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Ilan Perez[1,2], Loreleï Guéry[1,2], Matthieu Authier[3,4] and Daniel Gaertner[1,2]

1: MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France

2: Institut de Recherche pour le Developpement (IRD), UMR MARBEC, 87 Av. Jean Monnet, CS 30171, Sete Cedex 34203, France

3: Observatoire PELAGIS - UMS 3462, La Rochelle Université, 5 allée de l'Océan 17 000 La Rochelle

4: ADERA, 162 avenue Albert Schweitzer CS 60040, 33608 Pessac Cedex, France

Corresponding author: Ilan Perez (ilan.perez@ird.fr)

Authors' emails addresses: lorelei.guery@cirad.fr ; matthieu.authier@univ-lr.fr ; daniel.gaertner@ird.fr

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

41

1. Introduction

43

44   Small bigeye (*Thunnus obesus*) and small yellowfin (*Th. albacares*) tunas aggregate in mixed
45   schools with skipjack (*Katsuwonus pelamis*) and can be found in association with drifting fish
46   aggregating devices (dFADs) (Ariz et al., 1999; Hallier and Parajua, 1999). A majority of yellowfin and
47   bigeye tuna associated with dFADs are sized between 35 and 65cm FL (Pascual-Alayon et al, 2020;
48   Duparc et al., 2020) and are considered as juveniles (both species reach size of 100-110 cm FL at 50%
49   maturity; ICCAT, 2016). Skipjack, the main tropical tuna species fished on dFADs, is composed of
50   juveniles and adults (L50 around 42-50 cm FL; ICCAT, 2016). The proximal and distal mechanisms
51   behind aggregating behavior of tunas and skipjacks associated with floating objects are still unknown
52   (Fréon and Dagorn, 2000; Castro et al., 2002), and the ecological effects, i.e., on habitat structure or
53   foraging efficiency, need to be further explored (Hallier and Gaertner, 2008). Consequently, one of the
54   challenges of the multispecies characteristic of tropical tuna fishery on dFADs is to catch skipjack
55   while limiting the impact on the juveniles of the two other species of tunas. Indeed, increase in fishing
56   mortality for juveniles of bigeye and yellowfin tunas was evidenced since dFADs-fishing started in the
57   90's and have become one of the main purse-seine fishing methods since the 2010's in both Atlantic
58   and Indian oceans (Gaertner et al., 2015, Maufroy et al., 2017). In addition to the increasing number of
59   dFADs deployed at sea, new fishing technologies, like GPS buoy and echosounder equipped dFADs,
60   have been introduced, which allow fishermen to know in real time the location of the dFADs
61   (Torres-Irineo et al., 2011; Lopez et al., 2014; Maufroy et al., 2017) and estimate of the associated
62   biomass (Baidai et al., 2020). This was shown to have a positive effect on the fishing efficiency of the
63   purse seiners (Wain et al., 2020). Subsequently, catches of skipjack but also yellowfin and bigeye tuna
64   juveniles, and thus their mortality, have increased in the Atlantic tropical tuna fisheries (ICCAT,
65   2019a). This historic trend raises concerns about the sustainability of bigeye and yellowfin stocks
66   exploitation since an excessive catch of small fishes can lead to increased overfishing. The increasing
67   number of dFADs , associated with a general excess fishing capacity, may have contributed to the
68   fully-exploited status of the Atlantic yellowfin (ICCAT, 2019a), and bigeye overfished status (ICCAT,
69   2021).

70   In response to the state of bigeye tuna stock at that time, the European tuna producer organizations
71   established a voluntary moratorium – defined as a time-area closure – on dFADs fishing in 1997
72   (Goujon, 1998). The moratorium was subsequently adopted by the International Commission for the
73   Conservation of Atlantic Tunas (ICCAT) in 1999 as a mandatory management measure to reduce the
74   mortality of yellowfin and bigeye tuna juveniles by dFADs-fishing (Rec [98-01], ICCAT, 1998). Until
75   2019, four spatio-temporal moratoriums have been successively implemented in the Gulf of Guinea
76   (Table 1; Fig. S1) but none were based on a real ecological and scientific knowledge resulting from
77   proposals made by the Standing Committee on Research and Statistics (SCRS) of ICCAT. In 2019, the
78   SCRS evaluated the effect of the Rec [15-01] moratorium using the ICCAT 1°x1° catch data and
79   concluded that the moratorium was ineffective because there was no significant reduction in the annual
80   catch. Several other studies have questioned the usefulness of past moratorium for protecting juveniles
81   of tropical tunas in the Eastern Atlantic Ocean, but results were inconclusive or did not assess the
82   effectiveness of the moratorium for all three tropical tuna species (Torres-Irineo et al., 2011; Fonteneau
83   et al., 2016; Deledda et al., 2019).

