around FADs, the echo-sounder buoy data was analyzed using acoustic values and the methodology described by Uranga et al. (2021).

5.4.2.a Experimental FADs track trajectories

To merge both the 'Echo-sounder buoy' and 'Experimental FADs-Observer' databases, cross-checking processes and comparison analyses of these databases were conducted (Baidai et al. 2020 and Grande et al. 2019). Only records of experimental FADs and associated buoys that were consistent with the activation date and position data were considered for the analysis. Moreover, only trajectory segments and acoustic records during the experimental period were selected for analysis. Additionally, only segments recorded date/time after deployment were included for analysis, and trajectory segments longer than 7 days of interrupted buoy connection were excluded. A total of 1066 satellite buoys were included in this analysis.

5.4.2.b Experimental FADs position and acoustic data

A filtering process was implemented to refine the buoy data provided by the buoy companies, , which involved selecting records related to the operational period of the experimental FADs. This process excluded records for buoys that were on board, on shore, or contained anomalous data during analysis, such as speeds greater than 4 knots (kt), "NA-s", or satellite connection errors (Orue et al., 2019).

In order to estimate tuna and bycatch biomass aggregation from acoustic buoy data, a refining process was applied to the acoustic data, which involved filtering the acoustic layer (Uranga et al., 2021) (see section 5.4.5). Because authors know the technical details on the algorithms used to convert acoustic signal into biomass by certain buoy manufacturers, only buoys from *Marine Instruments* and *Satlink* companies were used for this part of the study. A total of 937 satellite echo-sounder buoys were included in this analysis.

5.4.3. Lifespan assessment

The assessment of the duration of the 'operational' life of experimental FADs (i.e., lifespan), based on the echo-sounder buoy data, was assessed by measuring the period from the day of deployment until the associated echo-sounder buoy was deactivated. The analysis was conducted for all deployed FADs and by prototype. The deactivation of the buoy, and thus disconnection between the buoy and the monitoring vessel, may occur due to various reasons, such as degradation of the experimental FAD, its retrieval, sinking, elimination, malfunctioning of the buoy, replacement of the buoy, transfer of ownership, or because it is outside of the fishing grounds indicated by the IATTC Resolution C-21-04.

5.4.4. Drifting performance assessment

The drifting performance of NEDs and control FADs was evaluated by analyzing their trajectory and speed. The experimental FADs were classified as having similar, partially similar, or divergent drifting behavior based on their speed and location using georeferenced data provided by the echo-sounder buoys. The analysis considered the speeds of all deployed experimental FADs, taking into account the observed differences in their drifting patterns. This analysis allowed comparisons of pairs of experimental FADs (NEDs and control FADs) and provided insights into the variability of drifting speeds among all deployed FADs and by prototype.

5.4.5. Tuna biomass assessment

The performance of aggregating biomass between NEDs and paired control FADs, and by prototype, was compared using echo-sounder buoy information (only data from *Satlink* and *Marine Instruments* was used due to the availability of technical information). The buoys, which provide information on geolocation and buoy movement also provide data on the biomass aggregated under the FAD by depth layer. The data are recorded from 3 to 115 m depth divided into 10 vertical layers with a resolution of 11.2 m for Satlink (3 m of blind zone), and from 0-150 m (divided into 50 layers with a resolution of 3 m) for Marine Instruments. To avoid potential non-tuna species interference, shallow layers (<25m) were excluded from analysis, as noted in Orue et al. (2019) and Uranga et al. (2021). To avoid discrepancies between buoy manufacturers, the estimation of tuna biomass was based on the sum of the biomass recorded between 25 m and 115 m. Only data recorded during sunrise, between 4 am and 8 am local time, were considered for analysis as they are the periods with the best echosounder biomass signals, as highlighted in Moreno et al. (2007) and Uranga et al. (2021). Daily biomass indexes were obtained by selecting the 0.9 quantile of the integrated acoustic energy observations, as described by Zudaire et al. (2021a) and Uranga et al. (2021).

6. RESULTS

6.1. Activities and interactions with experimental objects

Starting in the third quarter of 2019, a total of 780 NEDs (114 prototype 1, 395 prototype 2, and 271 prototype 3) and 764 paired control FADs were deployed by the end of 2022 (Table 1 and Fig. 9). Prototype 2 had a wider distribution (70°W–130°W; 7°N–17°S) than the other two prototypes, with a higher number of activities near the South American continent and the Galapagos Islands (Figure 8). Prototype 3 had a large longitudinal distribution (85°W–150°W), with most deployments between 3°N and 3°S. Prototype 1 had most of its activities observed between 115°W and 155°W, and between 7°N and 4°S (Figure 8). By the beginning of 2020, 50% of the experimental FADs had already been deployed, with the remaining 50% deployed in the remaining months until the end of 2022 (Figure 9).

During the study, there were very few redeployments for both NEDs and paired control FADs (n=13 and n=10, respectively), with most being for prototype 2 (n=12). A total of 86 visits (prototype 1, n=5; prototype 2, n=74; prototype 3, n=7) and 57 sets (prototype 1, n=8; prototype 2, n=46; prototype 3, n=3; Table 1 and Figure 8) were conducted on NEDs, while paired control FADs were visited and set 112 and 145 times, respectively (Table 1).

The analysis of the experimental FAD interactions provided insight into the variability of FAD fishing operations in the EPO. A large number of crew interactions on FADs was found in the EPO (Table 2). The vast majority of experimental FADs were not re-encountered after deployment (n=1268), followed by those being set upon after deployment (n=52), those being visited after deployment (n=46), and those being retrieved after a visit (n=42). The percentage of these four sets of interactions was slightly higher in traditional FADs (57%) than NEDs (43%; Table 2).

6.2. Catch per set

As of April 2023, a total of 1,918 mt of tuna has been caught in 57 sets on NEDs, with an average of 33.6 mt caught per set. In comparison, a total of 4,599 mt of tuna was caught in 145 sets on paired control FADs, with an average of 31.7 mt caught per set (Table 1). Both types of FADs had similar catch-per-set values to other short and long-term indicators on monitored FADs, such as in FAD-05-INF-A, FAD-06-01, FAD-07-01, SAC-13-06 and SAC-14-04.

To date, only eight matching pairs of NEDs and paired control FADs have been found for sets (Table 3), and unfortunately, only one of these pairs met the established spatiotemporal criteria. This matching pair was found outside the EPO and had a catch of 15 mt on the NED and 20 mt on the paired control FAD. They were set two days apart and separated by about 56.8 km (approximately 0.5 degrees). Due to data constraints, group comparisons with other objects in a specific spatial-temporal window were considered for analysis (see data analysis section for details) (Figure 10).

The catch-per-set ratios of the NEDs versus the FAD ranged from 0.1 to 11.9 across 25 groups (mean = 1.9; median = 0.9; Table 4). Similarly, the catch per set ratios of the paired control FADs versus the other traditional FADs ranged from 0.2 to 21.5 across 39 groups (mean = 2.2; median = 0.8; Table 5).

6.3. Condition of NEDs

Table 6 summarizes the observed conditions of the components of the three NED prototypes over time. Prototype 1 was observed 13 times, and the materials of both the floating and submerged components were found to be in good to very good condition after at least 2 months at sea. Prototype 2 was observed 113 times, and its components were generally considered to be in a very good condition for at least 2 months, and with good to fair condition until at least 3 months after deployment. In contrast, the NED design of prototype 3 had the least durability to date. This prototype was observed 10 times, and some of the materials, especially those in the submerged component, were found to be in poor condition between 1 and 2 months of deployment. However, the new cotton and rope materials used in the third and fourth batches of prototype 3 deployments appeared to improve material condition. These materials were found to be in good to excellent condition at a minimum of 2 months after deployment, respectively. It's important to note, however, that only 2 observations were made for each soak time period, and in one observation for the >90-day period, only the buoy was found.

It's worth noting that the 'NA' code shown in Table 6 represents different meanings in our analysis. Either a prototype does not contain a specific material or component (e.g., the submerged canvas of prototype 1), or the NED or some of its components could not be observed (e.g., only the satellite buoy was found).

In Figure 11, the distribution of days for the total soak time per prototype and paired control FADs is presented, which is estimated as the difference between the first deployment and retrieval or last encounter. Table 7 provides the minimum, maximum, mean, and the 25%, 50% (median), and 75% quantiles of total soak time for the experimental FADs, based on observer data.

For NED prototype 1, the total soak time varied between 24 and 139 days (>4.5 months), with a mean and median of 58 and 38 days, respectively. Prototype 2 had a total soak time ranging from 1 to 244 days (>8 months), with a mean and median of 44 and 40 days, respectively. On the other hand, prototype 3 had a total soak time ranging from 40 to 94 days (>3 months), with a mean and median of 68 and 67 days, respectively. The paired control FADs had a recorded total soak time ranging from 1 to 425 days (>14 months), with a mean and median of 91 and 72 days, respectively.

6.4. Lifespan assessment

Table 8 presents the minimum, mean, and maximum monitored periods (i.e., operational periods) in days for the experimental FADs, based on satellite echo-sounder buoy data. It is unclear why the buoys stopped transmitting data, but there are several possible causes such as malfunctions, sinking events, buoy replacement, or deactivation. This data was used as a proxy for the lifespan ('operational' life) of traditional FADs and the three NED prototypes, with a maximum of 854 days (mean = 176) for traditional FADs and a maximum of 790 days (mean = 193), 379 days (mean = 124) and 686 days (mean = 57) for NEDs prototypes 1, 2, and 3, respectively (Figure 12).

6.5. Drifting performance assessment

Figure 13 illustrates the drifting trajectories of experimental FADs from their deployment until the end of the monitoring period or the echo-sounder buoy was deactivated. The experimental FADs deployed off Peru drifted predominantly westward, in contrast to those deployed in the equatorial region, which tended to follow northwest or southwest directions due to equatorial currents.

The tested experimental FADs showed three different drifting patterns, as seen in Figure 14. Some FAD pairs had similar drifting patterns throughout the monitoring period (n=151). Others had partially similar patterns initially, but then diverged and showed different drift patterns (n=123). Finally, some pairs had divergent drifting patters from the time of deployment (n=19), and these drifts remained divergent until the end of the monitoring period. In some cases, comparisons between pairs were not possible because the matching pair was not found (n=182). Pairs that described an erroneous or interrupted pattern (n=49) were excluded from the analysis.

The distance between experimental FAD pairs was analyzed based on the three drifting patterns observed. The results (Figure 15) showed that divergent pairs had a greater distance than partially similar and similar drifting pairs. The median values of distance across NED prototypes followed the same trend, except for prototype 3, where similar drifting pairs showed shorter distances only until 60 days after deployment.

To analyze the speed difference between pairs, the same drift pattern classification was used. The median values of similar and partially similar drifting patterns showed a slight increase in speed during the first 30-40 days after deployment. In divergent pairs, a greater variability in speed was observed (Figure 16). However, the differences in speed were lower and more stable in pairs with similar drifting patterns. This behavior was also observed when analyzing the speed differences between pairs for each prototype.

Table 9 shows the maximum, mean, and minimum speed values observed for the deployed experimental FADs using buoy data. NED prototypes 1 and 2 had similar mean speed values (0.72 and 0.80 kt) to traditional FADs (0.71 kt), whereas NED prototype 3 had a slightly higher mean speed value (1.02 kt).

6.6. Tuna biomass assessment

Biomass estimates were obtained from the echo sounder buoys associated with the experimental FADs (*Marine Instruments*, n=604; *Satlink*, n=333; Table 10). The results showed the colonization process and the biomass dynamics for all experimental FADs and by prototype. The biomass index for traditional FADs increased consistently up to 80 days after deployment, while for NEDs, it increased up to 50-60 days after deployment (Figure 17). When considering the different NED prototypes, prototype 1 and 3 showed a consistent increasing trend in the biomass index until 75 and 60 days after deployment, respectively. However, NED prototype 2 had a consistent positive trend in the biomass index only up to approximately 30-40 days, and then maintained a more stable trend with a biomass index value around 25 (see Figure 17).

7. DISCUSSION

Prototype performance

Based on the current results, it was found that NEDs performed better when non- or low-processed natural materials were used, such as bamboo and balsa wood, which remained in very good condition throughout the testing period. Abaca fiber, especially when coated with natural rubber, was also found to be durable and maintained reasonable condition for at least 3 months of total soak time in prototypes 1 and 2. These materials were easily accessible locally and did not present significant logistical challenges, but It is important to consider potential constraints related to local availability and shortage if these materials are to be used at a larger scale in the EPO.

Based on these promising results, approximately 43 vessels under the TUNACONS FAD management plan are voluntarily using NED prototype 2 in at least 20% of their FAD deployments. Additionally, 12 more vessels from 2 Ecuadorian fleet companies are likely to adopt this initiative in the near future. However, cotton fibers used in prototype 3 did not achieve the expected results, particularly for those acquired for the first batch of the project. The improved cotton quality and changes to the design of this prototype showed an improvement in the duration of at least 90 days (Table 6), but few observations were made to draw a definitive conclusion.

Satellite buoy data showed that the maximum lifespan of paired control FADs was 854 days, while that of NED prototypes 1,2 and 3 was 790, 379 and 686 days, respectively. These results indicated a longer lifespan for NEDs than their total soak time using the "Experimental FADs-Observer" database. However, it is worth noting that unlike the "Experimental FADs-Observer", where the buoy 'life' is only recorded when is encountered and recorded by the observer, the 'Echo-sounder buoy' database records the buoy 'operational' life until it is deactivated.

