



Risks to large marine protected areas posed by drifting fish aggregation devices

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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 prioritizing enforcement and maximizing conservation benefits. Drifting fish aggregating devices (dFADs) are a highly effective fishing method employed in purse seine fisheries that attract and accumulate biomass fish, making fish easier to catch. However, dFADs are associated with several negative impacts, including high bycatch rates and lost or abandoned dFADs becoming beached on sensitive coastal areas (e.g., coral reefs). Using Lagrangian particle modeling, we determined the potential transit of dFADs in a large MPA around the Chagos Archipelago in the central Indian Ocean. We then quantified the risk of dFADs beaching on the archipelago's reefs and atolls and determined the potential for dFADs to pass through the MPA, accumulate biomass while within, and export it into areas where it can be legally fished (i.e., transit). Over one-third (37.51%) of dFADs posed a risk of either beaching or transiting the MPA for >14 days, 17.70% posed a risk of beaching or transiting the MPA for >30 days, and 13.11% posed a risk of beaching or transiting the MPA for >40 days. Modeled dFADs deployed on the east and west of the perimeter were more likely to beach and have long transiting times (i.e., posed the highest risk). The Great Chagos Bank, the largest atoll in the archipelago, was the most likely site to be affected by dFADs beaching. Overall, understanding the interactions between static MPAs and drifting fishing gears is vital to developing suitable management plans to support enforcement of MPA boundaries and the functioning and sustainability of their associated biomass.

Keywords: beaching, Chagos Archipelago, fisheries, marine protected area, pollution, purse seine, tuna

Riesgos para las Grandes Áreas Marinas Protegidas Ocasionados por los Dispositivos Agregadores de Peces a la Deriva

Resumen: El mapeo y la predicción del riesgo potencial que las actividades de pesca representan para las grandes áreas marinas (AMP), en donde la capacidad de manejo es baja pero la biomasa de peces puede ser de importancia global, son vitales para priorizar la aplicación y maximizar los beneficios de conservación. Los dispositivos agregadores de peces a la deriva (DAPd) son un método de pesca altamente efectivo y empleado en las pesquerías de redes de cerco. Estos dispositivos atraen y acumulan biomasa de peces, facilitando así la captura de peces. Sin embargo, los DAPd están asociados con varios impactos negativos, incluyendo tasas altas de captura accesorias y DAPd perdidos o abandonados que terminan varados en áreas costeras sensibles (p. ej.: arrecifes de coral). Mediante el modelado de partículas lagrangianas, determinamos el tránsito potencial de los DAPd en una AMP grande alrededor del Archipiélago Chagos en el centro del Océano Índico. Después cuantificamos el riesgo de varamiento de los DAPd en los arrecifes y atolones del arrecife y determinamos el potencial que tienen los DAPd de pasar por la AMP, acumular biomasa durante el trayecto y exportarla a áreas en las que es legal su pesca (es

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decir, transitar). Más de un tercio (37.51%) de los DAPd representaron un riesgo de varamiento o tránsito a través de la AMP durante >14 días y el 17.70% representó un riesgo de varamiento o tránsito a través de la AMP durante >40 días. Los DAPd modelados desplegados en el este y en el oeste del perímetro tuvieron mayor probabilidad de varamiento o de tener tiempos de tránsito largos (es decir, representaron el riesgo más alto). El Gran Banco de Chagos, el atolón más grande en el archipiélago, fue el sitio con mayor probabilidad de ser afectado por el varamiento de los DAPd. En general, el entendimiento de las interacciones entre las AMP estáticas y el equipo de pesca a la deriva es vital para el desarrollo de planes de manejo adecuados para respaldar el cumplimiento de los límites de las AMP y el funcionamiento y sostenibilidad de la biomasa asociada a ellas.

Palabras Clave: Archipiélago Chagos, área marina protegida, atún, contaminación, pesquerías, red de cerco, varamiento

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 (dFADs), is increasingly being used by tropical tuna purse seine fisheries (Maufroy et al. 2017). From 2007 to 2013 alone, a 4-fold 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.

