IOTC-2013-WPEB09-38
Received: 28 June 2013

FISHERIES OCEANOGRAPHY

FISHERIES OCEANOGRAPHY Fish. Oceanogr. 22:3, 147–153, 2013

How much do fish aggregating devices (FADs) modify the floating object environment in the ocean?

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ABSTRACT

Natural floating objects (e.g., logs) have always been a component of the habitat of tropical tunas. However, the introduction of fish aggregating devices (FADs) modifies this environment. To assess the changes due to the deployment of FADs, we compared the spatial distribution of natural and artificial floating objects (FADs), using data from observers onboard tuna purse seine vessels in the Indian Ocean from December 2006 to December 2008. Although natural objects occur more commonly in waters south of 7°S and FADs are more common in waters north of 7°S, all types of floating objects can be found everywhere. Using different spatial scales (quadrats of size 1° × 1°, 2° × 2°, 5° × 5°, and 10° × 10°), we computed the proportion of FADs observed in quadrats without natural objects. The scale of 2° × 2° quadrats represented a threshold: distributions of the two types of objects were different at scales smaller than this threshold. The strongest change that has occurred since the introduction of FADs (besides the increased catches) has been the dramatic increase in the total number of floating objects. Since the introduction of FADs, the number of objects has at least doubled everywhere (except in the Mozambique Channel and Chagos) and in some areas (e.g., Somalia area) the multiplication factor has reached as high as 20 or 40. Our study sets the ranges of values of key parameters of the floating object environment, which are crucial in the design of future experimental studies aimed at investigating the impacts of FADs on the ecology of tunas.

Key words: ecological trap, fish aggregating devices, floating objects, Indian Ocean, tuna

INTRODUCTION

Assessing ecosystem change resulting from human activities has become a major topic in modern ecology. Most human impacts on marine environments (e.g., chemical or physical pollution, as well as seabed destruction by various fishing gears) are considered to primarily affect coastal ecosystems. Although offshore ecosystems (high seas) usually experience a lower magnitude of anthropogenic impacts, the recent intensive use of drifting fish aggregating devices (FADs) by tropical tuna fisheries has raised questions regarding their impacts on such pelagic ecosystems. Objects such as logs, parts of trees or drift algae commonly drift on the surface of the ocean and naturally attract various species of fishes (see e.g., Greenblatt, 1979; Castro *et al.*, 2002). In the literature, Castro *et al.* (2002) found records of 333 species belonging to 96 families that, at some time, has been observed associated with floating structures. However, when considering only species that are commonly found around drifting floating objects in tropical waters, this number drops to between 30 and 40 species (Romanov, 2002; Taquet *et al.*, 2007) and, importantly, includes tropical tunas such as skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) tunas. The frequent association of tunas with floating structures was the reason for the development of log-fishing by long distance tuna purse seiner vessels (Dagorn *et al.*, in press). In this paper, we will use the term 'log' to refer to any natural floating object, and the term 'FAD' to refer to any man-made floating object deployed by fishers to enhance tuna catches. The term 'floating object' is used as the generic term representing all types of floating objects. Logs usually originate from large rivers or mangrove regions and are washed out to sea, where they drift with the currents. As such, logs have always been a part of the habitat of the species that naturally associate with floating objects. However, in the early 1990s, long distance purse seiners began constructing and deploying large numbers of FADs to increase their catch of tropical tunas: the amount of tropical tuna captured around both FADs and logs has represented a very large portion of the total annual catch in each ocean (Dagorn *et al.*, in press). Most FADs consist of bamboo rafts with nets

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Received 9 November 2011
Revised version accepted 29 August 2012

hanging below and are equipped with positioning buoys to allow them to be located remotely (Moreno *et al.*, 2007). Thousands of such FADs are regularly deployed in all oceans, which clearly represents a change in the floating object environment, a key element of the natural habitats of tropical tunas as well as other species that associate with floating objects.

