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POTENTIAL ENVIRONMENTAL IMPACTS CAUSED BY BEACHING OF DRIFTING FISH AGGREGATING DEVICES AND IDENTIFICATION OF MANAGEMENT SOLUTIONS AND UNCERTAINTIES

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SUMMARY

Drifting fish aggregating devices (dFADs) are widely used in tropical tuna purse seine fisheries to aggregate fish and make them easier to catch. The use of dFADs has been associated with a number of potential positive and negative impacts, touching on a range of ecological, economic and social issues. One negative environmental impact of dFADs is that they have the potential to wash ashore and become grounded or beached, potentially causing damage to marine habitats. However, other than anecdotal reports, this issue has received very little research attention to date. The lack of research on this topic means that the problem of beaching dFADs is not well defined, with the risk of beaching events mostly assumed and the extent and severity of impacts uncertain. The aim of this paper is to better characterise the potential problem of beaching dFADs. We examine the potential for dFAD beaching events to occur, which is determined by location of deployment, dispersal patterns, extent of efforts to prevent beaching events from occurring and, to a lesser extent, dFAD design. This discussion is illustrated with a case study examining the spatio-temporal dynamics of dFAD trajectories in the Indian Ocean and estimating the frequency of dFAD beaching events on coral reefs. The potential environmental impacts of beached dFADs are reviewed by looking at wider literature on other abandoned, lost, or otherwise discarded fishing gear, and we offer some thoughts on the classification of dFADs as marine pollution. Finally, we critically discuss a number of possible ways to reduce the number of dFAD beaching events on sensitive marine habitats. This includes regulatory measures, which would be applied by the tropical tuna Regional Fisheries Management Organisations or coastal and island state governments and advances in dFAD design, which would likely come from collaboration between fishing companies, researchers and NGOs/non-profit partnerships. Possible measures include reducing the overall number of dFADs in the water, i.e. though deployment limits, fee structures and reduced fleet capacity, or a localised reduction of dFAD deployments in sensitive areas; reduced lifetime of dFADs, through use of entirely bio-degradable materials; and the prevention of dFADs entering areas with sensitive habitats, through recovery initiatives (at sea and inshore) and innovative dFAD design.

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1. Introduction

Drifting fish aggregating devices (dFADs) are widely used in tropical tuna purse seine fisheries to aggregate fish and make them easier to catch. A typical dFAD has a floating element, usually a bamboo raft or plastic float, and a subsurface structure, usually old fishing netting or rope, around which fish associate in schools. Almost all modern dFADs are fitted with instrumented buoys that contain a GPS unit, which allows it to be tracked remotely. At any given moment a skipper can monitor the location of many tens, or even hundreds, of dFADs in real time. The most recent generation of dFADs are also fitted with echo-sounders that transmit biomass estimates and sometimes size composition of an associated school swimming beneath it, and in some oceans[6], auxiliary 'supply' vessels are used to manage the network of dFADs belonging to one or more purse seiners (Ramos et al., 2010; Assan et al., 2015).

Fishers typically deploy dFADs at the edge of major ocean current systems and allow them to drift for a period of weeks or months before catching tuna schools aggregated beneath them. Historically, dFADs were used to increase the number of naturally occurring floating objects in the ocean and boost fishing opportunities, although some fleets have now become reliant on dFADs to achieve the very large catches needed to remain profitable (Guillotreau et al., 2011; Davies et al., 2014). As a result, the number of dFADs in the ocean has increased considerably in the past 30 years (Fonteneau et al., 2013; Maufroy et al., 2017).

The use of dFADs has been associated with a number of potential positive and negative impacts, touching on a range of ecological, economic and social issues (for a recent review see MRAG, 2017). One negative environmental impact of dFADs is they have the potential to wash ashore and become grounded or beached[7], potentially causing damage to marine habitats. Other than anecdotal reports (e.g. Stelfox et al., 2015), this issue has received very little research attention to date. On the occurrence of observed dFAD beaching events, Balderson and Martin (2015) present a detailed investigation into the location, characteristics and source of beached dFADs in Seychelles. They show categorically that dFADs used by fleets in the region are washing ashore, and that coral reefs are the most impacted habitat, with dFAD sub-surface structure becoming entangled on reef structure. However, their study did not attempt to quantify the damage caused to habitat during entanglement. From a different perspective, and using a large dataset of GPS buoy positions, Maufroy et al. (2015) estimated that almost 10% of all dFADs deployed by French vessels in the Indian and Atlantic Oceans ultimately became beached. In the Atlantic, dFAD beaching events were concentrated along the coastline of the Gulf of Guinea, adjacent to the main purse seine fishing grounds, although some travelled much further and stranded on the Brazilian coastline. In the Indian Ocean, beaching events occurred more widely, with most events observed in Somalia, the Seychelles, the Maldives, and Sri Lanka. Beaching events were also observed in the British Indian Ocean Territory (BIOT) marine protected area.

The lack of research on this topic means that the problem of beaching dFADs is not well defined, with the risk of dFADs beaching events being mostly assumed and the extent and severity of beaching impacts uncertain. The aim of this paper is to better characterise the potential problem of beaching dFADs. Three specific objectives are:

- To discuss the potential for beaching events to occur, to characterise beaching risk and to identify knowledge gaps. We illustrate this discussion with a case study examining the spatio-temporal dynamics of dFAD dispersal in the Indian Ocean, specifically estimating the probability of dFAD beaching events on coral reefs;
- To examine the potential environmental impacts of dFAD beaching in terms of physical damage to coral reef and other shallow water habitats; and
- To identify and critically discuss possible approaches to managing the issue of beaching dFADs.

The focus of this paper is on dFADs, although it is noted that anchored FADs can escape their mooring and also have potential to cause damage to marine habitats. However, management options for minimising habitat damage caused by anchored FADs are likely to be more straightforward than for dFADs, and there is presumably a greater incentive for anchored FAD owners to reduce incidences of loss. Furthermore, the

[6] With the exception of the Eastern Pacific Ocean where supply vessels were banned from 1999.
[7] For the purpose of simplicity, this is hereafter referred to as beaching, but while recognising that dFADs may wash up or become entangled in many different shallow water habitat types.

impacts of sinking dFADs on deep water habitats (e.g. >100m) it not considered, although future research on this sub-topic is encouraged. There is also likely to be considerably fewer anchored FADs deployed in the oceans than dFADs (MRAG, 2017).

2. Potential for beaching events to occur

The risk of a dFAD beaching event occurring is determined by the number of dFADs in the ocean, the deployment location, dispersal patterns, the extent of efforts to prevent beaching events from occurring and dFAD design. Each of these different elements of risk are discussed below.