Results of the drifting patterns analysis showed that experimental FADs pairs had, in general, similar speeds and drifting behaviors. Moreover, tuna biomass aggregation analyses using echo-sounder information showed similar biomass index values for both traditional FADs and NEDs. However, the increasing trend after deployment was sustained longer by paired control FADs with 80 days than by NEDs with 50-60 days. This seems to be mainly caused by NED prototype 2, which had a shorter increasing trend in biomass index of only 30-40 days compared to NED prototypes 1 and 3, which had increasing trends until 75 and 60 days, respectively. This difference could be due, among others, to the spatial distribution of NED prototypes, with prototype 2 having a fairly eastern and central EPO distribution and distinct oceanographic characteristics compared to western EPO areas (Figure 8), likely with different dynamics in fish aggregation and encounter rates (FAD-07-01). Further analysis on tuna biomass aggregation on traditional FADs paired with NEDs prototype 2 may help to corroborate this assumption. Additionally, the shorter increasing trend in biomass index across NEDs may also be explained by their biodegradable nature, which causes them to decay faster than traditional FADs, hence progressively losing their cohesion and attraction to tuna before 80 days, as observed in the paired control FADs.

Dissemination and engagement

Engagement and feedback from industry and fishers are crucial to the success of the project. Therefore, it was essential to ensure that the objectives, methodology, and project dynamics were clearly understood, and that the NED designs and tracking methods were used correctly. To achieve this, posters describing the project's key functional matters were delivered and shared with the fleet, and regular workshops were organized with vessel participants and non-participants throughout the project (see Figure 18). The response from the fleet was positive, with some fishers sending general information and pictures of NEDs they encountered at sea, which helped to cross-check against observer data. The local project coordinator also regularly interviewed participant skippers on any matter related to the program, with particular interest in the NED prototypes used and their performance. To maintain a close and consistent relationship with the fleet, fishers from the two organizations (TUNACONS and AGAC) were regularly given project updates through online or in-person workshops in Manta and Posorja, Ecuador, or Spain. To date, all participants have provided useful feedback, proposed solutions to challenges, and expressed their full commitment to the project. In this regard, the IATTC staff will continue to engage regularly with the fleet in dedicated workshops in the near future.

Project challenges

The COVID-19 pandemic, which began in the first quarter of 2020, caused several adverse effects on the working dynamics of this project. Logistical difficulties hampered the collection of new data due to shortages of vessels and observers to go to at sea, and there were supply chain issues that delayed the construction of new NEDs, including shortages and availability of materials, as well as import and export constraints. The closure of factories, customs and borders, and restrictions on international and national shipments and travel contributed to these challenges, impacting NED construction and deployments. Despite these challenges, material availability improved, and restrictions and regulations have been easing since late 2021, allowing NED construction to gradually resume.

Although, in general, NEDs have performed reasonably well, some concerns were raised by participants during the prototype testing in the 3rd and 4th quarters of 2019. Efforts were undertaken to improve these prototypes and address fleets' concerns. For example, laboratory tests showed that the condition of the canvas and ropes of abaca fibers in prototype 2 could be improved when coated with natural products like rubber. The fishing crew noted a potential weakness in the connection between the submerged component and the floating component in prototype 1, leading to a slight modification to reinforce the link and reduce the potential loss of the submerged component. Additionally, two small nylon ropes running independently and in parallel to each abaca braided rope were added, and the method of tying and hanging the ropes was considered to ensure the performance of the abaca ropes was not compromised.

Similarly, problems associated with the cotton canvas, likely due to the quality of the material used, were reported for prototype 3. The prototype 3 NEDs deployed in the 4th quarter of 2019 and 1st quarter of 2020 appeared to break apart, particularly in the floating component, which increased the chances of satellite buoy detachment from the experimental object. However, experiments conducted during Phase 1 demonstrated that the performance of the cotton canvas could be improved by using better quality and ticker material. Therefore, it was decided to improve both the quality and thickness of the cotton for prototype 3 NEDs, with the changes set to be implemented for the 3rd quarter of 2021 and the last batch of deployment in 2022.

In addition to the issue with the cotton canvas, some of the ropes used in the submerged part for prototype 3 in the 4th quarter of 2019 and 1st quarter of 2020 appeared to be failing. Material was acquired from a new supplier to replace the ropes in the submerged component of prototype 3 NEDs for deployment in the 3rd quarter of 2021, based on the success of similar projects in other regions of the world where some of the participant companies had previously participated (Zudaire et al. 2021). However, the new material did not perform as expected, leading to another modification to the NED design to extend its durability. For the last batch of deployments, biodegradable ropes were replaced with synthetic ropes to ensure the NED's long-term cohesion and integrity and the fleet engagement with the project.

Minor modifications were also made to preserve the floatation and strengthen the connection between the submerged and surface components of prototype 3, such as the addition of small nylon ropes and an increase in the quantity of balsa wood used (Figure 19). As of the time of writing this report, only a handful of records have been collected and analyzed to determine the impact of these changes on the duration of prototype 3. However, preliminary results suggest that the improved cotton quality and design modifications have significantly increased the prototype's duration, at least up to 90 days (Table 6).

8. FUTURE WORK AND RECOMMENDATIONS

The IATTC staff is working and coordinating closely with other voluntary and scientific programs that are deploying biodegradable FADs in the region, such as the TUNACONS voluntary initiative and the ISSF jellyFAD project. Similarly, AGAC's fleets globally have initiated voluntary programs to transition towards using biodegradable FADs. It is important to continue processing and analyzing the information collected by the observers and other means, such as data from echo-sounder buoys, to better understand the at-sea performance of the different experimental objects. With the changes in the quality of some materials and minor design modifications in these three NED prototypes it may be desirable to update the analyses and results on the condition of NED materials in the near future by assessing their performance separately with an increased sample size. However, the results presented in this study are promising and could be considered to inform an effective and gradual implementation of biodegradable FADs in the region.

While some initiatives are underway to assess the drifting and durability performance of FADs with simpler designs (e.g., the jellyFAD, FAD-05-INF-B, Moreno et al. 2023), large-scale at sea experiments that address this issue are still lacking in the EPO. Therefore, it is desirable to have initiatives that consider testing simpler FAD designs with less material. In addition, it is necessary to engage in continuous participatory approaches with fishers to foster engagement and discover means to reduce material usage in FADs. This could be of particular interest for fleets using deeper FADs and operate mostly offshore and closer to the western border of the IATTC convention area, where deeper FADs have historically been used (FAD-05-INF-C, FAD-06-01, FAD-07-01).

Given the relatively less resilient and faster degradation nature of the NED components, it is reasonable to assume that biodegradable FADs may be more sensitive to manipulation than traditional FADs. Therefore, fishers would like to minimize unnecessary contact and rough manipulations with biodegradable FADs as much as possible to improve their functional life at sea, at least during experimental and implementation phases. In these cases, fishers should also be prepared with tools and materials that allow repairing or replacing components at biodegradable FADs at sea. However, fishers seem to be aware of these differences, and may already be affecting biodegradable FAD manipulation and fishing strategies. These assumptions would need to be confirmed and validated by data, such as empirical information and interviews, so that the real impacts of transitioning from traditional FADs to biodegradable FADs in the various fishing strategies can be assessed holistically.

Although 1531 experimental FADs were deployed during the project (780 pairs), 1066 and 937 buoys were used for life span/drifting performance and tuna biomass analyses, respectively. 277 pairs were excluded due to data inconsistencies (labeled as 'single': when the matching pair was not present, 'check': when the trajectory of one of the pairs described long interrupted periods, or 'error': when the buoy showed several conflicting trajectories), or because the buoy information was not available for several reasons, such as an observer recording the wrong serial number of the buoy, the buoy being deactivated immediately after deployment; or the vessel company not providing the buoy information during the experimental period. In some cases, the buoy belonged to a non-project participant vessel company. Additionally, for the acoustic signal analyses, in some cases, the buoys were manufactured by a company (e.g., *Zunibal*) for which no established analytical procedure existed to integrate them into the acoustic information database, therefore these data was not included in the analyses.

In order to complete the analysis with all the buoys associated with the experimental FADs, the staff will continue their efforts to obtain the remaining information, as well as make the necessary arrangements to incorporate the data from all buoys manufacturers into the analytical procedures in the near future.

Despite these challenges, the results of this study are overall promising and suggest that starting a transition to biodegradable FADs to reduce negative impacts on the associated species and ecosystems may be possible without compromising the effectiveness of the fishing method. Therefore, the following recommendations are made by the IATTC staff:

- Consider current prototypes 1 and 2, and to a lesser extent prototype 3[4], as potential examples for effective biodegradable FAD construction.
- Consider a gradual/stepwise transition process, including a timeline for the implementation of fully biodegradable FADs based on the current state of material availability.
- Reduce, to the extent possible and within the gradual process of biodegradable FAD implementation, the amount of material and the non-biodegradable components for NED design and construction, provided that fishing efficiency is not compromised.

[4] Full implementation of prototype 3 may require further research in collaboration with fishers.

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Zudaire, I., Moreno, G., Murua, J., Murua, H., Tolotti, M.T., Román, M., Lopez, J., Grande, M., Merino, G., Escalle, L., Hamer, P., Bazurko, O.C., Capello, M., Dagorn, L., Ramos, M.L., Abascal, F.J., Báez, J.C., Pascual-Alayón, P.J., Déniz, S., and Santiago, J., 2021. Biodegradable dFADs: current status and prospects. IOTC-2021-WGFAD02-09. https://www.iotc.org/documents/biodegradable-dfads-current-status-and-prospects.

Zudaire, I., Uranga, J., Salgado, A., Arregi, I., Krug, I., Santiago, J. and Grande, M., 2021a. Collaboration of AZTI on the ISSF project "large-scale deployment of biodegradable FADs with Ghanaian fleets in the Atlantic Ocean and Caroline Fisheries Company fleet in the Western Pacific". Elaborado por AZTI para ISSF.

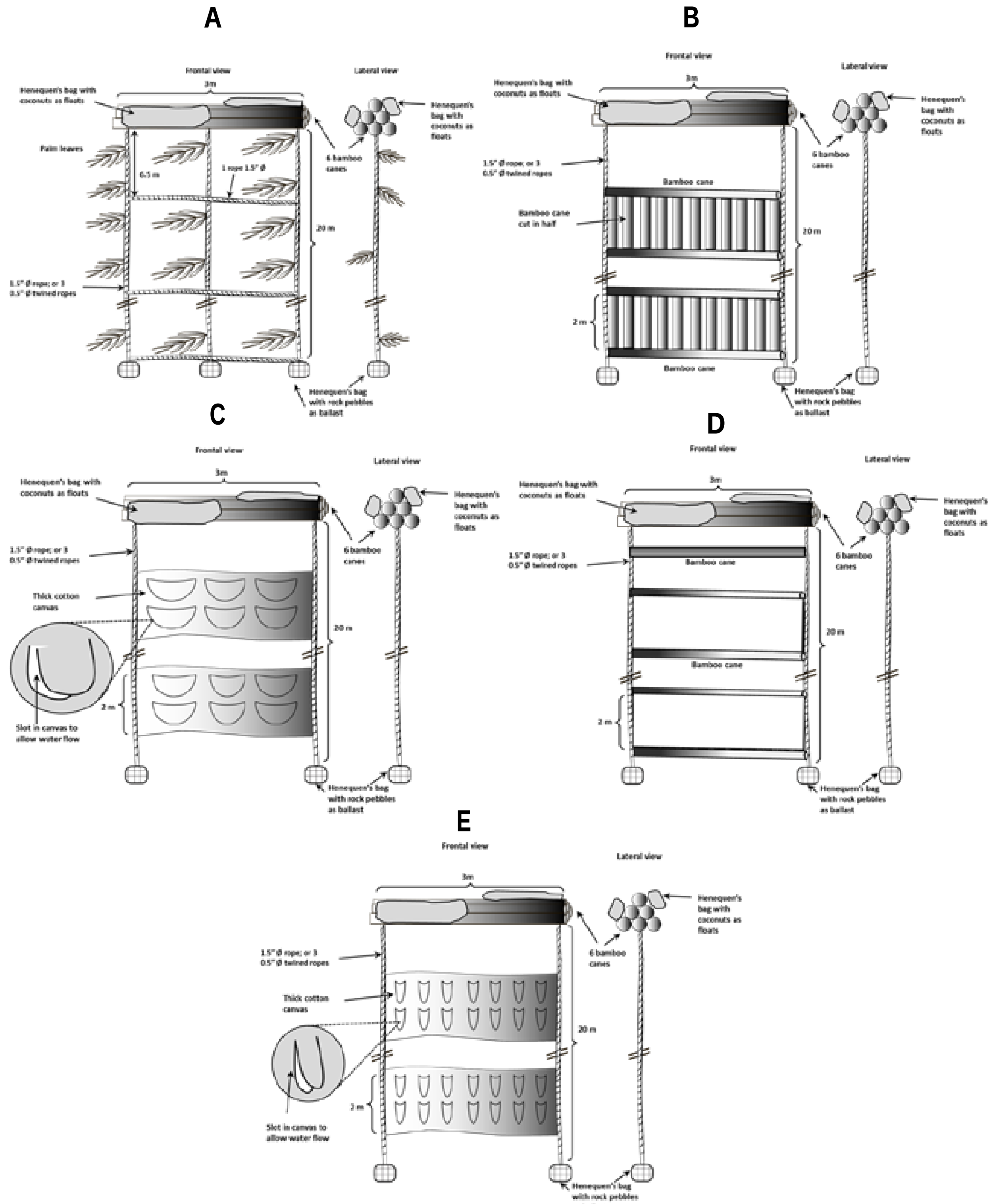


FIGURE 1. Prototypes 1(A) to 5 (E) used in Phase 1 (EU grant 7592).

