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Recovery at sea of abandoned, lost or discarded drifting fish aggregating devices

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Tropical tuna purse-seine fishing vessels contribute to abandoned, lost or discarded (ALD) fishing equipment by deploying large numbers of drifting Fish Aggregating Devices (dFADs). Here we analysed more than 80,000 dFAD trajectories (56,263 tracking buoys) in the Indian and Atlantic oceans from 2012 to 2018. We found that more than 40% of dFAD trajectories ultimately drifted away from fishing grounds, becoming ALD. About 20% of these lost dFADs passed within 50 km of major ports, indicating that port-based programmes could be effective in collecting ALD dFADs at sea. We also identified areas within the fishing grounds where most dFADs exit and where high-seas recovery could be valuable. For example, most dFADs leaving Indian Ocean fishing grounds along their eastern border at ~70° E, particularly in October–December, do not return to fishing grounds. Despite considerable logistical challenges, at-sea dFAD recovery offers promising options for reducing the ecological footprints of purse-seine fisheries.

Concerns about plastic debris in the world's oceans have increased and attracted attention from managers and policymakers, with international calls to address this issue[1]. Oceanic and coastal waters receive a large percentage of their waste and pollutants from land-based sources, with an estimated 4.8–12.7 million metric tonnes of plastic entering the ocean annually[2]. However, a recent study found that at least 22% of the marine litter originates from sea-based activities, and that abandoned, lost or discarded (ALD) fishing equipment was the predominant source of marine litter in the open ocean (up to 61%)[3]. Tropical tuna purse-seine vessels active in equatorial waters of the world's oceans deploy large numbers of drifting Fish Aggregating Devices (dFADs) to aggregate fish and facilitate their capture[4,5], with the total number of such devices potentially exceeding 100,000 annually[6,7]. A dFAD is typically made from a bamboo and/or metal raft equipped with plastic or balsa wood floats to ensure buoyancy, a submerged substructure that varies by ocean and fleet, but typically consists of ropes or rolled old purse-seine nets that can stretch up to 100 m below the surface, and a satellite-transmitting GPS-tracking buoy. Many of these materials consist of plastics or metals that are slow to decay[8,9]. dFAD fishing has become the dominant fishing mode for tropical tuna purse-seine fishers worldwide, representing in 2018 more than 2 million metric tonnes—60% of the worldwide purse-seine tropical tuna catch (A. Fonteneau, personal communication). Most importantly for this study, dFADs were recently assessed to have the third highest ALD risk of all fishing gears[10], and therefore may infringe international marine pollution law[11]. A recent study estimated that more than 90% of dFADs are never retrieved after deployment in the western and central Pacific Ocean[12], with some considering that this loss contributed as much as 225,720 metric tonnes of plastic debris over the period 2016–2020[13], although a more reasonable estimate for this time period would be on the order of 10,000 metric tonnes[14]. Thus, a large percentage of dFADs eventually end up drifting outside fishing grounds, altering pelagic environments[15] and later potentially threatening sensitive areas via stranding (often

referred to in previous literature as 'beaching'[4,5,16]), contributing to ghost fishing[17] and otherwise contributing non-biodegradable waste to the world's oceans[18].

Scientists, fishers and policymakers recognize that mitigation is needed to reduce dFAD loss and its environmental impacts[19,20]. Tuna regional fisheries management organizations (tRFMOs) currently limit the number of floating objects actively monitored per purse-seine vessel to 300 buoys in the Atlantic and Indian Oceans[21,22], although post-limitation increases in the number of French dFADs suggest these restrictions may not have reduced dFAD numbers[5]. In the Atlantic Ocean, 3-month time–area closures for dFAD activities (for example, deployment and fishing) have been implemented. In addition, tRFMOs encourage the use of biodegradable materials in the construction of dFADs[9]. However, identifying suitable biodegradable materials for dFAD construction has proven difficult and will probably take time[9,23]. A recent study has shown that dFAD strandings, which can lead to environmental damage even if dFADs are biodegradable, may be substantially reduced if specific spatial closures for dFAD deployments are adopted in the Indian and Atlantic Oceans[5]. However, this study also showed that closures will not be uniformly effective over space in reducing strandings. Furthermore, these closures only relate to strandings and do not take into account the other potential negative impacts of dFAD loss. Therefore, additional management options for reducing dFAD contributions to marine debris and environmental damage are needed.

dFAD recovery programmes are one promising approach to mitigating their negative impacts. In 2016, the EU purse-seine fishing industry, in collaboration with a local non-governmental organization (NGO) and the Seychelles Fishing Authority, implemented a programme called FAD Watch to reduce dFAD stranding in certain coastal areas of the Seychelles[24]. A dFAD detection system was set up to alert participants when dFADs arrived within 5 NM of the coast. A total of 109 dFADs were collected over the period 2016–2017. Although promising, scaling up this type of programme to an entire ocean basin may not be practical, particularly in small island

