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Assessing the effectiveness of dFADs fishing moratorium in the Eastern Atlantic Ocean for conservation of juvenile tunas from AOTTP data

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Abstract

Targeting tunas associated with drifting Fish Aggregating Devices (dFADs) raises questions on the sustainability of tropical tuna fisheries. To limit catches of juvenile tunas, multiple time-area dFADs-fishing moratoria have been implemented by ICCAT since 1998. In this study we assessed the effectiveness of two different dFADs time-area closures implemented for the protection of both bigeye and yellowfin tuna juveniles. Using Atlantic Ocean Tunas Tagging Program (AOTTP) data from 2016 to 2019, we estimated the relative risk for individuals tagged inside the moratorium strata to be recaptured inside in comparison to the recapture rate outside the spatio-temporal strata. AOTTP releases were not homogeneously distributed in terms of areas and school type, therefore to assess the effect of the moratorium without potential bias a matching procedure was used to rebalance the release areas. As a result of the matching procedure and subsequent filtering applied to the dataset, the number of bigeyes recaptures retained inside and outside the time-area closure were below the threshold from which any conclusion could be drawn. In contrast, our results show that a majority of yellowfin and skipjack tunas tagged within the closed area stayed within the closed area during the moratorium period. Consequently, the last moratorium can be considered as effective for these two species, at least during the months of fishing ban on dFADs.

Keywords:

FADs, tropical tunas, time-area closure, tagging, relative risk, propensity score matching

1. Introduction

Small bigeye (*Thunnus obesus*) and small yellowfin (*Th. albacares*) tunas aggregate in mixed schools with skipjack (*Katsuwonus pelamis*) and can be found in association with drifting fish aggregating devices (dFADs) (Ariz et al., 1999; Hallier and Parajua, 1999). A majority of yellowfin and bigeye tuna associated with dFADs are sized between 35 and 65cm FL (Pascual-Alayon et al, 2020; Duparc et al., 2020) and are considered as juveniles (both species reach size of 100-110 cm FL at 50% maturity; ICCAT, 2016). Skipjack, the main tropical tuna species fished on dFADs, is composed of juveniles and adults (L50 around 42-50 cm FL; ICCAT, 2016). The proximal and distal mechanisms behind aggregating behavior of tunas and skipjacks associated with floating objects are still unknown (Fréon and Dagorn, 2000; Castro et al., 2002), and the ecological effects, i.e., on habitat structure or foraging efficiency, need to be further explored (Hallier and Gaertner, 2008). Consequently, one of the challenges of the multispecies characteristic of tropical tuna fishery on dFADs is to catch skipjack while limiting the impact on the juveniles of the two other species of tunas. Indeed, increase in fishing mortality for juveniles of bigeye and yellowfin tunas was evidenced since dFADs-fishing started in the 90's and have become one of the main purse-seine fishing methods since the 2010's in both Atlantic and Indian oceans (Gaertner et al., 2015, Maufroy et al., 2017). In addition to the increasing number of dFADs deployed at sea, new fishing technologies, like GPS buoy and echosounder equipped dFADs, have been introduced, which allow fishermen to know in real time the location of the dFADs (Torres-Irineo et al., 2011; Lopez et al., 2014; Maufroy et al., 2017) and estimate of the associated biomass (Baidai et al., 2020). This was shown to have a positive effect on the fishing efficiency of the purse seiners (Wain et al., 2020). Subsequently, catches of skipjack but also yellowfin and bigeye tuna juveniles, and thus their mortality, have increased in the Atlantic tropical tuna fisheries (ICCAT, 2019a). This historic trend raises concerns about the sustainability of bigeye and yellowfin stocks exploitation since an excessive catch of small fishes can lead to increased overfishing. The increasing number of dFADs , associated with a general excess fishing capacity, may have contributed to the fully-exploited status of the Atlantic yellowfin (ICCAT, 2019a), and bigeye overfished status (ICCAT, 2021).

In response to the state of bigeye tuna stock at that time, the European tuna producer organizations established a voluntary moratorium – defined as a time-area closure – on dFADs fishing in 1997 (Goujon, 1998). The moratorium was subsequently adopted by the International Commission for the Conservation of Atlantic Tunas (ICCAT) in 1999 as a mandatory management measure to reduce the mortality of yellowfin and bigeye tuna juveniles by dFADs-fishing (Rec [98-01], ICCAT, 1998). Until 2019, four spatio-temporal moratoriums have been successively implemented in the Gulf of Guinea (Table 1; Fig. S1) but none were based on a real ecological and scientific knowledge resulting from proposals made by the Standing Committee on Research and Statistics (SCRS) of ICCAT. In 2019, the SCRS evaluated the effect of the Rec [15-01] moratorium using the ICCAT 1°x1° catch data and concluded that the moratorium was ineffective because there was no significant reduction in the annual catch. Several other studies have questioned the usefulness of past moratorium for protecting juveniles of tropical tunas in the Eastern Atlantic Ocean, but results were inconclusive or did not assess the effectiveness of the moratorium for all three tropical tuna species (Torres-Irineo et al., 2011; Fonteneau et al., 2016; Deledda et al., 2019).

