Fisheries Research 233 (2021) 105763

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Performance evaluation of a shallow prototype versus a standard depth traditional design drifting fish-aggregating device in the equatorial eastern Pacific tuna purse-seine fishery

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ARTICLE INFO

Handled by Niels Madsen

Keywords:
DFAD depth
Echo-sounder buoy
Eastern Pacific Ocean
Purse-seine fishery
Tropical tunas

ABSTRACT

An at-sea experiment was undertaken to evaluate the performance of 150 shallow depth (5 m) prototype drifting fish-aggregating devices (DFADs) with rope appendages, compared to 150 standard depth (~ 40 m) traditional design DFADs with purse-seine net appendages, in the equatorial eastern Pacific Ocean tuna purse-seine fishery, seeking a solution to reduce purse-seine fishing mortality on undesirable sizes of bigeye tuna. Following concurrent deployments of the two DFAD types along transects, the average daily drift speeds were significantly different but similar as were the drift trajectories among the two DFAD types. Based on evaluations of the time-series of acoustic data from the echo-sounder buoys attached to the shallow and standard depth DFADs, the average time before aggregation by non-tuna species was 15.3 d (range: 3.2–65.5) and 18.2 d (range: 1.1–101.2), respectively, and the average time before aggregation by tuna species was 62.2 d (range: 3.3–248.3) and 70.2 d (range: 1.5–270.5), respectively. Analyses of the catch per set data for tunas and non-tuna species, using generalized additive mixed models with Bayesian inference, indicated no significant differences in catch rates from sets on shallow and standard depth DFADs. There was a similar proportion of bigeye tuna in the catch for purse-seine sets on the shallow and standard depth DFADs.

1. Introduction

Flotsam and jetsam in tropical and subtropical waters of the world's oceans have long been known to aggregate numerous pelagic species, including the three principle commercially important tropical tuna species, skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*Thunnus obesus*) tunas (Hunter, 1968; Parin and Fedoryako, 1999; Castro et al., 2002). Since the early 1990′s, industrial tuna purse-seine fisheries throughout the world have been exploiting the associative behavior of the three principle tropical tuna species by deploying anchored and drifting fish-aggregating devices (FADs) to more efficiently increase their catches (Fonteneau et al., 2013; Scott and Lopez, 2014). During 2013–2017 about 54 % of the global tropical tuna purse-seine catch came from sets on tuna aggregations associated with FADs (ISSF, 2019).

Drifting fish-aggregating devices (DFADs) normally consist of two components, a raft or surface component, and an underwater component affixed to the underside of the raft. Rafts are generally constructed of bamboo timbers laced together with synthetic twine, purse-seine corks added for flotation, all of which is wrapped tightly with purse-seine netting to improve durability. The underwater component suspended beneath the raft is commonly made from purse-seine net weighted with chain or cable. A satellite Global Positioning System (GPS) buoy with an integrated echo-sounder is commonly tethered to the raft for tracking and evaluating acoustic data for detecting presence of tuna aggregations (Hall and Roman, 2013; Lopez et al., 2014; Moreno et al., 2016). Purse-seine fishing on tuna aggregations associated with DFADs can be more efficient than targeting unassociated schools because it can reduce search time and fuel consumption. Setting on DFADs requires less skill by captains of purse-seine vessels than setting on unassociated schools, resulting in higher proportions of successful sets. However, purse-seine fishing on tuna aggregations associated with DFADs also has some concerning disadvantages, including higher bycatch rates of non-tuna species and high fishing mortality on small undesirable sizes of bigeye tuna, resulting in reductions in their yield per recruit and maximum sustainable yield (Dagorn et al., 2013; Hall and

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https://doi.org/10.1016/j.fishres.2020.105763
Received 13 January 2020; Received in revised form 23 September 2020; Accepted 26 September 2020
Available online 13 October 2020

Roman, 2013; Leroy et al., 2013; Restrepo et al., 2017).

Bigeye tuna in the eastern Pacific Ocean (EPO) are the principal target species of several distant water longline fishing nations and comprise a significant component of the catch by purse-seine fisheries targeting tuna aggregations associated with DFADs (IATTC, 2020a, 2020b). Based on the recent stock assessment by the Inter-American Tropical Tuna Commission (IATTC) for bigeye tuna in the EPO, twenty-six of the forty-four reference model runs suggest that the spawning biomass at the beginning of 2020 is lower than the maximum sustainable yield (MSY) level, and that the fishing mortality in 2017–2019 is higher than the MSY level (Xu et al., 2020). Conservation and management measures adopted by the IATTC to reduce both longline and purse-seine fishing mortality on bigeye tuna (Anonymous, 2017) have been relatively ineffective at reducing purse-seine fishing effort as the number of sets on DFADs shows an increasing trend over the past ten years (Xu et al., 2019).

