

Acoustics for ecosystem research: lessons and perspectives from a scientific programme focusing on tuna-environment relationships

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Accepted 10 December 2002

Abstract

Fisheries management now extends from the stock to the ecosystem. The foundation for fisheries management on an ecosystem basis must lie in appropriate modelling of the ecosystems. A prerequisite for such models requires data on the two interactive components of the ecosystem: the biotope (physical environment), and the community of living species. In this context, acoustics become essential, as this tool can provide qualitative and quantitative data on various communities of species, and furthermore allows the seldom-attainable study of their interactions. In fact, acoustics allow the monitoring of entire communities, from plankton to large predators, as well as certain aspects of the physical environment, such as substratum characteristics. Acoustics have been used during the last two decades mainly to provide fishery-independent estimates of stocks. The intention of this paper is to promote the use of acoustics for studying marine ecosystems and to encourage the emergence of new generations of ecosystem models. As an example of integrative research based on acoustic data, we will present the approach and the results of a scientific programme (ECOTAP) carried out to study the tuna pelagic ecosystem in French Polynesia. We then discuss the use of acoustics as a tool for ecosystem-based studies and management.

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Keywords: Acoustics; Behaviour; Ecosystem approach; Pelagic ecosystem

1. Introduction

Ecosystem-based fisheries management has been widely promoted by fisheries management agencies and non-governmental organisations, and will soon be the preferred mode of management (e.g. FAO Reykjavik conference on responsible fisheries in the marine ecosystem: <http://www.refisheries2001.org/>). Interactions between organisms and their environment, and between organisms themselves, are complex and fishing is only one of the factors influencing aquatic communities. The foundation for fisheries management on an ecosystem-basis must lie in appropriate modelling of the ecosystems. Such modelling requires data on the two components of the studied ecosystem: the biotope (physical environment), and the community of living species, the biocoenosis. Some models often considered to be “eco-

system models” are already available (e.g. Ecopath, Ecosim, Ecospace; Pauly et al., 2000) but these are based mainly on trophic relationships between components of the studied communities. In addition, these models do not take explicitly into account the variability of the physical environment and the interactions between the physical environment and species communities. The search for a quantitative understanding of the dynamics of interactions between the biotic and abiotic components of marine ecosystems, and their effects on the dynamics of fish populations constitutes the foundation of modern fisheries oceanography (Dower et al., 2000). Furthermore, as stated by Denman (2000), “it is almost axiomatic to state that confidence in forecast will increase with the increased use of observations”. In other words, we need to develop our understanding to model better ecosystems. At present, the main difficulty resides in our lack of knowledge about the true functioning of ecosystems, primarily due to a lack of available data. In most cases, the only available data concern the exploited species (plus some punc-

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tual data on plankton or other parameters). As a consequence, most current models are based only on multi-species catch data, without any information on other key components of the system (micronekton for instance). These models might be using the term “ecosystem” in an incorrect way. From our point of view, it is of great importance to take care when using the term “ecosystem” else there is a strong risk of it losing its true meaning. An ecosystem approach seeks to study the main components of an ecosystem, knowing that a truly exhaustive study is impossible.

To comply with such an objective, acoustic techniques become essential. Acoustics represent the only tool allowing the simultaneous collection of qualitative and quantitative data on various communities of an ecosystem, from plankton to large predators, and also on abiotic parameters, such as substratum characteristics. Acoustic observations allow the user to investigate ecological relationships in a direct manner. Of course, other methods of observation should also be used in order to collect complementary data.

The purpose of this paper is to promote the use of acoustics for studying aquatic ecosystems and to encourage the emergence of new generations of ecosystem models. As an example of integrative research based on acoustic data, we will present a synthesis of the approach and results of a scientific programme (ECOTAP: Etude du comportement des thonidés par acoustique et par pêche/study of tuna behaviour using acoustics and fishing) carried out to study the tuna pelagic ecosystem in French Polynesia. We will then discuss

the potential of acoustics as a tool for ecosystem-based studies and management. It is important to note that our intention is not to provide an exhaustive review of the studies that have used acoustics coupled with other observation tools to observe different communities of pelagic ecosystems (e.g. Axelsen et al., 2000; Croll et al., 1998; Fiedler et al., 1998; Lebourges-Dhaussy et al., 2000; Marchal et al., 1996; Young et al., 2001), but rather to illustrate our approach through the example of one integrative study.

