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Acoustic estimation of longline tuna abundance

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The French Polynesia Economic Exclusive Zone is located in an important longline fishing ground for albacore (*Thunnus alalunga*), yellowfin (*T. albacares*) and bigeye tuna (*T. obesus*). Longline tuna abundance estimates using commercial catches are particularly biased when hook depth does not coincide with the depths at which tuna prefer to swim. To avoid catchability problems, a direct acoustic estimate of tuna abundance was made in the French Polynesia EEZ using a 38 kHz echo-sounder with a depth range of 500 m. Several biases can influence individual tuna target selection, such as the threshold effect, the risk of multiple target acceptance, the beam width effect and the reduction in target detection at depth. However, they all appeared to be limited in effect. Comparison with experimental longline catches shows that the acoustically selected targets appear to be representative of longline tuna distribution. A density of 1.33 fish per km^2, i.e. about 33.8 kg of tuna per km^2, was measured. Such a density is slightly greater than the estimate based on tuna catches, as the whole tuna habitat range is not sampled by most professional longlining.

Key words: acoustics, tuna, abundance estimation, echo-counting, target-strength.

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Introduction

Abundance estimates based on fishing catches are known to be biased (Fréon and Misund, 1999). Catch per unit effort (c.p.u.e.) depends on catchability, and therefore on resource accessibility, vulnerability and on fishing gear efficiency. Until recently observation of tuna was only possible when fish were captured or when they aggregated close to the surface. In this latter case tuna schools can be directly observed, using aerial radiometry (Petit and Kulbicki, 1983) or by sonar (Rees, 1996, 1998; Nishida *et al*., 1998). When used in an experimental manner sonar allows school detection on a very large horizontal range (up to 40 km) but can only be applied to aggregated tuna. The only way to estimate the abundance of large scattered tuna distributed down to more than 500 m has been the use of longline catches. Longline c.p.u.e. values are not necessarily good indices of tuna abundance, as hook depth must coincide with hydrologic optimal depth, which is not always the case (Hanamoto, 1987; Boggs, 1992; Hampton *et al.*, 1998). Acoustic methods are currently used for fish biomass estimation but have never been applied to tuna. One of the reasons was the lack of individual acoustic response (target-strength: TS) references, which is a principal requirement for biomass estimation using acoustics. Recent studies (Bertrand *et al*., 1999a, b; Josse and Bertrand, 2000) gave a preliminary range for tuna TS (Table 1). Those results can be used as a reference to select individual targets, which can be assimilated to tuna-like echoes during acoustic surveys. Acoustic tuna abundance estimation was carried out in French Polynesia for scattered fish targeted by longline fisheries, including large albacore (*Thunnus alalunga*), yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*). Here, a method of target selection for scattered tuna is described, acoustic validation and specific representativeness of the selection are discussed, and a protocol for acoustically estimating longline tuna biomass is proposed.

Material and methods

The observations were made during ECOTAP (studies of tuna behaviour using acoustic and fishing experiments) programme surveys on board the IRD R/V "ALIS" (28 m long). Experiments were carried out in the French Polynesia EEZ between 4 and 20°S and 134 and 154°W in the vicinity of the Society, Tuamotu and

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Table 1. Target-strength values for yellowfish (*Thunnus albacares*) and bigeye tuna (*T. obesus*) measured by Bertand *et al.* (1999a, b) and Josse and Bertrand (2000).

Species	Fork length (cm)	Estimated mass (kg)	Average TS (dB)	References
T. albacares	60	4	− 34.8	Bertrand *et al.* (1999a, b)
T. albacares	90	14	− 33.0	Bertrand *et al.* (1999a, b)
T. albacares	108	25	− 30.4	Bertrand *et al.* (1999a, b)
T. albacares	120	30	− 26.1	Bertrand *et al.* (1999a, b)
T. obesus	49.9	3	− 32.8	Josse and Bertrand (2000)
T. obesus	50.1	3	− 31.9	Josse and Bertrand (2000)
T. obesus	110	30	− 24.4	Bertrand *et al.* (1999a,b)
T. obesus	130	50	− 21.4	Bertrand *et al.* (1999a,b)

