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Spatio-temporal variability in drifting Fish Aggregating Device (dFAD) beaching events in the Seychelles Archipelago

Isla MacMillan [1,*], Martin J. Attrill [1], Taha Imzilen [2,3,4], Christophe Lett [2,3], Simon Walmsley [5], Clarus Chu [5] and David M. Kaplan [2,3]

[1]School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
[2]MARBEC, Université de Montpellier, CNRS, Ifremer, IRD, 34203 Sète, France
[3]Institut de Recherche pour le Développement (IRD), Avenue Jean Monnet, CS30171, 34203 Sète cedex, France
[4]Sorbonne Université, Collège Doctoral, 75005 Paris, France
[5]WWF-UK, The Living Planet Centre, Rufford House, Brewery Road, Woking, Surrey GU21 4LL, UK

*Corresponding author: tel: +44 1305 206635; e-mail: islamacmillanwork@gmail.com

Purse-seine fisheries use drifting Fish Aggregating Devices (dFADs), human-made floating objects, to facilitate the capture of tropical tunas. Currently, the majority of dFADs are constructed primarily of highly durable non-biodegradable materials and there is no legal obligation to recover dFADs after deployment, leading to beaching events and potentially negative environmental impacts. We assessed beachings as a function of intra- and inter-annual trends, water depth, distance from land, seasonality, and benthic habitat within the local context of the Seychelles Archipelago using trajectories of dFADs deployed by French purse seiners over 2008–2020. Overall, 3842 beaching events associated with 2371 distinct dFAD tracking buoys were identified. Beachings occurred most frequently during the winter monsoon (December–March). Due to the shallow Mahé Plateau, beachings occurred in both nearshore (≤ 5 km from land) and offshore (> 5 km) regions, predominantly in estimated depths less than 60 m. Despite representing < 20% of overall mapped habitat, the benthic habitat "Coral/Algae" had the highest beaching rate (35.3% of beachings), and therefore, beachings pose a significant concern for conservation. Our results provide a detailed view of the spatio-temporal pattern of beachings in the Seychelles, supporting the development of mitigation and prevention methods to reduce marine debris and perturbations to the marine environment.

Keywords: abandoned, lost or otherwise discarded fishing gear (ALDFG), coral reefs, marine conservation, marine litter, purse seine, tropical tuna fisheries.

Introduction

Globally, 12.7 million metric tonnes of anthropogenic debris enter the marine environment per year, of which abandoned, lost, or otherwise discarded fishing gear (ALDFG) represents > 10% (Macfadyen *et al.*, 2009; Sinopoli *et al.*, 2020). One source of ALDFG is derived from drifting fish aggregating devices (dFADs), recently classified as the ALDFG with the third-highest risk in terms of potential impact to the marine environment (Gilman *et al.*, 2021). DFADs are human-made floating objects deployed by purse-seine (PS) fishers in equatorial waters worldwide to aggregate tunas and facilitate their capture. Up to 121 000 dFADs are deployed annually (Gershman *et al.*, 2015), and this number continues to rise in some areas (Imzilen *et al.*, 2021). Risks due to dFAD use include, but are not limited to; higher juvenile tuna catch and higher bycatch compared to free-swimming schools (Kaplan *et al.*, 2014); transmission of toxins and microplastics into food webs, perturbation of pelagic and coastal environments (Hallier and Gaertner, 2008; Dagorn *et al.*, 2012; Imzilen *et al.*, 2021); reduced socioeconomic value of coastal regions due to derelict gear, and potential issues for navigation (Gilman *et al.*, 2021). Quantifying these risks is essential to reducing the environmental impacts of tropical tuna PS fishing.

Many fish species, particularly the commercially important tuna species such as skipjack (*Katsuwonus pelamis)*, juvenile yellowfin (*Thunnus albacares)*, and juvenile bigeye (*Thunnus obesus*), display a strong propensity to aggregate in large numbers beneath floating objects (FOBs) on the ocean's surface (Paryn and Fedoryako, 1999; Castro *et al.*, 2002; Dagorn *et al.*, 2012). Historically, FOBs were only encountered opportunistically, and consisted of naturally occurring objects (Riera *et al.*, 1999), such as algae (Kingsford, 1992, 1995) and logs (Greenblatt, 1979), and therefore, represented a minority of all fishing sets (Orue *et al.*, 2020). Marine capture fisheries have exploited this behaviour for millennia to easier and more consistent catches of FOB schools compared to free schools (Davies *et al.*, 2014a). Purse-seiners began deploying human-made dFADs in the mid-1980s in the Indian Ocean (Dempster and Taquet, 2004; Gershman *et al.*, 2015). FOB tracking technology has consistently improved over time, from short-range reflectors and radio beacons to satellite-linked GPS tracking buoys used since the early 2000s and, from ∼2011 onwards, buoys with integrated echo-sounders have allowed fishers to remotely track and estimate fishable biomass around FOBs (Lopez *et al.*, 2014; Davies *et al.*, 2014a; Cillari *et al.*, 2018; Hanich *et al.*, 2019; Orue *et al.*, 2019).

In recent years, over 80% of Indian Ocean French PS sets are around FOBs (Kaplan *et al.*, 2021*)*, in large part due to these technological advances and the impact of a yellowfin quota restricting free-swimming school catches. The majority of intentionally deployed FOBs are human-made dFADs (> 90% based on observer data 2013–2017), constructed

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using highly durable non-biodegradable synthetic materials (Zudaire *et al.*, 2018). Commonly, bamboo rafts and/or plastic floats are fitted with a subsurface structure comprised of synthetic netting or rope that can reach 80 m in length (Imzilen *et al.*, 2019), in addition to the electronic components (Davies *et al.*, 2017). As fishers currently have no legal obligation to recover dFADs once they have been deployed, the lack of proper disposal of many dFADs is a major concern for conservation. Nevertheless, PS fishing for tropical tunas is one of the most carbon-efficient methods of industrial fishing and, more generally, food production (Parker *et al.*, 2015); it has lower bycatch to catch ratios than many other fisheries (Kaplan *et al.*, 2014). As such, it is essential to carefully assess the negative impacts of purse seine fishing and find appropriate mitigation strategies to assure the long-term sustainability of this activity.

Once deployed, dFADs have the potential to drift > 10 000 km (Hanich *et al.*, 2019) and eventually become stranded or beached due to contact between the subsurface structure of the dFAD and the ocean floor. Though the term "stranding" is perhaps more appropriate when talking about offshore dFAD bottom contact, we have opted to use the term "beachings" throughout this study as it is widely used in the prior literature. Nevertheless, the two terms should be considered interchangeable in the context of this study. The potential impacts of beachings include the degradation of habitats, disruptions to ecological processes through the introduction of plastics into the food web, and physical damage or mortality to species through entanglement (Macfadyen *et al.*, 2009; Filmalter *et al.*, 2013; Davies *et al.*, 2017; Murua *et al.*, 2017; ISSF, 2019). A recent analysis of dFAD trajectory data estimates that ~15–20% of dFADs deployed since 2013 by the French fleet in the Indian and Atlantic Ocean eventually beach (Imzilen *et al.*, 2021), whereas discussions with European Union fishers suggest that more than 20% of dFAD deployments likely resulted in beaching events (Moreno *et al.*, 2018). In response to these potential impacts, a number of recent studies have examined dFAD beaching events to identify mitigation strategies, such as spatial dFAD deployment closures (Imzilen *et al.*, 2021) and dFAD retrieval at sea (Baske and Adams, 2019; Imzilen *et al.*, 2022). There also has been a range of management and scientific efforts to limit the number of dFADs (e.g. IOTC, 2019), to adopt use of non-entangling dFADs (Murua *et al.*, 2017), and develop viable biodegradable dFAD designs (Moreno *et al.*, 2020). Missing from existing work are regional examinations of large datasets of dFAD beachings that assess fine-scale beaching rates and identify highly impacted habitats to inform clean-up strategies. Therefore, within the Indian Ocean, we chose to investigate the Republic of Seychelles due to the importance of this area for PS fishing and landing of tropical tunas (GoS, 2014), as well as the sensitivity of its coastal habitats.

