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Spatial management can significantly reduce dFAD beachings in Indian and Atlantic Ocean tropical tuna purse seine fisheries

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1 **Abstract**

2 Debris from fisheries pose significant threats to coastal marine ecosystems
3 worldwide. Tropical tuna purse seine fisheries contribute to this problem via the
4 construction and deployment of thousands of human-made drifting fish aggregating
5 devices (dFADs) annually, many of which end up beaching in coastal areas. Here, we
6 analyzed approximately 40 000 dFAD trajectories in the Indian Ocean and 12 000
7 dFAD trajectories in the Atlantic Ocean deployed over the decade 2008-2017 to
8 identify where and when beachings occur. We find that there is tremendous promise
9 for reducing beaching events by prohibiting deployments in areas most likely to lead
10 to a beaching. For example, our results indicate that 21% to 40% (depending on effort
11 redistribution after closure) of beachings can be prevented if deployments are
12 prohibited in areas in the south of 8°S latitude, the Somali zone in winter, and the
13 western Maldives in summer for the Indian Ocean, and in an elongated strip of areas
14 adjacent to the western African coast for the Atlantic Ocean. In both oceans, the
15 riskiest areas for beaching are not coincident with areas of high dFAD deployment
16 activity, suggesting that these closures could be implemented with relatively minimal
17 impact to fisheries. Furthermore, the existence of clear hotspots for beaching
18 likelihood and the high rates of putative recovery of dFAD buoys by small-scale
19 fishers in some areas suggests that early warning systems and dFAD recovery
20 programs may be effective in areas that cannot be protected via closures if appropriate
21 incentives can be provided to local partners for participating in these programs.

22

23 **Keywords:** Marine pollution, Fishing debris, Coral reefs, Fish aggregating device
24 (FAD), Ocean currents

25 1 Introduction

26 Debris from fisheries pose significant threats to coastal marine ecosystems worldwide
27 (Tavares et al. 2017; Parton et al. 2019). Tropical tuna purse seine fisheries contribute
28 to this problem via their extensive use of drifting fish aggregating devices (dFADs)
29 (Consoli et al. 2020). Whereas historically purse seine vessels divided their fishing
30 effort between free-swimming fish schools and schools associated with naturally-
31 occurring floating objects (FOBs), they increasingly focus principally on FOB fishing
32 (Galland et al. 2016; Taconet et al. 2018). The attachment to FOBs of, first, radio
33 beacons in the mid-1980's and 1990's and then satellite-tracked, GPS-equipped buoys
34 from the early 2000's, and most recently the integration of echo-sounders in satellite-
35 tracked buoys have made this approach to catching tunas increasingly attractive to
36 fishers (Chassot et al. 2014; Lopez et al. 2014). These technological developments
37 have led purse seiners to manufacture and deploy large numbers of their own, human-
38 made dFADs (Maufroy et al. 2017), and today it is believed that over 100 000 of these
39 devices are deployed annually worldwide (Scott & Lopez 2014). dFADs typically
40 consist of a floating structure and of a submerged substructure stretching up to 80 m
41 below the surface (Imzilen et al. 2019). Some of the materials regularly used in dFAD
42 construction include non-biodegradables such as PVC and metal tubes for the raft
43 frames, ethylene vinyl acetate floats and plastic containers for buoyancy, and old
44 nylon nets and pieces of salt bags for the subsurface structure. The massive increase
45 in dFAD use poses a number of major concerns regarding ecological disturbance,
46 overfishing, increased bycatch and creation of marine debris (Amandè et al. 2010;
47 Dagorn et al. 2013; Filmalter et al. 2013; Maufroy et al. 2015). Most importantly for
48 the context of this paper, a significant fraction of these dFADs end up beaching (i.e.,

49 stranding in coastal environments) (Maufroy et al. 2015), potentially damaging
50 sensitive habitats such as coral reefs, and contributing to coastal marine debris and
51 ghost fishing (Balderson & Martin 2015; Stelfox et al. 2016; Zudaire et al. 2018). This
52 is of particular concern in a context of growing awareness of the extent of marine
53 plastic pollution, with abandoned and lost fishing gears having been shown to be a
54 major component of marine litter worldwide (Haward 2018; Lebreton et al. 2018;
55 Richardson et al. 2019).

56

57 Given these concerns, dFAD beachings are a major area of interest for science,
58 management and conservation. An initial examination of French dFAD spatio-
59 temporal use in the tropical Indian Ocean and Atlantic Ocean over the period 2007-
60 2011 indicated that ~10% of deployed dFADs ended up beached (Maufroy et al.
61 2015), highlighting the potential for considerable impacts on fragile coastal habitats
62 due to these events. A similar examination in the Western and Central Pacific Ocean
63 found that ~6% of all trajectories were likely to have beached over a two year period
64 (2016-2017; Escalle et al. 2019). However, given the significant differences in
65 bathymetry and circulation between the western and central Pacific Ocean , Indian
66 Ocean and Atlantic Ocean, and the more than four-fold increase in the number of
67 dFADs deployed by purse seiners in the Indian and Atlantic Oceans since 2011
68 (Katara et al. 2018; Floch et al. 2019), the extent to which existing literature applies to
69 current patterns of dFAD use is an important open question. Moreover, the French
70 fleet switched to almost exclusively using echo-sounder equipped dFAD tracking
71 buoys around 2012 (Chassot et al. 2014; Floch et al. 2019) and other major purse
72 seine fleets also started using this new technology on or before this date, potentially

73 altering the spatio-temporal distribution of dFAD deployments, fishing activity and
74 associated beaching events. In parallel, management measures have been taken by the
75 tuna regional fisheries management organizations to limit the total number of GPS
76 buoys used by each purse seine vessel in both the Indian and Atlantic Oceans, but
77 these measures have not directly addressed the spatial and temporal dynamics of
78 beachings and, therefore, their efficacy for reducing this problem is unknown. A new
79 analysis of dFAD beachings focused on spatio-temporal patterns that might be useful
80 for identifying appropriate mitigation measures to avoid beachings is therefore
81 urgently needed.

82

83 The goal of this paper is to quantify the impacts of dFAD beachings and identify
84 strategies for mitigating these impacts in the tropical Indian and Atlantic Oceans.
85 Using a large dataset of over 50 000 dFAD buoy trajectories, we first extend and
86 improve upon the analysis of Maufroy et al. (2015, 2018), estimating beachings for
87 the decade 2008-2017. We then identify deployment locations likely to lead to
88 beaching events, and, using this information, we are able to estimate the impact of
89 closing high beaching risk areas to dFAD deployments on the overall beaching rate
90 under a pair of reasonable fishing effort redeployment strategies. Results indicate that
91 there is indeed much promise in the Indian and Atlantic Oceans for reducing dFAD
92 beachings by implementing sensible spatial limitations on deployment locations.