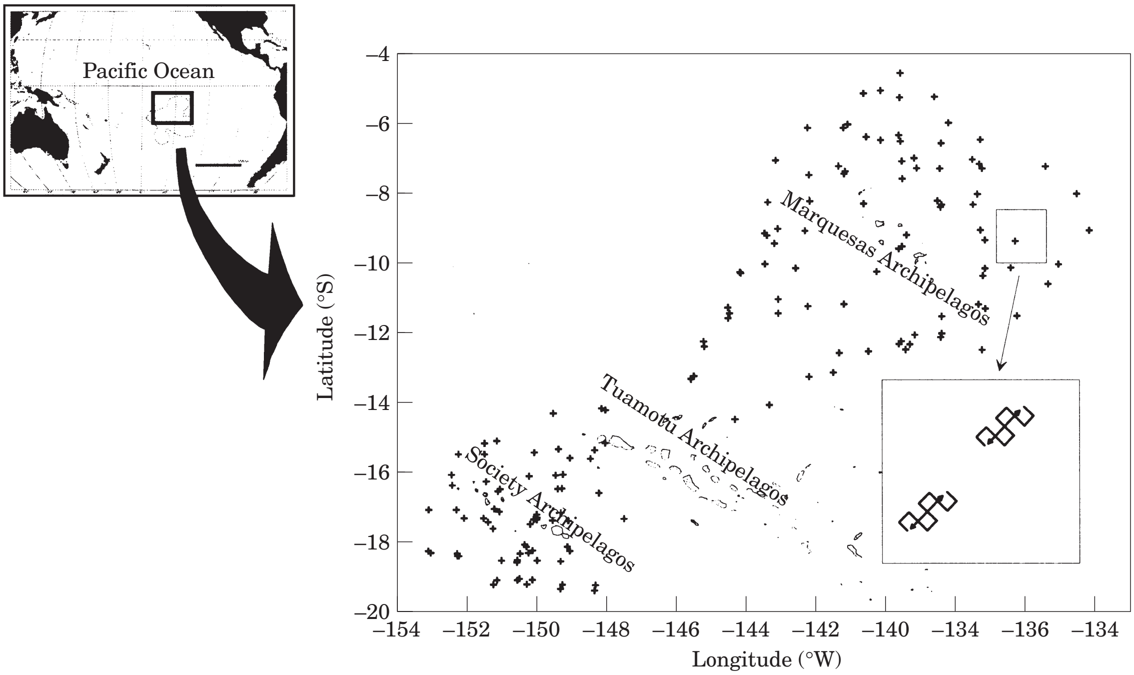

Figure 1. Longline station positions during ECOTAP cruises in French Polynesia. Lower right: daytime acoustic observations were conducted along rectangular tracks (simple line) above the long line (arrow-ended line).

Marquesas Archipelagos, from October 1995 to August 1997. A total of 132 diurnal rectangular acoustic survey carried out above the experimental longline sets were used (Fig. 1). Average distance covered during surveys was 30 nm at a speed of 7 knots.

Data acquisition

Acoustic data were collected with a SIMRAD EK500 (version 4.01) echosounder connected to a 38 kHz split-beam hull mounted transducer SIMRAD ES38B used with a pulse duration of 1.0 ms. The observation window was extended from the surface to 500 m in depth. Acoustic and navigation data were stored *via* Ethernet on a PC throughout SIMRAD EP500 software. The on-axis and off-axis calibration was performed with a 60 mm copper sphere using the standard procedure described in the EK500 manual (SIMRAD, 1993). The EP500 trace tracking procedure (SIMRAD, 1994) was used to extract single targets selected by EK500. Table 2 gives the main settings used during the ECOTAP cruises.

At least two approaches were possible for target selection. A first approach consisted of using all single targets selected by EP500 with an average TS in the range of results obtained by Bertrand *et al.* (1999a, b) and Josse and Bertrand (2000) without taking into account EK500 selection threshold bias. Such an approach favours data quantity. In contrast, a second

Table 2. Main settings of the SIMRAD EK500 echosounder used during ECOTAP cruises.

Operation Menu	Ping interval	0.0 (automatic)
	Transmit power	Normal 10
	Noise margin (dB)	
Tranceiver Menu	Absorption coef.	10 dB/km
	Pulse length	Medium
	Bandwidth	Auto
	Max. power (W)	2000
	2-Way beam angle (dB)	20.9
	Sv transducer gain (dB)	27.7
	TS transducer gain (dB)	27.8
	Angle sensitiv.	21.9
	3 dB beam angle (deg.)	6.9
	Alongship offset (deg.)	− 0.07
	Athw.ship offset (deg.)	0.21

approach favoured information quality with a more restrictive selection criteria. Individual fish selection using EK500 version 4.01 must be considered with great caution. Soule *et al.* (1995) warn that the risk of multiple targets acceptance is important. Because of this the second approach, which favours selection quality at the expense of quantity, was used.