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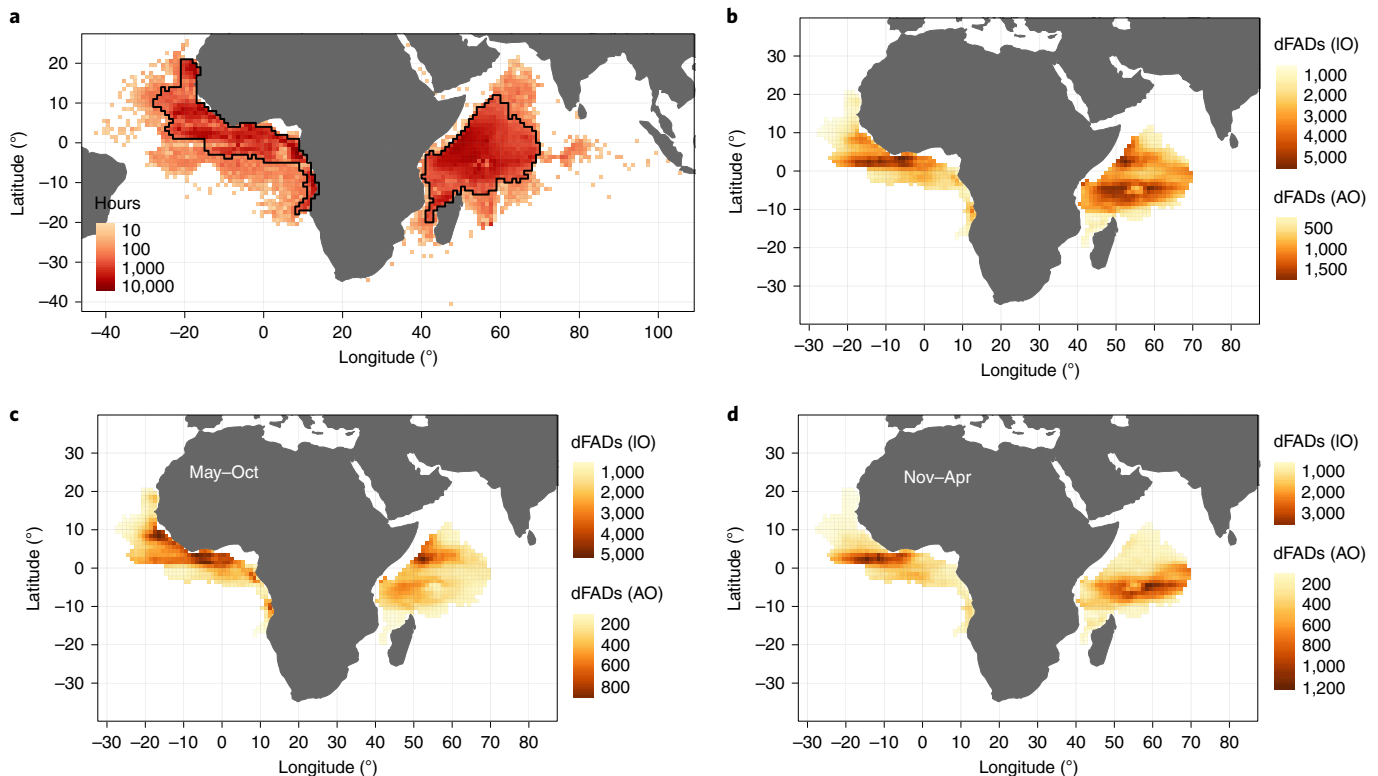
Fig. 1 | Core fishing zones and dFAD densities. a, Core fishing zones. Shading represents the total number of EU purse-seine fishing hours in each 1°×1° grid cell for the period 2012–2018. The thick solid curves delimit our definitions of core fishing grounds (primarily consisting of cells with >200 fishing hours over the study period). **b–d**, dFAD densities. Shading indicates the total number of times dFADs passed through each 1°×1° grid cell within the fishing grounds of the Indian Ocean (IO) and Atlantic Ocean (AO) for the entire period 2012–2018 (**b**), and for the months of May–October (**c**) and November–April (**d**).

systems[16]. Nevertheless, a recent analysis in the Indian and Atlantic Oceans indicates that up to ~50% of 'stranded' dFADs may actually consist of GPS buoy recoveries by artisanal fishers[5], suggesting that coastal dFAD recovery programmes may be effective.

The goal of this paper is to analyse the trajectories of dFADs in the Indian and Atlantic Oceans with respect to factors that may facilitate implementation of dFAD recovery programmes to reduce the negative ecological impacts of ALD dFADs. In addition to examining where and when dFADs exit main fishing zones, we identify typical dFAD transit paths outside fishing zones and where they are likely to pass close to major ports that could be used for recovery programmes (see Methods).

Results

Core fishing areas. Fishing activities occur mainly in the western Indian Ocean and the eastern Atlantic Ocean (Fig. 1a). These activities are more homogeneous in space in the Indian Ocean than in the Atlantic Ocean, where the fishing grounds are an elongated strip adjacent to West Africa with some notable gaps (often related to issues with obtaining exclusive economic zone (EEZ) access agreements). The total number of fishing hours in the core fishing grounds (Fig. 1a) represents 96.9% of all EU fishing hours in the Indian Ocean and 95.3% in the Atlantic Ocean.

Hotspots for dFAD fishing. Maps of the number of dFAD passages in each 1°×1° grid cell clearly identify hotspots for dFAD locations (Fig. 1b,c,d). In the Indian Ocean, passages of dFADs are concentrated in southern and northwestern parts of the fishing grounds. In the Atlantic Ocean, they occur most frequently in a longitudinal band located between 0° and 10° N (Fig. 1b). Seasonal variability is

most notable in the Indian Ocean where dFADs are concentrated in the southern part of the fishing grounds from November to April and in the northwestern parts (Somali upwelling zone) from May to October (Fig. 1c,d), consistent with known monsoon-driven seasonality in Indian Ocean circulation and fishing activities[25].

Loss of dFADs from fishing grounds. Overall, analyses of dFAD movements show that the proportions of dFADs that either remain within fishing grounds or definitively leave fishing grounds are roughly equal (40–45% each; Fig. 2), and considerably higher than those that leave and return: 62.5% of all tracked buoys eventually leave fishing zones never to return. Not surprisingly, dFADs that remain in fishing grounds are most often located in the interior of the fishing grounds (Fig. 2a–d). dFADs that leave and return, while infrequent, most often occur along the northwest and southeast borders of the fishing grounds in the Indian Ocean, and off West Africa and the Republic of Congo in the Atlantic Ocean (Fig. 2b–e). Even for dFAD passages in many interior areas of the fishing grounds, dFADs have a relatively high probability of eventually definitively leaving fishing grounds (>40%), with higher values in the northeastern and southwestern Indian Ocean and the northwestern and southern Atlantic Ocean (Fig. 2c–f).