2.1. How many dFADs are in the ocean?

The number of dFADs in the ocean at any given time is not known with certainty. It has been estimated that between 81,000 and 121,000 dFADs were deployed globally in 2013, although this estimate is uncertain due to the need to make assumptions on dFAD usage between fleets and extrapolation to fill data gaps (Gershman et al., 2015). The total number of dFADs deployed varies between the tropical tuna Regional Fisheries Management Organisation (tRFMO) convention areas. Using the estimates of Gershman et al., the highest number of dFADs are deployed annually in the WCPFC area (36.9% total global deployments), followed by IATTC (23.6%), ICCAT (21.5%) and IOTC (18.0%). The differences between these regions are broadly consistent with differences in the size of purse seine fleets (A. Fonteneau, unpublished data), but also reflect variation in the relative use of dFADs by vessels (i.e. disproportionately high use of dFADs in the Atlantic and Indian Oceans). In term of trends, the number of sets made on dFADs (and other floating objects) has been increasing in all regions with the exception of the WCFPC area, where it has levelled out (Fonteneau et al., 2013; Gershman et al., 2015; WCPFC, 2015; Hall and Román, 2016).

The number of dFADs in the ocean is also determined by the number that are lost (beached, sunk or stolen but not redeployed) or recovered. This is more difficult to estimate than deployments because most dFADs that become lost (e.g. become waterlogged and sink), do so without trace, and there has been no obligation to record the recovery of dFADs. However, some national dFAD management plans, which are required by all tRFMOs, do require information on lost FADs to be recorded. For example, Spain and Korea require that the last location of the dFAD is recorded, and France requires that the number of lost dFADs is reported quarterly.[8]

2.2. What factors determine how many dFADs may beach?

The chance that any given dFAD will become beached, assuming for the moment it will not be recovered or sink, depends on the ocean region, the time and location of its deployment, and to a lesser extent, the depth of its subsurface structure and the material it is made from.

The pattern of ocean currents in some regions may moderate the risk of a dFAD beaching. The direction and speed of movement of a dFAD on the ocean surface is driven primarily by surface currents, but also by wind and wave action. The density of dFADs in an ocean region is therefore not uniform, and dFADs tend to accumulate along current fronts and in circulation systems (Dagorn et al., 2013; Maufroy et al., 2015). In ocean regions where these currents systems are strong, such as in northwest Indian Ocean, dFADs tend to get trapped inside ocean gyres and away from coastline and islands. This may reduce the risk of beaching to a certain extent if dFADs are lost or recovered while in these contained systems. However, such retention within current systems is usually only temporary, and many dFADs do eventually drift away and may disperse widely (e.g. see Maufroy et al., 2015)

The chance of a beaching event is likely to be considerably higher when a dFAD is deployed into a current system that passes through an island archipelago or along a coastline. For example, in the eastern Pacific Ocean fishers deploy dFADs to the east of the Galapagos into a westerly current that carries them directly through archipelago (Hall and Román, 2016), where they risk beaching as they pass close to shore and over shallow marine habitats.

2.3. Case study: simulated dFAD beaching events in the Indian Ocean

Here we present a case study to illustrate the discussion on dFAD beaching risk by examining the spatio-temporal dynamics of dFAD dispersal in the Indian Ocean and estimating the probability of dFAD

[8] http://iotc.org/documents/fad-management-plans

beaching events on coral reefs in the region. The methods and results of this case stud analysis are presented below.

2.3.1. Material and methods

We used a Lagrangian transport model to simulate trajectories of dFADs deployed within the purse seine fishing grounds of the western Indian Ocean during 2006-2014 in order to evaluate the risk of beaching events on coral reefs. Ichthyop[9] is a Lagrangian tool distributed as a free Java software and offline simulations are conducted using surface currents available from hydrodynamic models or satellite remote sensing (Lett et al., 2008). In the present study, all simulations of dFAD drift were run using the Ocean Surface Currents Analyses Realtime (OSCAR) current data set accessible through OpenDAP protocol.[10] We used the 1/3-degree grid and 5-day interval resolution of the OSCAR data which have been shown to well describe the drift of FADs in near-surface currents of the Indian Ocean (Imzilen et al., submitted).

The dFAD purse seine fishery of the Indian Ocean is marked by a strong seasonality related to monsoon regimes (Davies et al., 2014; Kaplan et al., 2014). Areas of GPS buoy deployments have been shown to be highly correlated in time with FAD fishing grounds (Maufroy et al., 2017). Here, four distinct periods of GPS buoy deployments were considered to encompass the main patterns of seasonality of dFAD deployments at sea: (i) November-February, (ii) March-May, (iii) June-July and (iv) August-October (Maufroy et al., 2017). A buffer area of 200 km around the hotspots of dFAD deployment activities was used to introduce some spatial variability in the location of deployment within each season (Figure 1).

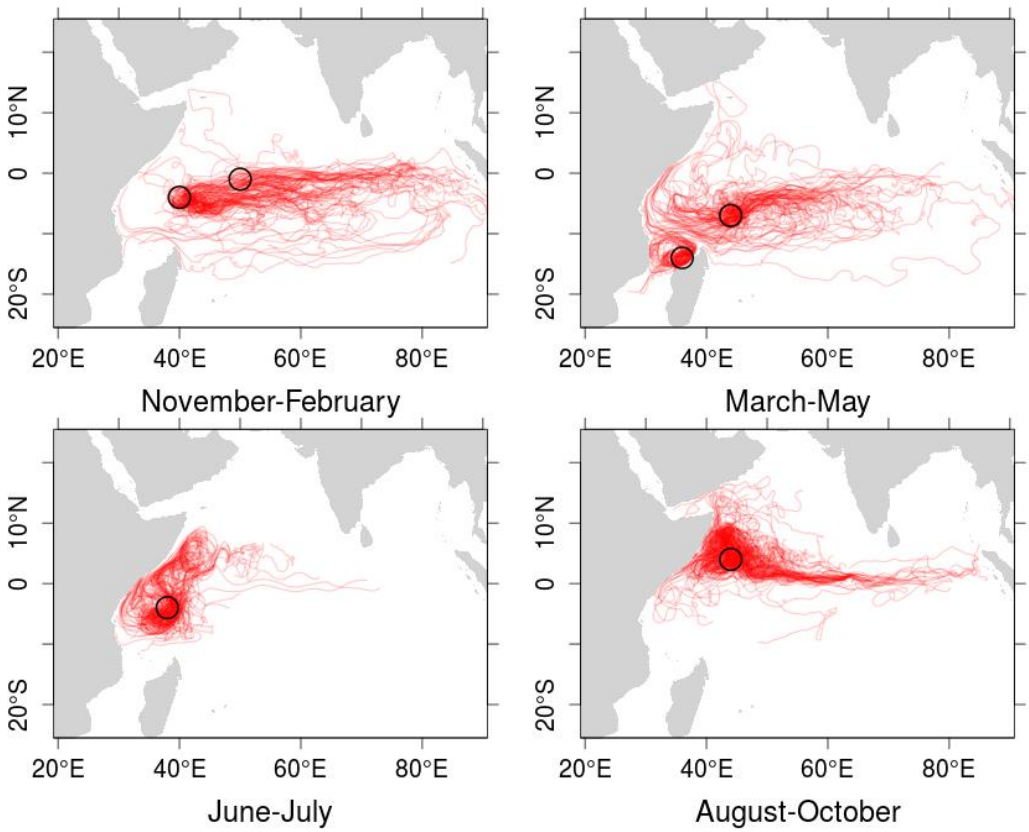

Figure 1 Observed long drifts (≥ 1 month) of floating objects equipped with French-owned GPS buoys and deployed during 2006-2014 within the seasonal hotspots of dFAD deployment activities (black circles) in the western Indian Ocean identified by Maufroy et al. (2017).