93

94 **2 Materials and methods**

95 **2.1 Data collection**

96

97 Through a collaboration with the French frozen tuna producers' organization
98 (ORTHONGEL), the French Institute of Research on Development (IRD) has access
99 to data on the locations of thousands of distinct GPS buoys attached to FOBs
100 deployed by the French and associated flags (Mauritius, Italy, Seychelles) purse seine
101 fleets operating in the tropical Indian and Atlantic Oceans from ~2007 onward
102 (coverage ~75-86% before 2010 and ~100% after that date; Maufroy et al. 2015).
103 Though GPS buoys can be attached to both natural FOBs and human-made dFADs,
104 the vast majority of FOBs in both oceans are now human-made dFADs (>90% of
105 buoy deployments in both oceans based on observer data for 2013-2017), and,
106 therefore, we will refer to these buoy trajectories as dFAD trajectories even though a
107 small fraction of them are for other types of objects. GPS buoys are attached to
108 dFADs deployed at sea by purse seine fishing vessels and their associated support
109 vessels. Buoys can also be exchanged on FOBs encountered at sea and the buoys
110 retrieved from the water are generally brought back to port where they can be
111 recovered by the owner vessel for reuse. A single GPS buoy may therefore be
112 redeployed several times, potentially on different dFADs. It is therefore important to
113 note that, in this paper, we use the term 'dFAD' to refer to the entire device consisting
114 of the floating object itself and the attached GPS buoy, whereas, the term 'buoy'
115 designates solely the GPS buoy.

116

117 Buoy location data are transmitted with a periodicity that varies along the buoy
118 trajectory, generally ranging from 15 minutes to 2 days. Buoy positions were filtered
119 to remove those that were emitted while the buoy was onboard using a Random Forest
120 classification algorithm that is an improvement over that developed in Maufroy et al.
121 (2015) (Appendix A). This improved classification algorithm is estimated to have an
122 error rate of ~ 2% when predicting onboard positions and ~ 0.2% for at sea positions
123 (Supplementary Table A4).

124

125 In this study, we used data of dFAD positions covering the decade 2008-2017. This
126 data set consists of ~15 million Indian Ocean positions representing a total of 38 845
127 distinct buoys and ~6 million Atlantic Ocean positions representing a total of 12 147
128 distinct buoys. Separately, locations and times for dFAD deployments are available in
129 French logbook data from 2013 onward.

130 **2.2 Identification of dFAD beaching events**

131

132 dFAD beachings were identified in two steps. The first step was to find dFADs that
133 had an abnormally small rate of movement for an extended period of time, whereas
134 the second step removed false positives (e.g., buoys onboard or at port) from this list
135 of potential beachings. A given dFAD position was considered to be a potential
136 beaching if: (1) at least 2 other later positions were within 200 m, and (2) all these
137 close positions span a time period exceeding 1 day. The 200 m threshold is based on a
138 dFAD snagged on the very bottom of its <100 m length nets hanging below the dFAD
139 swinging at most 100 m in each direction. The time span of at least 1 day is required
140 to avoid identifying as beachings multiple position emissions from a single buoy over

141 a short time period, such as occurs when the emission periodicity of dFAD positions
142 is modified to 15 min to facilitate detection by vessels before a fishing set.

143

144 In the second step, the putative beachings identified in this first step were filtered to
145 remove non-beaching events based on 4 tests: (1) the beaching is more than 10 km
146 from a major fishing port to avoid cases where dFAD buoys are at a port; (2) the
147 beaching event is <5 km from land or the water column depth is <100 m; (3) all
148 positions are classified at sea and there are no gaps in location emission exceeding 2
149 days over the 5 days preceding the beaching; (4) greater than 90% of all positions of a
150 given buoy within the time span of the potential beaching event are associated with
151 the beaching event (i.e., meet the distance criteria described above; this condition
152 avoids cases where a buoy happens to pass multiple times through the same area,
153 because of an eddy for example). Only beaching events meeting these 4 conditions
154 were considered for further analyses.

155

156 About half of the beachings identified by the conditions described above occurred in
157 the water. The other half were generally located on land close to small fishing ports or
158 coastal villages (Supplementary Fig. B2, Fig. B3 and Fig. B4). This suggests that
159 these buoys were retrieved by small-scale boats, likely fishers. As these boats
160 generally intercept dFADs in coastal areas and only collect the buoy for its valuable
161 electronics, leaving the raft and netting to drift, it is entirely possible that these dFADs
162 (without the buoy) later ended up beaching. Nevertheless, given the uncertainty
163 regarding the fate of these dFADs, calculations in this paper have been carried out
164 both including all beachings and including only beachings in the water. Unless

165 otherwise stated, statistics reported in the paper are for all beachings including those
166 on land. In the rest of this paper, beachings located in water and on land are
167 respectively referred to as “beachings along shore” and “recoveries displaced to
168 shore”.

169

170 The number of beaching events per km of the continental shelf was calculated by
171 counting all beachings occurring in each 5°x5° grid cell and then dividing that number
172 by the kilometers of continental shelf edge, defined by the 200 m isobath, within the
173 cell. The continental shelf edge was used instead of the coastline to avoid
174 anomalously high beaching rates for some very small islands surrounded by large
175 continental shelf areas.

176

177 For identifying beachings, classifying beachings as on land or at sea and determining
178 the continental shelf edge, coastline data were obtained from OpenStreetMap land
179 polygons (available at <https://osmdata.openstreetmap.de/data/land-polygons.html>;
180 accessed 2020-02-19) and bathymetry was obtained from the 30-arcsecond-resolution
181 General Bathymetric Chart of the Oceans (GEBCO v.2014; available at
182 https://www.gebco.net/data_and_products/gridded_bathymetry_data; accessed 2020-
183 02-19).

184 **2.3 Drift locations leading to beachings**

185

186 In order to identify dFAD drift locations that had a high risk to lead to a beaching
187 event, we calculated the fraction of buoys that beach within 3 months of a passage
188 through a given 1°x1° grid cell. This analysis was carried out over the entire study

189 period, but also by season to estimate seasonal variability in beaching risk. We
190 selected 3 months as the time limit as it is intermediate between the mean timespan of
191 at sea trajectories and that of the lifespan of a buoy in the dataset (i.e. 25 and 196
192 days, respectively), and because 3 months was considered a reasonable timespan over
193 which fishers and managers could reasonably be expected to predict and mitigate for
194 beaching likelihood. To ensure that results are not strongly sensitive to this choice,
195 additional analyses were carried out to calculate the fraction of buoys that beach
196 within 12 months. Note that individual buoy trajectories were separated into multiple
197 in water trajectories using breaks defined by gaps of more than 2 days or positions
198 classified as onboard representing more than 1 minute of trajectory time. The 1
199 minute limit was imposed to remove very short trajectory segments that were
200 problematic for the classification algorithm (Appendix A).

201

202 Since beachings threaten fragile marine habitats, especially coral habitats, we carried
203 out the same analyses focusing exclusively on beachings in coral reef areas. Data on
204 the global distribution of coral reefs were obtained from UNEP-WCMC, WorldFish
205 Centre, WRI, TNC (2018 ,version 4.0; available at [https://data.unep-](https://data.unep-wcmc.org/datasets/1)
206 [wcmc.org/datasets/1](https://data.unep-wcmc.org/datasets/1); accessed April 30, 2019).