The Atlantic Ocean Tuna Tagging Program (hereafter, AOTTP), which started in 2016 and ended in 2020, provided an opportunity to collect new information about tuna movements and investigate the effectiveness of the ICCAT time-area closures by supplying tag-return data for tropical tuna species over the whole ICCAT convention area. Following the method from Lambert et al. (2006), a first study from Deledda and Gaertner (2019) used the relative risk (RR) as a metric to assess the effect of the Rec [15-01] moratorium using AOTTP tag-return data. The RR (Daniel, 1999) is a metric which is traditionally used in health science and epidemiology "*to compare the occurrence of a disease or other health outcome between two groups: a group that is exposed to a certain treatment or risk factor—the exposed group—and a group that is not exposed to this treatment or risk factor, which is called the unexposed or control group*" (Noordzij et al., 2017). Until now the RR has been little used in fisheries science, mainly for assessing the bycatch survival using tag-return data (Hueter et al., 2006; Schopka et al., 2010; Rudershausen et al., 2013; 2019). Lambert et al., (2006) was, to our knowledge, the first study using RR to assess the effectiveness of a marine protected area (MPA).

The preliminary analysis led by Deledda and Gaertner (2019) showed that the 2017-2019 ICCAT moratorium (Rec [15-01]; ICCAT, 2015) was effective to avoid recapture of yellowfin juveniles within the moratorium time-area stratum. However, this study did not account for the heterogeneity in the AOTTP release process, leading to potential bias in the estimation of the RR. Indeed, due to different constraints (e.g., availability and survival of live bait aboard the tagging ship, tagging agreement within EEZ), the AOTTP marking framework was not a randomized sampling design. Tunas of different sizes were marked and released in different quantities between school types/structures (i.e., dFADs, anchored FAD, seamount, etc.) inside or outside the moratorium area defined in Rec[15-01] (i.e., between the «treated group» and the «exposed group» respectively). Based on the different attractiveness of these school types, the comparison between tunas marked inside and tunas marked outside the moratorium area might be biased due to the difference in number of school types sampled at release and at recapture. A solution to these issues can be found by calculating of the propensity score (PS), which is another health sciences inherited method. The PS is the probability of receiving one of the treatments being compared, given the measured covariates. The aim of propensity score matching (PSM) is to subsample the individuals from the exposed group and the treated group to keep only individuals that are comparable (Rosembaum and Rubin, 1983; Olmos and Govindasamy, 2015), e.g., here, in terms of release school type. As such, we use a PSM method in order to rebalance the sampling design with the aim to provide an unbiased estimate of the RR to assess whether the past dFADs-moratoriums Rec [98-01] and Rec [15-01] were effective in protecting juveniles of tropical tuna.

2. Material and methods

2.1. *The ICCAT moratoria and the Atlantic Ocean Tuna Tagging Program framework*

At the beginning of 1998 ICCAT implemented four separate spatio-temporal dFAD moratoriums in the Gulf of Guinea, where the purse seiner fishing effort is concentrated (**Fig. S1** in supplementary material), designed to reduce fishing mortality on multi-species aggregations associated with dFADs. The Gulf of Guinea is heavily influenced by northeast winds and the Guinean current, creating an oceanographically dynamic habitat with highly productive surface waters (Koranteng, 1995) suitable for various pelagic species, including tunas. These closures temporarily limit fishing effort on dFAD activities during several months within specified areas (**Table 1**). The Rec [15-01] moratorium was active in January and February during the AOTTP period limiting both dFAD catch and tag/recapture data in this area and making exploration of other area closures impossible. Consequently, it was only possible to assess the effectiveness of moratoria sharing the same regulation area: Rec [98-01] and Rec [08-01] moratoria. To simplify, we will hereafter use Rec [98-01] to designate both Rec [98-01] and Rec [08-01] moratoria. In addition, because Rec [98-01] and Rec [15-01] were not implemented during the same months (1st November to 31st January *versus* 1st January to 28th February), we recreated the effect of Rec [98-01] during November and December months by filtering out the recaptures made on dFADs during both November and December.

The AOTTP started in July 2016 and lasted until 2020 with a series of tagging campaigns in several regions of the tropical Atlantic Ocean (**Fig. 1**). A large majority of the releases (96.6%) were dominated by fish of length ranging between 21-80 cm FL[1], with average lengths of 51 cm (skipjack), 65 cm (yellowfin) and 67 cm (bigeye). The boats used for tagging were mainly live bait pole-and-line boats or small vessels dedicated to recreational activity. The tagging itself was conducted around

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[1] See AOTTP-ICCAT web page. https://datastudio.google.com/reporting/d6fb6831-a27f-4a85-a19c-8fe0bf662599/page/NoepB

different tagging school types, such as anchored FADs (aFADs), drifting FADs (dFADs), free schools (FSC), at the neighbouring of seamounts (SMO), and to a lesser extent atmospheric buoys, schools associated with the tagging boat or natural logs. Records of recovery are principally made at landing.

