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Typology and behaviour of tuna aggregations around fish aggregating devices from acoustic surveys in French Polynesia

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Abstract − Eighty-seven two-hour acoustic surveys (radius 0.8 nautical mile, vertical range 0–500 m) around 17 fish aggregating devices (FADs) were conducted in French Polynesia between December 1995 and February 1997. Associated tuna densities were calculated using two different techniques: echo counting when the fish had sufficient distances from each other and echo integration when the fish swam close together (in schools). No acoustic detection of tuna was observed during 27 of the 87 surveys, representing 81 % of all the nocturnal surveys and 15 % of the diurnal ones. The 60 other surveys showed three different classes of aggregations: (1) ‘deep scattered fish’, observed 45 times, (2) ‘intermediate scattered fish’, observed 16 times, and (3) ‘shallow schooling fish’, observed 16 times. Sometimes aggregations of different classes were observed beneath the same FAD. The size of the fish inside the aggregations (determined from target strength values), the distance between the individuals, and the depth of the fish all decreased from ‘deep scattered fish’ to ‘shallow schooling fish’ (100–300 m for ‘deep scattered fish’, 50–150 m for ‘intermediate scattered fish’, and above the depth of 50 m for ‘shallow schooling fish’). Fish densities also varied according to the class of aggregations: 7.3, 26, and 801 fish per km^3 on average for ‘deep scattered fish’, ‘intermediate scattered fish’, and ‘shallow schooling fish’, respectively. The highest densities were observed during daytime, while night-time observations indicated a variety of situations, from the absence of individuals to large amounts of fish. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

tuna fish / fish aggregating devices / acoustics / aggregation / behaviour / French Polynesia

Résumé − Typologie et comportement des agrégations thonières autour de dispositifs de concentration de poissons à partir de prospections acoustiques en Polynésie française. Quatre-vingt-sept prospections acoustiques, d’une durée de deux heures, ont été effectuées entre décembre 1995 et février 1997 en Polynésie française autour de 17 dispositifs de concentration de poissons (DCP). Les densités en thons, entre la surface et 500 m de profondeur et dans un rayon de 0.8 mille nautique autour des DCP, ont été estimées par écho-comptage en présence de poissons dispersés, ou par échointégration en présence de poissons agrégés en bancs. Lors de 27 prospections, (représentant respectivement 81 % et 15 % des prospections nocturnes et diurnes effectuées), aucune détection de thon n’a été observée. Les 60 autres prospections ont montré 3 différents types d’agrégation : (1) le type « poissons dispersés profonds » observé 45 fois, (2) le type « poissons dispersés intermédiaires » observé 16 fois et (3) le type « poissons en bancs superficiels » observé 16 fois. Différents types d’agrégation ont parfois été observés sous un même DCP. La taille des poissons (déterminée à partir des valeurs d’indice de réflexion individuel ou TS), la distance entre les individus et la profondeur des détections diminuent, alors que les densités augmentent, entre les types « poissons dispersés profonds » (7.3 poissons par km^3 entre 100 et 300 m de profondeur), « poissons dispersés intermédiaires » (26 poissons par km^3 entre 50 et 150 m) et « poissons en bancs superficiels » (801 poissons par km^3 entre la surface et 50 m). Les densités les plus fortes ont été observées de jour, alors que de nuit, différentes situations, depuis l’absence totale de détection jusqu’à la présence de densités élevées ont été rencontrées. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

thon / dispositif de concentration de poissons / acoustique / agrégation / comportement / Polynésie française

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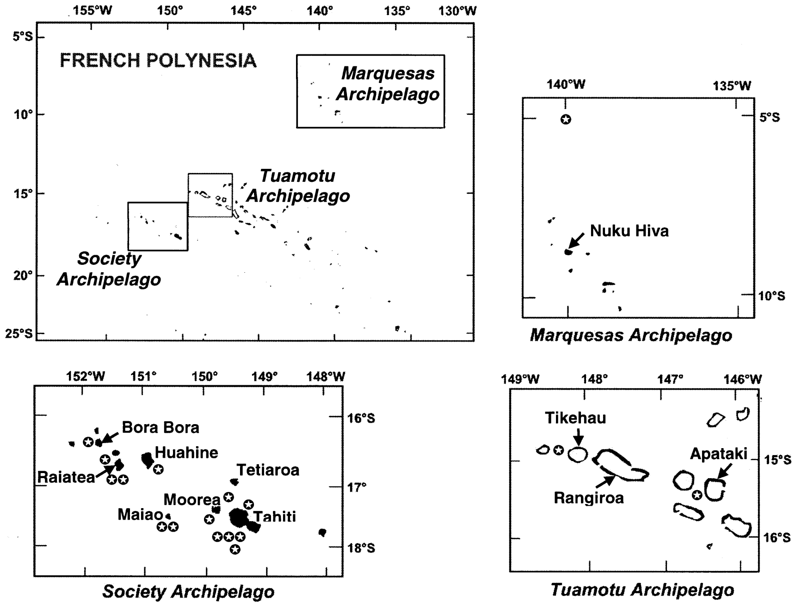

Figure 1. Geographical localization of FADs where echo surveys were conducted. ☆ FAD position.

