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

3
4 Ilan Perez^{1,2}, Lorelei Guéry^{1,2}, Matthieu Authier^{3,4} and Daniel Gaertner^{1,2}

5
6 1: MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France

7 2: Institut de Recherche pour le Développement (IRD), UMR MARBEC, 87 Av. Jean Monnet, CS
8 30171, Sete Cedex 34203, France

9 3: Observatoire PELAGIS - UMS 3462, La Rochelle Université, 5 allée de l'Océan
10 17 000 La Rochelle

11 4: ADERA, 162 avenue Albert Schweitzer CS 60040, 33608 Pessac Cedex, France

12
13 **Corresponding author:** Ilan Perez (ilan.perez@ird.fr)

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

16
17 **Abstract**

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

33
34 **Keywords:**

35 *FADs, tropical tunas, time-area closure, tagging, relative risk, propensity score matching*
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42 **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 (Rosebaum 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.

117

118 2. Material and methods

119

120 2.1. The ICCAT moratoria and the Atlantic Ocean Tuna Tagging Program framework

121

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 FL¹, 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

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

147

2.2. *Filtering with a time at liberty threshold*

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

161

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

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 (Rosenbaum 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:

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

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

197

198 Where B denotes a Bernoulli distribution and T_i 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):

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

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

243 **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 $1^{\circ} \times 1^{\circ}$ 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

252 **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 = 2.8×10^{-7} and $1.2 \times$
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

264 **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 $< 2 \times 10^{-16}$, $D = 0.06$) (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 were comparable in the balanced sample allowed to estimate an
277 unbiased RR (the same matching procedure was applied to skipjack tuna, **Fig. S4**).

278

279 **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

288 **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/10² 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

360 **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

386 **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

392 the initial sampling plan before performing the RR calculation to compensate for the lack of
393 randomization and homogeneity in the AOTTP tagging data. However, this procedure led to discard
394 large amount of data, testifying of a sub-optimal sampling design, particularly in the case of bigeye.
395 Indeed, less strict settings (e.g., not considering the length at release in the matching procedure) might be
396 necessary to preserve a significant quantity of bigeye capture-recapture data. However, this is not a
397 criticism of the matching procedure but rather highlights the need for a better design of the sampling
398 protocol for a future tagging program. This loss of data could result from the insufficient tagging effort
399 on bigeye (e.g., choice of spatio-temporal strata or school types less attractive for bigeye), despite the fact
400 that its level of exploitation is the most critical among the three species of tropical tunas.

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

411

412 **5. Conclusion**

413

414 The AOTTP data gave reliable information to assess the effectiveness of the Rec [15-01] and Rec
415 [98-01] moratoriums on dFADs-fishing in the Eastern Tropical Atlantic Ocean. Although
416 methodological adjustments to rebalance the sampling plan was necessary, the estimation of RR using
417 tag-return data was valuable to assess whether a dFADs time-area closure could be an effective
418 regulation measure to reduce the catch of small/juveniles of yellowfin tuna and of skipjack. However, the
419 RR method did not give a quantitative measure of the moratorium effectiveness at the annual scale and
420 thus, there are still uncertainties pending concerning the potential effects of the time-area closures on the
421 stock status. Moreover, we were not able to calculate a RR for the moratoria that had a different closure
422 area than Rec [15-01]. We claim that further tagging programs should account for the ecological habitat
423 of juveniles of the different species of tropical tunas in order to focus specifically on the detection of the
424 most suitable periods and areas for closure and significantly reduce their mortality.

425

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427

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433

434

435

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- 664

665 **Table 1:** Time and area of the successive moratoria put in force by ICCAT in 1998, 2004,
666 2011, and 2015.

