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LIFESPAN DYNAMICS OF BIODEGRADABLE AND CONVENTIONAL FISH-AGGREGATING DEVICES IN THE EASTERN PACIFIC OCEAN

Dan Ovando, Marlon Román, Dan Fuller, Cleridy Lennert-Cody and Jon Lopez

This document is produced in response to recommendation 1.8 of the 8th FADWG meeting, "*The scientific staff study the working lifespan of conventional and biodegradable FADs to evaluate the real needs of the fleet and the possible effects of the implementation of biodegradable FADs in the fishing operation*" (Meeting WGFAD-08 Report).

CONTENTS

SUMMARY

In response to Resolution C-23-04 and recommendation 1.8 of the FAD working group (FAD-WG) in 2024, this report presents an analysis conducted by the IATTC scientific staff on Fish-Aggregating Device (FAD) lifespan dynamics in the eastern Pacific Ocean (EPO), with a focus on differences between conventional (con-FADs) and biodegradable (bio-FADs). This analysis uses a FAD lifespan database created by the staff based on purse-seine observer records of FAD activities and interactions. For the purposes of this report, "lifespan" refers to the observed events between the deployment of a FAD at sea in an environment without a known fish aggregation or fishing activity (a deployment in a virgin environment or virgin deployment) and the eventual recovery of that FAD, or the last observed record of that FAD. Based on this database, we present a range of exploratory analyses, combined with statistical models to estimate the marginal effect of bio-FAD construction on FAD attributes, including catch of tropical tunas.

Results show that among FADs deployed before 2024, over 70% of deployed FADs tracked in our database were never observed again after deployment. Collectively, 22% of all FADs were listed as recovered, 13% when including only FADs deployed before 2024. 16% of FADs deployed before 2024 were set on at least once. FADs that were set on were generally set on by two or fewer individual vessels and set on between 1 to 5 times. Bio-FADs were on average set on 26 days sooner than con-FADs, based on the raw data and not controlling for any confounding difference between these two groups. Controlling for these differences, bio-FADs were set on average roughly 10% sooner than con-FADs. 80% of FADs had observed lifespans (i.e., fishing interactions and visits, or recoveries occurring between initial deployment and recovery or loss from the database) of 50 days or less. Less than 10% of bio-FADs had lifespans greater than or equal to 50 days, whereas roughly 14% of con-FADs had lifespans greater than or equal to 50 days.

Raw catch per set and total catch per lifespan were lower for bio-FADs than con-FADs for all tropical tuna species. However, raw differences between bio-FADs and con-FADs can be misleading as systemic differences in the deployment and fishing practices between these two groups exist. Bio-FADs were generally deployed by vessels with lower capacity, and concentrated in specific areas and times that are not representative of the broader EPO fishing grounds. In addition, bio-FAD use has been increasing in recent years. Because all of these factors need to be accounted for in order to provide a more reliable estimate of marginal bio-FAD effects, we used spatio-temporal delta models to control for potentially confounding variables in an attempt to better isolate the marginal effect of bio-FAD construction and fishing strategies. The models estimated that, while bio-FADs have, on average, slightly lower lifespan lengths (i.e., soak times) and number of sets per deployment, these differences do not translate into a statistically significant difference in average total lifespan catch for any of the tropical tunas (95% confidence intervals of the estimated marginal bio-FAD effect are generally between +8% and -15%).

1. INTRODUCTION

The fish-aggregating device (FAD) fishery in the eastern Pacific Ocean (EPO) has steadily expanded since the early 1990s, largely due to the increased efficiency of capturing tropical tunas that aggregate beneath these devices (e.g., FAD-09-01). However, like many fishing methods, FADs can have unintended ecological impacts, such as, for example, contributing to marine debris, pollution, and stranding events in sensitive habitats. In an effort to mitigate these effects, the Inter-American Tropical Tuna Commission (IATTC) adopted Resolution C-23-04, which establishes a stepwise transition to fully biodegradable FADs (bio-FADs) by 2031.

However, transitioning to biodegradable FADs can also impact the fleet's fishing strategies and operations in the short and long-term. Based on Resolution C-23-04 and recommendation 1.8 of the FAD working group (FAD-WG), which requested that the "*The scientific staff study the working lifespan of conventional and biodegradable FADs to evaluate the real needs of the fleet and the possible effects of the* *implementation of biodegradable FADs in the fishing operation*", this document evaluates the fishing dynamics and characteristics FADs different types of FADs to better understand and anticipate the potential effects of the implementation of biodegradable FADs in the EPO. We describe spatio-temporal attributes of FAD fishing dynamics, (e.g., deployment, sets, catches, soak time) in the EPO, with associated comparison of these FAD attributes between conventional (hereafter termed as "con-FAD") and biodegradable FAD (hereafter termed as "bio-FADs").

2. METHODS

2.1. DATA

2.1.1. The IATTC Observers' Floating Object Database

The IATTC observer program began in 1979 per an IATTC agreement in 1977, during its 34th meeting (IATTC, 1980). At that time, data collection was primarily focused on fishing interactions with marine mammals populations, catches of target species, and operational aspects of the tuna purse-seine fishery (Duffy et al., 2022, Joseph, 1994).

In 1992, during a special meeting of the IATTC, held in La Jolla (La Jolla Agreement) it was required that large purse-seine vessels ('*Class-6 vessels*'; >363 metric tons [t]) operating in the EPO shall carry an observer during each fishing trip in 1993. It also indicated that at least 50% of the observers on the vessels of each country member shall be from the IATTC with identical data collection forms. By then, the observer coverage on large purse-seines had virtually reached 100% (Duffy et al., 2022, Joseph, 1994).

Although intended for Class-6 vessels only, Class 1-5 purse-seine vessels (< 363 t) have been occasionally sampled by IATTC and national program observers, enabling the incorporation of fishing activities carried by the small tuna purse-seine fleet into the IATTC observer database. The Class 1-5 vessels' observer sampling has increased in recent years, roughly covering 34% of the small vessels' trips (DAT-02-02). This occurs due to varying reasons, such as abiding by AIDCP requirements to allow fishing during closure periods, to monitor the vessel does not use sealed wells (Resolution C-12-08), or the voluntary participation in the observer program by the TUNACONS fleet – a consortium of Ecuadorian vessels (EB-02-01; DAT-02-01; DAT-02-02; Duffy et al., 2022).

In 1987, IATTC observer data collection expanded to include the first records of non-marine mammal bycatch, specifically related to natural and man-made floating objects (Duffy et al., 2022). For this purpose, national and IATTC observers (hereafter "observers") used the "Flotsam Information Record" (FIR). Initially, the primary information collected included the date and location of the sighting of a floating object and whether a set was made upon it, or in its vicinity. Where possible, observers also recorded each floating object's dimensions, the percentage of total epibiota covering the entire structure, provided upper and lateral view drawings, and general information on the type (i.e., natural, man-made or artificial), shape, material, and color of the object.

In 1997, additional data fields were added to the FIR, including the maximum depth of the floating object, and additional codes describing different types and shapes of the object to accommodate new FAD designs, among others. In 2005, major updates were made to the FIR, mainly to better understand the activities and dynamics associated with the expansion of the FAD fishery. As part of these improvements, observers began recording the origin of each floating object - e.g., whether it was deployed by the owner vessel, found adrift regardless of ownership. The observers also documented additional details about specific components and materials of the object, the type of FAD interaction by the vessel crew, the method and equipment used to locate the FAD, and the technical specifications of its location-transmission equipment. This data was collected both when the object was found and when it was subsequently left adrift after crew interaction. Additionally, floating objects were assigned a unique object number and a consecutive encounter number that facilitates tracking of each FAD across interactions within the fishing trip.

During the *3rd Meeting of the Ad Hoc Permanent Working Group on FADs*, the review of data gaps for Resolutions C-16-01 and C-17-02, as well as its potential improvements recommended by the staff were summarized in the Document FAD-03-INF-A. As a result, in April 2019, the FIR was updated again to incorporate multiple recording of the serial numbers of the satellite-linked echosounder buoys used by fishers to identify the FAD at deployment (as required by Resolution C-19-01) and remotely monitor and locate FADs, including echosounder buoy replacements on FADs. This information made possible the tracking of FADs in the water across fishing trips. Unlike the previous 2005 version, this form also allowed the collection of further details on floating and submerged FAD components (e.g., mesh size, the type of component and the materials categorized as synthetic or natural). Because this study aims to analyze the lifespan of FADs by type when deployed (see Sections 2.1.2 and 2.1.3), which requires at-sea tracking, data from 2019–2024 were used as this was the period for which these data were available.

2.1.2. FAD Tracking Process and Database

The FAD fishery in the EPO involves a range of activities and interactions on FADs, detailed in Figure 1 . However, not all these activities – e.g., construction or repairs on board or land, are observed or recorded by the observers (Figure 1). In earlier years, FADs were constructed onboard fishing vessels using leftover fishing gear (e.g., netting, chains, ropes). More recently, with regulations requiring non-entangling and biodegradable materials (Res. C-23-04), many FADs are constructed in dedicated land-based facilities.

As mentioned above, recommendation 1.8 of the FAD-WG requested the IATTC scientific staff to study the "lifespan" of bio-FADs and con-FADs. For the purpose of this report, we define the observed lifespan ("lifespan" from now on) as the observed series of events of a FAD at sea, from the deployment of a it in a "virgin" environment (an area without a known current aggregation of tunas or fishing activity) until the recovery of that FAD, or the last observation of that FAD by the previously described observer programs. We explain this concept in greater detail below.

The only consistent identification physically present on a FAD after deployment (as required by Resolution C-19-01 and C-23-05) is the satellite-linked buoy identification number. A FAD lifespan begins when it is deployed in the water with an associated satellite-linked buoy identification number under "virgin" conditions - that is, when it is deployed at sea in an area without a known current aggregation of tunas or fishing activity. For each FAD the vessel interacts with, observers collect a series of information inherent to the FAD, including the deployment location, origin, components, and various interactions types (e.g., fishing sets, visits, buoy replacements, in-water modifications, retrievals or recoveries). If during the course of operations, the satellite-linked buoy on a FAD is replaced, observers note this interaction and the new buoy ID, allowing the FAD to be tracked with a new buoy ID. Therefore, FADs can be tracked in our database until the FAD is "recovered", meaning it was removed from the water and not returned in the same location and time where it was encountered, or until the FAD is no longer detected by an observer. After recovery, some activities - such as whether the FAD was modified onboard or in-land, had a new satellite-linked buoy attached, or no longer used in the fishery are not documented by observers. If a new satellite-linked buoy is attached to a particular FAD during these unobserved events after recovery, no more activity records can be linked to that individual FAD and a new FAD ID is generated if this is deployed at-sea again in a virgin environment.

As a result, what is reported here is not the complete physical lifecycle of a FAD, from original construction to reaching non-operational status (the totality of Figure 1). Instead, this report tracks the observed operation lifespan of a FAD at-sea (the green cells of Figure 1). For this reason, the same physical FAD infrastructure can in theory be a part of multiple FAD lifespans, each with a separate FAD identification number (FAD ID). In this analysis, therefore, the same physical FAD deployed in a virgin environment, recovered, and the re-deployed at a later date in a new virgin environment, would receive a new FAD ID. In other words, recovery denotes the end of the lifespan for a given FAD ID, but some or all physical components of that FAD might be deployed again at a different place and time. At this time, it would receive a new FAD ID, so long as this new environment and time is not the same as the prior FAD ID's recovery to constitute as a new virgin deployment. The fate of unrecovered FADs cannot be known with the data utilized in this study; it may sink, break apart, be recovered by a vessel without an IATTC observer, stay at sea, or get stranded.

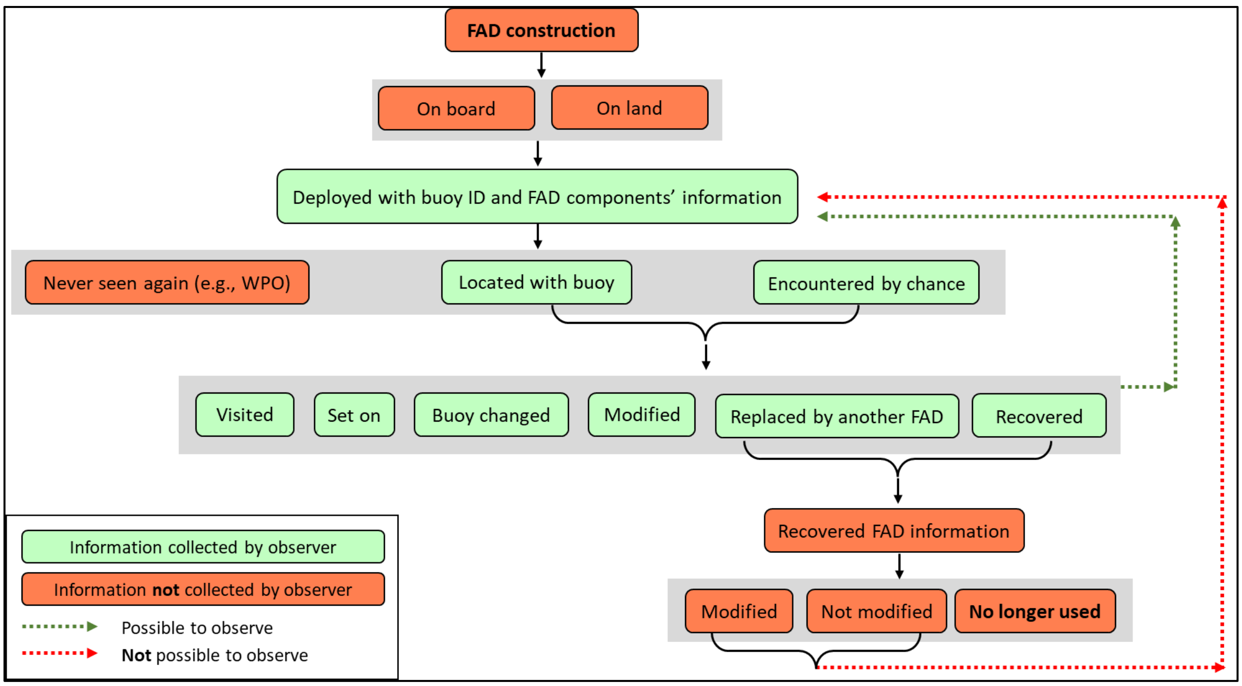

FIGURE 1. Activities and crew interactions that may occur over the complete lifecycle of a FAD.