There is bi-modal seasonality in the dFAD loss rate in both oceans (Fig. 3). For the Indian Ocean, there is a dominant peak in dFAD loss around November, followed by a secondary peak in May, whereas the less-marked seasonality in the Atlantic Ocean has broad peaks around July and around December. In both oceans, seasonality is primarily due to real differences in loss rates as opposed to differences in the number of deployments (that is, seasonality of the proportions in Fig. 3b are qualitatively similar to that of the
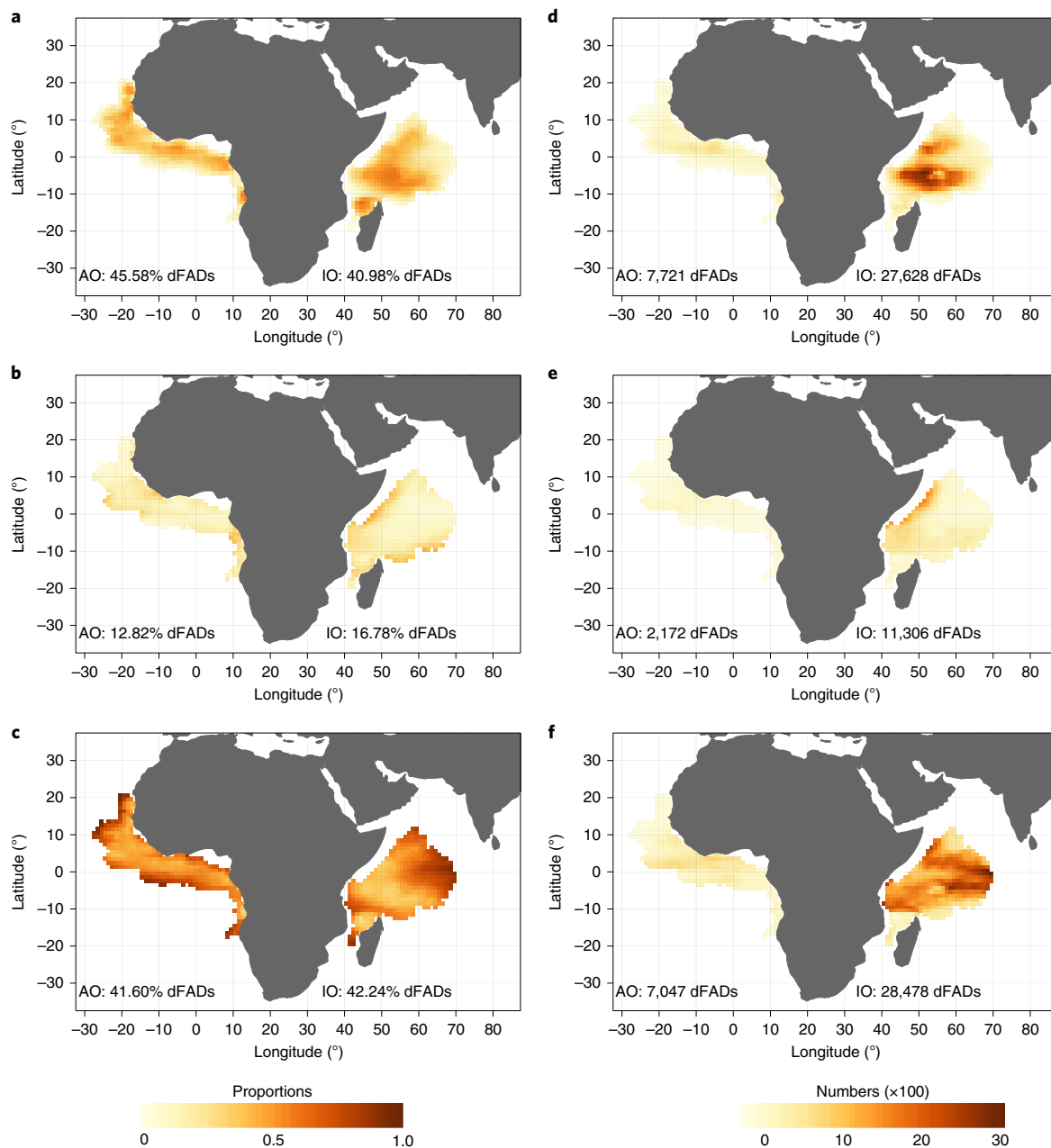
Fig. 2 | The fate of dFADs with respect to the fishing grounds. a–f, Maps of the proportions (**a–c**) and numbers (**d–f**) of dFAD passages that remain (**a,d**), leave and return (**b,e**), and definitively leave (**c,f**) the fishing grounds after passing through each 1° × 1° grid cell over the period 2012–2018 for the IO and AO. Text in each panel presents the percentages and total numbers of dFAD trajectories for the corresponding category.

absolute numbers in Fig. 3a). Surprisingly, loss in the Indian Ocean is relatively low just west of the Maldives from June to August compared with other times of the year (Supplementary Fig. 1) despite monsoon-driven eastward currents during these months.

The final recorded positions of dFADs that definitively leave fishing grounds are consistent with major surface ocean currents[26,27], being concentrated near, for example, the coasts of the Maldives and Somalia in the Indian Ocean, and Brazil and the Gulf of Guinea coasts in the Atlantic Ocean (Fig. 4a,b).

Proximity of lost dFAD trajectories to ports. Among the dFADs that definitively left the fishing grounds, 17.6% and 29.6% in the Indian and Atlantic Oceans, respectively, passed within 50 km of a port for a mean time of 3.2 days (Fig. 4d; 5.9% and 3.9% if considering

only large ports, Fig. 5 and Supplementary Table 1). Integrating dFADs that left and later return to fishing areas into analyses slightly decreases percentages (Supplementary Table 1). dFADs that definitively left fishing grounds primarily passed close to ports along the African coast, particularly, in Tanzania and Mozambique in the Indian Ocean, and in the Gulf of Guinea and Angola in the Atlantic Ocean (Fig. 4c). In these areas, from 30% to 100% of dFADs definitively leaving the fishing grounds passed within 50 km of a port. In the Indian Ocean, most dFADs exiting along the northwestern boundary of the fishing grounds passed near the large port of Mogadishu, Somalia (1,641 dFADs; 5.8%), whereas dFADs leaving from the southwestern boundary passed primarily near 2 medium-sized ports: Mombasa, Kenya (1,869 dFADs; 6.7%) and Dar Es Salaam, Tanzania (276 dFADs; 1.0%), and 5 small ports
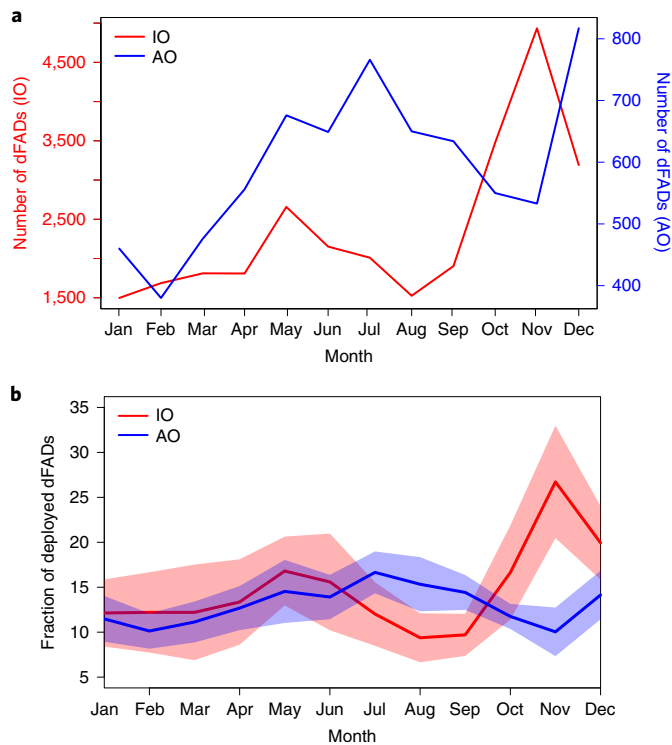
Fig. 3 | Monthly variability in the rate of dFADs definitively leaving the fishing grounds. a,b, Monthly variability in the total number (**a**) and percentage (**b**) of dFADs that definitively leave the fishing grounds over the period 2012–2018 for the Indian Ocean (red curves) and Atlantic Ocean (blue curves). The central lines in **b** indicate the mean percentage leaving fishing grounds averaged over the 7 years examined in this study, whereas the shaded regions around the central lines indicate 1 s.d. around the mean. An indication of interannual variability was not included in **a** because the increasing tendency in the total number of deployed dFADs made it impossible to compare across years.