[9] http://www.ichthyop.org
[10] http://www.oscar.noaa.gov

A set of 10 GPS buoy deployments was randomly selected among all deployments of French-owned GPS buoys observed within each season-specific buffer area during 2006-2014 (Maufroy et al., 2017). Selecting real deployments as starting points of the simulations allowed for assessment of the overall consistency of the simulations by overlaying observed dFAD trajectories with simulated drifts. The simulated duration of drift was set at 180 days since the great majority of dFADs have been shown to spend less than 100 days at sea in the Indian Ocean (Maufroy et al., 2015). For each of the 40 deployments (10 deployments x 4 seasons), 1000 simulations were conducted to account for uncertainties in ocean surface currents derived from OSCAR. Stochasticity in model runs was introduced through the means of horizontal dispersion implemented in Ichthyop through a horizontal diffusion coefficient (Peliz et al., 2007; Lett et al., 2008). All simulation results are provided for each season in Appendix I.

To illustrate the utility of the approach, the probability of dFAD beaching and stranding in western Indian Ocean coral reefs was computed as the proportion of simulated trajectories intersecting with the coral reefs of BIOT, Comoros, Maldives, and Seychelles. Shapefiles for these coral reefs were obtained from the UNEP World Conservation Monitoring Centre.[11] Estimates should be seen as conservative as model simulations assumed that no sinking nor retrieval of the dFAD occurred during the period of drift. Also, dFAD transport was simulated all along the period even in the case of a beaching or stranding event, potentially resulting in a dFAD being beached or stranded several times in the course of the simulation.

2.3.2. Results

Our simulations show that risk and location of dFAD beaching events are strongly dependent on areas and periods of deployment. Risks of beaching estimated as the proportion of six-month duration simulations intersecting with coral reef coverage of BIOT, Comoros, Maldives, and Seychelles are overall high (overall mean of 32.3%), with a large variability between seasons and simulations. Seychelles' coral reefs appear particularly exposed to dFAD beaching because of their prominent position within the main fishing grounds of the purse seine fleet. Simulations spanning six months result in a large variability of trajectories and final positions of dFADs (Figure S1). Horizontal dispersion modelled in Ichthyop resulted in some dFADs - deployed on the same day at the same position - to be transported along different currents and described by trajectories that diverged over time.

Overall, our simulations of dFAD dispersal are consistent with trajectories of floating objects observed from GPS buoy data (Figure S1). A few simulations however appear not able to capture the drift observed, e.g. simulation 19 which corresponds to a buoy deployed in April 2014 that drifted to the north of the western Indian Ocean before reaching the coast of Yemen (Figure S1b). Similarly, all runs of simulation 38 suggest a potential drift along the coasts of Somalia and Oman while the buoy deployed at the starting point of this simulation in October 2012 crossed the Indian Ocean and stopped emitting after having reached the north of Sumatra (Fig. S1d).

Simulations show that most dFADs deployed around the Seychelles in November-February tend to drift toward the eastern Indian Ocean along the South Equatorial Countercurrent, which predominates during the winter monsoon (Figure S1a) (Schott et al., 2009). In such case, dFADs appear to slip along between the Maldives and BIOT coral reefs and the overall proportion of trajectories intersecting with these coral reef areas was estimated to be low at around 4.7%. Some simulations, however, resulted in higher probability of beaching, i.e. simulation 3 resulting in 18.7% probability of beaching in the Maldives and simulation 6 resulting in 14.2% probability of beaching in BIOT (Figure S1a). During March-May, simulated deployments of dFADs around the Seychelles resulted in the floating objects to first drift toward the east before making a loop south and start drifting toward the north of the Mozambique Channel (Figure S1b). In March-May, the probability of dFAD beaching in the coral reefs of BIOT and Maldives was estimated to be very low at 0.4%. By contrast, coral reefs of the Seychelles and Comoros were the most exposed during this deployment season with an overall probability of beaching of 45%. Most simulations conducted for the season June-July showed a concentration of the drifts in the central western part of the WIO, along the coasts of Tanzania, Kenya and Mozambique, associated with a risk of beaching of about 10%, mostly in Seychelles coral reefs. Finally, deployments of dFADs off the coast of Somalia during August-October was associated with a high risk of beaching in the Maldives (overall probability of 29%) in relation with the Great Whirl gyre, which is active during the summer monsoon (Schott et al. 2009). It is noteworthy that the lifespan of buoys and dFADs during August-October in the

[11] http://data.unep-wcmc.org/datasets/1

Somalia area is low (mean = 15 days at sea) as it is the main dFAD fishing season characterized by a high turnover of the rafts and buoys which can be collected and redeployed elsewhere.

Our results must be seen as part of a modelling exercise and a first step to propose tools for predicting risk associated with time-areas of dFAD deployment. In particular, areas of particle release (i.e. deployments) were limited in this case study to small areas derived from the analysis of GPS buoys for only one segment of the purse seine fishing fleet of the Indian Ocean. Support vessels have been shown to deploy dFADs in areas outside fishing grounds so as to anticipate their drift expected to last from a few weeks to a few months to aggregate tuna (Assan et al., 2015). Information on periods and areas of dFAD deployments for the whole fishery (including supply vessels) is crucial to study the dynamics of dFADs at ocean scale. Also, an arbitrary choice of 10 distinct positions of deployment and 1000 simulations accounting for horizontal dispersion was made for each season while this may have a strong impact on our results. Future work will focus on optimizing the simulation scenarios to assess the robustness of the results to such parameters. Considering currents of higher resolution available from oceanographic models might be required, particularly in areas such as the Mozambique Channel characterized by complex mesoscale and sub-mesoscale oceanographic features (Hancke et al., 2014). Finally, the use of climatology of ocean currents (i.e. mean over several years) should be considered for predictions to reduce annual variability and uncertainties associated with global products such as OSCAR.

3. Potential environmental impacts of beached dFADs

The beaching of dFADs has the potential to cause physical impacts to marine habitats, although these are not well documented. There is also a question of whether dFADs, which are primarily constructed from non-biodegradable materials, constitute marine pollution. These two separate issues are explored below.

3.1. Physical impacts of dFAD beaching to marine habitats

To date, research on the environmental impact of dFADs has primarily focused on either the consequences of an increased capture of juvenile tunas (Dagorn et al., 2013; Fonteneau et al., 2015) or the entanglement of pelagic species within the dFAD structure (Filmalter et al., 2013; Blasi et al., 2016). While the impact of this beaching is not well documented or understood, analogous studies on other abandoned, lost, or otherwise discarded fishing gear (ALDFG) could highlight the likely impacts caused by beached dFADs.

