Chapter 3. How many fish in the sea and where?

Active acoustics to assess marine organisms

Anne Lebourges-Dhaussy

1 To establish balanced use between the users of a maritime space, the first step is to know this space: its abiotic characteristics and their dynamics; its biotic components, their distribution and dynamics; vulnerable areas and rich zones; mapping of fish habitats (LE PAPE *et al.*, 2014); the human and economic environments, etc. This initial diagnosis requires determining the distribution of living resources, exploited or not. For this purpose, the use of active acoustics was developed in the 1970s, and this method of assessing and observing the marine environment has since become commonplace in many countries around the world (in Europe, Australia, the United States, but also in Senegal, Morocco, Mauritania, Peru, Mexico, etc.). Its use has now been extended to the study of aquatic ecosystems as a whole, as fluctuations in fish populations cannot be explained without taking their environments into account. This non-intrusive and non-destructive method also has the advantage of being suitable for studying protected areas where biological sampling is not permitted.

The value of active acoustics

2 Acoustic data is a source of information for a range of components in a biocenosis and sometimes a biotope. The data is generally acquired continuously during oceanographic campaigns, from the surface to a depth of 1000 m or more. This provides a view of the ecosystem with a resolution unmatched by other approaches (on the order of a decimetre vertically and a few metres horizontally). By using several transmission frequencies, the different components of the ecosystem can be detected:

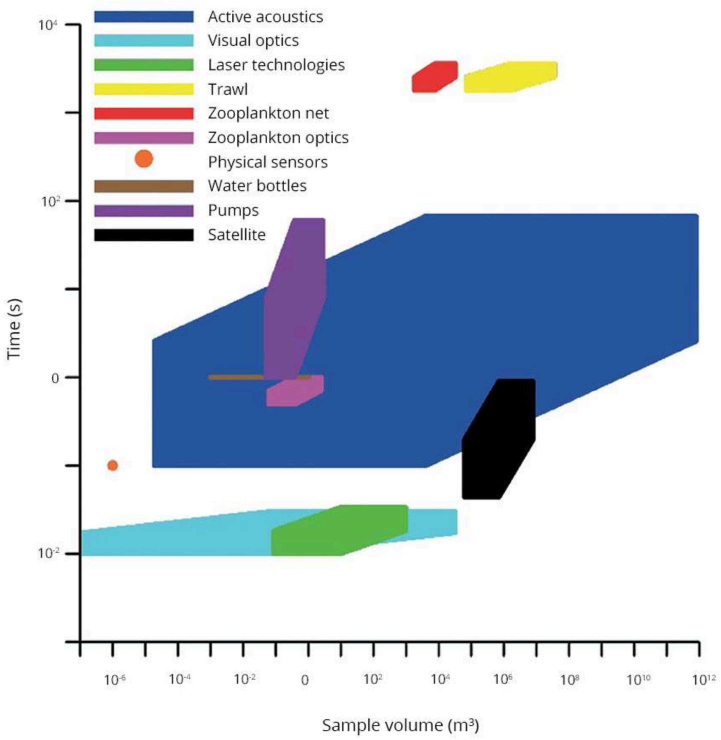
- strong physico-chemical gradients (of temperature, oxygen, density)
- the seabed and its geological composition
- zooplanktonic organisms (crustaceans and gelatinous organisms), in schools or in layers
- fish (from a few centimetres to several tens of centimetres), dispersed or aggregated

• top predators (e.g. tuna, marine mammals)

3 Acoustic data also provides information on the behaviour of organisms (vertical migrations, changes in the structure of organisms between day and night, movement in schools or dispersed, in layers, etc.). The information obtained is unique because of the spatial and temporal coverage it provides compared to other observation methods (fig. 1).

4 Acoustic data is thus essential to assess exploited and unexploited fish stocks and their trophic environment, to understand their nychthemeral, seasonal or interannual behaviour and predator/prey relationships, to define preferential habitats, etc., all of which is knowledge that can inform the choices necessary for marine spatial planning (MSP).