1. INTRODUCTION

Many types of tropical tuna fisheries take advantage of the fact that tuna aggregate around floating objects. For the last two decades, anchored man-made floating objects, known as fish aggregating devices (FADs), have greatly helped to develop and maintain artisanal tuna fisheries, especially in tropical islands of the Pacific and Indian Oceans. At the same time, purse seine fisheries extend the use of drifting FADs to increase catches.

Knowledge of fish behaviour and spatial structuring of tuna aggregation under floating objets has become a main stake in the management of tuna fisheries. Therefore, several approaches have already been used to study tuna aggregations. Ultrasonic telemetry techniques were used in Tahiti, Hawaii, and in the Indian Ocean to observe the fine-scale vertical and horizontal movements of FAD-associated skipjack *Katsuwonus pelamis* (Linnaeus, 1758), yellowfin *Thunnus albacares* (Bonnaterre, 1788) and bigeye *Thunnus obesus* (Lowe, 1839) tuna (Cayré and Chabanne, 1986; Holland et al., 1990; Cayré, 1991; Marsac et al., 1996; Bach et al., 1998; Josse et al., 1998; Marsac and Cayré, 1998; Brill et al., 1999). This method provides useful information about the behaviour of individuals. This behaviour however, may not always reflect the behaviour of entire aggregations and it appears necessary to observe aggregations and not only individuals. In this study we present acoustic observations of tuna aggregations with a discrimination between the echoes of tuna or tuna-like species and other ones. The objective of this work is to define the vertical and horizontal structures of tuna aggregations around FADs as well as their time dynamics, in order to identify aggregation patterns.

2. MATERIALS AND METHODS

The experiments were conducted in French Polynesia between December 1995 and February 1997 within the framework of the Ecotap programme (Studies of tuna behaviour using acoustic and fishing experiments), a joint project between two French research institutes (Ifremer: Institut français de recherche pour l'exploitation de la mer, and IRD: Institut de recherche pour le développement), and a French Polynesian institute (SRM: Services des ressources marines). Acoustic surveys were carried out around FADs anchored some nautical miles off the main inhabited islands of the Society and Tuamotu Archipelagos (*figure 1*). Similar surveys were carried out off the Marquesas Islands, around an instrumented oceanographic buoy anchored approximately 200 nautical miles from the nearest land.

Data were collected onboard the 28 m IRD Research Vessel 'Alis' equipped with a SIMRAD EK500 echo sounder (version 4.01). The sounder was connected to a SIMRAD ES38B hull-mounted, split-beam transducer producing pulse duration of 1.0 ms at 38 kHz. The beam angle was 6.9°. Calibration of acoustic equipment was performed with a 60 mm copper sphere using the standard procedure recommended by the manufacturer (Simrad, 1993). Measurements of the acoustic noise level according to the vessel speed were used to define the optimal speed survey (i.e. 7 knots, see Josse et al., 1999). Three survey patterns were defined, based upon a maximum survey time a priori fixed at 2 h (*figure 2*):

— transect 1, a star survey pattern with eight branches, each 0.8 nautical mile long and repeated twice (*figure 2a*),

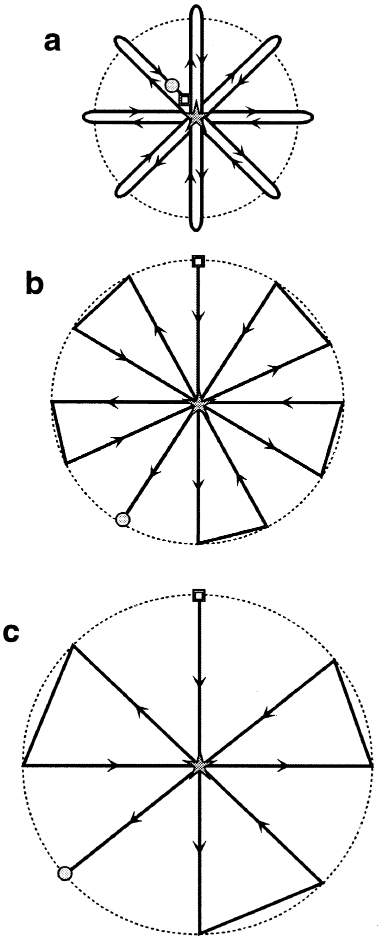

Figure 2. Survey patterns used during acoustic surveys around FADs in French Polynesia. ☆ FAD position; ▣ start of the survey; ○ end of the survey.