Old fishing nets are a common material used in dFAD construction and previous studies have shown ALDFG nets to entangle significant numbers of animals, a process termed 'ghost-fishing' (Laist, 1997; Stelfox et al., 2016). As ALDFG nets age, catch rates have been shown to decline (Revill and Dunlin, 2003; Tschernij and Larsson, 2003), possibly due to bio-fouling making nets more visible (Revill and Dunlin, 2003) or because bio-foul eventually weighs nets down, causing them to lose vertical height and come to rest on the sea floor where they have little to no fishing ability (Baeta et al., 2009). However, this is likely to be variable by habitat. For example, nets in shallow sandy bottom habitats may follow this pattern, yet nets caught on rocky bottoms, structures, or reefs could tear and form larger holes for larger animals to become entangled thus altering the catch selectivity of the net (Stelfox et al., 2016). In addition, ALDFG material may get colonised by smaller animals looking for food and shelter, which in turn could attract larger predators that may become entangled, potentially prolonging the fishing effect (Carr, 1987). Ghost fishing may be particularly damaging if it occurs in important foraging, spawning and nesting grounds, or if it intercepts migration routes (Gilman et al., 2010).

The design and nature of dFADs is widely variable but usually consist of sub-surface aggregating material made of old fishing nets tethered to a floating surface frame. Where nets are used, it is likely that monofilament nets are likely to have greater ghost fishing capacity. This is due to the higher visibility of the multifilament nets (Ayaz et al., 2006). Driven by concerns over shark and turtle entanglement within these nets, there has been a move towards changing dFAD designs to reduce entanglement (for details see MRAG, 2017). These consist of using smaller mesh sizes and replacing the sub-surface net curtains with rolled net 'sausages' (Franco et al., 2009; Balderson and Martin, 2015). However, these 'sausages' have been shown to unravel, questioning their efficacy at reducing entanglement rates. In addition, 'sausage' nets do not prevent the entanglement of corals, although dFADs built with synthetic rope appear to be less likely to become entangled (Balderson & Martin 2015). These factors have led to organisations, such as the International Seafood Sustainability Foundation (ISSF), calling for the term 'non-entangling' dFADs to be reserved for solely for those that contain no netting throughout their construction (ISSF, 2015).

Figure 2 Examples of dFADs beaching events in British Indian Ocean Territory marine protected area: subsurface netting entangled on coral (left) and washed ashore (right) Photos: D. Curnick/ZSL; T. Franklin/MRAG Ltd.

ALDFG has also been shown to degrade benthic habitats (Macfadyen et al., 2009), such as coral reefs as nets are prone to snagging on rocks, sponges and corals. Once snagged, the wind and wave forces exerted on the net may break away from the reef, damaging habitat in the process (Donohue et al., 2001). Fishing gear is then free to snag on another coral and thus the process repeats itself. Depending on the species and size of coral colonies, it may take long periods for the reef to recover from intense physical trauma as corals grow between 0.4-1.5 cm per year for massive species and up to 20 cm per year for branching species (e.g. Crabbe and Smith, 2005). Recovery from other physical traumas have been estimated at between five and ten years to recover from blast fishing (Fox and Caldwell, 2006), or ten (Connell, 1997) to 40-70 years (Dollar and Tribble, 1993) to recover from storm damage. In some cases, recovery can then follow a different trajectory and the reef becomes an altered community (Hughes et al., 2005). It is difficult to ascertain the impact of nets on other habitats, such as seagrasses, as few have studied the impact of ALDFG. However, seagrass growth is known to be very slow, 0.4-7.4 cm per year (Boudouresque and Jeudy de Grissac, 1983), and previous studies have shown that seagrass communities take can between 1.4-9.5 years to recover from mechanical scarring from boats (Kenworthy et al., 2002).

However, the impact of ALDFG is not restricted to the sub-tidal zone. If the ALDFG is not caught within an ocean gyre or caught on the benthos, then it will most likely come to rest along coastal beaches and shorelines. In some areas, ALDFG can account for more than half of the litter found on beaches (Hong et al., 2014). Beached litter can have both economic and ecological consequences. For example, beach litter may reduce a beach's aesthetic appeal to tourists and possibly reduce visitor numbers. Alternatively, litter can form a significant proportion of sea-bird nest building material (Schernewski et al., 2017; Votier et al., 2011) and can negatively affect turtle hatchlings trying to reach the sea (Özdilek et al., 2006).

3.2. Are dFADs categorised as marine pollution?

Most dFADs are constructed from non-biodegradable materials, including nylon, polyethylene, metal, plastics and electronic components (Figure 3). These materials typically degrade very slowly, often only break up into smaller pieces through mechanical action, and have the potential to pollute the marine environment. Synthetic materials such as these can then enter food-webs through ingestion by plankton (Setälä et al., 2014), turtles (Schuyler et al., 2012) and corals (Hall et al., 2015), potential severely inhibiting animal fitness (Wright et al., 2013). In addition to this chemical pollution, ALDFGs also have the potential to biologically pollute ecosystems through the transportation of invasive species which can disrupt community structure and cause local extirpations of native species (Derraik, 2002; Macfadyen et al., 2009).

Figure 3 Examples of different dFAD designs and construction materials used in the Indian and Atlantic Oceans. Materials used on the frame include bamboo (left), plastic tubing (middle) and metal tubing (right). Photos: E. Chassot – IRD; KR-C Kouakou - IRD/ORTHONGEL; Anon – IRD.

There is no clear consensus on whether dFADs breach international laws on marine pollution as it is difficult to define when it has become ALFDG. If a dFAD was deliberately discarded this would likely violate MARPOL Annex V, and would also likely contravene the London Convention, although the question of intentional discarding is complex and difficult to resolve. For instance, should a dFAD be considered as abandoned when it is no longer being used by a fisher? If so, at what point might that be, given that dFADs may be disregarded temporarily when they leave fishing grounds but tracked once again when they drift back in? Or, if a dFAD is considered as abandoned when its GPS buoy is detached, how should a dFAD deployed without a GPS buoy be classified? The definition is complicated further still by the frequent 'stealing' of dFADs at sea, when the GPS buoy belonging to one vessel is removed and replaced with another from the new vessel. Does the dFAD itself also change ownership, from a legal perspective?

Clearly the use of dFADs is subjective and the issue of abandonment is open to interpretation. In 2013, IOTC did not adopt a resolution proposed by EU-France to prohibit the abandonment of dFADs, presumably due in part to these uncertainties, and instead agreed that measures should be included in dFAD management plans of individual members. The issue of marine pollution is not a priority of tRFMOs, and indeed may be argued to fall outside the scope of international fisheries management, and consequently these questions may only be properly addressed when a legal case is brought against fishing companies.

4. Possible options for reducing dFAD beaching events

There are a number of possible ways to reduce the number of dFAD beaching events on sensitive marine habitats. This includes 1) regulatory measures, which would be applied by the tRFMOs or coastal and island state governments; 2) advances in dFAD design, which would likely come from collaboration between fishing companies, researchers and NGOs/non-profit partnerships; and 3) economic and market incentives, including penalties, which would be responded to by fishing companies and/or fishers. In this paper we focus only on regulatory measures and advances in dFAD design, although we encourage further discussion on the range of possible economic and market incentives (e.g. 'FAD-free' tuna produce) that could lead to a reduction in dFAD use. There may also be ways to minimise the severity of the impacts caused by a beached dFAD, such as using materials that cause minimal abrasion or that break apart easily. This may be an interesting avenue for research, with possible overlaps with current efforts to develop biodegradable dFADs, although is not discussed further here.