Various investigations have been conducted to evaluate factors contributing to catches of bigeye tuna by purse-seine vessels in the Pacific, including investigations of spatiotemporal distribution of catch and effort (Sibert et al., 2012; Lopez et al., 2019), fishing gear configurations (purse-seine net and DFAD depths) (Lennert-Cody et al., 2008; Satoh et al., 2008; Delgado de Molina et al., 2010), fishing gear configurations coupled with bigeye hot-spot analysis (Escalle et al., 2017), as well as fine-scale behavior of bigeye relative to skipjack and yellowfin tunas around DFADs (Schaefer and Fuller, 2005, 2013; Leroy et al., 2009; Matsumoto et al., 2016), each attempting to reveal practical solutions for reducing purse-seine fishing mortality on undesirable sizes of bigeye tuna.

Although large dynamic time-area closures in the Pacific may be effective at reducing purse-seine fishing mortality on bigeye tuna, such measures may also significantly reduce the skipjack tuna catch due to overlapping high catch areas (Lennert-Cody et al., 2016; Anonymous, 2018). Also, it does not appear that reducing purse-seine net depth is a viable solution because of the necessary minimum net depth to capture skipjack tuna and the small differences in depth distributions between skipjack and bigeye tunas when associated with DFADs (Schaefer and Fuller, 2013; Leroy et al., 2006; Matsumoto et al., 2016). The study by Satoh et al. (2008) reported that DFAD depth in the western and central Pacific Ocean (WCPO) purse-seine fishery was not a significant factor as to bigeye tuna catch, but area/time effects were significant. However, Lennert-Cody et al. (2008) reported that DFAD depth in the EPO purse-seine fishery was a significant factor as to bigeye catch, as were area/time effects.

During the International Seafood Sustainability Foundation (ISSF) purse-seine skipper's workshop in Manta, Ecuador in 2015 (Hall and Murua, 2015) fishers were consulted on the idea of whether reducing the maximum depth of appendages suspended beneath DFADs to 5 m would be effective at minimizing interactions with bigeye tuna. Most fishers agreed that having deeper appendages should result in aggregating more bigeye tuna. It was the consensus of the fishers at the 2015 workshop that the DFADs with only 5 m depth appendages would drift too fast and thus would not aggregate the bycatch colonizing species and tunas as well as DFADs with deeper appendages (> 20 m).

The objectives of this study are to evaluate the performance of a shallow protype DFAD compared to a standard depth traditional design DFAD in the equatorial EPO tuna purse-seine fishery, including drift speeds and trajectories, aggregation times, and catch rates for tuna and non-tuna species, seeking a solution to reduce purse-seine fishing mortality on undesirable sizes of bigeye tuna, sharks, and turtles.

2. Materials and methods

The ISSF arranged for an at-sea experiment to be undertaken by scientific staff of the IATTC in collaboration with an Ecuadorian company, Negocios Industriales Real S.A. (NIRSA), so as to utilize their fleet of 13 purse-seine tuna vessels to evaluate the performance of a shallow prototype DFAD compared to the standard depth traditional design DFAD used by the NIRSA fleet operating in the equatorial EPO (Murua et al., 2016).

2.1. DFADs and deployments

The surface rafts for the standard and shallow depth DFADs were similar dimensions (approximately: 1.2–1.5 m x 2.0–2.3 m) and construction materials, consisting of approximately 8 cm diameter bamboo timbers, laced together with twine and tightly wrapped with purse-seine netting to keep them intact during deployments of six months or greater (Fig. 1a). The appendages hung beneath the standard depth traditional design DFADs were 37−46 m in length, consisting of 1 or 2 coils of twisted and tied scrap tuna or sardine netting weighted with chain (Fig. 1b). The appendages hung beneath the shallow depth prototype DFADs were approximately 5 m in length and consisted of 4 ropes (3–5 cm diameter each) attached to the corners of the raft and, at the bottom to a split bamboo frame weighted with chain. Two coconut palm fronds were tightly laced to each of the 4 ropes (Fig. 1c). The 5 m length for the appendages beneath the shallow DFADs was selected to provide what we anticipated to be adequate drag and habitat to successfully aggregate tunas and provide a large difference in depth to that of the appendages used with the standard depth traditional design DFADs.

Marine Instruments M3i echo-sounder buoys (www.marineinstruments.es) were attached to each of the DFADs deployed. The M3i buoy records, processes, and transmits acoustic data, including graphical displays and estimates of biomass (tons) beneath a DFAD at specified time intervals through the Iridium satellite network. The echo-sounder incorporated into the M3i is manufactured by Marine Instruments and operates at a frequency of 50 kHz with source level power of 189–199 [dB re μPa @ 1 m]. The cone angle is 36 degrees and at 50 m depth it has a 32 m diameter. The observed depth range extends from the surface to 150 m and is separated into fifty depth intervals of 3 m each. Pings are emitted from the transducer every 5 min with a proprietary configuration. A report is generated every 2 h which transmits the best sounding within that 2 h interval. Raw acoustic backscatter (Maclennan et al., 2002) is converted into biomass in tons using a MI proprietary algorithm. An estimate of the total tons of biomass is provided every 2 h, with a 1-ton total biomass threshold, and the highest of those biomass values is reported daily. The M3i buoy data from each DFAD deployed for this study was received in real time following deployments directly on a computer at IATTC headquarters utilizing MI software.

