Drifting fish aggregation devices pose a considerable risk to large marine protected areas

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ARTICLE IMPACT STATEMENT

Left unchecked, drifting fish aggregation devices could reduce the efficacy of static marine protected areas

KEYWORDS

Beaching, Chagos Archipelago, Fisheries, Marine Protected Area, Pollution, Purse Seine, Tuna

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ABSTRACT

Mapping and predicting the potential risk of fishing activities to large marine protected areas (MPAs), where management capacity is low, but fish biomass may be globally important, is vital to prioritize enforcement and maximize conservation benefits. Using Lagrangian particle modelling we determine the potential transit of drifting fish aggregating devices (dFADs) entering a large MPA around the Chagos Archipelago in the central Indian Ocean: (i) to quantify the risk of dFADs beaching on the archipelago’s reefs and atolls, and (ii) determine the potential for dFADs to pass through the MPA, accumulate biomass and export it outside of the MPA boundary. We find over a third (37.51%) of dFADs would pose a risk (beaching or transiting >14 days), 17.70% pose a moderate risk (beaching or transiting >30 days), while 13.11% pose a high risk (beaching or transiting >40 days). Importantly, modelled dFADs deployed on east and west of the perimeter were more likely to beach and undertake long transiting times (i.e., high risk). The Great Chagos Bank, the largest atoll in the archipelago, was the most likely site to be impacted by dFADs beaching. Overall, understanding the interactions between static MPAs and drifting fishing gears is vital in developing suitable management plans to support enforcement of MPA boundaries and the health and sustainability of their associated biomass.
INTRODUCTION

With increasing awareness of the need to protect ocean habitats to meet international conservation goals, a number of large marine protected areas (MPAs) have recently been established (Davies et al. 2018). However, little attention has been given to the potentially negative interactions between such static MPAs and drifting fishing gears (Hanich et al. 2019). One drifting gear, drifting fish aggregation devices (hereafter ‘dFADs’), are increasingly being used by tropical tuna purse seine fisheries (Maufroy et al. 2017). Indeed, between 2007 and 2013 alone, a fourfold increase in their use in the Indian and Atlantic Oceans was observed (Maufroy et al. 2017). The concurrent rise in dFAD use and MPA establishments poses substantial management issues, due to the high potential for dFADs to cross MPA boundaries.

dFAD associated fishing activities have become incredibly efficient, with approximately 100,000 deployed each year (Gershman et al. 2015). By artificially modifying the surface habitat, dFADs attract an array of species, including commercially important tunas, such as skipjack (Katsuwonus pelamis) and yellowfin (Thunnus albacares), and non-commercial species, including silky sharks (Carcharhinus falciformis) (Castro et al. 2002). Biomass may begin to associate with ‘virgin’ dFADs (i.e., newly deployed) after just two weeks, with peak tuna biomass reached after approximately 40 days (Orue et al. 2019). Further, many dFADs are now equipped with satellite echo-sounder buoys, remotely providing fishers with near real-time dFAD location data and estimates of associated biomass (Lopez et al. 2014).

dFADs are however associated with several negative impacts, including the over exploitation of tuna stocks, high catches of juvenile tunas, and substantial bycatch (Amandè et al. 2010). Shark catch rates are twice as high in dFAD sets versus ‘free school’ sets (Clarke et al. 2011), with silky sharks comprising 95% of elasmobranch bycatch (Gilman 2011). Furthermore, as it is not feasible
to retrieve all deployed dFADs, some are lost or abandoned (Davies et al. 2014). Approximately 10% beach in coastal areas (Maufroy et al. 2015) where they may damage sensitive coastal habitats (Davies et al. 2017). As they largely consist of non-biodegradable materials, lost or abandoned dFADs are a significant source of marine pollution (Fonteneau et al. 2015), and sensitive marine fauna, such as marine turtles and sharks, can become entangled in the sub-surface netting (Filmalter et al. 2013).