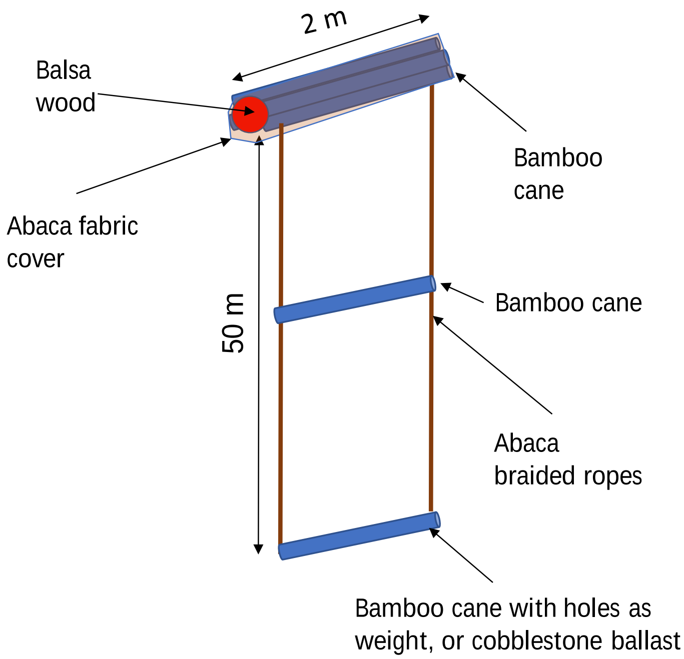


FIGURE 2a. NED prototype 1.

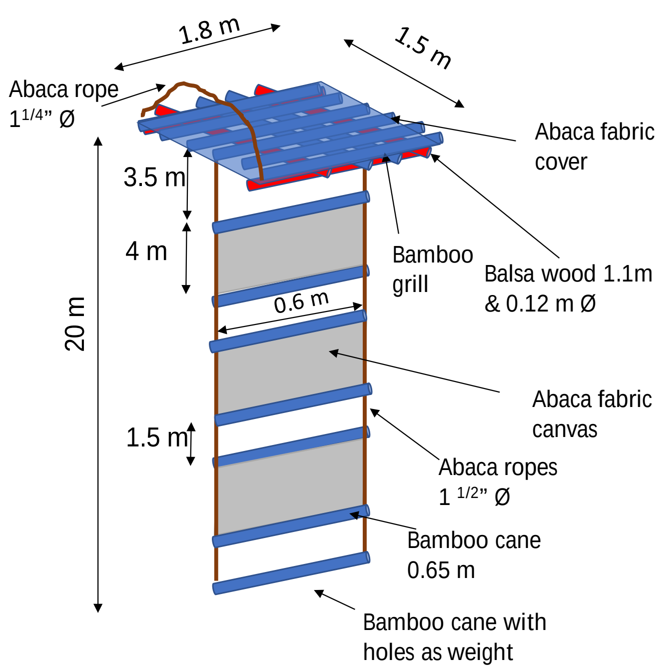


FIGURE 2b. NED prototype 2.

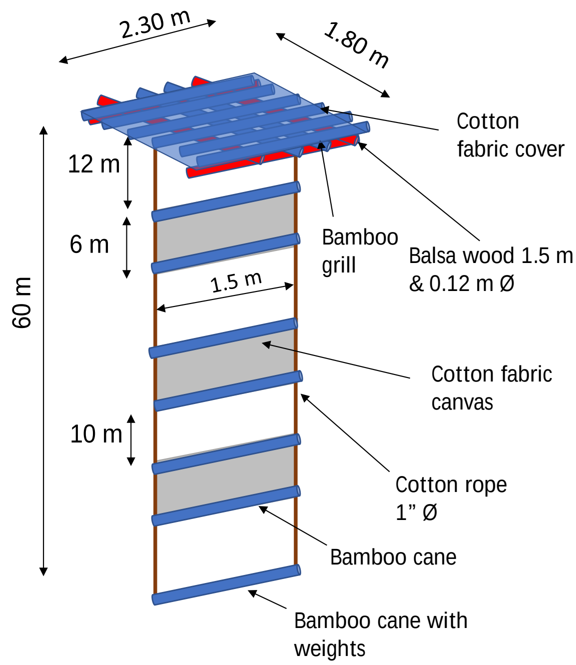


FIGURE 2c. NED prototype 3.

A

B

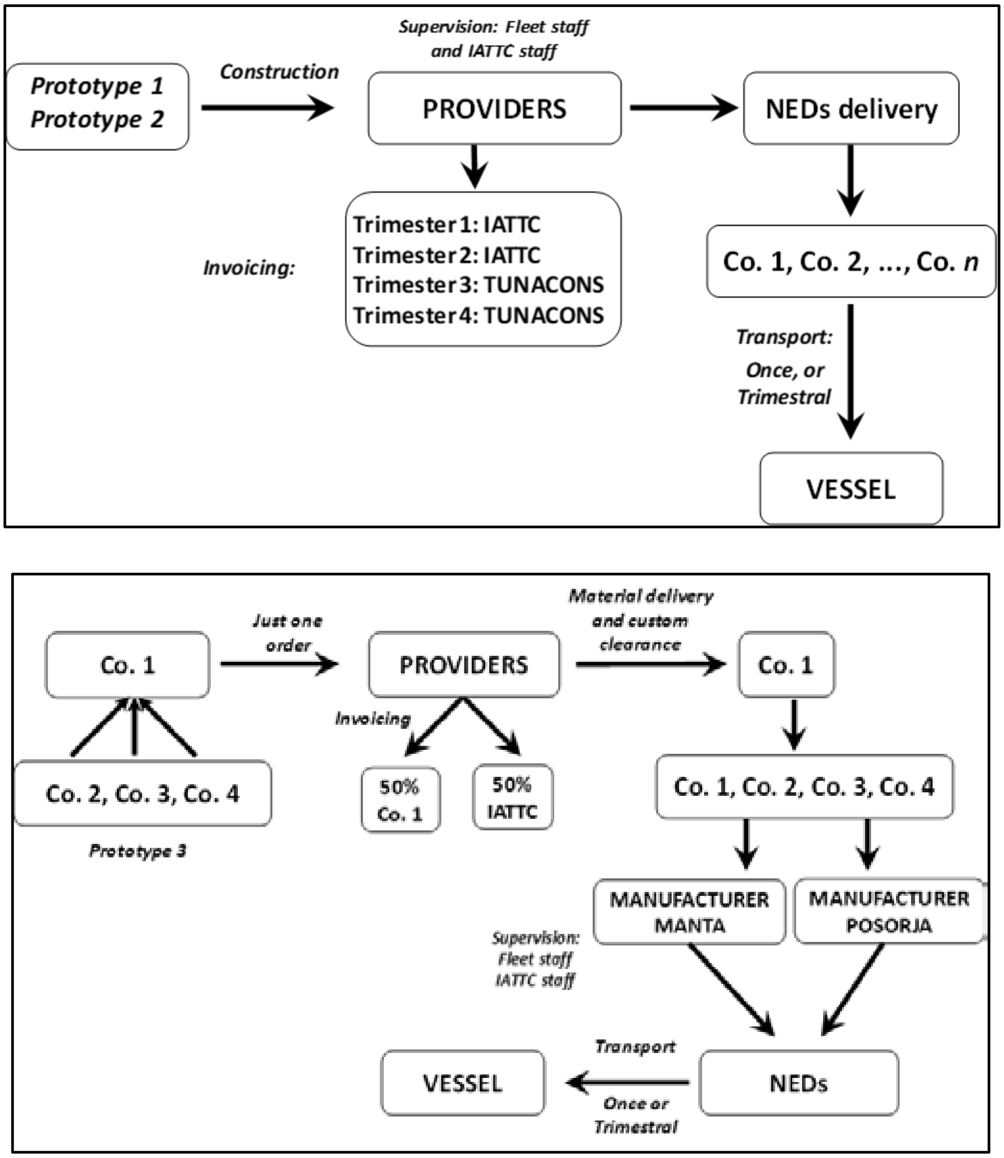


FIGURE 3. Flowchart showing construction and payment options for NEDs used by used by TUNACONS (A) and AGAC (B).

FIGURE 4. Colored metallic tags placed on both the raft and the buoys of experimental FADs; NEDs (green) and paired control FADs (red).

Comisión Interamericana del Atún Tropical

REGISTRO DE OBJETOS FLOTANTES COMPLEMENTARIO (ROF-C)

Utilice este registro exclusivamente para proveer información de los NED descritos en el instructivo

No. de Crucero: 1 5 0 0 0 0

No. de objeto	NE	NP	Levantado	Estructura superficial	Condición	¿Reemplazado?	Estructura bajo el agua	Condición	¿Reemplazado?
0 0 1	0 1	1	Sí [ ] No [ ]	Bambú	[1]	Sí [ ] No [X]	Lonas	[ ]	Sí [ ] No [ ]
Comentarios:				Lona envolvente	[1]	Sí [ ] No [X]	Soga principal	[1]	Sí [ ] No [X]
				Balsa	[1]	Sí [ ] No [X]	Soga de amarre	[1]	Sí [ ] No [X]
				Soga de amarre	[1]	Sí [ ] No [X]	Bambú (estructura)	[ ]	Sí [ ] No [ ]
							Bambú (lastre)	[1]	Sí [ ] No [X]

No. de objeto	NE	NP	Levantado	Estructura superficial	Condición	¿Reemplazado?	Estructura bajo el agua	Condición	¿Reemplazado?
0 0 2	0 1	3	Sí [X] No [ ]	Bambú	[2]	Sí [ ] No [X]	Lonas	[3]	Sí [ ] No [X]
Comentarios: AL SER REMOLCADO, PUDE OBSER				Lona envolvente	[3]	Sí [ ] No [X]	Soga principal	[3]	Sí [ ] No [X]
VAR LA PARTE COLGANTE DEL NED				Balsa	[2]	Sí [ ] No [X]	Soga de amarre	[3]	Sí [ ] No [X]
CERCA DE LA SUPERFICIE. NED				Soga de amarre	[3]	Sí [ ] No [X]	Bambú (estructura)	[2]	Sí [ ] No [X]
FUE LEVANTADO A LA MITAD.							Bambú (lastre)	[2]	Sí [ ] No [X]

FIGURE 5. An example of the observer complementary flotsam form (ROF-C).

Inter-American Tropical Tuna Commission

NED AND PAIRED FAD INFORMATION RECORD FOR TRIMARINE SKIPPERS (NPR-TS)

Vessel name	DATE YY	DATE MM	DATE DD	TIME	LATITUDE	N/S	LONGITUDE	W

A. General information. Use buoy code table below to indicate the satellite buoy manufacturer. When the buoy is replaced, use the space for Buoy 2. Use the condition codes table below to record the components condition.

Activity: Deployed ☐ Fished ☐ Visited ☐ | Was the object removed from the sea? Yes ☐ No ☐

Satellite or radio buoys

	Make / Model		Serial number		**Metallic tags**
Buoy 1				Tag 1:	
Buoy 2				Tag 2:	

Lifted: Yes [ ] No [ ]	NED floating structure (Raft)	Condition	Replaced?	NED underwater structure (Tail)	Condition	Replaced?
Prototype No.: [ ]	Bamboo	[ ]	Yes[ ] No [ ]	Canvas	[ ]	Yes[ ] No [ ]
Comments:	Canvas cover	[ ]	Yes[ ] No [ ]	Main rope	[ ]	Yes[ ] No [ ]
	Balsa wood	[ ]	Yes[ ] No [ ]	Tightening rope	[ ]	Yes[ ] No [ ]
	Tightening rope	[ ]	Yes[ ] No [ ]	Bamboo (structure)	[ ]	Yes[ ] No [ ]
				Bamboo (ballast)	[ ]	Yes[ ] No [ ]

Condition codes of degradable components

Code	Condition	Description
0	Not observed	Component is present, but its condition could not be observed (very turbid water, observed at night, etc.).
1	Excellent	New. With its natural color. No signs of damage or deterioration. Strongly attached to other components.
2	Very good	Little discoloration. No apparent signs of damage or deterioration. Firm cohesion with other components.
3	Good	Slightly worn. Few cracks/tears/discoloration. Cohesion with other components is relatively firm. Begins to show signs of weakness.
4	Fair	Evidence of wear. Several cracks/ tears. Cohesion with other components is weak. Very discolored.
5	Poor	Very deteriorated. Separated from other components. 50% has disappeared. Very discolored. Cohesion with other components is insufficient and very weak.
6	Very poor	Little evidence of its presence. More than 80% has disappeared. Very discolored. Cohesion is almost non-existent.

