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1 **Design and deployment of an affordable and long-lasting deep-water subsurface fish**  
2 **aggregation device**

3

4 **Running Title:** Design of a long-term subsurface FAD

5

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31

32 **Key-words:** FAD, fisheries, pelagic ecosystem, open-ocean, fisheries-independent data

33

34 **Data Sharing:** The data that support the findings of this study are available from the  
35 corresponding author upon request.

36

37

### Abstract

38 Fish aggregation devices (FADs) are used worldwide to enhance the efficiency of various  
39 fisheries. Devices consist of a floating or subsurface component designed to exploit natural fish  
40 behavior, using species' attraction to structure (e.g., *Sargassum* spp.) to aggregate fish and  
41 increase capture success in open ocean environments. Concerns have arisen regarding the scale  
42 and management of FAD-associated fisheries, however, the efficiency of FADs to aggregate fish  
43 also introduces the possibility for FADs to be used as conservation tools to study pelagic species  
44 ecology. Building on two successful and several failed deployments of anchored deep-water  
45 (>500 m) subsurface (10 m) FADs over three years in The Bahamas, and observations from the  
46 subsequent FAD monitoring program, the objectives of the paper are to: 1) provide details and  
47 considerations for the design, construction, and deployment of an affordable and durable deep-

48 water subsurface FAD that can be deployed using small boats; and 2) highlight the potential for a  
49 long-lasting moored FAD to be used as a sustainable and reliable scientific platform for pelagic  
50 species research and conservation, lending specifically to several research applications. This  
51 information will be useful for assessing the impacts that FADs and other anthropogenic marine  
52 infrastructure have on wild marine species, and their efficacy for conserving pelagic fish through  
53 increased encounters for study.

54

## 55 **Introduction**

56 The pelagic ocean is the largest habitat on earth by both surface area and volume,  
57 however, it is largely understudied compared to coastal or terrestrial ecosystems (Webb et al.  
58 2010). The pelagic zone of the ocean provides important ecosystem services such as food and  
59 oxygen production, carbon cycling, and climate stabilization (Robison 2009), and is known to  
60 harbor considerable biodiversity (Angel 1993). With offshore habitats under intense fishing  
61 pressures (Dulvy et al. 2008, Verity et al. 2002) and many fish stocks reaching either fully  
62 exploited or over-exploited levels (FAO 2018, Pons et al. 2017), the need for better science,  
63 management, and enforcement of the pelagic zone and its fisheries is evident and increasing.

64 One aspect of fish behavior, particularly seen in pelagic species, that has substantially  
65 contributed to their harvest is their propensity to aggregate around floating structure (Castro et al.  
66 2002, Girard et al. 2004). Over the past several decades, intentionally constructed fish  
67 aggregation devices (FADs) have become a ubiquitous tool in pelagic purse seine fisheries  
68 (Moreno et al. 2016) with more than half of all tuna landed globally caught using FADs (Miyake  
69 et al. 2010). A wide range of epi-pelagic fishes have been documented aggregating to floating  
70 structures (Castro et al. 2002) including many high-level predators such as scombrids (e.g.,

71 tunas), billfish, and pelagic sharks which are groups of fishes most at risk of over-exploitation  
72 (Baum et al. 2003; Baum and Myers 2004). It is estimated that 81,000 to 121,000 new FADs are  
73 deployed into the world's oceans annually, with many lost within the first year after deployment  
74 (Gershman et al. 2015). The scale of FAD use poses numerous challenges to ocean conservation  
75 and fisheries management, and such a rapid increase in fishing technology (i.e., FADs  
76 instrumented with GPS trackers and 'fish-finder' echosounders) have outpaced management  
77 developments (Baske et al. 2012). When working to manage an industry that utilizes such  
78 powerful fishing tools as FADs, extra attention must be applied to promote the sustainability of  
79 targeted stocks and bycatch.

80         Recently, there has been a concerted effort to utilize instrumented FADs and to work  
81 cooperatively with fishing industries to increase the capacity for pelagic species research in this  
82 often difficult to access and vast habitat (Brehmer et al. 2019, Davies et al. 2014). However,  
83 these initiatives typically use FADs that are actively fished and free-floating which may bias  
84 ecological research towards geographical areas that are chosen by fishing fleets and potentially  
85 mask ecological phenomena due to the nature of this extractive process. Additionally, most  
86 drifting FADs are not accessible by small boats with shorter ranges and have a relatively short  
87 functional life of less than one year before degrading or washing out of range and / or ashore,  
88 limiting the feasibility of long-term biological studies or oceanographic monitoring (Lopez et al.  
89 2017). Therefore, to address these concerns, it is important to invest in the collection of  
90 fisheries-independent data utilizing long-lasting anchored FADs to better understand the status  
91 and trends of commercially important fish stocks (Moreno et al. 2016). Depending on location,  
92 anchored FADs may allow greater accessibility to undertake monitoring work, can facilitate a  
93 wide array of instrumentation both above and below the surface of the ocean, and will allow for

94 longer studies to occur if designed properly. Few resources exist on the design, construction, and  
95 deployment of anchored FADs for study, despite their widespread use in the fishing industry.  
96 Existing studies and manuals typically describe FADs deployed from large boats or using  
97 materials that are either expensive or difficult to purchase and ship to remote locations (see  
98 examples in Table 1).

99         Here we detail the design, construction, deployment, and utility of an anchored deep-  
100 water, subsurface FAD that is durable and long-lasting, easily reproducible, and specifically  
101 intended to facilitate fish ecology and marine conservation research. The durability and moored  
102 nature of the design makes the FAD less prone to loss or damage, and the low cost of the FAD  
103 allows for the possibility of several to be deployed using small boats and facilitate much needed  
104 replication and manipulation in experimental designs, a component often lacking in this area of  
105 study. While the subsurface aspect of these FADs was designed to reduce surface-associated  
106 damage and tampering, and to facilitate specific research objectives, any potential trade-offs  
107 between constructing a subsurface FAD and fish attraction / aggregation are also a point of  
108 interest and are detailed below.