Consider the following example. A FAD is deployed with a satellite-linked buoy attached having serial number 123 and the FAD is given an identification number X. At some point in the future, the FAD and buoy are found or recovered together, but the buoy is replaced with a new buoy (serial number 456) while FAD X stays in the water or is redeployed at roughly the same place and time. The observer can track this exchange in buoy IDs, and so, preserve the identity of FAD X in the database. FAD X is then set upon or visited at a later date and eventually listed as "recovered". This sequence of events would constitute the full observed lifespan of FAD X. However, if FAD X is recovered after being visited or set upon and taken back to port, remodeled, and then re-deployed on a subsequent trip with a new buoy (by the same or a different vessel) with some or all of its original components, it will be considered as a new deployment and assigned FAD identification number Y. It is not possible to interrogate the database to identify whether FAD X and FAD Y share some or all of the same components since no observer would be able to document the change in buoy identification numbers.

The specific FAD tracking algorithm and process works as follows. Each deployed FAD is initially identified using the satellite buoy's serial number (buoy ID), and assigned a unique FAD identification number, as described above. Subsequent interactions with that FAD at sea were tracked via its buoy ID (Figure 2).

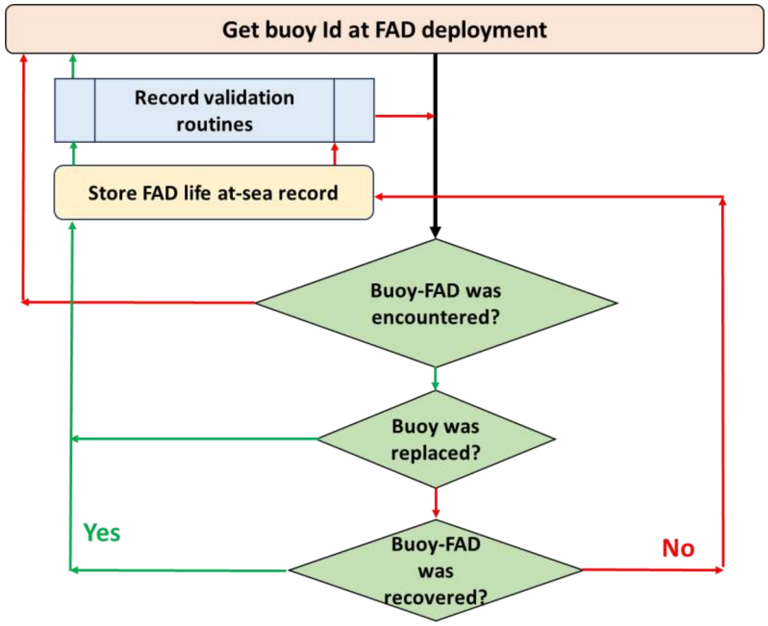

FIGURE 2. Algorithm used for tracking FADs at sea after deployments.

If a buoy was replaced during a FAD encounter and this process was documented by an observer, subsequent interactions with that FAD can be tracked using the buoy ID of the replacement buoy. All interactions related to a given FAD were assigned the same FAD ID. In cases where a new FAD deployment was recorded immediately following a non-recovery interaction, it was inferred that a FAD recovery or buoy replacement had occurred but was not documented in the OBJ database. In such instances, the ongoing FAD lifespan was terminated, and a new lifespan record was initiated for the newly deployed FAD with a corresponding new FAD ID number.

This process enabled an assessment of the quality of FAD interaction data and buoy ID collection by observers. It also identified several situations that could impact the reliability of FAD lifespan database results. These caveats were detected and flagged through validation routines, and associated records were removed from the analyses presented here.

Major caveats include:

1. *Unrecorded FAD deployment*. If a FAD deployment was not documented, subsequent interactions may be mistakenly attributed to original FAD ID (Figure 3).
2. *Unrecorded FAD recovery*. If a FAD is recovered but not recorded, and the buoy is later used in a new, unrecorded deployment—or if it is documented as replacing another buoy—, the lifespan of the original FAD may erroneously incorporate interactions from a different FAD (Figure 4).
3. *Unrecorded buoy replacement*. If a buoy replacement was not documented, subsequent interactions may be missing for that FAD ID.
4. *Missing or incorrect buoy ID recording*. There is no processing tool in place to correct missing or misrecorded buoy IDs when the interaction is not linked to another entry in the OBJ database (e.g., a single record FAD interaction for a trip). This may lead to caveat types 1 to 3.

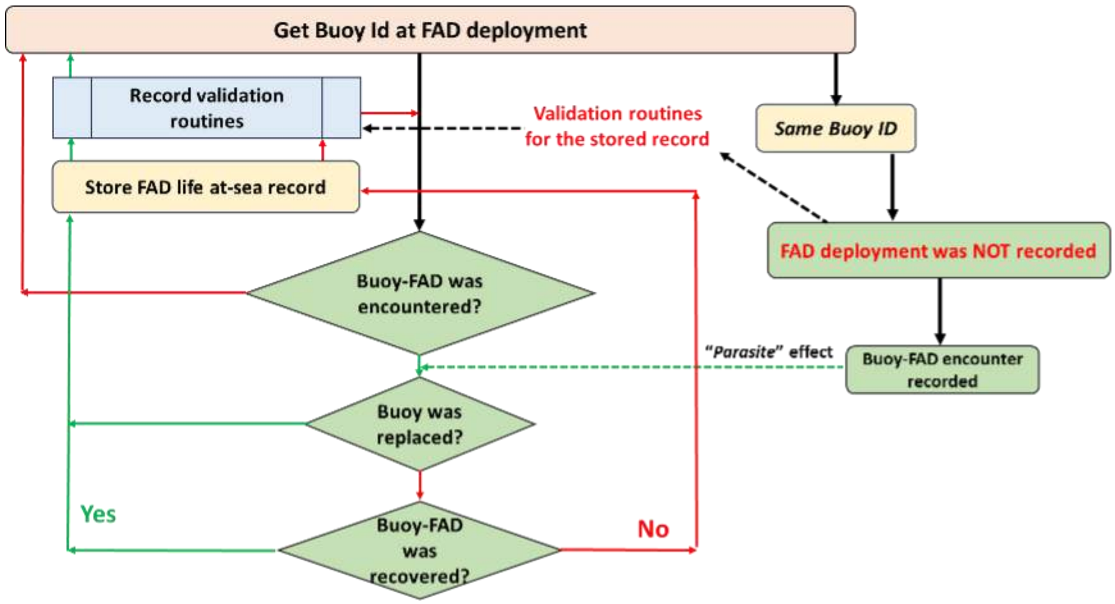

FIGURE 3. Caveat type 1: a FAD deployment occurred but it was not recorded.

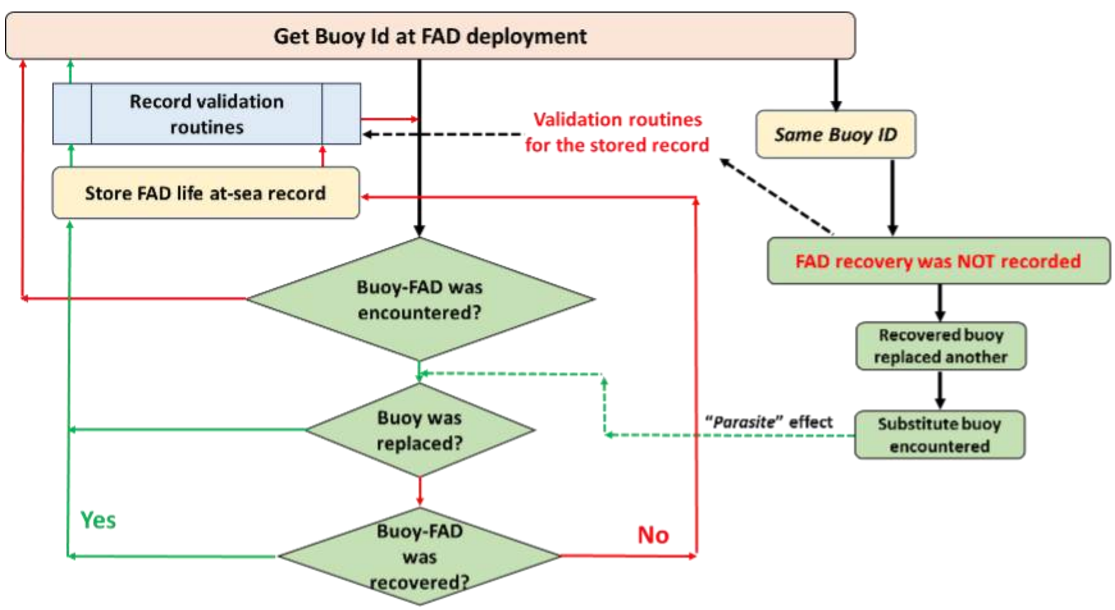

FIGURE 4. Caveat type 2: a FAD recovery occurred but it was not recorded.

Validation routines were established to identify and remove unreliable FAD interactions and IDs from the database, based on the caveats mentioned above. These routines helped detect, identify and flag:

1. *Mismatch in FAD origin*: A warning is triggered when the observer recorded the FAD origin as that "it came from the same vessel and same trip number", but the previous deployment record shows a different trip number. This helps identify cases related to the caveats 1-3 listed above.
2. *Unusual FAD speed*: A warning is generated if there are unusually high FAD speeds between consecutive activity records on the same FAD, suggesting that the FAD was on a vessel and thus, a potential FAD deployment or recovery was not recorded.

3. *Minimal Movement with Extended Soak Time between consecutive FAD interactions*: A warning is generated to detect erroneous sequences caused by extended drifting times within a small buffer zone, as FADs drift in space over time. This may also indicate an unrecorded FAD deployment or recovery.

These validation routines flagged these potential error cases and removed roughly 4% of the original number of FAD IDs in the database.

2.1.3. Biodegradable FAD Identification

Data for identifying biodegradable FADs (bio-FADs) was obtained from three sources:

1. The IATTC large-scale biodegradable FAD project, conducted during 2018-2022: European Union grant agreement under the EMFAF, project number 767592 "Testing Biodegradable Materials and Prototypes for Tropical Tuna FAD Fishery" (for more details, see Document FAD-06-02 and FAD-07-02).
2. The Tuna Conservation Group (TUNACONS), which provided, since 2021, data from the voluntary 20% Biodegradable FADs plan adopted by its associated fleets.
3. IATTC observers who completed, starting in 2022, a complementary FIR with information on biodegradable FADs. This form is the same as the one used for the IATTC large-scale biodegradable FAD project data collecting.

FADs not classified as biodegradable (bio-FADs) were assumed to be conventional FADs (con-FADs).

2.1.4. Data Filtering

Post-quality control filtering, this analysis used data from April 2019to December 2024. We removed any FADs from the database that showed anomalies in their data reporting per the validation routines described above. We also excluded natural FADs (logs and other naturally occurring floating objects, as ~98% of FADs in the EPO are man-made; FAD-09-01), and FADs that were reported to be set on within 7 days of initial deployment, as this is likely indicative of a non-virgin deployment. In total, filtering routines removed 7.8% of the FADs listed in the original database.

Since bio-FADs are not uniformly distributed throughout the fishing grounds, for scenarios where statistical models and comparisons are made between con-FADs and bio-FADs, we first filtered the data to only include sets within the convex hull formed by locations in which more than two interactions (deployments, sets, visits, or recoveries) with bio-FADs occurred (see red polygons in Figure 14). For analyses at the FAD level rather than set level, we only include FADs for which 100% of interactions occurred within the convex hull of the bio-FAD interaction grounds. This prevents the analysis from having to separate out the effects of bio-FADs from the effects of fishing in locations where bio-FAD interactions were not recorded.

The data used in this study end on December 2024. However, FADs deployed in the water prior to this date can be used beyond this date. To avoid truncation issues in our results, we restricted analysis of FAD lifespan length and total lifespan catch to FADs deployed before 2024, in order to allow analyzed FADs the opportunity to be in the water for up to a minimum of a year. For set-level analyses, we only included FADs deployed before October 2024, so that FADs have up to a minimum of three months of potential soak time available.

2.2. ANALYSES

2.2.1. Exploratory Analyses

We first conducted an exploratory analysis of the data to describe some basic features of the data used in this study. As part of this process, we classified FAD lifespans as having one of six fates:

1. *Deployed, unrecovered*: The FAD was deployed and was never observed again in the database;
2. *Fished, unrecovered*: The FAD was set on at least once after deployment but was never observed to be recovered;
3. *Fished, recovered*: The FAD was set on at least once after deployment and the lifespan ended with an observed recovery;
4. *Visited, unrecovered*: The FAD was visited at least once after deployment but was never recovered;
5. *Visited, recovered*: The FAD was visited multiple times after deployment and the lifespan ended with an observed recovery;
6. *Single visit, recovered*: The FAD was only visited once after deployment, and this single visit was a recovery event.

We also explored basic attributes of FAD lifespans like the location of FAD deployment and terminal events, recovery dynamics, set timing, number of vessel interactions, and raw tropical tuna catch per set and total tropical tuna catch over the course of the entire lifespan.

2.2.2. FAD Lifespan Length

We used two definitions for the deployment length of a FAD. The first, “lifespan length”, is simply the time (in days) between deployment and the last record for that FAD in the database. This includes all FADs used in this study, but is challenging to interpret due to the nature of FAD fishing and the observer program in the EPO. For example, FADs set on the edge of the fishing grounds have less of a chance of being seen again, due to their drifting outside of typical areas where fishing activity is observed. Thus, a FAD deployed the far west of the EPO may appear to have a short lifespan length, but it may still be an operating FAD in the other parts of the ocean where observers participating in the FAD observation program used here are absent.

To resolve this issue, we also performed analyses on a second measure of lifespan length, called “recovered lifespan length”. This is the same calculation as for “lifespan length” (final observed date minus initial date), but restricted only to FADs whose terminal fate or last recorded event was “recovered”. This removes potential issues with FADs being listed as unrecovered due to leaving the areas where IATTC observers are not present. However, note that only examining recovered FADs introduces alternative potential biases. For example, if fishers tend to prioritize the recovery of FADs that are in good condition when encountered, this could create a bias between the average lifespan length of all FADs and the average lifespan of recovered FADs.

2.2.3. FAD-based Tropical Tuna Catches

The FAD lifespan and the Daily Activity Records (DAR) database of tropical tuna were link and the skipjack (*Katsuwonus pelamis*, SKJ), yellowfin (*Thunnus albacares*, YFT) and bigeye (*Thunnus obesus*, BET) catches were extracted for each set. The catch data in the DAR database is provided by on-board observers and complemented with logbooks where not. These data are not a complete record of all the catch occurring in the region (omitting for example data from longline fisheries) but do provide good coverage of the purse-seine vessels. Using these data, we calculated the total lifespan catch and catch per set for each of the tropical tuna species, and for total tropical tuna, for each individual FAD ID.