Buoy code table – Make and model of buoys

MARINE INSTRUMENTS (Nautical) Model	Codes		SATLINK Model	Codes	
Unknown	MARD	100	Unknown	SATD	200
MDP	MDP	101	D+ battery	D+	201
MDS	MDS	102	D+ battery with echo-sounder	DS+	202
M2D	M2D	103	D+ solar	DL+	203
MSI	MSI	104	D+ solar with echo-sounder	DSL+	204
M3i	M3I	105	IDP solar with echo-sounder	ISL+	205
M3i+	M3I+	106	IDP solar disc with echo-sounder	ISD+	206
M4i	M4I	107	SLX solar "ECO"	SLX+	207

ZUNIBAL

Model	Codes		Model	Codes	
Unknown	ZUND	300	Tunabal-e7+ (F-series)	F7+	306
Tunabal-7	T07	301	Tuna8 Explorer	T8E	307
Tunabal-e7	TE7	302	Tuna8 Xtreme	T8X	308
Tunabal-e7+	T7+	303	Tuna8 Explorer (F-series)	F8E	309
Tunabal-7 (F-series)	F07	304	Zuni with no echo-sounder	ZO7	310
Tunabal-e7 (F-series)	FE7	305	Zuni-e with no echo-sounder	ZE7	311

Buoy without make or unknown make	DESC	0
Other type of non-satellite buoy	OTRN	900
Other satellite buoy of a make not indicated above	OTRS	911

FIGURE 6a. Data collecting for skippers and fishing crew of TRIMARINE's fleet (NPR-TS).

Comisión Interamericana del Atún Tropical

REGISTRO DE NED Y PAREJAS DE CONTROL PARA BARCOS SIN OBSERVADOR (RNC-NO)

Nombre del barco	FECHA AA	MM	DD	HORA	LATITUD	N/S	LONGITUD	W

A. Información general del objeto flotante. Use la tabla de códigos de boyas (abajo) para indicar el fabricante de la boya, así como la tabla para la condición del componente. Si la boya es remplazada, use el espacio para Boya 2.

Actividad: Sembrado [ ] largado [ ] visitado [ ] | **¿Subieron el objeto a bordo?** Sí [ ] No [ ]

Boyas satelitales o radio boyas	Marca / Modelo		Número de serie		Placas metálicas (N o T)
Boya 1				Marca 1:	
Boya 2				Marca 2:	

	Estructura superficial	Condición	¿Reemplazado?	Estructura bajo el agua	Condición	¿Reemplazado?
Levantado: Si [ ] No [ ]						
Prototipo No.: [ ]	Bambú	[ ]	Sí [ ] No [ ]	Lonas	[ ]	Sí [ ] No [ ]
Comentarios:	Lona envolvente	[ ]	Sí [ ] No [ ]	Soga principal	[ ]	Sí [ ] No [ ]
	Balsa	[ ]	Sí [ ] No [ ]	Soga de amarre	[ ]	Sí [ ] No [ ]
	Soga de amarre	[ ]	Sí [ ] No [ ]	Bambú (estructura)	[ ]	Sí [ ] No [ ]
				Bambú (lastre)	[ ]	Sí [ ] No [ ]

Códigos de condición de los componentes degradables

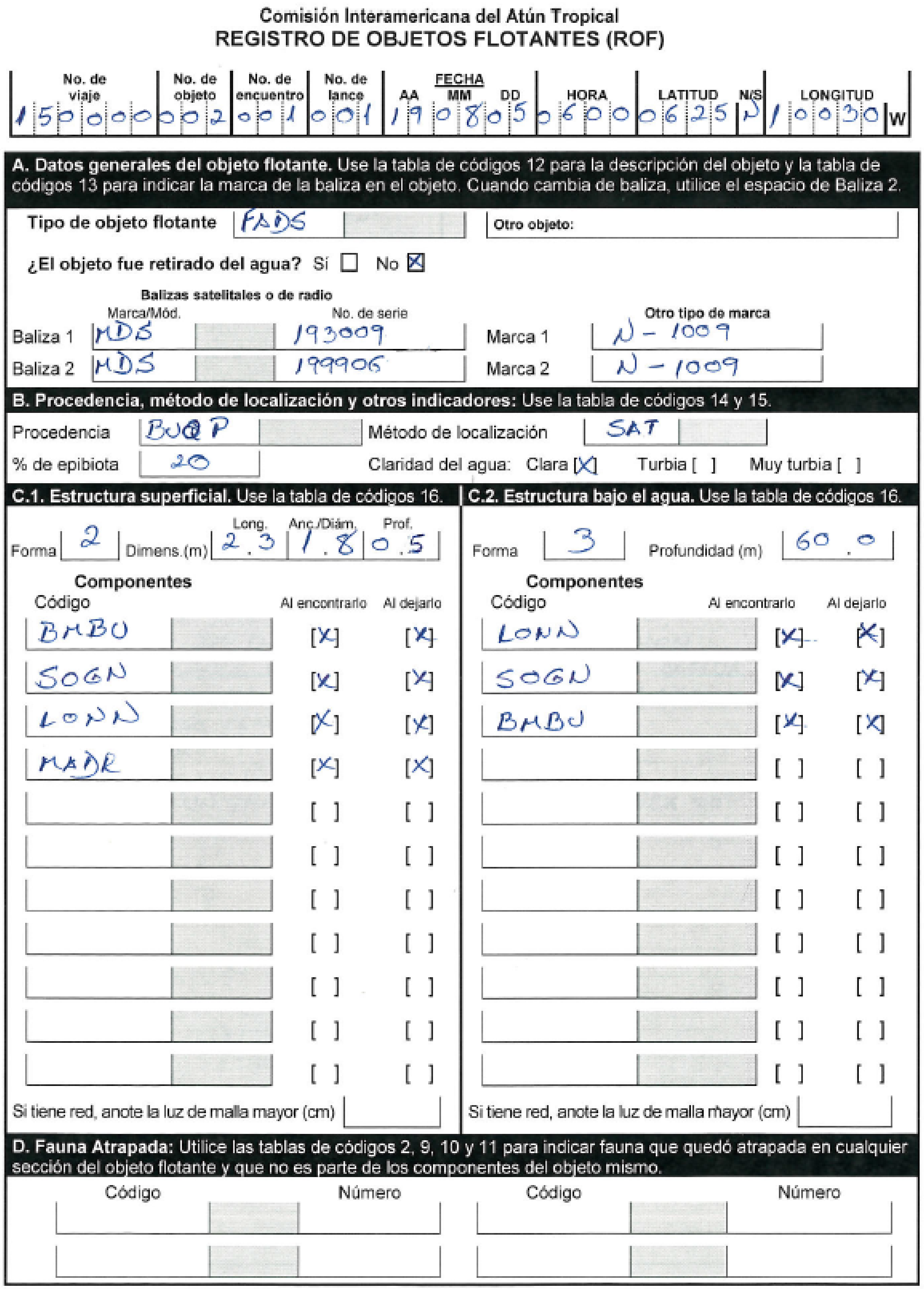
Código	Condición	Descripción
0	No observado	Componente está presente, pero no pudo observar su condición. (Agua muy turbia, observado en la noche, etc.)
1	Excelente	Nuevo. Con su color natural. Sin signos de daño o degradación. Fuertemente afianzado a los demás componentes.
2	Muy bueno	Poca decoloración. Sin signos de daños o degradación aparentes. Cohesión con los demás componentes es firme.
3	Bueno	Ligeramente desgastado. Pocas grietas/rasgaduras/decoloración. Cohesión con los demás componentes relativamente firme. Comienza a mostrar signos de debilidad.
4	Regular	Evidencia de desgaste. Varias grietas/rasgaduras. Cohesión con los demás componentes es débil. Muy decolorado.
5	Malo	Muy deteriorado. Está separado de los demás componentes. Ha desaparecido un 50%. Muy decolorado. Cohesión con los demás componentes es insuficiente y muy débil.
6	Muy malo	Con poca evidencia de su presencia. Ha desaparecido más del 80%. Muy decolorado. Cohesión casi inexistente.

Tabla de códigos de boyas – Marca y modelo de boyas

MARINE INSTRUMENTS (Nautical) Modelo	Códigos		SATLINK Modelo	Códigos	
Desconocido	MARD	100	Desconocido	SATD	200
MDP	MDP	101	D+ pila	D+	201
MDS	MDS	102	D+ pila con sonda	DS+	202
M2D	M2D	103	D+ solar	DL+	203
MSI	MSI	104	D+ solar con sonda	DSL+	204
M3i	M3I	105	IDP solar con sonda	ISL+	205
M3i+	M3I+	106	IDP solar disc. c/sonda	ISD+	206
M4i	M4I	107	SLX solar "ECO"	SLX+	207
ZUNIBAL					
Modelo	**Códigos**		**Modelo**	**Códigos**	
Desconocido	ZUND	300	Tunabal-e7+ (F-series)	F7+	306
Tunabal-7	T07	301	Tuna8 Explorer	T8E	307
Tunabal-e7	TE7	302	Tuna8 Xtreme	T8X	308
Tunabal-e7+	T7+	303	Tuna8 Explorer (F-series)	F8E	309
Tunabal-7 (F-series)	F07	304	Zuni sin sonda	ZO7	310
Tunabal-e7 (F-series)	FE7	305	Zuni-e sin sonda	ZE7	311

Baliza sin marca o marca desconocida	DESC	0
Otro tipo de baliza no satelital	OTRN	900
Otra baliza satelital de una marca no indicada arriba	OTRS	911

FIGURE 6b. Data collection form for skippers and fishing crew (RNC-NO) on vessels other than those in TRIMARINE's fleet.



Comisión Interamericana del Atún Tropical
REGISTRO DE OBJETOS FLOTANTES (ROF)

No. de viaje	No. de objeto	No. de encuentro	No. de lance	FECHA AA	MM	DD	HORA	LATITUD	N/S	LONGITUD
1500000	002	001	001	19	08	05	0600	0625	N	10030 W

A. Datos generales del objeto flotante. Use la tabla de códigos 12 para la descripción del objeto y la tabla de códigos 13 para indicar la marca de la baliza en el objeto. Cuando cambia de baliza, utilice el espacio de Baliza 2.

Tipo de objeto flotante: FADS | Otro objeto:

¿El objeto fue retirado del agua? Sí [ ] No [X]

Balizas satelitales o de radio

	Marca/Mód.	No. de serie		Otro tipo de marca
Baliza 1	MDS	193009	Marca 1	N - 1009
Baliza 2	MDS	199906	Marca 2	N - 1009

B. Procedencia, método de localización y otros indicadores: Use la tabla de códigos 14 y 15.

Procedencia: BUQP | Método de localización: SAT

% de epibiota: 20 | Claridad del agua: Clara [X] Turbia [ ] Muy turbia [ ]

C.1. Estructura superficial. Use la tabla de códigos 16.

Forma: 2 | Dimens.(m) Long. 2.3 Anc./Diám. 1.8 Prof. 0.5

Componentes

Código	Al encontrarlo	Al dejarlo
BMBU	[X]	[X]
SOGN	[X]	[X]
LONN	[X]	[X]
MADR	[X]	[X]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]

Si tiene red, anote la luz de malla mayor (cm)

C.2. Estructura bajo el agua. Use la tabla de códigos 16.

Forma: 3 | Profundidad (m): 60.0

Componentes

Código	Al encontrarlo	Al dejarlo
LONN	[X]	[X]
SOGN	[X]	[X]
BMBU	[X]	[X]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]
	[ ]	[ ]

Si tiene red, anote la luz de malla mayor (cm)

D. Fauna Atrapada: Utilice las tablas de códigos 2, 9, 10 y 11 para indicar fauna que quedó atrapada en cualquier sección del objeto flotante y que no es parte de los componentes del objeto mismo.

Código	Número	Código	Número

FIGURE 7. An example of the observer flotsam form (ROF).

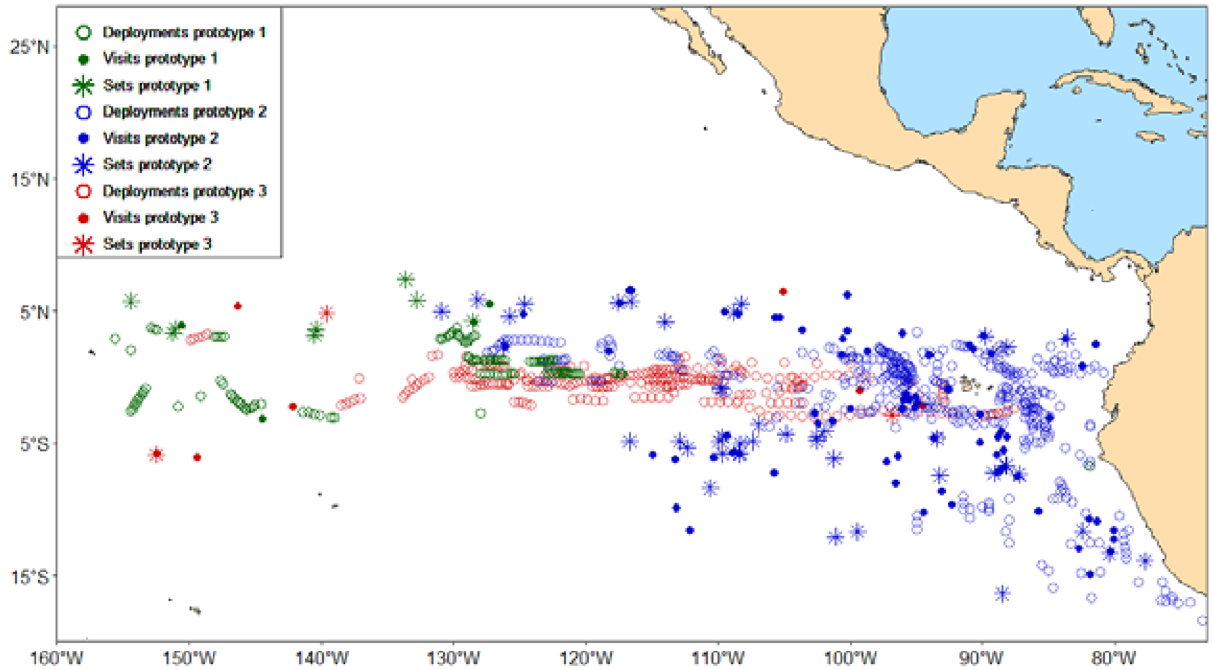


FIGURE 8. Spatial distribution of NED deployments, visits and sets from 2019–2023.