Fishing activities associated with dFADs have become incredibly efficient, and approximately 100,000 are 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 noncommercial species, including silky sharks (*Carcharhinus falciformis*) (Castro et al. 2002). Biomass may begin to associate with newly deployed dFADs after just 2 weeks, and peak tuna biomass is reached after approximately 40 days (Orue et al. 2019). Further, many dFADs are now equipped with satellite echosounder buoys that remotely provide fishers with near real-time dFAD location data and estimates of associated biomass (Lopez et al. 2014).

Drifting fish aggregating devices 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 fishing sets on free-swimming schools of fish (Clarke et al. 2011), and silky sharks can comprise 95% of elasmobranch bycatch (Gilman 2011). Furthermore, because 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). Because they largely consist of nonbiodegradable mate-

rials, 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 subsurface netting (Filmlalter et al. 2013).

Importantly, no tuna regional fisheries management organizations (t-RFMOs) require the recovery of dFADs or for vessels to take responsibility if dFADs affect coastal areas (Baske & Adam 2019). Importantly, 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 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 be broken and untraceable, but may also be deactivated by the fishing vessel (i.e., the vessel owner chooses to no longer receive data from the dFAD). Such deactivation and dFAD discard can currently be made with no consequence or reporting, amounting to the intentional disposal of fishing gear (characterized as littering), which should then be reported under The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V.

One of the largest MPAs, the British Indian Ocean Territory (BIOT) around the Chagos Archipelago, was established in 2010. Although no commercial fishing is allowed in the MPA, 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 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. Thus, dFADs 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 drift 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 quantified the threat posed by dFADs to large MPAs. We built a generalizable framework to simulate the dispersal

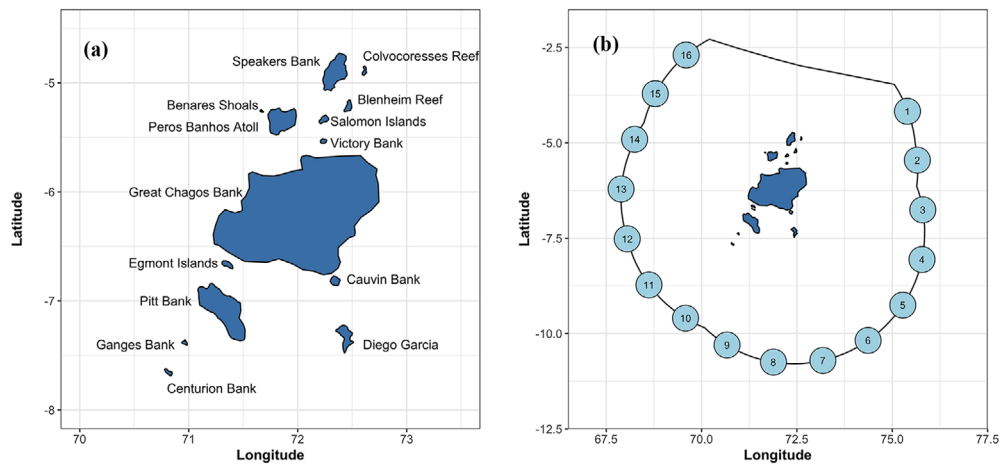


Figure 1. The 14 atolls or shallow banks (a) where drifting fish aggregation devices (dFADs) could beach in the Chagos Archipelago and (b) the 16 points on the perimeter of the large marine protected area (solid line) where dFADs were released.