The Seychelles is a global biodiversity hotspot located in the Western Indian Ocean (Figure 1), between 46°E–58°E and −3°S to −10°S consisting of 115 islands spanning an area of 1.4 million km^2 (Burt *et al.*, 2020). The circulation system within the Western Indian Ocean forms large gyres and mesoscale eddies on a seasonal basis that proliferate across the region. As a result, there is high biological productivity as a product of entrainment of nutrient-rich waters by eddies and upwelling (Xie *et al.*, 2002; Chassot *et al.*, 2019), including a diverse range of ecologically important habitats that support high levels of fish and coral species richness and biomass (Sheppard and Obura, 2005; Burt *et al.*, 2020; Haupt, 2020). However, these eddies and current fronts are also known to accumulate litter, including dFADs (Dagorn *et al.*, 2013; Imzilen *et al.*, 2021), and could contribute towards the retention of marine debris in the area.

Ecosystem services provided by these ecologically important habitats are integral to human welfare within the Seychelles and throughout the broader region (Burt *et al.*, 2020). Therefore, it is essential to ensure the health of these ecosystems to maximize resilience to future global change (Burt *et al.*, 2020). The Seychelles has been an important tuna fishing ground within the Indian Ocean since 1980s and is the principal port of call for Indian Ocean tuna fleets from countries world-wide (GoS, 2014). This industry represents ~17% of Seychelles employment and provides 68% of the entire export trade, contributing significantly to the Seychelles' economy (Christ *et al.*, 2020). Thus, tuna fishing and specifically dFAD use has many economic advantages for the Seychelles and other coastal nations in the Indian Ocean. This complicates dFAD management regarding the introduction of restrictions on dFAD use, therefore, necessitating a balanced perspective when developing mitigation strategies.

The aim of this study is to assess the drivers and extent of dFAD beaching events within the marine environment of the Seychelles EEZ, including a comprehensive analysis of the distribution of these beaching events with respect to fine-scale habitat data. Beaching events are assessed as a function of intra- and inter-annual trends, water depth, and distance from land, seasonality, benthic habitat, and rebeaching events. Investigating these patterns and drivers provides insights essential to the development of effective, regional prevention, and mitigation measures for dFAD beachings.

Methods

Data collection

For the purposes of this study, a dFAD beaching event is defined as any extended period (> 24 h) over which a deployed dFAD is relatively motionless, presumably due to entanglement of the dFADs subsurface structure with the ocean bottom. DFAD beaching events in the Seychelles EEZ were identified using data on the trajectories of GPS tracking buoys attached to dFADs deployed by the French fleet (including French-associated vessels under other flags) over the period 2008–2020. The buoy manufacturer (Marine Instruments for the majority of the study time period and data) estimates that GPS position errors are considerably less than 20 m, but the error may reach 20 m immediately after the buoy has been switched on following a period of inactivity (V. Calvete, pers. commun.).

These data are available through a collaborative agreement between the French National Research Institute for Sustainable Development (IRD) and the French frozen tuna producers' organization ORTHONGEL. The detailed methodology for basic data processing and identification of beaching events largely follows that presented in Imzilen *et al.* (2021). Alternatively, a brief explanation can be found in the supplementary materials (Appendix A1).

One important difference between our beaching identification procedure and that of Imzilen *et al.* (2021) is that we did not impose any water column depth or maximum distance from land criteria for beachings. The large, shallow Mahé plateau with an average depth under 60 m (Mees, 1993) could potentially produce beachings far from the coast. Furthermore, rapid changes in bathymetry in some areas of the Seychelles may be poorly reflected in coarse GEBCO bathymetry data. As such, we preferred to include putative beachings far from land or estimated to be in deep water, using additional detailed examinations of their spatial distribution and of individual trajectories to assess whether or not these events are consistent with true beaching events.

A small number of beaching events in the Seychelles ($n = 241$) found to be fully on land based on intersection with OpenStreetMap land polygons (see below for description of data sources) were excluded as these likely were the result of coastal fishers removing the buoy from the dFAD, so that the true position of the beaching, if any, would be unknown (Imzilen *et al.*, 2021).

Additionally, to avoid overcounting of beachings due to small spatial displacements of beached dFADs (e.g. due to low velocity dragging along the ocean floor), beaching events were "grouped" by identifying sequences of beaching events that were separated by no more than 500 m and no more than 2 d (between the last point in the previous beaching and first point in subsequent beachings). If a series of beachings met these conditions, then they were considered a "group" and only the first such beaching was considered. Though > 90% of buoys in the Indian Ocean are deployed on dFADs (Maufroy *et al.*, 2017), GPS buoys are also deployed on natural objects (e.g. logs) or other non-dFAD objects of anthropogenic origin. As our data do not distinguish between these two, the beaching events in this study encompass all FOBs, though the vast majority are presumed to be dFADs and for simplicity we will use this term to refer to all objects in this study.

The initial dataset contained 58 309 tracked buoys deployed in the Indian Ocean and, after these filters were applied, our dataset consisted of 3842 observed beachings within the Seychelles between 20 January 2008 and 30 December 2020. Beaching event data were coupled with benthic habitat data (~4 m spatial resolution) obtained from the Allen Coral Atlas (ACA; 2020; available at https://allencoralatlas.org/; accessed 30/08/2020), bathymetry data (30 arc seconds ~ 1 km) obtained from the General Bathymetric Chart of the Oceans (GEBCO v.2014 available at https://www.gebco.net/data_and_products/gridded_bathymetry_data/; accessed 13/07/2020), and OpenStreetMap land polygons (v.2019; available at https://osmdata.openstreetmap.de/data/land-polygons.html; accessed 09/07/2020). By intersecting beaching positions with these data, observed beaching events were assigned water depth (m), distance from land (km) and habitat type values.

Data analysis

Intra- and inter-annual trends

To depict intra- and inter-annual variation, beaching events were plotted by month and year between 2012 and 2020. There was a small amount of missing data (~10–25%) for the period 2008–2010 that might have given a skewed perspective; therefore, these years were excluded in this aspect of the analysis. A Poisson Generalized Linear Model (GLM) was utilized to test the influence of "years" and "months" on the number of beaching events to detect intra- and inter-annual patterns. An offset was used in the GLM to account for the difference in the number of days in each month:

$$glm(Unique\ Beachings \sim year + month$$
$$+offset\left(\log\left(number\ days\ in\ month\right)\right).$$

A Tukey *post hoc* test was applied to the GLM model outputs to test for months that grouped together to further indicate the presence of seasonal trends.

When quantifying seasonal effects, beaching events were aggregated according to the four seasonal regimes that affect the hydrography in the region as previously described by Orue *et al.* (2019) and Schott and McCreary (2009). The seasons are in reference to the boreal seasons and are as follows: (i) spring intermonsoon during April and May, (ii) summer monsoon throughout June–September, (iii) autumn intermonsoon during October–November and, (iv) winter monsoon during December–March. When reporting beaching rates by season, rates were corrected to account for the difference in the number of days in each season.