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110

## **Methods**

111

### **FAD Design**

113         The main design objectives were to create a long-lasting subsurface anchored FAD  
114 without any surface markers, deep enough to avoid surge-associated damage or navigational  
115 hazards, while still shallow enough to be accessible to divers and avoid pressure-related damage

116 to the steel buoys. Additionally, the FAD needed to easily facilitate equipment mounting to act  
117 as a stable platform for various fish ecology and marine conservation investigations.

118 The FADs used in our study consisted of a concrete anchor block (122 cm L x 122 cm W  
119 x 84 cm H = 1.25 m<sup>3</sup>; ~2900 kg weight on land, ~1620 kg weight in water), a vertical mooring  
120 line (600 m of 5,817 kg minimum tensile strength one inch polypropylene) and two tethered  
121 subsurface steel buoys (surplus naval buoys, 71 cm diameter, 54 kg weight / 181 kg buoyancy  
122 each; Fig. 1). A depth of 10-15 m subsurface was decided to be an acceptable target range for  
123 the floats, although subsurface FADs are not commonly deployed at bottom depths > 600 m  
124 (study site depth) which is novel here (Chapman et al. 2005). At the time of writing, two of  
125 these FADs have remained in place for over 3 years (December 2017 – May 2021) and have  
126 withstood wind and surge from multiple passing hurricanes (<100 kph winds). The FADs were  
127 visited weekly for the first 2.5 years, and then monthly thereafter.

128 Existing designs found in scientific papers and technical reports did not conform to all  
129 our objectives, therefore a new and unique design was utilized here. For example, Weng et al.  
130 (2013) used a subsurface FAD at a bottom depth of 415 m, however, the buoy depth of 50 m was  
131 inaccessible to divers. Further, details of an array of subsurface FADs around Okinawa, Japan  
132 indicate subsurface FADs at bottom depths up to 2000 m. However, the materials and  
133 deployment were costly, and structure depth ranged from 20 m to 100 m subsurface which  
134 minimizes survey time available for divers or renders it inaccessible (Sokimi 2006). The closest  
135 example to those used here is a subsurface FAD array in Hawaii described by Higashi (1994)  
136 with a bottom depth range of 366 m to 549 m and a buoy depth of 18 m to 21 m, but little detail  
137 describing the construction and deployment are available. From the limited information  
138 available, it suggests a large naval vessel was used for deployment and that the FAD construction

139 used galvanized steel cable, suggesting neither a simple nor cheap construction and deployment  
140 process.

141

## 142 **Construction**

143 Steel reinforcing lattice (#4 rebar) was laid as the concrete was being placed, and a  
144 stainless-steel round stock bail (Fig. 2) was incorporated beneath the last layer of lattice so that  
145 the top of the bail protruded from the center of the block to aid in mooring line attachment. A  
146 shackle (7/8" bolt through) was used to attach 4 meters of 3/4" long-link chain to the bail anchor  
147 point between the block and mooring line. The chain was used to prevent chaffing of the anchor  
148 line against the anchor block in the event of converting the structure to a surface FAD.

149 However, this was determined to be unnecessary for subsurface orientation because the tension  
150 in the mooring line, by default, prevents the anchor line from contacting the anchor block. This  
151 was followed by a 7/8" bolt through shackle, a 7/8" eye by eye swivel, another 7/8" shackle and  
152 finally a size 4 rope connector (Samson Nylite, Ferndale, Washington, USA; Fig. 3).

153 Eight-strand 1" polypropylene line (5,817 kg minimum tensile strength) was used as the  
154 mooring line and attached to rope connectors via an eye-splice. The rope connector prevented  
155 the eye splice from chaffing against the metal rigging. End-to-end splices were used any time  
156 the line needed to be extended. The same series of hardware was repeated at the end of the line  
157 (rope connector, swivel, and shackle). However, this series was then followed by a 7/8" master  
158 link (Fig. 3).

159 The floating portion of the FAD structure was comprised of two round 71 cm diameter  
160 steel buoys (54 kg weight, 181 kg buoyancy each) tethered to the master link using 2 meters of  
161 1/2" three-strand polypropylene line that was eye-spliced through a rope thimble. This is similar

162 in size and surface area to the flotation component of drifting FADs used in some commercial  
163 tuna fisheries (personal observation). However, FADs used in commercial fisheries often  
164 incorporate subsurface netting, palm fronds, synthetic streamers, or other structure below the  
165 surface. These additions were not included in this design to avoid animal entanglement  
166 (Filmlalter et al. 2013) and to maintain clearance along the mooring line for equipment  
167 deployment (hydrophones, acoustic receivers and oceanographic monitoring equipment) and  
168 retrieval during future stages of the research program.

169

## 170 **Deployment**

171 Several location parameters were taken into consideration when selecting locations for  
172 the subsurface FADs, and the Exuma Sound (near the Cape Eleuthera Institute and base of  
173 research operations) was ideally suited for this. First, a deep-water drop off was located near-  
174 shore and accessible from the research station. Second, the area is a known migration route for  
175 pelagic fishes. Although the bathymetry had not been accurately described, several known depth  
176 points from previous deep-water research were used to select suitable locations and to  
177 predetermine mooring line lengths.