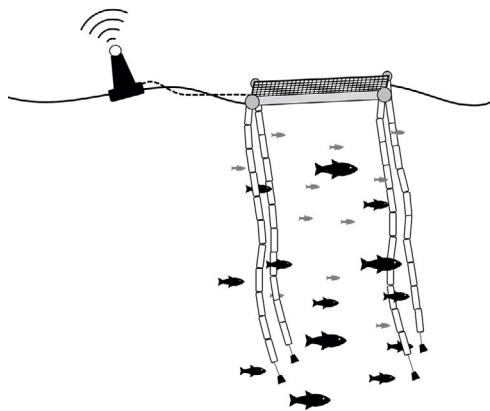


Figure 2. Schematic of a typical drifting fish aggregation device (dFAD) and an image of a dFAD beached on a reef in the Chagos Archipelago (photo by Dan Bayley).

patterns of dFADs through time and space and highlight locations on the MPA perimeter from which dFADs entering would pose the greatest risk of beaching or transiting through and accumulating biomass that could be exported into fishable areas. We also determined a combined factor risk score. This approach provides an essential risk profiling tool that can help t-RFMOs build sustainable management of purse seine fisheries and enable 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 (Fig. 1a). Extending out to the full 200-nm EEZ, the MPA surrounding it totals approximately 640,000 km² and encompasses over 60,000 km² of shallow coral reefs. Prior to MPA

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 (D.C. personal observation).

We determined the potential transit of dFADs through the MPA to quantify the spatial and temporal risk of dFADs beaching on the archipelago's atolls and submerged banks (hereafter sites) and assessed the potential for dFADs to transit through the MPA, accumulate fish biomass, and export it into fishable areas (Fig. 2). To model dFAD movement, we used a passive particle dispersal model, run within the Connectivity

Modelling System (CMS) (<http://code.google.com/p/connectivity-modeling-system>) (Paris et al. 2013). This is a community multiscale probabilistic model of particle dispersal based on a stochastic Lagrangian framework. The CMS was chosen because 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 (Raitos et al. 2017) to estimations of reef connectivity (Wang et al. 2019). The model was forced by surface circulation, quantified at daily intervals, and had a spatial resolution of 1/48 degree grid (approximately 2 km) after a reparameterization from the original resolution of 1/12 degree grid (approximately 8 km) (HYCOM, <https://www.hycom.org>). The CMS runs offline. It applies the velocity fields of the ocean circulation model to each particle with a fourth-order Runge–Kutta numerical discretization method that is applied over space and time (Paris et al. 2013). Particles were modeled as surface-drifting rectangular rafts of approximately 6 m² surface area and a 20-m subsurface 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. The drag factor was 0.5 m²/s².

At 16 source locations on the perimeter of the MPA (Fig. 1B), 500 particles were deployed (i.e., new dFADs, total $n = 8000$ particles) and their drifts modeled. 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 3 deployment periods (November to January, December to February, and January to March). To account for interannual variation in oceanographic patterns associated with the Indian Ocean Dipole (IOD) (Saji et al. 1999), each deployment period was also undertaken across 3 fishing seasons: negative (2015/2016), positive (2016/2017), and neutral (2018/2019) IOD phases.

To validate our particle tracking models, we compared our modeled drifts with *in situ* drifter data. Similar to dFADs, drifters follow near-surface currents in the Indian Ocean (Imzilen et al. 2019). We therefore downloaded 3 drifter tracks from the Global Drifter Program database (<http://ftp://ftp.aoml.noaa.gov/phod/pub/buoydata/>) that crossed the territory from December 2018 to February 2019 (Fig. 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 modeled particle release ($n = 100$ particles) and the *in situ* drifter locations.

Particle intersection with 1 of the 14 geographical features (islands, submerged banks, or atolls) of the archipelago (Fig. 1A) within each of the 3-month deployment periods was deemed a beaching event. At this point, the particle drift was terminated and its location was recorded (hereafter beached). 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 (hereafter transit). We assumed that no sinking, resuspension, retrieval, or inter-dFAD interaction occurred in deployment periods.