The deployment of FADs in the ocean could modify this environment in two ways. First, FADs can be deployed in or drift into areas where there previously were no logs. In this way FADs can create new areas with floating objects. Secondly, FAD deployment can increase the number of floating objects in areas that already had logs (even at very low densities). This study addresses the question of modifications of the tropical pelagic habitat due to the deployment of FADs by tuna purse seiners. We consider that the population of logs represent the natural state and that FADs represent changes due to human activities. We therefore base our analyses on the comparison of the distributions and numbers of logs and FADs. We focus our research on the western Indian Ocean where log- and FAD-fishing has been of great importance since the beginning of the fishery in the early 1980s. During the last three decades, more than 50% of the catch from purse seine vessels in this ocean has come from sets on floating objects (more than 75% in 2009), composed of 67% of skipjack tuna, 25% of yellowfin tuna and 8% of bigeye tuna (Dagorn *et al.*, in press). Two hypotheses are tested to assess the degree of habitat modification due to FADs: (1) FADs occupy areas that are free of natural floating objects (creating new floating object areas) and (2) FADs have drastically increased the density (or numbers) of floating objects in areas where natural objects already occur. Assessing the habitat alteration feeds studies aiming at investigating the effects of FADs on the ecology of marine species, such as the investigation of the hypothesis of FADs acting as ecological traps (Marsac *et al.*, 2000; Hallier and Gaertner, 2008).

MATERIALS AND METHODS

Data

The tuna purse seine fleet operating in the western Indian Ocean is mainly composed of Spanish and French vessels. European observers embark onboard these vessels for trips of 5–7 weeks to monitor by-catch, discards and all activities linked to the use of floating objects (e.g., deployment of FADs or visits to FADs). Only data collected after December 2006 could be used as this corresponds to the period when about 10% of the fleet began to regularly take observers. At the time of the analysis, data were available until December 2008 for both fleets, for a total of 52 fishing trips over 2 years. Observers note the type of floating objects encountered by the vessels: FADs (man-made), natural or others (mainly objects from human pollution). When aggregating all data for all seasons and all areas, 2279 objects were encountered: 65% FADs, 18% natural floating objects, 17% others (this last category will not be considered in the study). To be more synchronous with the general movement of the fleet, fishing seasons and areas, and to get spatio-temporal windows with enough data, we decided to pool data by quarters delayed by 1 month: the 1st quarter corresponds to December, January, February; 2nd quarter corresponds to March, April, May, and so on.

Changes in spatial distributions

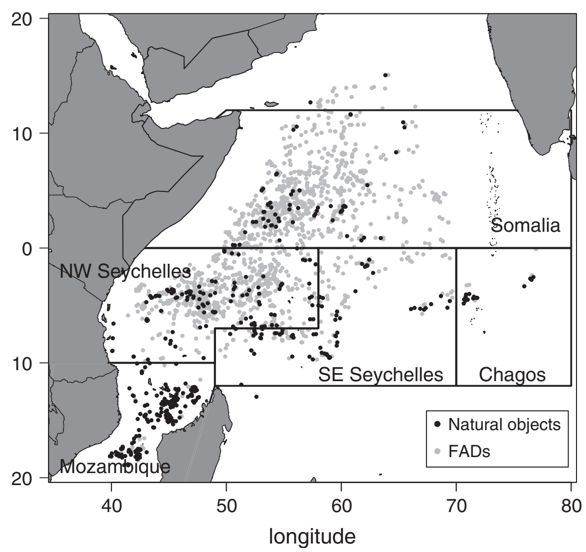
The first goal of this study was to evaluate if FADs occupy areas that were free of logs, creating new areas of floating objects. The answer is obviously scale-dependent as, for instance, at a point scale all FADs occupy an ‘area’ free of natural objects, whereas at the ocean scale they all belong to the same area. We thus considered different scales consisting of quadrats of size $1° \times 1°$, $2° \times 2°$, $5° \times 5°$, and $10° \times 10°$, with the aim of identifying the threshold at which the distributions differ. For each quadrat and quarter, we computed the proportion of FADs observed in quadrats without natural objects. A high value of this index (close to 1) indicates that FADs and logs do not occupy the same areas, whereas a low value (close to 0) shows that the spatial distributions of the two types of objects are essentially identical. To compensate for the drastic differences between the number of FADs and natural objects, depending on the area, we randomly sub-sampled as many of the more abundant type as were experimentally sampled for the less abundant type by the observers.