178 Following the construction of the individual components on land, the anchor was  
179 transported into shallow water at a nearby marina using a crane truck. Although in this case a  
180 crane truck was used, the block could be constructed on a platform at the edge of the water and  
181 deployed using rollers or a winch for simplicity. Once the anchor was submerged, three lift bags  
182 (SP2000, Subsolve, North Kingstown, Rhode Island, USA) were attached to the anchor bail  
183 using a release under load mechanism (Sea Catch TR7, MacMillan Design, Gig Harbor,  
184 Washington, USA). A safety line was attached between the block and lift bag to prevent

185 premature deployment. Lift bags were inflated with compressed air and the anchor raised off the  
186 bottom for towing behind a small boat. The tow line was attached above the release mechanism  
187 so that if the anchor block dropped unexpectedly the weight of the anchor would not damage the  
188 boat. Once at the deployment location, a second small vessel slowly released the mooring line  
189 overboard and onto the surface of the water down current and away from the anchor attachment  
190 point. A polyethylene ball float was attached to the free end of the mooring line to aid in  
191 visualization of the rope during and after deployment. Following the deployment of the mooring  
192 line from the vessel, snorkelers attached the anchor chain to the bail using a shackle, removed the  
193 safety line between the block and the lift bags, and released the load-bearing mechanism using a  
194 nylon rip cord thus dropping the block (Fig. 4). The location of the drop was positioned to be  
195 1/3 of the depth up-current of the targeted FAD location to account for drag on the line pulling  
196 the block in the down-current direction.

197         Following the anchor drop, the excess mooring line on the surface was recovered. The  
198 mooring line was then elongated using lift bags attached at depth to simulate the ultimate tension  
199 on the line from the FAD buoys. To do so, divers on SCUBA attached a lift bag to the mooring  
200 line using a Prusik hitch at 25 m depth and filled the lift bag with compressed air (Fig. 5).  
201 Following the lift bag's ascent to the surface, this process was continued until the line was under  
202 approximately 600 kg of tension, evidenced by the 900 kg lift bag filled to approximately 66% of  
203 total volume, and positioned at a static depth of 10 m without further elongation. At least 24  
204 hours were allowed for a complete tidal cycle, and to allow the mooring line to undergo phase  
205 one creep (stretching) to its ultimate length under load. If this time period resulted in reduced  
206 tension, or if the lift bags reached the surface, the mooring line elongation process was repeated.  
207 When the line was determined to have undergone all elongation, an eye-splice was used to attach

208 a rope protector to the mooring line just above the lift bag. A shackle, master link, and a 15 m  
209 safety line with a fully inflated SP2000 lift bag were attached to the trailing end of the mooring  
210 line at the surface to further ensure the mooring line did not retract. Two individually rigged  
211 steel buoys were spliced onto the master link. After the attachment was complete, the lift bag  
212 under tension was released allowing the recoil of the mooring line to submerge the buoys to a  
213 depth of 10 to 15 m, at which point the inflated surface lift bag prevented any possible further  
214 descent. A small polyethylene buoy was finally attached to the master link and filled with  
215 compressed air as needed to fine tune buoyancy to the targeted 10 m depth resting point. Lastly,  
216 a safety line (3/8" Spectra 12-strand braided line, 6,305 kg minimum tensile strength) was tied to  
217 the master link, run through each eye-attachment point on the two buoys and tied back to the  
218 master link. In the case of eye-ring failure or a buoy tether being severed, this line provides a  
219 cut-resistant back-up to avoid the loss of a buoy or the entire FAD.

220

## 221 **Removal Potential**

222 While the durability and moored nature of the FAD design presented here results in a  
223 robust and maintainable platform for longer time scales, these FADs are removable using the  
224 same equipment and process needed for deployment and users can therefore avoid contributing  
225 marine debris to the ocean following the conclusion of research activities. Although this would  
226 involve some effort, divers repeatedly deploying lift bags down the mooring line will slowly  
227 raise the anchor block which can then be towed to shallow water and allow for retrieval of the  
228 entire FAD.

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## **Results and Discussion**

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**Design Considerations**

Materials and operations were all considered and selected to not only meet the project objectives, but to be accessible by a wide array of potential users including those at remote field stations or research groups with limited funding and resources. It has been shown that price is often a limiting factor during FAD creation and installation in remote island locations, and although this is typically documented in the scope of bolstering fishing communities (Bell et al. 2015), financial restraints will similarly apply to research groups. During the development and expansion of the Pacific FAD fishery, 2000 to 3000 USD was targeted for a reasonable total cost for a deep-water FAD intended to last approximately 2 years (Chapman et al. 2005), so the 5000 USD total cost per FAD in this project was deemed appropriate when designing for a durable longer-lasting structure. Longevity is also a high concern for surface FADs, with wave/weather damage or vandalism frequently leading to loss of the FAD in less than two years (Chapman et al. 2005, Tilley et al. 2019). Inspections in June 2019 (one and a half years after deployment), using deep sea submersible surveys in the area, revealed that all parts of the FAD design inaccessible to divers remain in good condition. The concrete anchor block, steel connections (shackles, chain, swivels, etc.), polypropylene mooring line and steel buoys were all considered to be affordable and possible to source and ship to a remote location and are standard options for offshore FADs (Chapman et al. 2005). Recently, there has been considerable effort to construct FADs from biodegradable materials to decrease marine debris and the potential negative impacts on wildlife such as entanglement (Moreno et al. 2018). Increasing longevity through careful design and robust synthetic materials was pursued during this project, although this could easily be adapted for a shorter-lived but biodegradable version. Additionally, the FADs were deployed

254 using only SCUBA divers, a crane truck (or equivalent for pushing the anchor into the water), lift  
255 bags, and two 8 m long inboard panga vessels. One possible price reduction was tested by using  
256 three A-6 sized polyethylene buoys (Polyform A-6) instead of steel buoys, however this was  
257 quickly proven to not work. Flexible buoys expand or contract with minimal changes in water  
258 depth associated with the mooring line stretching or contracting, which in turn changes the  
259 buoyancy and prevents a stable target depth. Additionally, several flexible buoys showed marks  
260 consistent with teeth punctures by predatory fishes. Therefore, steel buoys soon replaced the  
261 flexible buoys after deployment of the first FAD and are highly recommended. Alternative  
262 mooring line materials were also considered, and materials such as Spectra or Dyneema are cut-  
263 resistant and would dramatically reduce phase 1 creep (stretching), making buoy placement at a  
264 target depth easier, however, these options are considerably more expensive and were avoided  
265 for this reason.