Figure 1. Spatio-temporal coverage of an observation unit for different in situ methods



The minimum resolution of the measurement is indicated by the lower left corner of each polygon and its maximum extension by the upper right corner.
Source: Trenkel et al. (2011)

Method

Principles

5 The physical principle of active acoustics is based on the propagation of acoustic waves in the water, which come into contact with the biotic components present in the marine environment. Propagation takes the form of a succession of compression-dilatations of the medium, which are supported by the particles that constitute it. An acoustic wave cannot propagate in a vacuum, it needs a particulate support. Each

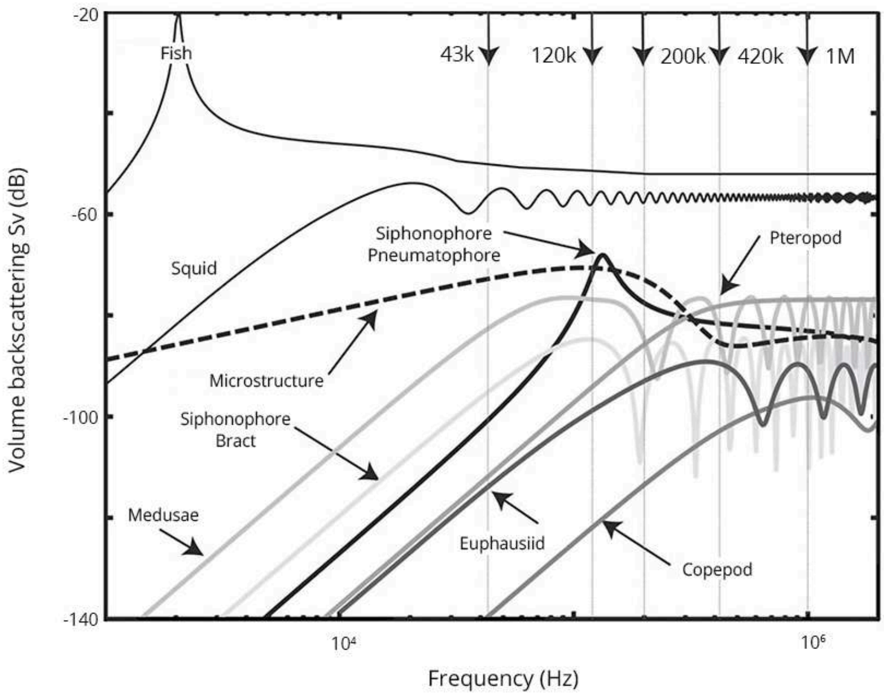
particle transmits a local pressure anomaly to its neighbour, which then propagates this to the next particle. When a change of density occurs in the medium, the obstacle presents more or less resistance to the movement of the particle, modifying the way in which the pressure anomaly is transmitted. Thus, part of the energy transmitted by the acoustic wave is reflected back to the source (as an echo) and the other part continues to propagate beyond the obstacle.

6 The ability of a target to reflect an acoustic wave is mainly determined by its density difference with the surrounding medium, in this case seawater or fresh water, and by the contrast in wave propagation speed between the medium and the target. Echoes will be strong whether they come from targets denser than water (rocks) or less dense (gas bubbles, water–air interface). Marine organisms containing a gaseous inclusion, such as some planktonic organisms (syphonophores to pneumatophores), or a gas swim bladder, such as many pelagic fish (sardines, anchovies, tuna, etc.), are very good reflectors.

7 The reflective properties of targets are a function of their density, size, shape and orientation with respect to the direction of the wave and its frequency. For a number of well-studied and documented fish species, equations quantify the relationship between the reflectivity index of a fish and its total length (SIMMONDS and MACLENNAN, 2005). For other species, such as triggerfish around Fernando de Noronha (Brazil), documentation does not exist; in this case, it is necessary to calculate these relationships from field data (SALVETAT *et al.*, 2022).

8 In the range of ultrasonic frequencies used, from about 18 to 400 kHz, organisms can have highly variable responses depending on the frequency (fig. 2). Multi-frequency systems are thus used to exploit the characteristics of the targets (fish, crustaceans, gelatinous animals, etc.) in order to better classify them. In this way, the fish, their predators and their prey can be observed simultaneously through the acoustic data.