The minimum number of detections to track a fish was set to three. Such a criterion minimizes the risk of multiple target acceptance but may lead to an underestimation of the number of fish targets. For the EP500 selection, considering results from Bertrand *et al.* (1999a, b) and Josse and Bertrand (2000), a − 38 dB threshold was applied on mean fish TS to exclude targets with lower TS than longline tuna. As a final step, fish selection was meticulously validated manually using EP500 plots and paper echograms.

The number of selected targets was then converted into density. For that purpose, sampling volume was determined from maximal angular target position in the acoustic beam according to depth. In that way, volume calculation takes into account the beam shrinking that occurs after a limit depth due to echo-sounder directivity. The number of fish was converted to density by volume (number by km^3) and by surface area (number by km^2).

Results and discussion

A total of 361 tracks of fish with TS consistent with the range of tuna TS were selected. The average density was 2.66 fish per km^3, or 1.33 fish per km^2. In almost 20% of the surveys, no fish were detected and the presence of three fish or more occurred in only 20% of the surveys (Fig. 2). Target-strength range varied between − 35 and − 16 dB with a mean value of − 21.7 dB (Fig. 3).

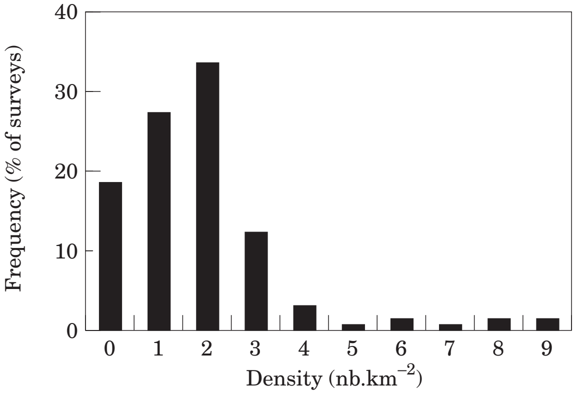

Figure 2. Histograms (% of surveys) of the density (number of fish per km^2) of the selected individual targets.

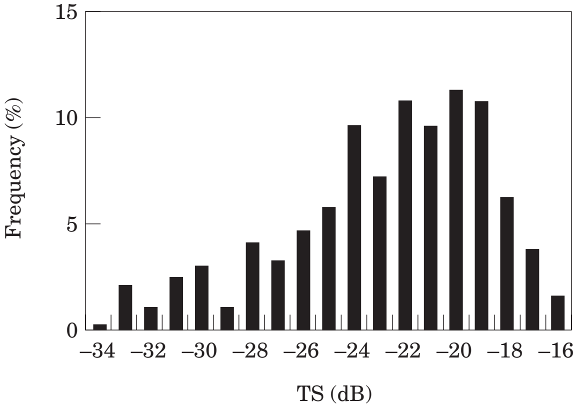

Figure 3. Target-strength histogram of selected individuals targets.

Bertrand *et al.* (1999c), using acoustics and pelagic trawls, made a typology of tuna prey (micronekton) distribution in the study area. They showed that the Polynesian EEZ could be divided into three zones with different characteristics (Fig. 4). The richest zone (2) is principally located between 8 and 13°S and corresponds to a weak convergence. Two zones with very different hydrological features but with comparable micronektonic abundances surround the 8–13°S band. To the north, waters are enriched by equatorial upwelling, but intense organic matter remineralization limits oxygen availability below the mixed layer. To the south, waters are influenced by the great southern gyre and display oligotrophic features, which are less favourable to micronekton development. Fish density, as detected by acoustics and mean target-strength, was then calculated for the whole study area and for each micronektonic zone (Table 3). Tuna density was significantly higher (Kruskal–Wallis test, $p<0.01$) in zone 2 where prey levels are higher. The lowest density was encountered in zone 3 where micronekton abundance is average but

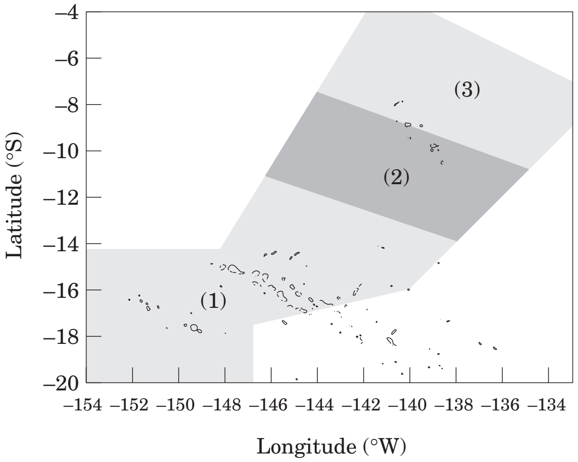

Figure 4. Micronektonic abundance zones from Bertrand *et al.* (1999c).