— transect 2, a star survey pattern with eight branches, each 1.2 nautical miles long, without duplicate (*figure 2b*),

— transect 3, a star survey pattern with twelve branches, each 1.0 nautical mile long, without duplicate (*figure 2c*).

The transect 1 pattern, already used during previous acoustic surveys around FADs in French Polynesia (Depoutot, 1987; Josse, 1992; Bach et al., 1998), allows an increase in the number of runs close to the FAD and exploration of an area a priori wide enough to take into account the whole aggregation. The two other survey patterns make the navigation close to the FAD easier, and allow extension of the area prospected. On the other hand, the number of runs close to the FAD is reduced.

All the acoustic measurements were carried out between the surface and a depth of 500 m. SIMRAD EP500 software (Simrad, 1994) was used to record, via ETHERNET on a personal computer (PC), acoustic and navigation data from the EK500 echo sounder.

In order to estimate the tuna densities associated with FADs, surveyed areas were partitioned into 30° or 45° angular sectors based upon the survey pattern used. Each angular sector was then subdivided into volumes, using the sector's distance to the FAD (0.1 nautical mile increments) and an arbitrary depth category. Depth categories included one 40-m layer from depths between 10 and 50 m, and nine 50-m layers for depths between 50 and 500 m (see Josse et al., 1999). In each elementary sampling unit thus defined, the densities, expressed as a number of fish per unit volume, were then determined by echo counting in the presence of scattered fish, or by echo integration in the presence of schools. All analyses were limited to a radius of 0.8 nautical mile around the FAD, irrespective of the type of survey pattern carried out.

The applicability and validation of the two techniques (echo counting and echo integration) used to estimate tuna densities around FADs were presented in Josse et al. (1999). Echo counting is a technique which allows to obtain direct quantitative estimations of fish density (Kieser and Ehrenberg, 1990), provided that the fish are sufficiently distant from each other so that their echoes can be discriminated. A split-beam system allows direct application of this technique (Misund, 1997), following three steps. The first step consists of identifying and counting all the fish. The EP500 'trace tracking' procedure allows the automated recognition of a single fish detected over one or more successive pings. In a second step, each identified fish must be allocated to the elementary sampling unit corresponding to its space location. EP500 specifies the depth of each identified target, but its geographical position must be researched in the raw data files. The third step consists of converting the number of fish obtained in a basic sampling unit into a density value. This step requires the knowledge of the water volume sampled by the acoustic beam which is characterized by its beam angle. A split-beam system allows easy determination of the beam angle from the angular co-ordinates associated with individual echoes. Thus, the beam angle was determined using all the angular data associated with tuna and non-tuna echoes observed during the different surveys around FADs (see Josse et al., 1999).

In echo integration, contrary to echo counting, no restriction of use related to dispersion of fish occurs. This method can thus apply when fish are aggregated in schools. The acoustic densities were extracted from each sampling unit by using the EP500. The acoustic densities were then transformed into absolute densities, which requires the knowledge of the average target strength index (TS) of the detected fish. The TS values were extracted from each survey using the EP500 'trace tracking' procedure. An average TS was then calculated and used to transform the acoustic

Table I. Target strength values (TS) for yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) from the literature.

Species	Fork length (cm)	Estimated weight (kg)	Average TS(dB)	References
Thunnus albacares	60	4	–34.8	Bertrand et al., 1999a, b
	90	14	–33.0	
	108	25	–30.4	
	120	30	–26.1	
Thunnus obesus	49.9(*)	3	–32.8	Josse and Bertrand, in press
	50.1(*)	3	–31.9	
	110	30	–24.4	Bertrand et al., 1999a, b
	130	50	–21.4	

(*) Mean value

densities into absolute densities (expressed as a number of fish per volume unit).

Knowledge of fish TS is of prime importance for acoustic estimation both with echo counting and with echo integration. When echo counting is used for tuna biomass estimation, it is necessary to count only echoes from tuna and to exclude other echoes. When echo integration is used, it is necessary to know the mean TS value of the detected targets (i.e. the mean TS values of the detected tuna) to convert acoustic densities into tuna densities. Experiments were carried out within the framework of the Ecotap programme to determine TS values for yellowfin and bigeye tuna (see Bertrand et al., 1999a, b; Josse and Bertrand, in press; and *table I*).