2. Example of an ecosystem approach: the ECOTAP programme

The integrative objective of the ECOTAP programme was the direct and simultaneous observation of tuna (i.e. albacore, *Thunnus alalunga*; bigeye, *Thunnus obesus* and yellowfin tuna, *Thunnus albacares*), their prey and the hydrologic environment using acoustics, CTD probes, ultrasonic tracking, instrumented longline fishing, pelagic trawling and the analysis of stomach contents (Fig. 1).

3. Materials and methods

Data were collected on-board the IRD R/V “Alis” (28 m long) during ECOTAP experiments carried out in the French Polynesian exclusive economic zone. The study was conducted between 4 and 20°S and 134 and 154°W, in the

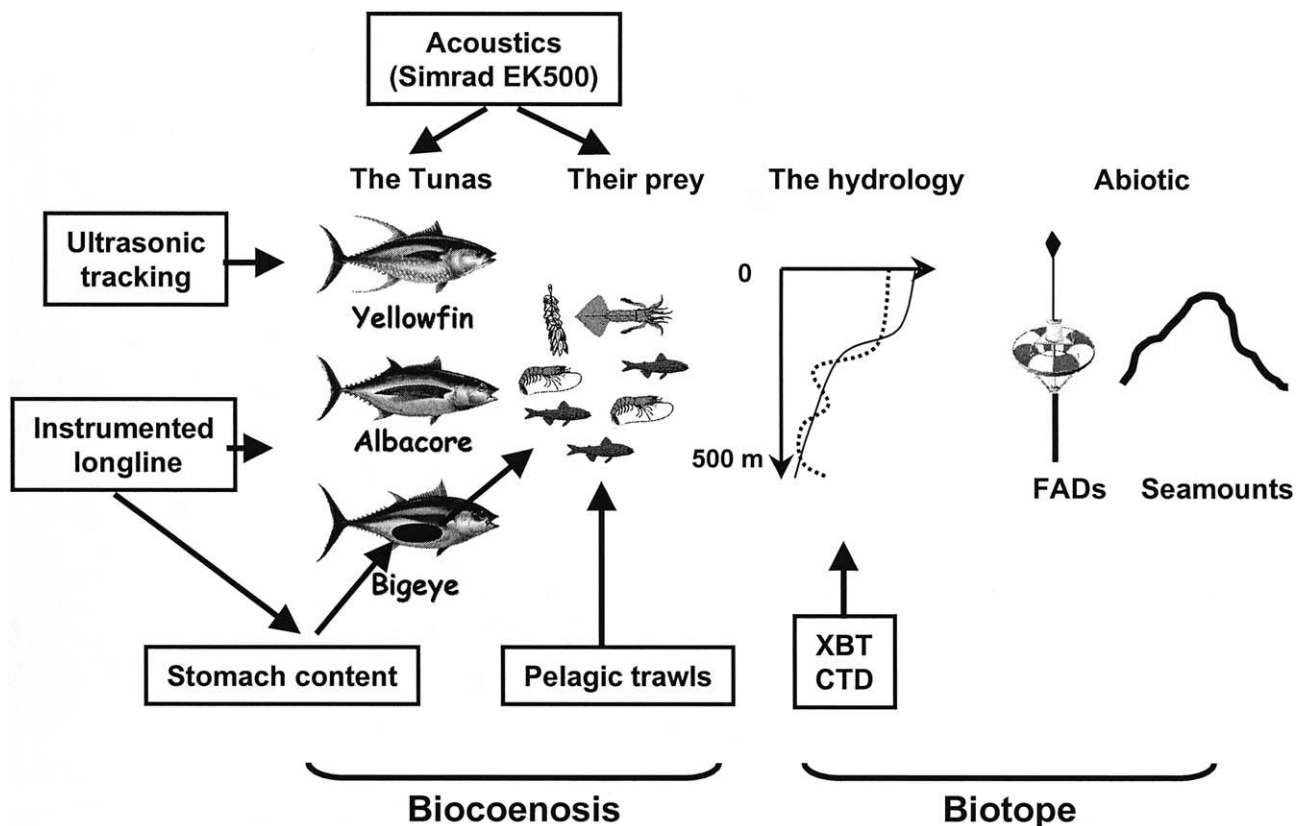


Fig. 1. Schematic outline of the ecosystem approach used during the ECOTAP programme.