2.2. *Filtering with a time at liberty threshold*

To disentangle the natural movement of tunas and the potential disturbing effect of the tagging event on the fish released, a filter was applied to release-recapture data based on short time at liberty. According to ecological assumptions on the attractiveness of tropical tuna to floating objects (Hallier and Gaertner, 2008), we assumed that tunas released in free schools behave without disturbance and thus should be considered as the tuna movement reference behavior. As it was evidenced that for short time at liberty the movement of tuna can be impacted by the characteristic of the school type at release (e.g., a fixed structure such as seamount or aFAD), we conducted for each species released and recaptured in free school, a pair-wised Wilcoxon test between each tuna moving distance box plot to determine the threshold beyond which tunas' displacement is assumed to be unaffected by the stress suffered by the fish during the tagging event. Then, we assumed that this short-term disturbing effect is the same for tunas tagged in other school types and removed recaptures with a time at liberty lower than this threshold.

2.3. Rebalancing the tagging sampling plan with a matching procedure

Tag-recaptures are not homogeneous over time and the distribution of recoveries are asymmetrical among fishing gears, dominated by purse seiners and live bait pole-and-line vessels with only a few recoveries reported by longline vessels. Each of the tagging events are independent and therefore school types were not sampled in the same way. Consequently, the distribution of school types is uneven especially between outside and inside the moratorium (**Fig. 1**, **Table 2**). Comparing the distance travelled at time at liberty, shows that tuna moved less when associated with a fixed school type (e.g., seamount, aFAD) than when released in other conditions (**Fig. 2**). This observation has a consequence regarding the comparability of the tunas and must be considered to assess the causal effect of dFAD fishing closure for the protection of juveniles tropical tunas. In randomized sampling, treated and control groups can often be compared directly because the units (here, the individuals) are likely to have similar characteristics, while in non-randomized sampling, a direct comparison may be inaccurate because the units exposed to one treatment differ systematically from the control group (Rosenbaum and Rubin, 1983). In most fishing datasets used to estimate a causal effect of a treatment variable it was evidenced that the treatment variable is not independent to the background covariables, due to the constraints linked to the recollection of commercial data (Rosembaum and Rubin, 1983). A solution to compare two groups with different treatment is to use matching methods to identify a group of control units that is comparable to treated units (Authier et al., 2013). The propensity score facilitates the construction of matched sets with similar distributions of the covariates, without requiring close or exact matches for all the individual variables (Stuart, 2010). Here, matching was conducted on all tagging data to identify a control group among juveniles tagged outside a dFADs time-area closure period. PSM is the most used matching method (Rosenbaum and Rubin, 1983), achieving comparability between treatment and control groups using a univariate score that integrates several variables thought important to be balanced (Shipman et al., 2017). PSM is estimated as the linear predictor in a logistic regression wherein the response variable is either a unit (here a tuna) which received the treatment of interest (that is tagged during a dFADs fishing closure, value = 1) or not (value = 0). The goal is to find in the entire dataset a subset of observations similar to one that would result from a perfectly blocked, and possibly randomized, experiment (**Fig. S2**). With the objective to disentangle the effect of noisy factors we needed to match individuals tagged inside the moratorium area with comparable tunas tagged outside the area. PSM thus involves first the estimation of a PS, which is the probability of receiving a treatment, here defined as an individual being tagged within a dFADs time-area closure.

The GAM used for PS estimation was:

$$T_i|X_i \sim \mathcal{B}(\Pr_i)$$

$$\text{Logit}\,(\Pr_i) = PS_i = \beta_0 + \beta_1 \times \text{ Length at tagging}_i + \beta_2 \times \text{ School Type \_i}$$

Where B denotes a Bernoulli distribution and Ti takes the value 1 when tuna i was tagged inside the dFADs-fishing moratorium, and 0 otherwise. Covariates X_i are any of the variables measured at tagging event.

Covariates included in the GAM were the fork length of the tuna and the school type, both at release. Fork length was chosen because we assumed the mobility of an individual can be linked to its size (Hallier, 2005); and school type, because there was some evidence that the range of displacement of a tagged fish is impacted by the nature of the school type at release. In addition, it was showed that the proportion of school type at release differed inside and outside the moratoriums.

Once the PS has been estimated for each individual, the matching procedure was performed with the R package *Matchit* (Ho et al., 2011). By default, the PS matching goes in descending order from the highest PS to the lowest PS. This allows the units that normally do not find close match to be matched first. However, in our case, this method led to matched pairs that had different PS due to different characteristics. To deal with this issue, we applied a random nearest neighbour method, where the treated units were drawn at random and matched with the nearest neighbour into the control group. To cap the PS difference in the matched pairs at less than 20% of the standard deviation, we set a calipee length to $0.2 \times \hat{\sigma}$, where $\hat{\sigma}$ is the empirical standard deviation of the PS distribution. To sum up, with the PSM, each tuna tagged outside the moratorium is paired with one tuna tagged inside the moratorium of the same school type at tagging event and the same size class (+- 5cm).