84   The Atlantic Ocean Tuna Tagging Program (hereafter, AOTTP), which started in 2016 and ended in
85   2020, provided an opportunity to collect new information about tuna movements and investigate the
86   effectiveness of the ICCAT time-area closures by supplying tag-return data for tropical tuna species
87   over the whole ICCAT convention area. Following the method from Lambert et al. (2006), a first study
88   from Deledda and Gaertner (2019) used the relative risk (RR) as a metric to assess the effect of the Rec
89   [15-01] moratorium using AOTTP tag-return data. The RR (Daniel, 1999) is a metric which is
90   traditionally used in health science and epidemiology "*to compare the occurrence of a disease or other*
91   *health outcome between two groups: a group that is exposed to a certain treatment or risk factor—the*
92   *exposed group—and a group that is not exposed to this treatment or risk factor, which is called the*
93   *unexposed or control group*" (Noordzij et al., 2017). Until now the RR has been little used in fisheries

94   science, mainly for assessing the bycatch survival using tag-return data (Hueter et al., 2006; Schopka et
95   al., 2010; Rudershausen et al., 2013; 2019). Lambert et al., (2006) was, to our knowledge, the first study
96   using RR to assess the effectiveness of a marine protected area (MPA).

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

2. Material and methods

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

122   At the beginning of 1998 ICCAT implemented four separate spatio-temporal dFAD moratoriums in
123   the Gulf of Guinea, where the purse seiner fishing effort is concentrated (**Fig. S1** in supplementary
124   material), designed to reduce fishing mortality on multi-species aggregations associated with dFADs.
125   The Gulf of Guinea is heavily influenced by northeast winds and the Guinean current, creating an
126   oceanographically dynamic habitat with highly productive surface waters (Koranteng, 1995) suitable
127   for various pelagic species, including tunas. These closures temporarily limit fishing effort on dFAD
128   activities during several months within specified areas (**Table 1**). The Rec [15-01] moratorium was
129   active in January and February during the AOTTP period limiting both dFAD catch and tag/recapture
130   data in this area and making exploration of other area closures impossible. Consequently, it was only
131   possible to assess the effectiveness of moratoria sharing the same regulation area: Rec [98-01] and Rec
132   [08-01] moratoria. To simplify, we will hereafter use Rec [98-01] to designate both Rec [98-01] and
133   Rec [08-01] moratoria. In addition, because Rec [98-01] and Rec [15-01] were not implemented during
134   the same months (1st November to 31st January *versus* 1st January to 28th February), we recreated the
135   effect of Rec [98-01] during November and December months by filtering out the recaptures made on
136   dFADs during both November and December.

137   The AOTTP started in July 2016 and lasted until 2020 with a series of tagging campaigns in several
138   regions of the tropical Atlantic Ocean (**Fig. 1**). A large majority of the releases (96.6%) were
139   dominated by fish of length ranging between 21-80 cm FL[1], with average lengths of 51 cm (skipjack),
140   65 cm (yellowfin) and 67 cm (bigeye). The boats used for tagging were mainly live bait pole-and-line
141   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

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

145
146 **2.2. *Filtering with a time at liberty threshold***
147

148 To disentangle the natural movement of tunas and the potential disturbing effect of the tagging event on
149 the fish released, a filter was applied to release-recapture data based on short time at liberty. According to
150 ecological assumptions on the attractiveness of tropical tuna to floating objects (Hallier and Gaertner,
151 2008), we assumed that tunas released in free schools behave without disturbance and thus should be
152 considered as the tuna movement reference behavior. As it was evidenced that for short time at liberty the
153 movement of tuna can be impacted by the characteristic of the school type at release (e.g., a fixed
154 structure such as seamount or aFAD), we conducted for each species released and recaptured in free
155 school, a pair-wised Wilcoxon test between each tuna moving distance box plot to determine the
156 threshold beyond which tunas' displacement is assumed to be unaffected by the stress suffered by the fish
157 during the tagging event. Then, we assumed that this short-term disturbing effect is the same for tunas
158 tagged in other school types and removed recaptures with a time at liberty lower than this threshold.