vicinity of the Society, Tuamotu and Marquesas Archipelagos, from October 1995 to August 1997. Acoustic data collected with a SIMRAD EK500 connected to a 38 kHz split beam transducer, were recorded to observe both tuna (by echo counting or echo-integration) and their prey (by echo-integration) (Bertrand et al., 1999b; Bertrand and Josse, 2000a; Josse et al., 1999). Acoustic observations were also performed around fish aggregating devices (FADs) to study tuna aggregations (Josse et al., 1999). Temperature, salinity and dissolved oxygen profiles were collected using a probe Seacat SBE 19 (Seabird Electronics, Inc.) between the surface and more than 500 m in depth. A total of 80 000 hooks were deployed during 163 fishing operations conducted using an experimental longline instrumented with hook timers and time-depth recorders (Bach et al., 2003) in order to estimate both time and depth of capture using a model developed by Bach et al. (1996). Micronekton sampling was done using a fry pelagic trawl (5 mm mesh) coupled with echo sounding (Bertrand et al., 2002a). Stomach contents of fish caught by longline were fixed in 10% formalin, then organisms were sorted and weighed at the laboratory (Bertrand et al., 2002a). The tracking equipment we used was a VEMCO system (Shad Bay, Nova Scotia, Canada), 50 kHz, 500 and 1000 PSI equipped with pressure sensor (Josse et al., 1998; Dagorn et al., 2000a).

All of these observational techniques were used to study the relationships between tuna and their environment (biotic and abiotic) as shown in Fig. 1. The main results obtained using an echosounder as the central tool and some potential applications of these results in fisheries science are presented in Table 1.

3.1. Tuna observation

Tuna horizontal and vertical distribution was studied indirectly using an instrumented longline and directly using sonic tracking and acoustics (Fig. 2, Table 1). The simultaneous use of acoustic and ultrasonic tracking allowed studying the fine scale behaviour of tunas and to precise the role of the biotic and abiotic parameters on their horizontal and vertical movements (Josse et al., 1998; Dagorn et al., 2000a, b; Dagorn et al., 2001). Another application of such approach was the measurement of the target strength (TS) of fish individually identified, swimming free in their environment (Bertrand et al., 1999a). An example of spin off of such study was the demonstration that bigeye tuna was more able to adjust the volume of its swimbladder than other physoclists (Bertrand and Josse, 2000b). Furthermore, knowledge on tuna TS allowed the direct observation and assessment of adult tuna dispersed in their environment (Bertrand and Josse, 2000a). Performing tuna direct observation is essential as indirect methods are known to be biased particularly when fishing gears do not sample the whole vertical habitat of tunas. Catchability is a key parameter when using fishing data and a comparison of acoustic tuna observations and longline catch data thus allowed tackling the issue of longline tuna catchability.

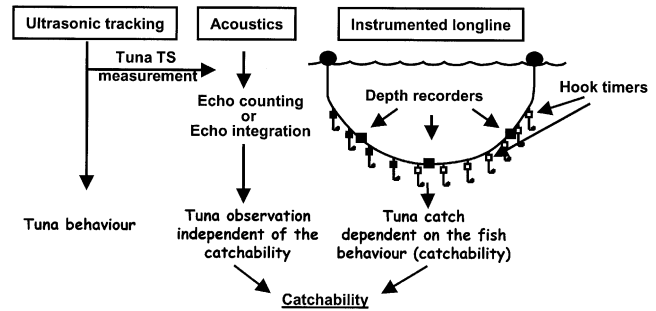


Fig. 2. Schematic outline of tuna observation.