2.4. *Recapture and Relative risk*

Following Lambert et al. (2006), we assessed the effectiveness of moratorium strata using the RR metric. The RR is the ratio of 2 proportions (i.e., rates):

$$RR = \frac{p_{out}}{p_{in}}$$

Where p_{out} is the proportion of individuals recaptured among those tagged outside the area of the moratorium, and p_{in} is the proportion of individuals recaptured among those tagged inside the area of the moratorium. To echo epidemiology terminology, the individuals tagged outside the moratorium are considered as the “exposed group” which is exposed to the “being captured” risk. The individuals tagged inside the moratorium are considered as the “treated group”, where the treatment is the moratorium, which is supposed to protect individuals from being captured. If RR is greater than 1, the recapture rate is lower for tunas tagged inside the moratorium meaning that the regulation is effective. Conversely, a RR lower than 1 means that the recapture rate is higher for the fish tagged inside the moratorium, i.e., the regulation has a deleterious impact. To compute the RR, we selected only the total number of fish tagged and recaptured during the months of the closure. A preliminary analysis showed that the RR might be influenced by a low number of individuals recaptured among fishes tagged inside the moratorium (i.e., a number of individuals too low to estimate p_{in}). Because matching involves a stochastic component with a random nearest neighbour pairing, output from this procedure could, by chance, generate some differences in the number of matched pairs of juvenile tunas between two algorithm runs. Due to the uncertainty in matching, we found that the number of matched tunas could vary about ± 5 individuals between iterations. This difference should not significantly affect the numerator p_{out} because the number of recaptured individuals in the outside group was high. However, because the number of tunas tagged inside and recaptured anywhere was generally low (<10) and reached 0 in some cases, it might have an effect on the denominator p_{in} and, consequently, on RR. To deal with this issue, we ran the algorithm 5000 times for each species and moratorium case, to get a distribution of RR values that account for the matching uncertainty (**Fig. S3**).

2.5. *Commercial catch data*

To check if the RR unbiased estimation gives a realistic assessment of the moratoria efficiency, we used the ICCAT Task II purse-seine catch by 1°x1° degree square x month by fishing mode. We mapped the monthly dFAD catch data for the period 2017-2018, to identify a potential change in dFADs-fishing behavior during and outside the time/area closure of Rec [15-01] moratoria implementation.

3. Results

3.1. *Filtering with a time at liberty threshold*

To evaluate whether a tagging event may disrupt natural movements or initial displacement, linear displacements for each species were aggregated into time at liberty bins. Only individuals in free schools were considered in the analysis and the results showed a significant increase in the distance travelled after 3 days at liberty for skipjack and yellowfin (pair-wised Wilcoxon test *p-value* = 2.8×10^{-7} and 1.2×10^{-13}, respectively), whereas there was no significant increase for bigeye tuna (*p-value* = 0.08) (**Fig. 3**). We considered this 3-days threshold to represent a reasonable trade-off between methodological consistency and species-specificities and thus filtered out all individuals tagged in all school types across the 3 studied species with less than 3 days of liberty. Filtering out tunas with less than 3 days at liberty excluded a small fraction of data: during the moratorium period (both Rec[15-01] and Rec[98-01]), less than 1% of individuals per species were under this time at liberty limit.

3.2. *Rebalancing the tagging sampling plan with a matching procedure*

Before matching, i.e., with the initial dataset, the distributions of PS of yellowfin tunas tagged inside and tagged outside the moratorium were significantly different (discrete Kolmogorov-Smirnov test *p-value* < 2×10^{-16}, $D = 0.06$) (see left part of **Figure 4**). The PS distribution of the initial sample groups showed a similar main mode around 0.4, but also two distinct peaks which means that many individuals are not comparable between the two groups. The low values mode corresponds to tunas tagged inside the moratorium which have a low probability of belonging to the outside group. On the contrary, the high value mode in the outside group PS distribution corresponds to individuals that have a high probability of having the same characteristics, and hence, to belong to the outside group. The PSM procedure aims to remove these distribution tail modes (up to 45% of data available) and keep the central mode corresponding to comparable individuals. The balance of the samples was highly improved (**Fig. 4,** right part) while the distribution of the adjusted sample was statistically not different (*p-value* = 0.06, D = 0,42). The fact that the PS distributions where comparable in the balanced sample allowed to estimate an unbiased RR (the same matching procedure was applied to skipjack tuna, **Fig. S4**).

3.3. *Relative risk*

For both Rec [15-01] and Rec [98-01] moratoriums, the RR was much greater than 1 meaning that they were effective for protecting both juveniles of yellowfin tunas and skipjack tunas (**Table 3**). No bigeye tuna tagged inside the moratorium and recaptured was kept by the matching procedure, in any of the 5000 iterations for each moratorium, even when we expanded the time period to three months (for Rec [98-01]). Consequently, the effectiveness of these moratoriums on bigeye tunas could not be assessed. No clear difference in effectiveness was detected between the Rec [15-01] and Rec [98-01] closure periods.

3.4. *Commercial catch data*

ICCAT Task II catch data showed that the Rec [15-01] moratorium, which was implemented in January-February 2017 and January-February 2018, induced a significant reduction in catch within its time-area closure (**Fig. S5**). During the months of closure the dFADs catch dropped to near zero inside the moratorium area (0.1% and 0.4% of the total dFAD catch in January and February respectively) which accounted for 58.4% and 65.5% of the total dFAD catch in December and March – the months before the beginning and after the end of the closure, respectively. As the moratorium area was fished only for free schools during the closure it is logical that the number of recoveries inside the area is low, which impacts the total number of recoveries in all areas. This explains the high RR values observed in our study.