(108 to 1,748 dFADs; 10.1%) (Fig. 5 and Table 1). In the Atlantic Ocean, dFADs definitively leaving fishing grounds passed primarily near Gulf of Guinea ports, especially the large port of Pennington Oil Terminal off Nigeria (275 dFADs; 3.9%), 6 medium ports (92 to 273 dFADs; 12.8%) and 5 small ports (93 to 287 dFADs; 10.8%) (Fig. 5 and Table 1). Among the dFADs passing close to a port, one-third (33.6%) eventually strand or have their tracking buoys recovered by coastal fishers (31.5% of dFADs passing close to large ports, and 34.9% close to medium ports)[5]. The percentage passing close to ports ranges from ~0–10% for a buffer distance of 10 km to ~25–45% for a buffer distance of 100 km (Fig. 4d, and Supplementary Tables 2 and 3).

Discussion

Relevance for design of dFAD recovery programmes. Our results provide guidance for implementing effective dFAD recovery programmes. More than 40% of dFAD trajectories in the Indian and Atlantic oceans drifted away from fishing grounds never to return, potentially later stranding in coastal areas (Imzilen et al.[5] estimated that 10–20% of all French dFADs eventually strand, whereas 16.0% of our trajectories that definitively leave fishing zones strand). This loss represents at least 529 tonnes yr^{-1} of marine litter for the French fleet[5,14] and probably 2–3 times that weight including all purse seiners in the two oceans[28]. More than 20% of dFAD trajectories that drifted away from fishing grounds passed within 50 km of a port (ranging from 3.3% to 31.6% for cut-off distances from 10 to

100 km; potentially underestimated due to remote deactivation of GPS buoys by purse seiners). This result suggests that coastal dFAD recovery programmes could be complementary to other mitigation measures, such as dFAD buoy limits already implemented by tRF-MOs and spatio-temporal dFAD deployment closures proposed by Imzilen et al.[5]. Indeed, Imzilen et al.[5] showed that prohibiting dFAD deployments in areas that would probably lead to strandings would principally protect coastal areas of the southwestern Indian Ocean and the eastern Gulf of Guinea, whereas we found that dFADs exiting fishing grounds from other areas, such as the northwestern Indian Ocean and the northern Gulf of Guinea, passed close to regional ports and could potentially be recovered at sea. Although our results are specific to the French and associated purse-seine fleet (representing ~1/3–1/2 of catch and dFAD deployments of all fleets[28]), available data indicate that other purse-seine fleets have similar spatio-temporal patterns of deployments[28], suggesting that our results are applicable to the entire tropical tuna purse-seine fishery in the Indian and Atlantic oceans.

These results contrast somewhat with existing analyses from the western and central Pacific Ocean, where it was estimated that 36% of dFADs ended up outside fishing grounds, but that the final recorded position of these abandoned dFADs were typically far from ports (502–952 km)[29]. Although these differences may be related to the larger spatial scales of the Pacific Ocean, additional analyses based on examinations of entire trajectories are needed to assess viability of recovery programmes based on ports.

Consequences of spatial and temporal variation of dFAD loss. High seas recovery could also be structured around our results on where important percentages of buoys exit fishing grounds towards the high seas. In the Indian Ocean, dFADs definitively leaving from the eastern border (70° E) end up stranded in or transiting through the Maldives and the eastern Indian Ocean. This happens relatively less frequently in the period from June to August and becomes much more frequent from October to December. Low loss rates during June to August are consistent with known seasonal patterns in dFAD deployment and fishing during this period[4,25]. At that time of the year, dFADs are deployed by fishers with the intent that they drift along the eastern African coast until they reach the main dFAD fishing grounds off Somalia, avoiding strong monsoon-driven currents favourable to eastward export of dFADs from July to December[27]. This is followed by a more intense dFAD fishing season during August–October. Finally, starting in October/November, a period of transition towards fishing further south in the Indian Ocean occurs, with relatively more focus on free-swimming school sets[25,30], probably contributing to abandonment of dFADs in the northern Indian Ocean in the last quarter of the year.

In the Atlantic Ocean, dFADs lost to the high seas exit fishing grounds mostly from the northwestern border (between 10° and 20° N) and southwestern border (2°–5° S), which is consistent with transport by the North Equatorial and South Equatorial Currents[26]. Although the seasonality of loss is less marked in the Atlantic Ocean than in the Indian Ocean, the peak months of July and December are associated with transitions in the spatio-temporal distribution of deployments from principally deploying just north of the equator off of West Africa to focusing on the Gulf of Guinea further east[30]. These transitions could lead to increased dFAD abandonment in areas highly susceptible to export of dFADs, although seasonality in currents may also play a role.