2.2.4. Biodegradable FAD Effects

An increase in use of bio-FADs has been observed in the EPO in recent years. In order to assess the impacts of bio-FAD construction, the extent to which other factors besides construction type might affect FAD-related attributes such as lifespan length, catch per set, and total lifespan catch have to be considered. If bio-FADs are deployed randomly, then any differences between bio-FADs and con-FADs would likely be due to the attributes inherent of the bio-FADs relative to the con-FADs. However, if bio-FADs are deployed and used in systemically different ways than con-FADs, the impacts of these differences need to be controlled for in any accurate assessment of bio-FAD effects. In this case, the resulting estimated bio-FAD effects that control for these observed potential confounders would be “marginal FAD effects” or the effects attributable to differences in construction.

Given estimates of FAD-based catches, we sought to estimate the marginal effect of bio-FAD construction on various aspects of the activities of a FAD, including timing to first set, time between sets, lifespan length, number of sets per lifespan, mean catch per set per lifespan and mean total catch per lifespan. For each of these analyses, we attempt to control for potential factors that might affect these attributes other than whether or not a particular FAD is a bio-FAD. For that purpose, we generally control for underlying spatio-temporal fields for the variable in question (e.g., catch per set), as well as factors such as the capacity of the vessels deploying or setting on the FAD, as appropriate.

The maximum depth of the underwater part of the FAD are available on each observed FAD as well, which may influence tuna catches (Lennert-Cody et al., 2008; Lopez et al., 2019). However, we do not control for maximum depth, as the depth of the bio-FADs was established through consultation with the fishing fleet and barely changes in the database, indicating that the effect of FAD depth may be somewhat confounded with bio-FAD construction in this study. As such, bio-FAD-related results assume the current FAD depths typically used in bio-FAD construction are maintained.

The effects of bio-FAD construction on total lifespan catch (i.e., lifetime catch - the amount of tuna caught on a particular FAD over the course of a lifespan) is a function of the number of sets on that FAD. However, in calculating the marginal effect of bio-FAD construction on lifetime catch per FAD, this is not conditioned on the number of sets. We made this choice in case the number of sets made on a FAD is in some way endogenous to its status as a bio-FAD. FADs are equipped with satellite-linked echosounder buoys that report information on the size of the aggregation under the FAD. If bio-FADs have systemically higher or lower tuna biomass, and that difference can be detected by the satellite-linked buoy’s echosounders, it is conceivable that the effect of the bio-FAD on tuna biomass might cause fishers to set, more or less, on them. Therefore, controlling for the number of sets might mask part of the effect of the bio-FAD itself. To better understand the implications of this assumption, we also ran a model estimating the effect of bio-FAD construction on catch per set as a compliment to the total catch analysis that removes possible effects of construction on the number of sets made.

The FAD catch data have two general issues that need to be accounted for in modeling efforts intended to separate out the effects of bio-FAD construction. The first is the large number of zeros. Most FADs are never fished and so have zero total lifespan or lifetime catch. For those that are fished, catches for individual tuna species are often zero (e.g., only skipjack were caught). These zeros need to be properly accounted for while estimating average lifespan catch and average catch per species per set. The second is that, due to the nature of the fishery and the target species, the data have clear spatio-temporal correlations that need to be accounted for in order to properly estimate and interpret uncertainty around estimates; treating every FAD observation as independent and identically distributed will artificially inflate sample sizes and generally underestimate uncertainty.

To resolve both of these issues we used sdmTMB spatial-temporal models with a delta-gamma link function (Anderson et al. 2024). All models were established in R (R Core Team, 2024). This delta-gamma model is comprised of a Binomial regression fit to the presence or absence of catch at a given FAD, while the positive catches are fit to a Gamma distribution. For the underlying spatial mesh of the spatio-temporal model we enabled anisotropy, which allows the degree of spatial correlations to vary along a direction, and specified a minimum allowed triangle edge "length" of 2.5 degrees, after testing a range of potential grid sizes (smaller values indicate a higher resolution spatial field). The spatio-temporal model included spatially correlated latent effects each year that follow a random-walk. We note that the use of degrees rather than length for the underlying mesh is not strictly correct, but since the EPO fishing grounds cross multiple Universal Transverse Mercator (UTM) zones a simple conversion from latitude and longitude to eastings and westings is not possible, and therefore, degrees were used. Given that this study is not interested in the values of the underlying spatiotemporal fields *per-se* (which would require correctly calculating the surface area of each polygon of the spatial field), we argue that this choice has meaningful impacts. See Thorson (2017) for a discussion of these types of models and their use in fisheries systems.

We explored a range of alternative models, including combinations of a Poisson-Link Delta model (Thorson 2017), a Tweedie distribution, with and without anisotropy, a range of mesh sizes for the spatiotemporal field, and with spatial random effects alone or spatio-temporal random effects. The model configuration presented in this report was selected by AIC selection, noting that AIC selection may have flaws when applied to a mixed effects model (Anderson et al. 2024 and references therein), and visual examination of DHARMA residual diagnostics (Hartig, 2024). The choice that most improved model performance (in terms of AIC and residual analysis) was whether or not the model had spatio-temporal latent effects (as opposed to only spatial effects). All other choices (e.g., grid size, presence of anisotropy) had relatively small impacts.

Given that one of the goals of this study is to estimate the effect of bio-FADs on fishing attributes, the delta model configuration poses a complication, as rather than a general bio-FAD effect, separate bio-FAD effects for each component of the delta model are estimated. In order to estimate a net effect of bio-FADs on catch across both phases of the delta model, we simulated counterfactual experiments to estimate the average marginal effect of being a bio-FAD. For that purpose, the data was filtered to only include bio-FADs, and a copy of that data was created but artificially labeled all bio-FADs as con-FADs. We then generated predicted values from the delta model fit to the full bio-FAD array (taking into account the uncertainty and covariance across estimated parameters) for each of these two datasets, and calculated the average percent difference between the two predictions across all observations. This process estimates the marginal effect of the variable of interest (in this case bio-FAD status) conditional on the distribution of the other covariates in the database. We repeated this process 250 times to generate a simulated distribution of effect sizes, allowing us to calculate the mean and 95% confidence intervals for the estimated bio-FAD effect. The effects generated through this process can be interpreted as the percent change in the outcome of interest estimated to be caused by bio-FAD use.

2.2.5. Skipper Survey Results

The IATTC staff has participated in or organized a series of fisher workshops since 2020. These workshops are open dialogue spaces where, in addition to receive training on specific topics of interest, skippers are invited to participate in voluntary and anonymous surveys that cover multiple relevant themes for the staff and the Commission, including changes in the fishing strategy, bycatch release operations, and FADs, among others. In the most recent year, these questions were mostly focused around the fishing dynamics of bio-FADs – e.g., deployment strategies, reasons and areas for FAD loss, FAD duration, unrecovered FADs, soak time effect, improvements in FAD construction.

In the 2024-2025 skipper workshop cycle, a total of 208 fishers participated in the survey. The number of participants exceeded 400 during 2020-2023. Some of the results of the survey relevant to the questions investigated in this paper are presented below. Since this study heavily relies on FADs, only survey responses from participants that reported that their main fishing strategy is on FADs (>90% of participants in 2020-2023 and 65% of participants in 2024-2025) were considered.

3. RESULTS AND DISCUSSION

Post filtering, the database contained 159,877 unique FAD IDs, of which 154,318 are con-FADs and 5,559 bio-FADs.

FAD fate

The distribution of FAD fates was relatively similar between con-FADs and bio-FADs. Among FADs deployed before 2024 (giving them one full potential year to be observed in our database), most FADs (near 70%) were deployed and never reported recovered by the IATTC observer program. Note that this does not mean that they were not recovered by some other program or actor, but the current data cannot elucidate the ultimate fate of these unrecovered FADs in this study. The majority of FADs that were never recovered were also never set on. Collectively, 22% of all FADs were listed as recovered, 13% when including only FADs deployed before 2024. 16% of FADs deployed before 2024 were set on at least once. Bio-FADs were nearly twice as likely to have a fate of "single visit, recovered" than con-FADs (Figure 5).

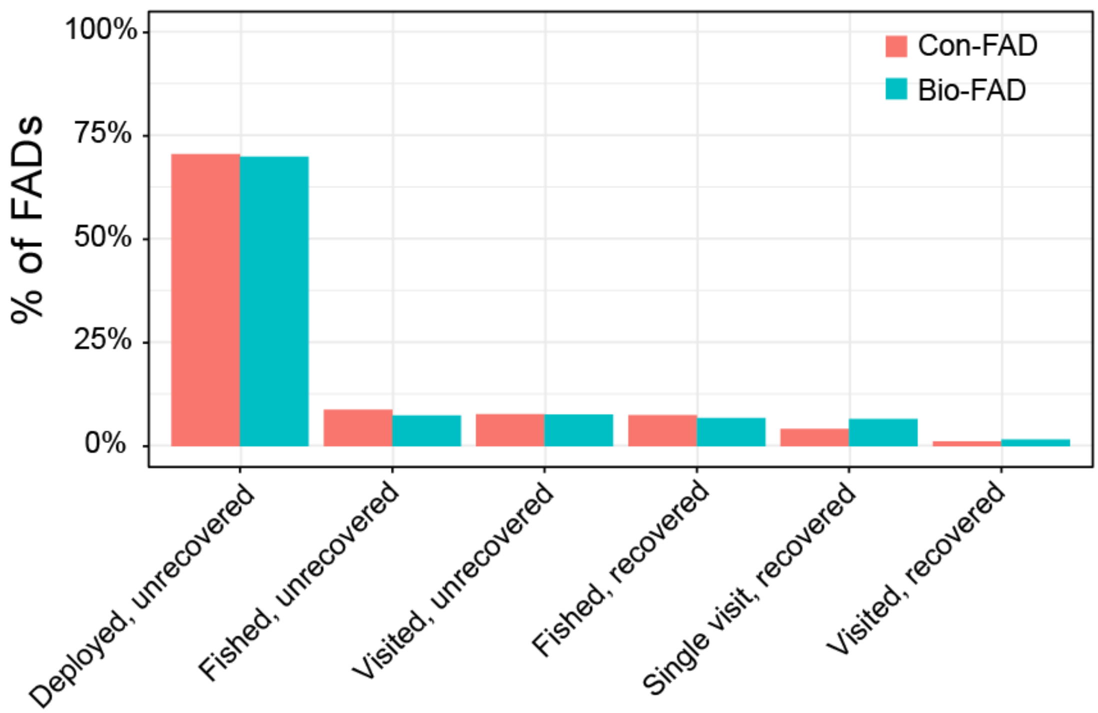

FIGURE 5. Distribution of deployment outcomes over the study period for conventional (con-FAD) and biodegradable (bio-FAD) FADs. Only FADs deployed before 2024 included to ensure that deployed FADs had up to one year reach their ultimate deployment outcome in the database.

Deployments and recoveries

FADs deployed in the northeast (i.e., 0-5N and <120W) and southwestern corner (i.e., Peru area) of the deployment grounds were the most likely to be recovered (Figure 6). Terminal FAD recoveries ("recoveries" in the last recorded event), regardless of deployment location, were more common in the edges of the fishing grounds, with special emphasis on the more western parts (>90-100W) of the fishing grounds north (>5N) and south (>5S) of the equator, where, in certain pockets, the percentage of recovered FADs exceeded the 50% (e.g., the area between 100W and 120W and >10S) (Figure 7).

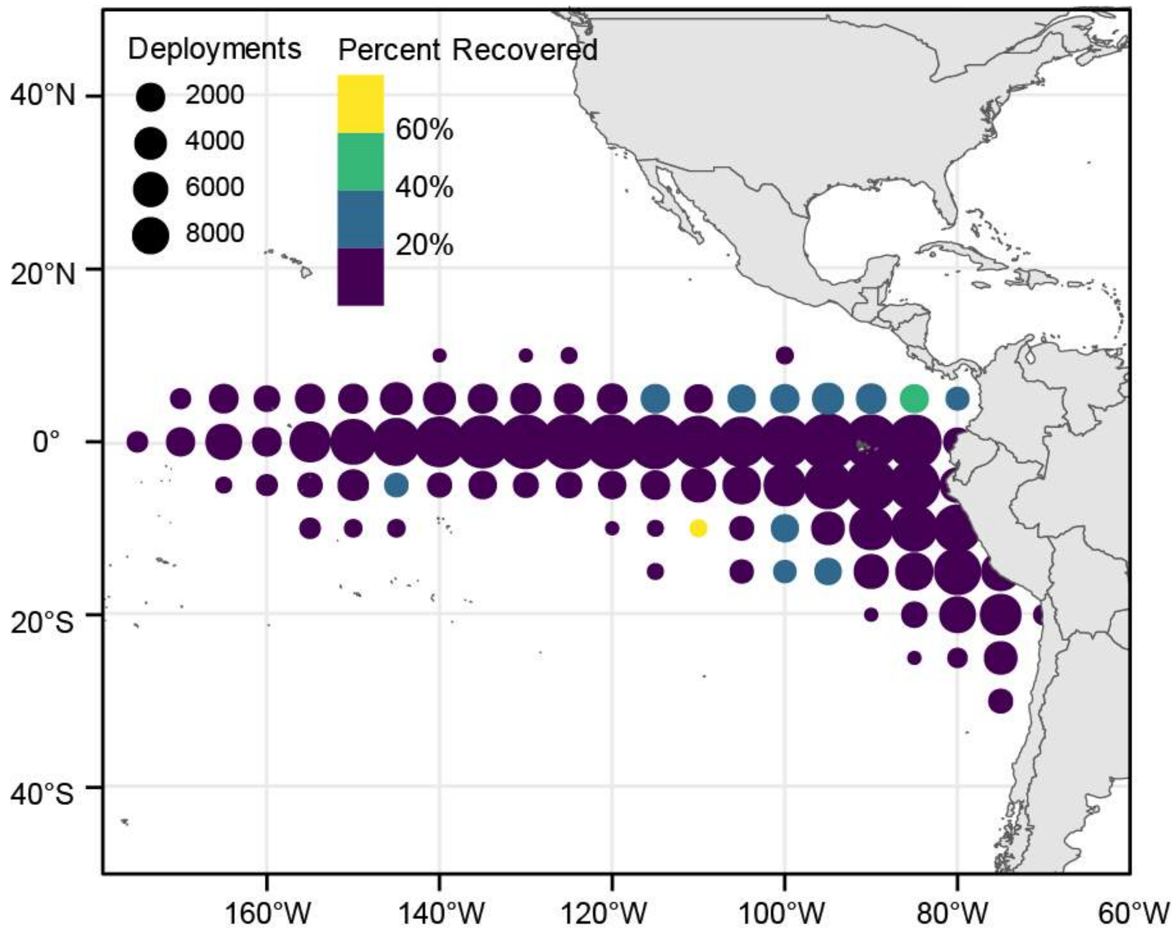

FIGURE 6. Spatial distribution of FAD deployment locations, with color indicating the proportion of FADs deployed at that location that were eventually observed to be recovered.