3.2. Tuna prey observation

Tuna prey (i.e. micronekton) distribution was studied through acoustics, pelagic trawls and stomach content analysis (Fig. 3, Table 1). Micronekton and particularly mesopelagic fish such as myctophids plays a major role in the pelagic ecosystems. The importance of this component was often underestimated in the past due to a lack of efficient observation methods. Actually mesopelagic fishes and squids are very poorly sampled by direct methods. However, acoustics allows the direct study of micronekton distribution and structuring at large and small scales. In the Central Pacific using acoustics and pelagic trawls data we showed that micronekton distribution was different from general ideas raised in bibliographical data but not supported by direct observations. Direct data allowed us to propose a schematic model of ecosystem functioning (Bertrand et al., 1999b). Stomach contents were then considered in order to determine (1) how tuna forage according to a given environment, and (2) whether stomach contents are a good indicator of prey diversity and of actual diet. The comparison of pelagic trawl catches, stomach contents and echo-integration data highlights a number of contradictions but each method gives complementary data (Bertrand et al., 2002a, Table 1). We could put into perspective the concept of reduced food availability for tunas in the pelagic environment. Tuna have developed physiological capacities (e.g. thermal inertia and swimbladder efficiency) to dive enough during daytime to exploit the migrant micronektonic species. Each tuna species foraging in specific ecological niche defined in the vertical plan. Finally acoustic observation of tuna prey allowed showing that studies of tuna feeding behaviour may be biased when carried out on tuna caught by a passive gear such as longline.

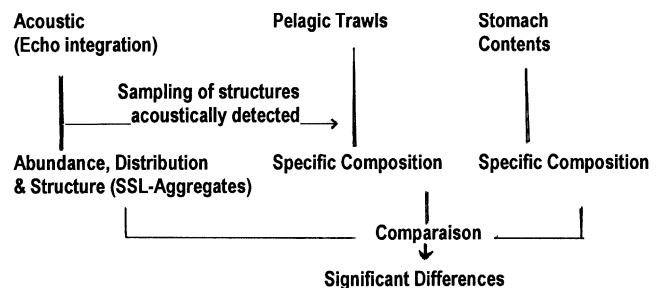


Fig. 3. Schematic outline of tuna prey observation.

Table 1

A synthesis of results obtained during the ECOTAP programme based on acoustic data. Some potential applications of these results in fisheries science are also listed. (1) Bertrand et al. (1999a); (2) Bertrand and Josse (2000a); (3) Josse and Bertrand (2000); (4) Bertrand and Josse (2000b); (5) Josse et al. (1998); (6) Dagorn et al. (2000a); (7) Dagorn et al. (2001); (8) Dagorn et al. (2000b); (9) Dagorn et al. (2000d); (10) Josse et al. (1999); (11) Josse et al. (2000); (12) Dagorn et al. (2000c); (13) Bertrand et al. (1999b); (14) Bertrand et al. (2002a); (15) Bertrand et al. (2002b)