Challenges facing recovery programmes. While the information provided in this paper on spatio-temporal patterns of dFAD loss provides an essential foundation for implementing dFAD recovery strategies, there are several important practical challenges to the success of such efforts. Most efforts towards reducing or removing marine debris after it has been created have so far focused on
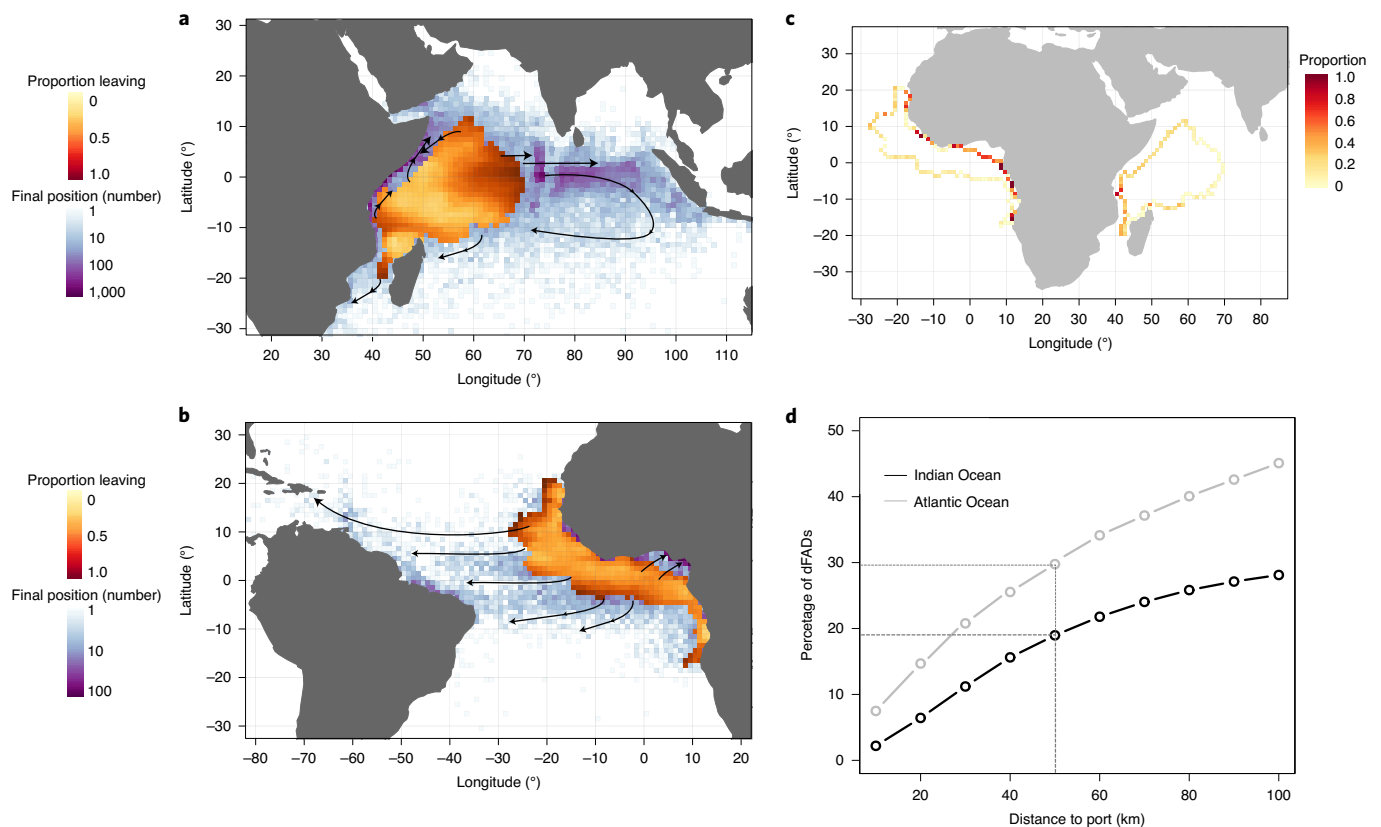
Fig. 4 | Dominant directions followed by dFADs and the proportion of these dFADs that pass close to ports. a–d, Quantitative and qualitative indicators of the dominant directions followed by dFADs after definitively leaving fishing grounds in the Indian (**a**) and Atlantic (**b**) oceans, as well as the proportion of these dFADs that pass close to ports (**c**,**d**). Brown colours in **a** and **b** represent the proportion of dFADs passing through each 1° × 1° grid cell of the fishing grounds that end up definitively leaving (same as in Fig. 2c), whereas blue colours represent the number of final positions of these dFADs in each grid cell (note that the blue colour bar is on a log scale). Black arrows represent typical drift directions followed by dFADs as determined by a qualitative review of their trajectories. The proportion of these dFADs that pass within 50 km of ports as a function of location along the border of the purse-seine fishing grounds is shown in **c**, whereas how the overall percentage of dFADs definitively leaving the fishing grounds that pass close to ports varies as a function of maximum distance to ports is shown in **d**. Dashed horizontal and vertical lines in **d** indicate the percentage of dFAD that pass within 50 km of ports.

beach clean-ups[31,32]. Such operations are costly, time-consuming and only capture a fraction of the overall debris[18,33]. Recovery at sea is a promising alternative solution[34], but this requires consolidating systems to observe these debris[35] and understanding their drift[36], as well as putting in place appropriate incentives and socio-economic and political frameworks[37]. Broadly, data availability (for example, access to near-real-time location data from all fleets), equipment availability (for example, appropriately sized and equipped vessels for collecting large debris such as dFADs)[32], recovery programme structure (for example, collaboration with local fishers, NGOs and/or nation-states; use of support vessels, and/or chartering of dFAD recovery vessels) and funding sources (for example, reuse of recovered tracking buoys or dFAD plastic floats, and/or polluter-payer systems collected at dFAD deployment or manufacturing) need to be optimized to recover a maximum number of dFADs while minimizing costs and fishing impacts. These considerations highlight the importance of identifying areas leading to losses and multiple ports of different sizes from which operations could potentially be conducted, as we have done above, as well as careful analysis of the possible impediments to implementation of recovery programmes.

Some possible impediments to dFAD recovery programmes are environmental, strategic or geopolitical. For instance, although the Somali coast is identified as a dFADs stranding hotspot in winter[5] and has potential for a port-based recovery programme as we show here, recovering dFADs along this coast is unlikely to be a priority due to the area's relatively limited number of

sensitive habitats, such as coral reefs, and because of the difficult and dangerous socio-political situation in the country and its adjacent waters. On the other hand, the Maldives archipelago is likely to be a priority given that it is an area with high dFAD stranding rates on coral reefs[5] and also has many dFADs that leave fishing grounds and never return. Implementing a recovery programme in this area could be particularly valuable, especially given that the Maldives is well integrated into regional maritime transport and tuna fisheries. However, implementing such a programme for a large island chain composed of >1,000 individual islands will probably be complex. Extensive collaboration with regional stakeholders, such as research institutes, fisher associations and NGOs, as well as buoy manufacturers, would be essential to operationalize a recovery programme in the Maldives and elsewhere.