Beaching events per island

Beaching events per island were calculated utilizing a 5 km from land buffer zone around the land polygon of each island. This buffer zone was used to account for not only the island itself, but also its barrier reef and lagoon. Only beachings within the 5 km buffer were kept for this analysis ($n = 1178$). Number of beachings per island was then extracted by associating each beaching to the nearest island using each island's individual feature identification (FID) code to avoid double counts of beachings within buffer zones that overlapped.

A linear regression was conducted to ascertain whether there was a significant relationship between island size (log transformed due to large range in island sizes) and the number of beaching events (also log transformed).

Beaching events per island group

The Seychelles spans 1.4 million km^2 (Burt *et al.*, 2020), with clear and distinct island groups separated by expanses of deep ocean between each group. Beaching events were categorized into the island groups displayed in Figure 1. The perimeter length of each island group was calculated using the GEBCO derived 100-m depth contour within the island group polygons (Figure 1). To test the relationship between number of beaching events and the size (perimeter km) of each island group, a linear regression was performed. Given the large range in island group sizes, both number of beachings and island sizes were log transformed before performing the linear regression.

Although the Fortune Bank and Correira Bank do not contain islands, these areas were included within the analysis as separate island groups as beaching events occurred at these locations due to their shallow depth.

Habitat composition and benthic habitat classes

A Poisson GLM was conducted to test the influence of habitat class on the number of beaching events, including an offset to account for the area of each habitat class (km^2).

Rebeaching events

Rebeaching is defined in this study as individual dFADs (recognized by buoy identification number) having multiple independent beaching events within the dataset. These events are likely due to the dFAD dislodging from its original

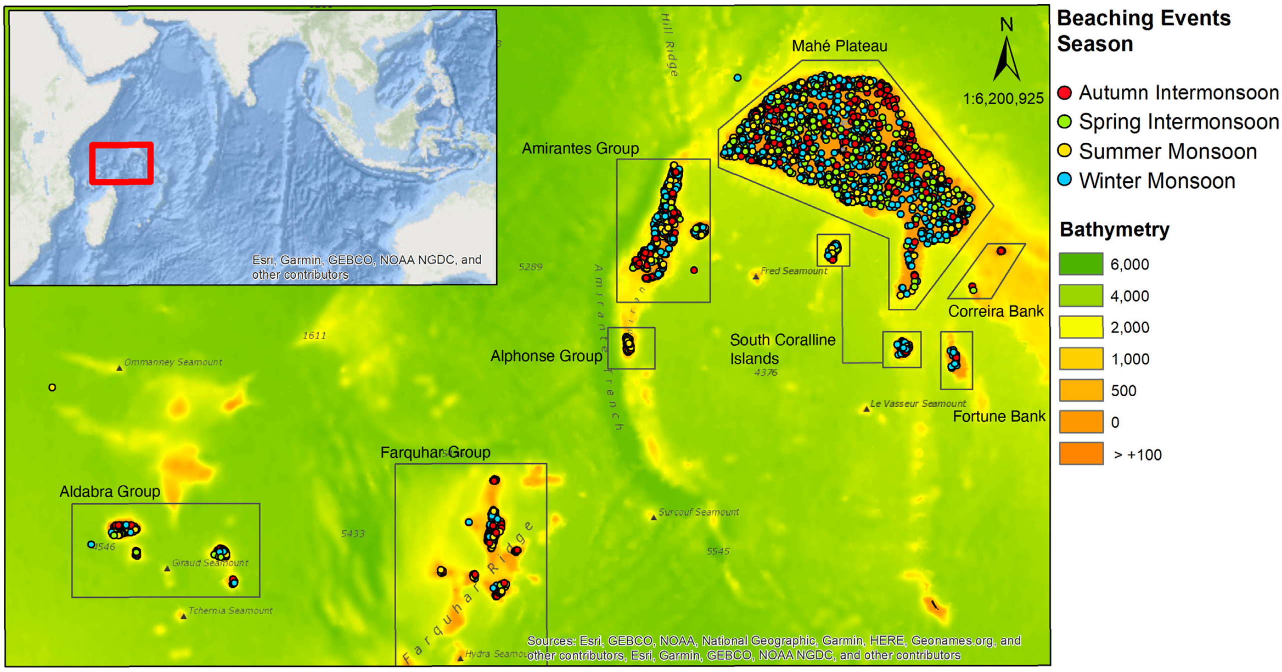

Figure 1. Extent of beaching events across the Seychelles Archipelago, coordinated to the season the event occurred, including bathymetry of the area. Inset: location of the Republic of Seychelles within the Indian Ocean.

position and then snagging or "beaching" again at a later date. All such rebeaching events were identified after applying the conditions that filtered the putative beaching events including the short spatio-temporal distance beaching grouping procedure described above.

To assess the impact of rebeachings in all previous analyses, we also carried out analyses considering only the first beaching of each dFAD (i.e. removing rebeaching events), and results are qualitatively similar to those including all beachings (Supplementary Table B1; Figures C1a, b and C2a, b).

The location (nearshore, i.e. $\leq$ 5 km from shore, versus offshore, i.e. $>$ 5 km from shore) of the initial beaching event of each unique buoy was calculated and a binomial GLM was then conducted with location (i.e. nearshore versus offshore) as a predictor and whether or not each unique buoy had one or more rebeaching events as the response variable to determine if distance to the coast played a role in the frequency of rebeaching events.

Analysis tools

All geospatial mapping and visualization were carried out using ArcGIS v.10.7. Statistical tests were undertaken using R (R Core Team, 2020). R package "multcomp" was utilized to conduct the Tukey *post hoc* test applied to GLM outputs within the interannual analysis.

Results

Overview of beaching events within the Seychelles

Identified beaching events ($n = 3842$) were widely distributed across the entire Seychelles archipelago, though there is a clear relationship between the distribution of beachings and regional bathymetry (Figure 1). Though many beachings occur in the immediate vicinity of islands, a substantial number also occur over shallow water areas, such as the Mahé Plateau and Fortune Bank. Of all dFADs released by the French Fleet within the Indian Ocean, the Seychelles EEZ accounted for 47.5% of beachings, followed in terms of importance by the EEZs of Somalia (15.3%) and the Maldives (9%; see Supplementary Table B2). The in-water drift time before initial beaching was on average 35 days (central 50% of data = 18–65 days; range = 3–801 days).

Analyses of beaching depth and distance to shore identified the areas in the Seychelles that were most at risk of beaching events (Table 1). Primarily, beachings occurred in waters up to a depth of 40 m and within 20 km of the coast (46.5% of all beachings). However, there are a large number of beachings occurring more than 40 km from the coast (33.2%), predominantly due to beachings on the Mahé Plateau and in particular along the north-western edge of this plateau (Figure 2; Supplementary Figure C3). Interestingly, the majority of beaching events occur $>$ 5 km from the coast (63.6%).

A small number of beachings were nominally recorded as being above sea level ($n = 222$) and others were recorded as being in waters with $>$ 60 m depth ($n = 607$ with 322 having water column depth $>$100 m). Qualitative examination of the trajectories associated with these "deep water" or "above sea level" beachings revealed no indication that they were associated with interactions with fishing vessels (e.g. abnormal speed, changes in direction, or increased buoy ambient temperature measurement variability; Supplementary Figures C4–C6) and the majority occurred along shelf edges or close to shore where one would expect rapid changes in bathymetry to not be accurately reflected in coarse GEBCO bathymetric data (Supplementary Figure C7). As such, we determined these to be true beaching events where the dFAD subsurface structure interacted with the ocean floor.

Our estimates for the beaching rate of French dFADs in the Seychelles EEZ are approximately 5 times higher than those

Table 1. Number of beaching events as a function of depth and distance from land[a].