207 **2.4 Deployment risk**

208

209 To assess potential for reducing the dFAD beaching rate, we investigated closing areas
210 of high beaching risk to dFAD deployments. Deployment locations were obtained
211 from logbook data, whereas probability of beaching for a given deployment location
212 was estimated as described above. Logbook deployment data was used instead of

213 putative deployments from reconstructed dFAD trajectories because, though the
214 random forest position classification model has a very high accuracy rate and
215 predicted deployment locations do approximately follow the spatial distribution of
216 logbook deployment locations (Maufroy et al. 2015), accurately predicting
217 deployment locations is quite difficult and error prone given that a single error
218 anywhere in the trajectory will split the trajectory, generating a new false deployment
219 (Maufroy et al. 2015). Given the high quality of logbook data, it was considered that
220 this was the most accurate estimate of recent dFAD deployment locations.

221

222 Multiplying dFAD deployments by the proportion of devices beaching allowed us to
223 predict the reduction in beachings that would result from closing a given area.
224 Different sized areas corresponding to specific percentages of all pre-closure
225 deployments were closed in order of beaching risk going from highest to lowest. Two
226 hypotheses were considered regarding the number and spatial distribution of
227 deployments after closing an area to deployments: (1) closures eliminate deployments
228 that would have occurred in closed areas (i.e., fishing effort reduction occurs), and (2)
229 closures displace deployments formerly in closed areas to remaining unclosed areas in
230 proportion to the relative density of deployments prior to implementation of closures
231 (i.e., “fishery squeeze” occurs; Halpern et al. 2004).

232 **3 Results**

233 The number of French buoys deployed per year has increased dramatically and
234 continuously over the decade 2008-2017, especially in the Indian Ocean (Fig. 1a).
235 Over that period, more GPS buoys were deployed in the Indian Ocean (~ 40 000) than

236 in the Atlantic Ocean (~ 12 000). The percentage of all deployed dFADs that ended up
237 beaching has also dramatically increased from ~3.5% in 2008 to ~20% in 2013 (Fig.
238 1b; these numbers are roughly halved if we count only beachings along shore). After
239 2013, the percentage of dFADs that beached stabilizes at ~15-20% in the Indian
240 Ocean and ~19-22% in the Atlantic Ocean. In total, we obtained 7187 beaching events
241 for the Indian Ocean and 2283 for the Atlantic Ocean.

242

243 Maps of these 9470 beaching locations clearly identify coastal beaching hotspots (Fig.
244 2a and Supplementary Fig. C1a). Beachings occur in several zones in the Indian
245 Ocean, including southern Somalia, Kenya, Tanzania, Seychelles and the Maldives. In
246 the Atlantic Ocean, they occur mainly along the West African coast and the Gulf of
247 Guinea between 20°N and 20°S. In both oceans, beachings also sporadically occur in
248 more remote areas outside typical purse-seine fishing grounds (Maufroy et al. 2017),
249 such as Indonesia, South Africa, Brazil and the Caribbean. Including only beachings
250 that occur along the shore, the number of beaching decreases mostly along the
251 western and north-eastern African coasts and in the Maldives (Fig. 2b and
252 Supplementary Fig. C1b), indicating that significant rates of putative recovery of
253 dFAD buoys occur in those areas.

254

255 In both oceans, the proportion of dFADs beaching within 3 months of passing through
256 a 1°x1° grid cell shows high spatial heterogeneity, with hotspots of beaching
257 likelihood clearly visible (Fig. 3a). In the Indian Ocean, the Gulf of Aden, Oman,
258 Mozambique Channel, eastern and northern Madagascar, northern Maldives, western
259 India, Sri Lanka and western Indonesia are all high risk areas for beaching. In the

260 Atlantic Ocean, the Gulf of Guinea, southern West Africa, the northern coast of South
261 America and Caribbean have high proportion of beaching. Including only beachings
262 that occur along shore reduces beaching proportions in all areas and reduces the
263 importance of some coastal areas characterized by a high density of small-scale
264 fishers, such as in the vicinity of the Arabian Peninsula, the northern Gulf of Guinea
265 and West Africa (Fig. 3b). Increasing the temporal window from 3 months to 12
266 months increases somewhat the spatial area over which proportion of beaching is non-
267 negligible, but overall spatial patterns remain the same (Supplementary Fig. C2).
268 Seasonal variability in dominant currents impacts beaching risk in predictable ways.
269 For example, in the Indian Ocean, during the winter monsoon, onshore currents create
270 an area of high proportion of beaching east of Somalia, but this high risk area
271 disappears during the upwelling favorable period of the summer monsoon
272 (Supplementary Fig. C4). However, seasonal variability in the Atlantic Ocean was
273 weak (Supplementary Fig. C5). Finally, focusing exclusively on dFAD beachings on
274 coral reefs narrowed the areas of high beaching risk to the north-west of the Maldives,
275 Seychelles, northern Madagascar, the Mozambique Channel and the Caribbean
276 (Supplementary Fig. C6).

277

278 Major areas of dFAD deployments during 2013-2017 spanned the whole fishing
279 grounds of the French and associated flags purse seine fishery (Fig. 4a-b). In the
280 Atlantic Ocean, dFADs were deployed all along the coast of West Africa, from
281 Mauritania down to Angola with the most intense activity being observed along the
282 equator and off the coasts of Mauritania, Gabon and Angola. In the Indian Ocean,
283 dFADs were deployed in the Western Indian Ocean, including the Exclusive

284 Economic Zones of the Seychelles, Comoros, Kenya, French overseas territories and
285 northwest of Madagascar in the northern Mozambique Channel. dFADs deployments
286 were particularly frequent North-West of the Seychelles.

287

288 Combining spatial proportions of dFADs that beached (Fig. 3a-b) with observed
289 dFAD deployment positions (Fig. 4a-b), we estimated the expected change in
290 beachings and dFAD deployments due to prohibiting dFAD deployments in the
291 highest risk areas for both oceans. Under all scenarios of dFAD deployment
292 redistribution, spatial prohibitions are predicted to significantly reduce beaching rates.
293 For example, if we prohibit dFAD deployments in areas corresponding to the 20% of
294 deployments with highest beaching risk, we can prevent 37% of beachings in the
295 Indian Ocean and 40% in the Atlantic Ocean in the absence of dFAD deployment
296 effort redistribution, and 21% and 25% of beachings in the Indian Ocean and Atlantic
297 Ocean, respectively, even if we allow for dFAD deployment redistribution to areas
298 with less beaching risk (Fig. 5a). These percentages are even higher when we focus on
299 the proportion of beaching including only beachings that happen along shore, with up
300 to a 52% reduction in beachings in the Atlantic Ocean even if the total number of
301 deployments is conserved via effort redistribution (grey dashed line in Fig. 5b).

302

303 Spatial prohibitions can be optimized to account for seasonal variability in beaching
304 risk. For example, if areas corresponding to the 20% of deployments in areas with the
305 highest beaching risk for each quarter are closed to dFAD deployments
306 (Supplementary Fig. C7), we predict a 27% and 28% reduction in the Indian Ocean

307 and Atlantic Ocean, respectively, even if dFAD deployment redistribution is allowed
308 (Fig. 5c).