Importantly, no tuna Regional Fisheries Management Organizations (t-RFMOs) require the recovery of dFADs or for vessels to take responsibility if they impact coastal areas (Baske & Adam 2019). There is now increasing interest in defining the responsibilities of dFAD owners, in accordance with international instruments on gear marking, reporting of lost gear, and plastic pollution. In this respect, RFMOs distinguish between dFADs that are “active” and “inactive”, but only limit only on the number of “active” dFADs a vessel may have in the water at a given time. Inactive dFADs, which are not limited, may have broken and become untraceable, but may also be deactivated by the fishing vessel, with the vessel owner choosing to no longer receive data from the dFAD. Such deactivation and dFAD discard can currently be made with no consequence or reporting, amounting to ‘intentional’ ALDFG disposal (and characterized as littering), which should then be reported under MARPOL Annex V.

One of the largest no-take MPAs, the British Indian Ocean Territory (BIOT) MPA around the Chagos Archipelago, was established in 2010. dFADs frequently drift through, sometimes beaching on the archipelago’s islands and reefs (Davies et al. 2014). From 2014 to 2017, 95 cases of recovered lost or abandoned gear were recorded in the MPA, with the vast majority dFADs (Clark, Moir et al. 2015). The BIOT Administration (BIOTA) classifies dFADs in the MPA as ‘lost and abandoned fishing gear’ and removes them if they wash up on shore or become entangled on a reef. dFADs thus represent a significant source of pollution to the MPA. Further,
it has been postulated that fishers may intentionally deploy dFADs on the perimeter of large MPAs to transit through, with the intention to aggregate and export biomass into fishable areas (Boerder et al. 2017).

Using the Chagos Archipelago as a case study, we quantify the threat posed by dFADs to large MPAs. We build a generalizable framework to simulate the dispersal patterns of dFADs through time and space and highlight locations on the MPA perimeter from where dFADs entering would pose the greatest risk of (i) beaching or (ii) transiting through and accumulating biomass that could be exported into fishable areas, while also (iii) providing a combined factor risk score. This approach provides an essential risk profiling tool, assisting t-RFMOs in building sustainable management of purse seine fisheries, and enabling MPA managers to adjust enforcement efforts to better protect the habitats and fish biomass from drifting fishing gears.

METHODS

The Chagos Archipelago is a series of coral atolls and submerged banks in the central Indian Ocean (Figure 1A). Extending out to the full 200nm EEZ, the MPA surrounding it totals ~640,000km², encompassing over 60,000km² of shallow coral reefs. Prior to establishment, licenses were granted to an international fleet of longliners and purse seiners targeting tuna and billfish (Koldewey et al. 2010; Curnick et al. 2020). The purse seine fishery was highly seasonal, associated with the fleet migrating across the western Indian Ocean and fishing in the territory during the winter monsoon season, November to January (Davies et al. 2014; Dunn & Curnick 2019). Approximately 30% of the purse seine fishing effort was associated with dFADs (Curnick pers comms).
We determined the potential transit of dFADs through the MPA to quantify the spatial and temporal (i) risk of dFADs beaching on the archipelago’s atolls and submerged banks (‘sites’, hereafter), and (ii) assess the potential for dFADs to transit through the MPA, accumulate fish biomass and export it into fishable areas (Figure 2). To model dFAD movement, we utilized a passive particle dispersal model, run within the Connectivity Modelling System (CMS) (Paris et al. 2013, http://code.google.com/p/connectivity-modeling-system). This is a community multi-scale probabilistic model of particle dispersal, based on a stochastic Lagrangian framework. The CMS was chosen as it provides an accurate representation of Lagrangian ocean circulation and oceanic phenomena (advection, dispersion, retention), and gives a statistical representation of dispersal probabilities. To account for uncertainties, the model applies a random walk to the motion of the particles to represent the sub-grid scale motion in the turbulence module. This tool has been used in a broad range of applications from the dispersion of coral larvae (Raitsos et al. 2017) to estimations of reef connectivity (Wang et al. 2019). The model was forced by surface circulation, quantified at daily intervals, and a spatial resolution of 1/48 degree grid (~2km) after a reparameterization from the original resolution of 1/12 degree grid (~8km) (HYCOM, https://www.hycom.org). The CMS runs off-line, applying the velocity fields of the ocean circulation model to each particle using a 4th order Runge–Kutta numerical discretization method, applied both in space and time (Paris et al. 2013). Particles were modelled as surface drifting rectangular rafts of ~6m² surface area, with a 20m sub-surface net structure, akin to those used commonly in the Indian Ocean (Franco et al. 2009). Particles were neutrally buoyant and passive to prevailing oceanographic currents, with a drag factor of 0.5m²/s².