4. Discussion

4.1. *Moratorium effectiveness*

The main objective of ICCAT moratoria was to reduce juvenile tuna catches associated with dFAD-fishing. We showed that the dFAD moratoriums put in place by Rec [98-01] and Rec [15-01] were effective to limit the catch of small yellowfin tunas and skipjack tunas. A RR greater than 1 means that tunas tagged within the closed area stayed within the closed area during the moratorium period. Applying a matching procedure to minimize the bias due to confounders, our study reinforced the preliminary results of Deledda and Gaertner (2019) on the effectiveness of Rec [15-01] to protect juveniles of yellowfin, at least during the months of the closure because the results may be different when using year-round data. In contrast no conclusion can be drawn for bigeye tuna due to the low number of release-recapture in the strata of interest. It must be stressed that previous works highlighted the weak effect of Rec [98-01] to Rec [11-01] to reduce purse seiners catch because purse seiners showed high mobility and reallocated their effort to fishing grounds surrounding the moratorium area (Torres-Irrineo et al., 2011; Fonteneau et al., 2016). Our results may differ from previous cited works because we did not use catch data to assess the effectiveness of the moratorium and we only looked at the RR between the beginning and the end of the period of closure. The RR results showed that extending the closure from 2 to 3 months, as was the case in Rec [98-01], was still efficient but did not increase the protection effect; likely because tuna have more chance to leave the closed area for a longer closure period. However, we still have little evidence of how another closure area could outperform Rec [98-01] and Rec [15-01] area in terms of effectiveness. As an alternative solution, Dunn et al. (2016) discussed the fact that mesoscale (month/10^2 km scale) time-area closures could be improved in their efficiency by using finer-scale (1–10 km) dynamic management measures. It was shown that such a management scheme would be more efficient for highly mobile pelagic species such as tropical tunas and their associated species and could have both positive ecological and economical after-effects (Armsworth et al., 2010; Lewison et al., 2015, Hilborn et al, 2021 and Pons et al., 2022). As such, we suggest exploring the possibility of establishing moratorium and/or applying spatial dynamic management in areas previously defined as an ecologically important area for tunas, such as essential fish habitats (EFH). EFHs, if identifiable for tunas, may be better potential areas to improve the protection of the main tropical tuna juveniles, since they act as nursery or foraging zones for juveniles (Rosenberg et al., 2000).

4.2. *The challenges of pelagic time-area closures*

Permanent marine protected areas (MPAs) and time-area closure have been increasingly used as a key strategy for both fisheries management and conservation of marine biodiversity. They showed some benefits such as the restoration of the ecological states of habitats (Turner et al*.*, 1999), increasing biomass and biodiversity (Vilas et al., 2020) and reduction of bycatch (Hobday and Hartmann, 2006; O'Keefe et al., 2014; Hoos et al., 2019). However, numerous authors pointed out the scarcity of preliminary studies before the designation of MPAs that led to non-optimized areas and/or seasons of closure, specifically for pelagic species (Field et al., 2006; Abbott and Haynie, 2012; Kaplan et al., 2010, 2013; Hilborn et al., 2021). Pelagic species, such as tropical tunas, are highly mobile and their migratory behavior is still poorly understood. Their conservation framework thus led to the designation of exceedingly large protected area, which consequently have significant costs (Game et al., 2009). Kaplan et al. (2010) discussed how a targeted approach, with local fishing closures on nurseries or spawning sites might be implemented to optimize the management. However, in practice, this targeted approach may fail because excessive fishing effort may be concentrated at the borders of the MPA (a common harvesting tactic known as "*fishing the line*"). Because of the known significant spillover for large pelagic species, the "*fishing the line*" effect would counterbalance the benefits of the MPA (Kellner et al. 2007; Torres-Irineo et al., 2011). Using effort data, Torres-Irineo et al. (2011) showed a clear "*fishing the line*" effect at the borders of the previous Rec [11-01] moratorium, but in the absence of a statistical analysis we did not notice such a large effect during the Rec [15-01] period, even if significant catches were observed at the borders of the moratorium area (**Fig. S5**). In light of the results discussed in the previous section, one of the explanations for the effectiveness of the moratoria was the compliance of the dFADs spatio-temporal closure by the tropical purse-seine fishery. Such acceptance from the fishing industry to observe a moratorium suggests that a less restrictive scientific-based definition of time-area closure (e.g., alternate smaller mobile strata) could be respected and may obtain similar or better efficiency in terms of reduction of juvenile catches. However, we must keep in mind that some uncertainty remains, e.g. is the decrease in catch due to natural seasonality or to the consequence of the ban on FAD-fishing. For all these reasons the Standing Committee on Research and Statistics (SCRS) of ICCAT recommended further analysis to identify months that minimize yellowfin and bigeye juvenile catches while maintaining skipjack catches (ICCAT, 2021).