159
160 **2.3. *Rebalancing the tagging sampling plan with a matching procedure***
161

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

193
194 The GAM used for PS estimation was:

195     $T_i | X_i \sim \mathcal{B}(\mathrm{Pr}_i)$

196   Logit $(\mathrm{Pr}_i) = PS_i = \beta_0 + \beta_1 \times$ Length at tagging$_i$ + $\beta_2 \times$ School Type $\_i$

197

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

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

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

216
217   **2.4. *Recapture and Relative risk***

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

220 $$RR = \frac{p_{out}}{p_{in}}$$

221   Where p_{out} is the proportion of individuals recaptured among those tagged outside the area of the
222 moratorium, and p_{in} is the proportion of individuals recaptured among those tagged inside the area of the
223 moratorium. To echo epidemiology terminology, the individuals tagged outside the moratorium are
224 considered as the "exposed group" which is exposed to the "being captured" risk. The individuals tagged
225 inside the moratorium are considered as the "treated group", where the treatment is the moratorium,
226 which is supposed to protect individuals from being captured. If RR is greater than 1, the recapture rate is
227 lower for tunas tagged inside the moratorium meaning that the regulation is effective. Conversely, a RR
228 lower than 1 means that the recapture rate is higher for the fish tagged inside the moratorium, i.e., the
229 regulation has a deleterious impact. To compute the RR, we selected only the total number of fish tagged
230 and recaptured during the months of the closure. A preliminary analysis showed that the RR might be
231 influenced by a low number of individuals recaptured among fishes tagged inside the moratorium (i.e., a
232 number of individuals too low to estimate p_{in}). Because matching involves a stochastic component with
233 a random nearest neighbour pairing, output from this procedure could, by chance, generate some
234 differences in the number of matched pairs of juvenile tunas between two algorithm runs. Due to the
235 uncertainty in matching, we found that the number of matched tunas could vary about ± 5 individuals
236 between iterations. This difference should not significantly affect the numerator p_{out} because the number
237 of recaptured individuals in the outside group was high. However, because the number of tunas tagged
238 inside and recaptured anywhere was generally low (<10) and reached 0 in some cases, it might have an
239 effect on the denominator p_{in} and, consequently, on RR. To deal with this issue, we ran the algorithm
240 5000 times for each species and moratorium case, to get a distribution of RR values that account for the
241 matching uncertainty (**Fig. S3**).

242

2.5. *Commercial catch data*

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

248

249   **3. Results**

250
251

3.1. *Filtering with a time at liberty threshold*

253   To evaluate whether a tagging event may disrupt natural movements or initial displacement, linear
254   displacements for each species were aggregated into time at liberty bins. Only individuals in free schools
255   were considered in the analysis and the results showed a significant increase in the distance travelled
256   after 3 days at liberty for skipjack and yellowfin (pair-wised Wilcoxon test *p-value* = 2.8 x 10^{-7} and 1.2 x
257   10^{-13}, respectively), whereas there was no significant increase for bigeye tuna (*p-value* = 0.08) (**Fig. 3**).
258   We considered this 3-days threshold to represent a reasonable trade-off between methodological
259   consistency and species-specificities and thus filtered out all individuals tagged in all school types across
260   the 3 studied species with less than 3 days of liberty. Filtering out tunas with less than 3 days at liberty
261   excluded a small fraction of data: during the moratorium period (both Rec[15-01] and Rec[98-01]), less
262   than 1% of individuals per species were under this time at liberty limit.

263

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

265   Before matching, i.e., with the initial dataset, the distributions of PS of yellowfin tunas tagged inside
266   and tagged outside the moratorium were significantly different (discrete Kolmogorov-Smirnov test
267   *p-value* < 2 x 10^{-16}, D = 0.06) (see left part of **Figure 4**). The PS distribution of the initial sample groups
268   showed a similar main mode around 0.4, but also two distinct peaks which means that many individuals
269   are not comparable between the two groups. The low values mode corresponds to tunas tagged inside the
270   moratorium which have a low probability of belonging to the outside group. On the contrary, the high
271   value mode in the outside group PS distribution corresponds to individuals that have a high probability of
272   having the same characteristics, and hence, to belong to the outside group. The PSM procedure aims to
273   remove these distribution tail modes (up to 45% of data available) and keep the central mode
274   corresponding to comparable individuals. The balance of the samples was highly improved (**Fig. 4,** right
275   part) while the distribution of the adjusted sample was statistically not different (*p-value* = 0.06, D =
276   0,42). The fact that the PS distributions where comparable in the balanced sample allowed to estimate an
277   unbiased RR (the same matching procedure was applied to skipjack tuna, **Fig. S4**).