4.1. Fewer dFADs in the water

Fewer dFADs deployed and at liberty in the oceans would, following the law of averages, reduce the frequency of beaching events. This could be a reduction in dFAD numbers overall, or a localised reduction in dFAD deployments in areas with the highest risk of beaching events occurring.

4.1.1. Overall reduction in dFAD numbers

The concept of limits imposed by tRFMOs on the use of dFADs or on the capacity of purse seine fleets has been the subject of wider discussions on the sustainability of tropical tuna fisheries (Davies et al., 2014; Fonteneau et al., 2015; MRAG, 2017). We do not attempt to reproduce these discussions here, but pick out a number of possible management measures that would in theory reduce the number of dFADs in the

ocean. We also note that, to date, three tRFMOs have implemented limits on dFAD use, either on the number of GPS buoys that can be actively monitored (IOTC and ICCAT) or the number of sets made on dFADs (WCPFC); however, none of these limits directly place a cap on the number of dFADs that can be deployed.

Deployment limits

Setting a limit on the number of dFADs that can be deployed per vessel in a given period (e.g. year, month) would directly restrict the number of dFADs entering in the oceans. Compliance with such a measure would require monitoring by observers, either on board or using an electronic monitoring system (EMS). Alternatively, dFAD deployments could be monitored by contracting parties and non-contracting parties (CPCs) or tRFMOs directly using data provided by satellite tracking companies. However, to ensure accurate accounting, any deployment limit monitored remotely in this way would need to be accompanied by the additional requirement that all dFADs are deployed with an activated GPS buoy. Again, compliance with this would need to be carefully monitored by fishery observers.

A challenge to this system, at least from the perspective of some fleet owners, is if and how to allow for replacement of dFADs that are lost at sea. Maintaining a predetermined maximum number of dFADs in the ocean would require a coordinated monitoring and accounting system along the lines of that described above, i.e. every dFAD is deployed with a GPS buoy, and, when the a vessel's deployment limit is reached, a replacement dFAD can be deployed only when it can be proven from tracking data that a previously deployed dFAD has been lost. This could be administered by fishing companies, but would require agreement within tRFMOs on when a dFAD is considered as lost and the protocol to establish this from GPS data. There would also need to be agreed standards for reporting initial and replacement dFAD deployments to allow for the monitoring of compliance.

Fees on FAD ownership

An alternative mechanism to reducing the total number of dFADs in use might be to introduce a fee on the deployment of dFADs beyond a pre-determined number set by the tRFMO. For instance, a vessel might be allowed to deploy 150 dFADs free of charge, but pay a fee for each additional dFAD deployed above this limit, possibly on an increasing sliding scale. This would raise the difficult question of how many dFADs should vessels be allowed to deploy for free, with fleet owners adopting a high-dFAD strategy presumably arguing for a higher limit than those with a more free school targeted strategy. The same challenges with respect to monitoring compliance and allowing for replacement dFADs would apply as described above for deployment limits.

A pay-per-dFAD model could in theory create an economic incentive against the proliferation of dFADs, or at least would encourage fishing companies to investigate the concept of an economically optimal number of dFADs for their operations. The revenue generated from deployment fees might also be used by tRFMOs to pay for dFAD recovery measures (see Section 4.3). However, such an incentive based approach may not significantly limit or reduce dFAD use if fishing companies determine that deploying additional dFAD is worth the cost.

Reduction in fleet capacity

In some regions, a reduction in the capacity of purse seine fleets – either through the number of vessels or their size – may result in an overall reduction in the use of dFADs. This is based on the observation that the use of dFADs has increased against a background of increasing fleet capacity, and that larger vessels are more dependent on high dFAD-use strategies (Davies et al., 2014). Similarly, a reduction in dFAD use may be achieved through a reduction in the number of supply vessels, which typically allow seiners to deploy and monitor a larger number of dFADs. However, this approach would only be effective assuming a linear relationship between the deployment of dFADs and the capacity of the fleet (or the number of supply vessels). While this has appears to be true for growth in dFAD use to date, at least in the Indian Ocean (Davies et al., 2014), there is a possibility that a shrinking fleet would attempt to deploy a greater number of dFADs per vessel in an attempt to maintain the number of dFADs in the water.

4.1.2. Localised reduction in dFAD deployments

Prohibiting the deployment of dFADs in certain zones and/or at certain times of the year may result in a disproportionate reduction in dFAD beaching events. This localised measure would not aim to reduce the overall number of dFADs deployed, but rather to prevent the practice (intentional or not) of deploying dFADs into areas that, due to the prevailing current systems, have a high probability of beaching on islands or coastlines. This would likely require agreement within tRFMOs on what is considered as 'high' probability (e.g. >50%, >90%). Proposed zones and time periods to prohibit dFAD deployment could be identified by analysing historical dFAD GPS tracks, or using simulation modelling that takes into account variability in oceanographic processes (see Section 2.3). It is likely that proposals for dFAD no-deployment zones would be submitted by coastal and island states that wish to reduce dFAD beaching events in their waters, although there may also be some interest from fishing companies that are seeking to reduce the risk of losing their dFADs and mitigate the environmental impacts of their operations (e.g. to achieve environmental certification standards).

4.2. Reduced lifetime of dFADs

There are currently initiatives aimed developing dFADs constructed using entirely biodegradable materials (e.g. Moreno, et al., 2016). The purpose of these initiatives is ostensibly to avoid pollution when dFADs sink or wash up in coastal areas, but biodegradable dFADs would also be expected to break apart at sea more quickly than conventional dFAD designs and therefore reduce the overall risk of beaching events occurring. However, precisely how quickly biodegradable dFADs break apart, and to what extent this will reduce the rate of beaching events, it not known and will likely depend on the materials used, the location of deployment and the ocean region. The effective working life of a dFAD is a key question in developing biodegradable designs, with fishers generally requiring a lifetime of between 5 and 12 months depending on the ocean region (Moreno, et al., 2016). With that in mind, this initiative would appear to be most relevant for those dFADs that drift for many months outside the main the fishing grounds (or the deployment locations that result in these trajectories).

4.3. Prevent dFADs entering sensitive areas

The most targeted approach to reducing the frequency of dFAD beaching events is to prevent dFADs from entering sensitive coastal areas. However, achieving this may also require particularly high investment of resources (by fishing companies, primarily) or innovative dFAD design concepts. Two possible initiatives are described below.