Water column depth (m)	Distance from land (km) 0–< 5	5–< 10	10–< 15	15–< 20	20–< 30	30–< 40	> 40
0–< 10							
751	**221**	**180**	**99**	21	21	**368**	
10–< 20	**116**	47	36	17	10	33	**189**
20–< 40	**144**	**64**	**62**	49	34	29	**255**
40–< 60	39	28	49	39	**56**	45	**233**
> 60	**128**	48	**59**	47	**51**	42	**232**

[a]Values ≥ 50 indicated in bold.

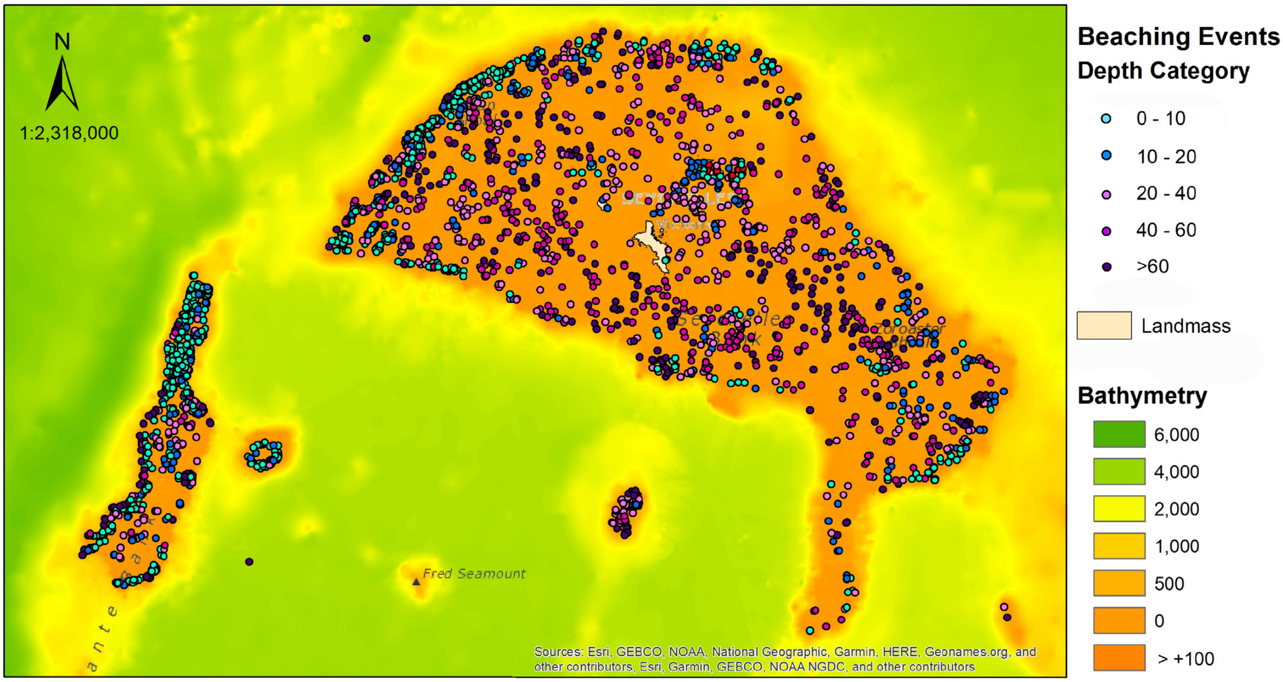

Figure 2. Beaching events by depth category and bathymetry of the Mahé Plateau and Amirantes Group.

estimated by Zudaire *et al.* (2018) for part of the Spanish fleet for 2016–2017. This is difference is primarily due to the 550 m maximum distance to land condition used by Zudaire *et al.* (2018) as imposing this condition on our data produced beaching rates roughly equivalent to theirs (see Supplementary Appendix A2 for more details).

Intra- and inter-annual trends

The number of beaching events increased rapidly between 2012 and 2016, with a distinct overall annual percentage increase (Figure 3a). The number of beaching events then reached a plateau between 2016 and 2020, with little change in the total number of beachings from year to year (Figure 3a). The number of beaching events varied significantly between years (Figure 3a; GLM; $X^2 = 795.42$, $df = 8$, $p < 0.001$) and between months (Figure 3b; $X^2 = 315.65$, $df = 11$, $p < 0.001$). Intra-annual trends show a clear seasonality in the number of beaching events (Figures 3a and b). Prior to 2015, proportions of beaching events were relatively similar between the winter monsoon (28.7%), summer monsoon (28.4%), and spring intermonsoon (26.2%) with the least proportion of beaching events occurring in the autumn intermonsoon (16.7%). After 2015, seasonality is more marked with the greatest proportion of beaching events occurring within the winter monsoon (43.4%), followed by the spring intermonsoon (21.1%), the summer monsoon (19.9%), and the autumn intermonsoon (15.6%). See Supplementary Information A3 for the results of the Tukey *post hoc* test.

Seasonal patterns of beachings manifested primarily in the overall beaching rate as opposed to the spatial distribution of beachings occurring throughout the Seychelles, though beachings are somewhat more southern (i.e. off the Mahé Plateau) in the summer monsoon than in the winter monsoon (Supplementary Figure C8a and b).

Beaching events by island and island group

There was a significant relationship between the number of beaching events and increased island size ($F_{1,75} = 5.44$, $p < 0.05$; Figure 4a). However, the large amount of unexplained variance (the adjusted R^2 of the model is 0.0552) indicates that increased size is not the sole factor influencing the number of beaching events (Figure 4a). For example, a large proportion of the most impacted locations within the Seychelles were some of the smallest islands (e.g. St François (Alphonse Group), Remire and African Banks (Amirantes Group) accumulated 80, 44, and 39 beachings, respectively; Supplementary Table B3 and Figure C9), suggesting further mechanisms influencing beaching beyond just available area.