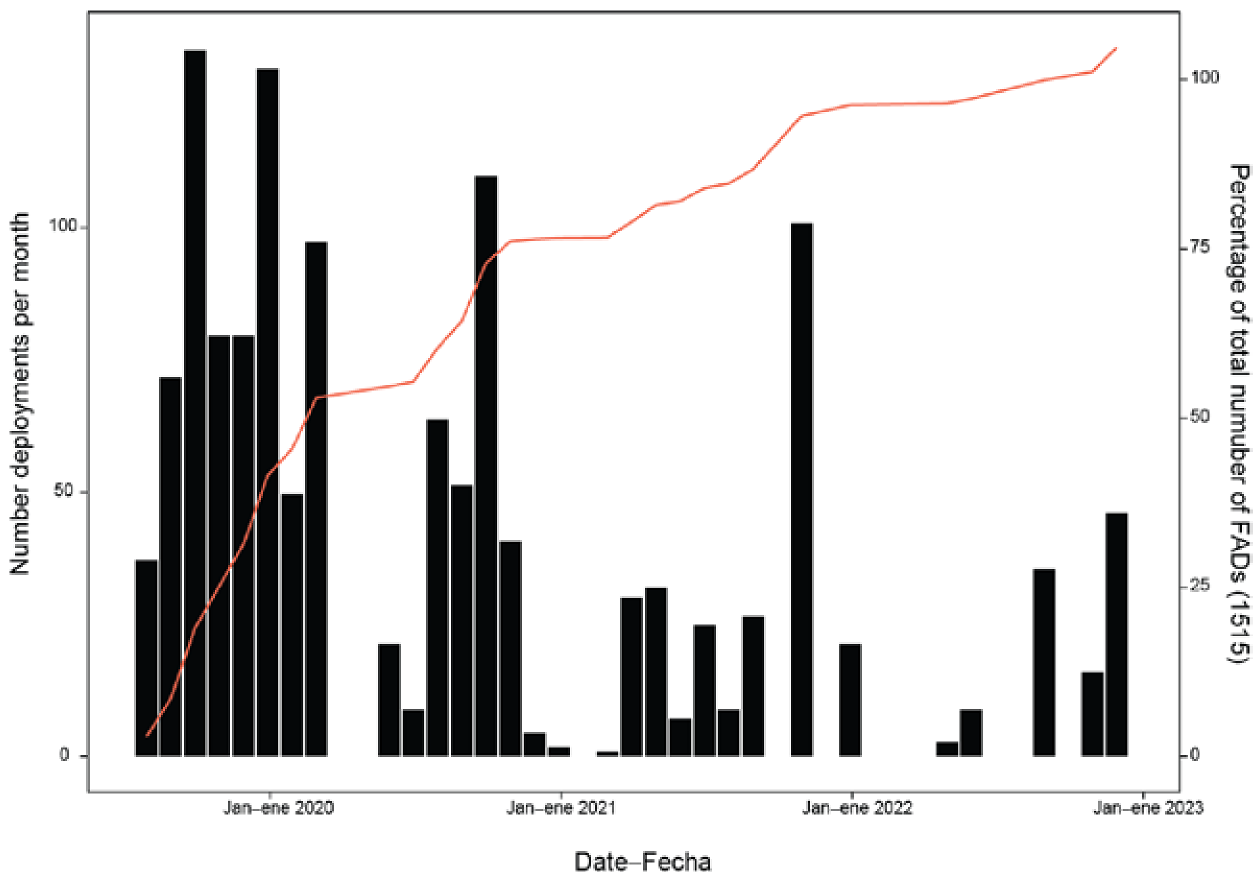


FIGURE 9. Temporal distribution of NED deployments, from 2019–2023.

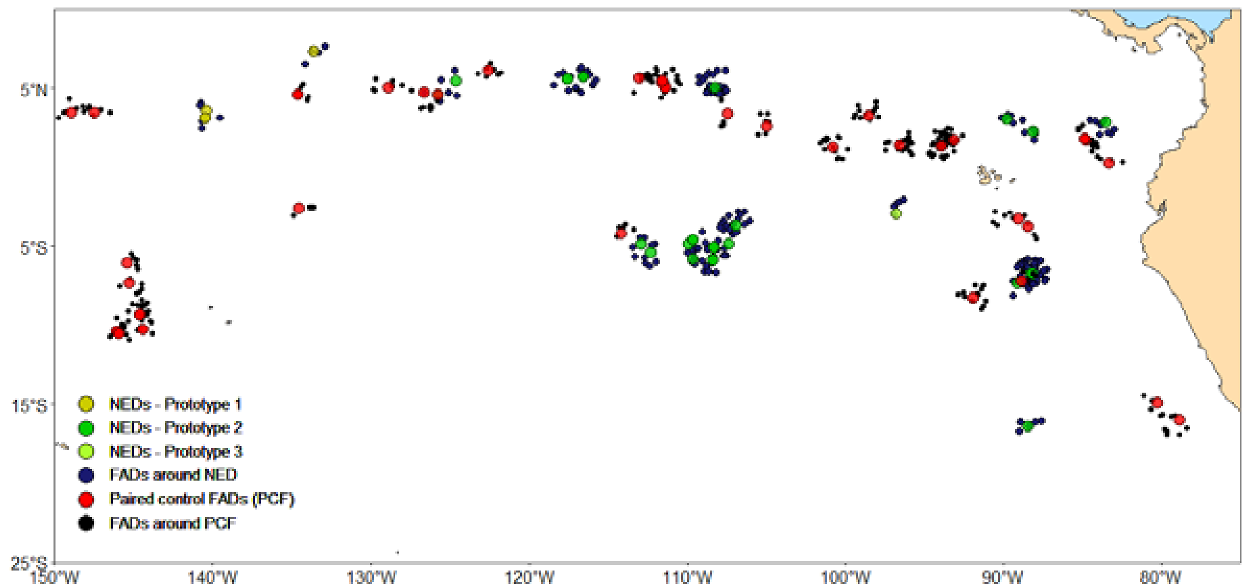


FIGURE 10. FAD sets made at a 1-degree radius and 7 days before or after a set on a NED or paired control FAD.

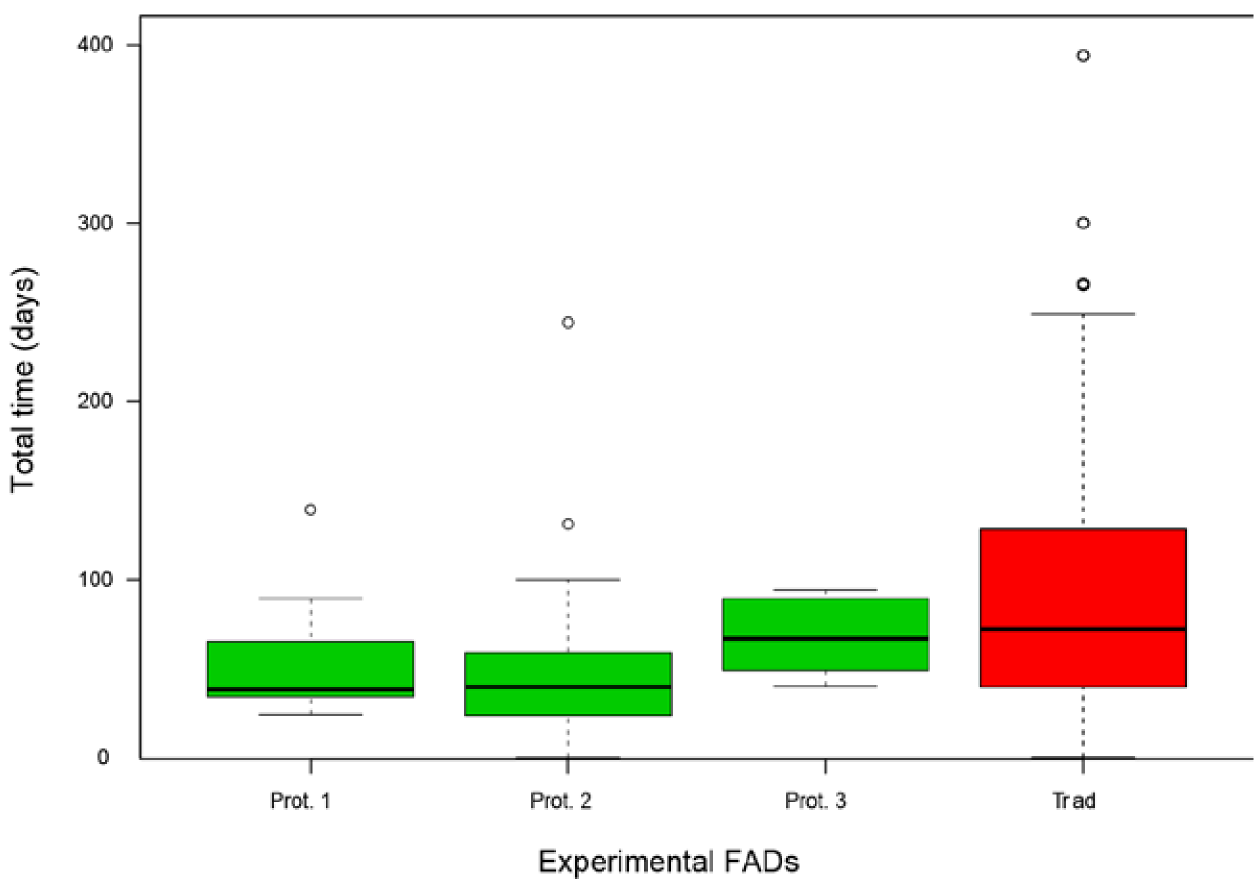


FIGURE 11. Distribution of total soak time of experimental FADs between first deployment and retrieval or last encounter, based on observer data. Prot.: prototype. Trad: Paired control FAD.

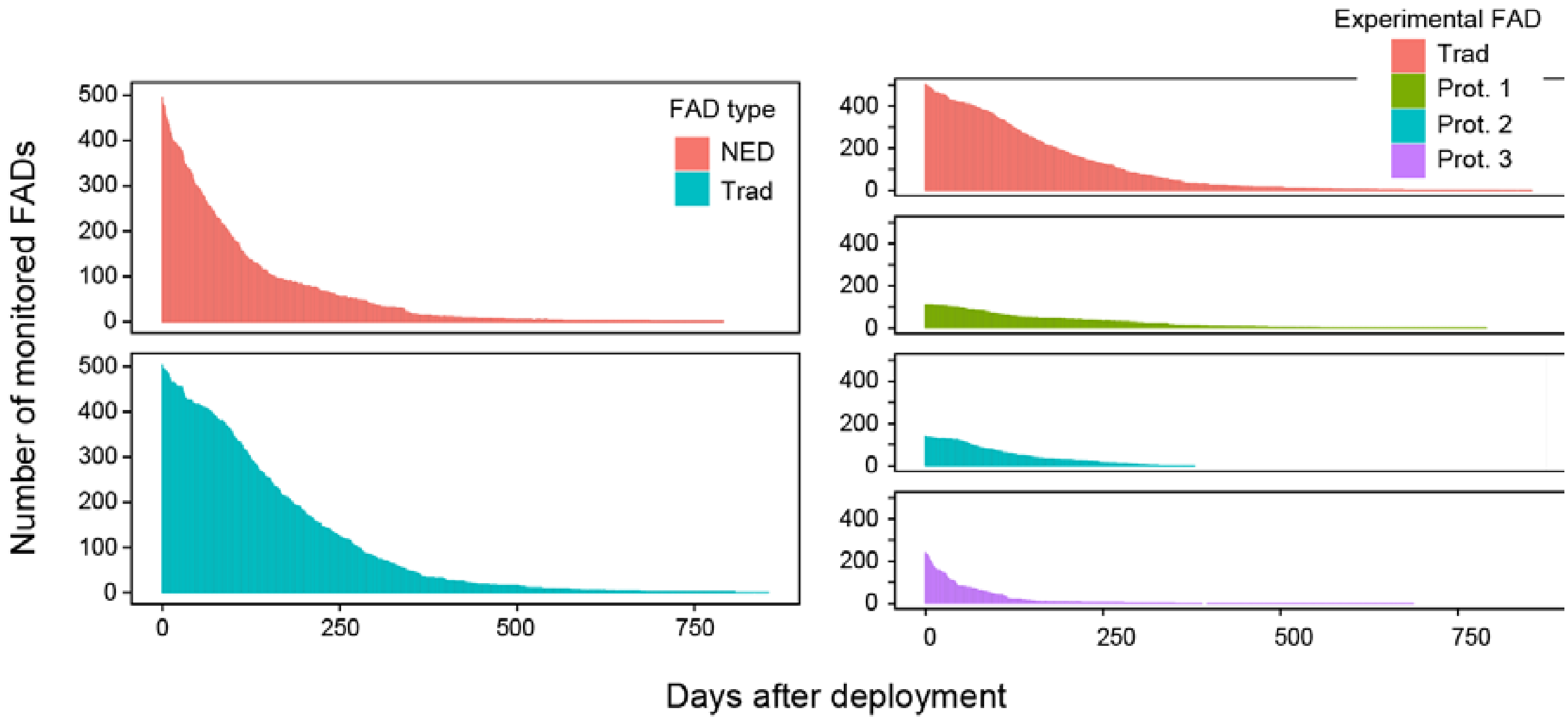


FIGURE 12. Monitored period, measured in terms of the number of active buoys by day after deployment for NED and traditional FADs (A), as well as for the NED prototypes (B). Trad: Paired control FADs. Prot.: Prototype.