Topics	Tools	Main results	Secondary results	Fisheries science application
Tuna acoustic observation	Echosounder, Ultrasonic tag, Trolling	First tuna TS measurements (1, 2, 3). Preliminary tuna TS relationships to fish length and swimbladder volume (3)	Bigeye ability to adjust the volume of their swimbladder better than might be supposed for other physoclists fish (1, 4)	Direct acoustic tuna observation.
Tuna distribution	Echosounder, Experimental longline	Tuna observation and abundance estimation independent of commercial fishing activities (i.e. independent of catchability) (4)	At a regional scale, tuna distribution related to prey distribution (4)	Direct tuna biomass estimators, particularly when the population is not fully exploited and/or the whole vertical range of vertical habitat is not sampled by longliners.
Tuna swimming behaviour	Echosounder, Ultrasonic tag, CTD, Agent based model	Role of the biotic and abiotic environment in the horizontal and vertical behaviour of tuna (5, 6, 7, 8). Modelling tuna vertical behaviour according to the biotic environment (9)	Respective role of biotic and abiotic conditions	Model tuna horizontal and vertical swimming behaviour, e.g. (9).
Tuna aggregation behaviour	Echosounder, Vertical longline, Fuzzy logic model	Typology and behaviour of tuna aggregated around floating objects (7, 10, 11). Modelling tuna aggregation behaviour according to the local environment (12)	Size dependant behaviour of fish around FADs (11)	Method for tuna aggregation studies. Aggregated tuna densities direct estimation. Data for tuna management. Model tuna aggregative behaviour, e.g. (12).
Micronekton distribution	Echosounder, pelagic trawl, stomach content data, CTD	Direct observation and typology of micronekton distribution. Schematic model of ecosystem functioning (13). Role of deoxygenated water and remineralisation process. No direct relation between plankton and micronekton distribution in the Central Equatorial Pacific (13). Fine characterisation of scattering structures (14)	Role of micronekton spatial structure in ecosystem functioning (13, 15)	Predictive models of tuna forage should incorporate environmental limiting factors. Necessity to take into account the structure of micronekton distribution (scattered vs. patchy).
Tuna feeding behaviour	Echosounder, pelagic trawl, Experimental longline, stomach content data	Determination of how tuna forage according to a given environment, and how tuna diet as ascertained from stomach content, can be a good indicator of prey diversity and of actual diet (14)	The classic concept of reduced tuna food availability in the tropical pelagic environment seems relative (14)	Studies of tuna feeding behaviour when carried out on tuna caught by longlining may be biased (should be taken into account in tropho-dynamic models).
Tuna spatial occupation	Echosounder, pelagic trawl, Experimental longline, CTD	Definition of an index for the vertical volume of tuna habitat according to abiotic conditions. Determination of the biotic and abiotic factors influencing bigeye, albacore and yellowfin tuna spatial occupation (15)	Revisiting of the role assigned to oxygen gradients on tuna distribution. New data on habitat limits of tropical tuna (tolerance vs. temperature and dissolved oxygen) (15)	Quantitative and qualitative data to fit models on tuna behaviour, distribution, etc.
Tuna catchability with a longline	Echosounder, pelagic trawl, Experimental longline, stomach content data, CTD	Determination of the biotic and abiotic factors influencing tuna catchability. Role of the scale of observation and of the prey spatial structure in the tuna catchability with a longline (15)	Observation of a “cryptic” biomass of bigeye tuna (15)	Elements allowing better interpretation of longline CPUE (e.g. prey patch characteristics should be taken into account for resource management or modelling).

3.3. Tuna-environment relationships

Knowledge on precise tuna distribution and habitat characteristics allows an examination of tuna-environment relationships (Fig. 4, Table 1). We defined an index of the vertical volume of tuna habitat according to abiotic conditions. Inside such “abiotic habitat”, we showed that tunas are likely to adopt depths where prey are presents rather than depth of preferred temperature or dissolved oxygen (DO). A spin off

of such study was a new interpretation of the role assigned to oxygen gradient in tuna distribution (Bertrand et al., 2002b). The relation between tunas and their environment have strong impacts in their catchability. To interpret longline catch data, in addition to abiotic parameters, the scale of observation and the type of prey distribution are key factors. On a regional scale, tuna CPUE and prey abundance are positively correlated. On a finer scale, when prey are abundant and patchy distributed this correlation become negative

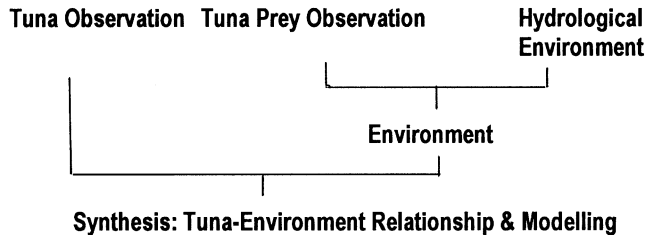


Fig. 4. Schematic outline of tuna-environment approach.

as if tunas preferred to feed on prey rather than on dispersed baits. Longline rates are thus higher in area with high prey-density, but at a small scale inside such areas, very dense patches reduced the catchability of albacore and bigeye tunas (Bertrand et al., 2002b).