278

3.3. *Relative risk*

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

287

3.4. *Commercial catch data*

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

298

299 **4. Discussion**

300
301   **4.1. *Moratorium effectiveness***

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

329

330   **4.2. *The challenges of pelagic time-area closures***

331   Permanent marine protected areas (MPAs) and time-area closure have been increasingly used as a key
332 strategy for both fisheries management and conservation of marine biodiversity. They showed some
333 benefits such as the restoration of the ecological states of habitats (Turner et al., 1999), increasing
334 biomass and biodiversity (Vilas et al., 2020) and reduction of bycatch (Hobday and Hartmann, 2006;
335 O'Keefe et al., 2014; Hoos et al., 2019). However, numerous authors pointed out the scarcity of
336 preliminary studies before the designation of MPAs that led to non-optimized areas and/or seasons of
337 closure, specifically for pelagic species (Field et al., 2006; Abbott and Haynie, 2012; Kaplan et al., 2010,
338 2013; Hilborn et al., 2021). Pelagic species, such as tropical tunas, are highly mobile and their migratory
339 behavior is still poorly understood. Their conservation framework thus led to the designation of
340 exceedingly large protected area, which consequently have significant costs (Game et al., 2009). Kaplan

341   et al. (2010) discussed how a targeted approach, with local fishing closures on nurseries or spawning sites
342   might be implemented to optimize the management. However, in practice, this targeted approach may
343   fail because excessive fishing effort may be concentrated at the borders of the MPA (a common
344   harvesting tactic known as "*fishing the line*"). Because of the known significant spillover for large
345   pelagic species, the "*fishing the line*" effect would counterbalance the benefits of the MPA (Kellner et al.
346   2007; Torres-Irineo et al., 2011). Using effort data, Torres-Irineo et al. (2011) showed a clear "*fishing the*
347   *line*" effect at the borders of the previous Rec [11-01] moratorium, but in the absence of a statistical
348   analysis we did not notice such a large effect during the Rec [15-01] period, even if significant catches
349   were observed at the borders of the moratorium area (**Fig. S5**). In light of the results discussed in the
350   previous section, one of the explanations for the effectiveness of the moratoria was the compliance of
351   the dFADs spatio-temporal closure by the tropical purse-seine fishery. Such acceptance from the
352   fishing industry to observe a moratorium suggests that a less restrictive scientific-based definition of
353   time-area closure (e.g., alternate smaller mobile strata) could be respected and may obtain similar or
354   better efficiency in terms of reduction of juvenile catches. However, we must keep in mind that some
355   uncertainty remains, e.g. is the decrease in catch due to natural seasonality or to the consequence of the
356   ban on FAD-fishing. For all these reasons the Standing Committee on Research and Statistics (SCRS)
357   of ICCAT recommended further analysis to identify months that minimize yellowfin and bigeye
358   juvenile catches while maintaining skipjack catches (ICCAT, 2021).

359

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

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

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

385

4.4. *Strengths and weaknesses of the AOTTP framework*

387   Our study provides an answer with regards to evaluating the efficiency of spatio-temporal
388   conservation issues with AOTTP data. Although AOTTP data give priceless information on tuna
389   movements, we showed that future studies must pay attention to the stratification of release conditions
390   (tagging structures, such as school types, and time and area tagging operations), as it has a large impact
391   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.