At 16 source locations on the perimeter of the MPA (Figure 1B), 500 particles were deployed (i.e., ‘virgin’ dFADs, total $n = 8,000$ particles) and their drifts modelled. Source locations were selected based on the recent distribution of purse seine fishing activity (Kroodsma et al. 2018). As such, source locations were evenly spread around the MPA perimeter, except for the northern boundary.
with the Maldives. To account for variation across the traditional purse seine fishing season around the Chagos Archipelago (Dunn & Curnick 2019), particle release was also undertaken across three time periods ('deployment periods': November to January, December to February, January to March). To account for inter-annual variation in oceanographic patterns associated with the Indian Ocean Dipole (IOD) (Saji et al. 1999), each deployment period was also undertaken across three fishing seasons, representing negative (2015/2016), positive (2016/2017), and neutral (2018/2019) IOD phases.

To validate our particle tracking models, we compared our modelled drifts to in-situ drift data, as like dFADS, drifters follow near-surface currents in the Indian Ocean (Imzilen et al. 2019). We therefore downloaded three drifter tracks from the Global Drifter Program database (ftp://ftp.aoml.noaa.gov/phod/pub/buoydata/) that crossed the territory between December 2018 and February 2019 (Figure 1A). We released the “virtual” dFADS at the same location and time of drifters and compared closest Euclidean distances between the averaged simulated model track from the full range of probabilities generated by the underlying modelled particle release (n = 100 particles) and the in-situ drifter locations.

Particle intersection with one of the 14 geographical features (islands, submerged banks or atolls) of the archipelago (Figure 1A) within each of the three-month deployment periods was deemed a ‘beaching event’. At this point, the particle drift was terminated, and location recorded ('beached', hereafter). For dFADs that did not beach, the number of days spent within the MPA, defined by the number of days between first entry and first exit of the boundary, was calculated ('transit', hereafter). We assumed that no sinking, resuspension, retrieval or inter-dFAD interaction occurred within deployment periods.
We used linear regression models to investigate whether there was (i) a relationship between successful beaching, deployment source ($n = 16$) and deployment period (month nested within fishing season) ($n = 9$), and then (ii) whether particular sites ($n = 14$) were more likely impacted by beachings. Beaching likelihood may also be associated with site area (Table 1). Therefore, we standardized site area (site area/sum total area of all sites * 100) and used linear regression to examine whether there was a relationship between beaching likelihood and standardized site area ($\text{km}^2$). Lastly, we graphically displayed the drift patterns of all dFADs (The Mathworks Inc. 2018) (Figure 3; Supporting Information Figures S1-S8).

dFAD transit was categorized based on published colonization rates (Orue et al. 2019). Specifically, these were: transit time >14 days (estimated time for tuna to first associate with virgin dFAD), transit time >30 days (estimated time for peak non-tuna biomass), and transit time >40 days (estimated time for peak tuna biomass). These represented dFADs with ‘any’, ‘moderate’ and ‘high’ risk of accumulating and exporting biomass, respectively. We used linear regression to examine the relationship between transit category ($n = 3$), deployment source and deployment period. For each source to gain an overall dFAD risk score, we graphically plotted combined probabilities of dFAD beaching and dFAD transit >14 days.