4.3. ***Advantages and disadvantages of RR and possible alternative methods***

Until now the RR has been little used in fisheries management and time-area closure assessment. However, RR is mainstream in epidemiology, a discipline which is also plagued by a limited ability to perform random sampling (Maldonado and Greenland, 2002). Aside from Deledda and Gaertner (2019) for tuna fisheries, few papers applied this metric to answer marine ecology issues. By using tagging data, Lambert et al. (2006) assessed the efficiency of a marine sanctuary on blue crab (*Callinectes sapidus*) spawning stock zone using RR, and, Hueter et al. (2006) used a logistic model to compute RR as an estimator of the survival of shark bycatch in gillnet fisheries. This justifies the choice of RR because conventional tagging data are moderately accessible, and the metric is easy to compute and interpret.

However, a small relative change in the probability of a common event's occurrence can be associated with a large relative change in the opposite probability, i.e. the probability of the event not occurring (Simon et al., 2001). RR: (1) is sensitive to covariates, such as fisheries dependent variables (e.g., catchability and fishing effort) that influence the response variable (here, the recapture of the tagged fish), and (2) will be affected by the balance of the initial sampled dataset. An issue to deal with is the integration of the covariables in the model (Hueter et al. 2006). To reduce a potential bias when computing the RR, we used the matching procedure which is a simple and relatively fast way to create a control and a treated group composed of individuals-sharing the same characteristics. Nonetheless, we do not recommend this methodology when the data are scarce, especially if the unadjusted groups are too different, as the exclusion of some individuals in each group may have an important effect on the RR value. To overcome this aspect, Rudershausen et al. (2014, 2019) implemented a RR computation in a Bayesian framework to assess bycatch survival in long line fisheries. The Bayesian model was fitted to deal with the spatial heterogeneity in the treatments and the variations of recapture effort between sites and provided robust estimates without losing any data. This Bayesian framework for RR could be a promising approach to improve the assessment of the efficiency of the ICCAT spatio-temporal management measures in the future.

4.4. ***Strengths and weaknesses of the AOTTP framework***

Our study provides an answer with regards to evaluating the efficiency of spatio-temporal conservation issues with AOTTP data. Although AOTTP data give priceless information on tuna movements, we showed that future studies must pay attention to the stratification of release conditions (tagging structures, such as school types, and time and area tagging operations), as it has a large impact on the estimates of the movement rates between areas. The matching methodology allows us to rebalance the initial sampling plan before performing the RR calculation to compensate for the lack of randomization and homogeneity in the AOTTP tagging data. However, this procedure led to discard large amount of data, testifying of a sub-optimal sampling design, particularly in the case of bigeye. Indeed, less strict settings (e.g., not considering the length at release in the matching procedure) might be necessary to preserve a significant quantity of bigeye capture-recapture data. However, this is not a criticism of the matching procedure but rather highlights the need for a better design of the sampling protocol for a future tagging program. This loss of data could result from the insufficient tagging effort on bigeye (e.g., choice of spatio-temporal strata or school types less attractive for bigeye), despite the fact that its level of exploitation is the most critical among the three species of tropical tunas.

Beyond the use of the RR, tag-return data can be used in various ways for the assessment of MPAs effectiveness. Schopka et al. (2010) used a closed approach by comparing the distribution of recoveries between the studied protected area and the surrounding areas, highlighting issues with fisheries dependent recaptures as well. As for many fisheries studies, recoveries are conditioned by fishing activities and the sampling design is not optimal "*a priori*" for scientific studies. The use of conventional tags to assess the effectiveness of a moratorium may seem paradoxical to the extent that the decrease in fishing effort inside the area of closure decreases the probability to recover a tagged fish. One option, suggested by Schopka et al. (2010), is that adding electronic tagging or telemetry data would compensate the inherent limitations of the AOTTP tag-return approach in the evaluation of spatio-temporal moratorium on dFAD.

5. Conclusion

The AOTTP data gave reliable information to assess the effectiveness of the Rec [15-01] and Rec [98-01] moratoriums on dFADs-fishing in the Eastern Tropical Atlantic Ocean. Although methodological adjustments to rebalance the sampling plan was necessary, the estimation of RR using tag-return data was valuable to assess whether a dFADs time-area closure could be an effective regulation measure to reduce the catch of small/juveniles of yellowfin tuna and of skipjack. However, the RR method did not give a quantitative measure of the moratorium effectiveness at the annual scale and thus, there are still uncertainties pending concerning the potential effects of the time-area closures on the stock status. Moreover, we were not able to calculate a RR for the moratoria that had a different closure area than Rec [15-01]. We claim that further tagging programs should account for the ecological habitat of juveniles of the different species of tropical tunas in order to focus specifically on the detection of the most suitable periods and areas for closure and significantly reduce their mortality.

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Table 1: Time and area of the successive moratoria put in force by ICCAT in 1998, 2004, 2011, and 2015.

ICCAT Rec.	Closure period	Start	End	Latitude (N)	Latitude (S)	Longitude (E)	Longitude (W)	Restriction
15-01	Jan-Feb	2017	2019	5°N	4°S	Coast	20°W	No dFAD sets
11-01	Jan-Feb	2012	2016	Coast	10°S	10°W	20°W	No dFAD sets
04-01	Nov	2005	2010	5°N	0°S	10°W	20°W	No catch
98-01	Nov-Jan	1999	2001	5°N	4°S	Coast	20°W	No dFAD sets

Table 2: Proportion of releases made on the main school types inside and outside the moratorium area.