Initially 50 standard and 50 shallow depth DFADs were deployed from the NIRSA *FV* Milena A (62 m length, 900 t capacity), sequentially in pairs within about 100 m distance, along 7 transects between 3 °S -1 °N and 89°-107 °W during 25 June through 20 July 2015 (Fig. 2a). These 100 DFADs were monitored from June 2015 through October 2016. Next 100 standard and 100 shallow depth DFADs were deployed from the NIRSA *FV* Via Simoun (69 m length, 975 t capacity), sequentially in pairs within about 100 m distance, along 2 transects between 2 °S -2 °N and 100°-116 °W during 9–13 March 2017 (Fig. 2b). These 200 DFADs were monitored from March 2017 through December 2017. Each DFAD deployment was recorded by the navigator on a data form which included data fields for DFAD type, deployment position and date, M3i buoy number and the NIRSA ID numbers assigned and painted on each buoy. In addition, the IATTC observer aboard monitored and recorded the deployments to independently verify the DFAD types with the buoy ID numbers.

2.2. Experimental design

Drift speeds and trajectories were compared for the two DFAD types from first deployment until the DFAD was interacted with in some way. This included, being set by a NIRSA vessel, being set or stolen by a competing vessel, being repurposed, and termination of the experiment. Both the speed and bearing information from the buoy, as well as

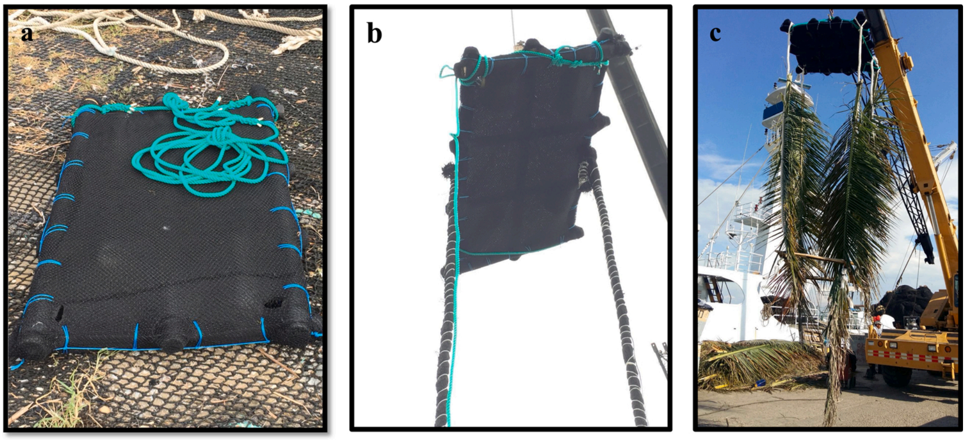

Fig. 1. Photographs of the surface raft used for all drifting fish-aggregating devices (DFADs) (a), the standard depth (~40 m) DFAD with purse-seine net twisted and tied appendages (b), and the shallow depth (5 m) DFAD with rope appendages and palm fronds (c).

information provided by the NIRSA captains were used to assess whether buoys had been interacted with. This analysis included speeds and trajectories recorded twice daily and from deployment until an interaction was determined to have occurred.

For estimation of the aggregation times of non-tunas and tunas at DFADs, previously reported depth distributions were used as criteria for classification of the daily acoustic data displays from the M3i buoys for assigning presence or absence of non-tunas and tunas. The depth distribution criteria utilized for non-tunas and tunas, when associated with DFADs, were derived from ultrasonic telemetry experiments (Schaefer and Fuller, 2005, 2013; Forget et al., 2015), and archival tag depth records (Schaefer et al., 2009). The criteria utilized for the classification of the time series of daily acoustic data was acoustic back scatter shallower than 25 m were assumed to be non-tunas and those deeper than 25 m were assumed to be tunas. The detection of non-tunas or tunas present at a DFAD, for the first time since it was deployed, was defined as the time at which any acoustic back scatter was recorded. This included instances where the presence of non-tunas and tunas was evident in the acoustic back scatter data but did not exceed the 1-ton biomass threshold of the marine instrument's software. Acoustic back scatter observed in the daily acoustic data needed to be present in one or more 2 -h intervals during daylight hours and for a period of > 3 days to be considered valid for classification of the presence of non-tunas or tunas at DFADs. Only the acoustic back scatter from buoys tethered to DFADs which were deployed for the first time were considered in this study in the estimation of aggregation times for non-tunas and tunas for the shallow and standard depth DFADs. To ensure the analyses of drift speeds and trajectories was only conducted for initial deployments of DFADs, a thorough review of the acoustic data for each buoy was utilized to determine whether DFADs had been set, stolen, or repurposed. In some instances, DFADS were stolen or removed from the water prior to non-tunas or tunas aggregating and were therefore not included in the analyses.