4.3.1. Recovery at sea

It may be possible for dFADs to be intercepted and recovered on board before they drift into coastal areas. This would be possible by real-time monitoring GPS buoy tracking data and establishing an alert system to warn of likely beaching events. The effectiveness of any such recovery initiative would likely require additional regulation on dFAD use, namely that the entire dFADs must be recovered from the water (i.e. both the GPS buoy and the raft component) and also the prohibition of GPS buoy deactivation until the dFAD is recovered. Together these measures would ensure that no dFAD structures are left in the water, and that compliance can be monitored using GPS buoy tracking data.

There are likely to be considerable practical challenges and limitations associated with this solution, including travel distances required to intercept dFADs, which types of vessel can undertake dFAD recoveries (e.g. must be equipped with crane for extraction from the water), and possibly the availability of space on board to store recovered dFADs. Realistically, fishing companies may choose to deploy specialist recovery vessels that could intercept 'rouge' dFADs, rather than task seiners or supply vessels to do this, which would likely be disruptive to fishing operations. These vessels may traverse whole ocean regions, or more likely, be based within one or more EEZs.

The geographic scope of at sea recoveries is likely to be determined by whether dFAD recovery is required by tRFMO conservation and management measures (CMMs), or established through bilateral agreements between fishing companies and individual coastal states. For the former, all potential beaching events in all areas would need to be avoided, which would present the greatest logistical challenge for fishing companies (even if a CMM specified avoidance of beaching events on sensitive habitats only). For the latter, only beaching events in certain locations would need to be avoided, and fishing companies are perhaps more likely to base recovery vessels in those countries with which they have agreements (although this may not be possible in some remote areas).

4.3.2. Recovery post-beaching

The environmental impact of dFAD beaching could be minimised by recovering dFADs that have become entangled on habitat as swiftly as possible. One such inshore recovery initiative has been launched in the Seychelles, where a part of the purse seine industry has engaged with several Seychelles-based organisations[12] to develop a 'FAD Watch' initiative for reporting and retrieving dFADs that are approaching coral habitats and have, or are likely to become, beached. The system works on a proximity alert system, with a local organisation sent the position of a GPS buoy by the tracking service provider when it enters a buffer zone around a coral reef. In theory, the dFAD is then intercepted and recovered, and brought back to land for recycling. However, in reality there have been a number of challenges in accessing remote areas, locating dFADs in the water and safely disentangling netting caught on deeper habitat (e.g. requiring diving) (Island Conservation Society, pers. comm.).

While the intention of inshore recovery initiatives may be sound, there are questions on the effectiveness of this approach in minimising environmental impact, and whether locally-run initiatives can function in all areas. The majority of the environmental damage caused by dFAD netting and rafts to sensitive habitat may occur relatively quickly, for instance within hours or days, giving only a short window of opportunity make a meaningful recovery. However, more knowledge is needed on the timeline and severity of damage to different habitat features (e.g. reef, seagrass, mangroves), and subsequent recovery rates, to better determine what an appropriate recovery response time should be. More generally, at a regional and global level, inshore recovery initiatives are likely to be very limited in their geographic scope, as in many areas it may be difficult or impossible to recover beached dFADs due to an absence of local partners, lack of human resources or equipment and/or limitations on access.

4.3.3. FAD design

These has been some experiment with dFADs constructed with deep subsurface structures (e.g. >70m), which have been shown to drift with deeper currents that do not intersect coastal (D. Itano, pers. comm.). This passive method of dFAD self-avoidance may be relatively cheap to adopt, although there may be issues with storage space on board. However, there may be unintended fishing mortality and stock management consequences associated with deeper nets, e.g. increased catch of deeper-foraging species such as bigeye (WCPFC, 2015). Also, beaching events that do occur may be more severe given there will be a greater amount of subsurface structure to become entangled with habitat.

It may be possible to design self-propelled 'smart dFADs' that are able to actively avoid shorelines and shallow atolls. These could be remote-controlled or autonomous, for example following a pre-determined course or programed with a 'coastline avoidance' protocol. There are clear design challenges associated with this concept, although it is likely that much of the hardware and technology required does already exist (e.g. propulsion devices[13], satellite communication, autonomous programing). It is also very likely that smart dFADs would have a much higher unit costs than conventional (and even biodegradable) dFADs. This increased cost would be expected to affect uptake by the purse seine industry, although it would be interesting to explore whether smart dFADs would improve efficiency, for instance by remaining in the most productive zones, and to what extent this might offset the increased unit cost.

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6. References

[12] OPAGAC has entered into an agreement with the Island Conservation Society (ICS), Islands Development Company Ltd (IDC) and Seychelles Fishing Authority (SFA)

[13] For example, Wave Glider: https://www.liquid-robotics.com/platform/how-it-works/

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Appendix I Simulations of dFAD dispersal from the main recent seasons and deployment areas of the purse seine fishing fleet operating in the western Indian Ocean