Table 3. Fish density as detected by acoustics in the whole study area and for each of the three zones of micronekton abundance determined by Bertrand *et al.* (1999c).

	Total	Zone 1	Zone 2	Zone 3
Density (no · km^{-2})	1.33	1.33	1.87	0.69
Mean TS (dB)	− 21.7	− 21.6	− 21.3	− 23.5

where habitat range is limited by the presence of deep deoxygenated waters.

It is necessary to determine the validity of the individual targets selection by studying the influence of the threshold and of methodological constraints. The species representativeness must also be studied according to tuna TS references and spatial distribution of ECOTAP experimental longline tuna catches. A plot of the selected individual targets, which also shows limits set by the selection threshold and the maximal depth of detection of a target on-axis and off-axis, allows a discussion of the validity of the selection (Fig. 5). This is achieved by considering separately the threshold effect, multiple target acceptance bias, beam width effect and echo-sounder target detection limits at depth.

Threshold effect

A − 38 dB threshold was applied to fish selection. What is the associated risk of underestimating the number of tuna? The stochastic nature of TS may lead to occasional TS values, calculated over few pings, lower than − 38 dB even for a fish with higher mean TS (calculated over a large number of echoes). Large amplitude of variation in fish TS is common (Dawson and Karp, 1990; Ona, 1990; MacLennan and Simmonds, 1992; Rose and Porter, 1996; Misund, 1997; Bertrand *et al.*, 1999b). The threshold was chosen based on results from Bertrand *et al.* (1999a, b) and Josse and Bertrand (2000). The lower TS (− 34.8 dB) in these earlier studies was measured on a 60 cm long yellowfin tuna (Table 1). Longline catches are only exceptionally composed of tuna with a size equal to or smaller than 60 cm long. Therefore, even when taking into account TS variability for a given fish, the risk of fish underestimation can be assumed to be low with a − 38 dB threshold. After manual validation, no fish with mean TS on a track lower than − 35 dB were retained (Fig. 5).

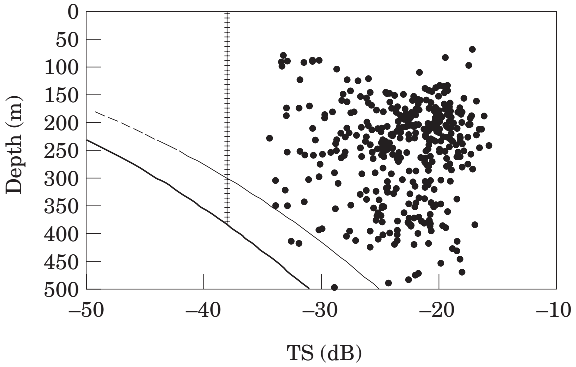

Figure 5. Plot of selected target-strength versus depth pairs (points) according to the threshold limit (hatched line) and the maximal depth of detection of targets on-axis (bold line) and off-axis (spotted line).

Multiple target acceptance bias

The manual validation of selected tracks appeared essential as a bias due to multiple targets acceptance was clearly observed when micronekton aggregates were present. Aggregations of micronekton were often recognized as being single targets with TS consistent with the tuna's range. It is not satisfactory to base a selection on a manual validation for several reasons. Manual validation is both time consuming and introduces an important risk of subjectivity. Better selection algorithms may eliminate the requirement for manual validation. Soule *et al.* (1997) point out that the version 5.0 of EK500 echo sounder is more accurate but, "Due to physical limitation, complete rejection of overlapping echoes is impossible to achieve with single frequency *in situ* TS systems". The use of a double frequency is one solution, but the classical 38–120 kHz pair cannot be used when a 500 m range is considered. However, here, manual validation was necessary to limit multiple target acceptance mainly when micronekton aggregations were present. In that way, fish overestimation is reduced. Taking into account the choice to favour quality criteria during manual validation and the fact that tuna echoes can be hidden when large amounts of micronekton are present, bias tends towards fish underestimation rather than overestimation.