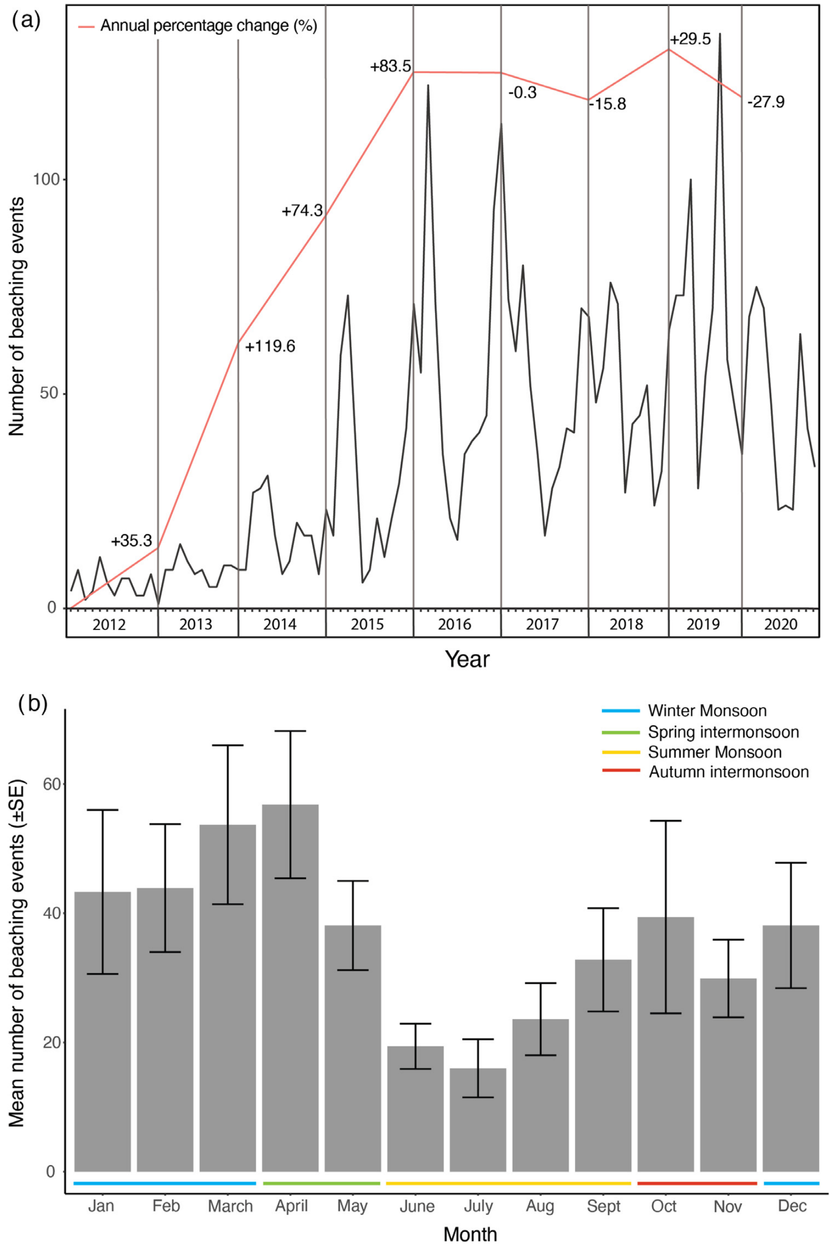

Figure 3. (a). Interannual variation depicted by the observed number of beaching events per month throughout 2012–2020 (black), including the annual percentage change (red) between years beginning 2012. (b). Intra-annual variability depicted by mean beaching events (± standard error) throughout January–December (2008–2020).

Beaching events significantly increased with island group perimeter (km; $F_{1,6} = 13.6$, $p < 0.05$; Figure 4b), with a much tighter relationship (the adjusted R^2 of the model is 0.6429). At the extremes, the largest island group, Mahé Plateau (2463.55 km), accounted for 51.2% of all beachings, whereas the smallest island group, Correira (61.55 km), accounted for 0.2% of beaching events (Supplementary Table B4).

Habitat composition and benthic habitat analysis

Overall, 1371.5 km^2 of benthic habitat that surrounded islands in the Seychelles was mapped by the ACA (Table 2). The overall habitat composition was predominantly Sand (31.63%), followed by coral/algae (19.24%), seagrass (19.13%), rubble (9.91%), rock (9.51%), and microalgal mats (8.86%; Table 2).

Due to the limited spatial extent of the ACA data (areas < 10 m depth), we were only able to assign habitat classes to 725 beaching events. There were significant differences between the number of beaching events between each habitat class ($X^2 = 116.87$, $df = 5$, $p < 0.001$; Table 2). Out of the beaching events that intersected with the benthic habitat data layer, the most impacted benthic habitat class was coral/algae (constituting over a third of all events, despite representing only 19.24% of the habitat data area; Table 2). This further indicates that the distribution of beachings is not random, but rather coral/algae clearly traps dFADs disproportionately more than the other habitat classes (Table 2). This is illustrated by Figure 5, which depicts the trajectory of a single buoy

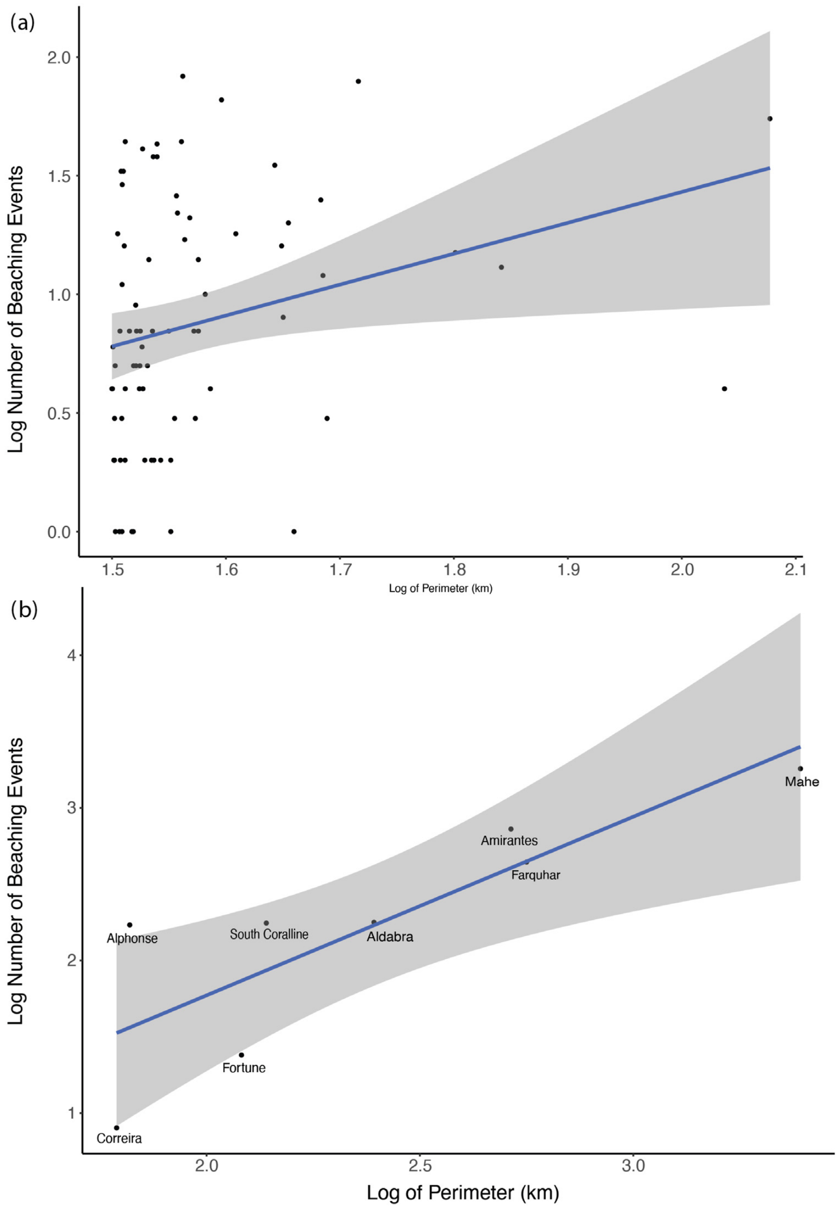

Figure 4. Relationship between log number of beaching events and log perimeter (km) of islands (a) and island groups (b) within the Seychelles (2008–2020).

Table 2. Number of beaching and rebeaching events per benthic habitat class[b].

Benthic habitat class	Mapped area of each benthic habitat class (km^2)	Number of beaching events per habitat type by unique buoys (first beaching event of each unique buoy)	Number of beaching events per habitat type by buoys that rebeached (all subsequent beaching events)	Total number of beaching events per benthic habitat class	Percentage of the number of beaching of the overall total (%)
Coral/algae	263.84 (19.24%)	153	103	256	35.3
Microalgal mats	121.56 (8.86%)	16	15	31	4.3
Rock	130.39 (9.51%)	68	19	87	12
Rubble	135.97 (9.91%)	64	16	80	11
Sand	433.79 (31.63%)	120	14	134	18.5
Seagrass	262.34 (19.13%)	123	14	137	18.9

[b]Only includes beachings that intersected with the habitat data ($n = 725$).