We also calculated the mean minimal distance between floating objects, i.e., the distance from one to its closest neighbour. This was done for all floating objects (FADs and logs together) as well as within each category of floating objects.

Changes in densities

For the quantitative assessment (change in numbers of floating objects in the ocean), we divided the western Indian Ocean into several zones following the Indian Ocean Tuna Commission (IOTC) zones for fisheries data: Somalia, South East Seychelles, North West Seychelles, Mozambique Channel, Chagos (Fig. 1). One can then count the number of objects of each type in each of these zones and determine how much

Figure 1. Map representing all FADs and logs recorded by observers during 2007 and 2008, with indication of the geographical strata used in the analysis.



the total number of floating objects has increased compared with a hypothetical state of only logs.

RESULTS

FADs and logs were encountered in all the fishing zones exploited by the fishery (Fig. 1). Logs are dominant in waters south of 7°S, and in particular in the Mozambique Channel, whereas FADs are much more abundant north of 7°S. As fishers only enter the Mozambique Channel for a limited period of time (mainly 2nd quarter), information about FAD densities and distribution in that area during the three other quarters is lacking.

Changes in spatial distribution

At the scale of quadrats of 1° × 1°, most FADs (>50%) are located in quadrats that are free of logs, which shows a difference in the spatial distribution between these two types of objects at this scale (Fig. 2). At the scales of quadrats of 5° × 5° and 10° × 10°, the two types appear to have similar spatial distributions, with the scale of quadrats of 2° × 2° representing an intermediate situation.

For all quarters except the 2nd (Mozambique Channel), the average minimal distance between two FADs is lower than between two logs (Fig. 3), which shows that the density of FADs is greater than that of logs (except in the Mozambique Channel). The average minimal distance between all objects of a given quarter (logs and FADs together) is quite constant (mean 33.2 km, SD 5.6 km; Table 1), whereas the average minimal distance between logs of a given quarter is quite variable among quarters, with averages ranging from 33.3 to 106.7 km (mean 72.3 km, SD 27.2 km; Table 1).

Changes in densities

The increase in the total number of floating objects due to the presence of FADs is very low for the Mozambique Channel (multiplication factor of 1.1) and the Chagos (Table 2). There are now in average two to four times more floating objects in the SE Seychelles. The effects of FADs in NW Seychelles is larger, in particular during the 3rd and the 4th quarters. Finally, the Somalia area is certainly the area that has experienced the most changes in terms of numbers of floating objects. The multiplication factor can reach up to 20 (4th quarter of 2008) or 40 (4th quarter of 2007). We consider that the increase in the number of floating objects in the northern part of the ocean occurs year-round, but with varying factors.

DISCUSSION

Hypothesis 1 (FADs occupy areas free of floating objects) is rejected at scales larger than quadrats of 2° × 2°, but not at smaller scales, whereas our results are in favour of hypothesis 2 (FADs drastically increase the number of objects). When the tuna purse seiners started to fish in the Indian Ocean in the early 1980s, they soon found many floating objects, more than they typically had found in the other oceans (e.g., Atlantic Ocean). As such, a large portion of the catch came from fish associated with natural objects from the outset of the fishery (Dagorn *et al.*, in press). The density of objects in the Mozambique Channel is naturally high, as the area is quite small and logs regularly drift in from both the eastern coast of Africa and Madagascar. It is this high density that explains why fishers do not deploy many new FADs in this area. However, because they knew that tunas naturally aggregate around objects in the Somalia area (a larger area), but that densities of logs were quite low, they progressively deployed more and more FADs in this area, as well as around the Seychelles. The minimal distance between objects also reflects the densification of the array of floating objects: due to the large deployment of FADs, floating objects (FADs and logs) are found closer to each other. Furthermore, the introduction of FADs has led to areas now being rather similar distances between floating objects (e.g., densities) in some areas, whereas regional differences exist with logs (considered the situation before the use of FADs).