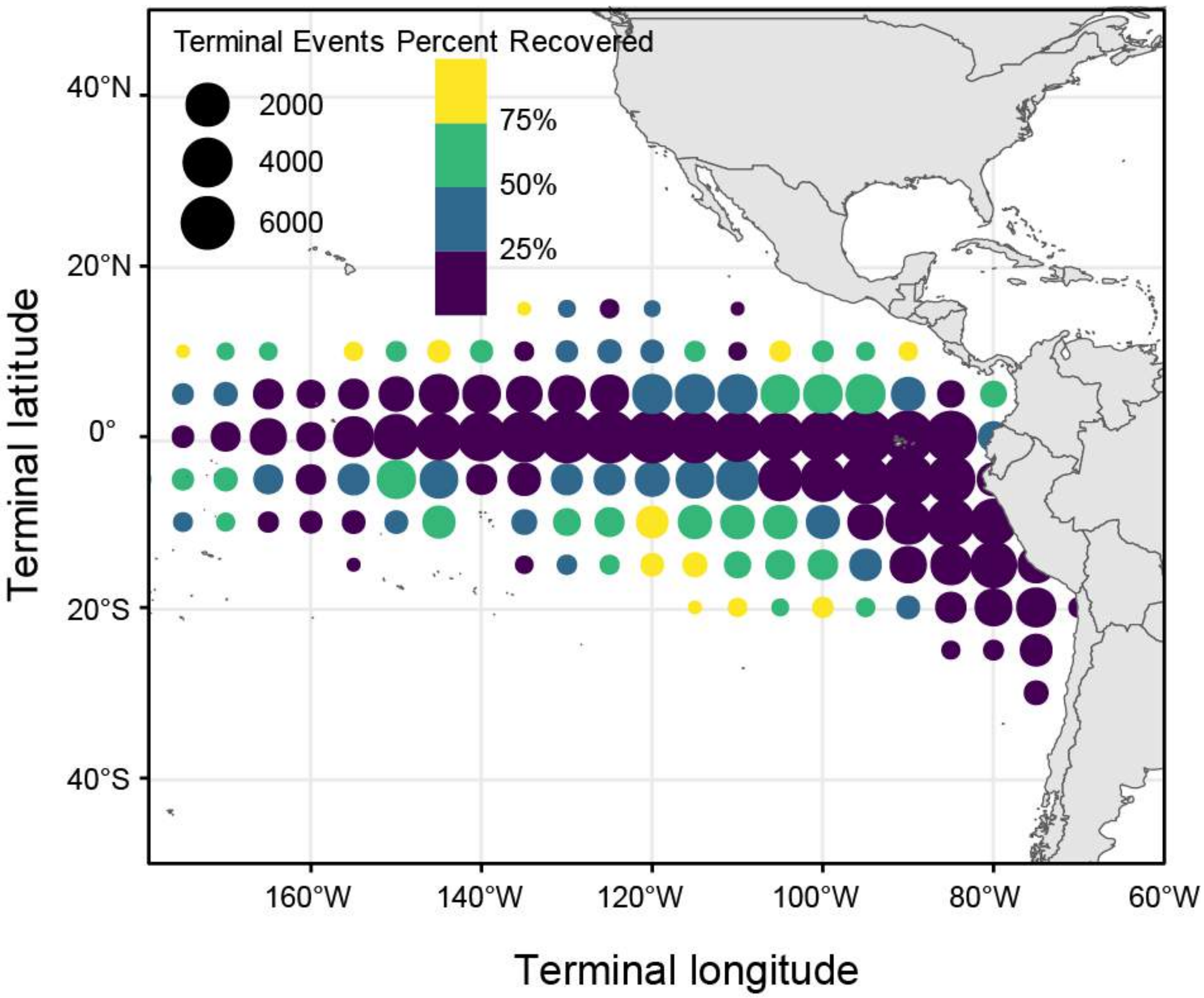

FIGURE 7. Spatial distribution of terminal locations in the database, with color indicating the proportion of FADs whose terminal event at that location was listed as recovery.

FAD lifespan duration

FAD observed lifespan lengths had a wide range, with the majority never being set on, with 80% of FADs showing lifespan lengths of 50 days or less. Most FADs have a lifespan of 0 days (meaning they were deployed and never seen again), as such only slightly above 30% of FADs survive to at least one day. Average bio-FADs were less likely to survive to a given lifespan length than con-FADs (Figure 8).

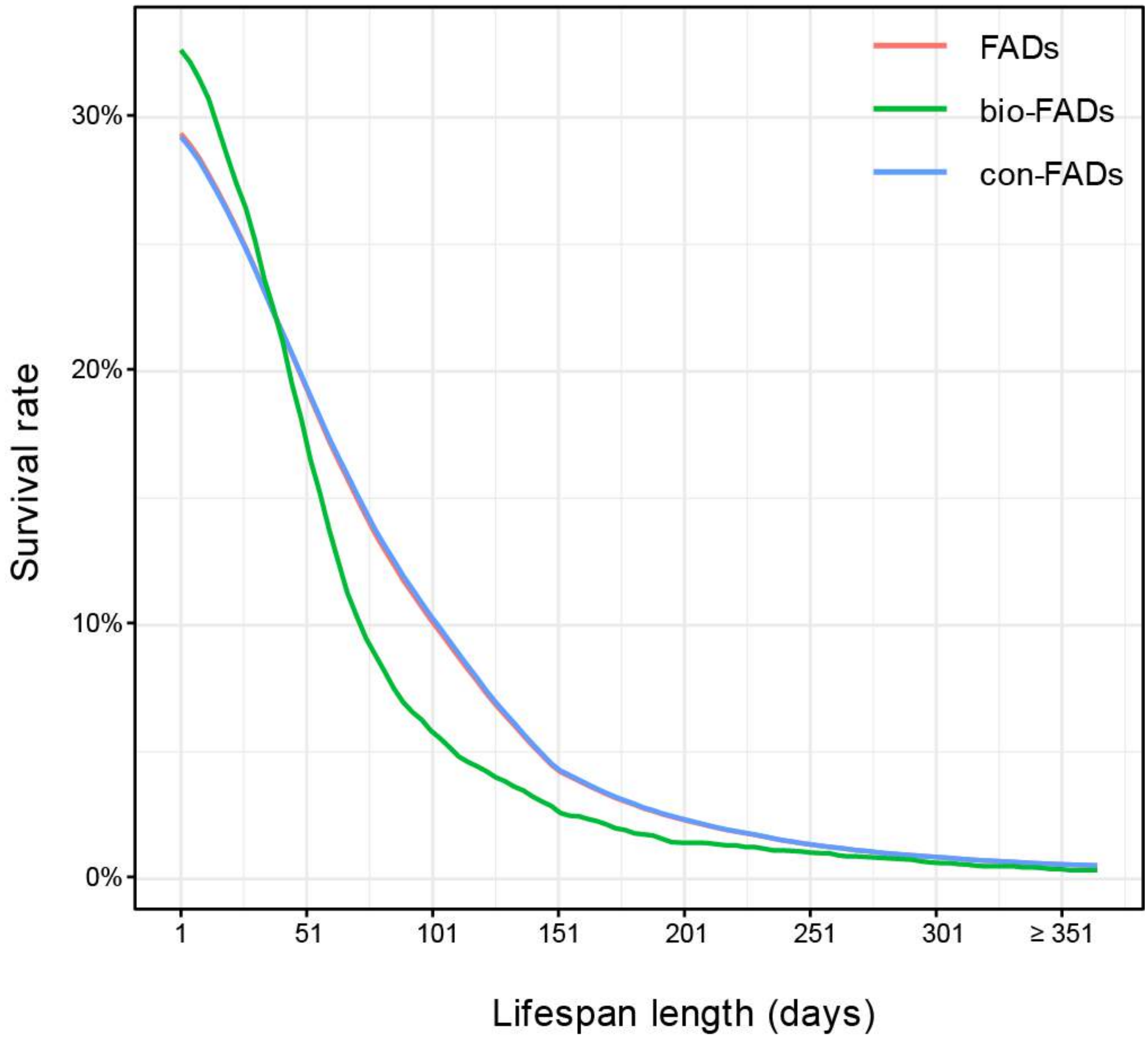

FIGURE 8. Empirical survival curves of FADs observed in the database. X-axis shows observed deployment length in days (days between last observation in the database and first observation), y-axis shows percent of FADs with observed lifespan lengths equal to or greater than the value on the x-axis. Note that these are raw data that do not account for systemic differences in deployment characteristics between bio-FADs and con-FADs.

FAD visits and sets

Given that all FADs are seen in the database at least once (i.e., deployment), most FADs are interacted with (visited or set on) by two or fewer vessels, with only a few being interacted with by as many as six vessels (Figure 9). For FADs that are set on (16% of analyzed FADs), most were set on less than five times (Figure 10).

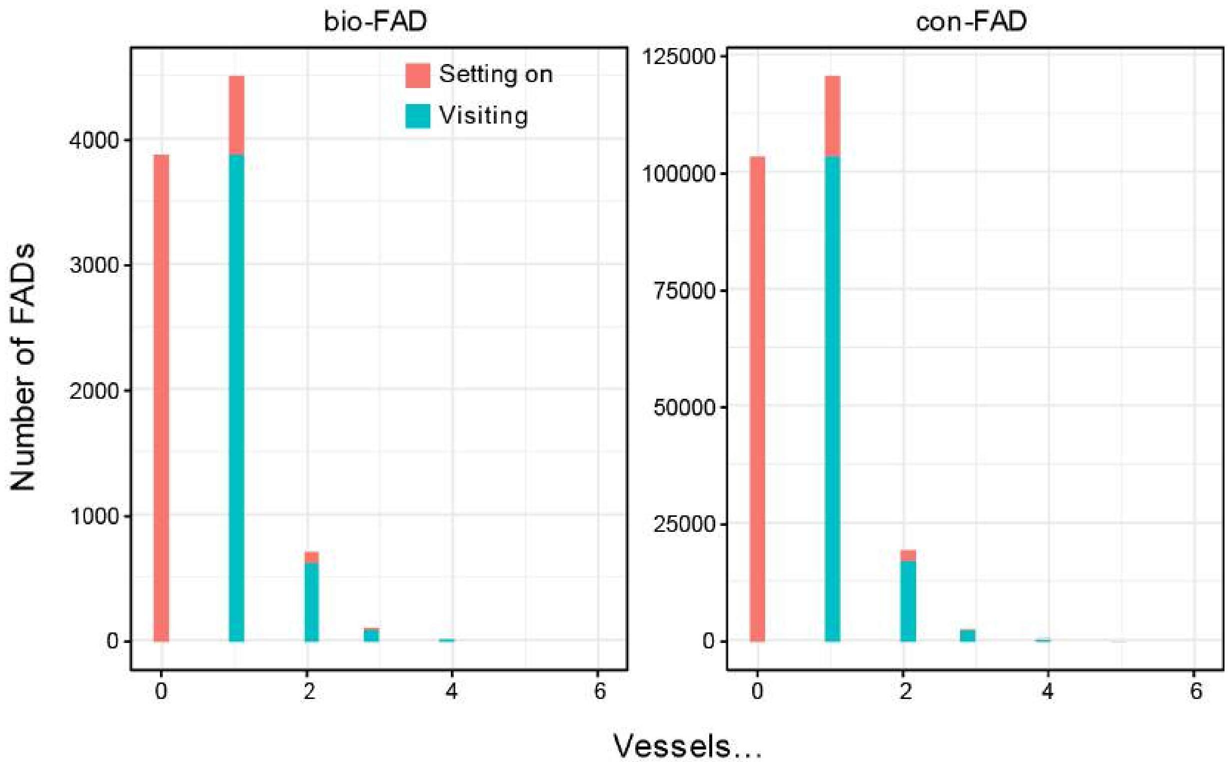

FIGURE 9. Number of vessels visiting or setting on individual FADs, per lifespan, for biodegradable (bio-FAD) and conventional (con-FAD) FADs.

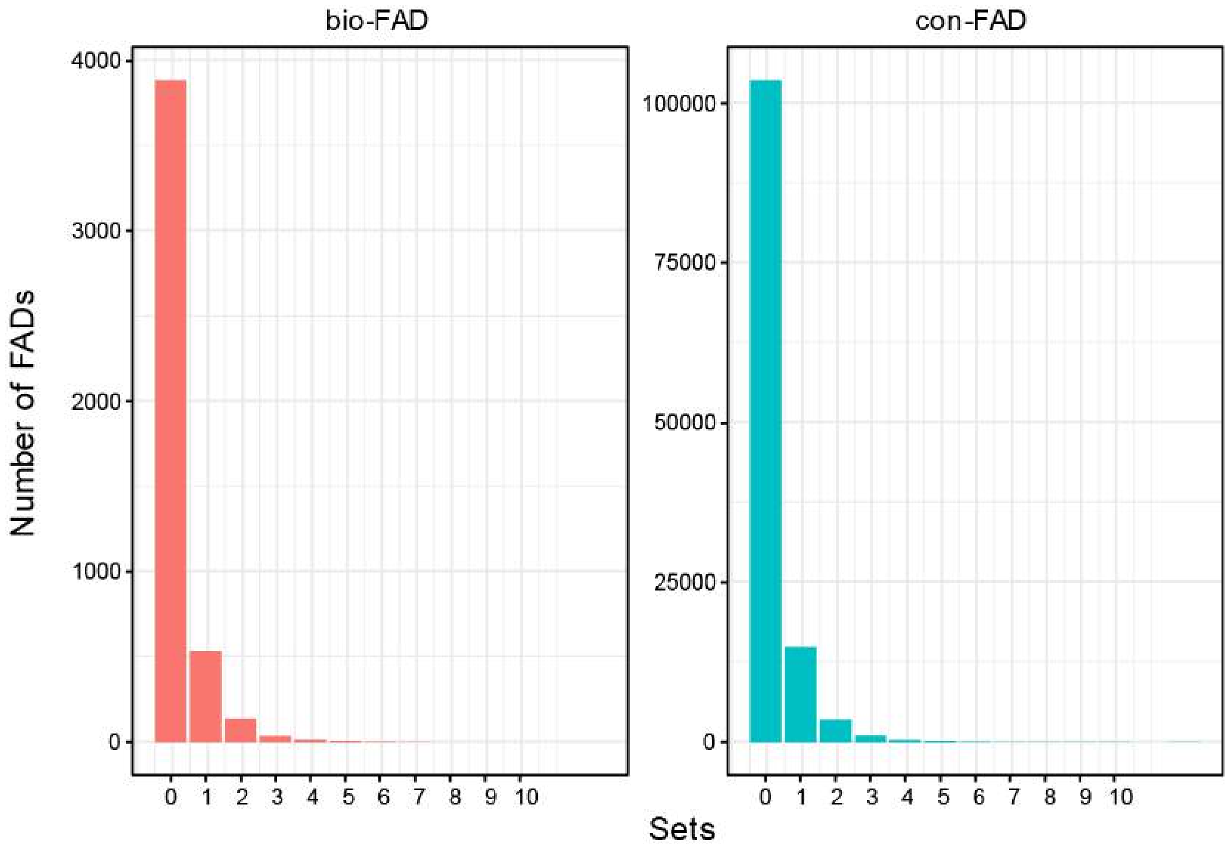

FIGURE 10. Total number of sets per lifespan, for biodegradable (bio-FAD) and conventional (con-FAD) FADs.