	Released Outside			Released Inside		
School type	YFT	BET	SKJ	YFT	BET	SKJ
dFAD	1277	936	413	1457	686	628
FSC	97	35	714	0	0	0
aFAD	38	4	21	994	31	93
Seamont	761	135	261	0	0	0
Total Released	2173	1110	1409	2451	717	721
Total Recoveries	223	52	81	28	7	5

Table 3: Relative risk computed for yellowfin (YFT), bigeye (BET) and skipjack (SKJ) tunas for Rec [98-01] and Rec [15-01] moratoria. The RR was not calculated for BET as the matching procedure eliminated individuals tagged inside the moratorium.

ICCAT Rec.	15-01		98-01	
Species	RR	95% C.I.	RR	95% C.I.
YFT	77.2	35.8-180	9.6	4.3-31
BET	NA	NA	NA	NA
SKJ	41.5	24-75	38.2	15-48

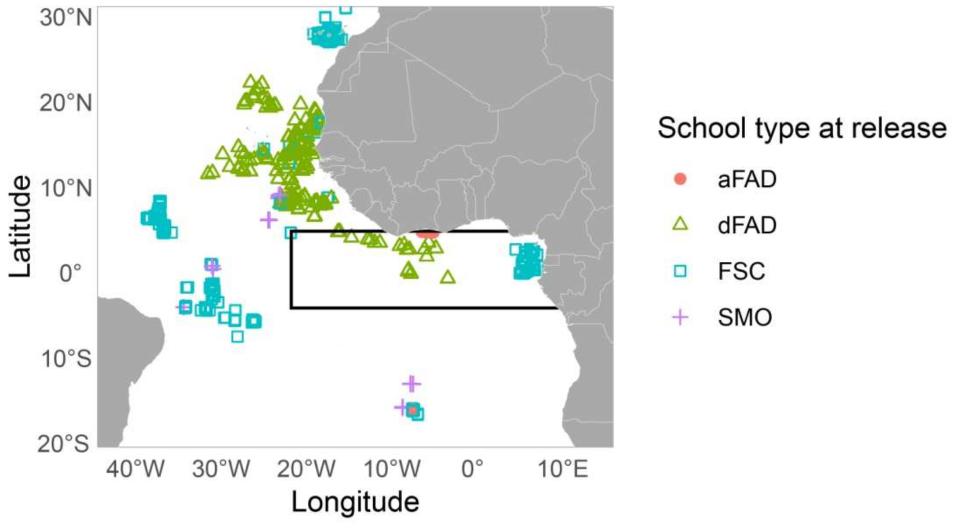

Figure 1: Release locations for BET, YFT, and SKT from tagging efforts conducted during the AOTTP project. The colored icons represent each of the school types at the time of release (aFAD = Anchored FAD, FSC = Free school and SMO = Seamount). The area outlined in black represents the region defined in Table 1 for moratorium 1.

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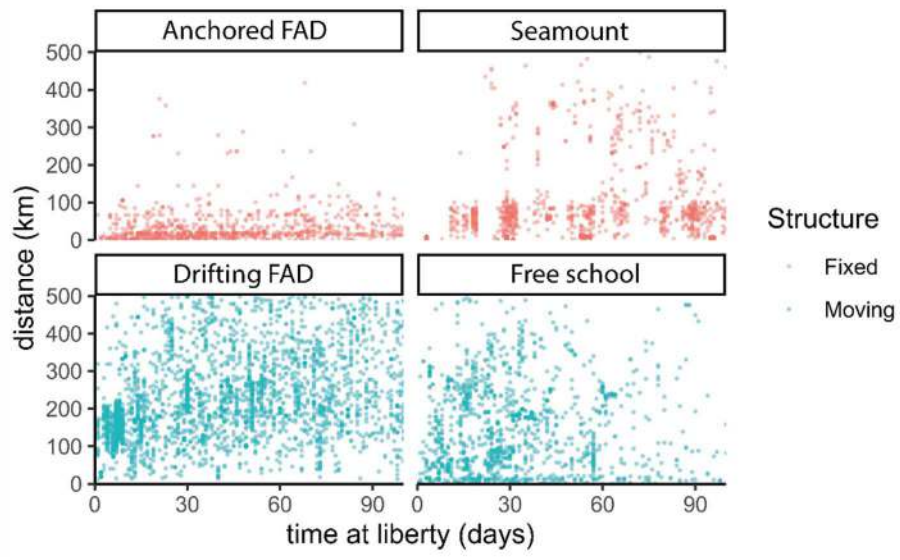

Figure 2: Relation between time at liberty and distance travelled by tunas tagged in association with fixed structures: anchored FADs (aFAD) and seamounts (SMO), upper part of the figure and in association with moving structures: drifting FADs (dFAD) or free schools (FSC), in the bottom half of the figure; the number of recoveries was: aFAd = 7,284, SMO = 11,453, dFAD = 29,391, FSC = 37,495.