**RESULTS**

We found high spatial and temporal variation in the drift patterns of dFADs entering the MPA (Figure 3; Supporting Information Figures S1-S8). Across all deployment periods, 8.13% of dFADs beached. The likelihood of beaching was structured by a significant interaction between deployment period and deployment source ($F_{120, 1872} = 2.59, p<0.01$). The greatest proportion of beaching occurred in the 2015-2016 fishing season (11.17%), with the lowest beaching in the
2016-2017 season (6.21%), while dFADs initially released in November were less likely to beach (4.02%) than those initially released during January (10.40%; Supporting Information Table S1). The greatest proportion of beaching from dFADs released in November were from northern sources (sources 2 and 16) although overall risk was low during this period. Risk increased in subsequent months, with the principal risk coming from eastern sources in December (2-4), and relatively evenly across all sources in January (Figure 4), although principally from the east.

Beaching risk was significantly structured by an interaction between site and deployment period \((F_{104, 1890} = 2.06, p<0.01)\), with most beaching likely to occur on the Great Chagos Bank. When comparing the likelihood of beaching across standardized sites, there was a significant difference in likelihood between sites \((F_{13, 2002} = 3.49, p<0.01)\). The Ganges Bank was more likely to be impacted by beaching \((p<0.01)\), with no other sites likely to have significantly higher beaching.

Overall, 29.38% of all dFADs released drifted for >14 days before exiting the MPA. Of these dFADs, 9.57% drifted >30 days, and 4.98% >40 days. However, the likelihood of high transit times was significantly associated with deployment source \((F_{15, 416} = 3.51, p<0.01)\) and deployment period \((F_{8, 423} = 3.63, p<0.01)\). Between fishing seasons, the 2015 - 2016 season had the highest likelihood of long transit times (more than 14, 30 and 40 days: 35.08%, 13.15 and 7.86% respectively), while dFADs released during the January deployment period were more likely to show a high transit time than those released during November and December (Figure 4; Supporting Information S9 and S10). Differences in transit times were also dependent on deployment source. During November, high transit times were more likely for particles entering from the east (between 26.40% and 52.53% from sources 1-7) and northwest (54.93% from sources 15 and 24.20% from source 16), while during December the highest likelihood of long transit times came from sources 3-7, 10 and 13-16, ranging from 24.27 to 58.87%). In January, the likelihood of long transit times from sources 4, 14 and 15 exceeded 80%. The highest
likelihood areas were in the east (sources 3-6) and west to northwest (sources 11-16, ranging from 29.60% to 87.73%) (Figure 4).

When considering the combined effect of beaching risk and transit risk (>14 days), we estimate that 37.51% of dFADs entering the MPA pose a management concern. This reduces to 17.70% and 13.11% for transit times of more than 30 or 40 days, respectively. In addition, the combined risk (beaching and transit >14 days) was greatest for dFADs deployed in January (47.26%) and lowest for dFADs deployed in November (29.88%) (Figure 4; Supporting Information S9 and S10). When comparing spatially across months, combined risk to the MPA is greatest from deployments in the north and east for dFADs in November (sources 1-7, 15 and 16), the west and east for dFADs deployed in December (sources 2-7 and 10-16), and similar for dFADs deployed in January (sources 1-6 and 10-16). dFADs deployed in January from sources 4 (99.73%) and 14 (96.00%) posed the greatest combined risk throughout the study period (Figure 4).

There was little difference in the overall path of the averaged modelled tracks when compared to in-situ drifter data (Supporting Information S11). The path of the drifter 64825340 (total distance 1613km) differed by an average of only 1.47km [+/- 0.17] across 51 days, drifter 65606490 (total distance 1650 km) differed by an average of 1.58km [+/- 0.24] over 73 days, while drifter 64824700 (total distance 1131km) only differed by an average of 2.07 km [+/- 0.43] across 42 days of drifting.

DISCUSSION

Here we demonstrate that drifting fishing gears have the potential to considerably undermine the effectiveness of large MPAs. Depending on dFAD colonization rates adopted, between 16% and
37% of all dFADs entering the BIOT MPA pose a management risk, either through beaching or transiting. However, risk was not even across space and time. Strategic deployment of dFADs on the MPA’s perimeter by fishers to maximise drift times could result in up to 88.33% of dFADs drifting through the MPA for >14 days before exiting. Given that is sufficient time for tuna and tuna-associated species to colonize a dFAD (Orue et al. 2019), then these drifting gears have the potential to export biomass and devalue large MPAs. Specific MPA legislation is thus urgently required to monitor drifting fishing gear and focus enforcement efforts to negate potential impacts.