309 Focusing exclusively on beachings in coral reefs, prohibiting the 20% of deployments
310 in the Indian Ocean with the highest beaching risk to corals reduces coral reef
311 beachings by 27% assuming dFAD deployment redistribution (Supplementary Fig.
312 C8b), but the zones prohibited differ significantly from those that would be prohibited
313 to reduce all beaching events (compare Fig. 4a and Supplementary Fig. C8a).

314

315 Closing the highest beaching risk areas to dFAD deployments is particularly effective
316 at reducing beaching events in the south-western Indian Ocean and in the eastern Gulf
317 of Guinea in the Atlantic Ocean (Fig. 6). If one focuses exclusively on coral reef
318 beaching, then significant beaching reductions in the Indian Ocean are also seen in the
319 Maldives and off Indonesia (Supplementary Fig. C9). These results apply both with
320 and without dFAD deployment redistribution post closure implementation.

321 **4 Discussion**

322 The overriding conclusion to be drawn from our results is that there is potentially a lot
323 to be gained in terms of reduction in the rate of dFAD beachings from spatio-temporal
324 closures for dFAD deployments by purse seine fishing vessels in the Indian and
325 Atlantic Oceans. We examined a wide range of scenarios for closure objectives,
326 implementation, and post-closure effects: considering all beachings versus just
327 strandings along shore; considering all coastal zones versus just coral reefs;
328 implementing static versus quarterly varying closures; and post-closure effort
329 reduction versus effort redistribution to remaining open areas. In all cases, closing the

330 riskiest areas for beaching is predicted to produce a tremendous reduction in
331 beachings. Analyses of recent dFAD deployments in the Indian Ocean by the Spanish
332 fleet (the dominant other fleet in both oceans) indicate that Spanish and French
333 deployments have quite similar spatial distributions (Katara et al. 2018). This suggests
334 that our results may be applicable to all fleets, though access to dFAD trajectory data
335 should be enhanced to confirm this. Perhaps most encouraging, high risk areas
336 generally are relatively coherent in space so that it should be feasible from a
337 management perspective to implement closures (e.g., south of 8°S in the Indian Ocean
338 and coastal zones in the Gulf of Guinea in the Atlantic Ocean). In both oceans, the
339 riskiest areas for beaching are not coincident with areas of high dFAD deployment
340 activity or fishing activities (Maufroy et al. 2015), suggesting that these closures
341 could be implemented with relatively minimal impact to fisheries. The beaching
342 reduction across coastal areas spared by the closures for dFAD deployment is highest
343 in the south-western Indian Ocean and in the eastern Gulf of Guinea in the Atlantic
344 Ocean, suggesting that our proposed deployment closure strategy is particularly
345 efficient to protect these areas. The north-western Indian Ocean and the northern Gulf
346 of Guinea, which both represent hotspots of beaching, are less protected by the
347 closures for dFAD deployments. However, high rates of putative recovery of dFAD
348 buoys by coastal boats in these areas indicate that beaching early warning systems and
349 dFAD recovery programs may be effective in areas that cannot be protected via
350 closures if appropriate incentives can be provided to local partners for participating in
351 these programs.
352

353 As reported elsewhere (Maufroy et al. 2015; Floch et al. 2017, 2019), the number of
354 dFADs deployed in both oceans has dramatically increased over the last decade. More
355 surprising, the fraction of dFADs that end up beaching increased significantly over the
356 period 2008-2013, after which time the fraction stabilizes. As this 2008-2013 period is
357 coincident with a number of changes in the fishery, such as the switch to echosounder
358 buoys (2010-2012), an increase in the prevalence of dFAD fishing as opposed to
359 fishing on free-swimming schools (Assan et al. 2019; Floch et al. 2019) and the
360 fallout from Somali piracy (~2007-2011), it is hard to assign a specific cause to this
361 pattern. One hypothesis is that as the number of dFADs has increased, the fraction of
362 dFADs that are never fished upon has become more and more important to the point
363 that after 2013 the fraction beaching simply reflects the balance one would expect in
364 the absence of fishing between dFADs that beach versus dFADs that sink at sea. The
365 stabilization of the beaching rate after 2013 may also be partially due to the
366 implementation after 2014 of industry and/or regional fisheries management
367 organizations' limits on the number of buoys monitored by purse seine vessels
368 (ICCAT 2019; IOTC 2019a) as fishers may remotely deactivate non-productive
369 dFADs to remain under industry limits, resulting in the loss of location information
370 for these dFADs that continue to drift at sea and may later beach.

371

372 The risk of beaching depends strongly on upper ocean circulation and its seasonal
373 variability. In the Indian Ocean, the African coast south of the equator represents a
374 high beaching risk area throughout the year due to the westward flowing Northern
375 Equatorial Madagascar Current (Schott et al. 2009) that drives dFADs to the coasts of
376 Mozambique and Tanzania. In the northern Indian Ocean, high beaching risk areas

377 change with monsoon regimes. The Somali coast represents a high beaching risk area
378 in the winter when the Somali Current flows westwards (Schott & McCreary 2001),
379 but not during the summer, when the western Maldives become a high risk area due to
380 monsoon driven eastward circulation. There is less effect of seasonality on beaching
381 risk in the Atlantic Ocean, where areas of high beaching risk are driven by more-
382 stable dominant circulation patterns. Along the western coast of Africa, beachings are
383 related to the North Equatorial Countercurrent and the Guinea Current flowing
384 eastwards, whereas high risk areas along the northern coast of South America and the
385 Caribbean are linked to the South Equatorial, North Equatorial, North Brazil and
386 Caribbean Currents flowing westwards (Bourles et al. 1999).

387

388 Our estimates of dFAD beaching rates after 2013 are higher than those estimated in
389 the western central Pacific (Escalle et al. 2019) and in previous examinations in the
390 Indian and Atlantic Oceans (Maufroy et al. 2015; Zudaire et al. 2018). Escalle et al.
391 (2019) examined an area of the Pacific characterized principally by many small island
392 chains, perhaps explaining lower beaching rates with respect to the continental land
393 masses of the Indian and Atlantic Oceans. In the Indian and Atlantic Oceans, Maufroy
394 et al. (2015) examined the period prior to 2013 for which we also find lower beaching
395 rates. Zudaire et al. (2018) were principally concerned with the more-limited area of
396 the Seychelles Archipelago, which is composed of a large set of small islands similar
397 to the area examined by Escalle et al. (2019) in the western central Pacific. They also
398 considered a somewhat more restrictive definition of beaching.

399

400 There have been several recent management changes regarding the use of dFADs that
401 may alter future dFAD beaching patterns, highlighting the importance of continuous
402 monitoring of dFAD trajectories. The Indian Ocean Tuna Commission (IOTC) and the
403 International Commission for the Conservation of Atlantic Tunas (ICCAT) currently
404 limit the number of buoys monitored by an individual purse seine vessel at any given
405 time to 300 (ICCAT 2019) and 350 (IOTC 2019a) buoys in the Atlantic Ocean and
406 Indian Ocean, respectively, and these limits are may decrease over time. The IOTC
407 has also implemented a resolution to progressively reduce and phase out the number
408 of support vessels that assist purse seiners with the management of dFADs (IOTC
409 2019b). These changes may lead purse seine vessels to optimize their use of dFADs in
410 a number of ways. One potential outcome would be that fishers remotely deactivate
411 dFADs that are likely to beach or drift outside of areas of interest so as to remain
412 under industry limits. This practice is of much concern as it would result in the loss of
413 information on the extent and location of dFAD beachings currently made available
414 via fishing companies on a voluntary basis. Tuna regional fisheries management
415 organizations should put in place appropriate incentives or other measures to assure
416 that this information loss does not occur.