During the Ecotap programme, 87 acoustic surveys were carried out around 17 FADs. Some surveys were done in the same 24-hours period on the same FAD to collect information on the temporal evolution of the aggregations and therefore, construct series of surveys. Tuna were acoustically observed during 60 surveys. A visual analysis of the echograms of each survey, coupled to a search of the individual targets with the EP500 software, showed differences between 3-D organisation of tuna around FADs. According to these differences, the detection of tuna was classified into three categories: (1) presence of 'deep scattered fish' (45 times); (2) presence of 'intermediate scattered fish' (16 times); and (3) presence of 'shallow schooling fish' (16 times). Sometimes, two or more categories were observed together in the same survey. When one or both of the two first categories were observed with the last one, it was not possible to quantitatively characterize each category. For the first two classes, the echo counting technique was systematically employed. For the last category, echo integration was systematically applied as it was not always possible to identify all the individuals.

3. RESULTS

3.1. No acoustic detection of tuna

In 27 surveys (31 % of the surveys) no tuna were detected. Seventeen of them were nocturnal surveys and ten were diurnal surveys, which corresponds to 81 % and 15 % of the surveys, respectively. In particular, around two FADs in the Society Archipelago, observations were made over 24-hour periods, which indicates that no fish were around or beneath those two FADs during a period of 24 hours. In the other series of observations where in some surveys no fish were detected, no sequential pattern of aggregation types found before or after the absence of fish can be drawn. All the three types of aggregations were found in those series of surveys.

3.2. Deep scattered fish

This type of aggregation was observed forty five times: thirty two times alone, ten times in the presence of 'intermediate scattered fish' and three times in the presence of 'shallow schooling fish'. We will only show results when 'shallow schooling fish' were not simultaneously observed, because in those cases it was not possible to quantitatively differentiate the aggregation types. The average density per survey was 7.3 fish per km^3, which corresponded to 25 individuals per survey (*table II*). Highest densities were observed close to the FAD. They then decreased and the minimum values were found between 0.5 and 0.6 nautical mile from the FAD. High densities were also found at the edge of the sampling area (0.8 nautical mile). Fish were observed from the depth of 10 m down to 500 m, but 92 % of the fish was distributed between 100 m and 300 m. The average distance between two fish along a same branch was 240 m (number of observations $n = 29$, SD = 340 m).

TS values varied between –34.4 and –19.0 dB, giving a mean value of –23.0 dB. Two peaks of TS values were observed, the first one between –26 and –28 dB, and the second one between –20 and –22 dB (*figure 3a*). The comparison with TS values found by Bertrand et al. (1999a, b) indicates that these fish are likely to be large tuna of more than 100 cm fork length (FL). However, the acoustic techniques do not make it possible to identify the species directly, without access to complementary data such as, for example, simultaneous fishing data.

Table II. ‘Deep scattered fish’: densities (d: number of fish·km^{-3}) and numbers of fish (*n*) per depth and distance to the FAD strata*.

Depth strata (m)		Distance to the FAD strata (nautical mile) 0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.0–0.8
10–50	d									
	n									
50–100	d	12.9								0.2
	n	0.1								0.1
100–150	d	12.5	7.7	20.1	7.6	7.7		26.5	37.6	18.2
	n	0.1	0.1	0.5	0.3	0.4		1.9	3.0	6.3
150–200	d	56.7	32.1	21.3	37.0	21.3	11.0		13.4	16.1
	n	0.3	0.5	0.6	1.4	1.0	0.7		1.1	5.6
200–250	d	43.4	35.4	19.8	25.2	15.5	8.6	6.1	32.1	19.1
	n	0.2	0.6	0.5	0.9	0.8	0.5	0.4	2.6	6.6
250–300	d	58.2	17.4	13.5	8.5	3.5	5.0	6.9	24.0	12.1
	n	0.3	0.3	0.4	0.3	0.2	0.3	0.5	1.9	4.2
300–350	d	10.2		3.0		3.0	8.9		11.5	5.0
	n	0.1		0.1		0.1	0.5		0.9	1.7
350–400	d					2.6				0.4
	n					0.1				0.1
400–450	d									
	n									
450–500	d									
	n									
10–500	d	19.8	9.5	7.9	8.0	5.5	3.4	4.0	12.1	7.3
	n	1.0	1.5	2.1	3.0	2.6	2.0	2.8	9.6	24.5

* These values are means calculated from 42 echo surveys.

3.3. Intermediate scattered fish

This type of aggregation was observed sixteen times: two times alone, ten times in the presence of ‘deep scattered fish’, and four times with the presence of both ‘deep scattered fish’ and ‘shallow schooling fish’. These four surveys will not be considered in the present results. An average density per survey of 26 fish per km^3 characterizes the 12 other surveys, i.e. 87 fish per survey (*table III*).

The highest densities were found close to the FAD (the values are 40 times higher than those encountered for ‘deep scattered fish’). These densities rapidly decreased with an increasing distance from the FAD, to drop to zero at 0.4 nautical mile. The densities were observed from the surface down to 200 m, but 94 % of the fish were found between 50 and 150 m. The average distance between two fish along a same branch was 39 m (n = 100, SD = 72 m).