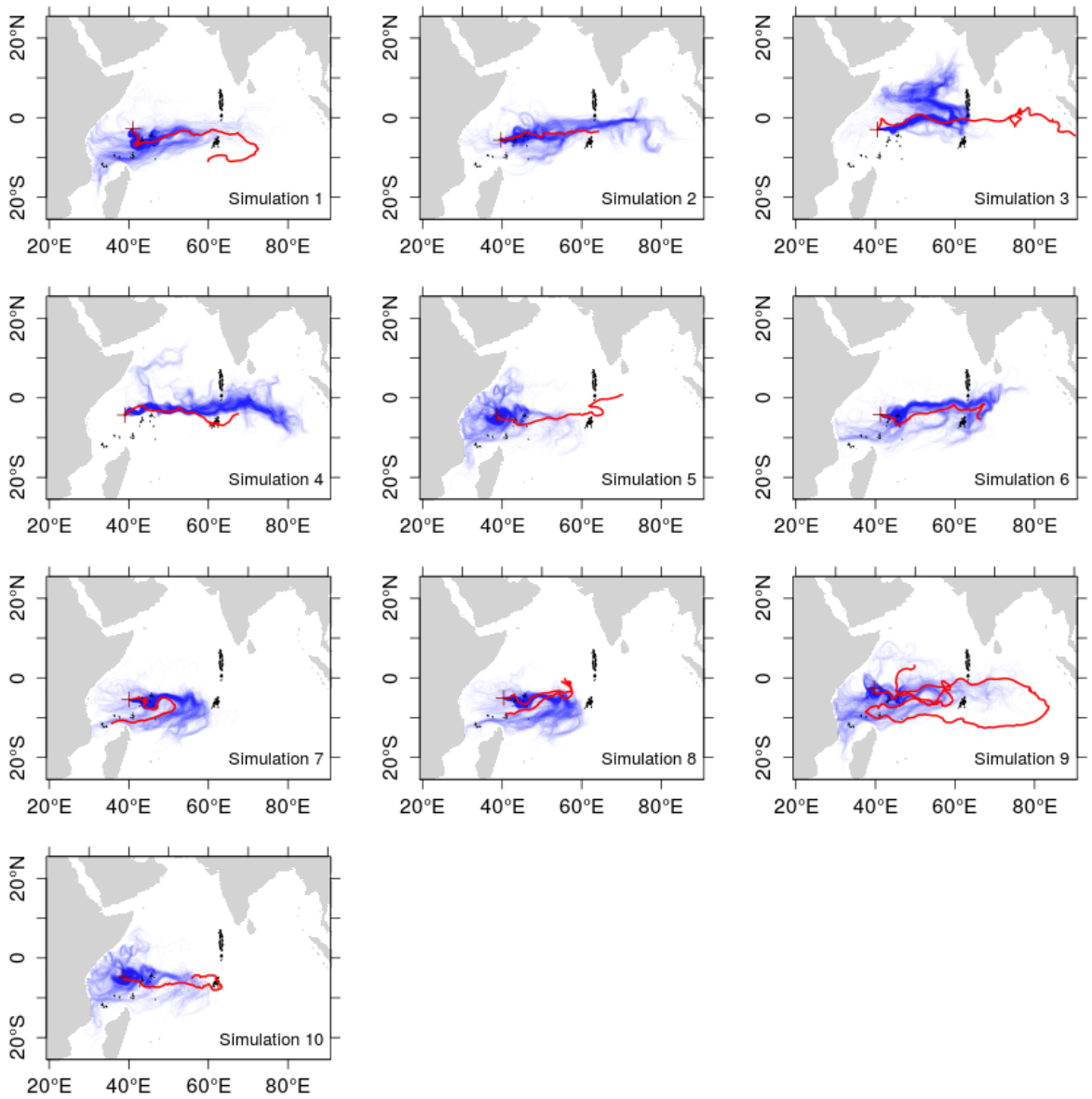

Figure S1a Simulations of dFAD trajectories (blue lines) from deployment locations (+) in the Indian Ocean in the main deployment area of the season November-February (see text for details). Red lines indicate observed trajectories of dFADs deployed at sea and black areas indicate coral reefs.

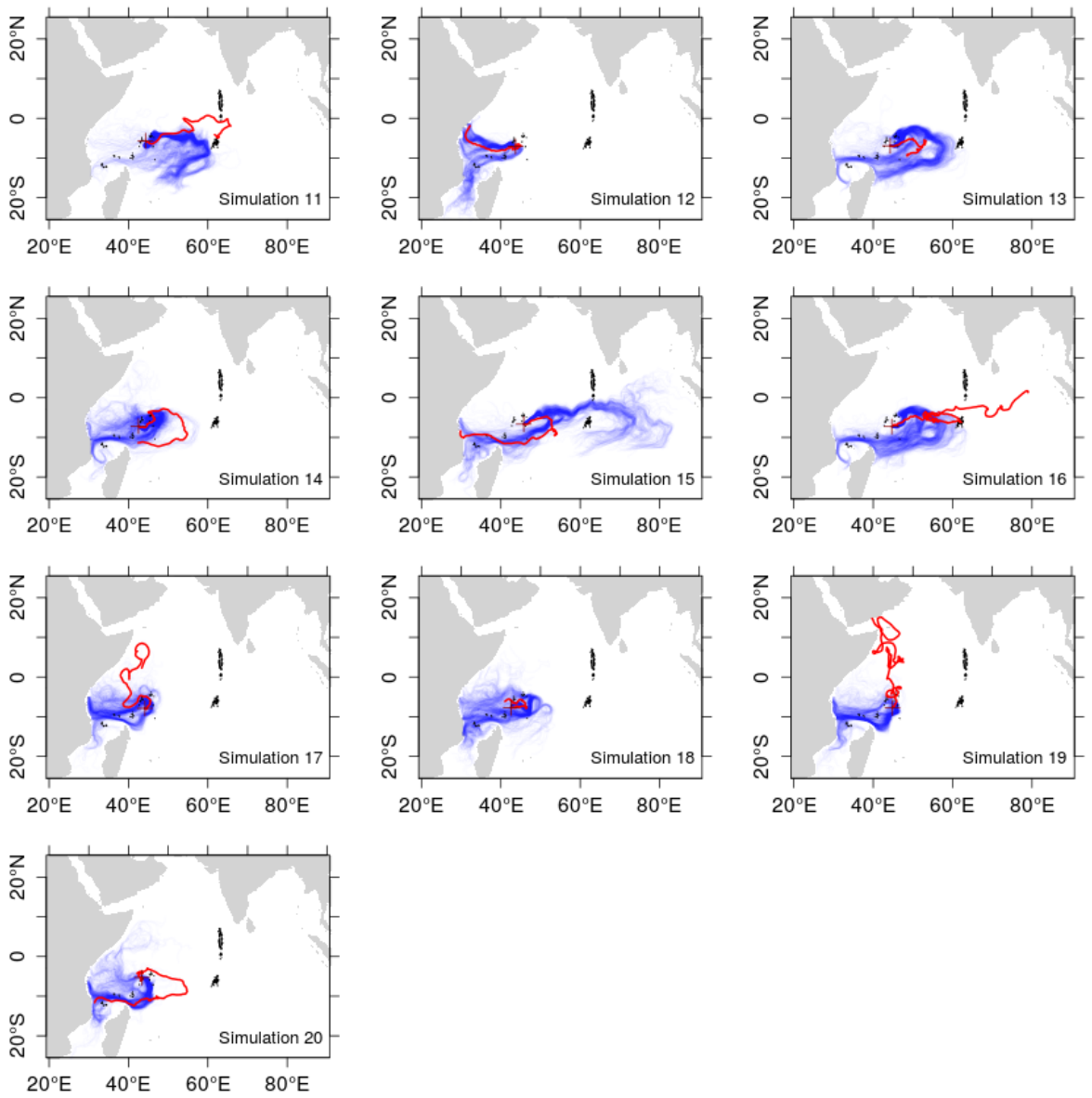

Figure S1b Simulations of dFAD trajectories (blue lines) from deployment locations (+) in the Indian Ocean in the main deployment area of the season March-May (see text for details). Red lines indicate observed trajectories of dFADs deployed at sea and black areas indicate coral reefs.