Beam width effect

No fish were selected at a depth less than 70 m (Fig. 5). This may be the consequence of a combination of both the beam angle effect and selection criteria. Effective beam angle for TS selection determined from angular position is 9.2°. With such a value, the acoustic beam diameter is 11 m at a distance of 70 m from the transducer. Thus, the probability of tracking a large tuna for at least three pings when the vessel speed is 7 knots is low. Therefore, a risk of fish underestimation exists in the first 100 m of depth. Results of ultrasonic tracking studies in the study area (Bach *et al.*, 1998; Josse *et al.*, 1998; Dagorn *et al.*, 2000) and of experimental longline catches (ECOTAP unpublished data) show that free swimming tuna are rarely distributed close to the surface at daytime. Consequently, bias due to beam width is probably very weak.

Echo-sounder target detection limits at depth

Small target underestimation can occur due to the threshold effect but also to the acoustic beam shrinking at depth. Maximum depth of detection of an individual target decreases with TS. When approaching the depth limit to detection of a target located in the acoustic beam, the beam angle progressively decreases. Thus, the effective echo-sounder angle decreases from a limit depth. Maximal depth of detection of a target on the beam axis can be determined from using:

$\mathrm{TS} \geq 40 \log \mathrm{R} + 2\alpha \mathrm{R} - \mathrm{SL} + \mathrm{NL} + \mathrm{SNR} + \mathrm{NM}$ (Josse *et al.*, 1999),

where R is the range (i.e. the depth), α is the attenuation coefficient, SL is the source level, NL is the noise level, SNR is the signal to noise ratio and NM is the noise margin. The limit depth to detection of a target located on the edge of the beam depends on the sounder directivity. Maximum gain compensation used during data acquisition was 6 dB. Thus, at the limit depth of detection, to be detected, a target located at the maximal angular distance must be 6 dB higher than a target located in the beam axis.

The risk of underestimating the number of weak targets (− 35 dB) begins at 350 m (Fig. 5). As was discussed above, such a target corresponds to yellowfin tuna less than 60 cm long. Such a size of fish was never observed as deep as 350 m in telemetric tracking experiments carried out in French Polynesia (Cayré and Chabanne, 1986; Abbes *et al.*, 1995; Bach *et al.*, 1998; Josse *et al.*, 1998). No yellowfin tuna even much longer than 60 cm were caught below 380 m during ECOTAP experiments (ECOTAP unpublished data). Only bigeye and albacore were caught below 400 m. If TS measurements on bigeye (Table 3) and empirical results on albacore (discussed below) but also ECOTAP catches and telemetric tracking experiments, are considered, fish able to dive below 400 m are large enough to have TS greater than − 30 dB. Thus the risk of under estimating small tuna targets exists deeper than 350–400 m but it is probably very minor.

As was discussed above, four different potential biases may affect the selection of tuna echoes, but their effects are probably weak. In addition to those biases, the fact that the acoustic range was limited to 500 m must be considered. In the Society Archipelagos, some fish were caught deeper than 500 m, and so some deep tuna were probably not detected. How can these potential biases effect the specific representativeness of selected targets? To answer this question, results will be discussed according to tuna TS references, and ECOTAP experimental longline tuna catches.

Comparison between individual targets and target-strength references

The only information on tuna TS is derived from the ECOTAP programme and solely concerns yellowfin and bigeye tuna (Table 1). No TS measurements were validated on albacore. Nevertheless, information about albacore TS can be extracted from studies conducted around FADs. Josse *et al.* (2000) defined three kinds of aggregations. One of these, the “deep scattered”, supposed to be mainly composed of albacore compared with catches from the artisanal fleet in the same depth layer. The corresponding TS vary between − 34.4 and − 19.0 dB, with a mean of − 23.0 dB. Such a range is consistent with results obtained in this study, but also with selection criteria and the methodological constraints. However, albacore TS appears high and the mean TS value needs to be discussed. The swimbladder is supposed to be responsible for 90–95% of the backscattering energy (Foote, 1980). At an equal size, yellowfin TS is lower than for bigeye because the latter has a swimbladder with a larger volume (Bertrand *et al.*, 1999b). The albacore swimbladder is proportionally more voluminous than in yellowfin but smaller than in bigeye (Bard *et al.*, 1998). The shape of the albacore swimbladder is elongated. Thus, at equal volume, the swimbladder cross-section is higher for albacore than bigeye. More than the volume itself, it is the cross section, which contributes to TS (MacLennan and Simmonds, 1992). Therefore, even if the albacore swimbladder volume is lower than in bigeye, the difference between the two species is reduced when the cross section is taken into account. This may explain why albacore TS is high.