Estimates of non-tuna and tuna catches for each set were obtained and recorded by trained scientific observers following consultations with the vessel's engineer. These estimates are made for every set while executing duties outlined by the agreement on the international dolphin conservation program (AIDCP), including the completion of tuna tracking forms (TTF) mandated for all vessels fishing under the AIDCP (Anonymous, 2015). Observers are well trained in identification of non-tunas and tunas, including the identification and separation of small yellowfin versus small bigeye tuna (Schaefer, 1999). Estimates of the catch by species for non-tuna and tunas are made for each brail, a known volume. During the brailing process the vessels engineer carefully observes from below deck the catch going down the chute and into the wells. The chute system is wide just before entering the well so fish are spread out providing the engineer a clear look, which enables reasonably accurate estimates of the species composition within each brail. Once the brailing process is complete, observers consult with the engineer on the well deck, and the estimates of catches of non-tuna and tuna species are agreed upon and both parties collaboratively fill out the TTF.

An evaluation was conducted comparing the highest daily (24 h) biomass (tons) reported by M3i buoys attached to DFADs, during the three-day period prior to sets made by NIRSA purse-seine vessels, to the estimated total catch in tons. There were 67 sets analyzed, excluding 7 sets with no catch and 10 sets where acoustic buoy data wasn't available. A scatter plot of the data is presented along with the results from a correlation analysis.

2.3. Statistical modeling approach

Analyses of catch rates for tuna and non-tuna species were conducted using generalized additive mixed models (GAMMs) with Bayesian inference for sets on standard and shallow depth DFADs. These models were fit using the Stan computation engine with NUTS sampling (Stan Development Team, 2016; Carpenter et al., 2017) using the brms wrapper package for R (Bürkner, 2017). Implementation was applied using weakly informative regularizing priors (Gelman et al., 2008; Park and Casella, 2008) with posterior samples sourced from four chains and 12 k iterations after a warmup of 2000 iterations.

A Bayesian geoadditive GAMM, with hurdle lognormal likelihood, was fit to the set specific tuna species catch (tons) (Kammann and Wand, 2003; Wood, 2006; Gilman et al., 2018). The model was chosen because the lognormal likelihood distribution was appropriate for the catch in tons, and using hurdle accounts for the zero catch sets. The response variable was catch in tons, and there were ten predictors (DFAD type, days since DFAD deployed, proportion of bigeye present in the catch, georeferenced location, time of set, month of set, net depth, sea surface temperature (SST), chlorophyll *A* concentration (ChlA), and set as a random effect).

A range of geoadditive GAMMs were fit to the non-tuna species catch per set (number of individuals). The response variable was numbers of individuals caught given ten predictors (DFAD type, species group, days since DFAD deployed, location, time of set, month of set, net depth, SST, ChlA, and set as a random effect).

Leave-one-out cross (LOOC) validation was used to determine the best fit model from the suite of models fit with different likelihood functions (Vehtari et al., 2017). Model fits were evaluated using graphical posterior predictive checking procedures (Gelman et al., 2014) within the bayesplot package for R (Gabry, 2016). The four posterior predictive check tests for the best-fit Bayesian GAMM were a density overlay, maximum prediction and two summary statistics