Source location is important in determining risk. Here, dFADs entering on the east and west side highly likely to beach or have the potential to export biomass (i.e., high risk). Yet, it is important to consider the behaviour of adjacent fisheries. Automatic Identification System (AIS) data show that purse seiners are operating on both the BIOT MPA’s eastern and western perimeter (Kroodsma et al. 2018). Active satellite transducers have been documented across the southeast and northwest quadrants of the MPA (Anonymous, pers comms), in-line with evidence of fishers intentionally deploying dFADs into current systems upstream of MPA boundaries (Hall & Román 2016). Yet, the use of dFADs in the region is predominantly focussed in the western Indian Ocean, including in the waters adjacent to the Chagos Archipelago (Imzilen et al. 2019). Thus, whilst the probability of dFADs posing a risk might be high on the east, the number of dFADs entering, and subsequently the realised risk, may be higher on the west.

The Great Chagos Bank was the most likely site to be impacted by beaching, due predominantly to its size. The Great Chagos Bank is 81 times larger (>13,000km²) than the next largest site within the MPA. This atoll is also relatively shallow, with a mean depth of approximately 40m, giving a high likelihood that the underlying netting of a dFAD would negatively impact its coral reef and seagrass habitats. If damaged by mechanical action, such as due to dFAD grounding, it may take years for underlying coral or seagrass to recover (see Davies et al. 2017). The reefs of
the Chagos Archipelago are regionally significant (Sheppard et al. 2012), supporting reef fish biomass six times greater than elsewhere in region (Graham et al. 2013), and act as a source of biological diversity for over-exploited sites further west (Sheppard et al. 2013). Any impact of dFADs to the Chagos Archipelago is therefore likely to be locally and regionally significant and should be proactively mitigate against.

The likelihood of dFADs beaching is also influenced by season and interannual climatic oscillations, and therefore management measures should be temporally dynamic. The highest proportion of beaching here occurred during a negative Indian Ocean Dipole (IOD), with the lowest occurring during a positive IOD. Such differences may be partially explained by differences in current patterns. During a negative IOD, where westerly winds intensify along the equator, resulting in warm water being pushed east (Saji et al. 1999), current speed weakens in both the north (~0.3m/s) and south (0.1m/s) of the MPA. In comparison, during a positive IOD phase, where westerly winds weaken, current speed is much stronger, with an average speed of ~0.55m/s in the north and ~0.15m/s in the south of the MPA. Such high current strength during the positive IOD may therefore push dFADs out of the region. In comparison, during the negative phase, the less intense current strengths may lead to dFADs travelling shorter distances from the region, increasing the likelihood of moving close to the atolls and submerged reefs and thus beaching.

It is important to consider the spatial ecology and behaviour of vulnerable species when evaluating the potential impact of dFADs drifting through MPAs. Tagging studies have reported few instances of large pelagic fishes leaving the MPA (Carlisle et al. 2019), and historical fisheries data indicate possible residency behaviour of yellowfin tuna around the Chagos Archipelago. Commercial (skipjack and yellowfin tuna) and bycatch species (e.g. silky sharks) known to reside around the Chagos Archipelago (Koldewey et al. 2010) regularly aggregate in large numbers
around dFADs (Castro et al. 2002; Gilman 2011). Such species would therefore be expected to associate with dFADs transiting through the MPA and be exported outside of the MPA boundary and into fishable areas. Already burdened by illegal fishers predominantly targeting sharks (Ferretti et al. 2018; Tickler et al. 2019), the BIOT MPA, like many large MPAs, has limited enforcement capacity, being patrolled by a single enforcement vessel. This vessel has satellite support, but balances patrol activities with border protection, scientific research, and maintenance of the island and reef environments. Given its multipurpose nature, the vast scale of the MPA and the potential for drifting fishing gears to export substantial biomass outside of the boundary, risk assessments, such as those presented within the current work, are urgently needed to prioritize activities in both time and space. We argue that alignment of enforcement activities with ocean particle modelling results within the present work will enhance enforcement activities and streamline the use of the limited resources available.