Figure 2. Echo levels as a function of frequency for the main biological groups, at a density of one organism/m3 of water



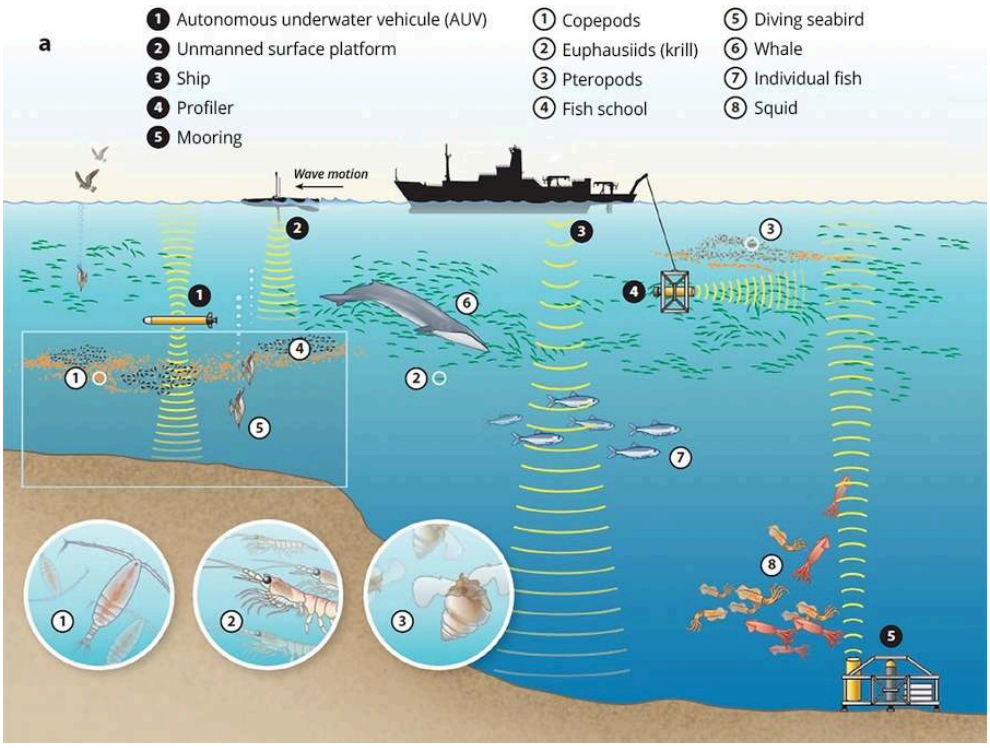
Microstructure: change in density of the medium; syphonophore and medusa: cnidarians; euphausiid and copepod: crustaceans; pteropod: molluscs.
Source: LAVERY *et al.* (2007)

Implementation

9 There is a wide variety of acoustic equipment. The most commonly used are mounted on the hull of research vessels. However, they provide data at the time of the field mission only and detect targets only from the surface. To detect deep targets (sometimes at several hundred metres), at distances where hull-mounted equipment does not provide sufficient resolution and/or provides data for which the signal-to-noise ratio becomes too low, there are autonomous sounders that can be directed close to the targets of interest in order to obtain better quality and much more spatially refined measurements. Other devices are designed to provide time series and are installed on moorings. Some very high frequency equipment, used as profilers, is dedicated to the detection of zooplankton (fig. 3).

10 A depth sounder (see black circle 3 in figure 3) is used continuously for the duration of a typical survey. Generally, it emits a wave into the water every second: at 10 knots, this corresponds to an emission every 5 m. The wave propagates to depths that are greater the lower the frequency used. Typically, at 38 kHz, it is possible to detect fish to a depth of about 1000 m. The vertical resolution is a few centimetres. The data is quasi-continuous both vertically and horizontally.