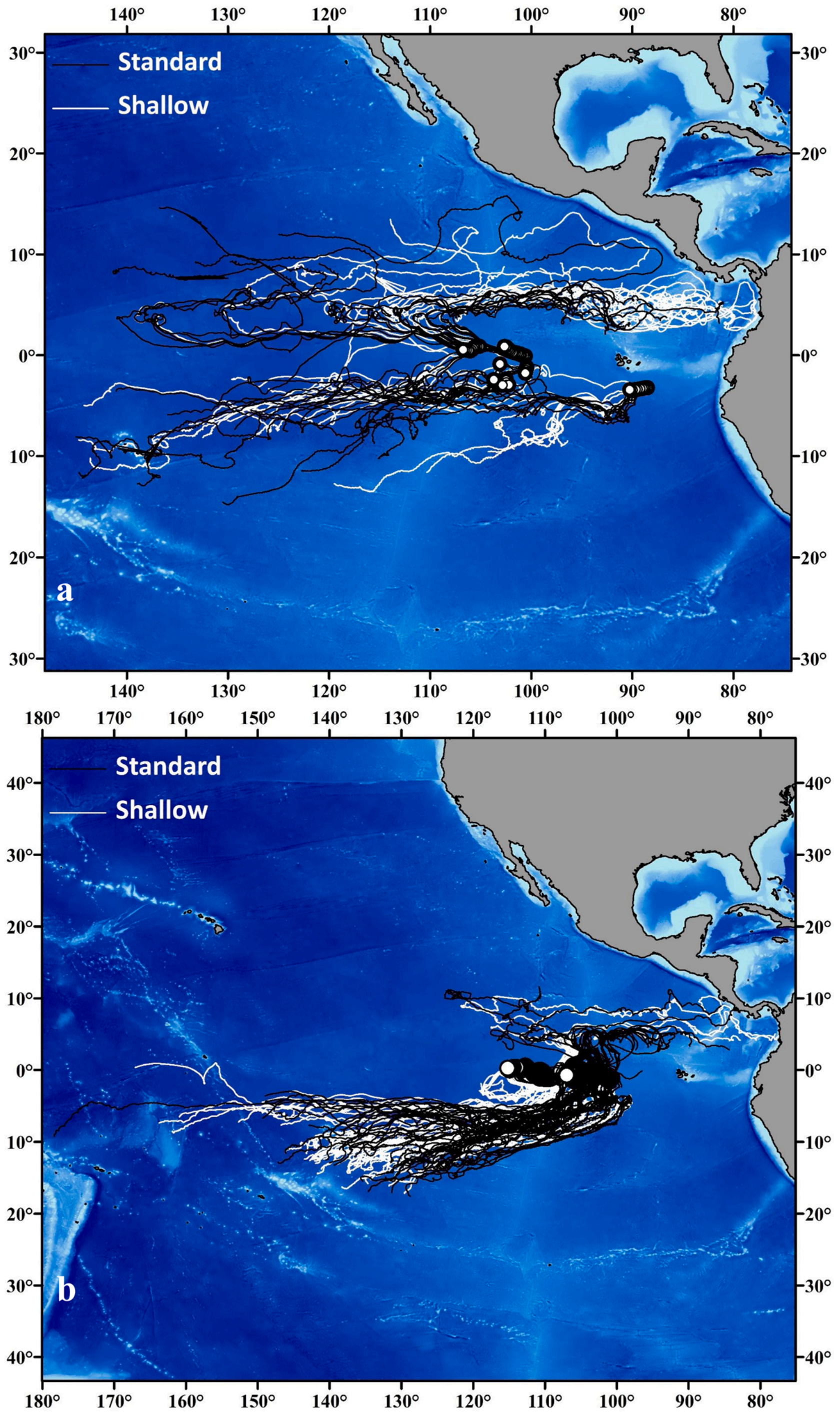

Fig. 2. Deployment locations and drift trajectories for the initial 100 (a) and subsequent 200 (b), concurrent deployments of shallow and standard depth drifting fish-aggregating devices (DFAD). The drift trajectories displayed are for the time period from first deployment until there was an interaction by a vessel with the DFAD.

(mean, standard deviation).

3. Results

3.1. Drift speeds and trajectories

The average daily drift speeds following concurrent deployments of 150 standard and 150 shallow depth DFADS over an average of 183.2 days (range: 6.7–429.0) and 176.4 days (range: 8.2–494.6) were 0.59 kn (range: 0–3.05) and 0.60 kn (range: 0.0–3.2), respectively. ANOVA indicated there was a significant difference in the drift speeds between the two DFAD types ($F = 65.37$, $P = 0.00$). The drift trajectories for the standard and shallow depth DFADs, from the first (Figs. 2a) and second deployment locations (Figs. 2b), were similar.

3.2. Aggregation times for tunas and non-tunas

The average number of days from the time each of 143 standard depth DFADs were deployed until there were non-tunas and tunas associated, based on evaluations of the acoustic data from the M3i buoys, was 18.2 d and 70.2 d, respectively. The average number of days from the time each of the 146-shallow depth DFADs were deployed until there were non-tunas and tunas associated, based on evaluations of the acoustic data from the M3i buoys, was 15.3 d and 62.2 d, respectively (Table 1). ANOVAs indicated that the number of days post-deployment before aggregation by non-tuna species is significantly less than the number of days post-deployment for aggregation by tuna species to standard depth ($F = 114.6$, $P = 0.0$) and shallow depth ($F = 148.6$, $P = 0.0$) DFADs. ANOVAs also indicate there is a significant difference between the standard depth and shallow depth DFADs in the number of days post-deployment before aggregation by non-tuna species ($F = 4.2$, $P = 0.04$), but there is no significant difference between the two types of DFADs in the number of days post-deployment before aggregation by tuna species ($F = 1.6$, $P = 0.2$).

3.3. Biomass estimates from M3i buoys

For 67 observations consisting of total biomass estimates derived from the M3i buoys, attached to standard and shallow depth DFADs, and the observed total catch from sets by the fleet of NIRSA purse seine vessels at those same DFADs, the correlation coefficient is 0.098 (Fig. 3). For 55 (82.1 %) of the 67 observations, there is a bias in overestimation of the total biomass reported from the echo-sounder buoys to be present at a DFAD compared to the actual total catch at that DFAD, with an average percent difference of 99.7 %.

3.4. Catch rates of tunas and non-tunas

There were only 49 sets on the 150 standard depth DFADs deployed (32.7 %) and only 35 sets on the 150-shallow depth DFADs deployed (23.3 %) by 13 NIRSA tuna purse-seine vessels during the period of 16 July 2015 to 11 June 2017, between 6° to 15°N and 81° to 149°W. The average total tuna catch per set on standard depth DFADs was 17.6 tons and on shallow depth DFADs was 22.6 tons. The average proportion of bigeye tuna per set on standard depth DFADs was 0.28 and on shallow DFADs was 0.26 (Table 2).

The Bayesian geoadditive GAMM, with hurdle lognormal likelihood, fit to the set specific tuna species catch, indicated there was no significant difference in catch rates between the two DFAD types as shown in Fig. 4. In the analyses of the tuna species catch rates, using the geoadditive GAMM, the effect of 9 of the 10 predictor variables were not significant, and only set, the random effect, was significant in accounting for much of the heterogeneity.