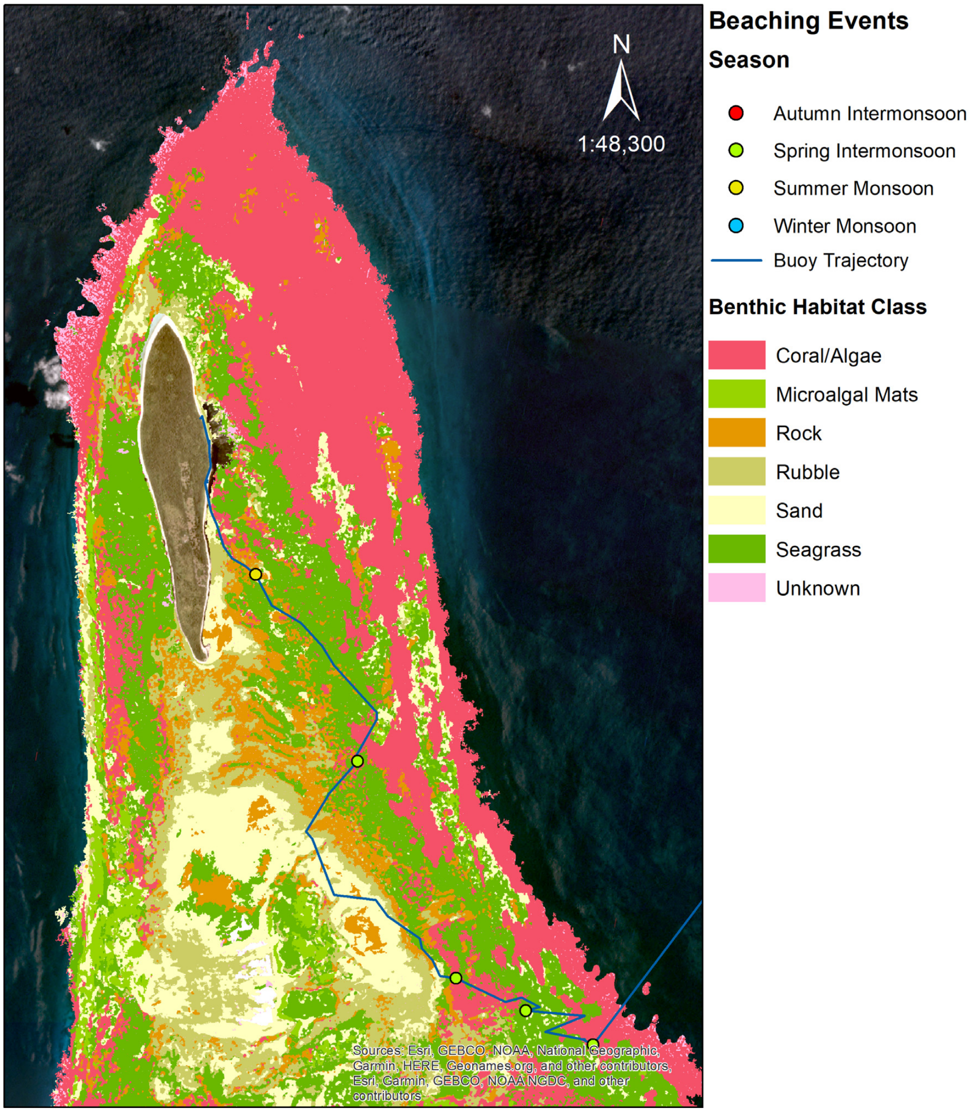

Figure 5. Rebeaching events conducted by a single dFAD at Providence Island within the Farquhar Group. Direction of travel began at sea moving towards the island.

between identified beaching events, whereby the buoy appeared to beach several times within coral/algae before its final position was recorded.

Rebeaching events

The 3842 beaching events recorded between 2008 and 2020 were caused by 2371 individual dFAD buoys and 802 buoys (33.8% of the overall number of unique buoys) were associated with rebeaching events. Rebeaching events accounted for 38.3% of all beachings recorded between 2008 and 2020 (a total of 1471; Figure 6). Though the largest number of buoys only beached once, one dFAD rebeached a total of 35 times over a period of 11 months and 8 d. The timespan between rebeaching events varied widely from as little as 3 d to over 5 years.

Initial offshore (> = 5 km from the coast) beaching events were significantly more likely to be followed by a subsequent rebeaching event than initial nearshore (< 5 km from the coast) beachings (Figure 5; $X^2 = 35.643$, $p < 0.001$). Overall, 69.3% of rebeaching events occurred offshore.

Discussion

Marine debris derived from fishing operations is of international concern and has been acknowledged to be one of the most prominent and destructive sources of litter within the ocean (FAO, 2020). Abandoned, lost or otherwise discarded fishing gear (ALDFG) is increasingly pervasive with severe environmental and socioeconomic ramifications (Richardson *et al.*, 2019). Our study provides a unique opportunity to examine, on a fine scale, the areas and habitat types impacted by one particular type of ALDFG: beached dFADs. The dataset we examined includes nearly 4000 dFAD beaching events occurring within the Seychelles EEZ over a 1-year period and corresponding to over 2000 individual dFADs tracking buoys. Beaching events were observed throughout the Seychelles Archipelago (Figure 1), including in remote areas renowned for their pristine habitats (Supplementary

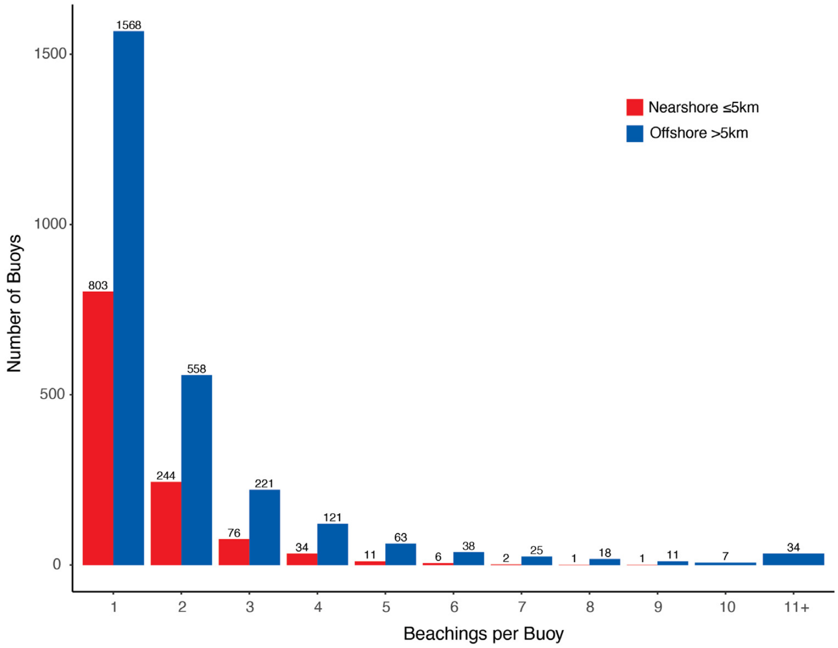

Figure 6. Number of uniquely identified drifting Fish Aggregation Devices (dFADs) that recorded single to multiple beaching/rebeaching events, comparing nearshore (≤ 5 km from shore) and offshore (>5 km from shore).

Table S3 and Figure C10; Haupt, 2020). Our dataset does not include beachings from other components of the Indian Ocean PS fleet, such as the Spanish fleet which represent more than 50% of the total Indian Ocean European-fleet dFAD deployments (Katara *et al.*, 2018). It has also been reported that 40% of dFADs found within the Seychelles did not have a satellite buoy attached and, therefore, may not appear in our dataset (Balderson and Martin, 2015). Fishers also may remotely deactivate dFAD tracking buoys before they beach. Based on these factors, it is likely that our dataset considerably underestimates the total magnitude of dFAD beachings in the Seychelles.