Table 4. Distribution of density of selected targets and c.p.u.e. in number of fish per 100 hooks (ECOTAP, unpublished data) according to zone.

Zone	Targets	All tunas	Albacore	Bigeye	Yellowfin
Z1	1.33	1.38	1.00	0.30	0.09
Z2	1.87	1.94	0.88	0.58	0.48
Z3	0.69	0.84	0.03	0.38	0.43

Table 5. Tuna biomass estimates from acoustic density results.

	Total	Zone 1	Zone 2	Zone 3
Density (nb $\cdot$ km^{-2})	1.33	1.33	1.87	0.69
Mean tuna weight (kg)	25.4	24.2	23.9	33.2
Biomass density (mg $\cdot$ m^{-2} or kg $\cdot$ km^{-2})	33.8	32.2	44.8	22.8

In the present study, mean TS of selected targets is −21.7 dB. The mean TS varies between −21.3 dB in zone 2 and −23.5 in zone 3 (Table 1). These average TS are very high, as they are just lower than TS measured on a 50 kg bigeye tuna (Table 1). However, because TS are expressed in dB and therefore on a logarithmic scale, high TS have a strong influence on mean TS as the mean is calculated after transformation to an arithmetic scale.

Is it possible to determine if target selection corresponds to one of the three tuna species or is composed of a mix of the three species? At an equal size, yellowfin tuna are assumed to have the lowest TS of the three tuna species exploited by longline in French Polynesia. Mean TS is lower in zone 3 (Table 3) where albacore are almost absent from longline catches and yellowfin contribute to close to 50% of tuna catches (Table 4). Such a result supports the hypothesis that selected targets stem from a mixing of tuna species. Of course, targets of other large pelagic fish with a swimbladder, such as billfish may have been selected, but no references on target-strength are available. The bias due to selection of other large pelagic fish is probably limited, as tuna are numerously dominant in the French Polynesian EEZ.

Spatial distribution of selected targets

Assumption of a multi-specific composition of the acoustic selection is reinforced if frequency of individual targets selection and ECOTAP catches for all three species or each species individually are compared by zone (Table 4). ECOTAP catches can be considered to be less biased than commercial ones as the whole range of tuna habitat was sampled. The spatial distribution of the target density and of the c.p.u.e. for all three tuna species combined are linearly correlated (Table 4). In contrast, the distribution of the densities and of tuna c.p.u.e.s species by species differ (Table 4).

Acoustic abundance and tuna biomass

It has been shown that acoustics allow for the selection of individual scattered tuna echoes. The selection of tuna targets appears qualitatively robust, but may be quantitatively biased. Acoustic tuna density estimates must be compared with other estimates to check whether or not the order of magnitude of the acoustic estimate is realistic. Individual targets densities were converted to biomass using individual mean tuna weight from ECOTAP catches (Table 5).

No tuna biomass estimates are available in the study area or even in the central Pacific. Josse *et al.* (2000) measured by acoustics a density of 3.65 "deep scattered" tuna per km^2 around FADs. This assumes that for that kind of fish, the aggregation factor of FADs is 3 in French Polynesia. If this concentration is assumed to be accurate, a comparison with the results of this study seems to indicate that the order of magnitude of scattered tuna is realistic.

Sharp (1978) assumes that "if tunas were truly uniformly dispersed in their habitat they would be so rarely encountered as to be virtually non-existent". This author proposes a density of 10 kg of yellowfin every 2.8 km^2 (0.36 fish per km^2) in the eastern tropical Pacific, which is also in the same order of magnitude that tuna density measured by acoustics. It confirms that acoustics allows the observation of such "virtually non-existent" tuna.

The extrapolation of acoustic tuna density estimation to the whole Polynesian EEZ North of 20°S, with a surface area of 2.9×10^6 km^2, lead to an estimation of biomass of about 100 000 tons (170 000 tons for the whole Polynesian EEZ, i.e. 5×10^6 km^2) if the average biomass per km^2 is used (Table 5). The estimate is similar if the calculation is made according to the estimated tuna density for the three zones (Table 5) extended to the total EEZ.