417

418 This study would not have been possible without access to a long and extensive time
419 series of data on French dFAD trajectories. Though access to these extensive datasets
420 is still quite limited for most fishing fleets worldwide, there are a number of
421 encouraging signs of increased reporting of dFAD deployments and other dFAD
422 activities to tuna regional fisheries management organizations (IOTC 2019a; Escalle
423 et al. 2020). We are hopeful that comprehensive datasets from all purse seine fishing

424 fleets will be available in the near future, permitting better estimates of the impacts of
425 management options and the development of real-time tools for the management of
426 dFAD impacts on marine ecosystems.

427 **5 Supporting information**

428

429 Supporting information available online comprises details of the new classification
430 model for onboard and at sea states of dFAD trajectory data (Appendix A), and
431 quantification of beachings occurred in water (beachings along shore) and on land
432 (recoveries displaced) (Appendix B), as well as additional figures presenting the
433 number of French dFADs beached in each 5°x5° cell, proportions of beaching using a
434 12 month time window, seasonal variability in beaching risks and beaching risks for
435 coral reefs (Appendix C).

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438 **Figure Captions**

439 **Fig. 1** (a) Annual number of new buoys deployed by the French and associated flags
440 purse seine fleet in the Atlantic (grey) and Indian (black) oceans over the period 2008-
441 2017 and (b) percentage of these buoys that beached. The lines in (b) with solid
442 circles include all beachings, whereas the lines with solid triangles include only
443 beachings identified along shore. Beachings along shore and recoveries displaced to
444 shore were separated via intersection with OpenStreetMap land polygons.

445 **Fig. 2** The number of French dFAD beachings recorded in our data per km of
446 continental shelf edge in each $5^\circ \times 5^\circ$ grid cell for the period 2008-2017. Darker areas
447 indicate higher rates of beaching. In (a), all beachings are considered, whereas in (b)
448 only beachings along shore are included. Beachings along shore and recoveries
449 displaced to shore were separated via intersection with OpenStreetMap land polygons.
450 Note that our dFAD trajectory data is incomplete before ~ 2010 , so the absolute
451 number of beachings per kilometer is likely somewhat higher than values shown in
452 the figure, though differences are likely to be small as the number of dFADs was far
453 lower before 2010 than after 2010.

454 **Fig. 3** Maps of the proportion of dFADs that beached within 3 months after passing
455 through each $1^\circ \times 1^\circ$ grid cell over the period 2008-2017. In (a), all beachings are
456 considered, whereas in (b) only beachings along shore are included. Beachings along
457 shore and recoveries displaced to shore were separated via intersection with
458 OpenStreetMap land polygons. Note that the color intervals are unevenly distributed
459 to highlight the low values.

460 **Fig. 4** Density maps representing the number of dFAD deployments in each $1^{\circ} \times 1^{\circ}$ cell
461 recorded in logbook data for the period 2013-2017. The thick, solid curves delimit
462 areas representing the 20% of deployments most likely to produce a beaching within 3
463 months of a dFAD passing through those areas. In (a), all beachings are considered,
464 whereas in (b), only beachings along shore are included. Beachings along shore and
465 recoveries displaced to shore were separated via intersection with OpenStreetMap
466 land polygons.

467 **Fig. 5** Predicted reduction in beaching rate as a function of the amount of area put
468 aside in annual (a-b) or quarterly (c-d) closures to dFAD deployments. Areas are
469 closed from most likely to least likely to produce a beaching within 3 months of
470 deployment, with area being quantified along the x-axis in terms of the fraction of
471 deployments that occurred in closed areas prior to their closure. Black and grey dotted
472 lines correspond to the null expectation of what the corresponding black and grey
473 curves would look like if all areas had the same beaching risk, and are the same in the
474 Indian and Atlantic Oceans. In (a) and (c), all beachings are considered, whereas in
475 (b) and (d), only beachings occurring along shore are included. Beachings along shore
476 and recoveries displaced to shore were separated via intersection with OpenStreetMap
477 land polygons.

478 **Fig. 6** Map representing the predicted reduction in beaching when the 20% of dFAD
479 deployments most likely to produce a beaching within 3 months are prohibited (see
480 areas in Fig 4a), without (values on the left of the colorbar) and with (values on the
481 right of the colorbar) dFAD deployment effort redistribution to non-prohibited areas.

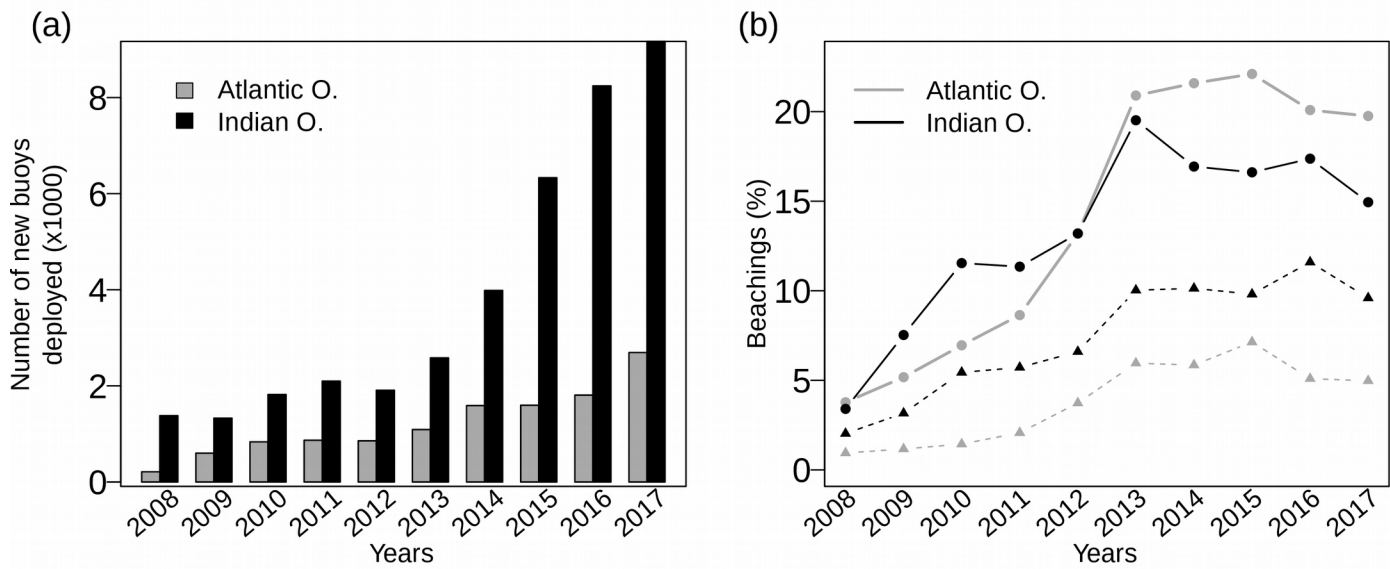


Fig. 1 (a) Annual number of new buoys deployed by the French and associated flags purse seine fleet in the Atlantic (grey) and Indian (black) oceans over the period 2008-2017 and (b) percentage of these buoys that beached. The lines in (b) with solid circles include all beachings, whereas the lines with solid triangles include only beachings identified along shore. Beachings along shore and recoveries displaced to shore were separated via intersection with OpenStreetMap land polygons.