Acknowledgements

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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.

| School type	Released Outside			Released Inside		
	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

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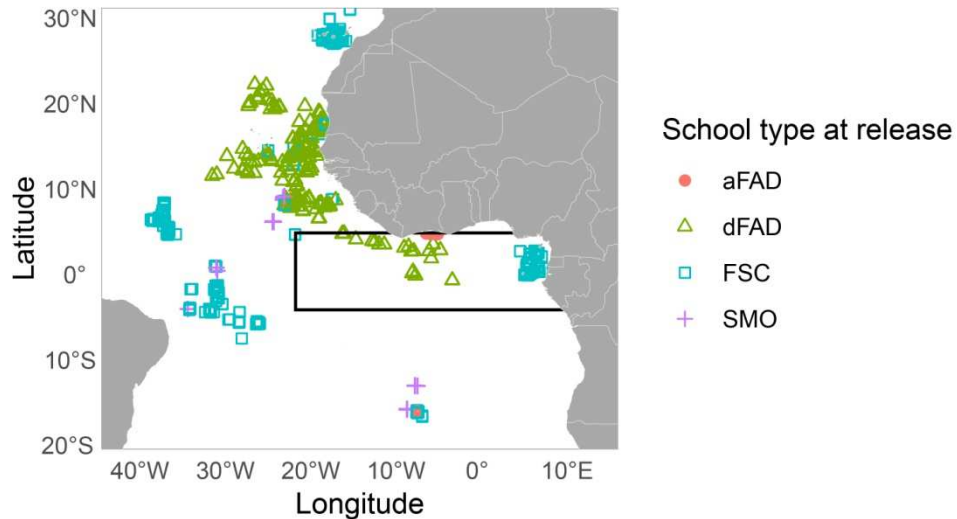
Figure 1: Release locations for BET, YFT, and SKT from tagging efforts conducted during the
AOTTP project. The colored icons represent each of the school types at the time of release
(aFAD = Anchored FAD, FSC = Free school and SMO = Seamount). The area outlined in black
represents the region defined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

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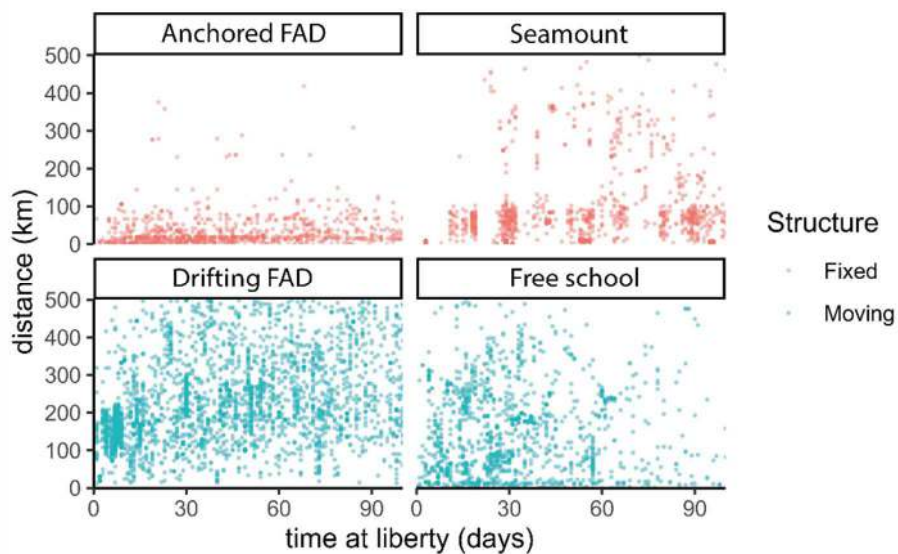
Figure 2: Relation between time at liberty and distance travelled by tunas tagged in
association with fixed structures: anchored FADs (aFAD) and seamounts (SMO), upper part
of the figure and in association with moving structures: drifting FADs (dFAD) or free schools
(FSC), in the bottom half of the figure;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