Beaching rates in the Seychelles show clear seasonal patterns that could be useful for focusing dFAD beaching prevention, mitigation, and clean-up programs. Most beachings occurred from December to May during the winter monsoon and spring intermonsoon seasons (Figure 3a and b). During these periods, tropical tuna PS fishing is predominantly in equatorial waters of the Indian Ocean, immediately west of the Seychelles and northern Madagascar, whereas in other periods of the year fishing is predominantly further south or north (Kaplan *et al.*, 2014). Throughout the winter and spring monsoon seasons, surface currents are dominated by the eastward South Equatorial Counter-current (Schott *et al.*, 2009), which produces favourable conditions to transport dFADs from fishing grounds to the Seychelles (Figure 3a and b; Supplementary Table B2). This pattern of transport may also help explain the large number of beachings observed in the northwestern parts of the Mahé Plateau and the Amirantes group of islands (Figure 2) as these would be the first shallow-water areas encountered by eastward drifting dFADs.

The number of beachings per year in the Seychelles increased substantially between 2012 and 2016 before stabilizing somewhat after this time-period (Figure 3a and b). Seasonality in beachings is also more marked after 2015. The time-period 2012–2016 corresponds to a period during which the French fleet significantly increased dFAD deployments (Imzilen *et al.*, 2021), likely driven by the long-term response of the fleet to Somali piracy (Chassot *et al.*, 2012), and enhanced dFAD catches due to the use of echosounder buoys (Wain *et al.*, 2021). During this period, French patterns of dFAD deployments also increasingly resembled those of Spanish vessels (Katara *et al.*, 2018), which historically focused more heavily on dFAD fishing (Davies *et al.*, 2014a, b). These trends included a transition from fishing heavily on free-schools (FS) during winter towards an increasingly dFAD-centric fishing strategy year-round (Kaplan *et al.*, 2021), explaining the observed increase in both beaching rates (Figure 3a and b).

Though island size is significantly related to the number of beachings (Figure 4a and b), much of the variance between islands in beaching rates ($R^2 = 0.0552$) is not explained by size, demonstrating that size is not the only influential factor in terms of the mechanics of dFAD beaching. DFAD beaching events have been found to be influenced by numerous factors such as the quantity and location of dFADs deployed near landmasses, ocean circulation, and local bathymetry (e.g. Escalle *et al.*, 2019; Imzilen *et al.*, 2021). Additionally, fine-scale variability in both currents and deployment locations can drastically alter trajectories and final positions of dFADs (Escalle *et al.*, 2019). These factors may explain the observed variability, though future studies using currents, dFAD trajectories and transport models should be carried out to clarify this. Beaching events also had a strong positive linear relationship with island group size (perimeter), indicating that within the scale of the entire archipelago, size is the dominant factor explaining beaching rates in the Seychelles. Interestingly, despite containing no islands, both Correira and Fortune Banks were included within the analysis as beaching events were identified within these highly remote areas (Figure 1; Supplementary Table B4). This points towards the possibility that dFADs are beaching within other remote offshore areas, such as seamounts and ridges, which are known to be associated with increased productivity and high biodiversity (Morato *et al.*, 2010; Yesson *et al.*, 2020).

Our analysis of beaching events as a function of distance to shore and water column depth indicate that most beachings occur close to shore (< 20 km) and in shallow waters (< 40 m depth), but the Seychelles is characterized by a notable number of beachings that occur further from shore (Table 1). These offshore beachings are primarily attributable to the Mahé Plateau and Amirantes group (Figure 2). These two areas are comprised of shallow plateaus or banks that span areas of ~31 000 km^2 and ~ 6300 km^2, respectively, with average water depths between 44–65 m and 11– 27 m, respectively (Taylor, 1968; Hamylton *et al.*, 2012; Figure 2). Considering dFADs subsurface structure can extend up to ~50 m in the Indian Ocean (Imzilen *et al.*, 2019), these areas present perfect conditions for the entrapment of dFADs. Additionally, the Mahe´ Plateau is encircled by an incomplete shallow ridge (shoal complex) of 10–20 m deep, which is reflected in the large number of shallow-water beachings in the north-western part of the plateau. Shoals in the region have been described to have highly abundant and unique habitat diversity (Marsac *et al.*, 2020), which suggests that the Mahe´ Plateau also supports a similar level of diversity. This highlights the importance of quantifying the impacts of these offshore "beachings" in addition to more familiar coastal beaching events.

FAD-Watch is an important conservation and multisectoral initiative in the Seychelles whose objective is to reduce the number of coastal dFAD beaching events and has been operational since 2016 (Zudaire *et al.*, 2018). By utilizing a 5 and 3 nm buffer zone (5.6 km and 9.26 km, respectively) alert system around islands, FAD-Watch participants locate and intercept dFADs prior to reaching the shore or vulnerable coastal habitats (Zudaire *et al.*, 2018). Our analysis highlights the large number of beaching events far from land and in remote and potentially ecologically important areas, which may provide evidence to support potential future expansions of the FAD-Watch program to these areas. Our findings also support the need to conduct more extensive habitat mapping to assess the impact of beachings in these offshore regions, particularly the aggregations on the Mahé Plateau.

An important and interesting finding of this study is the high frequency of rebeaching events (Figure 6). Overall, 33.8% of identified dFADs were associated with at least one other rebeaching event, and rebeaching events constituted 38.3% of the overall number of beaching events within the dataset. This high proportion of rebeaching events indicates that the consequences of dFAD beaching events cannot be limited to one singular event, but rather to a series of events. As an example, one dFAD was found to have beached 11 times in total over a 4-month period, travelling a total of 58 km from the first to the last beaching if the direction of travel was linear. The final part of this buoy's movements is depicted in Figure 5, where the buoy beaches within various habitat classes before its final recorded position. Given the subsurface structure of dFADs, it is likely that below water netting will have dragged through the variety of benthic habitats between beachings, potentially causing damage over a wider area than has previously been considered.

Within the Seychelles, coral reefs have reportedly been the most commonly impacted habitat type by ALDFG (Duhec *et al.*, 2015), which agrees with our findings (Table 2). The dFAD beaching events that intersected with the Allen Coral Atlas (2020) benthic habitat map occurred most commonly within coral/algae habitats followed by seagrass, despite these habitats constituting only 19.24% and 19.13%, respectively, of the overall habitat cover (Table 2). It is important to note, however, that these results may be biased by the purpose of the mapping conducted by ACA, which was primarily to quantify the spatial extent of coral reefs globally for conservation purposes, with less prioritization towards other habitat types or larger spatial extents (maps were predominantly within areas < 10 m depth; ACA; Kennedy *et al.*, 2020). Irrespective of this, previous studies have reported dFADs with coral fragments entangled in the netting, as well as entanglement over coral colonies (Zudaire *et al.*, 2018). The detrimental effects for corals of ALDFG have been widely acknowledged in the literature, including the introduction of disease through tissue abrasion, fragmentation, light and oxygen deprivation, mortality, and in more severe cases, death of the entire reef (Balderson and Martin, 2015; Lamb *et al.*, 2018; Baske and Adams, 2019; Mueller and Schupp, 2020). Given the large size, long-distance transport capabilities of dFADs and their complex mix of material types, beached dFADs can undoubtedly contribute to these threats to sensitive coral habitats and our analysis indicates that a large fraction of dFAD beachings in the Seychelles occur in coral reef areas.