266         The subsurface aspect of the FAD design was chosen for several reasons related to the  
267 objectives of the project. First, 10 m depth was found to greatly minimize movement of the  
268 structure by surge or during windy weather, and would prevent any potential boat strikes, adding  
269 to the longevity of the infrastructure. Additionally, 10 m is an easily accessible and safe depth  
270 for both SCUBA and freedivers to work or deploy/retrieve equipment and does not pose any  
271 serious pressure-related stress to the buoys or equipment (at 2 atmospheres).

272

### 273 **Research Applications and Conclusions**

274         The subsurface anchored design of the FADs used in this study has proven to be a stable  
275 and diverse scientific platform for more than three years. Many of the epipelagic fish species  
276 that occur in the region have been documented at the FADs, ranging in trophic level and size

277 (Table 2). These anchored FADs allow the fish community to be continually monitored over  
278 long temporal scales and can facilitate short and long-term experimental studies through  
279 increased accessibility that would not be possible when using conventional offshore drifting  
280 FADs. It is possible that these long-term stationary fish censuses could be representative of  
281 actual population trends, and these data would therefore be useful to fisheries managers.  
282 Additionally, Dagorn et al. (2010) previously argued that anchored FADs are acceptable and  
283 useful proxies for drifting FADs to address research questions such as the ecological trap  
284 hypothesis, and that they pose accessibility advantages while maintaining contextual similarities  
285 to their drifting counterparts. A variety of methods that have been recently performed on surface  
286 FADs and would be well-suited to this FAD design, many of which were proposed by Moreno et  
287 al. (2016) as research priorities, are detailed in Table 3.

288         The subsurface aspect of the FADs used in this study, combined with the buoyancy of the  
289 buoys used (362 kg of lift total), resulted in a taut mooring line. Therefore, this design presents  
290 several unique opportunities for research activities. First, equipment can be shuttled up and  
291 down the mooring line with a simple rigging system, enabling fixed depth/location deployment  
292 of various instruments. This would otherwise be difficult without a taut mooring line.  
293 Additionally, keeping the structure underneath the surface and away from any surge or waves  
294 results in a nearly silent structure, presenting opportunities for investigation into fish sensory  
295 biology in the open ocean, and for better hydroacoustic data collection (e.g., hydrophone  
296 deployment for cetacean surveys). Finally, this tension ensured that the FAD buoys remained at  
297 the known GPS location and did not sway with tidal or current flow. Although this study area  
298 does not experience significant currents, locations with strong tidal flow should consider the  
299 impact of horizontal forces on the FAD and mooring line.

300           Strategically designed FADs that are not open access can act as useful research platforms  
301 to develop new monitoring approaches while maintaining the integrity of the study population  
302 and enhance our understanding of how anthropogenic activity is affecting marine biodiversity.  
303 For example, many animals that utilize pelagic FADs are fish species known to undergo long  
304 migrations (Hallier and Gaertner 2008) which can be difficult to study. Whether following  
305 seasonal changes in food abundance, thermal windows, or breeding opportunities (Alerstam et al.  
306 2003), this migratory behavior most likely exposes them to various fisheries pressures and  
307 potential overexploitation. Knowledge of how migratory animals respond to variable conditions  
308 experienced during migration is a central component to understanding long-distance movement  
309 patterns and their management. If data are collected consistently, this information can help  
310 estimate population size, increase understanding of demographic variables needed in the  
311 development of population viability models, reveal how wild fish species are impacted by  
312 anthropogenically altered habitats, and can potentially be used for novel conservation  
313 applications. These include the construction of scientific platforms (such as deep-water  
314 subsurface FADs) along known migration routes to aid in the study of elusive migratory animals,  
315 or the ability to alter movements of migratory animals through protected seascapes by enhancing  
316 habitat preferences in these areas to minimize harvest. By utilizing FAD-based equipment such  
317 as video cameras or acoustic telemetry receivers, information on behavior during migration can  
318 be collected and used in fisheries conservation.

319           Pelagic animals are inherently difficult to study due to the expanse of their habitat, life  
320 history, and behavior, resulting in a comparatively weak understanding of pelagic species  
321 ecology and biology (Block et al. 2003). Therefore, in response to the recent call for developing  
322 methods to collect fisheries-independent data to be used in management and stock assessments

323 (Moreno et al. 2016), a network of economical, instrumented, research-oriented subsurface  
324 FADs such as those proposed here could provide substantial ecological and fisheries data that is  
325 desperately needed to effectively conserve pelagic ecosystems and their biodiversity.

326

327

### **Authors' Contributions**

328 TV, ES conceptualized the manuscript; ES, TV, MC wrote the manuscript and all authors  
329 contributed substantially to revisions and accept responsibility for this work.

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331

### **Literature Cited**

332 Alerstam, T., A. Hedenstrom, S. Akesson. 2003. Long-distance migration: evolution and  
333 determinants. *Oikos* 103:247-260.

334 Angel M.V. 1993. Biodiversity of the pelagic ocean. *Conservation Biology* 7(4):760-772.

335 Baske A., J. Gibbon, J. Benn, A. Nickson. 2012. Estimating the use of drifting fish aggregation  
336 devices (FADs) around the globe. Pew Environmental Group Discussion Paper.

337 Baum J.K., and R.A. Myers. 2004. Shifting baselines and the decline of pelagic sharks in the  
338 Gulf of Mexico. *Ecology Letters* 7:135-145.