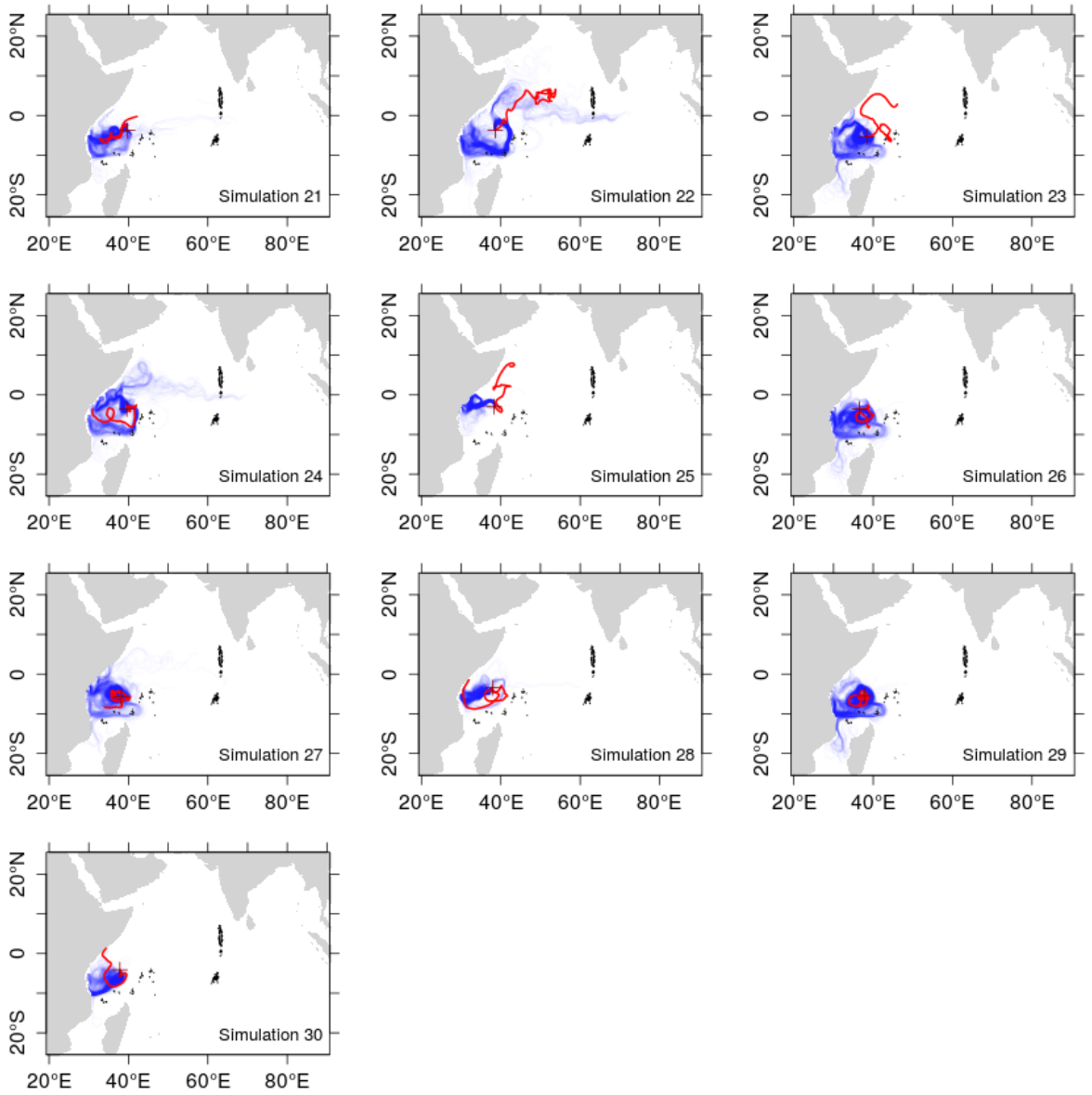

Figure S1c Simulations of dFAD trajectories (blue lines) from deployment locations (+) in the Indian Ocean in the main deployment area of the season June-July (see text for details). Red lines indicate observed trajectories of dFADs deployed at sea and black areas indicate coral reefs.

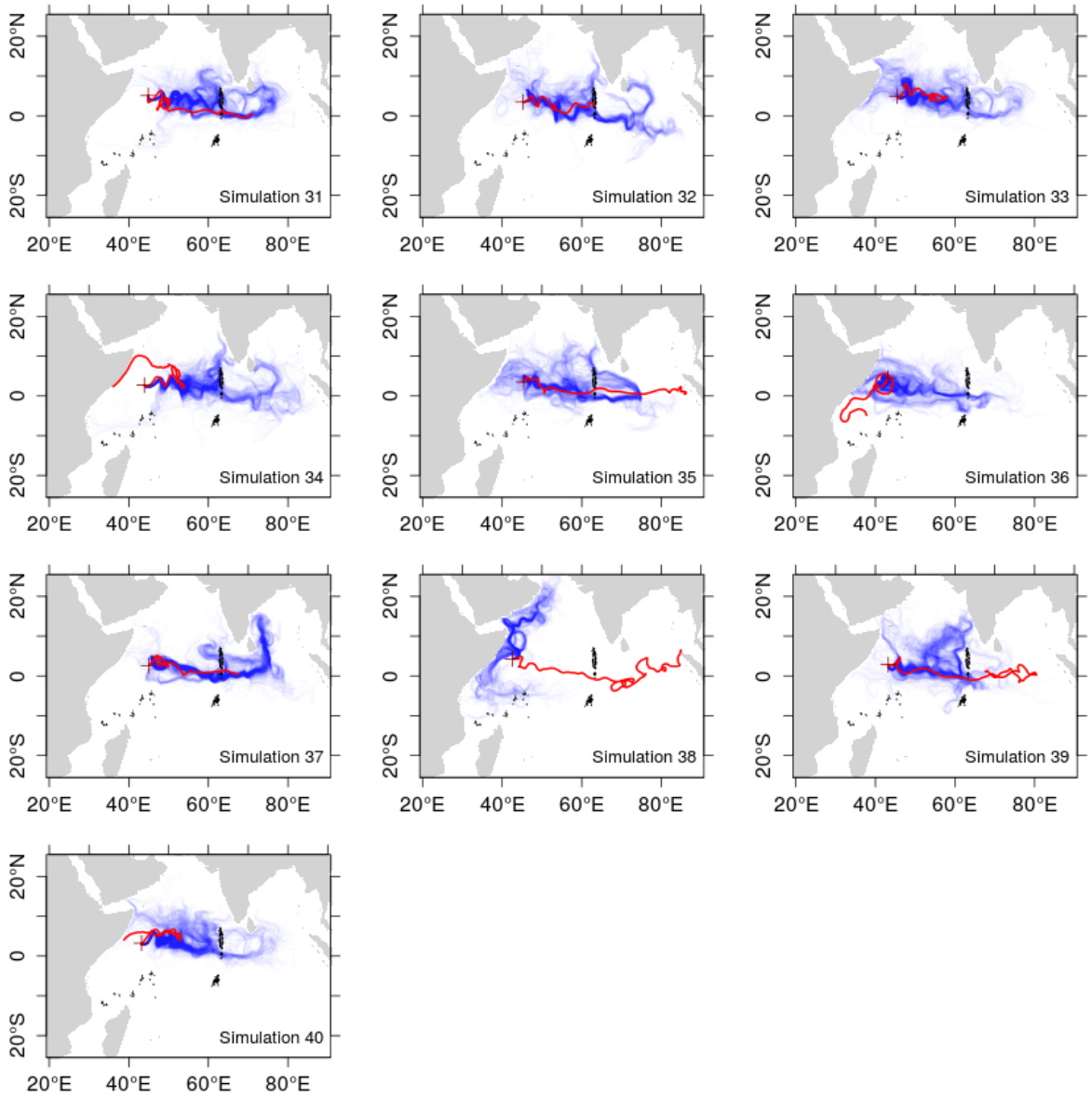

Figure S1d Simulations of dFAD trajectories (blue lines) from deployment locations (+) in the Indian Ocean in the main deployment area of the season August-October (see text for details). Red lines indicate observed trajectories of dFADs deployed at sea and black areas indicate coral reefs.