We used linear regression models to investigate whether there was a relationship between successful beaching, deployment source ($n = 16$), and deployment period (month nested within fishing season) ($n = 9$) and then whether particular sites ($n = 14$) were more likely affected by beaching. Beaching likelihood may also be associated with site area (Table 1). Therefore, we standardized site area (site area/sum total area of all sites $\times 100$) and used linear regression to examine whether there was a relationship between beaching likelihood and standardized site area (km²). Last, we graphically displayed the drift patterns of all dFADs (The Mathworks Inc. 2018) (Fig. 3; Appendices S1–S8).

The dFAD transit was categorized based on published colonization rates (Orue et al. 2019) as transit time >14 days (estimated time for tuna to first associate with a new dFAD), transit time >30 days (estimated time to reach peak biomass that is not tuna), and transit time >40 days (estimated time to reach 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 (Fig. 3; Appendices 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%); the lowest beaching occurred in the 2016–2017 season (6.21%). The dFADs initially released in November were less likely to beach

Table 1. Geographical features and approximate area where drifting fish aggregation devices may beach in the Chagos Archipelago.

Geographic feature	Receiver location number	Area (km ²)
Centurion Bank	1	26.2
Ganges Bank	2	15.9
Diego Garcia	3	212
Pitt Bank	4	1,365
Egmont Islands	5	49.8
Great Chagos Bank	6	13,472
Cauvin Bank	7	67.2
Victory Bank	8	21.9
Salomon Islands	9	47.6
Blenheim Reef	10	52.6
Peros Banhos Atoll	11	563
Benares Shoals	12	4.4
Speakers bank	13	563
Colvocoresses reef	14	23.4