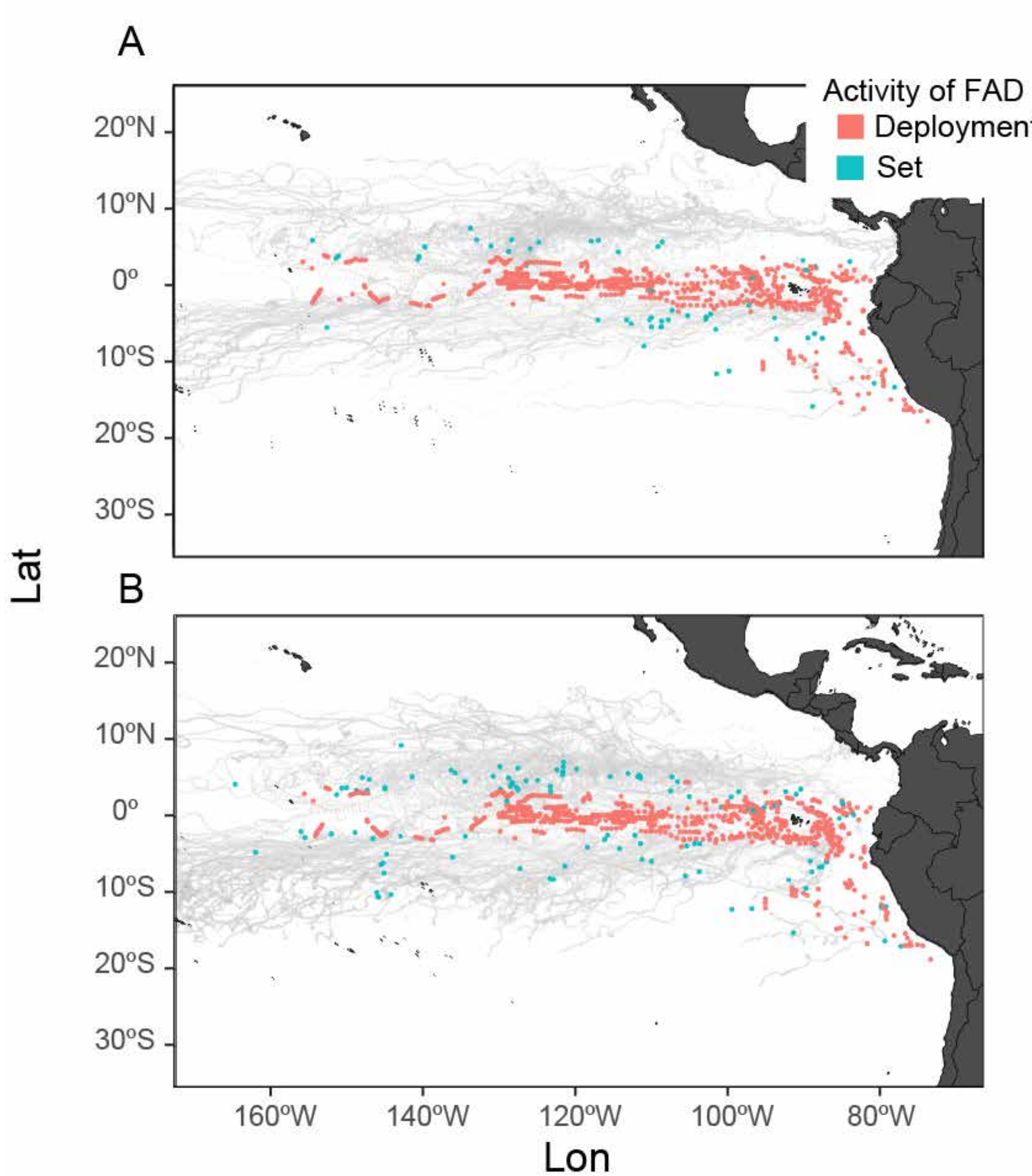


FIGURE 13. Drifting trajectories of NEDs (A) and traditional FADs (B) from deployments to sets or last satellite buoy communication. Trad: Paired control FADs.

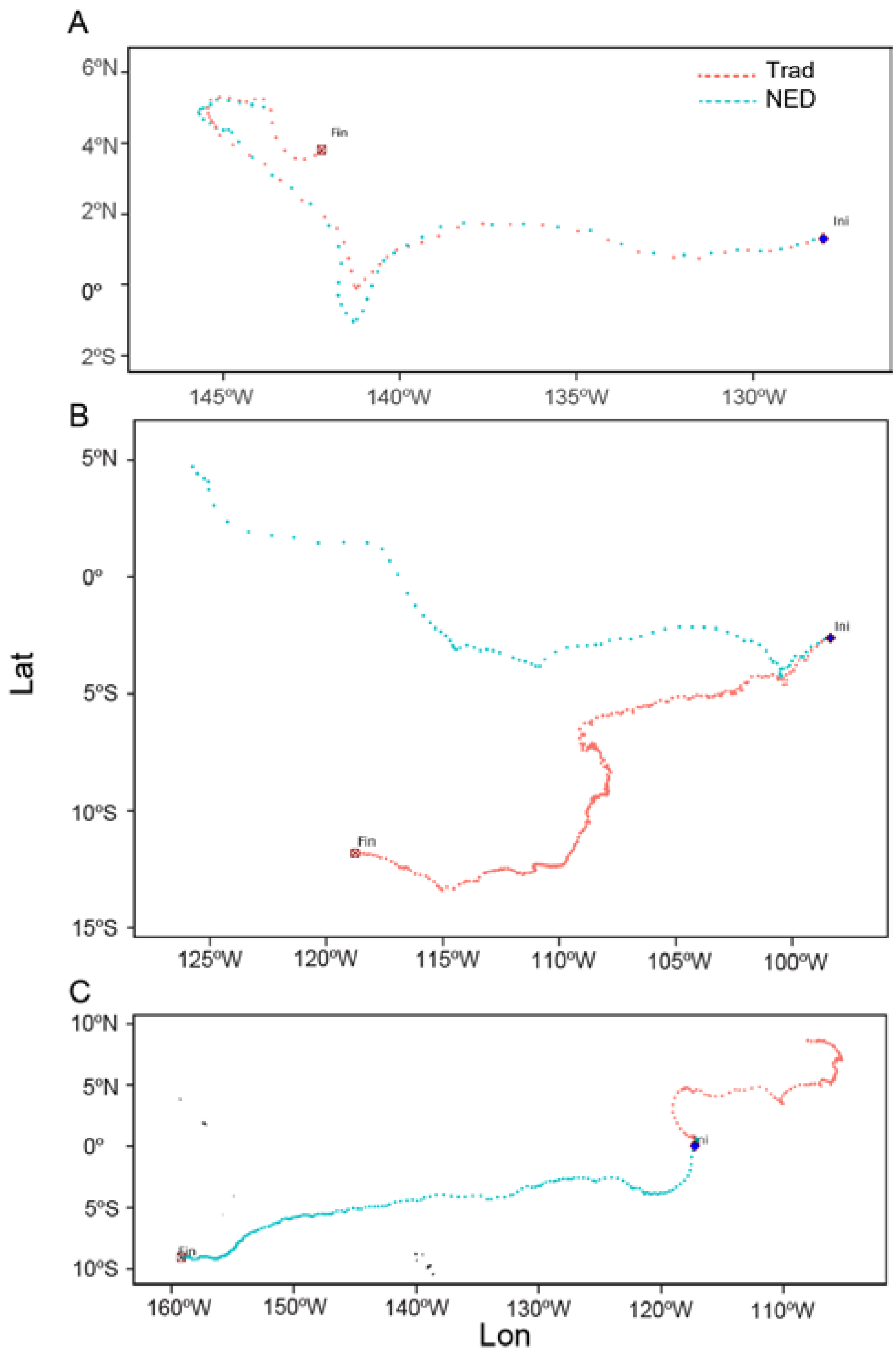


FIGURE 14. Patterns observed in the drifting trajectories of pairs of experimental FADs: similar (A), partially similar (B) and divergent (C). Red dots: Paired control FAD trajectories. Light blue dots: NED trajectories

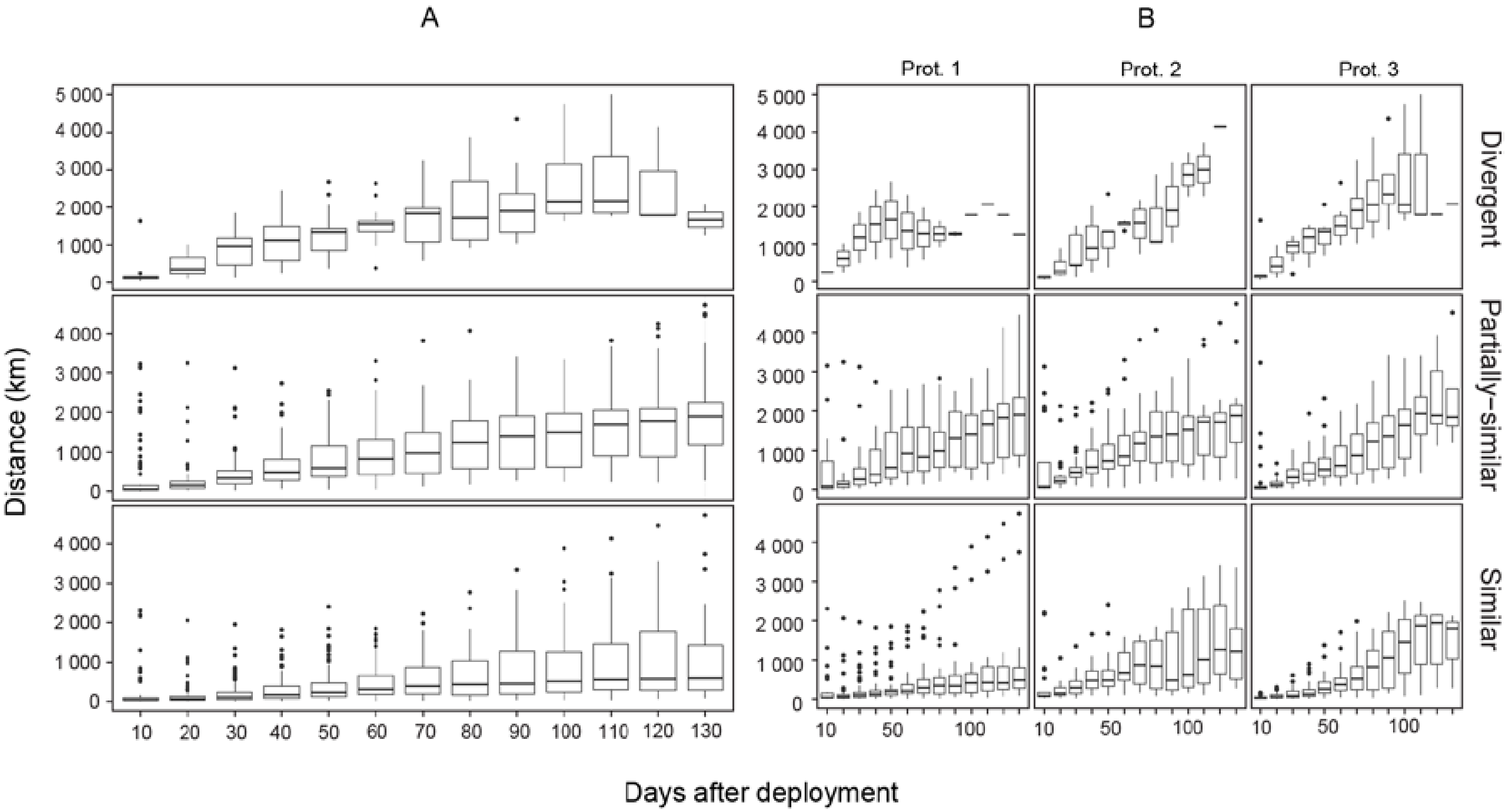


Figure 15. Observed distance difference among pairs of experimental FADs by similar, partially similar and divergent drifting patterns between: NEDs combined (A) and by NED prototype (B). Prot.: Prototype. Days after deployment were limited to 4 months for plotting.