The TS values varied between –40.3 dB and –18.7 dB giving a mean value of –30.6 dB and a single mode between –36 and –34 dB (*figure 3b*). These values likely correspond to tuna of less than 100 cm FL, according to Bertrand et al. (1999a, b) and Josse and Bertrand (in press).

3.4. Shallow schooling fish

This type was observed sixteen times around only two FADs. These aggregations are characterized by an average density of 801 fish per km^3, i.e. 2 708 fish per survey (*table IV*). The higher densities were located close to the FAD and between the depths of 10 and 50 m. Despite some small schools observed in the same vertical range but further from the FAD, densities were very low outside this area. The fish detected in the first 0.1 nautical mile around the FAD and between the depths of 10 and 50 m represented 72 % of the tuna detected. The average distance between two fish could not be calculated for this class as it was often lower than the acoustic beam diameter (2RTan(α/2)), where α is the beam angle and R the depth). For instance, at a depth of 50 m, two fish 6 m away from one another could not be distinguished.

The TS values varied between –45.9 dB and –18.8 dB for a mean value of –32.6 dB. Two modes were observed. The first between –42 and –40 dB and the second between –32 and –28 dB (*figure 3c*). Troll-fishing around one of the two FADs indicated that the aggregations were mainly composed of juvenile bigeye tuna with an average FL of 50 cm (Josse and Bertrand, in press).

3.5. Temporal dynamics

The biomass observed for the ‘shallow schooling fish’ type was at a maximum after sunrise. It then decreased during daytime. The night-time biomass varied between an absence of fish to a great quantity of aggregated fish, but even in this last case, the biomass was lower than the one observed during daytime (*figure 4*). This cycle was also observed for the two

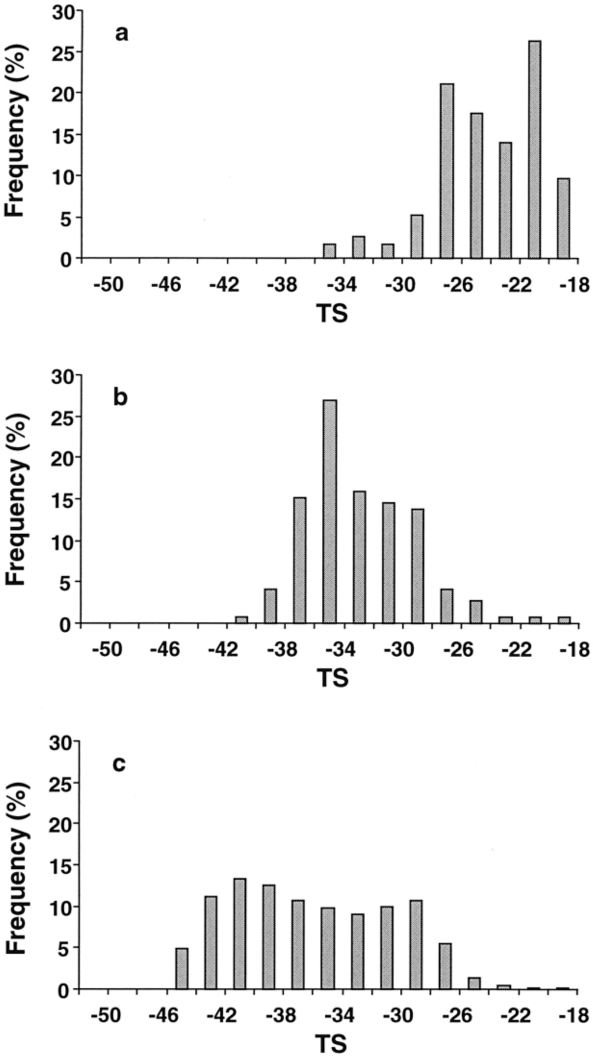

Figure 3. Distribution of TS values for the three types of aggregation: (a) 'deep scattered fish', (b) 'intermediate scattered fish' and (c) 'shallow schooling fish'.

other aggregation types, but was more obvious for 'shallow schooling fish' because of the high observed densities.

4. DISCUSSION

Despite a significant scientific interest in tuna associated with floating objects, the structure and the dynamics of the aggregations are badly known. Several studies have focused on the individual behaviour of tuna around FADs using acoustic telemetry (Cayré and Chabanne, 1986; Holland et al., 1990; Cayré, 1991; Marsac et al., 1996; Bach et al., 1998; Josse et al., 1998; Marsac and Cayré, 1998; Brill et al., 1999), but very few have been dedicated to the direct observation of tuna aggregations beneath FADs.