3.4. Tuna behaviour modelling

Observations of the prey of tuna distribution and structuring allowed the construction of a simplified model of prey spatial distribution and temporal dynamics. Models of tuna behaviour based on ultrasonic and acoustic observations were then developed to reproduce tuna horizontal (near floating objects, Dagorn et al., 2000c) and vertical (Dagorn et al., 2000d) behaviour according to their environment (Table 1). Modelling applications can be much larger. Predictive models of tuna forage should incorporate environmental limiting factors as we showed that assuming a direct relationship between micronekton and lower trophic levels is not always appropriate (Bertrand et al., 1999b). Modelling tuna distribution and behaviour is a multi-parameter work. For instance, in the vertical plan, inside their range of abiotic habitat, tuna distribution is related to the distribution of prey. Prey vertical position is controlled by irradiance (e.g. Widder and Frank, 2001; Frank and Widder, 2002), but also by the presence of deoxygenated waters at depth or the structure of the food web (Bertrand et al., 1999b, 2002a, b). Finally acoustics, which was the central tool allowing the construction of such theoretical scheme is also needed to validate potential models on tuna distribution according to the ecosystem structure.

4. Acoustics for ecosystem research: lessons and perspectives

In the case of the present programme (Table 1), as in the case of other integrative studies based on acoustics (e.g. Croll et al., 1998; Lebourges-Dhaussy et al., 2000), such an approach led to significant scientific findings. However, as already stated by Brandt and Mason (1994), acoustics should be used much more often as a central tool for the study of ecosystems and ecological modelling. Although these techniques are certain to become increasingly popular, using acoustics and interpreting data with relevance are not always simple tasks, particularly for non-acousticians.

A research programme focusing on ecosystem functioning is based foremost on biology, ecology and ethology. For

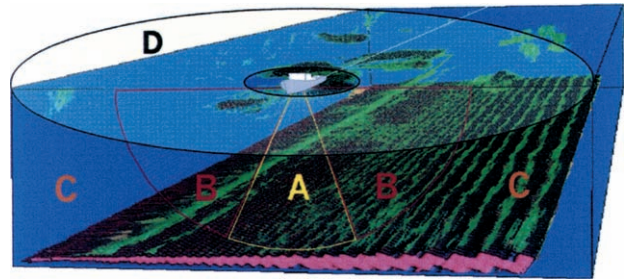


Fig. 5. Drawing of the future “ideal” multibeam system for fisheries acoustics and ecosystem research (Gerlotto, personal communication). (A) beams forming the “vertical multi-beam echosounder” area (in this area, TS values can be calculated using standard methods, assuming the organisms are normally insonified on their dorsal aspect); (B) beams forming the “school structure and biomass measurement” area (here, the background noise due to side lobe echoes on the bottom are not present, and the characteristics of the schools can be measured with precision); (C) area at distance longer than the depth, for shoal counting and cluster analysis; (D) combined with a 360° long range sonar to study school behaviour.

the scientists involved, acoustics represent a tool (i.e. not a research topic) allowing qualitative and/or quantitative, direct and simultaneous observations of the main biotic and some abiotic components of an ecosystem.

Studying ecosystems and understanding the functional relationships connecting the various compartments of the ecosystem at various space-time scales often requires observations on large vertical and/or horizontal ranges. The limitations of acoustics are dynamic and vary according to ambient noise levels and many other parameters (e.g. frequency, acoustic power). For example, at 38 kHz, with the vertical range we used during the ECOTAP programme (i.e. 500 m), we were continuously close to the echosounder’s limits for echo-integration and echo-counting (Josse et al., 1999). This kind of limitation is often difficult to explain to non-acousticians. As more and more researchers are brought to use these techniques, it is essential that acousticians make an effort towards non-specialists in order to promote acoustics and to make these techniques accessible and comprehensible. The acoustician must adapt tools and methods to these new objectives. In addition, it is the role of the acoustician to validate and to interpret acoustic data in relation to data from other observation tools.

Carrying out ecosystem studies often implies the need for huge amounts of data. Acoustic data are known to be extremely voluminous, particularly if we want to be able to re-process them with different thresholds. Finally, studies on fish behaviour (mainly schooling and avoidance behaviour) and also on TS, etc. should remain important research focuses, as they still constitute major biases when observing aquatic ecosystems acoustically.