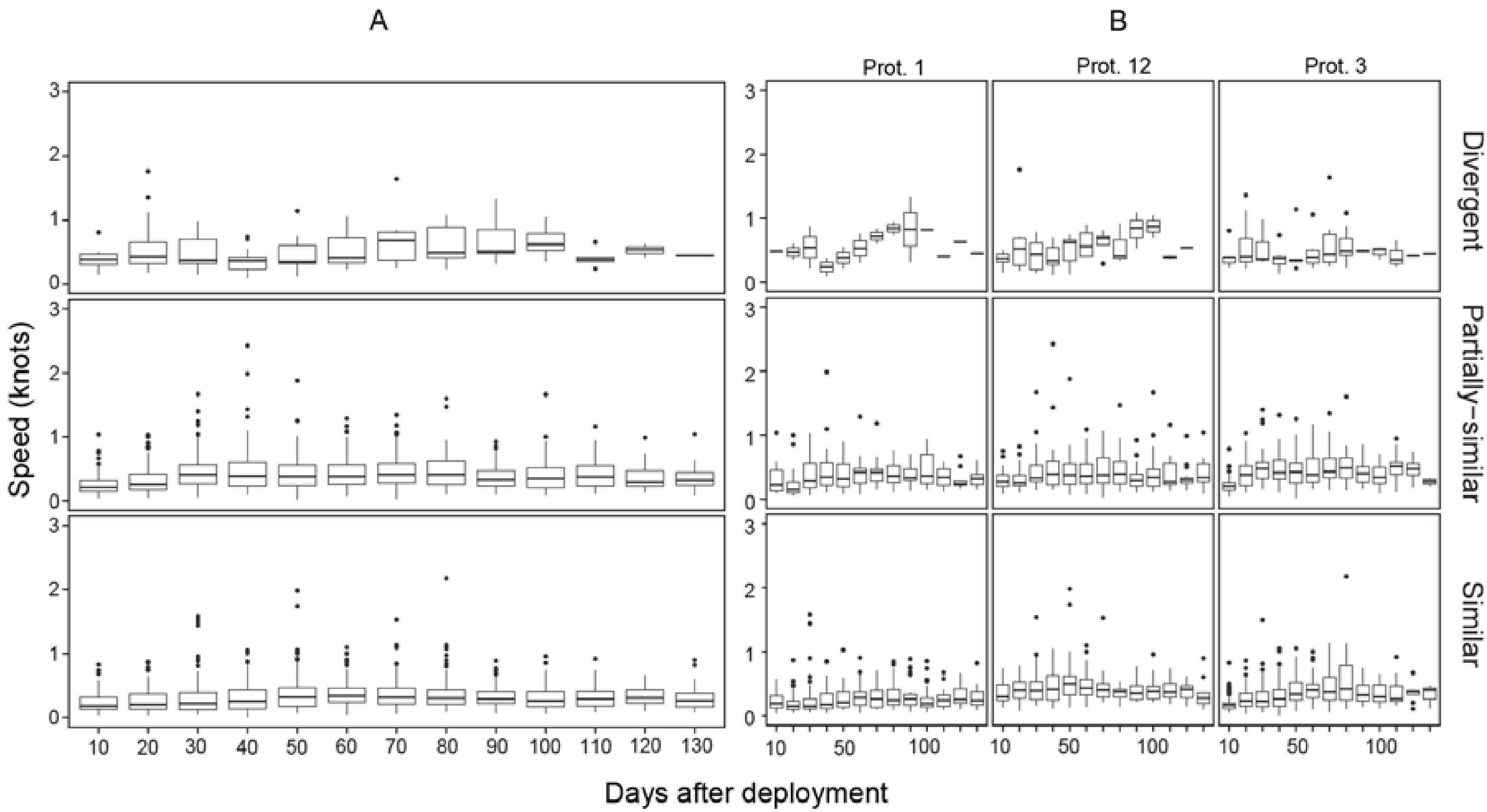


Figure 16. Observed mean speed difference among pairs of experimental FADs by similar, partially similar and divergent drifting patterns between: NEDs combined (A) and by NED prototype (B). Prot.: Prototype. Days after deployment were limited to 4 months for plotting.

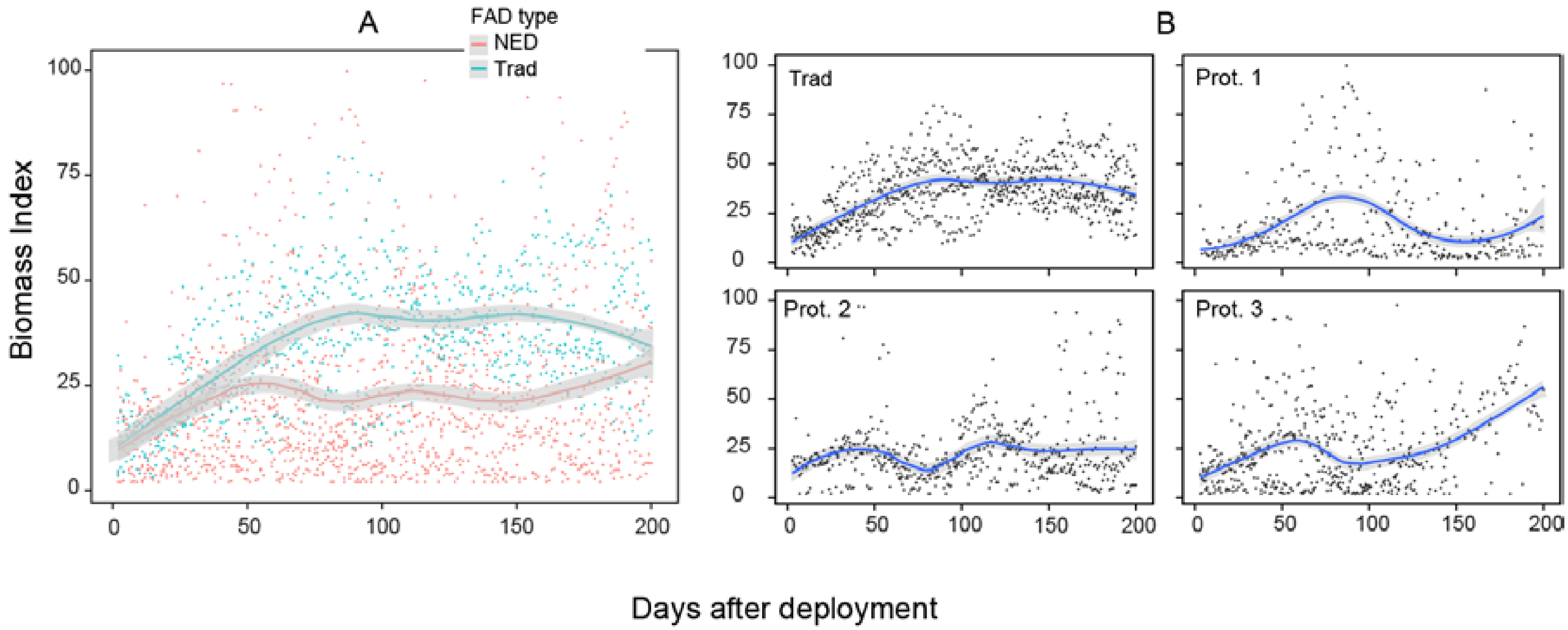


Figure 17. Tuna biomass index (y-axis) by day after deployment (x-axis) by experimental FADs (A), and by traditional FADs and NED prototypes (B). Trad: Paired control FADs. Prot.: Prototype. Days after deployment were limited to 200 days.

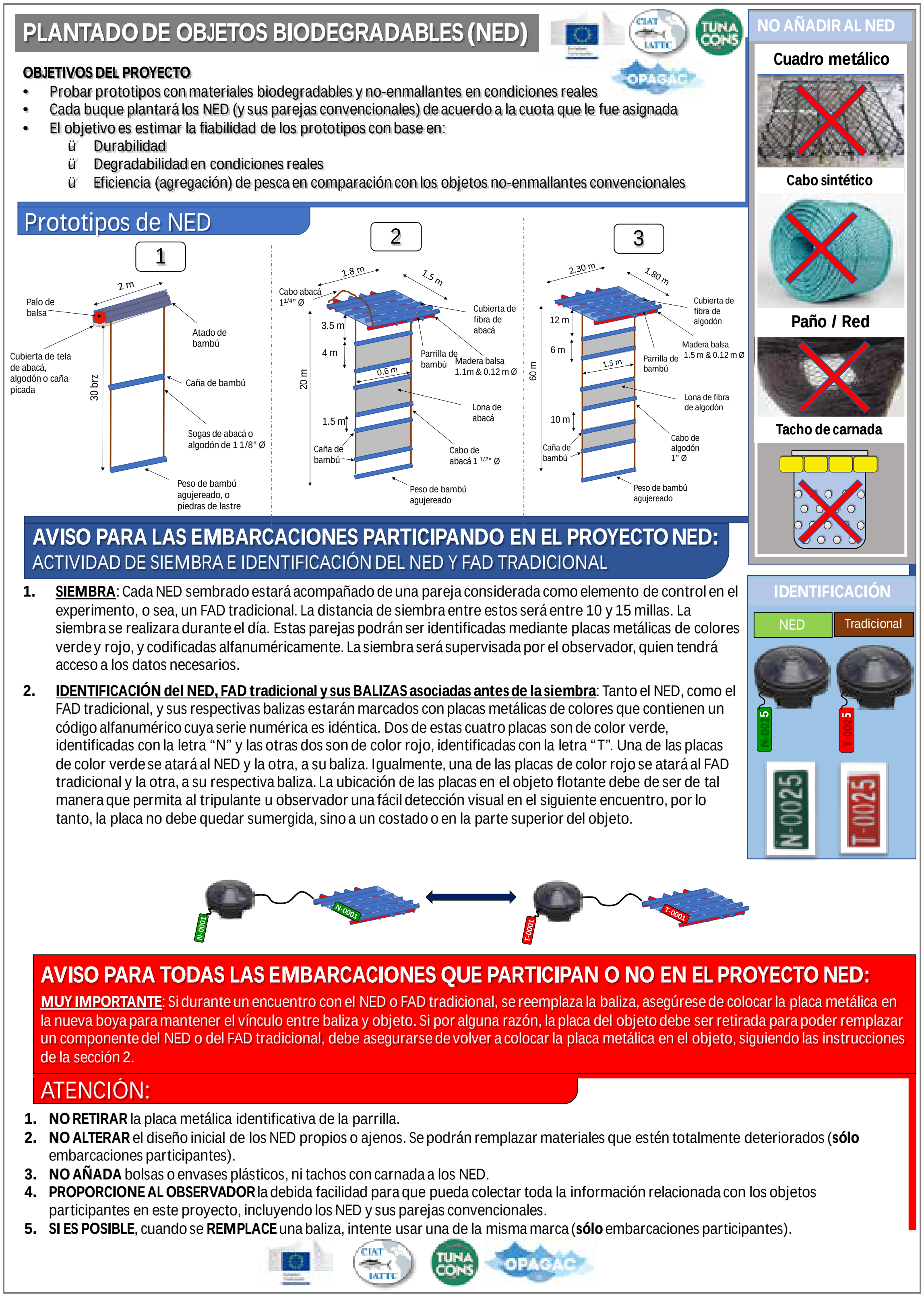


FIGURE 18. Poster for project information dissemination.

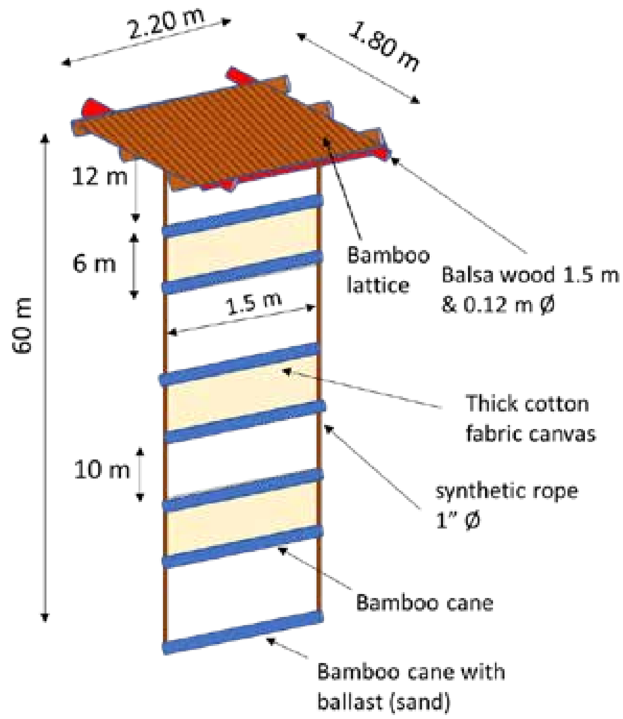


FIGURE 19 Additions and modifications to improve durability of Prototype 3. Note that synthetic rope will only be used in the last batch of deployments (still pending). Deployments of 3rd quarter of 2021 consisted of NEDs with a biodegradable cotton-based rope that was successfully used and implemented in other ocean regions by some vessels of the same fleet.

TABLE 1. Summary of NED and paired control FAD interactions.

	Deployments	Visits	Sets	Catch (mt)	Catch per set (mt)
NED – Prototype 1	114	5	8	488	61
NED – Prototype 2	395	74	46	1342	29.2
NED – Prototype 3	271	7	3	88	29.3
Total NEDs	780	86	57	1918	33.6
Paired control FAD	764	112	145	4599	31.7

TABLE 2. Number of crew interactions on each experimental FAD.