We modelled the dispersal of dFADs with underwater structures that extended down 20m, typical of those used in the Indian Ocean (Franco et al. 2009). However, dFAD characteristics vary between fleets and by ocean. Indeed, dependent on fleet, subsurface structure can go down to 60m in the Indian Ocean, whereas, in the eastern Pacific Ocean, dFADs are usually 30m deep and 80 - 100m in the Atlantic (Lopez & Scott 2014). The deeper the underwater structure extends, the greater the probability of beaching events. We conservatively estimated that all dFADs would beach on one of the geographical features if intersected. Yet fine-scale data on current and flow dynamics around the geographical features of the Chagos archipelago and high-resolution bathymetry are lacking. The presence of reefs and islands can create complex flow dynamics, such as eddies and ‘sticky water’ effects (Andutta et al. 2012) that may impact the drifts of dFADs and other marine debris. The incorporation of these fine scale local resolution data in areas of complex oceanography, coupled with coarser resolution in the open ocean, into future studies could significantly improve the accuracy of beaching estimates (Critchell et al. 2019). We also did
not account for resuspension post-entanglement and thus may have overestimated beaching rates on some features. Resuspended dFADs may beach on another feature or pose a high risk by undertaking a long transit time within the MPA boundary. Lastly, tuna aggregate around deep dFAD structures faster (Orue et al. 2019) and deeper dFADs are likely to move slower, owing to the greater drag force produced, increasing the time for biomass to aggregate around it. A recent resolution on FAD management in the Indian Ocean placed no restrictions on the depth to which dFAD structures can be deployed. Therefore, as dFAD structures are generally getting deeper (Hall & Román 2016), it is highly likely that the risks posed by these structures to all MPAs (both in beaching and exporting biomass) will substantially increase in the future.

Our estimates on the potential for dFADs to export biomass may also be considered conservative. We used 14 days as our lowest threshold. However, previous studies have shown that associations of tuna to dFADs can occur earlier (Orue et al. 2019). Fishers in the Indian Ocean previously estimated that non-tuna species can colonize virgin-FADs in just one week (Moreno et al. 2007). In addition, the efficacy of dFADs to attract target species is known to also vary according to ambient environmental conditions. For example, Orue et al. (2019) hypothesized that dFAD attractiveness in the Indian Ocean varies seasonally and spatially, with tuna more likely to associate with dFAD structures when ocean productivity is lower. To broaden our understanding of the role that drifting fishing gear may have on fish communities within MPAs, the exact relationship between population density, ocean productivity and dFAD attractiveness must be advanced.

One possible benefit of FADs (dFADs and anchored fish aggregating devices) for MPAs, is their potential as scientific research platforms (Moreno et al. 2016). dFADs equipped with echo-sounders can provide estimates of colonization rates (Orue et al. 2019) and much needed and cost-effective fisheries-independent indices of abundance data (Moreno et al. 2016; Santiago et
Such data could be invaluable in improving our understanding of the spatial and temporal distributions of tuna and other pelagic predators within large MPAs. Furthermore, FADs may also enable researchers to deploy a suite of other instruments, such as acoustic tag receivers (Dagorn et al. 2007; Robert et al. 2013), hydrophones or environmental sensors, to better understand their biotic and abiotic environment (Moreno et al. 2016). However, prior to any scientific deployments, risks would need to be carefully mitigated against. In addition to the risks focussed on here, drifting fishing gears can also be a direct source of microplastic pollution (Cole et al. 2011) through material degradation that can then be ingested by plankton (Setälä et al. 2014) and corals (Hall et al. 2015), and can import damaging invasive species (Derraik 2002).