339 Baum J.K., R.A. Myers, D.G. Kelhler, B. Worm, S.J. Harley, P.A. Doherty. 2003. Collapse and  
340 conservation of shark populations in the northwest Atlantic. *Science* 299:389-392.

341 Bell J.D., J. Albert, S. Andrefouet, N.L. Andrew, M. Blanc, P. Bright, D. Brogan, B. Campbell,  
342 H. Govan, J. Hampton, Q. Hanich, S. Harley, A. Jorari, M. Lincoln Smith, S. Pontifex,  
343 M.K. Sharp, W. Sokimi, A. Webb. 2015. Optimising the use of near shore fish  
344 aggregating devices for food security in the Pacific Islands. *Marine Policy* 56:98-105.

345 Block B.A., D.P. Costa, G.W. Boehlert, R.E. Kochevar. 2003. Revealing pelagic habitat use: the  
346 tagging of Pacific pelagics program. *Oceanologica Acta* 25:255-266.

347 Brehmer P., G. Sancho, V. Trygonis, D. Itano, J. Dalen, A. Fuchs, A. Faraj, M. Taquet. 2019.  
348 Towards an autonomous pelagic observatory: experiences from monitoring fish  
349 communities around drifting FADs. *Thalassas* 35:177-189.

350 Buckley T.W., and B.S. Miller. 1994. Feeding habits of yellowfin tuna associated with fish  
351 aggregation devices in American Samoa. *Bulletin of Marine Science* 55(2-3):445-459.

352 Castro J.J., J.A. Santiago, V. Hernandez-Garcia. 1999. Fish associated with fish aggregation  
353 devices off the Canary Islands (central-east Atlantic). *Scientia Marina* 63(3-4):191-198.

354 Castro J.J., J.A. Santiago, A.T. Santana-Ortega. 2002. A general theory on fish aggregation to  
355 floating objects: an alternative to the meeting point hypothesis. *Reviews in Fish Biology*  
356 *and Fisheries* 11:255-277.

357 Chapman L., B. Pasisi, I. Bertram, S. Beverly, W. Sokimi. 2005. Manual on fish aggregating  
358 devices (FADs): lower-cost moorings and programme management. Secretariat of the  
359 Pacific Community.

360 Dagorn L., D. Pincock, C. Girard, K. Holland, M. Taquet, G. Sancho, D. Itano, R. Aumeeruddy.  
361 2007. Satellite-linked acoustic receivers to observe behavior of fish in remote areas.  
362 *Aquatic Living Resources* 20:307-312.

363 Dagorn L., K.N. Holland, J. Filmalter. 2010. Are drifting FADs essential for testing the  
364 ecological trap hypothesis? *Fisheries Research* 106:60-63.

365 Davies T.K., C.C. Mees, E.J. Milner-Gulland. 2014. The past, present and future use of drifting  
366 fish aggregating devices (FADs) in the Indian Ocean. *Marine Policy* 45:163-70.

367 Doray M., E. Josse, P. Gervain, L. Reynal, J. Chantrel. 2007. Joint use of echosounding, fishing  
368 and video techniques to assess the structure of fish aggregations around moored fish  
369 aggregating devices in Martinique (Lesser Antilles). *Aquatic Living Resources* 20:357-  
370 366.

371 Dulvy N.K., J.K. Baum, S. Clarke, L.J.V. Compagno, E. Cortés, A. Domingo, S. Fordham, S.  
372 Fowler, M.P. Francis, C. Gibson, J. Martínez, J.A. Musick, A. Soldo, J.D. Stevens, S.  
373 Valenti. 2008. You can swim but you can't hide: the global status and conservation of  
374 oceanic pelagic sharks and rays. *Aquatic Conservation: Marine and Freshwater*  
375 *Ecosystems* 18(5):459-482.

376 FAO 2018. The state of world fisheries and aquaculture 2018- meeting the sustainable  
377 development goals, Rome. License: CC BY-NC-SA 3.0 IGO.

378 Filmalter J., P. Cowley, F. Forget, L. Dagorn. 2015. Fine-scale 3-dimensional movement  
379 behaviour of silky sharks *Carcharhinus falciformis* associated with fish aggregating  
380 devices (FADs). *Marine Ecology Progress Series* 539:207-223.

381 Filmalter J.D., M. Capello, J.-L. Deneubourg, P.D. Cowley, L. Dagorn. 2013. Looking behind  
382 the curtain: quantifying massive shark mortality in fish aggregating devices. *Frontiers in*  
383 *Ecology and the Environment* 11(6):291-296.

384 Gershman D., A. Nickson, M. O’Toole. 2015. Estimating the use of FADs around the world.  
385 Pew Environmental Group.

386 Gervain P., L. Reynal, J. Defoe, M. Ishida, E. Mohammed. 2015. Manual of best practices in  
387 fisheries that use moored fish aggregating devices: FAD design, construction and  
388 deployment. *CRFM Special Publication* 6(1):1-55.

389 Girard C., S. Benhamou, L. Dagorn. 2004. FAD: fish aggregating device or fish attracting  
390 device? A new analysis of yellowfin tuna movements around floating objects. *Animal*  
391 *Behavior* 67:319-326.

392 Hallier J.-P., and D. Gaertner. 2008. Drifting fish aggregation devices could act as an ecological  
393 trap for tropical tuna species. *Marine Ecology Progress Series* 353:255-264.

394 Higashi G.R. 1994. Ten years of fish aggregating device (FAD) design development in Hawaii.  
395 *Bulletin of Marine Science* 55(2-3):651-666.

396 Itano D., S. Fukofuka, D. Brogan. 2004. The development, design and recent status of anchored  
397 and drifting FADs in the WCPO. Working Paper INF –FTWG-3, Standing Committee on  
398 Tuna and Billfish.