Cillauren (1994) studied tuna aggregations around FADs anchored off Efate Island in Vanuatu from artisanal troll-fishing data. Mixed schools of skipjack and yellowfin tuna were mostly present within 200 m of the FAD, with exceptional captures beyond 500 m. Yellowfin tuna were caught closer to the FADs than skipjack tuna. The highest catches of yellowfin tuna were taken towards midday, whereas an increase in skipjack tuna catches occurred one hour before sunset. These results however, do not necessarily reflect the behaviour of the entire aggregation. Results obtained from troll-fishing operations depend on the feeding motivation of fish and on the fish-gear interactions.

Acoustic data, on the contrary, provide information about the biomass without using fishing gear. Depoutot (1987) and Josse (1992) made acoustic observations around FADs in French Polynesia using a SIMRAD EYM 'single beam' echo sounder with a frequency of 70 kHz. The echo sounder used did not allow the collection of data below a depth of 120 m. Moreover, in the absence of any data on tuna TS, the authors could not distinguish between tuna or tuna-like species echoes and other species echoes. From one series of surveys, Depoutot (1987) concluded that in shallow waters (above 40 m), the biomass is mostly concentrated around the FAD during the night, while during daytime, fish are observed below 60 m. Josse (1992) observed acoustic detection between 10 and 60 m during daytime, but no detection during the night. This daytime biomass appeared in the morning and disappeared in the afternoon. Considering tuna catches by local fishermen using the drop-stone fishing technique (Moarii and Leproux, 1996), the author also concluded there was a secondary concentration encountered during daytime, below 150 m. Other acoustic observations were done around FADs in French Polynesia using a BIOSONICS model 102 'dual beam' echo sounder with a frequency of 120 kHz (Bach et al., 1998). For the first time, the presence of isolated fish down to the depth of 250 m, the maximum vertical range of the echo sounder used, was observed. However, it is difficult to compare those results with those of the present study as the authors did not observe the same vertical range and, above all, could not distinguish tuna or tuna-like species echoes from other ones. Other small fish of various families (Carangidae, Balistidae, etc.) are known to aggregate around FADs in this region, a few metres below the surface, and could therefore be observed by the echo sounder. Moreover, during night-time, the detection may also correspond to organisms of the Sound Scattering Layer (Myctophidae, etc.) that ascend to the surface layer after sunset.

The scientific echo sounder used in the present study allows determination of the TS of the organisms. Low values characterize small fish while higher TS values represent larger fish (see Bertrand et al. 1999a; b and Josse and Bertrand (in press) for tuna TS values). However, it is not possible to acoustically identify the species without complementary data. The size of the

Table III. ‘Intermediate scattered fish’: densities (d: number of fish.km^{-3}) and numbers of fish (n) per depth and distance to the FAD strata*.

Depth strata (m)		Distance to the FAD strata (nautical mile)								
		0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	Total
10–50	d	902								14
	n	4								4
50–100	d	5 017	818	683	219					194
	n	27	13	18	8					66
100–150	d	2 401	158							45
	n	13	3							16
150–200	d	207								3
	n	1								1
200–250	d									
	n									
250–300	d									
	n									
300–350	d									
	n									
350–400	d									
	n									
400–450	d									
	n									
450–500	d									
	n									
10–500	d	852	100	70	22					26
	n	45	16	18	8					87

* Means calculated from 12 echo surveys.

Table IV. ‘Shallow schooling fish’: densities (d: number of fish·km^{-3}) and numbers of fish (*n*) per depth and distance to the FAD strata*.

Depth strata (m)		Distance to the FAD strata (nautical mile)								
		0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.0–0.8
10–50	d	451 425	2 309	339	8		161	405	1 338	7 612
	n	1 946	30	7	0.2		8	23	86	2 100
50–100	d	55 219	2 020	361			201			1 020
	n	298	33	10			12			352
100–150	d	18 233	5 597	1 070	10	5				633
	n	98	90	29	0.4	0.2				218
150–200	d	2 687	329							57
	n	14	5							20
200–250	d	42	232		113					24
	n	0.2	4		4					8
250–300	d	618	60							12
	n	3	1							4
300–350	d	600	51							12
	n	3	0.8							4
350–400	d	387								6
	n	2								2
400–450	d									
	n									
450–500	d									
	n									
10–500	d	44 788	1 034	174	13	0.5	34	33	109	801
	n	2 365	164	46	5	0.2	20	23	86	2 708

* Means calculated from 16 echo surveys.