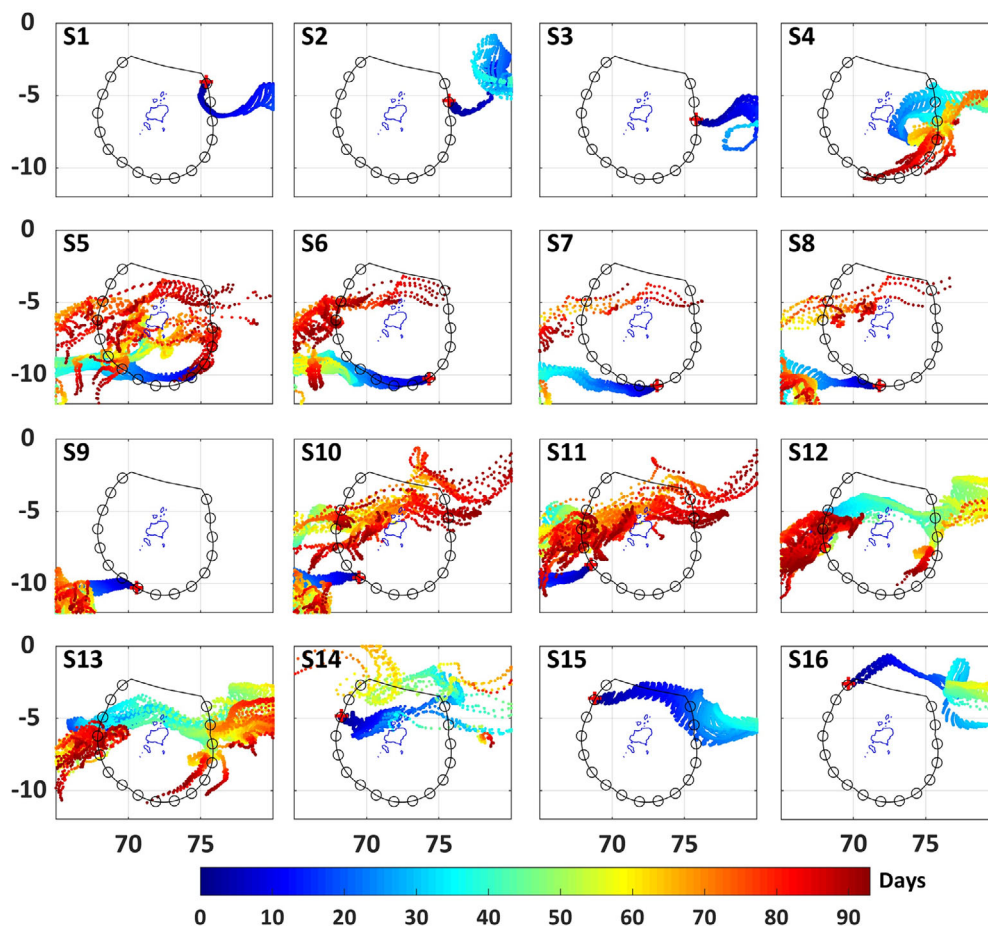


Figure 3. The predicted dispersal routes of drifting fish aggregation device (dFADs) released from 16 source locations around the Chagos Archipelago in January 2017 (days, duration of dFAD drift in days). The dFAD movement was predicted with a passive particle dispersal model run within the Connectivity Modeling System (CMS) (Paris et al. 2013).

(4.02%) than those initially released in January (10.40%) (Appendix S9). 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 (Fig. 4), although principally from the east.

Beaching risk was significantly structured by an interaction between site and deployment period