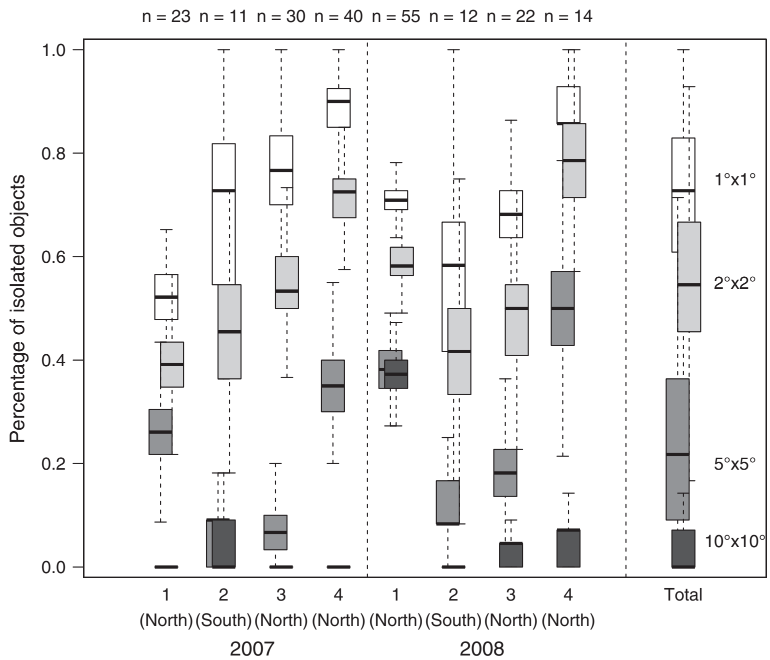


Figure 2. Boxplots of the percentage of FADs observed in quadrats without natural objects, for quadrats of 1° × 1° (white), 2° × 2° (light grey), 5° × 5° (drak grey) and 10° × 10° (black), for each quarter of 2007 and 2008 (North and South indicate if floating objects were mainly located North or South of 7°S for the corresponding quarter).

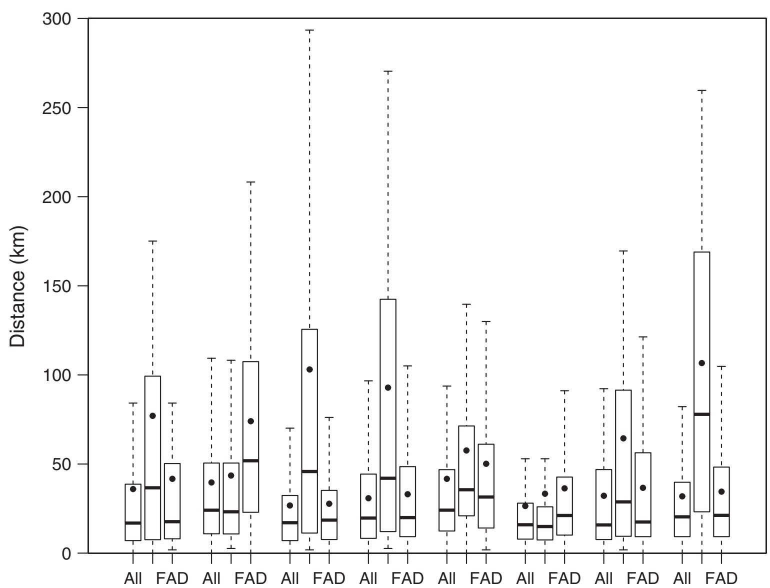


Figure 3. Boxplots representing the distributions of distance towards the nearest neighbour by quarter. Results obtained for all types of floating objects, and for logs and FADs, respectively. Points are situated at the mean level (to be compared with the median indicated by the boxplots).