The best-fit model for non-tuna species catch per set was a Bayesian geoadditive GAMM with hurdle negative binomial likelihood. There was no significant difference in non-tuna species catch per set between the two DFAD types as shown in Fig. 5. The effect of 9 of the 10 predictor variables were not significant, and only set, the random effect, was significant in accounting for much of the heterogeneity in non-tuna species catch rates.

4. Discussion

Based on the results in this study there is no evidence that shallow depth DFADs will attract less bigeye tuna than standard depth DFADs in the EPO. Furthermore, the mixed layer depth (MLD) in the EPO is relatively shallow (Fiedler and Talley, 2006), and bigeye, skipjack and yellowfin tunas commonly remain above the MLD with overlapping

Table 1
Summary of aggregation times (days) by non-tunas and tunas for the standard depth and shallow depth drifting fish-aggregating devices (DFADs), estimated using acoustic data from the Marine Instruments M3i echosounder buoys tethered to those DFADs. The difference in numbers of observations (n) is due to DFADs not aggregating non-tuna or tuna during the study period, or DFADs being stolen or repurposed prior to an aggregation forming.

	Standard			Shallow		
	n	$\bar{x}$	Range	n	$\bar{x}$	Range
Non-Tuna	143	18.2	1.1 – 101.2	146	15.3	3.2 – 65.5
Tuna	128	70.2	1.5 – 270.5	130	62.2	3.3 – 248.3

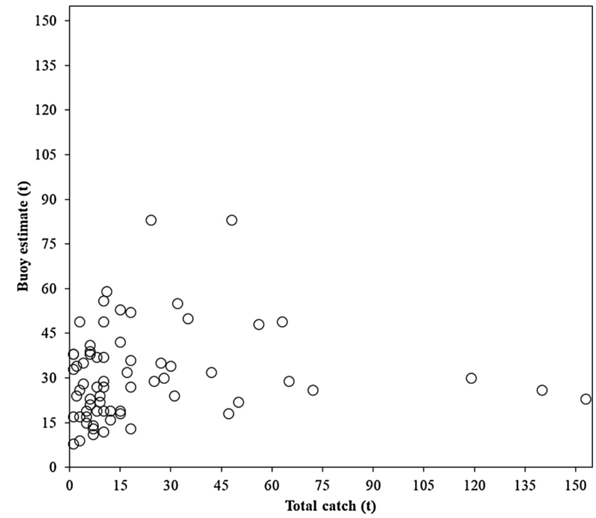

Fig. 3. Estimated total catch in each of 67 sets on drifting fish-aggregating devices plotted against the highest daily biomass value reported from the M3i echo-sounder buoys, during the 3-day period preceding the set.

Table 2
Metadata for 84 sets by the Negocios Industriales Real S.A. fleet of 13 purse-seine vessels for the standard depth and shallow depth drifting fish-aggregating devices, and catch statistics for skipjack (SKJ), bigeye (BET), and yellowfin (YFT) tunas.

	Standard	Shallow
Number of sets	49	35
Range in set dates	7/16/2015 – 11/06/2017	7/19/2015–10/13/2017
Range in set locations	15°S - 6°N 91°W - 148°W	10°S - 5°N 81°W - 149°W
Average (range) SKJ catch (t)	9.8 (1–117)	13.0 (0–144)
Average (range) BET catch (t)	6.6 (0–134)	6.7 (0–35)
Average (range) YFT catch (t)	1.2 (0–20)	2.9 (0–13)
Average (range) total tuna catch (t)	17.6 (0–140)	22.6 (0–153)
Average (range) proportion of BET	0.28 (0–0.96)	0.26 (0–0.83)

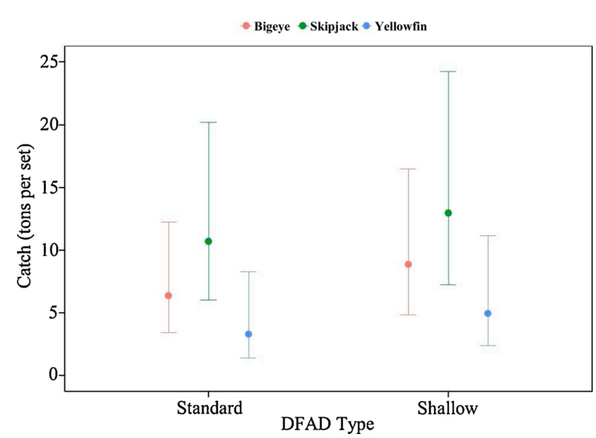

Fig. 4. Expected catch rate in tons per set by standard and shallow depth drifting fish-aggregating devices (DFADs) and the 95 % uncertainty intervals from fitting catch data for individual tuna species within a Bayesian geoadditive GAMM with hurdle log-normal likelihood.