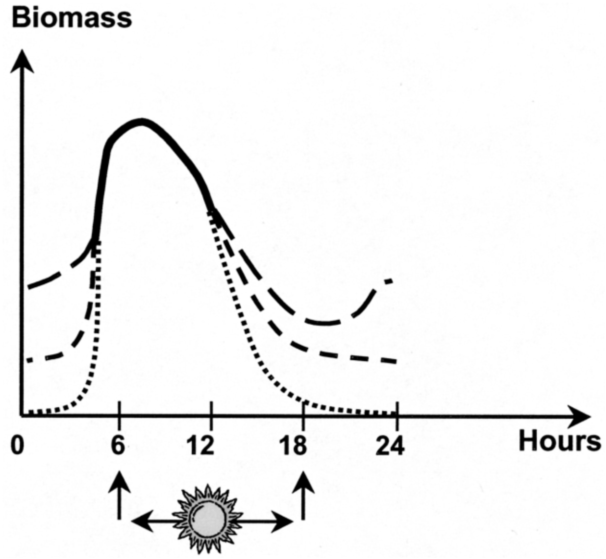

Figure 4. Temporal evolution of the aggregated biomass on a 24-hours basis from acoustic data. In solid line: average situation observed during the first part of the day. In dotted lines: different situations observed in the afternoon and during the night.

tuna comprising the aggregations, the distance between two individuals, and the depth of fish decrease from the type ‘deep scattered fish’ to the type ‘intermediate scattered fish’, then to the type ‘shallow schooling fish’ (*figure 5*), while the density of fish increases. This typology argues for a size-dependent behaviour of fish around FADs. Larger fish occupy the deepest waters and do not really seem to form a structured aggregation. Smaller fish are found in shallower waters and form schools that stay close to the FAD. This size-dependent vertical distribution is commonly accepted for fish schools or fish aggregations, but has rarely been confirmed by in situ observations (Parrish, 1989).

Anchored FADs are known to have some effects on tuna movements (Cayré and Chabanne, 1986; Holland et al., 1990; Cayré, 1991; Kleiber and Hampton, 1994; Bach et al., 1998; Josse et al., 1998; Marsac and Cayré, 1998), implying consequences for the spatial distribution and residence time of fish in an area. If it is assumed that all tuna that are present in an area can be attracted by FADs located within that area, all the different individuals (species and sizes) should be found around or beneath a FAD. The behaviour of fish however, might be different depending on the species and the size of fish, and the proportion of each category might therefore change.

Data collected on some small artisanal fishing boats in Tahiti showed interesting species composition (*table V*). Local fishermen use two different techniques to catch fish around FADs. The more frequently used fishing technique is the drop-stone technique (Moarii and Leproux, 1996) where hooks are set between the depths of 150 and 350 m, depending on the strategy and current conditions. Such depths correspond to the depth strata where ‘deep scattered fish’ were observed by acoustic methods. The other technique is trolling to catch fish in the first few metres below the surface. All the captures are made during daytime. Around 85 % of the overall catch in number of fish are taken with the first fishing technique, i.e. deep fishing. These results are in agreement with our results, as aggregated schools of small individuals were very rarely observed around FADs in the Tuamotu or the Society Archipelagos. When fish were detected by the echo sounder, the ‘deep scattered fish’ type was always observed, which shows that large fish in deep waters are more frequently encountered than smaller schooling fish. Fish caught by the drop-stone technique are likely to belong to this class. Composition of FAD-associated captures indicates that the ‘deep scattered fish’ are likely to be mainly large albacore *Thunnus alalunga* (Bonnaterre, 1788) and yellowfin tuna (> 100 cm fork length). Fish of this category showed feeding motivation beneath FADs as they reacted to the baited hooks.

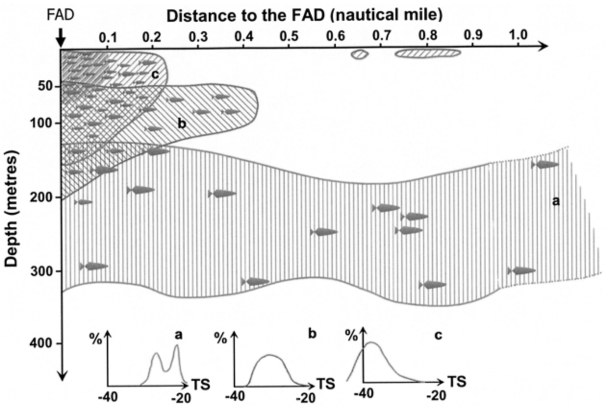

Figure 5. Typology of aggregations around a fish aggregating device: (a) ‘deep scattered fish’, (b) ‘intermediate scattered fish’ and (c) ‘shallow schooling fish’. For each type of aggregation, a schematic histogram of TS values distribution observed is represented.