399 Lopez J., G. Moreno, C. Lennert-Cody, M. Maunder, I. Sancristobal, A. Caballero, L. Dagorn.  
400 2017. Environmental preferences of tuna and non-tuna species associated with drifting  
401 fish aggregating devices (DFADs) in the Atlantic Ocean, ascertained through fishers’  
402 echo-sounder buoys. *Deep-Sea Research II* 140:127-138.

403 Lopez J., G. Moreno, G. Boyra, L. Dagorn. 2016. A model based on data from echosounder  
404 buoys to estimate biomass of fish species associated with fish aggregating devices.  
405 *Fisheries Bulletin* 114:166-178.

406 Merten W., R. Rivera, R. Appeldoorn, K. Serrano, O. Collazo, N. Jimenez. 2018. Use of video  
407 monitoring to quantify spatial and temporal patterns in fishing activity across sectors at  
408 moored fish aggregating devices off Puerto Rico. *Scientia Marina* 82(2).

409 Mills D., and A. Tilley. 2019. Exploring options to improve livelihoods and resource  
410 management in Timor-Leste’s coastal communities. Report for the Australian Centre  
411 for International Agricultural Research FR2019-46.

412 Miyake M.P., P. Guillotreau, C.-H. Sun, G. Ishimura. 2010. Recent developments in the tuna  
413 industry. FAO Fisheries and Aquaculture Technical Paper 543.

414 Moreno G., L. Dagorn, M. Capello, J. Lopez, J. Filmalter, F. Forget, I. Sancristobal, K. Holland.  
415 2016. Fish aggregating devices (FADs) as scientific platforms. Fisheries Research  
416 178:122-129.

417 Moreno G., R. Jauhary, S.M. Adam, V. Restrepo. 2018. Moving away from synthetic materials  
418 used at FADs: evaluating biodegradable ropes degradation. Collective Volume of  
419 Scientific Papers 74(5):2192-2198.

420 Pons M., M.C. Melnychuk, R. Hilborn. 2018. Management effectiveness of large pelagic  
421 fisheries in the high seas. Fish and Fisheries 19:260-270.

422 Robison B.H. 2009. Conservation of deep pelagic biodiversity. Conservation Biology 23:847-  
423 858.

424 Sokimi W. 2006. Fish aggregating devices: the Okinawa/Pacific experience. Fish. News.- South  
425 Pacific Commission, 119, 45.

426 Taquet M., M. Blanc, L. Dagorn, J.D. Filmalter, A. Fonteneau, F. Forget, J.C. Gaertner, R.  
427 Galzin, P. Gervain, M. Goujon, P. Guillotreau, O. Guyader, M. Hall, K. Holland, D.  
428 Itano, J.P. Monteagudo, B. Morales-Nin, L. Reynal, M. Sharp, W. Sokimi, M. Tanetoa, S.  
429 Yen Kai Sun. 2011. Artisanal and industrial FADs: A question of scale. Tahiti conference  
430 reviews current FAD use and technology. Fisheries Newsletter 136:35-45.

431 Tilley A., S.P. Wilkinson, J. Kolding, J. Lopez-Angarita, M. Pereira, D.J. Mills. 2019. Nearshore  
432 fish aggregating devices show positive outcomes for sustainable fisheries development in  
433 Timor-Leste. Frontiers in Marine Science 6:487.

434 Tolotti M.T., F. Forget, M. Capello, J.D. Filmalter, M. Hutchinson, D. Itano, K. Holland, L.  
435 Dagorn. 2020. Association dynamics of tuna and purse seine bycatch species with  
436 drifting fish aggregating devices (FADs) in the tropical eastern Atlantic Ocean. Fisheries  
437 Research 226:105521.

438 Verity P.G., V. Smetacek, T.J. Smayda. 2002. Status, trends and the future of the marine pelagic  
439 ecosystem. Environmental Conservation 29(2):207-237.

440 Webb T.J., E. Vanden Berghe, R O'Dor. 2010. Biodiversity's big wet secret: The global  
441 distribution of marine biological records reveals chronic under-exploration of the deep  
442 pelagic ocean. PLoS ONE 5(8):e10223.

443 Weng J.S., M.K. Hung, C.C. Lai, L.J. Wu, M.A. Lee, K.M. Liu. 2013. Fine-scale vertical and  
444 horizontal movements of juvenile yellowfin tuna (*Thunnus albacares*) associated with a  
445 subsurface fish aggregating device (FAD) off southwestern Taiwan. Journal of Applied  
446 Ichthyology 29:990-1000.

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## Tables

462 Table 1. Selected examples from a search of studies using anchored FADs that include  
 463 information on materials or deployment, that are subsurface (or ‘midwater’), or that were  
 464 deployed in depths  $\geq 500$  m and therefore comparable to our proposed design. ‘Buoy Depth’ of  
 465 0 represents a surface FAD. Substantial and replicable information must be included on  
 466 materials used or deployment processes to qualify as ‘Yes’.

<b>FAD Type</b>	<b>Bottom Depth (m)</b>	<b>Buoy Depth (m)</b>	<b>Materials Info</b>	<b>Deployment Info</b>	<b>Location</b>	<b>Reference</b>
Surface and subsurface	300-2000	0-?	Yes	Yes	Pacific Islands	Chapman et al., 2005
Surface	<200	0	Yes	Yes	Timor-Leste	Mills & Tilley, 2019
Surface	100-3000	0	Yes	Yes	Caribbean	Gervain et al., 2015
Surface and subsurface	1000-2000	50-100	Yes	No	Japan	Sokimi, 2006
Surface and subsurface	146-2761	0-18	Yes	No	Hawaii	Higashi, 1994
Surface	<5000	0	Yes	No	Pacific Islands	Itano et al., 2004
Subsurface	415	50	No	No	Taiwan	Weng et al., 2013
Surface and subsurface	50-2500	?	No	No	Pacific Islands	Taquet et al., 2011
Surface and subsurface	300-700	0-?	No	No	Pacific Islands	Bell et al., 2015
Surface	260-600	0	No	No	Puerto Rico	Merten et al., 2018
Surface	50-500	0	No	No	Canary Islands	Castro et al., 1999
Surface	1000-2200	0	No	No	American Samoa	Buckley & Miller, 1994
Surface	2000-2500	0	No	No	Martinique	Doray et al., 2007

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472 Table 2. Species documented on these subsurface FADs in the Exuma Sound during the course  
 473 of a 2.5 year camera survey (in preparation for publication elsewhere), separated into resident  
 474 intransigent versus ephemeral circumnavigant species, compared to other epipelagic fishes  
 475 documented in the Exuma Sound (personal communication: Z. Zuckerman, Cape Eleuthera  
 476 Institute) but remain absent from our subsurface FAD surveys. An asterisk (\*) denotes species  
 477 present within first 6 months after FAD deployment.