In recent years, fishers have been deploying more and more FADs, which could rapidly lead to changes in the distribution of floating objects. It is therefore very important to maintain observer programs to continually monitor potential changes in this distribution. We only used data collected by observers, as fishers do not note all floating objects they encounter in their logbooks. They only report the objects which they set. To assess the changes due to the deployment of FADs, it is essential to collect information on all objects found in the ocean and this currently is only available from observers' data. However, it is noteworthy that if fishers could note in a rigorous manner all floating objects they encounter (indicating the type of the object, date, time and location), acting as observers of the ocean, the amount of data would increase considerably. Moreover, complete knowledge of the locations of instrumented floating objects would help. This information is in the hands of fishers, as they have the positions of all their tracking buoys. As these data are very sensitive (they represent a major information resource used in determining the fishing strategy of each skipper), a delayed (e.g., 6-month) database would serve the scientific purpose without affecting the real-time efficiency of the skippers (Dagorn *et al.*, in press). In terms of spatio-temporal coverage of the ocean, it is worth noting that our sampling is limited by the fishers' strategy. For instance, purse seiners never visit the Mozambique Channel outside of the 2nd quarter and therefore no information on floating objects can be obtained for this area during other periods of the year. There may also be some areas that are never visited by purse seine vessels (out of their fishing grounds) and where artificial FADs and/or natural objects may drift, such as the eastern part of the Indian Ocean. Fishery-independent surveys would allow the characterization of the distribution of floating objects outside the main fishing grounds and seasons.

Consequences for the ecology of pelagic species

Many hypotheses have been proposed to explain why tropical tunas (and other species) associate with floating objects (see review in Castro *et al.*, 2002; Fréon and Dagorn, 2000). One of them is the indicator log that hypothesize (Hall, 1992) natural floating objects could be indicators of productive areas, either because most natural floating objects originate in rich areas (e.g., river mouth, mangrove swamp) and remain within these rich bodies of water, or because they aggregate in rich frontal zones. The association of tunas with any floating object may then be a result of an evolutionary process where tunas use these indicators to find or stay in contact with rich waters. Following this hypothesis, FADs could act as ecological traps because tunas could be misled by FADs (Marsac *et al.*, 2000; Hallier and Gaertner, 2008). If FADs drive the associated fauna to biologically poor areas (a change in their migration routes), this could have detrimental effects on their biology (e.g., growth). This hypothesis is mainly based on the idea that FADs occupy areas where logs are not found. Our results indicate that, relative to their different abundances, logs and FADs occupy different 1° × 1° quadrats but similar 5° × 5° areas. If we consider that logs and FADs are outcomes of point processes driven by a probability field consisting of two components, one for the large scales (5° × 5°) and one for the small scale (1° × 1°), we find that the large scale component is common to logs and FADs, whereas the small scale component is not. In absolute terms (i.e., numbers), the picture is somewhat different but not contradictory, as FADs are encountered one order of magnitude more often than logs even over large areas. New small (1° × 1°) patches of floating objects (FADs) are now observed, but they are usually located within larger areas (5° × 5°) that naturally have logs. Therefore, our results show that (1) the processes for FADs to drive tunas to new areas, and possible consequences of such movements on the biology of individuals, could occur at scales smaller than 2° × 2° and (2) the processes for FADs to retain tuna longer in some areas should be investigated, considering that the density of floating objects has been multiplied by a factor of 40 in some areas.

Tunas are known to travel long distances and their habitat largely exceeds 2° × 2° areas. Therefore, one could consider that the ecological consequences of

Table 1. Mean (and SD) of median and mean minimal distance (in km) between objects.

Type of floating objects	Quarterly medians, km	Quarterly means, km
All	19.2 (3.4)	33.2 (5.6)
Logs	24.9 (11.8)	41.7 (14.6)
FADs	38.1 (18.9)	72.3 (27.2)

Table 2. Multiplication factor of the number of floating objects due to the introduction of FADs, for each zone and quarter.