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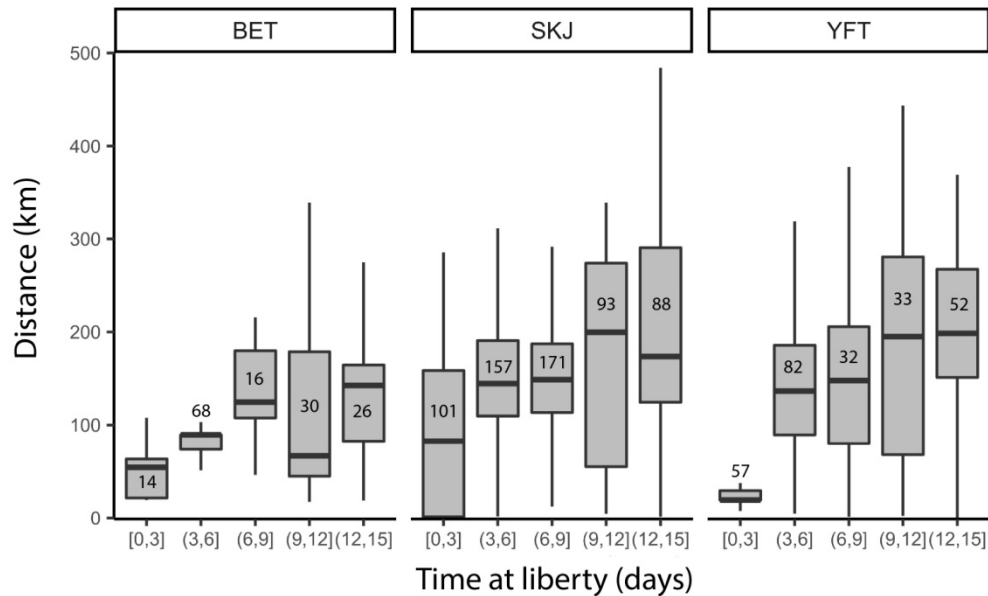
Figure 3: Distance travelled by the three main species of tropical tunas (BET for Bigeye, SKJ for Skipjack and YFT for Yellowfin) in free schools depending on their time at liberty. Error bars represent the distance between the first and third quartiles (i.e., the inter-quartile range). Numbers represent 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.

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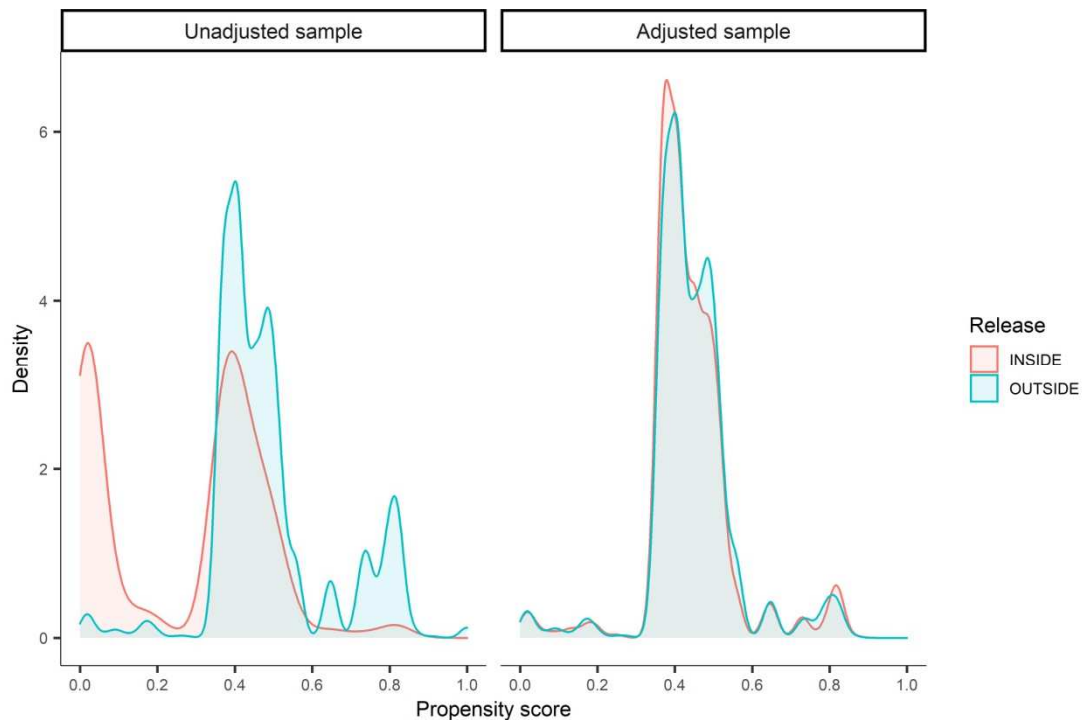
Figure 4: Comparison of the distributions of the propensity scores of the treatment group (Released inside the moratorium, in red) and the control group (Released outside the moratorium, in blue), before and after the matching procedure for yellowfin tuna. Before matching, the inside and outside distributions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