Present on subsurface FAD surveys		Absent from subsurface FAD surveys
Intransigent	Circumnavigant	Recorded in Exuma Sound
<i>Aluterus Monoceros</i> *	<i>Acanthocybium solandri</i> *	<i>Carcharhinus longimanus</i>
<i>Balistes capriscus</i> *	<i>Carcharhinus falciformis</i> *	<i>Istiophorus albicans</i>
<i>Cantherhines</i> spp.*	<i>Carcharhinus obscurus</i>	<i>Kajikia albidus</i>
<i>Canthidermis sufflamen</i> *	<i>Cheilopogon melanurus</i>	<i>Makaira nigricans</i>
<i>Carangidae</i> spp.*	<i>Coryphaena hippurus</i> *	<i>Scomberomorus cavalla</i>
<i>Caranx latus</i> *	<i>Elagatis bipinnulata</i> *	
<i>Caranx ruber</i> *	<i>Galeocerdo cuvier</i> *	
<i>Decapterus</i> spp.*	<i>Hemiramphus</i> spp.	
<i>Decapterus macarellus</i> *	<i>Sarda sarda</i>	
<i>Peprilus triacanthus</i>	<i>Sphyrna barracuda</i> *	
<i>Seriola rivoliana</i> *	<i>Sphyrna mokorran</i>	
	<i>Thunnus albacares</i>	
	<i>Thunnus</i> spp.	

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488 Table 3. Recently utilized methods for FAD-based research that lend well to a stable, subsurface  
 489 platform.

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<b>Examples of surface FAD-based methods</b>				
<b>Method</b>	<b>Species</b>	<b>Data Collected</b>	<b>Potential Influence of Data</b>	<b>References</b>
Acoustic telemetry attachment	Fish	Residence (presence/absence), some behavioral patterns	Reduction in fisheries interactions and bycatch	Tolotti et al., 2020 Filmalter et al., 2015 Dagorn et al., 2007
Video survey	Humans, fish	Fishing activity, species presence/aggregation dynamics	Managing FAD use, understanding aggregation	Merten et al., 2018 Doray et al., 2007
Echosounder/modelling	Any	Biomass	Understanding ecosystem effects of FADs	Lopez et al., 2016
Animal collection	Bivalve	Muscle tissue for stable isotope analysis, stomach contents	Characterize low levels of pelagic food web, ecosystem-based management, diet analysis	Unpublished data (B. Talwar, Cape Eleuthera Institute)

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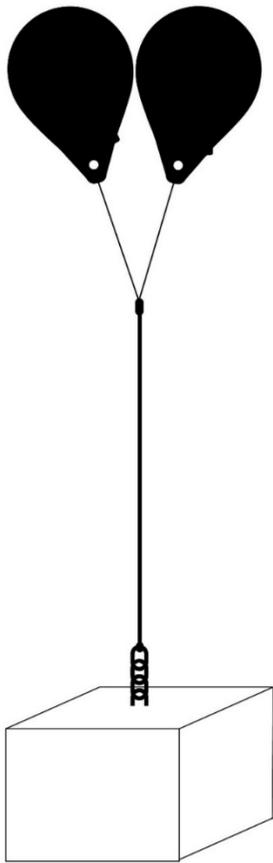
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## Figures



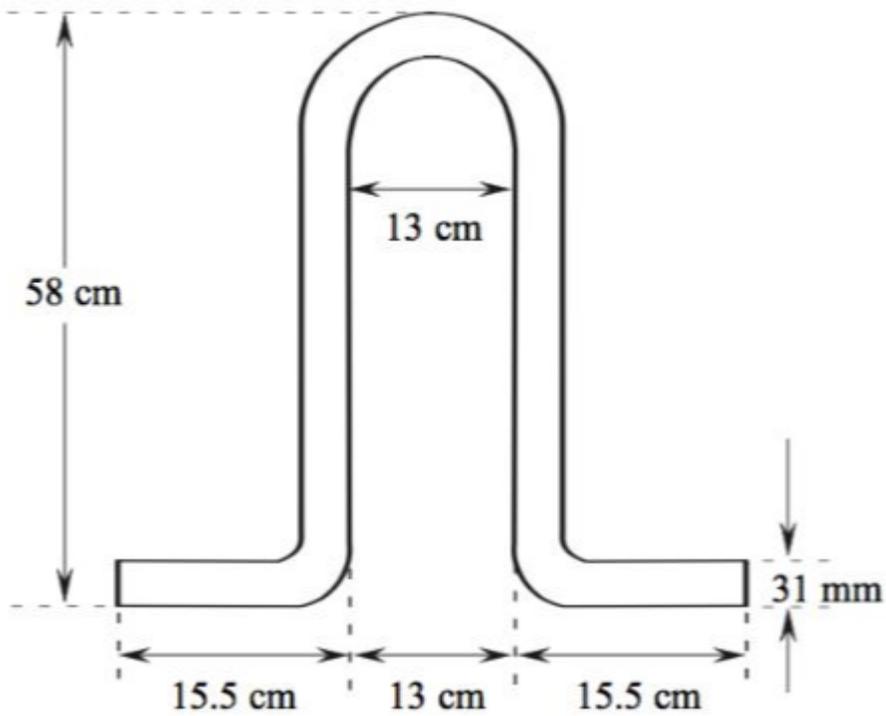
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508 Figure 1. Schematic of the subsurface fish aggregation device (FAD) currently being used at The  
509 Cape Eleuthera Institute, The Bahamas. FAD design consists of a concrete anchor block,  
510 mooring line, and two steel buoys. Steel buoys are moored 10m below the sea surface to prevent  
511 detection by fishers and to create tension and verticality in the mooring line for gear deployment.  
512 Diagram not to scale.