Quarter	Somalia	NW Seychelles	SE Seychelles	Mozambique	Chagos
Dec 2006–Feb 2007	4.4	6.4	3.8	NA	NA
Mar 2007–May 2007	2.5	3.4	5	1.1	NA
Jun 2007–Aug 2007	9.6	11.3	1	NA	NA
Sep 2007–Nov 2007	40.4	14.2	2.6	NA	NA
Dec 2007–Feb 2008	Inf	3.4	2.3	NA	1.4
Mar 2008–May 2008	Inf	4.8	3.3	1.1	NA
Jun 2008–Aug 2008	3.6	5	5	NA	NA
Sep 2008–Nov 2008	19.4	13.3	5	NA	NA
Total 2007–2008	13.3	6.3	2.9	1.1	1.4

NA, not available; Inf, infinity.

tunas being driven to areas where they would not have been, at the scale of 2° × 2°, are minor. However, this hypothesis should clearly be investigated through appropriate observations of their movements (e.g., measure of residency times of tuna within areas smaller than 2° × 2) along with fine-scale investigations of their physical condition.

The effects of different densities of FADs on tuna movements have not yet been addressed. One might consider that the residency time of tunas in an area would increase with the density of floating objects. However, floating objects might not be the only factor affecting such behavioural patterns, as they may also adapt the time they spend in one area to its richness (i.e., prey density), as suggested by the idea free distribution theory (Fretwell and Lucas, 1970). This possible interplay between FADs and prey on the residency time of tunas in one area has not been investigated as yet. Acoustic telemetry has enabled scientists to provide information on the time spent by tunas around FADs and in arrays of anchored FADs (Ohta and Kakuma, 2005; Dagorn *et al.*, 2007; Mitsunaga *et al.*, 2012; Robert *et al.*, 2012). However, it is difficult to obtain such estimates for drifting FADs, as this would require equipping all drifting FADs in an area with automated acoustic receivers, which is hardly feasible. However, the striking difference in the vertical behaviour observed between associated and non-associated bigeye tuna, and to a lesser extent yellowfin tuna, allows the use of archival tagging to obtain such information (Schaefer *et al.*, 2009; Schaefer and Fuller, 2010). These studies in the eastern Pacific Ocean not only revealed that the mean residence times of tunas around drifting objects were only a few days, similar to what was observed for tunas around anchored FADs (Ohta and Kakuma, 2005; Dagorn *et al.*, 2007; Mitsunaga *et al.*, 2012; Robert *et al.*, 2012), but indicated that during prolonged periods at liberty, very few association events were observed. However, determining the driving forces behind tuna movements (or any pelagic fish) remains a scientific challenge.

Only a few solid empirical examples have shown the existence of ecological traps, mainly because most studies adopted demographic approaches as opposed to behavioural ones (Robertson and Hutto, 2006). The prerequisite to assess the impacts of FADs on the ecology of tunas is to characterize the changes due to human activities, which was not done in the case of FADs and tropical tunas. Our study sets the ranges of values of key parameters (i.e., the spatial scales and the multiplication factor of the density of objects) of the floating object landscape, highlighting a primary concern for the increase in object density. This is crucial in designing future experimental studies aiming at investigating the impacts of FADs on the ecology of tuna.

ACKNOWLEDGEMENTS

This study was carried out with financial support from the Commission of the European Communities, specific RTD programme of Framework Programme 7, 'Theme 2 – Food, Agriculture, Fisheries and Biotechnology', through the research project MADE (Mitigating adverse ecological impacts of open ocean fisheries), contract #210496. This work does not necessarily reflect the Commission's views and in no way anticipates its future policy in this area. We are very grateful to the observers involved in data collection, to the fishing masters and fishing companies for their close collaboration with the obervers, and to IRD/IEO/AZTI scientists. These observer programs are financed through the European Data Collection Regulation, EC-DCR No.1543/2000, 1639/2001 and 1581/2004. We thank P. Cauquil, L. Floch and A. Damiano (IRD) for database development and management. We also would like to sincerely thank John Filmalter for his valuable help with the grammatical editing.

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