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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

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

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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

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

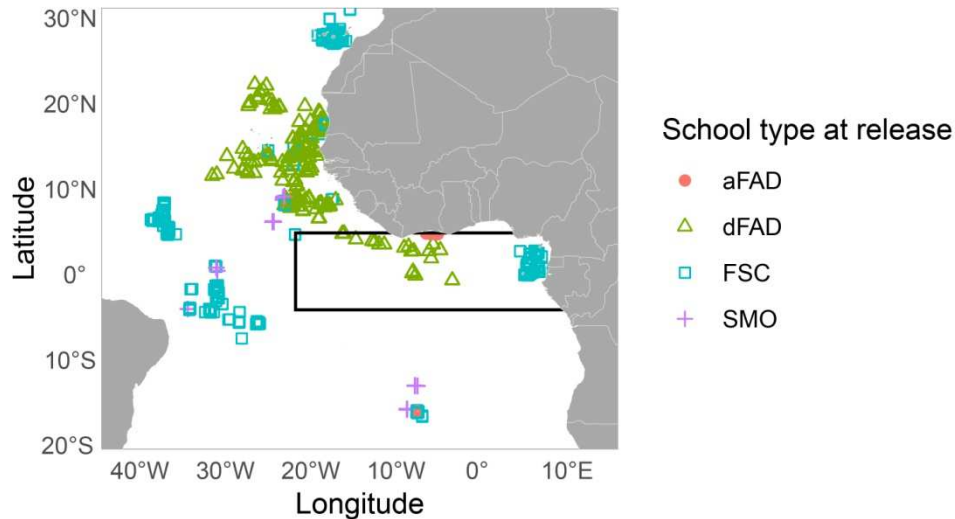
697

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

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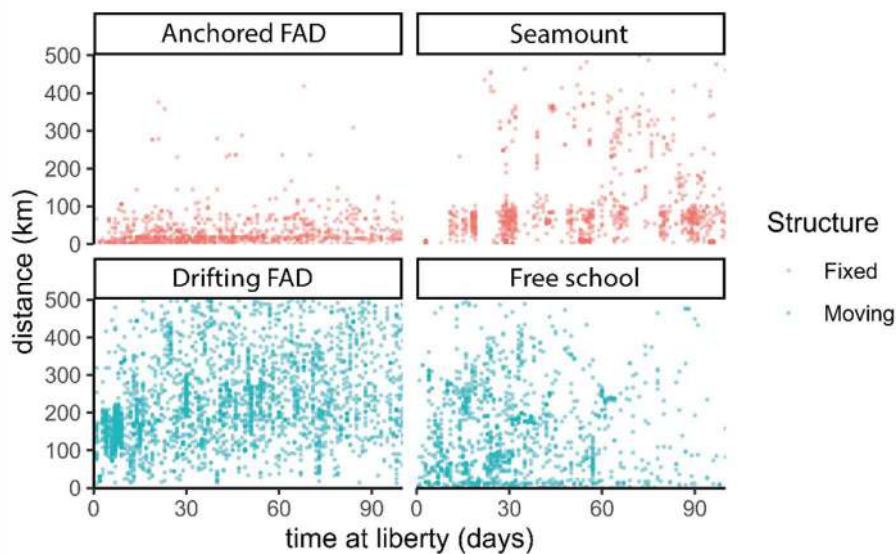
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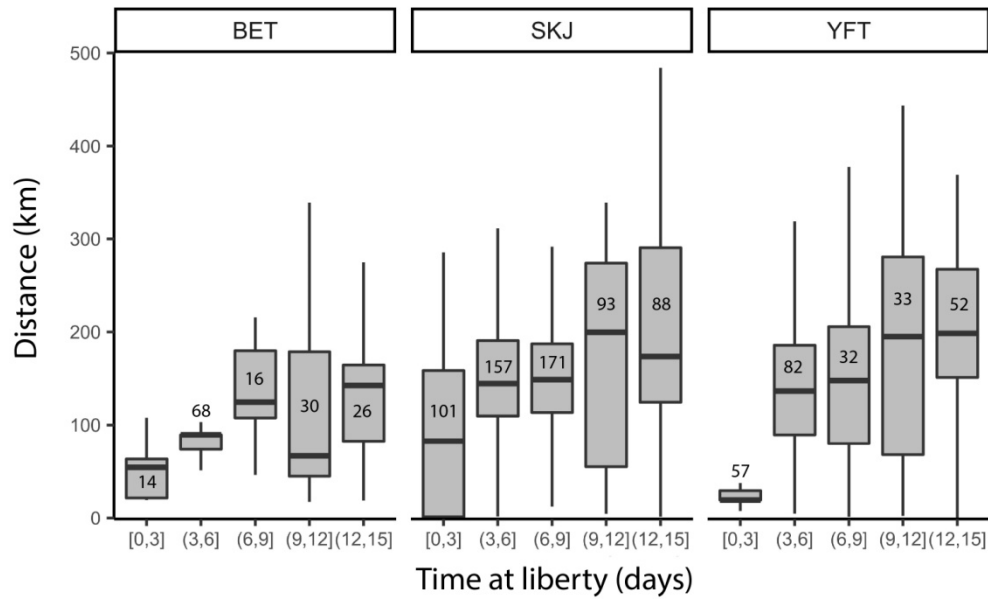
708 **Figure 1:** Release locations for BET, YFT, and SKT from tagging efforts conducted during the
 709 AOTTP project. The colored icons represent each of the school types at the time of release
 710 (aFAD = Anchored FAD, FSC = Free school and SMO = Seamount). The area outlined in black
 711 represents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