Another major challenge for at-sea dFAD recovery is availability of appropriate vessels to remove dFADs from the water. The vertical subsurface structure of dFADs generally stretches from 50 to 80 m below the surface. The weight of the materials used to build dFADs and the numerous sessile organisms that attach to the 'dFAD tail' eventually make dFADs very heavy (up to hundreds of kilograms) and therefore difficult to remove from the water. Complete removal is probably only possible for medium to large vessels with an appropriate crane or winch for hauling heavy material. Purse-seine vessels themselves could participate in dFAD recovery efforts, but this would be costly and disruptive to fishing. For smaller vessels, it may only be possible to remove some parts of the dFAD, potentially
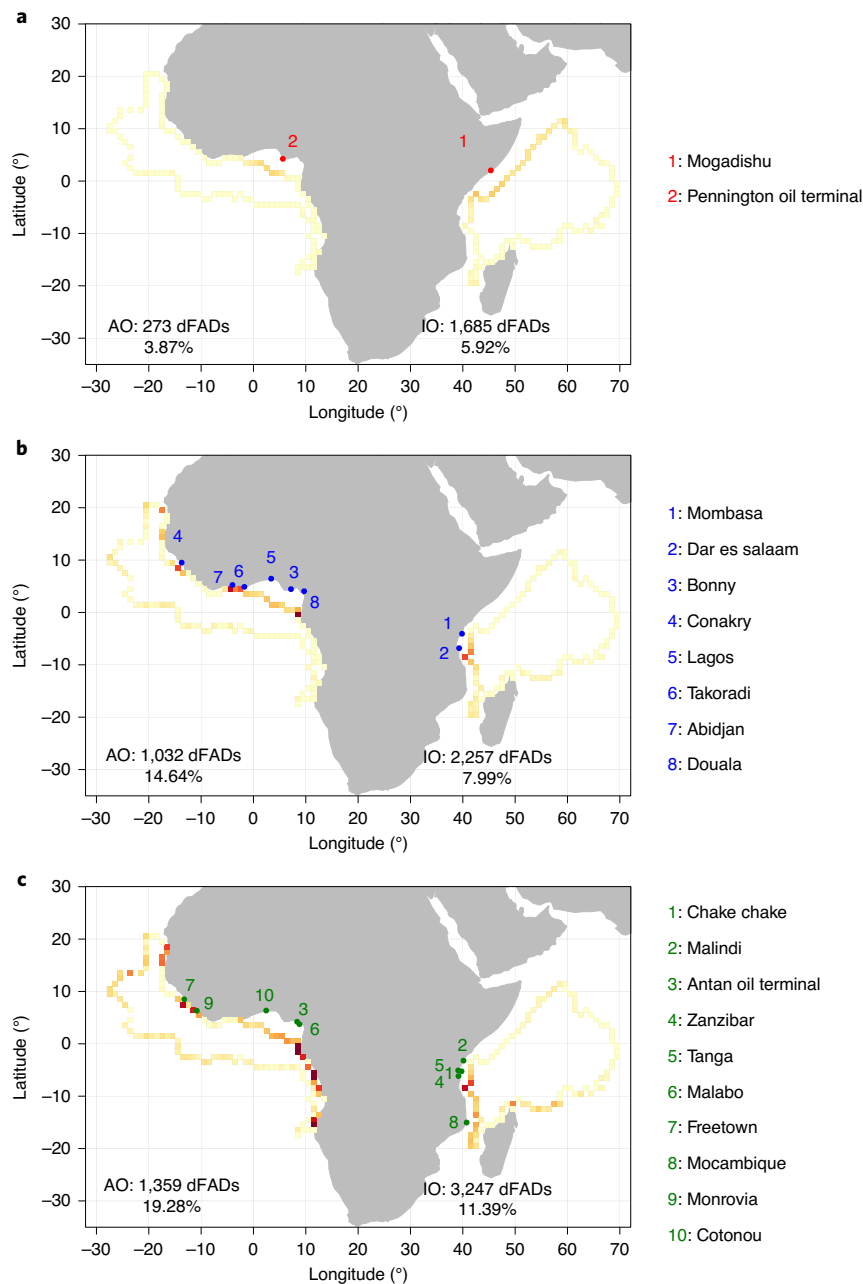
Fig. 5 | dFADs at the border of fishing grounds that definitively leave fishing grounds and pass close to ports. a–c, Proportion of dFADs at the border of fishing grounds that definitively leave fishing grounds and pass close (km) to large (**a**), medium (**b**) and small (**c**) ports. Note that all dFADs are taken into account even if they pass near several port categories and that only ports for which more than 90 dFADs passed within 50 km are indicated by name. The text on each panel indicates the total number and percentage of dFADs for each port category in the IO and AO.

aided by natural breakdown of the object or acoustic release systems, such as the GPS buoy, plastic flotation devices and/or surface raft metallic or plastic structural elements. However, this could still be extremely useful as the remaining material will normally sink before reaching coastal environments, thereby potentially avoiding the most important environmental impacts. This strategy would be particularly valuable if the subsurface structure can be made of biodegradable materials[9,23,38]. Imzilen et al.[5] suggested that the removal of GPS buoys by artisanal fishers is already occurring in coastal areas. Therefore, if dFAD tracking information can be made accessible and appropriate incentive mechanisms are put in place to encourage recovery of dFAD elements, this strategy could substantially reduce marine debris from dFADs. Other practical considerations should be taken into account once at port, such as the availability of

infrastructure for shipping, disposing of, recycling and/or reusing tracking buoys and other dFAD components. All of these potential impediments can be addressed, but they will require active engagement from fishers, tRFMOs, NGOs and coastal nations.

Complementary measures. In addition to such recovery programmes, existing complementary measures controlling the numbers of dFADs present at sea (for example, limits on the number of operational GPS-tracking buoys and limits on the use of support vessels) may need to be strengthened, as a higher number of dFADs obviously contributes to higher risks of marine debris and stranding. Lowering limits on the number of dFADs may also encourage vessels to increase sharing of buoy information, thereby maximizing use of dFADs and potentially reducing dFAD loss. However, oddly

Table 1 | Numbers and percentages of dFADs that definitively leave the purse-seine fishing grounds of the Indian and Atlantic oceans and pass within 50 km of specific large, medium and small ports over the period 2012–2018

Country[a]	Port name[b]	Distance to fishing area (km)	Port size	Total dFAD passes[c]	Percentage of dFAD passes	Unique dFAD passes[d]	Percentage of unique dFAD passes[d]
SO	Mogadishu	290	Large	1,641	5.76	1,641	5.76
KE	Mombasa	128	Medium	1,869	6.56	1,771	6.22
TZ	Dar es salaam	152	Medium	276	0.97	271	0.96
TZ	Chake chake	137	Small	1,748	6.14	535	1.88
KE	Malindi	96	Small	520	1.83	36	0.13
TZ	Zanzibar	201	Small	267	0.94	98	0.34
TZ	Tanga	209	Small	231	0.81	70	0.26
MZ	Mocambique	136	Small	108	0.38	101	0.36
NI	Pennington oil terminal	249	Large	275	3.90	275	3.90
NI	Bonny	300	Medium	273	3.87	178	2.53
GV	Conakry	65	Medium	172	2.44	172	2.44
NI	Lagos	311	Medium	136	1.93	123	1.75
GH	Takoradi	30	Medium	134	1.90	130	1.84
IV	Abidjan	28	Medium	98	1.39	98	1.39
CM	Douala	346	Medium	92	1.31	88	1.25
NI	Antan oil terminal	357	Small	287	4.07	143	2.03
EK	Malabo	304	Small	157	2.23	82	1.16
SL	Freetown	55	Small	111	1.78	71	1.01
LI	Monrovia	20	Small	102	1.45	100	1.42
BN	Cotonou	264	Small	93	1.32	12	0.17

[a]The country names corresponding to the postal abbreviations cited in the table are: SO, Somalia; NI, Nigeria; KE, Kenya; TZ, Tanzania; GV, Guinea; GH, Ghana; IV, Ivory coast; CM, Cameroon; EK, Equatorial Guinea; SL, Sierra Leone; MZ, Mozambique; LI, Liberia; BN, Benin. SO to MZ represent the ports located in the Indian Ocean, while the rest of the countries represent ports located in the Atlantic Ocean.
[b]Only ports for which at least 90 dFADs pass within 50 km are presented in the table. [c]All dFADs are taken into account even if they pass close to several port categories. [d]dFADs are only taken into account if they do not pass close to other larger ports.

enough, such measures may aggravate problems of ALD dFADs if their consequences are not accurately anticipated. For example, limits on the number of tracked dFADs implemented by tRFMOs have modified the strategy of some components of the purse-seine fishery, encouraging them to remotely deactivate satellite-transmitting GPS-tracking buoys when dFADs leave fishing grounds to maintain the number of operational buoys below authorized limits. The loss of position information prevents the tracking of dFADs outside fishing grounds and may result in under-estimation and spatial bias in estimates of the risks of stranding and loss[5,39]. A potential solution would be to consider ALD dFADs as part of a stock of 'recoverable dFADs' that are not counted as part of the individual vessel's quota of operational buoys, but for which position information is transmitted and made available to partners involved in recovery programmes[39]. Other useful options to facilitate the recovery of buoys include limiting the per vessel number of deployments instead of limiting the number of tracked dFADs and/or making new deployments contingent on recovery of an equivalent number of already deployed dFADs. The current tRFMO-implemented reduction in the number of support vessels in the Indian Ocean is also likely to increase the loss of dFADs because these vessels may be used to recover dFADs before they leave fishing grounds, highlighting the urgent need for complementary dFAD management and recovery approaches.