Acoustic tuna biomass estimation is high compared with the biomass estimation based on fishing catches (Bard, 1999; Bertrand, 1999) even if, as discussed above, it is unlikely that fish underestimation occurred in this study. This result illustrates the fact that the whole vertical tuna habitat range is not sampled by longline hooks and that the tuna population is underestimated by c.p.u.e.s. This bias is more important South of Tuamotu Archipelagos where bigeye tuna are almost absent in longline tuna catches (Chabanne *et al.*, 1993; Fonteneau, 1997) when they were numerous in deep ECOTAP catches (ECOTAP, unpublished data). As a consequence, acoustics are probably a better tool to estimate longline tuna abundance than c.p.u.e.-values when the population is not fully exploited and/or the whole vertical range of habitats is not sampled by longline.

Conclusion

This study shows that longline tuna distribution and abundance can be determined by acoustics independently of commercial fishing activities. Furthermore, acoustic methods permit direct biomass estimates to be made, unlike using c.p.u.e.-values. Unfortunately, species recognition between tuna species is not yet possible. Improvement in acoustics will probably allow faster data processing and facilitate estimations of tuna abundance. There are many possible fields of application: it can improve stock management and fishing power by allowing the exploitation of new areas or depth layers; comparing acoustic tuna observations and fishing catches may improve knowledge of catchability; lastly, acoustic fish observations may improve knowledge of the distribution and behaviour of large pelagic tuna.

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References

Abbes, R., Asine, A.-S., Bach, P., Josse, E., Lebourges, A., and Wendling, B. 1995. Etude du comportement des thonidés par l'acoustique et la pêche à la palangre en Polynésie Française. Rapport de la Campagne ECOTAP. Doc. Int. EVAAM/IFREMER/ORSTOM. 157 pp.

Bach, P., Dagorn, L., Bard, F.-X., Abbes, R., Bertrand, A., and Misselis, C. 1998. Experimental research and fish aggregating devices (FADS) in French Polynesia. SPC FAD Information Bulletin, 3: 3–19.

Bard, F. X., Bach, P., and Josse, E. 1998. Habitat, ecophysiologie des throns: quoi de neuf depuis 15 ans? ICCAT Symposium of Sao Miguel, June 1996, Beckett, J. S. Eds, L(1): 319–341.

Bard, F. X. 1999. Estimation du potential en thons profonds de la ZEE polynésienne. *In* ECOTAP, Etude du comportement des thonidés par l'acoustique et la pêche à la palangre en Polynésie Française505–523. Ed. by R. Abbes, and F.-X. Bard. Rapp. Final Convention Territoire/EVAAM. IFREMER/ORSTOM no. 950170, Chap. 11.

Bertrand, A. 1999. Le système (thon–environnement) en Polynésie Française: caractérisation de l'habitat pélagique, étude de la distribution et de la capturabilité des thons, par méthods acoustiques et halieutiques. Thèse de Doctorat de l'ENSAR, 308 pp.

Bertrand, A., Josse, E., and Massé, J. 1999a. Preliminary results of acoustic target strength measurements of bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*). *In* Proceedings of the 5th Indo-Pacifique Fish Conference, Nouméa, 1997, pp. 443–450. Ed. by B. Séret, and J.-Y. Sire. Société Française d'Ichtyologie, Paris. 866 pp.

Bertrand, A., Josse, E., and Massé, J. 1999b. *In situ* acoustic target-strength measurement of bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*) by coupling split-beam echosounder observations and sonic tracking. ICES Journal of Marine Science, 56: 51–60.

Bertrand, A., Le Borgne, R., and Josse, E. 1999c. Acoustic characterisation of micronekton distribution in French Polynesia. Marine Ecology Progress Series. 191: 127–140.

Boggs, C. H. 1992. Depth, capture time, and hooked longevity of longline-caught pelagic fish: timing bites of fish with chips. Fishery Bulletin, 90: 642–658.

Cayré, P., and Chabanne, J. 1986. Marquage acoustique et comportement de thons tropicaux (albacore: *Thunnus albacares*, et listao: *Katsuwonus pelamis*) au voisinnage d'un dispositif concentrateur de poissons. Océanographie Tropicale, 21: 167–183.

Chabanne, J., Abbes, R., and Josse, E. 1993. La pêche palangrière asiatique dans la Z.E.E. de Polynésie Française: analyse des données disponibles pour la période 1984–1992. Centre ORSTOM de Tahiti, Archives d'Océanographie, 93-04: 28 pp.

Dagorn, L., Bach, P., and Josse, E. 2000. Behaviour pattern of large bigeye tuna (*Thunnus obesus*) in the open ocean determined using ultrasonic telemetry. Marine Biology. In press.