Echo counting was used by Bertrand and Josse (in press) to estimate the longline tuna abundance in the French Polynesia exclusive economic zone (EEZ) between the surface and a depth of 500 m. A density of 1.3 fish per km^2, 2.7 fish per km^3, was found. This value was obtained inside an area where all the FADs of the present study were located. If only the ‘deep scattered fish’ class is considered, the average density around FADs anchored in nearshore area (7.3 fish per km^3) was nearly 2.7 higher than the density observed in the open ocean without FADs. It is not possible, however, to determine if these differences were due to an attractive effect of FADs or to a nearshore versus offshore effect of the biological environment.

The ‘intermediate scattered fish’ class was very rarely observed alone. It was most of the time observed in association with ‘deep scattered fish’. As fishermen do not frequently set their hooks in depths

Table V. Catches made around FADs by small artisanal fishing boats in Tahiti in 1997*.

Species	Fishing gear	Number of fish		Total weight		Mean weight (kg)
		n	%	kg	%	
Thunnus alalunga	Drop-stone	615	69.8	11 675	62.6	19.0
Thunnus albacares	Drop-stone	125	14.2	5 382	28.8	43.1
Thunnus obesus	Drop stone	3	0.3	177	0.9	59.0
Katsuwonus pelamis	Trolling	56	6.4	109	0.6	1.9
Coryphaena hippurus	Trolling	44	5.0	427	2.3	9.7
Acanthocybium solandri	Trolling	2	0.2	22	0.1	10.7
Small tuna	Trolling	25	2.8	75	0.4	3.0
Billfish	Trolling	11	1.2	796	4.3	72.4

* The total fishing effort during the year for all these boats was 361 fishing days. The category 'small tuna' represents either yellowfin (*Thunnus albacares*) or bigeye (*T. obesus*) tuna of less than 5 kg. The category billfish gathers the sworfish *Xiphias gladius* (Linnaeus, 1758), the blue marlin *Makaira mazara* (Jordan and Snyder, 1901) and the striped marlin *Tetrapterus audax* (Philippi, 1887).

corresponding to the acoustic detection of these fish, artisanal fishing data cannot be used to determine the species and size composition of this class. TS values show that fish are smaller than those composing the 'deep scattered fish' group, and the few experimental catches made during the scientific surveys tend to indicate that these fish are mainly yellowfin tuna with a fork length between 60 and 100 cm, with some albacore tuna with less than 100 cm fork length.

Experimental troll-fishing showed that fish composing the 'shallow schooling fish' were mainly small bigeye and yellowfin tuna (mean size of 50 cm fork length, see Josse and Bertrand, in press). The two series of surveys made around the FAD anchored north of the Marquesas Islands always showed the presence of 'shallow schooling fish' while only one series of surveys around one FAD anchored in the Society Archipelago exhibited the presence of this type of aggregation. The observation of 'shallow schooling fish' of small bigeye and yellowfin tuna might be due to the northern location of this buoy, in an area where small tuna are likely to be more abundant than in the Tuamotu or Society Archipelagos.

Series of several two-hour surveys over the same FADs and over a short period (24 hours for instance) allowed the study of the temporal evolution of the aggregated tuna biomass. The maximum biomass seems to occur during daytime and a total of 81 % of the nocturnal surveys did not show the presence of fish around FADs. This result may confirm a behaviour pattern reported by different authors: some fish tagged with an ultrasonic device spent the daytime at the FAD site and left it at night (Holland et al., 1990; Cayré, 1991; Bach et al., 1998; Marsac and Cayré, 1998). Some nocturnal surveys however, indicated the presence of fish aggregated around FADs, which also confirms some other sonic tagging experiments where fish spent the entire duration of the track associated with the FAD, day and night (Cayré and Chabanne, 1986; Bach et al., 1998). Even if the present acoustic data tend to confirm that fish are mostly aggregated beneath FADs during daytime, the presence of associated fish during night-time is in agreement with the variety in diel horizontal patterns observed for individual fish. Individuals composing an aggregation might behave differently, as shown by the different patterns observed using ultrasonic telemetry. The co-occurrence of different individual behaviours should lead to different dynamics for the aggregations, as observed in the current study. The number of nocturnal surveys in this study however, was inferior to the number of diurnal surveys (21 versus 66), and more comparative observations between daytime and night-time aggregations should be developed.

5. CONCLUSION

This data represents the first acoustic characterization of tuna aggregations around FADs. The three different types of aggregations i.e.: 'deep scattered fish', 'intermediate scattered fish' and 'shallow schooling fish', seem to be related to different sizes (and maybe species) of fish, as shown by the TS values. The structure and the dynamics of some aggregations observed with this acoustic tool complement results on fine-scale movements of individuals observed by acoustic telemetry. If we add the fact that acoustics also provide information about the biological environment of fish (Josse et al., 1998), we thus have two useful and complementary tools to improve our knowledge on tuna behaviour around floating objects. These tools should be used together for studying tuna aggregations, especially on drifting floating objects.

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