For FADs that were set upon, the days to first set ranged from seven days (the minimum soak time allowed by the database creation process) to more than a year. Among FADs that were set on, bio-FADs were, on average, set on 26 days sooner than con-FADs, based on the raw data and not controlling for any confounding difference between these two groups (Figure 11).

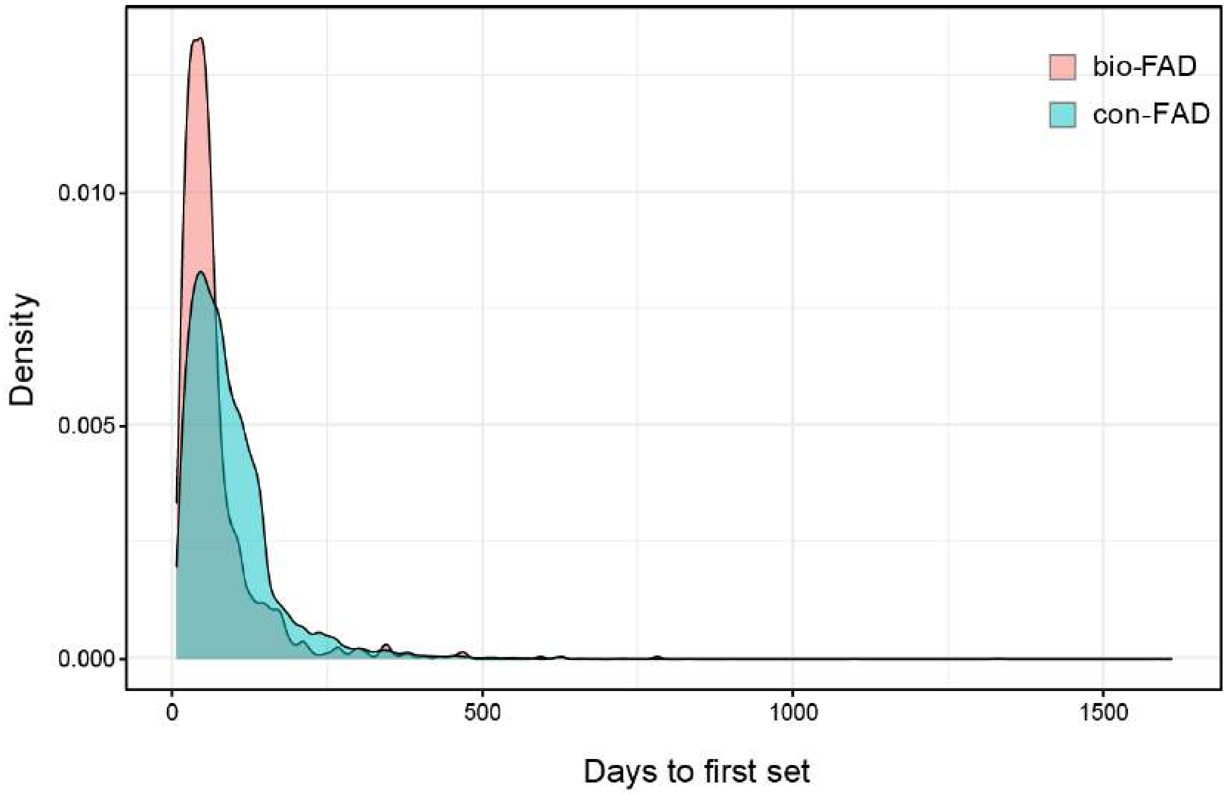

FIGURE 11. Distribution of days to first set for FADs that were set on at least once, for biodegradable (bio-FAD) and conventional (con-FAD) FADs.

Based on the raw catch per set and total catch per lifespan data, bio-FADs had lower catch per set and total observed lifespan catch than con-FADs for all tropical tunas (Figure 12). However, bio-FADs are not randomly deployed, which can make raw values misleading to interpret and attribute the result to the bio-FAD construction itself.

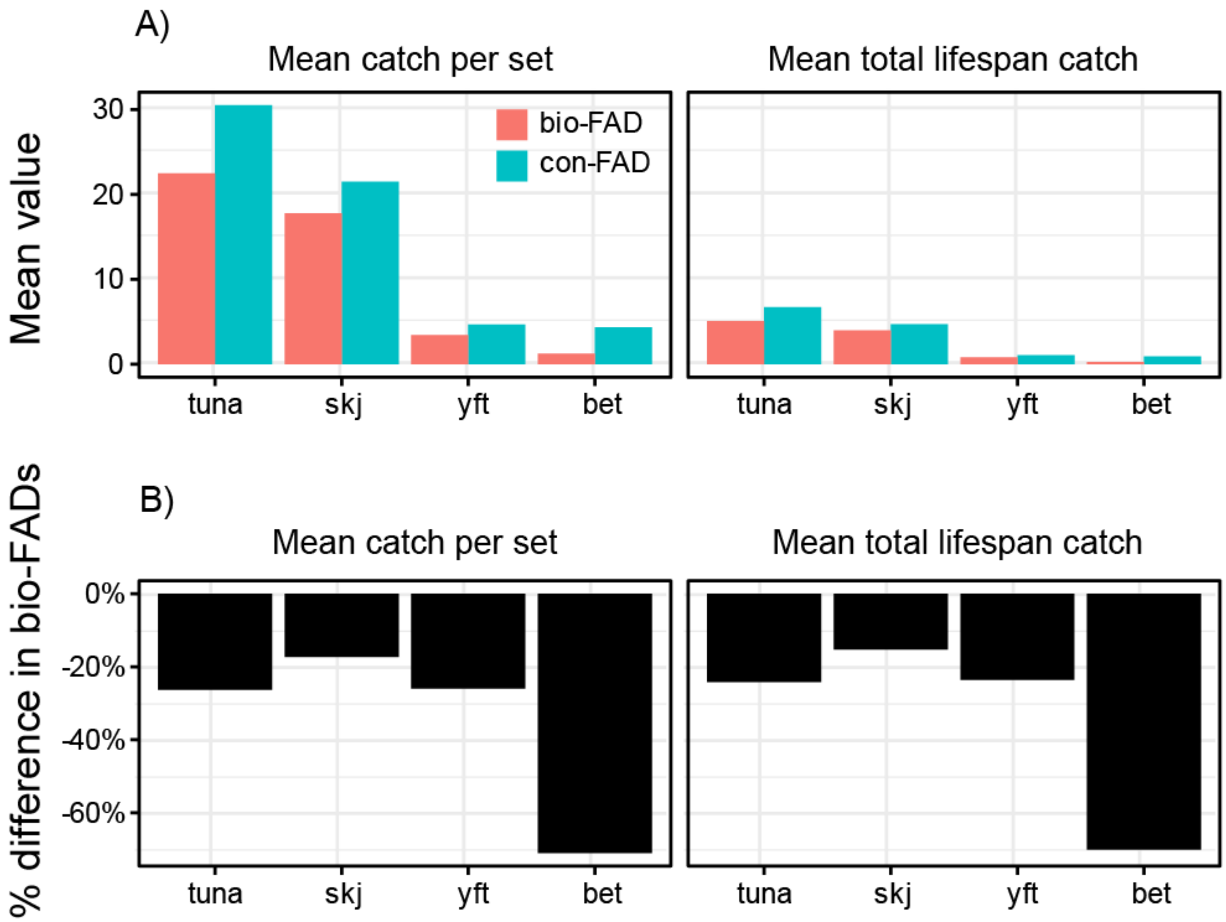

FIGURE 12. A) Raw mean catch per set and total observed lifespan catch by tuna group broken out by biodegradable (bio-FAD) and conventional (con-FAD) FADs. B) Percentage difference in raw outcomes between bio-FADs and con-FADs. "tunas" refers to total of all three tropical tuna species.

Marginal Effects of Biodegradable FADs

The previous section presented raw differences between bio-FAD and con-FAD lifespan characteristics. However, bio-FAD deployments and use are highly non-random and thus, comparisons between bio-FADs and con-FADs can be misleading and attribute the difference to the nature of bio-FADs, rather than systemic differences in unrelated variables, such as the fishing location or the capacity of vessels.

Bio-FAD deployments were concentrated in the north-eastern part of the FAD deployment grounds (Figure 13). Similarly, Bio-FAD sets are concentrated in particular locations of the FAD fishing grounds, with hotspots around and specifically west of the Galapagos (Figure 14). The proportion of sets on bio-FAD has significantly increased over time, going from near 0% pre-2020 to a peak of 10% in late 2023 (Figure 15). These spatio-temporal patterns need to be accounted for in any assessment of differences in FAD outcomes between con-FADs and bio-FAD. Bio-FADs were also systemically shallower than con-FADs, but this effect was treated as an intrinsic part of the bio-FAD status or design, rather than a confounding covariate in this analysis (Figure 16).

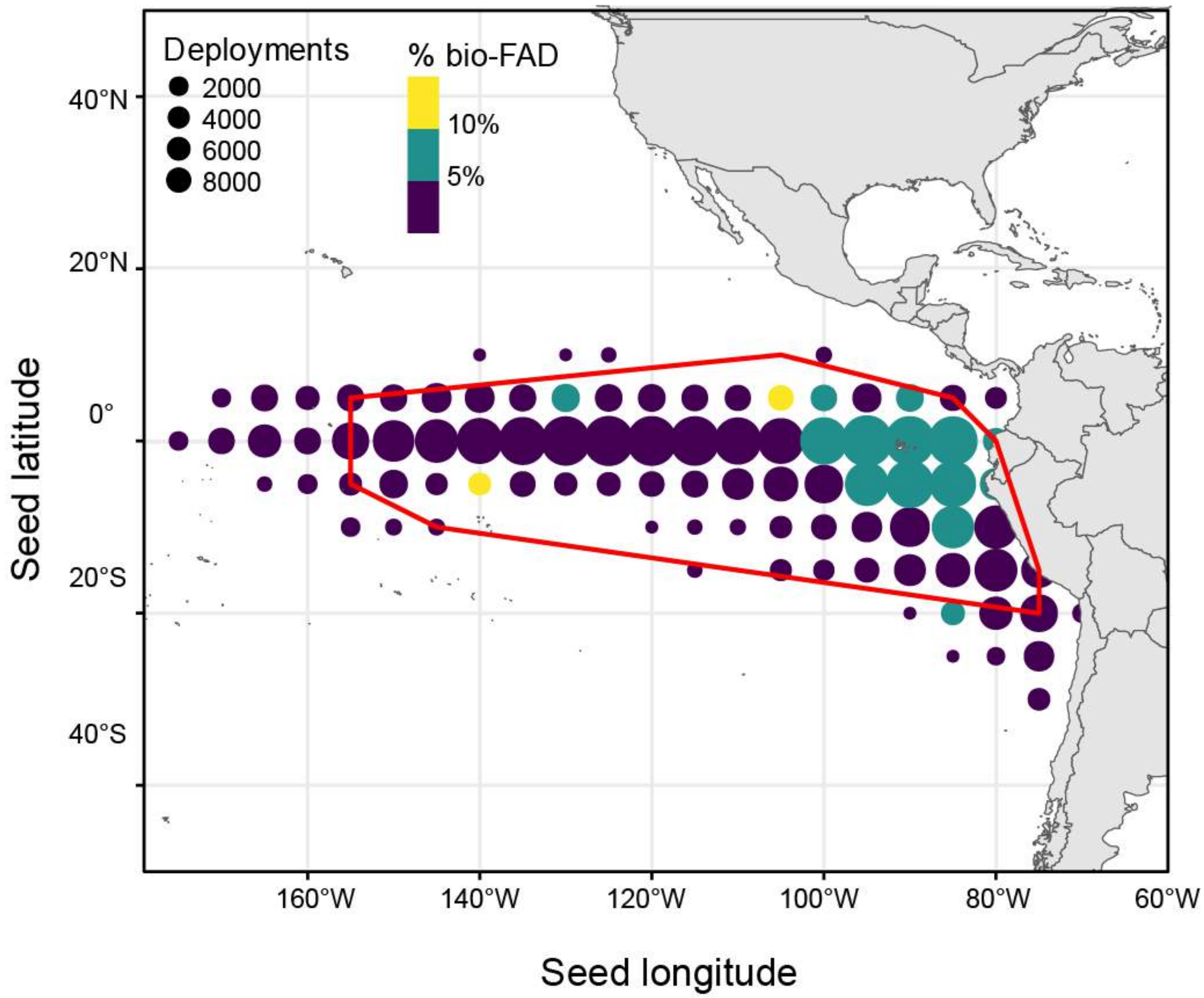

FIGURE 13. Percent of FAD deployments classified as biodegradable FADs (bio-FAD) over study period. Red polygon shows core bio-FAD interaction area.