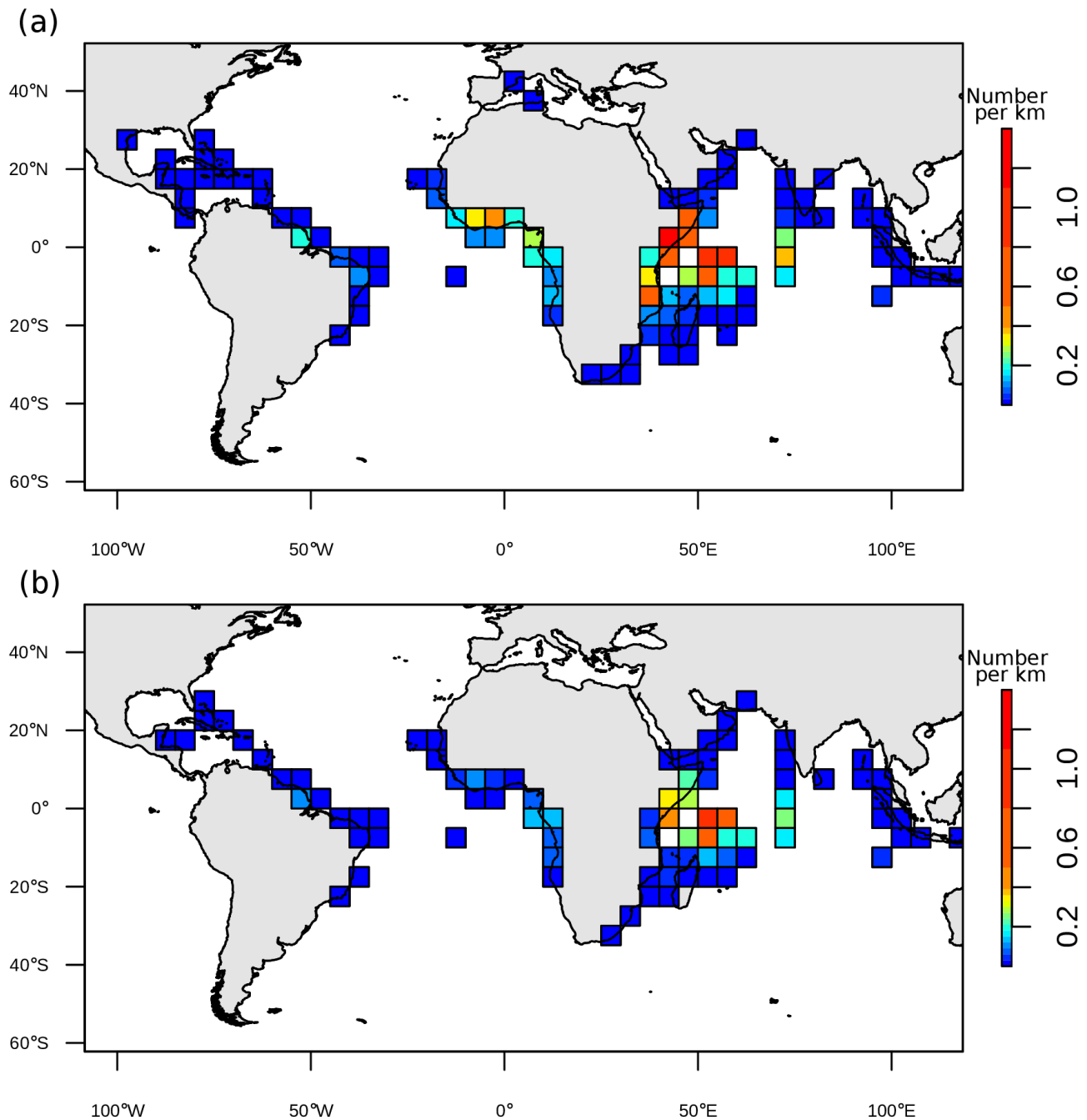


Fig. 2 The number of French dFAD beachings recorded in our data per km of continental shelf edge in each 5°x5° grid cell for the period 2008-2017. Darker areas indicate higher rates of beaching. In (a), all beachings are considered, whereas in (b) only beachings along shore are included.

Beachings along shore and recoveries displaced to shore were separated via intersection with OpenStreetMap land polygons. Note that our dFAD trajectory data is incomplete before ~2010, so the absolute number of beachings per kilometer is likely somewhat higher than values shown in the figure, though differences are likely to be small as the number of dFADs was far lower before 2010 than after 2010.