Dawson, J. J., and Karp, W. A. 1990. *In situ* measures of target-strength variability of individual fish. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 264–273.

Fonteneau, A. 1997. Atlas of tropical tuna fisheries. World catches and environment. ORSTOM Eds, Paris, 192 pp.

Foote, K. G. 1980. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. Journal of the Acoustical Society of America, 67: 2084–2089.

Fréon, P., and Misund, O. A. 1999. Dynamics of pelagic fish distribution and behaviour: Effects on fisheries and stock assessment. Blackwell Science, London. 348 pp.

Hanamoto, E. 1987. Effect of oceanographic environment on Bigeye tuna distribution. Bulletin of the Japanese Society of Fishery Oceanography, 51: 203–216.

Hampton, J., Bigelow, K., and Labelle, M. 1998. A summary of current information on the biology, fisheries and stock assessment of bigeye tuna (*Thunnus obesus*) in the Pacific Ocean, with recommendations for data requirements and future research. Technical report, Secretariat of the Pacific Community. Oceanic Fisheries Programme no. 36, 46 pp.

Josse, E., and Bertrand, A. 2000. *In situ* acoustic target strength measurements of tuna associated with a fish aggregating device. ICES Journal of Marine Science, 57: 913–920.

Josse, E., Bach, P., and Dagorn, L. 1998. Simultaneous observations of tuna movements and their prey by sonic tracking and acoustic surveys. Hydrobiologia, 371/372: 61–69.

Josse, E., Bertrand, A., and Dagorn, L. 1999. An acoustic approach to study tuna aggregated around Fish Aggregating Devices. Aquatic Living Resources, 12(5).

Josse, E., Dagorn, L., and Bertrand, A. 2000. Typology and behaviour of tuna aggregations around Fish Aggregating Devices from acoustic surveys in French Polynesia. Aquatic Living Resources, 13(4). In press.

MacLennan, D. N., and Simmonds, E. J. 1992. Fisheries acoustics. Chapman and Hall, London. 325 pp.

Misund, O. A. 1997. Underwater acoustics in marine fisheries and fisheries research. Reviews in Fish Biology and Fisheries, 7: 1–34.

Nishida, T., Inagaki, T., Miyashita, K., and Kishino, H. 1998. Estimation of southern bluefin tuna recruitment off Esperence in Western Australia based on sonar information. Proceedings of the 49th Annual Tuna Conference, Lake Arrowhead, California, May 18–21 1988, 50.

Ona, E. 1990. Physiological factors causing natural variations in acoustic target strength of fish. Journal of the Marine Biological Association of the UK, 70: 107–127.

Petit, M., and Kulbicki, M. 1983. Radiometrie aérienne et prospection thonière dans la zone économique exclusive de Polynésie Française. ORSTOM Tahiti, Notes et Documents Océanographiques, 20: 98 pp.

Rees, C. D. 1996. Modelling of acoustic detection of yellowfin tuna in the Eastern Tropical Pacific fishery area. Contract (40ABNF510351), Report NCCOSC 541, San Diego, CA. 83 pp. plus appendices.

Rees, C. D. 1998. Active towed-array acoustic system design for yellowfin tuna in the Eastern Tropical Pacific fishery area. Contract (43ABNF61572), Report NCCOSC 541, San Diego, CA. 58 pp. plus appendices.

Rose, G. A., and Porter, D. R. 1996. Target-strength studies on Atlantic cod (*Gadus morhua*) in Newfoundland waters. ICES Journal of Marine Science, 53: 259–265.

Sharp, G. D. 1978. Behavioral and physiological properties of tunas and their effects on vulnerability to fishing gear. *In* The Physiological Ecology of Tunas, pp. 397–449. Ed. by G. D. Sharp, and A. E. Dizon. 485 pp.

Soule, M., Barange, M., and Hampton, I. 1995. Evidence of bias in estimates of target strength obtained with a split-beam echo-sounder. ICES Journal of Marine Science, 52: 139–144.

Soule, M., Barange, M., Solli, H., and Hampton, I. 1997. Performance of a new phase algorithm for discriminating between single and overlapping echo in a split-beam echo-sounder. ICES Journal of Marine Science, 54: 934–938.

SIMRAD 1993. SIMRAD EK500 Scientific echo sounder operator manual. SIMRAD Subsea A/S Horten, Norway. 204 pp.

SIMRAD 1994. SIMRAD EP500 echo processing system. SIMRAD Subsea A/S Horten, Norway. 76 pp.