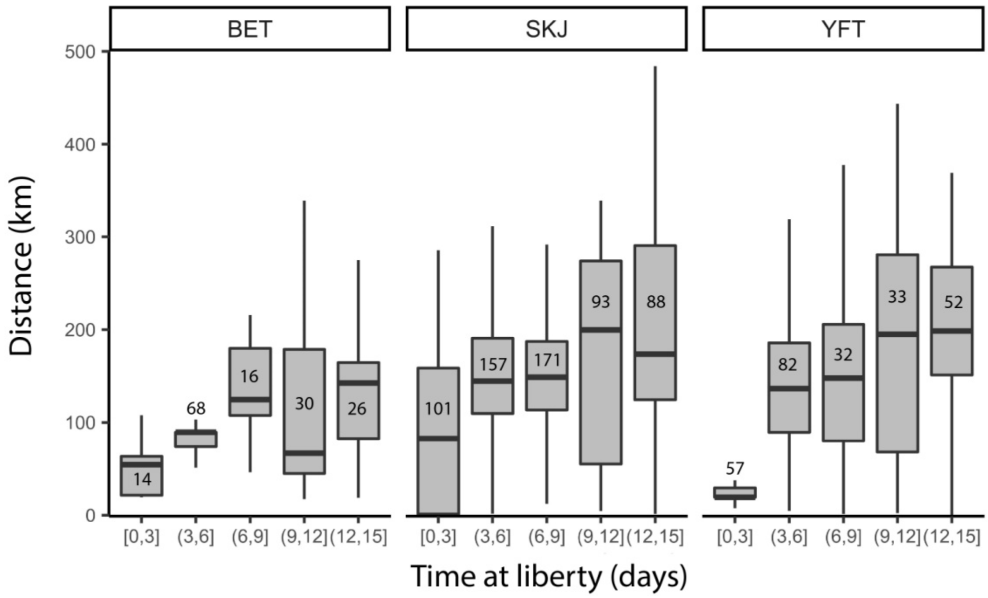

Figure 3: Distance travelled by the three main species of tropical tunas (BET for Bigeye, SKJ for Skipjack and YFT for Yellowfin) in free schools depending on their time at liberty. Error bars represent the distance between the first and third quartiles (i.e., the inter-quartile range). Numbers represent recoveries by class of time at liberty. Pairwise Wilcoxon test: no significant difference between the 0-3 days at liberty class and other classes of time at liberty for bigeye tuna, but significant for yellowfin and skipjack tunas.

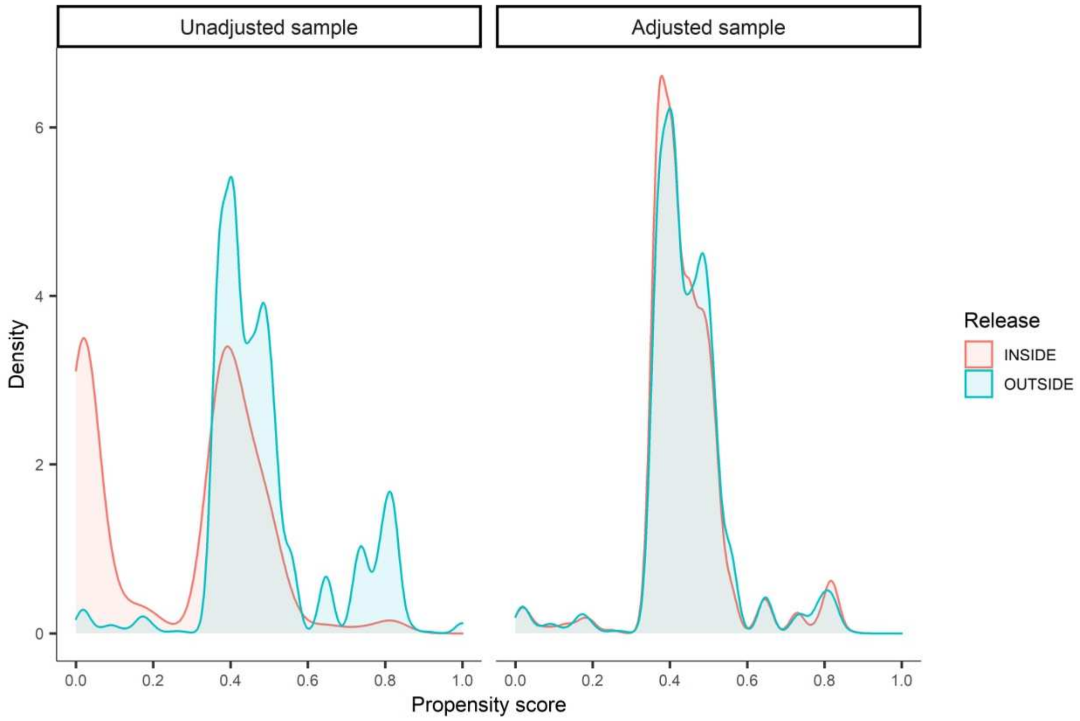

Figure 4: Comparison of the distributions of the propensity scores of the treatment group (Released inside the moratorium, in red) and the control group (Released outside the moratorium, in blue), before and after the matching procedure for yellowfin tuna. Before matching, the inside and outside distributions were significantly different. After matching, the two distributions are not significantly different.