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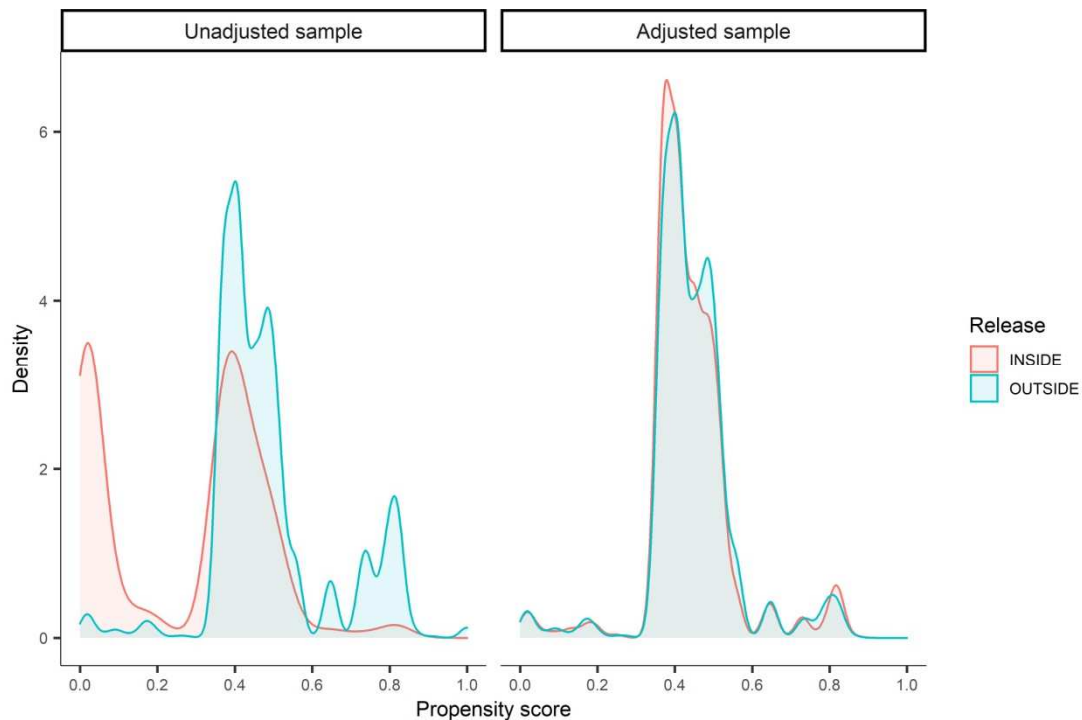
713

714 **Figure 2:** Relation between time at liberty and distance travelled by tunas tagged in
 715 association with fixed structures: anchored FADs (aFAD) and seamounts (SMO), upper part
 716 of the figure and in association with moving structures: drifting FADs (dFAD) or free schools
 717 (FSC), in the bottom half of the figure; the number of recoveries was: aFAD = 7,284, SMO =
 718 11,453, dFAD = 29,391, FSC = 37,495.



719

720 **Figure 3:** Distance travelled by the three main species of tropical tunas (BET for Bigeye, SKJ
 721 for Skipjack and YFT for Yellowfin) in free schools depending on their time at liberty. Error
 722 bars represent the distance between the first and third quartiles (i.e., the inter-quartile
 723 range). Numbers represent recoveries by class of time at liberty. Pairwise Wilcoxon test: no
 724 significant difference between the 0-3 days at liberty class and other classes of time at
 725 liberty for bigeye tuna, but significant for yellowfin and skipjack tunas.
 726



727

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