Financial considerations. A final question about dFAD recovery programmes is how they could be financed. The logistical challenges described above, such as chartering appropriate recovery vessels, involve substantial costs that cannot be ignored. The most simple and logical financing scheme would be a polluter-payer programme whereby vessels, dFAD manufacturers and/or fishing nations pay some monetary amount per ALD dFAD, potentially in proportion to its expected negative impacts, into an independently run and verified clean-up fund. The basic elements for identifying which vessels, fishing companies and/or nations are deploying dFADs are largely in place via tRFMO reporting requirements, dFAD vessel logbooks and purse-seine observer programmes. The detailed spatio-temporal maps provided here and in Imzilen et al.[5] identify where the losses and impacts are occurring, thereby providing a blueprint for apportioning such funds geographically.

Missing elements. The missing elements for reducing dFAD loss are mostly political: facilitating access to tracking and activation-deactivation information for all ALD dFADs (for example, the EU recently objected at the 2nd Indian Ocean Tuna Commission (IOTC) ad hoc working group on dFADs to making dFAD data publicly available for scientific purposes); implementing requirements for appropriate disposal of ALD dFADs; and improving collaboration between industry and regional stakeholders concerned with clean-up programmes. Although these missing elements may seem formidable, there are very promising precedents for rapidly addressing these types of issues. Throughout the 2010s, various initiatives of purse-seine fleets, national scientists, tRFMOs and organizations such as the International Sustainable Seafood Foundation (ISSF) have allowed the rapid adoption of mitigation measures. This was the case for non-entangling dFADs[40], best practices guidelines for the release of sensitive species[41–43], exhaustive observer coverage[44,45] and dFAD management plans[46], which are all

required for ISSF-participating fishing companies if they wish tuna from their fishing vessels to be accepted by ISSF member canneries. A similar approach could be used to address dFAD loss, using the fulcrums of the ISSF, Marine Stewardship Council certification and European Union (EU) environmental regulations to extend the commitments already made by some of the fleets (for example regarding data availability and tests of recovery mechanisms) to other fleets and other areas, and therefore rapidly transform industry behaviour for the benefit of all.

Methods

Data sources and analysis tools. This paper is based on a combination of EU purse-seine fishing effort data from 2012 to 2018, which we used to define core fishing grounds, and data on the trajectories of dFAD tracking buoys deployed by French and French-associated vessels over the same time period, which we used to identify where and when dFADs drift outside fishing zones. EU purse-seine fishing effort data were obtained from public catch-effort datasets available from the IOTC[47] and the International Commission for the Conservation of Atlantic Tunas[48]. We used EU (including French, Spanish, Italian and Mayotte flagged vessels) instead of just French effort data to have the most accurate description of zones where dFADs had a notable probability of being fished upon by any purse-seine vessel. The average distribution of French fishing effort does not show strong differences from that of the entire EU, so this decision did not notably impact the results.

The GPS locations of satellite-transmitting tracking buoys attached to dFADs used by the French and associated (Mauritius, Italy, Seychelles, Belize) purse-seine and support vessels (that is, vessels that do not fish, but simply deploy and maintain a network of dFADs for other fishing vessels) operating in the Indian and Atlantic oceans are available from 2007 onward through a collaborative agreement between the French National Research Institute for Sustainable Development (IRD) and the French frozen tuna producers' organization ORTHONGEL (coverage 75–86% before 2010 and ~100% after that date[4]). Although tracking buoys can be attached to any floating object (for example, natural debris such as logs) and not just dFADs (that is, floating objects built and deployed by fishers specifically to aggregate fish), most floating objects encountered by purse seiners in recent years are dFADs (>90% based on observer data). For simplicity, we will therefore use the term 'dFAD' to refer to all types of floating objects to which tracking buoys are attached. The sampling periodicity of dFAD positions varies from approximately 15 min to 2 d, with buoys deployed during the study period typically emitting between 2 and 4 positions per day. Raw position data includes a mix of ~90% positions in the water and 10% positions onboard a vessel (for example, from transit periods preceding deployment or after recovery at sea). Onboard positions were removed so that individual buoy trajectories could be broken into a series of in-water trajectories using a Random Forest (onboard versus at sea) classification algorithm based primarily on buoy speed and speed variability[5]. dFAD in-water trajectories were defined as series of uninterrupted successive positions classified as in-water with no temporal gaps in location data exceeding 2 d. We used dFAD trajectories from 2012 to 2018. This period was chosen as a representative recent period characterized by the deployment of large numbers of dFADs for which exhaustive position information is available. This period also avoids perturbations to the fishery caused by the closure of the Chagos EEZ to fishing, Somali piracy, the introduction of echosounder buoys before 2012 and the consequences of COVID-19 in 2020 (impacting the eventual fate of some trajectories starting in 2019). This trajectory dataset consists of 97,353 Indian Ocean (in-water) trajectories representing a total of 43,047 distinct buoys and 26,839 Atlantic Ocean trajectories representing a total of 13,216 distinct buoys. dFAD trajectory data were stored in a PostgreSQL relational database (version 10.14-1) with the PostGIS extension for geospatial data (version 2.4.8). Trajectories spanning less than 2 d were removed from analyses because visual inspection of ~100 such short trajectories revealed that they were associated with errors in the in-water-onboard position classification algorithm, rapid recoveries and redeployments, or interactions with low-velocity (presumably) artisanal fishing vessels in specific coastal areas, all of which occurred almost exclusively at the very beginning or very end of much longer in-water trajectories and none of which are a concern for dFAD loss studied here. Removing these trajectories reduced the dataset to 67,412 Indian Ocean trajectories and 16,940 Atlantic Ocean trajectories (23.5% of all in-water trajectories spanned <2 d, corresponding to 0.09% of the total drift time in the dataset). Sensitivity of results to this cut-off of 2 d was examined by repeating pertinent analyses for cut-offs of 3 and 5 d (Supplementary Tables 2 and 3). Data on port locations, sizes and characteristics, which we used to assess proximity of dFADs to potential bases for recovery programmes, were obtained from the World Port Index (WPI) database provided by the National Geospatial-Intelligence Agency[49]. Statistical analyses and data visualization were carried out using R[50] with functionalities provided by the sf[51] and tmap[52] packages.