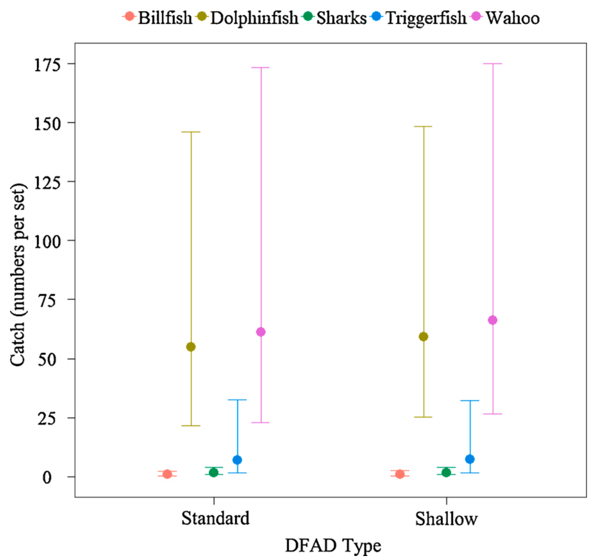

Fig. 5. Expected catch rate in numbers per set by standard and shallow depth drifting fish-aggregating devices (DFADs) and the 95 % uncertainty intervals from fitting non-tuna catch data for individual species within a Bayesian geo-additive GAMM with hurdle negative binomial likelihood.

depth distributions when associated with DFADs (Schaefer and Fuller, 2013).

Since in the WCPO where the MLD is significantly deeper and bigeye tuna exhibit somewhat greater depth distributions than skipjack and yellowfin tunas when associated with DFADs (Matsumoto et al., 2006; Leroy et al., 2009), it may be tempting to consider undertaking a similar experiment to this study. However, considering the average catch per set of bigeye tuna in the purse-seine fishery on DFADs in 2018 in the WCPO is less than 1.7 mt (Brouwer et al., 2019), much lower than that in the EPO of about 5 mt (Xu et al., 2019) it may not be feasible to determine whether there are significant differences in the proportions of bigeye tuna from sets on shallow versus standard depth DFADs in the WCPO, without obtaining a very large number of observations from tuna purse-seine sets on both DFAD types in order to have sufficient statistical power to detect any significant differences.

4.1. Drift speeds and trajectories

Contrary to the opinions expressed by purse-seine tuna fisherman at an ISSF skipper's workshop in Manta, Ecuador in 2015 that shallow depth DFADs would not perform well at aggregating tunas because they would drift too fast, compared to standard depth DFADs (Hall and Murua, 2015), the drift speeds and drift trajectories for the shallow and standard depth DFADs, were found to be similar in this study. The results in this study should not be surprising considering the aggregations of tunas in the EPO captured historically from purse-seine sets on various types of flotsam and jetsam included those with either very shallow or no subsurface structures (Hall et al., 1999). It would appear from the results in this study, and from other observations reported in the scientific literature, there is no justification in having subsurface appendages with a similar configuration as used in this study suspended beneath DFADs any deeper than 5 m to prevent DFADs from drifting too fast to attract aggregations of tropical tunas.

4.2. Aggregation times for tunas and non-tunas

The results of several investigations reporting the timeline before aggregation at floating objects in tropical waters by non-tuna and tuna species (Hunter and Mitchell, 1967; Castro et al., 2002), along with results from interviews with purse-seine tuna fisherman on this subject (Moreno et al., 2007a) are in agreement with the findings of the current study that the aggregation process of floating objects normally begins with non-tuna species.

Conflicting results to the pattern in the aggregation process of DFADs initially by non-tunas followed by tunas found in this study are reported by Orue et al. (2019a). Those authors evaluated the acoustic data sets from 962 Satlink echo-sounder buoys attached to DFADs in the Indian Ocean and concluded that the average times for tunas followed by non-tunas to aggregate at DFADs were 13.5 ± 8.4 and 21.7 ± 15.1 days, respectively. The same depth intervals as the current study, shallower or deeper than 25 m, were used as criteria by Orue et al. (2019a) in assessing echo-sounder buoy acoustic data for assuming the presence at DFADs of non-tuna and tuna species, respectively.

Orue et al. (2019a) also reported a significantly faster aggregation time by tunas on deeper DFADs in the Indian Ocean, but no significant difference in aggregation times for non-tuna species in relation to DFAD depth. Whereas in the current study there was no significant difference in the aggregation times by tunas with the shallow and standard depth DFADs, but there was a significantly faster aggregation time observed for non-tuna species on the shallow depth DFADs compared to the standard depth DFADs.

4.3. Biomass estimates from M3i buoys

The bias observed in overestimation of total biomass at DFADs from the M3i buoys in this study, appears to be caused by the common occurrence of micronekton in the acoustic data. Vertically migrating deep scattering layer organisms closely associated with the thermocline at night (Sameoto, 1986) are acoustically represented and the manufacturer's data processing algorithm does not exclude them, providing only estimates of total biomass.