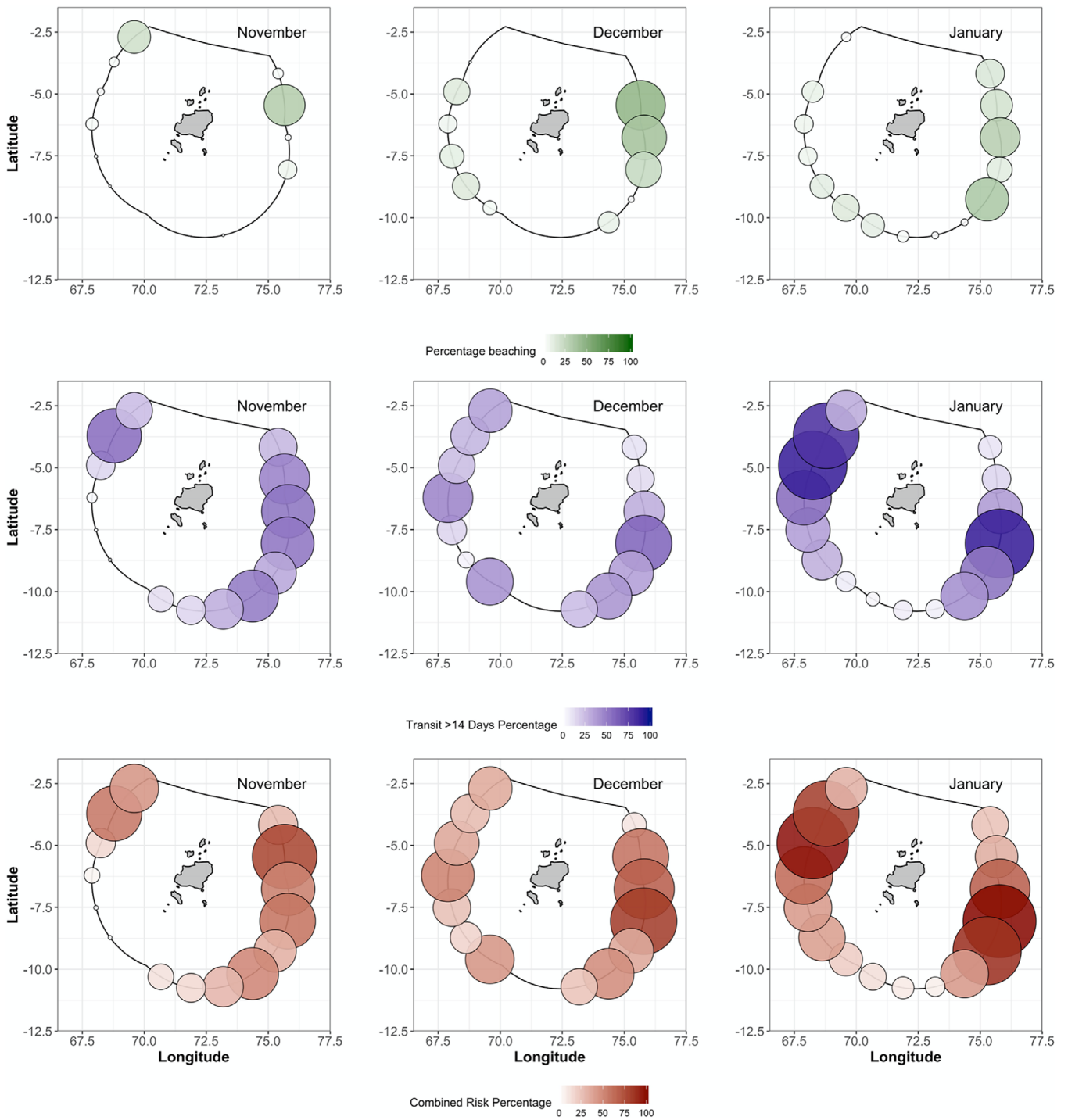


Figure 4. The risk of drifting fish aggregation devices (dFADs) entering the Marine Protected Area (MPA) around the Chagos Archipelago over 3 months (November, December, and January) and from 16 source locations around the MPA’s perimeter (circle center points, location where dFADs were released; no circle, no dFADs predicted to pose a risk; circle size and color intensity, percentage of dFADs predicted to pose a risk; green, risk of becoming beached; purple, risk of drifting through the MPA for >14 days; red, risk of beaching or drifting through the MPA for >14 days).

($F_{104, 1890} = 2.06$, $p < 0.01$); most beaching was estimated 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 affected by beaching ($p < 0.01$); no other sites were 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), whereas dFADs released during the January deployment period were more likely to show a high transit time than those released during November and December (Fig. 4; Appendices S10 and S11). Differences in transit times were also dependent on deployment source. During November, high transit times were more likely for particles entering from the east (26.40–52.53% from sources 1–7) and northwest (54.93% from source 15 and 24.20% from source 16), whereas during December the highest likelihood of long transit times came from sources 3–7, 10, and 13–16 (range: 24.27–58.87%). 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, range: 29.60–87.73%) (Fig. 4).

When considering the combined effect of beaching risk and transit risk (>14 days), we estimated that 37.51% of dFADs entering the MPA pose a management concern. This lessened to 17.70% and 13.11% for transit times of >30 and >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%) (Fig. 4; Appendices S10 and S11). When comparing spatially across months, combined risk to the MPA was 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). The dFADs deployed in January from sources 4 (99.73%) and 14 (96.00%) posed the greatest combined risk throughout the study period (Fig. 4).

There was little difference in the overall path of the averaged modeled tracks when compared with *in situ* drifter data (Appendix S12). The path of the drifter 64825340 (total distance 1613 km) differed by an average of only 1.47 km (SD 0.17) across 51 days, drifter 65606490 (total distance 1650 km) differed by an average of 1.58 km (SD 0.24) over 73 days, and drifter 64824700

(total distance 1131 km) differed by only an average of 2.07 km (SD 0.43) across 42 days of drifting.

Discussion

We demonstrated that drifting fishing gears have the potential to considerably undermine the effectiveness of large MPAs. Depending on dFAD colonization period adopted, from 16% to 37% of all dFADs entering the BIOT MPA posed 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 maximize 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), 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 were highly likely to beach or had the potential to export biomass. Yet, it is important to consider the behavior of adjacent fisheries. Automatic identification system 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 source), 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 focused in the western Indian Ocean, including in the waters adjacent to the Chagos Archipelago (Imzilen et al. 2019). Thus, although the probability of dFADs posing a risk may be high from the east, the number of dFADs entering, and subsequently the realized risk, may be higher from the west.