Clarifying the legal status of drifting fishing gears, and dFADs in particular, is urgently required to remove the ambiguity over the measures that coastal states with MPAs can put in place. The IOTC defines fishing as “…the actual or attempted searching for, attracting, locating, catching, taking or harvesting of fishery resources or any activity which can reasonably be expected to result in attracting, locating, catching, taking or harvesting of fishery resources…”. It is thus reasonable to state that dFADs are indeed ‘fishing’ whilst drifting, and therefore any dFADs drifting through a no-take MPA are likely violating national jurisdiction. However, substantial actions are required by the MPA’s coastal state to ensure such activities do not occur within their jurisdiction. First, dFADs need to be effectively located and monitored within MPAs. For example, a high number of dFADs were recorded in the Phoenix Islands Protected Area (PIPA) and contributed to the development of a dFAD registration and tracking initiative across the eight Pacific Island States (Hanich et al. 2019). Second, large MPA managers need to engage with t-RFMOs and support and contribute to resolutions that promote responsible management of dFADS by fishers and flag states. For example, IOTC resolution 19/02 (IOTC 2019) requires, as of 1 January 2020, daily information on all active dFADs to better manage important fish stocks. Also encouraged are: the deployment and management of dFADs to minimize the probability of loss or incursion
into protected waters; the use of ecologically friendly dFADs to reduce ghost fishing (Franco et al. 2009); and the increased use of biodegradable materials. This is emphasized in the updated guidelines for implementing MARPOL Annex V (International Convention for the Prevention of Pollution from Ships: Annex V) that notes that fishing gears, once discharged, are harmful substances and thus fishers are required to minimize the probability of loss, report losses, and to maximize recovery. Third, is the need to develop appropriate mechanisms to retrieve dFADs within MPAs and dispose of dFAD construction materials effectively. Overall, large MPAs, for all their benefits, are not a silver bullet in the conservation and management of marine biodiversity, and thus more emphasis needs to be placed on their integration and interactions with surrounding fisheries, if they are to maximise conservation benefits.


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Table 1. Geographical features, along with approximate area (km$^2$), where drifting fish aggregation devices may beach within the Chagos Archipelago.

<table>
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<tr>
<th>Geographic feature</th>
<th>Receiver location number</th>
<th>Area (km$^2$)</th>
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</thead>
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<tr>
<td>Centurion Bank</td>
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<td>26.2</td>
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<tr>
<td>Ganges Bank</td>
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<td>15.9</td>
</tr>
<tr>
<td>Diego Garcia</td>
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<td>212</td>
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<td>Pitt Bank</td>
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<td>Victory Bank</td>
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<td>Colvocoresses reef</td>
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Figure 1. The fourteen atolls or shallow banks (A) where drifting fish aggregation devices (dFADs) could beach within the Chagos Archipelago. The 16 points on the perimeter of the large marine protected area (solid line) where dFADs were released (B).
Figure 2. Schematic of a typical drifting fish aggregation device (dFAD) and an image of a dFAD beached on a reef within the Chagos Archipelago (image courtesy of Dan Bayley). The exact style and structure of dFADs may vary between fleets, but usually consist of a floating raft, sub-surface structure (e.g. rolled up fishing nets), and a GPS tracker. In the Indian Ocean, surface rafts are typically ~6m² in surface area, with a 20 m sub-surface net structure (Franco et al. 2009).
Figure 3. The predicted dispersal routes of drifting fish aggregation device (dFADs) released from 16 source locations around the Chagos Archipelago in January 2017. dFAD movement was predicted using a passive particle dispersal model run within the Connectivity Modeling System (CMS) (Paris et al. 2013), a multi-scale probabilistic model of particle dispersal based on a stochastic Lagrangian framework. Colour scale represents duration of dFAD drift in days.
Figure 4. The risk posed by drifting fish aggregation devices (dFADs) entering the Marine Protected Area (MPA) around the Chagos Archipelago across the three months (November, December and January) and from 16 source locations around the MPA’s perimeter. The center point of each circle represents the source location where dFADs were released. If no circle is present, no dFADs were predicted to pose a management concern. Size and colour of circles represent the percentage of dFADs that were predicted to become beached (top row, green), to
drift through the MPA for more than 14 days (middle row, purple), to beach or drift through the MPA for more than 14 days (bottom row, red).