Operativity	Experimental FADs	Trad	NED
Deployment	1268	601	667
Deployment-Set	52	39	13
Deployment-Visit-Retrieval	46	21	25
Deployment-Visit	42	25	17
Deployment-Set-Retrieval	17	14	3
Deployment-Visit-Retrieval-Redeployment	17	8	9
Unknown	16	12	4
Deployment-Set-Set	13	11	2
Deployment-Visit-Set	8	4	4
Deployment-Visit-Visit	5	2	3
Deployment-Visit-Set-Set	4	2	2
Deployment-Visit-Set-Retrieval	4	1	3
Deployment-Set-Set-Set	3	2	1
Deployment-Set-Set-Visit	3	2	1
Deployment-Visit-Visit-Retrieval	3	3	0
Deployment-Set-Set-Retrieval	2	2	0
Deployment-Set-Visit	2	1	1
Deployment-Visit-Set-Visit	2	0	2
Deployment-Set-Set-Visit-Visit-Set	1	1	0
Deployment-Set-Set-Visit-Visit-Set-Set	1	0	1
Deployment-Set-Set-Visit-Visit-Visit-Set	1	0	1
Deployment-Set-Retrieval-Redeployment	1	0	1
Deployment-Set-Retrieval-Redeployment-Set	1	0	1
Deployment-Set-Retrieval-Redeployment-Set-Retrieval	1	1	0
Deployment-Set-Visit-Set	1	1	0
Deployment-Set-Visit-Set-Set-Set-Set-Retrieval	1	1	0
Deployment-Set-Visit-Retrieval	1	1	0
Deployment-Set-Visit-Visit-Set	1	1	0
Deployment-Visit	1	0	1
Deployment-Visit-Set-Set-Set	1	0	1
Deployment-Visit-Set-Retrieval-Redeployment	1	1	0
Deployment-Visit-Set-Visit-Set	1	0	1
Deployment-Visit-Set-Visit-Set-Retrieval	1	1	0
Deployment-Visit-Retrieval-Redeployment	1	0	1
Deployment-Visit-Retrieval-Redeployment-Visit	1	0	1
Deployment-Visit-Visit-Set	1	1	0
Deployment-Visit-Visit-Set-Set-Set-Set-Set-Visit	1	1	0
Deployment-Visit-Visit-Set-Set-Set-Retrieval	1	1	0
Deployment-Visit-Visit-Set-Retrieval	1	1	0
Deployment-Visit-Visit-Set-Visit-Set-Visit	1	1	0
Deployment-Visit-Visit-Visit	1	1	0
Deployment-Visit	1	0	1
Total	**1531**	**764**	**767**

TABLE 3. NEDs (N) and paired control FADs (T) that were deployed and set upon; Lon: longitude; Lat: latitude; mt: metric tons; Nm: nautical miles.

Tag Id	Deployment date	Set date	Deployment Lon	Deployment Lat	Set Lon	Set Lat	Tuna catch (mt)	Prototype	Set time apart (days)	Set distance apart (Nm)
N 1	9/18/2019	10/30/2019	-88	2	-88.13	2.28	5	2	5.0	352.7
T 1		11/4/2019	-87.85	1.93	-93.93	1.37	15			
N 2	12/3/2019	1/19/2020	-84.35	-9.22	-87.22	-7.35	50	2	90.2	86.6
T 2		4/18/2020	-84.2	-9.22	-86.97	-5.93	1			
N 3	1/10/2020	1/23/2020	-79.28	-11.87	-80.4	-13.32	0	2	21.0	190.6
T 3		2/13/2020	-79.45	-11.87	-79.28	-16.3	10			
N 4	6/12/2020	6/23/2020	-86.8	-5.38	-88.18	-6.7	55	2	18.0	76.3
T 4		7/11/2020	-86.92	-5.58	-89.08	-5.8	0			
N 5	3/13/2020	4/22/2020	-125.38	2.82	-128.18	5.82	35	2	86.9	393.9
T 5		7/18/2020	-125.63	2.83	-134.65	4.62	20			
N 6	8/1/2020	10/13/2020	-88.05	-2.02	-108.42	-5.83	207	2	9.0	166.8
T 6		10/22/2020	-88.03	-2.27	-111.2	-5.6	0			
N 7	5/13/2021	6/15/2021	-152.85	3.77	-151.27	3.32	15	1	2.0	30.7
T 7		6/17/2021	-152.93	3.8	-151.53	2.88	20			
N 8	11/13/2021	2/15/2022	-113.17	0.07	-139.62	4.83	12	3	88.0	1068.3
T 8		5/14/2022	-113.02	0.03	-121.8	5.88	15			

TABLE 4. Comparisons between NEDs, and their associated tuna catch, and FADs or paired control FADs that were closely related in time and space. CPS: catch per set.

Group	Prototype	NED sets	FAD sets	Total sets	NED catch	FAD catch	Total catch	NED CPS	FAD CPS	CPS NED FADs rate	Year
1	2	1	5	6	5	8	13.0	5	1.6	3.1	2019
2	2	1	32	33	15	1239	1254	15.0	38.7	0.4	2019
3	2	1	8	9	19	353	372	19	44.1	0.4	2019
4	3	1	5	6	61	263	324	61	52.6	1.2	2019
5	1	2	6	8	1308	330	1638	654	55	11.9	2019
6	1	2	5	7	327	300	627	163.5	60	2.7	2020
7	2	2	6	8	43	619	662	21.5	103.2	0.2	2020
8	2	2	14	16	43	617	660	21.5	44.1	0.5	2020
9	2	1	5	6	70	296	366	70	59.2	1.2	2020
10	2	2	42	44	260	763.3	1023.3	130	18.2	7.2	2020
11	2	2	43	45	65	780.3	845.3	32.5	18.1	1.8	2020
12	2	1	8	9	2	43	45	2	5.4	0.4	2020
13	2	1	4	5	18	143	161	18	35.75	0.5	2020
14	2	1	8	9	14	288.01	302	14	36	0.4	2020
15	2	2	7	9	180	302	482	90	43.1	2.1	2020
16	2	2	4	6	45	62	107	22.5	15.5	1.5	2020
17	2	4	10	14	1884	642	2526	471	64.2	7.3	2020
18	2	3	11	14	212	550	762	70.7	50	1.4	2020
19	2	1	5	6	2	187	189	2	37.4	0.1	2020
20	2	1	5	6	14	223	237	14	44.6	0.3	2020
21	2	4	7	11	232	396	628	58	56.6	1	2020
22	2	1	5	6	15	193	208	15	38.6	0.4	2020
23	1	1	4	5	30	127	157	30	31.8	0.9	2021
24	2	1	6	7	5	88	93	5	14.7	0.3	2021
25	2	1	18	19	25	741	766	25	41.2	0.6	2021

TABLE 5. Comparisons between paired control FADs, and their associated tuna catch, and FADs or paired control FADs that were closely related in time and space. CPS: catch per set. Trad: Paired control FADs.

Group	Trad sets	FAD sets	Total sets	Trad catch	FAD catch	Total catch	Trad CPS	FAD CPS	Trad /FAD CPS rate	Year
1	1	4	5	10	55	65	10	13.8	0.7	2019
2	1	29	30	15	1194	1209	15	41.2	0.4	2019
3	1	21	22	7	613.3	620.3	7	29.2	0.2	2019
4	1	13	14	10	446	456	10	34.3	0.3	2019
5	1	4	5	30	145	175	30	36.3	0.8	2019
6	1	8	9	35	255	290	35	31.9	1.1	2020
7	1	5	6	25	162.0	187.0	25	32.4	0.8	2020
8	2	5	7	524	66	590	262	13.2	19.8	2020
9	2	4	6	131	34	165	65.5	8.5	7.7	2020
10	2	10	12	76	359.5	435.5	38	36.0	1.1	2020
11	2	11	13	19	192.6	211.6	9.5	17.5	0.5	2020
12	1	4	5	5	66	71	5	16.5	0.3	2020
13	1	8	9	10	269.8	279.8	10	33.7	0.3	2020
14	1	4	5	10.14	45.2	55	10.1	11.3	0.9	2020
15	1	6	7	105	29	134	105.0	4.9	21.5	2020
16	1	7	8	43	920.6	963.6	43	131.5	0.3	2020
17	1	5	6	140	320	460	140	64.0	2.2	2020
18	1	7	8	30	233.4	263.4	30.0	33.3	0.9	2020
19	1	6	7	110	247	357	110	41.2	2.7	2020
20	1	4	5	25	128	153	25	32.0	0.8	2020
21	2	6	8	135	171.0	306.0	67.5	28.5	2.4	2020
22	2	4	6	172	534	706	86.0	133.5	0.6	2020
23	2	4	6	43	228	271	21.5	57.0	0.4	2020
24	1	12	13	4	262	266	4.0	21.8	0.2	2020
25	1	16	17	28	500	528	28.0	31.3	0.9	2020
26	1	13	14	3	196	199	3	15.1	0.2	2021
27	1	5	6	10	215	225	10	43.0	0.2	2021
28	2	10	12	84	733.0	817.0	42	73.3	0.6	2021
29	2	9	11	136	544	680	68.0	60.4	1.1	2021
30	2	22	24	84	1101	1185	42.0	50.0	0.8	2021
31	1	12	13	20.2	213.1	233.3	20.2	17.8	17.9	2021
32	2	8	10	136	573	709	68.0	71.6	0.9	2021
33	1	4	5	18	50.0	68.0	18.0	12.5	1.4	2021
34	2	10	12	260	211	471	130.0	21.1	6.2	2021
35	2	12	14	65	331	396	32.5	27.6	1.2	2021
36	1	6	7	35	156	191	35.0	26.0	1.3	2021
37	1	9	10	34	396	430	34.0	44.0	0.8	2021
38	1	4	5	40	88	128	40.0	22.0	25.6	2022
39	1	12	13	12	215	227	12.0	17.9	17.5	2022

TABLE 6. Mean of the NED condition based on soak time. N: number of prototypes in each category of soak time. 0: Not observed; 1: Excellent; 2: Very good; 3: Good; 4: Regular; 5: Poor, and 6: Very Poor. NA: A NED that is not composed of a specific material (e.g., the submerged canvas of prototype 1), or the NED or some of the components were lost and only the satellite buoy was found (e.g., '>90' soak time of prototype 3).

			Floating component				Submerged component				
Soak time (days)	Prototype	N	Bamboo	Canvas	Balsa	Tightening rope	Canvas	Main rope	Tightening rope	Bamboo	Bamboo (ballast)
1-30	1	5	1.8	1.8	1.4	1.4	NA	1.8	1.7	1.3	1.8
31-60	1	4	1.5	1.8	1.2	1.8	NA	2.5	1.5	1.3	1.5
61-90	1	3	2.9	3.8	2.1	2.2	NA	3.5	2.5	1	2.9
>90	1	1	3	3	2	1	NA	3	3	NA	3
1-30	2	64	1.6	1.9	1.6	1.8	1.8	1.9	1.9	1.6	1.5
31-60	2	35	1.9	2.2	2	2.1	2.2	2.3	2.2	2.1	2.1
61-90	2	12	2.2	3.4	2.4	2.6	3.4	3.6	3.3	3.2	3.4
>90	2	2	4.5	6	4.5	5	6	6	6	6	6
1-30	3	2	4	4.5	1.5	4.2	3	2.8	3	3	3
31-60	3	4	2.2	5.6	2.8	2.9	5.2	4.4	5.2	5.2	5.2
61-90	3	2	3	NA	1	3	3	4.5	3	3	3
>90	3	2	1	NA	NA	1	1	1	1	1	NA

TABLE 7. Total soak time of experimental FADs between first deployment and last removal or last encounter form the observer database. N: number of NEDs or FADs; Min: minimum; Max: maximum; Q: quantile.

Experimental FAD	N	Min Soak time (days)	Max soak time (days)	Average (days)	Q (.25)	Q (.5) (median)	Q (.75)
NED - Prototype 1	13	24	139	58	34	38	65
NED - Prototype 2	113	1	244	44	24	40	58
NED - Prototype 3	10	40	94	68	52	67	87
Paired control FAD	229	1	425	91	40	72	128

TABLE 8. General lifespan information on the monitored period of the experimental FADs.

Experimental FAD	N	Number of records	Life-span (min)	Life-span (mean)	Life-span (max)
NED - Prototype 1	110	2802	0	192.6	790
NED - Prototype 2	143	1459	0	123.8	379
NED - Prototype 3	241	171	0	56.7	686
Total NEDs	494	1130	0	106.4	790
Paired control FAD	503	1855	0	176.2	854

TABLE 9. General information of drifting speeds of the experimental FADs.

Experimental FAD	N	Number of records	Speed (min)	Speed (mean)	Speed (max)
NED - Prototype 1	110	2802	0	0.72	4
NED - Prototype 2	143	1459	0	0.80	4
NED - Prototype 3	241	171	0	1.02	4
Total NEDs	494	1130	0	0.89	4
Paired control FAD	503	1855	0	0.71	4

TABLE 10. Acoustic data from echo-sounder buoys, by company, included in the analysis.

Buoy company	NED - Prototype 1	NED - Prototype 2	NED - Prototype 3	Total NEDs	Paired control FAD
Marine Instruments	-	124	189	313	291
Satlink	106	4	65	176	158