Definition of core fishing grounds. Core fishing grounds were characterized by first calculating the total number of 'fishing hours'—the standard effort unit considered to monitor purse-seine fisheries available in public-domain catch-effort

datasets—in each 1°×1° grid cell including all fish school types (free-swimming and object-associated tuna schools). Only cells with >200 fishing hours over the study period were kept as the initial basis for defining core fishing grounds. Then we removed isolated outlying cells, and filled in small gaps and irregularities in the remaining areas to produce a single, connected definition of 'core fishing grounds' for each ocean (hereafter referred to simply as 'fishing grounds' when there is no possibility for confusion; Fig. 1 and Supplementary Fig. 2). Using other cut-offs for the minimum amount of fishing effort in a grid cell (100 h and 300 h) produced only minor changes in the core fishing grounds (Supplementary Fig. 2), hence only results for the 200 h cut-off (representing 96.2% of all fishing effort, 95.3% in the Atlantic and 96.9% in the Indian Ocean) are presented in this paper.

dFAD movements to and from fishing grounds. The positions within the core fishing grounds of each dFAD in-water trajectory were classified into one of three categories on the basis of the eventual fate of the dFAD: (i) the dFAD remains in the fishing grounds throughout the remaining part of the trajectory, (ii) the dFAD leaves the fishing grounds at some point during the remaining part of the trajectory, but later drifts back into the fishing grounds and (iii) the dFAD definitively leaves the fishing grounds during the remaining part of the trajectory never to return. Areas within a fishing ground most likely to lead to a dFAD drifting away and, subsequently, being lost or stranded were identified by first breaking in-water trajectories into a series of 'passages' through individual 1°×1° grid cells of the fishing grounds (composed of all sequential positions within a given grid cell). Probability of loss (by month or over the entire study period) was then assessed on the basis of the percentages of these dFAD 'passages' for a given cell assigned to each of the three fate categories mentioned above. Since in a real dFAD recovery programme there would be no a priori way to separate buoys that leave definitively from those that leave and return, we at times grouped them together when calculating statistical results, but we kept the two categories separate in figures and for certain statistics as fishers are interested in those deployments that return to fishing areas.

Proximity to ports. For the dFADs that definitively leave core fishing grounds, the proximity of their trajectories to ports of different size categories was calculated to assess the feasibility of local recovery programmes. We calculated in each 1°×1° grid cell along the borders of the fishing grounds the proportion of those dFADs definitively leaving the fishing grounds but later passed within 50 km to a port in the WPI database. We chose the distance of 50 km to port as an approximate limit on the basis of the feasibility of dFAD recoveries within a reasonable amount of time by the medium-sized vessels likely to be used for such operations. The passages of dFADs close to ports were broken down according to port size categories (small, medium and large as recorded in the WPI database; very small ports were excluded from analyses) because size is potentially an important factor for the port to have the capacity to maintain a recovery vessel and/or be able to transport valuable dFAD components (for example, the tracking buoy, the recovery of which is a potential source of revenue for such programmes) to major purse-seine ports of call. Sensitivity of results to the size of the buffer around ports was assessed by varying the buffer distance from 10 km to 100 km.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

EU purse-seine fishing effort data were obtained from public catch-effort datasets available from the Indian Ocean Tuna Commission (https://iotc.org/data/datasets/latest/CESurface) and the International Commission for the Conservation of Atlantic Tunas (https://iccat.int/en/accesingdb.html).
Data on port locations, sizes and characteristics used in this paper were obtained from the World Port Index (WPI) database provided by the National Geospatial-Intelligence Agency (https://msi.nga.mil/Publications/WPI).
Given the confidential nature of the dFAD trajectory data used in this paper, requests for data access should be addressed directly to the Ob7 (https://www.ob7.ird.fr/) pelagic ecosystem observatory using the email address: adm-dblp@ird.fr.

Code availability

All data analyses and visualization scripts are available as an Rmarkdown document by request to the corresponding author.

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Author contributions

T.I., C.L. and D.M.K. designed the study with significant advice and input from E.C.; T.I. and D.M.K. had primary responsibility for data collection, analyses and manuscript preparation; A.M. and M.G. provided insight on industry response to and potential buy-in for dFAD recovery programmes, and also provided feedback on the manuscript as a whole.

Competing interests

All of the authors work for institutions that benefit from and work towards the sustainability of the tropical tuna purse-seine fisheries of the Indian and Atlantic oceans. The MARBEC laboratory at which T.I., C.L. and D.M.K. work has primary data management responsibility for fisheries data produced by French tropical tuna purse-seine fisheries and has a long history of contributing to the management of tuna fisheries. E.C. works for the IOTC, the regional fisheries management organization that is responsible for managing tuna fisheries in the Indian Ocean. A.M. and M.G. work for ORTHONGEL, an NGO representing the French tropical tuna purse-seine fishing industry.

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Software and code

Policy information about availability of computer code

Data collection	PostgreSQL relational database (version 10.14-1) with the PostGIS extension for geospatial data (version 2.4.8).
Data analysis	R (R Core Team, 2021) with functionalities provided by the sf (Pebesma, 2018) and tmap (Tennekes, 2018) packages.

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EU purse-seine fishing effort data were obtained from public catch-effort datasets available from the Indian Ocean Tuna Commission (https://iotc.org/data/datasets/latest/CESurface) and the International Commission for the Conservation of Atlantic Tunas (https://iccat.int/Data/t2ce_PS91-18_bySchool.7z).
Data on port locations, sizes and characteristics used in this paper were obtained from the World Port Index (WPI) database provided by the National Geospatial-Intelligence Agency (https://msi.nga.mil/Publications/WPI).
Given the confidential nature of the dFAD trajectory data used in this paper, requests for data access should be addressed directly to the Ob7 (https://www.ob7.ird.fr/en) pelagic ecosystem observatory using the following email address: adm-dblp@ird.fr.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We analyzed dFAD trajectories in the Indian and Atlantic Oceans from 2012–2018 to assess loss of dFADs from core fishing grounds.
Research sample	>80,000 dFAD trajectories (56,263 tracking buoys) in the Indian and Atlantic Oceans from 2012–2018 for the French tropical tuna purse seine fleet.
Sampling strategy	All available data over the study period was used.
Data collection	dFAD trajectory data were made available to the IRD/MARBEC from 2007 onward through a collaborative agreement between the French National Research Institute for Sustainable Development (IRD) and the French frozen tuna producers' organization ORTHONGEL
Timing and spatial scale	2012-2018; tropical Atlantic and Indian Oceans
Data exclusions	Data were classified using a random forest classification algorithm to remove onboard positions and the resulting in water trajectories were limited to those >2 days in length to remove small trajectories created by classification errors at the beginning and end of much larger in water trajectories.
Reproducibility	All code for analyses is contained in a single Rmarkdown document.
Randomization	All trajectory data were used and there was no need for randomization.
Blinding	Not relevant for the type of trajectory and fishing effort data being analyzed.

Did the study involve field work? ☐ Yes ☒ No

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