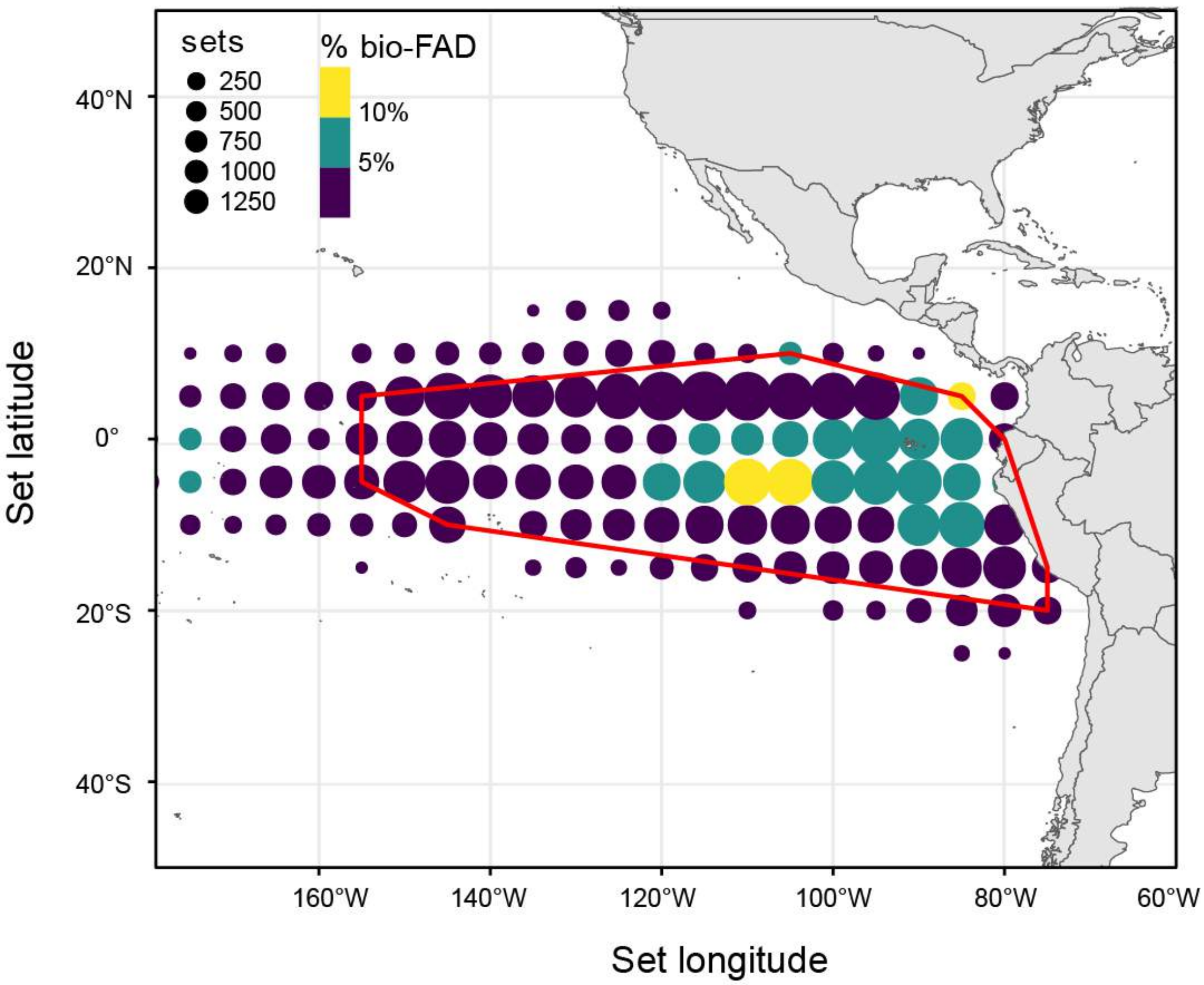

FIGURE 14. Percent of FAD sets occurring on biodegradable FADs (bio-FAD) over study period. Red polygon shows core bio-FAD interaction area.

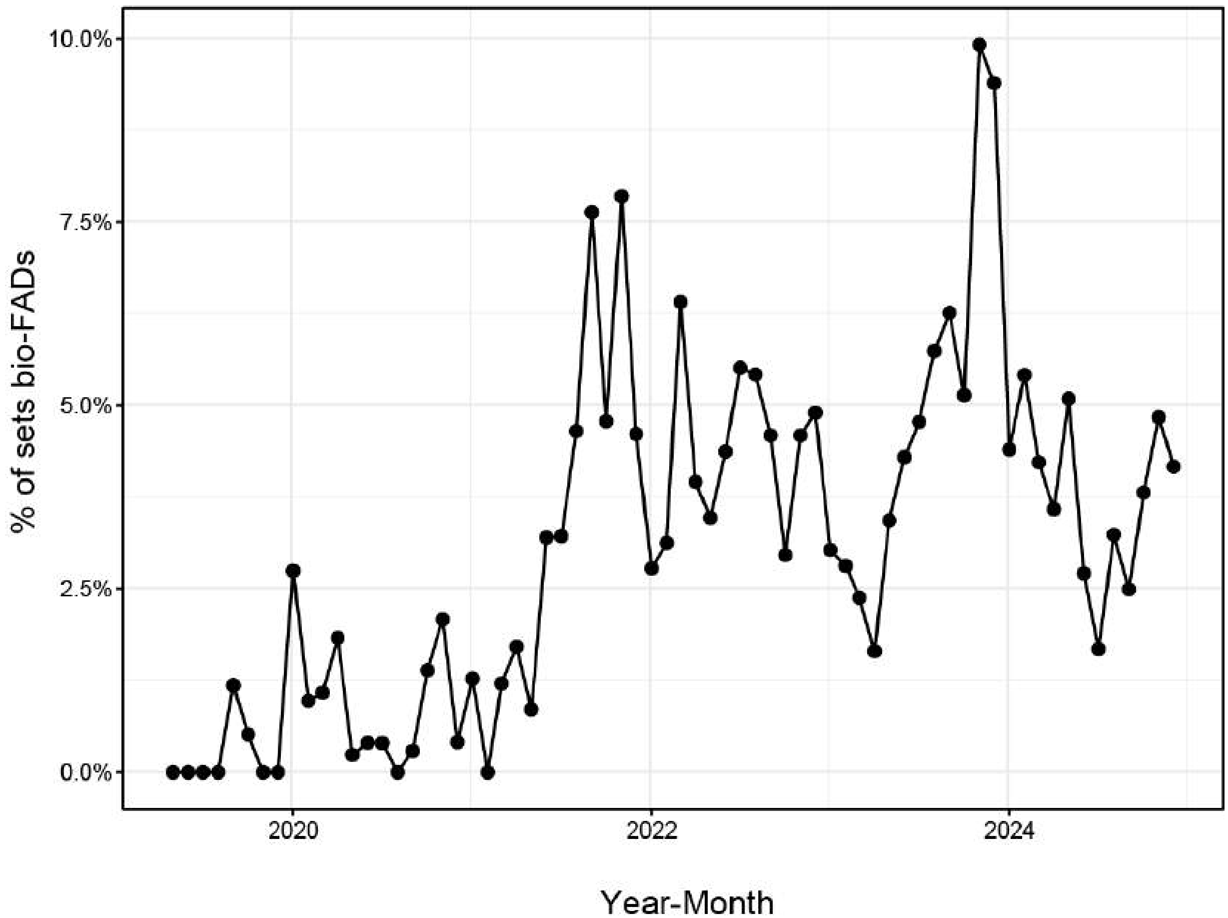

FIGURE 15. Percent of observed FAD sets that occurred on biodegradable FADs (bio-FAD) over time.

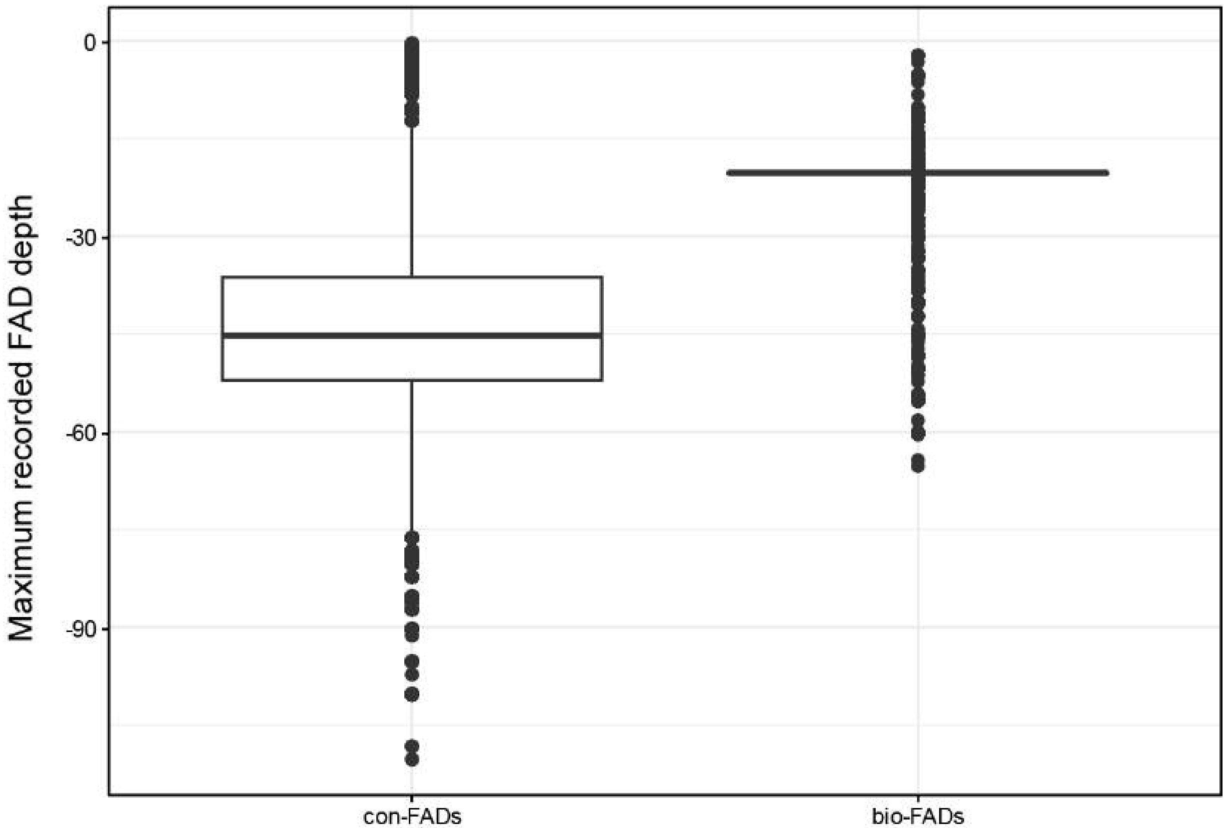

FIGURE 16. Distribution of maximum recorded FAD depth for biodegradable (bio-FAD) and conventional (con-FAD) FADs.

Given these systemic differences in many potentially confounding variables between bio-FADs and con-FADs, we sought to estimate the marginal effect of bio-FAD status, controlling for these potential confounders as best as possible given the available data, as described in the methods. We note that, although the models established in this study do not include a formal causal identifications strategy, they are preferable to the raw differences, as the estimated marginal effects are still less susceptible to omitted variable bias than the raw differences in mean values.

Controlling for the year and location of deployment, the capacity of the vessel deploying the FAD, and bio-FAD status, bio-FADs that were set on at least once were set on roughly 10% (7%–13%) sooner than con-FADs (Figure 17).

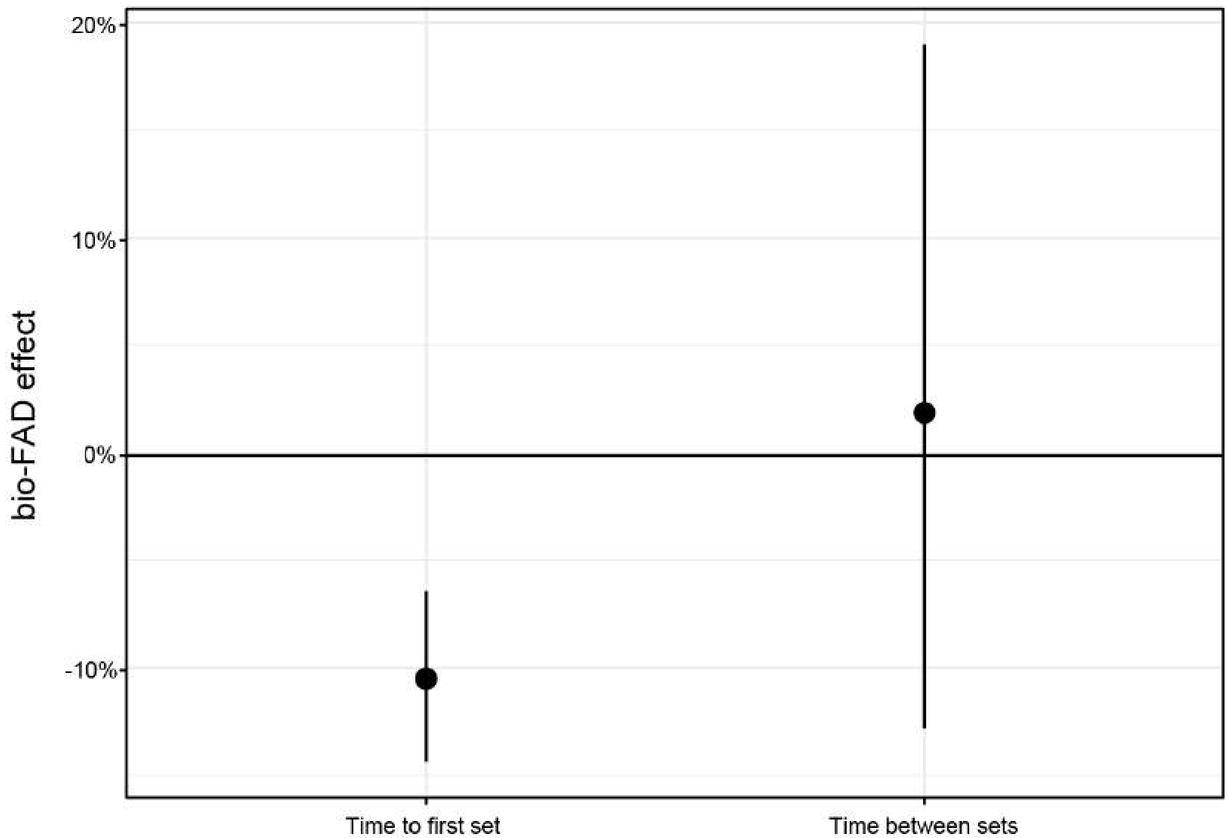

FIGURE 17. Estimated marginal difference in time to first set between biodegradable (bio-FAD) and conventional (con-FAD) FADs controlling for spatio-temporal effects and the capacity of the vessel deploying the FADs that were set on at least once.

Controlling for the year and location of deployment, the average capacity of the interacting vessels, and bio-FAD status, bio-FADs on average had shorter observed lifespan lengths than con-FADs, approximately -8% (-5% to -17%) for all FADs and a similar but more uncertain result for the subset of FADs that were eventually recovered (Figure 18). Controlling for the same attributes, This difference propagates into the difference in the total number of lifespan sets, with bio-FADs estimated to have roughly 13% fewer sets than con-FADs during their lifespan, with 95% confidence intervals between -20% and -6% (Figure 19).