The number of acoustic tools available for ecosystem approaches is increasing from year to year. However, no universal tool exists. Choosing an echosounder, for example, is not solely limited to the choice of a manufacturer, but also implies compromises such as choosing one or several frequencies, a beam width, etc.; decisions which themselves depend on the desired range, the studied communities, and so

on. These choices, which can sometimes appear commonplace for an “expert” acoustician, are again often difficult to explain to non-acousticians. Furthermore, to perform an “ideal” ecosystem study you may actually need one or several research vessels, a multifrequency echosounder to maximise species recognition, a multibeam sonar to take full advantage of school behaviour observation, a TAPS™ acoustical zooplankton sensor vertically undulating to maximise plankton observation, high performance software for acoustic data processing (e.g. Movies + or Echoview), an autonomous underwater vehicle, as well as CTD probes, micronekton and plankton pelagic trawls (and/or purse seine, longline, etc.), remote sensing data on SST, chlorophyll, and more. In other words, you need something near to an armada. Of course, such a deployment of force is often out of reach and sometimes inoperative due to interference and other concerns.

In the near future we can reasonably hope that new integrative tools will be available to study ecosystems. New systems should be derived from recent developments in multibeam echosounders (Gerlotto et al., 1999, 2000; Mayer et al., 2002). An “ideal” system for fisheries acoustics (Fig. 5) could be composed of a “180° multi-beam echo sounder” where central beams calculate TS values using standard methods; lateral beams are used to determine 3D structures and perform biomass measurement; and long range lateral beams are employed in shoal counting and cluster analysis (Fig. 5). All of this could be combined with a 360° long-range sonar to study school behaviour. With such a tool we should obtain a real scan of the ecosystem’s composition and be able to study fish behaviour. Acousticians and ecologists will need to collaborate in the development of such a tool. Number of “non-acousticians” still believe that acoustics are only used for biomass estimation, since many “acousticians” use acoustic data only in this way (see Fernandes et al., 2003 for a review of acoustic applications in fisheries science). When acoustically assessing a stock, much effort is devoted to removing echoes from plankton or micronekton. This information is considered to be pure noise and simply eliminated. However, such information is fundamental to the study of predator-prey relationships and more generally to understand and model resource distribution and ecosystem functioning. We can reasonably consider that micronekton is a key component when modelling pelagic ecosystem. In that way acoustics should play a major role when constructing theoretical models of ecosystem functioning but also to validate mathematical models. Many laboratories all over the world dispose of a huge amount of data stocked with information about the biomass and distribution of “non-targeted species” (predator, prey, competitor, etc.). Fisheries ecologists should capitalise on these data for the purpose of integrative studies. This implies that researchers who may not have any knowledge of acoustics should make the effort to exploit such data in a fruitful way. In the future, estimates could be made routinely for targeted species, and also for other organisms. Such efforts are unavoidable if we want to move towards

truly ecosystem-based management. This implies for instance that all the frequencies available on a research vessel should be used on a routine basis. To move further in this direction, some projects are seeking to develop “plug on play” echosounders and other acoustic tools in order to make routine observations of ecosystems from moored buoys, merchant ships, fishing ships (e.g. Melvin et al., 2002), and others.

The joint application of acoustic techniques, which allow direct monitoring of the ecosystems at different spatiotemporal scales, and powerful new modelling methods, should lead to considerable progress in our knowledge and management of ecosystems, but will require that acousticians, ecologists, and modellers work hand in hand. If this challenge is undertaken, acoustics will certainly be the most important and commonly used observation tool of aquatic ecosystems in coming decades.

Acknowledgements

The Government of French Polynesia supported this research. The authors wish to thank the officers and crew of the R/V “ALIS” for their kind assistance during experiments. Sincere thanks are extended to all of our colleagues from SRM, IFREMER and IRD, who worked with us during the ECOTAP programme. We are also grateful to François Gerlotto for very helpful comments. Gareth Lawson is warmly thanked for revisiting the English of this paper.

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