The daily total biomass estimates provided by the M3i buoys are the highest value of the twelve 2 h time interval estimates. It appears more logical that the total biomass estimates from echo-sounder buoys should only be based on acoustic data collected during daytime, between the morning and evening periods of nautical twilight, with a minimum depth threshold incorporated, based on known daytime depth distributions for the three principle species of tropical tunas when associated with DFADs, by oceanographic regions. Escalle et al. (2019) reported total biomass estimates from 4546 Satlink (www.satlink.es) and 583 Zunibal (www.zuniball.es) echo-sounder buoys deployed on DFADs in the WCPO in 2016–2018 showed no relationship to actual catch, but that overall the biomass estimates by the echo-sounder buoys were higher than actual catches, as found in this study

Echo-sounder buoys are incapable of providing data for accurate estimates of the biomass of tuna aggregations at DFADs because they only receive acoustic data from the tunas within the relatively narrow cone of the echo-sounder and the aggregations are normally much more diffuse around DFADs, commonly extending out to a radius of at least 0.5 nm (Moreno et al., 2007b; Schaefer and Fuller, 2013). Echo-sounder acoustic data only provides information on what is within the cone area at any point in time, which is why captains and navigators of tuna purse-seine vessels commonly use omni-directional sonars aboard their vessels which provide information on the horizontal and vertical dimension of tuna aggregations from which they more accurately estimate the biomass in tons of tuna aggregations before making sets (Schaefer and Fuller, 2007; Fuller and Schaefer, 2014).

4.4. Catch rates of tunas and non-tunas

We used a similar analytical approach to that of Gilman et al. (2018) for the analyses of the effects of shallow versus standard depth DFADs on catch rates of tuna and non-tuna species. The analyses consisted of a Bayesian inferential procedure to fit GAMMs to the purse-seine set specific catch rates. A Bayesian statistical approach was chosen over frequentist statistics because it is fundamentally sound, very flexible, produces clear and direct inferences, and makes use of all available information (O'Hagan and Forster, 2004).

For purposes of this study it was assumed the estimates for tuna species catch per set, recorded by observers aboard vessels in consultation with engineers, were accurate. However, considering the difficulties in precisely estimating tuna species catch per set at-sea aboard vessels, bigeye catch compositions may be underestimated and those for skipjack and/or yellowfin overestimated (Anonymous, 2002, 2018; Murua et al., 2020). Any bias in these estimates of tuna species catch per set are assumed to be equivalent for sets on the shallow and standard depth DFADs. Similarly, estimates of non-tuna catch per set are equally representative of the catch from the shallow and standard depth DFADs. Observer estimates of total tuna catch per set, based on counts of the number of brails, are also assumed to be accurate. The study by Murua et al., 2020, in evaluating the performance of electronic monitoring (EM) aboard purse-seine vessels fishing in the EPO, reported the estimates for total tuna catch per trip to be similar between the observer, EM, and cannery estimates. All observers used the same methods to derive the catch estimates by set for tunas and non-tunas in this study, as part of their professional responsibilities, which are outlined in the TTF guidelines (Anonymous, 2015).

Although the average total tuna catch per set on shallow depth DFADs was 22.6 tons and that on standard depth DFADs was only 17.6 tons, the analyses indicated there was no significant difference in the total tuna catch between the two DFAD types. This result is due to the low statistical power to detect an effect because of the small number of purse-seine sets recorded for both DFAD types. The average proportion of bigeye tuna per set on shallow DFADs was 0.26 and standard DFADs was slightly higher at 0.28, but again because of the low statistical power no significant difference was detected in the average proportion of bigeye tuna per set between the two DFAD types. A future research priority for evaluating the performance of more environmentally friendly DFAD designs, including those that are non-entangling and biodegradable, should include a power analysis to design at-sea experiments with sufficient sample sizes to potentially detect significant differences in tuna and non-tuna catch rates.

5. Conclusions

Results of this investigation are informative regarding previously undocumented information on the performance of a shallow prototype versus a standard depth traditional design DFAD, including drift speeds and trajectories, aggregation times and catch rates of tuna and non-tuna species. The results of the catch rate analyses indicate the shallow prototype DFADs produced equivalent quantities of total tunas per set as those for the standard depth traditional design DFADS. However, the shallow depth DFADs did not aggregate significantly less bigeye tuna than the standard depth DFADs as indicated by similar proportions captured in sets on the two DFAD types.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This investigation was a collaborative effort between the International Seafood Sustainability Foundation (ISSF), the Inter-American Tropical Tuna Commission (IATTC), and Negocios Industriales Real S. A. (NIRSA). We are grateful to ISSF and the Food and Agriculture Organization's Common Oceans/Areas Beyond National Jurisdiction Tuna Projectfor providing the financial support to undertake the at-sea experiment. Special thanks to Victor Restrepo (ISSF, Vice President, Science) and Leonardo Aguirre (NIRSA, fleet manager) for their enthusiastic support throughout the project. We are grateful to Marine Instruments, especially Greg Hammann, for his technical support and guidance throughout the project. We also thank the IATTC and Ecuadorian National Program Observers whom assisted with this investigation by collecting essential data during trips aboard NIRSA purse-seine vessels. We are grateful to Greg Hammann, Victor Restrepo, and two anonymous reviewers for their constructive comments on earlier drafts of this article.

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