The Great Chagos Bank was the most likely site to be affected by beaching, due predominantly to its size. The Great Chagos Bank is 81 times larger (>13,000 km²) than the next largest site within the MPA. This atoll is also relatively shallow, with a mean depth of approximately 40 m, meaning there is a high likelihood that the underlying netting of a dFAD would negatively affect its coral reefs and seagrasses. If damaged by mechanical action, such as from dFAD grounding, it may take years for underlying coral or seagrass to recover (Davies et al. 2017). The reefs of the Chagos Archipelago are regionally significant (Sheppard et al. 2012). They support reef fish biomass 6 times greater than elsewhere in region (Graham et al. 2013) and act as a source of biological diversity for over-exploited sites farther west (Sheppard et al. 2013). Any

impact of dFADs on the Chagos Archipelago is therefore likely to be locally and regionally significant and should be proactively mitigated.

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

It is important to consider the spatial ecology and behavior of vulnerable species when evaluating the potential impact of dFADs drifting through MPAs. Tagging studies report few instances of large pelagic fishes leaving the MPA (Carlisle et al. 2019), and historical fisheries data indicate year-round presence of yellowfin tuna around the Chagos Archipelago (Curnick et al. 2020). 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 to be exported outside 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, such as many large MPAs, has limited enforcement capacity (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 ours, are urgently needed to prioritize activities in time and space. We argue that alignment of enforcement activities with our ocean-particle modeling results will enhance enforcement activities and streamline the use of the limited resources.

We modeled the dispersal of dFADs with underwater structures that extended down 20 m, typical of those used in the Indian Ocean (Franco et al. 2009). However, dFAD characteristics vary between fleets and by

ocean. Depending on the fleet, subsurface structure can go down to 60 m in the Indian Ocean, whereas in the eastern Pacific Ocean and the Atlantic dFADs are 30 and 80–100 m deep, respectively (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 affect 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, in 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. Finally, 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, because 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 show that associations of tuna to dFADs can occur earlier (Orue et al. 2019). Fishers in the Indian Ocean previously estimated that species that are not tuna can colonize new FADs in just 1 week (Moreno et al. 2007). In addition, the efficacy of dFADs to attract target species is known to vary according to ambient environmental conditions. For example, Orue et al. (2019) hypothesized that dFAD attractiveness in the Indian Ocean varies seasonally and spatially; tuna are more likely to associate with dFAD structures when ocean productivity is low. To broaden 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). A series of scientific dFADs equipped with echosounders could 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 al. 2017). Such data could be invaluable in improving 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 improve understanding of their biotic and abiotic environment (Moreno et al. 2016). However, prior to scientific deployments, risks would need to be carefully mitigated. In addition to the risks we focused on, drifting fishing gears can also be a direct source of microplastic pollution (Cole et al. 2011) because the dFAD material degrades. These degraded materials can then be ingested by plankton (Setälä et al. 2014) and corals (Hall et al. 2015). It is also possible that dFADs, like lost or abandoned fishing gears, can be a vector for the import of 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 Indian Ocean Tuna Commission (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 while they drift; therefore, dFADs drifting through a no-take MPA are likely violating national jurisdictions. However, substantial actions are required by the MPA's coastal state to ensure such activities do not occur in their jurisdictions. 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 8 Pacific Island States (Hanich et al. 2019). Second, managers of large MPAs need to engage with t-RFMOs and support and contribute to resolutions that promote responsible management of dFADs by fishers and vessel flag states (the state under whose laws the fishing vessel is registered or licensed). 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 deployment and management of dFADs to minimize the probability of loss or incursion into protected waters; use of ecologically friendly dFADs to reduce ghost fishing (Franco et al. 2009); and increased use of biodegradable materials. These are emphasized in the updated guidelines for implementing MARPOL 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 in MPAs and effectively dispose of dFAD construction materials. Overall, large MPAs, for all their benefits, are not a silver bullet in the conservation and management of marine biodiversity; thus, more emphasis needs to be placed on their integration and interactions with surrounding fisheries if they are to maximize conservation benefits.

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Supporting Information

Additional information is available online in the Supporting Information section at the end of the online article. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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