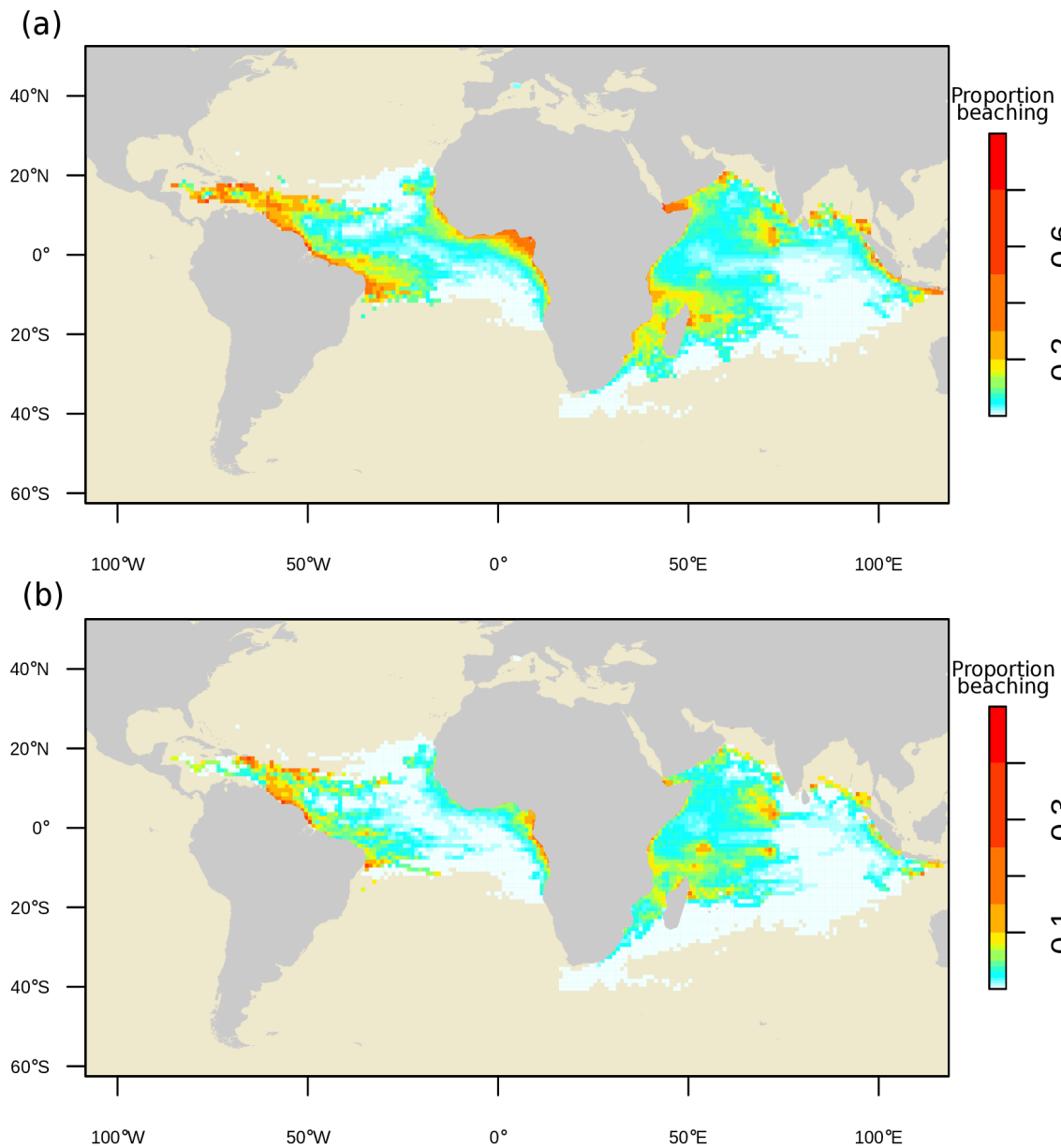


Fig. 3 Maps of the proportion of dFADs that beached within 3 months after passing through each $1^\circ \times 1^\circ$ grid cell over the period 2008-2017. In (a), all beachings are considered, whereas in (b) only beachings along shore are included. Beachings along shore and recoveries displaced to shore were separated via intersection with OpenStreetMap land polygons. Note that the color intervals are unevenly distributed to highlight the low values.

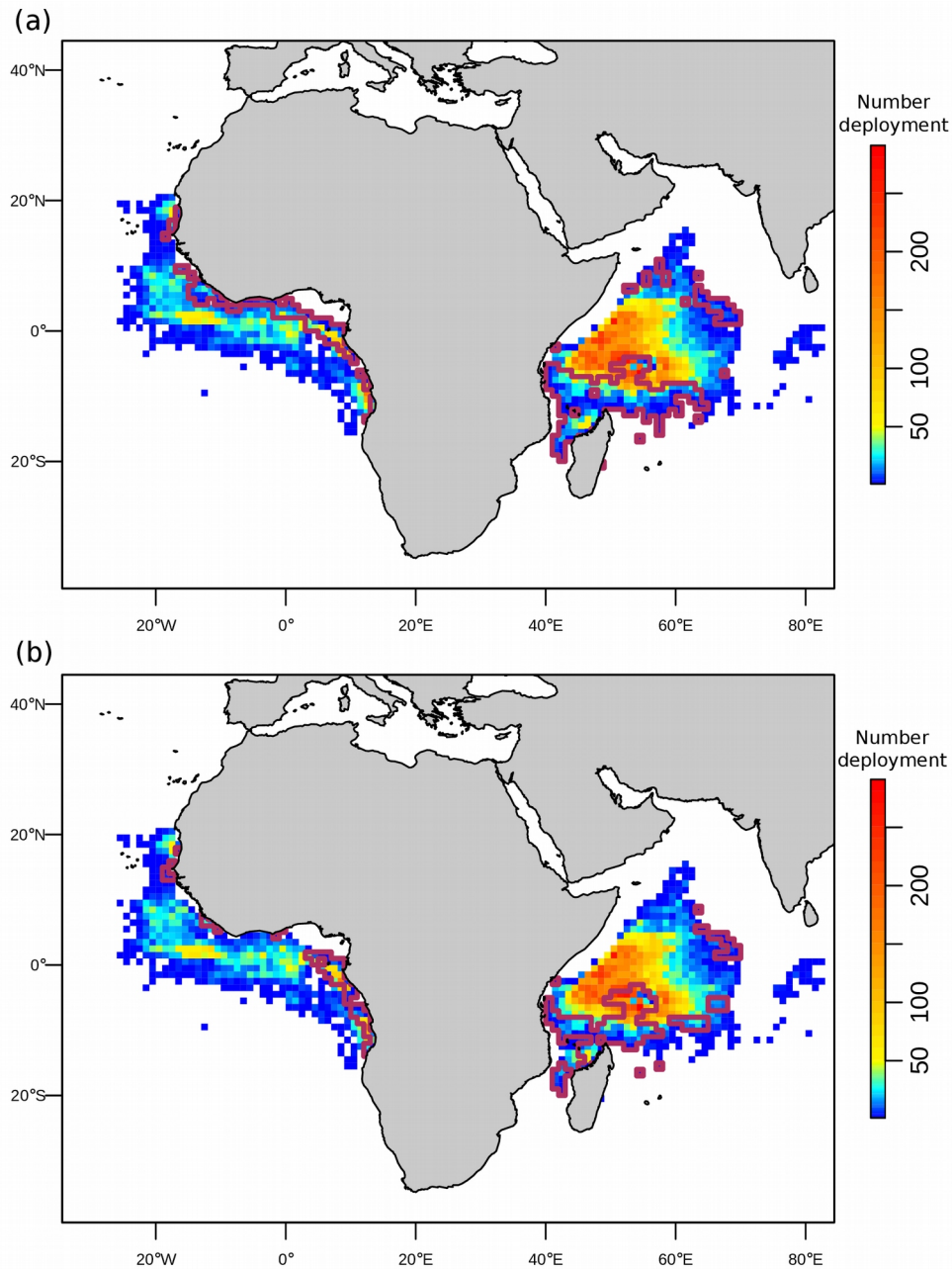


Fig. 4 Density maps representing the number of dFAD deployments in each $1^{\circ} \times 1^{\circ}$ cell recorded in logbook data for the period 2013-2017. The thick, solid curves delimit areas representing the 20% of deployments most likely to produce a beaching within 3 months of a dFAD passing through those areas. In (a), all beachings are considered, whereas in (b), only beachings along shore are included. Beachings along shore and recoveries displaced to shore were separated via intersection with OpenStreetMap land polygons.