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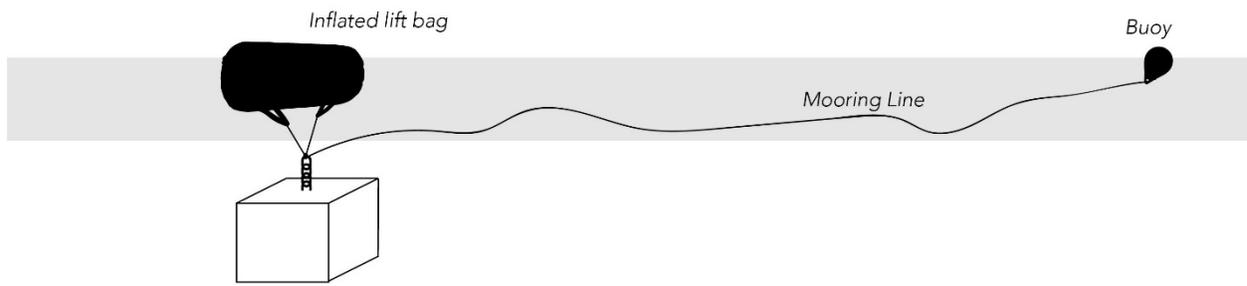
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517 Figure 2. Stainless steel round stock bail that was incorporated into the top of the concrete  
518 anchor block to serve as the attachment point between the block and metal chain, which was the  
519 beginning of the mooring line.



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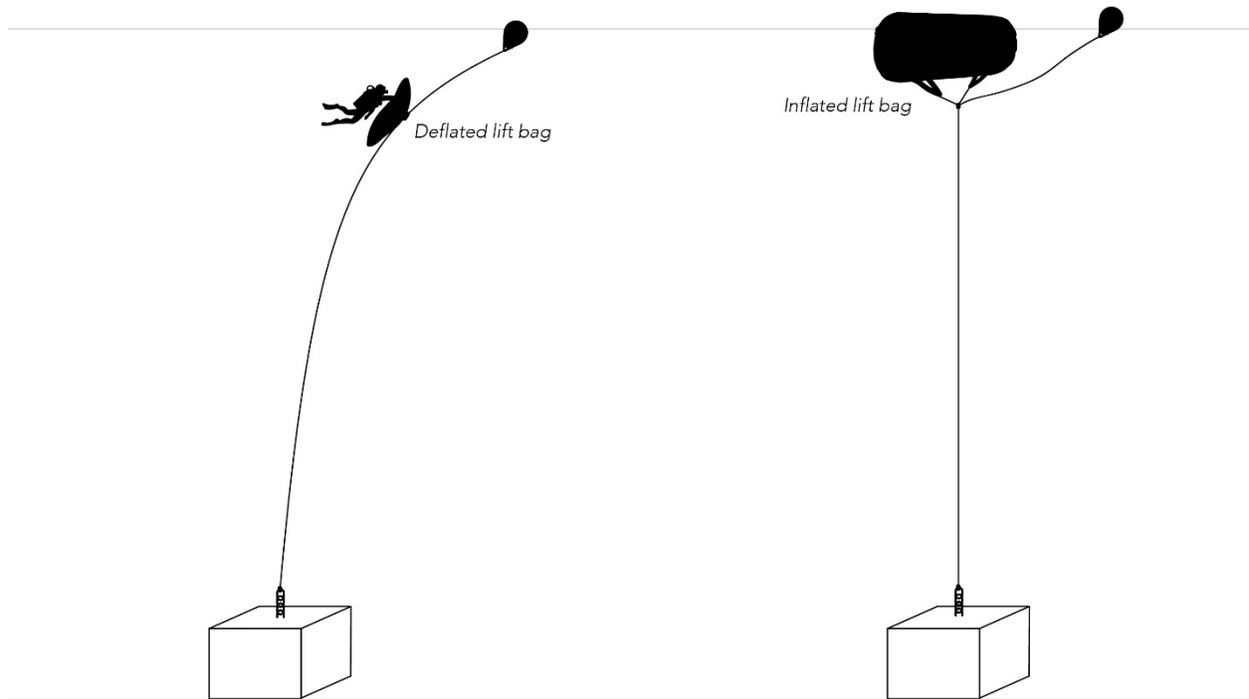
521 Figure 3. Top end of the mooring line showing an eye splice to a rope connector, swivel, bolt  
522 through shackle, and 7/8" master link to which the buoys (and a safety line during deployment)  
523 were attached.



 Anchor block target

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525 Figure 4. Initial stage of the FAD deployment process. The concrete anchor block is suspended  
526 by lift bags and attached to the mooring line that has been deployed overboard onto the sea  
527 surface down-current from the anchor. The anchor is positioned 1/3 the length of the mooring  
528 line up-current of the targeted resting location.



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530 Figure 5. Schematic showing the process of removing slack from the mooring line following  
531 deployment. A diver attaches a deflated lift bag to the slack mooring line using a Prusik hitch  
532 and slowly inflates the bag. This process is repeated until the desired tension on the mooring line  
533 has been reached and the steel buoys are then attached.

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