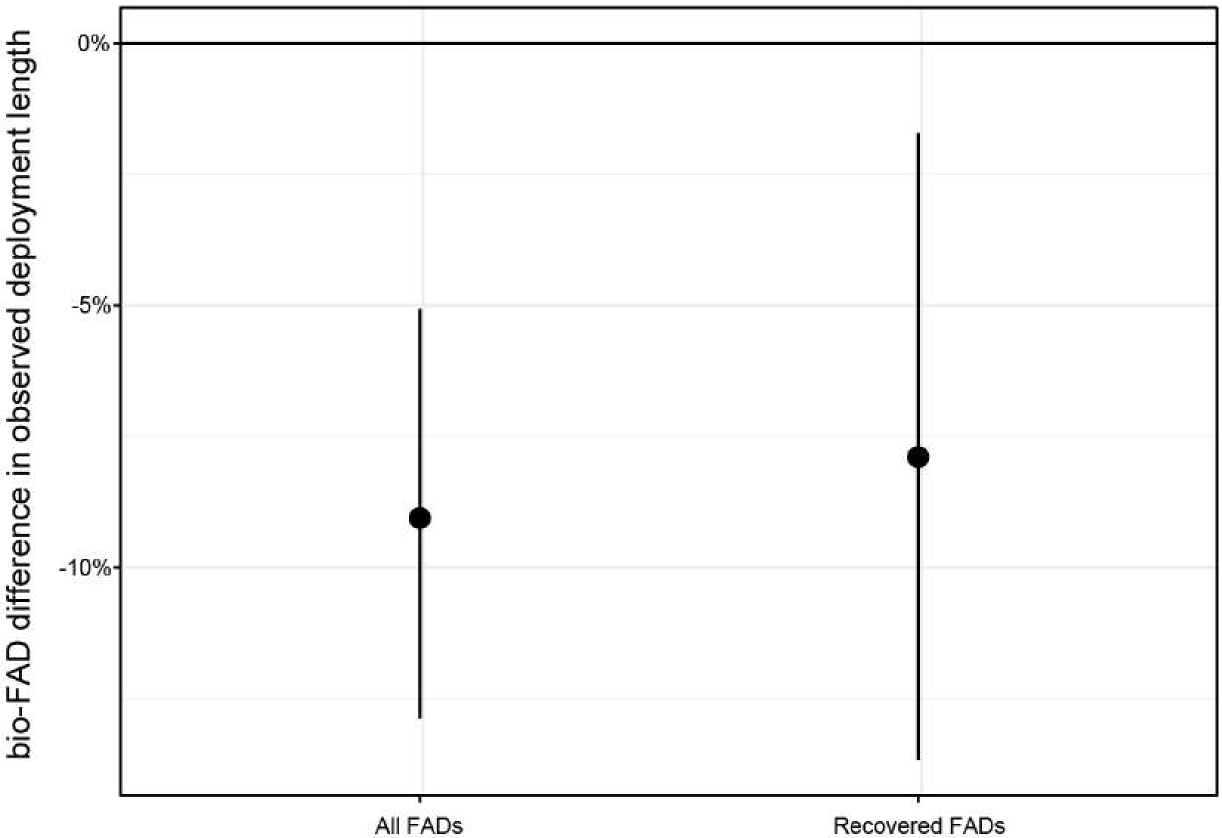

FIGURE 18. Estimated marginal difference in lifespan length between biodegradable (bio-FAD) and conventional (con-FAD) FADs for recovered (A) and all deployed (B) FADs. Note that in order to have a lifespan value a FAD must be interacted with at least twice (i.e., deployment and another activity). Marginal effects control year and location of deployment, the total capacity of the interacting vessels, and bio-FAD status.

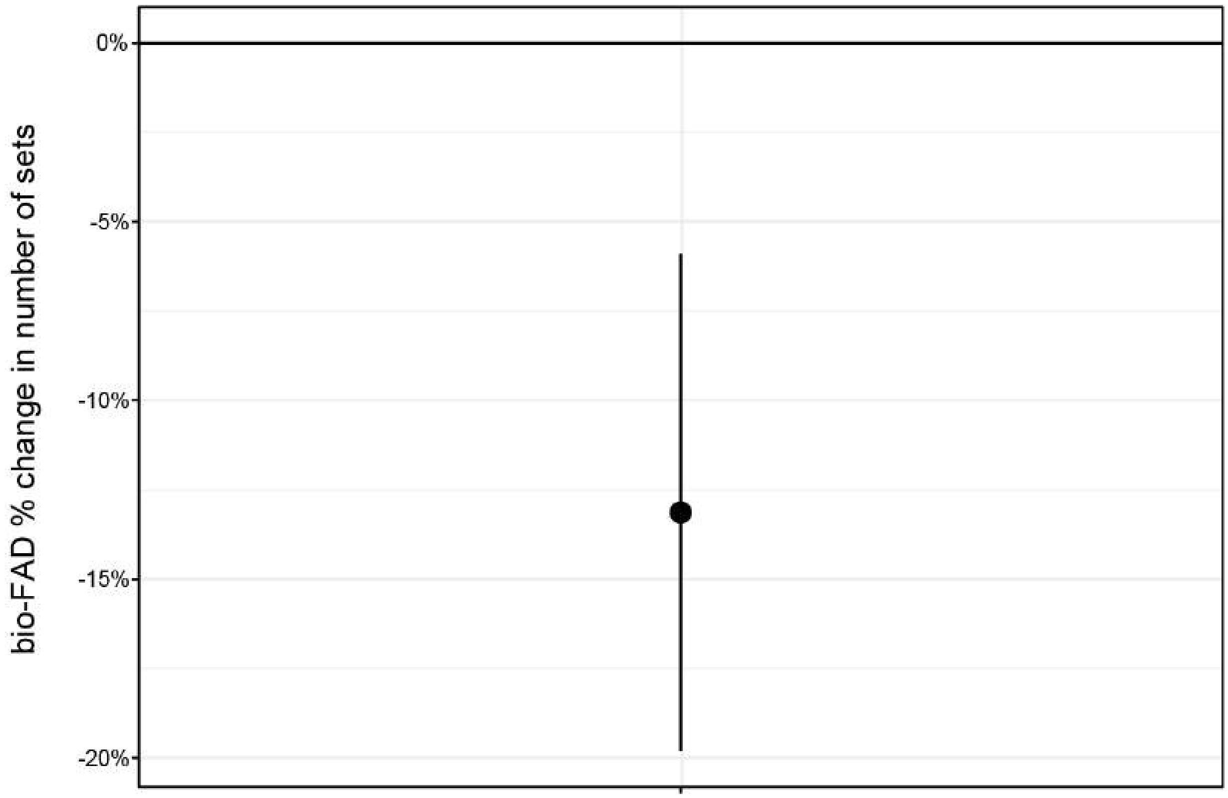

FIGURE 19. Marginal effect of bio-FADs on the total number of sets per FAD lifespan, relative to con-FADs. Marginal effects control year and location of deployment, the total capacity of the interacting vessels, and bio-FAD status.

The raw data shows substantially lower catch per set and total lifespan catch on bio-FADs compared to con-FADs. However, systemic differences between the deployment and setting process for biodegradable versus con-FADs could explain this difference. To account for this, we estimated the marginal effect of bio-FADs on lifespan catch and catch per set per tuna species and total catch controlling for the capacity of vessels deploying the FADs, deployment month, and underlying spatio-temporal random effects. After controlling for these variables, bio-FADs did not have, on average, statistically significantly lower lifespan catches for any of the tuna species or combined catch, with 95% confidence intervals generally between 8% and -15% (Figure 20). In total, these estimates suggest that the differences in raw total lifespan catch observed between bio-FADs and con-FADs are better explained by differences in other covariates such as deployment time, location, and vessel capacity.

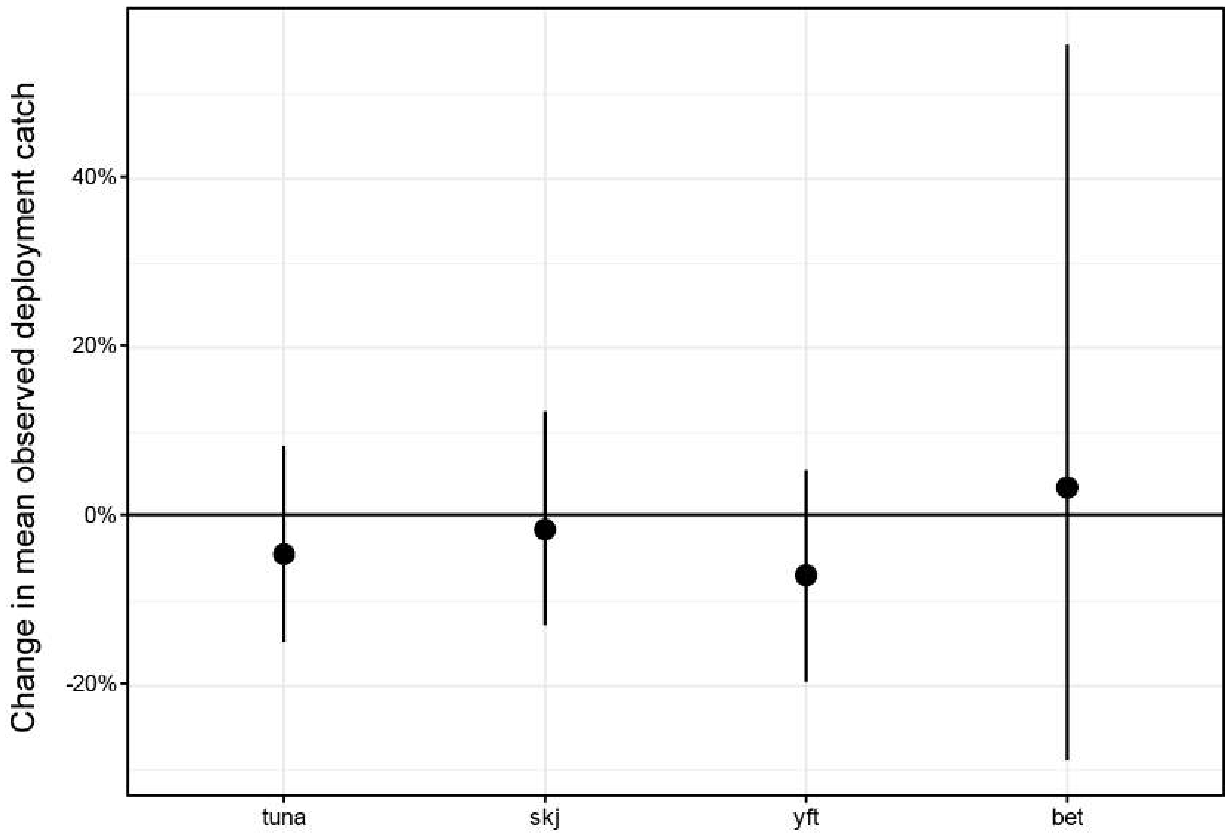

FIGURE 20. Marginal effect of biodegradable (bio-FAD) FADs on total lifespan catch of tropical tuna, relative to conventional (con-FAD) FADs. Marginal effects control for year and average fishing locations, the average capacity of the interacting vessels and the capacity of the deploying vessel and bio-FAD status. The category "tuna" refers to the total lifespan catch of all three tropical tuna species.

Running the same spatio-temporal delta model procedure on catch per set instead of total lifespan catch, bio-FADs only had statistically significantly lower catch per set for YFT (mean -10%, 95% confidence intervals between -3% and -17%). However, for the other tropical tuna species or combined catch the models did not estimate significant differences or a precise zero effect either. Similar to the total lifespan catch, these results suggest that the large differences in raw catch per set between bio-FADs and con-FADs is better explained by other confounding variables (e.g., set location and vessel capacity) rather than bio-FAD construction itself (Figure 21). These results are in some ways consistent with the findings of Schaefer et al. (2021), although they did not examine differences between con-FADs and bio-FADs, but instead between shallow and standard depth FADs. However, as previously noted, the bio-FADs evaluated in this study are systemically shallower than con-FADs. Therefore, our result of no significant difference in catch per set between bio-FADs and con-FADs found here supports the finding of no difference between shallow and standard sets by Schaefer et al. (2021).

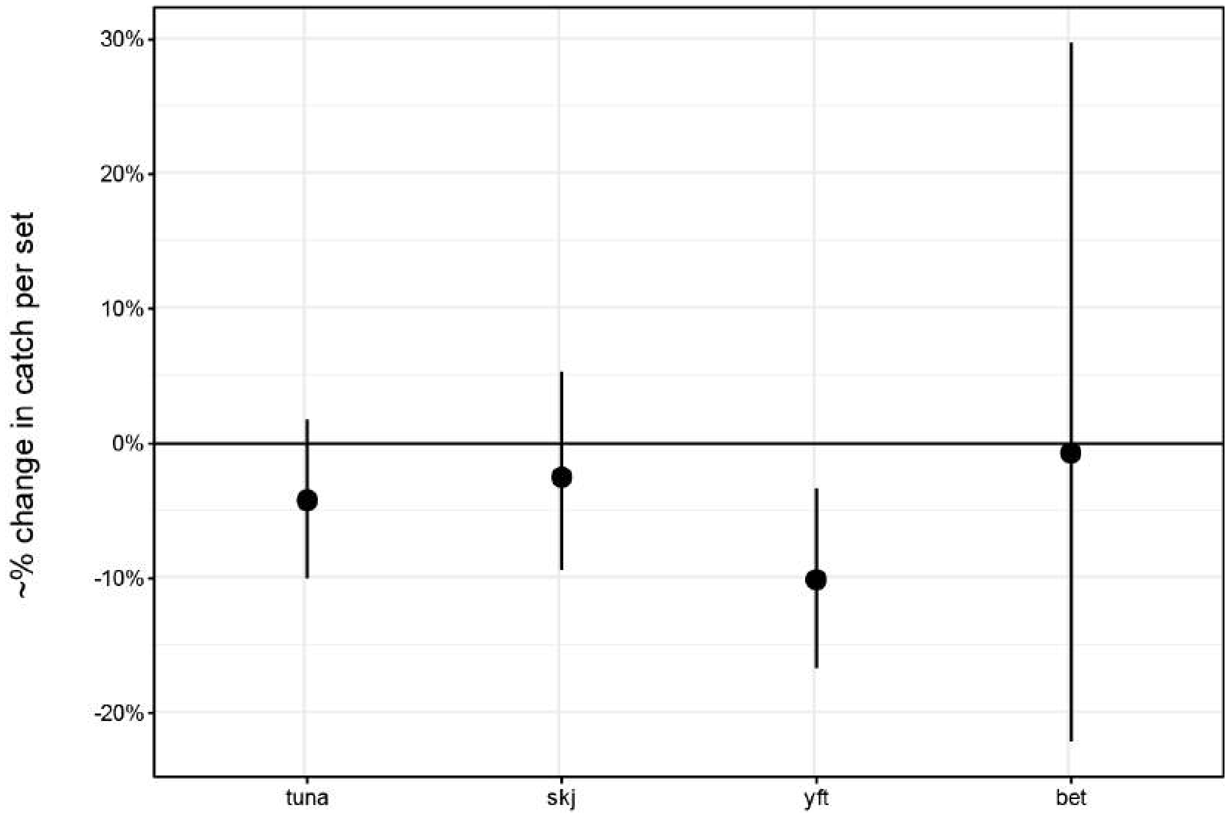

FIGURE 21. Marginal effect of biodegradable construction (bio-FAD) on catch per set of tropical tunas, relative to conventional (con-FAD) FADs. Marginal effects control for year and fishing locations, the capacity of the setting vessels, and bio-FAD status. The category "tunas" refers to the combined total catch of all three tropical tuna species.