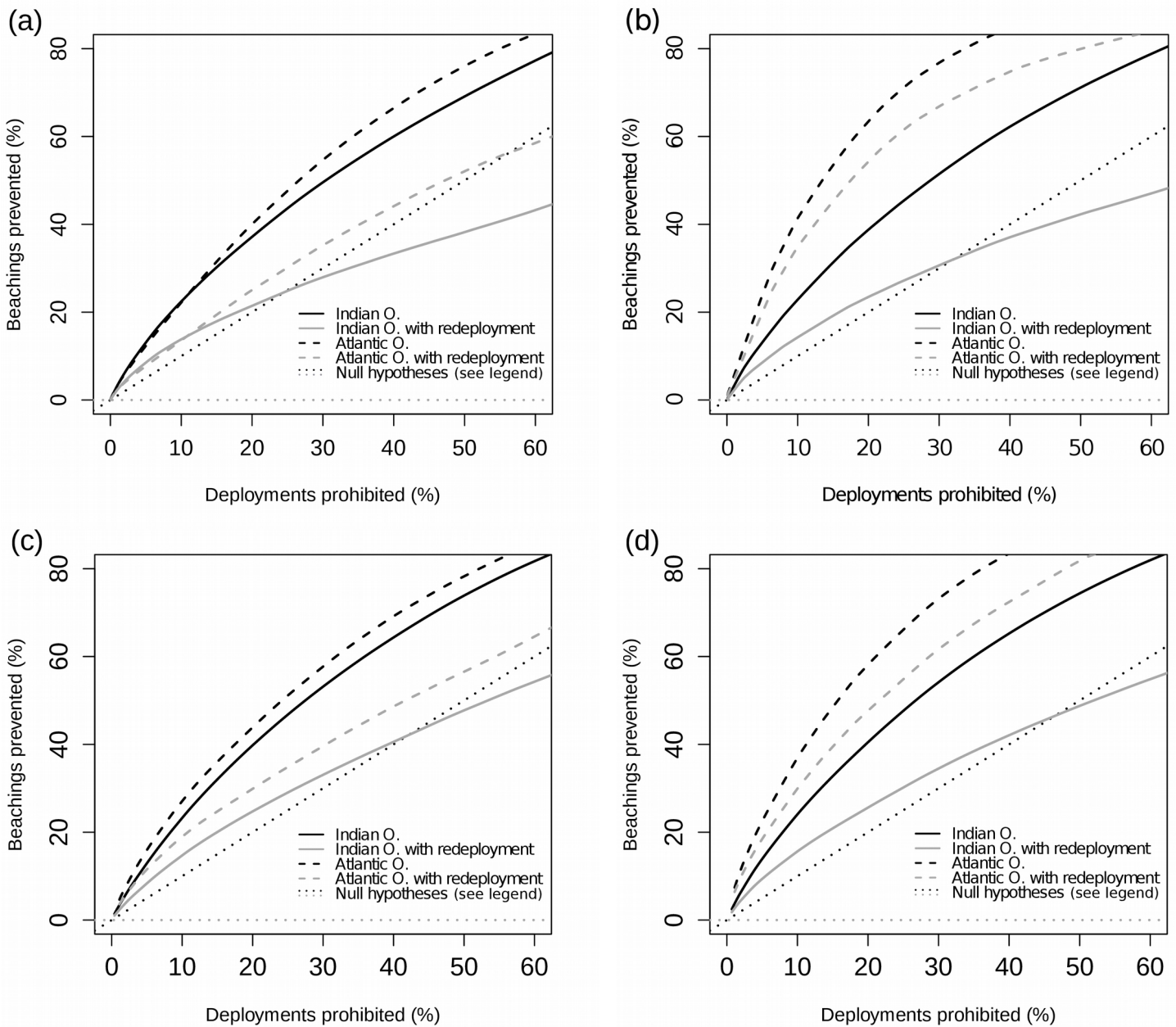


Fig. 5 Predicted reduction in beaching rate as a function of the amount of area put aside in annual (a-b) or quarterly (c-d) closures to dFAD deployments. Areas are closed from most likely to least likely to produce a beaching within 3 months of deployment, with area being quantified along the x-axis in terms of the fraction of deployments that occurred in closed areas prior to their closure. Black and grey dotted lines correspond to the null expectation of what the corresponding black and grey curves would look like if all areas had the same beaching risk, and are the same in the Indian and Atlantic Oceans. In (a) and (c), all beachings are considered, whereas in (b) and (d), only beachings occurring along shore are included. Beachings along shore and recoveries displaced to shore were separated via intersection with OpenStreetMap land polygons.

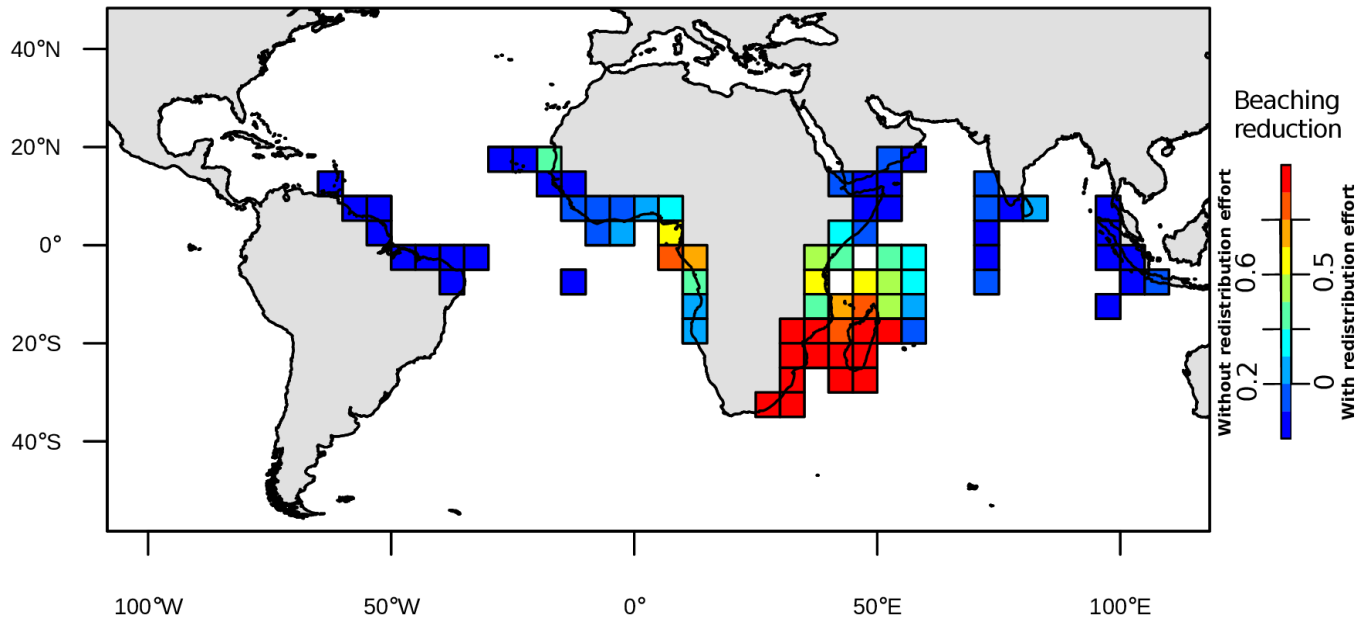


Fig. 6 Map representing the predicted reduction in beaching when the 20% of dFAD deployments most likely to produce a beaching within 3 months are prohibited (see areas in Fig 4a), without (values on the left of the colorbar) and with (values on the right of the colorbar) dFAD deployment effort redistribution to non-prohibited areas.