It is difficult to ascertain the damage that ALDFG, and in particular dFADs, may cause to seagrass as studies pertaining to this subject are limited. Nevertheless, the entanglement of seagrass within dFAD netting has been observed in dFADs retrieved during clean-up operations (Zudaire *et al.*, 2018). Therefore, impacts may be similar to mechanical disturbance derived from anchor scars and chain scour of boats in coastal regions. Abrasion can lead to tissue damage and thus increase susceptibility to disease or reduce chlorophyll production capabilities (Broad *et al.*, 2020). Uprooting can result in decreased frond density that aids in the attenuation of hydrodynamic forces, which can lead to further erosion (Broad *et al.*, 2020). High density seagrass beds protect corals from bleaching via light attenuation (Iluz *et al.*, 2008) and seagrass plays an important role in carbon sequestration (Duarte and Krause-Jensen, 2017). Therefore, protecting seagrasses is both locally and globally important. Whilst dFAD damage to seagrass may or may not be as severe as that of metal anchors and chains, the substantial netting, and subsurface structure of dFADs suggest that they have the potential to do significant damage. The data presented here identify seagrasses as an important area for assessing dFAD beaching impacts on coastal ecosystems and highlight that rebeaching events may spread damage over a wider area.

In 2019, the Seychelles Island Foundation (SIF) conducted a clean-up operation at Grande Terre Island, Aldabra Atoll, to determine the extent of marine litter in the environment and to estimate the expected costs of clean-up (Burt *et al.*, 2020). Over 5 weeks, 26.4 tonnes of marine litter were collected from the coastal region which consisted largely of fishing-related gear (60%, 15.8 tonnes of the total), including buoys, dFADs (n = 13), nets, and ropes. The remaining unrecovered litter was estimated to be 513.4 tonnes, of which fishing-related items contributed ~83% (426 tonnes) of the overall estimated litter composition (though the majority of this was not dFADs). On average, the cost of a clean-up operation of the entire Grande Terre Island was estimated to be US$4.68 million with an overall range of $1.95 million—$7.28 million (Burt *et al.*, 2020). Given this estimate was conducted for Grande Terre only, the severity of the problem and the costs of a Seychelles-wide clean-up program are potentially considerable. Our results regarding spatial and temporal patterns of beaching provide detailed information for focusing efforts on prevention and clean-up in the most highly impacted areas, thereby potentially allowing reduced costs and enhancing the efficiency of such operations.

St François Island (the southernmost island of the Alphonse Group) has the highest rate of beachings per unit perimeter within the Seychelles, despite being one of the smallest islands, accounting for 80 of recorded beaching events within 5 km of its shores (Supplementary Figure C9 and Table B3). In 2015, 40 beached dFADs were removed as part of a scientific study from the surrounding marine environment of St François (Balderson and Martin, 2015). Spatial information (latitude and longitude), date, and habitat type of the beached dFADs removed as part of this study were provided to us by the Island Conversation Society (ICS) to identify any similarities between the beaching events identified within the present study and those removed by Balderson and Martin (2015). Seven of the 40 dFADs retrieved from St François were within extremely close proximities (< 0.12 km) to the dFAD beaching events within the present study. Assuming that these actually represent the same beaching events, one dFAD was removed after beaching for just 4 d, but two were beached for 5 years prior to being removed. This suggests that beaching events can have long-term impacts on marine ecosystems if not prevented, or promptly removed, after beaching. As we were only able to potentially identify seven of the 40 beached dFADs in Balderson and Martin (2015), these results highlight that our study is likely a significant underestimate of the total number of beachings in the Seychelles.

Despite this underestimation of total beaching events, the extremely close proximity of the seven beaching events removed *in-situ* by the ICS to those identified within the present study is a promising validation of the conditions implemented to identify beaching events within this study. Consequently, our methodology may be used to quantify the contribution of dFADs to the costs of clean-up across the entire Seychelles utilizing the costs calculated by Burt *et al*. (2020). This may be an effective step towards identifying optimal economic and ecological outcomes that inform fisheries management decisions within local and small-scale contexts.

Worldwide efforts have been made by both fleets and research institutions towards the development and use of biodegradable FADs (BIOFADs; FADs constructed with biodegradable materials in which only buoys for flotation and electronic components are made of plastic; Delgado de Molina *et al*., 2007; Franco *et al*., 2009; Moreno *et al*., 2021; Roman *et al*., 2020; Zudaire *et al*., 2020). Governance measures implemented by Tuna Regional Fisheries Management Organisations (tRFMOs), specifically the Indian Ocean Tuna Commission (IOTC) prohibited the construction of dFADs using netting or meshed materials on 1 January 2020 and, commencing 1 January 2022, further encourages the use of biodegradable materials (IOTC Res. 19/02). These measures are undoubtedly an important and positive step towards greater sustainability within the tropical tuna PS industry, though the extent of their observance remains to be quantified.

BIOFADs that degrade after their useful lifetime ($>$ 6 months; Moreno *et al*., 2018; Wang *et al*., 2021) may significantly reduce the impact and number of FAD beachings worldwide. However, this may not be effective within the Seychelles, considering we found that the majority of beachings occurred between 18 and 65 d (0.5–2 months) after deployment. BIOFADs that beach or become stranded within a relatively short period may continue to cause physical impacts to fragile habitats, such as coral reefs, due to the entanglement of intact ropes or panels (Escalle *et al*., 2019). Therefore, future studies assessing the drift time and trajectories prior to FAD beaching, coupled with spatial closures for dFAD deployments (Imzilen *et al*., 2021), may contribute to ensuring that BIOFADs degrade before reaching vulnerable habitats, whilst enabling durability for their required lifespan.

We identified a number of data gaps in our study that limited potential analyses and that should be a focus for future data collection efforts. One of them is the limited availability and spatial extent of fine scale benthic habitat maps. This greatly reduced the proportion of beaching events for which a habitat type could be determined, potentially introducing bias into our results (e.g. if coral habitats were more likely to be mapped than other habitat types). As habitat mapping is essential for many aspects of marine spatial planning and management (Vassallo *et al*., 2018), it is our hope that this data gap will be filled through acoustic, satellite, and multibeam sampling and through advances in machine learning (Mohamed *et al*., 2020).

Finally, the analyses in this paper were only possible because the French fleet provided scientific access to data on dFAD trajectories. Though access to dFAD trajectory data for all PS fleets is rapidly improving (Maufroy *et al*., 2017; Zudaire *et al*., 2018; Orúe *et al*., 2019, 2020; Imzilen *et al*., 2021; Escalle *et al*., 2019, 2021), restrictions on data access and/or use of data for scientific purposes are still quite common, and single, cross-cutting analyses involving all components of the PS fishery in an ocean remain quite challenging and rare. The evidence we present above suggests that this data gap is quite important and should be addressed in the future. Increasing dFAD deployment location and trajectory information reporting requirements at the national, European, and regional fisheries management organization (RFMO) levels represents promising progress towards filling this gap and offers hope for the development of focused clean-up programs, thereby reducing the important contribution of dFADs to ALDFG.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Authors' contributions

I.M. devised the project, conducted majority of the analyses, interpretation of the results, designed the figures, and wrote the manuscript. M.A., C.L., and D.M.K. supervised. M.A. aided interpretation of the results and revised the manuscript throughout. T.I. and C.L. provided technical assistance and C.L. also revised manuscript. S.W. and C.C. conceived the topic and supervised the initial stages of the work. D.M.K. and C.L. devised final project direction. D.M.K. performed specific analyses, aided interpretation of the results, contributed towards writing of the manuscript and its critical revision, and aided with the majority of corrections in response to reviewers. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Data availability statement

Given the confidential nature of the data used in this article, requests for data access should be addressed directly to the Ob7 (https://www.ob7.ird.fr/en/) pelagic ecosystem observatory using the following e-mail address: adm-dblp@ird.fr.

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