Skipper Surveys

The survey focused on the fishing dynamics of bio-FADs (2024-2025), and FADs in general (2020-2023), and included questions on FAD deployment strategies and loss, reasons and areas for FAD loss, FAD duration, unrecovered FADs, soak time effect, improvements in FAD construction.

Skippers self-reported a decreasing trend in the number of total FADs lost from 2020 to 2023, with the number of specifically bio-FADs reported as lost per year per vessel showing a similar result to overall FAD loss in 2023 (Figure 22). In 2020, the most common response to the number of FADs lost per vessel per year was "greater than 100", whereas in 2023 the most common response was 20-50. In 2024, the most common response to the number of specifically bio-FADs lost was per vessel per year was 1-20. In both periods, about 50% of participants claimed to lose a maximum of 50 FADs per year, with 20% losing more than 50 FADs per year.

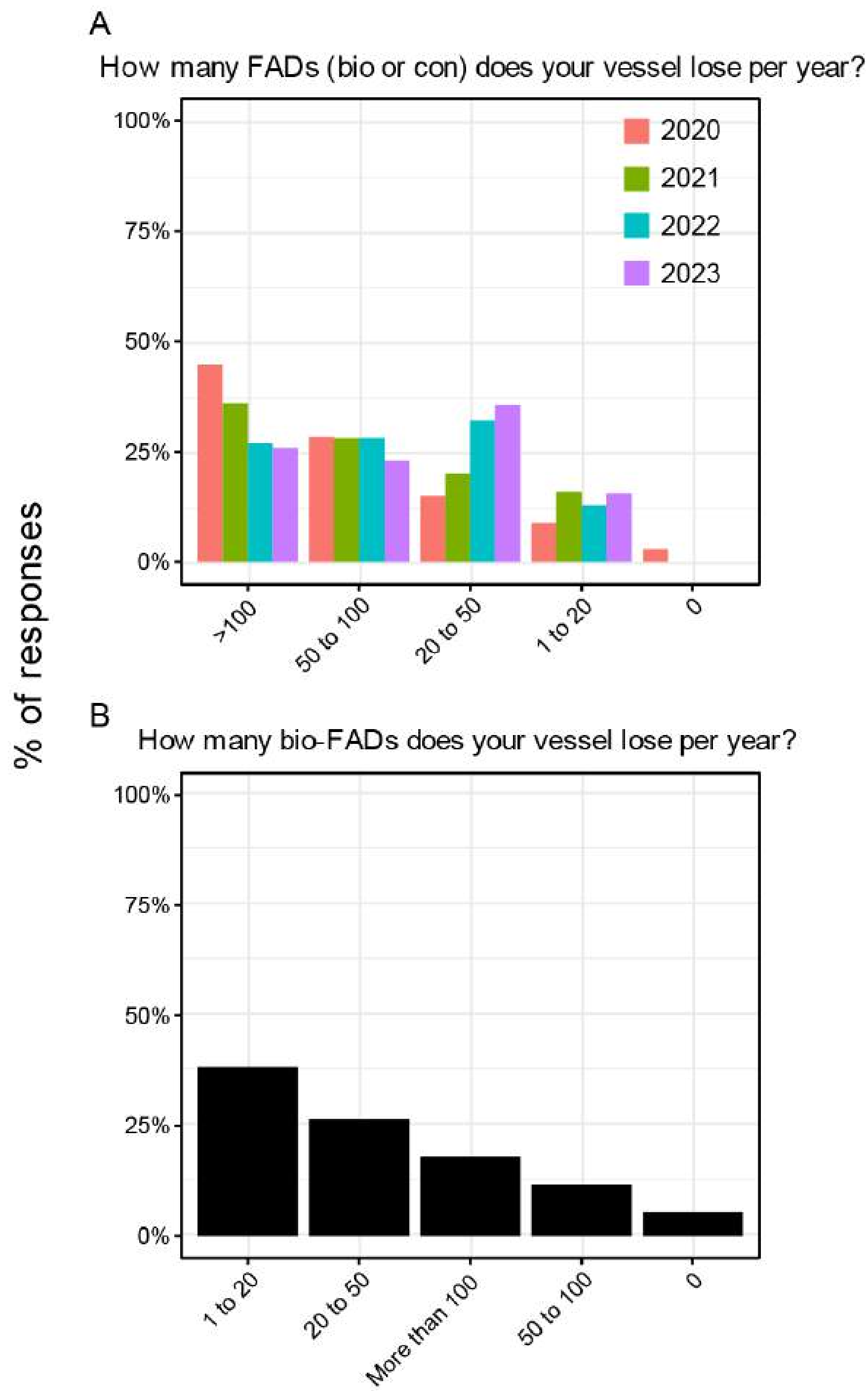

FIGURE 22. A) Number of FADs lost per vessel per year, self-reported by participants in skipper surveys conducted during skippers workshops from 2020 to 2023. B) Number of bio-FADs lost per vessel per year, self-reported by participants in the skipper survey conducted in 2024-2025.

There was a consistent trend both over time and across all FADs and bio-FADs that the most common reasons for FAD loss were, in order or importance, being taken by another vessel, leaving the fishing grounds, or being destroyed (Figure 23). Interestingly, when focused on bio-FADs, “destroyed/sank” was the second most selected option in 2024-2025.

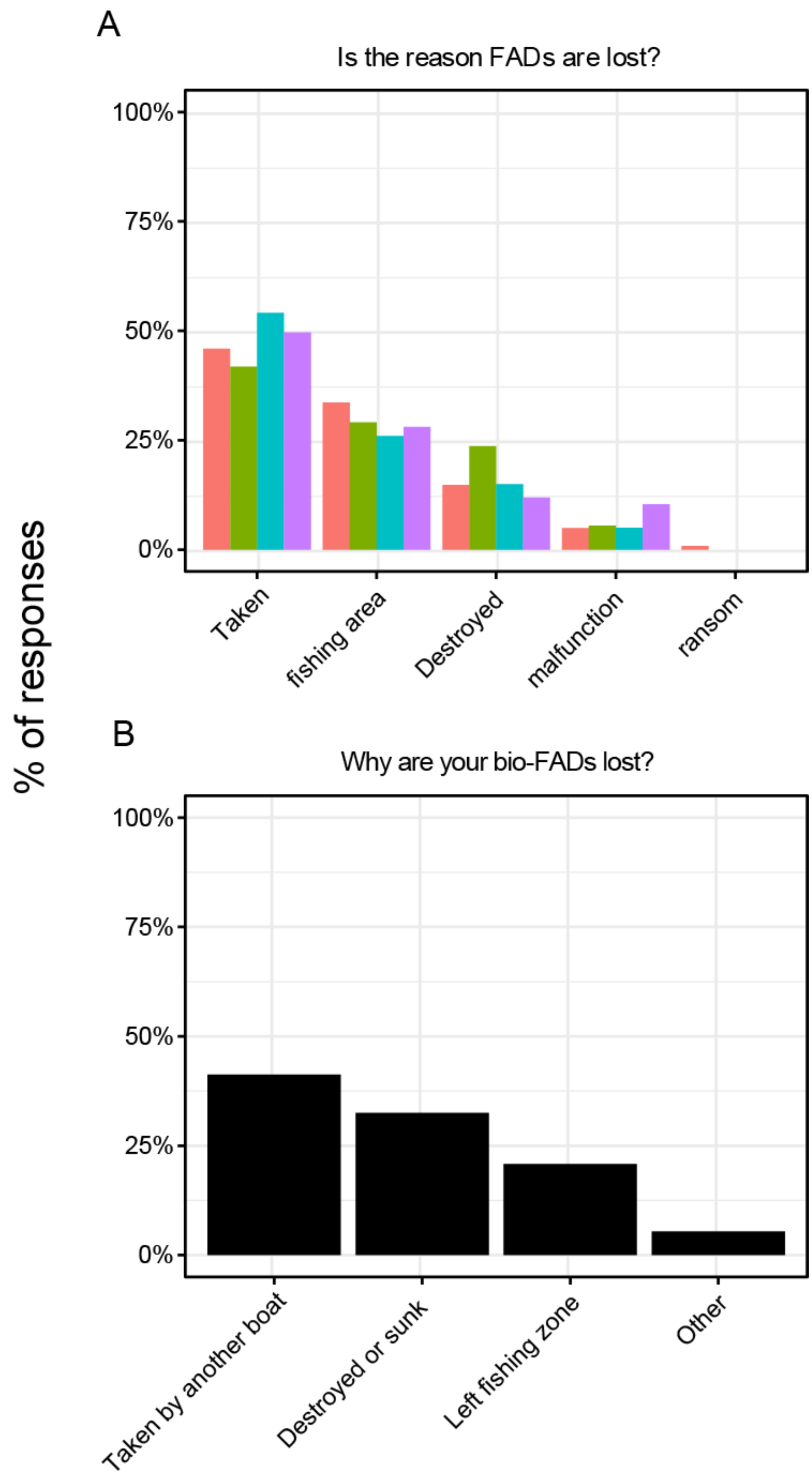

FIGURE 23. A) Reasons for FAD loss self-reported by participants in skipper surveys conducted during skippers workshops from 2020 to 2023. B) Reasons for bio-FAD loss self-reported by participants in skipper survey workshops from 2024 through 2023.

When asked about the areas where FADs are lost, similar patterns were observed in 2024-2025 (bio-FADs) and 2020-2023 (all FADs), with most participants claiming that most of the FADs are lost around Galapagos and between 100-120W, followed by the area west of 120W and the Peru area.

When asked about FAD duration, about 75% of participants in 2024-2025 mentioned that bio-FADs last less than 6 months, while 50-70% of participants in 2020-2021 and >70% in 2024-2025 claimed that con-FADs lasts more than 6 months (30% of participants in 20204-2025 say con-FADs last more than 12 months).

When asked about unrecovered FADs, >80% of participants in the 2024-2025 survey report that 20 bio-FADs or less per year and vessel are left drifting in the water. In the 2020-2023 surveys, about 50% of participants claim to leave 20 FADs or less per year and vessel drifting in the water, whereas the other 50% leave a minimum of 20 FADs per year and vessel unrecovered in the water. This suggests that skippers might currently be more motivated to recover FADs at sea to avoid potential losses.

In 2024-2025, skippers were also asked about the time needed these days to set on a FAD, compared to 5 years ago. Results are inclusive, with ~25% responding "faster than before", 40% responding "slower than before", and 25% responding "no difference".

Similarly, in 2024-2025, skippers were asked about the improvements on bio-FADs in the last 2-3 years. This question had mixed and inconclusive responses, with skippers selecting "no difference" 18% of the time, "more efficient and last longer" 28-24% of the time, and "less efficient and last less" 24-29% of the time. This result suggests that, in some cases, the fleet might be improving the best use and fishing strategy for bio-FADs.

4. CONCLUSIONS AND RECOMMENDATIONS

The observer-derived database presented in this document provides a comprehensive and valuable view of the FAD lifespan dynamics in the EPO. This work identified 'hotspots' of FAD deployment (Figure 6), FAD recovery (Figure 7), and tracked the relative frequency of different outcomes and metrics associated to a FAD lifespan (Figure 5). In addition, the study found that most FADs (>70%) are deployed and never observed or interacted with again and 80% of FAD interactions that occur occur within the first 50 days after deployment. Escalle et al. (2019) and Gomez et al. (2020) which reported a very similar rate of FADs being unused or interacted with post deployment in other parts of the world (i.e. western and central Pacific Ocean). Despite this high rate of unused FADs, the average FAD—across all fished and unfished FADs and bio-FAD and con-FADs—caught roughly 6.65 t of tropical tuna per deployment. The average current price per ton of tuna in 2025 is, $1,500 – $2,000, resulting in average revenue per FAD lifetime of $9,975 – $13,300. This average revenue per FAD lifespan is substantially higher than the average cost of construction for a single FAD. While numerous other costs affect the ultimate profitability of a single FAD lifespan, the wide margin between average FAD lifespan revenue and average FAD construction costs may help explain how such a high rate of FAD loss may be economically viable.

This work also examined differences between bio-FADs and con-FADs. While bio-FADs have lower raw average catch per set and average total lifespan catch than con-FADs, most of this difference seems to be explained by systemic differences in the attributes of bio-FAD and con-FAD deployment and associated fishing vessels. Controlling for these confounding variables, no significant differences were estimated in catch per set (except for YFT) or total lifespan catch between bio-FADs and con-FADs (Figure 20-21). However, this does not mean that the effect of bio-FAD construction on total lifespan catch is estimated to be precisely zero; instead, the estimates presented here suggest that the effect may lie between +8% and -15%, which includes zero.

As mentioned above, these estimated marginal effects control for potential confounders such as differences in the fishing strategy or capacity of vessels fishing bio-FADs versus con-FADs and differences in the spatio-temporal attributes of the variable in question (e.g., catch per set of different species in space and time). However, only observed variables can be controlled for without an experiment, which affects the strategy to robustly isolate the causal effect of bio-FAD status. As such, it is possible that the reported marginal effect sizes might still be affected by omitted variable bias due to omission of some unobserved variable that is correlated with the treatment (bio-FAD status) and the outcome (e.g., catch per set). For example, if vessels that do or do not primarily use bio-FADs have systemically higher or lower access to the acoustic data under the fished FADs, omitting this variable from the model might bias our results. However, the results presented in this document control for many of the obvious systemic differences between bio-FAD and con-FADs, and as such, present an improvement over analyzing raw differences between these two groups.

The results presented here are made possible by the work of purse-seine observers in the IATTC area. While these data are incredibly valuable, as shown here, and allow for rigorous monitoring of FAD use dynamics when at sea, they are limited in that FADs can drift out of areas where observers operate or be picked up or interacted with by vessels lacking an IATTC observer. Along with this observer database, the IATTC staff has now access, since 2022, to a robust database of satellite-linked buoy tracks associated with these FADs (Resolutions C-21-04 and C-24-01). These data, ideally complemented with the historic satellite-linked buoy data not available to the staff yet, could be used to inform efficient FAD recovery programs, incentive systems and spatial management options for the FAD fishery (e.g., spatial deployment risk indices). Such initiatives could play a key role in reducing FAD losses at sea, ultimately decreasing stranding events and supporting the science-based management of FAD numbers. Future studies could complement and enhance the observer data used here to better understand the fate of FADs that are not observed by IATTC observers, similar to what is described in Escalle et al. (2019). Since FADs may move between Convention Areas in the Pacific Ocean, collaboration at the Pacific Ocean scale between t-RFMOs and their scientific bodies is desirable.

Based on the above, the IATTC staff recommends that:

The IATTC take measures to secure the necessary data and resources to better understand the ultimate fate of unrecovered FADs, and enacts management efforts as appropriate to mitigate the impacts of FAD strandings and promote FAD recovery programs, including through the use of incentive systems and spatial management options.

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