Figure 3. Acoustic devices used for ecosystem studies



Source: Benoit-bird and Lawson (2016)

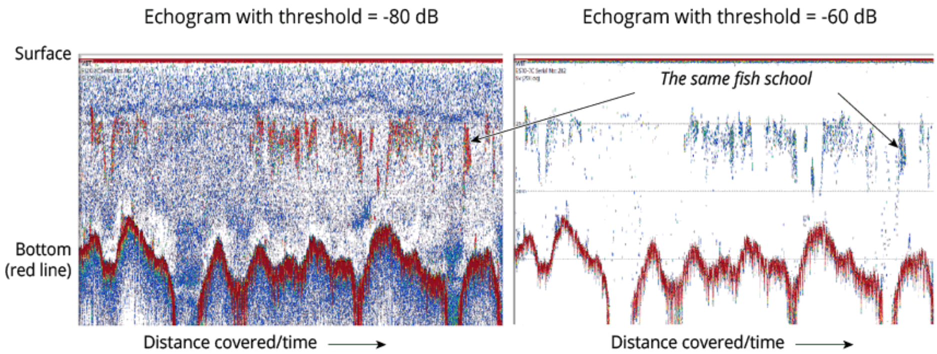
Assessing marine organisms

11 Active acoustics tools and methods were initially developed at the beginning of the 20th century to determine the depth of the ocean floor beneath a ship (the first echo sounder was marketed in 1925), particularly after the sinking of the Titanic (Juhel, 2005). The first mention of the use of a sounder to assess marine organisms dates from 1935 in an article in *Nature* on the detection of cod shoals in a Norwegian fjord with an echo sounder (Sund, 1935). Then as now, this is the only approach that makes it possible to "see", from the surface to the seabed, continuously along the ship's path, the reflective organisms present in the water column. As the reflectors are varied and of all sizes, depending on the frequency or frequencies used, it is possible to obtain a fairly exhaustive representation of the underwater "landscape". However, scientists have been primarily interested in fish, responding to the need to assess stocks of commercial interest in order to better manage them.

12 Stock assessments are based on the principle of echo integration, which is itself underpinned by a principle of linearity: for a given sampled volume, the reverberated acoustic energy results from the linear combination of the individual contributions of the organisms present in this volume. The higher the concentration of fish and/or the larger the fish, the higher the acoustic energy. "Echo integration" consists of summing the vertical samples of acoustic energy received in an integration cell, i.e. a given water height (e.g. the water column) for a given distance travelled (typically 1 nautical mile at sea).

13 In this integration cell, there may be a fish of several species, as well as zooplankton, gelatinous organisms, etc. So the first step is to select the share of fish in the total received acoustic energy. Applying a data analysis threshold of -60 dB (as in the example of figure 4) is sometimes sufficient to separate fish (acoustic energy above the threshold) from other organisms in the same trophic environment (acoustic energy below the threshold). In some cases, a classification algorithm based on the differentiated frequency responses of fish and other organisms can be used to better account for fish (MORENO *et al.*, 2007; FERNANDES, 2009; BALLÓN *et al.*, 2011; KORNELIUSSEN *et al.*, 2016; KORNELIUSSEN, 2018).

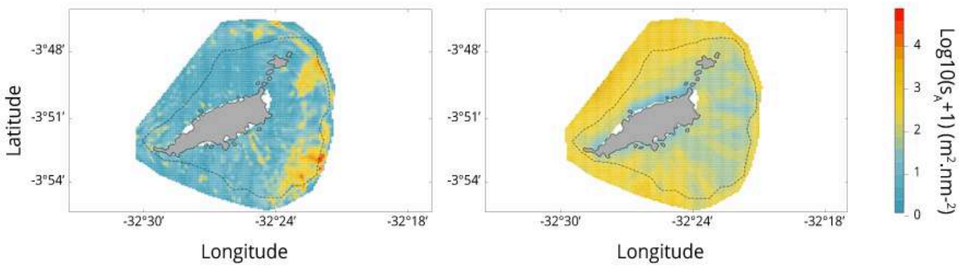
Figure 4. **Example of an echogram from the Farofa2 campaign ("Tropical Atlantic Interdisciplinary Joint Laboratory on physical, biogeochemical, ecological and human dynamics", LMI Tapioca) around Fernando de Noronha (Brazil) with two different thresholds (-80 dB on the left and -60 dB on the right).**



Source: A. Lebourges-Dhaussy

14 Once the proportion of acoustic energy related to fish has been identified, a map of their distribution can be made, as well as a map of the distribution of other types of organisms (fig. 5).

Figure 5. **Spatial distribution of fish (left) and other organisms (right) around the island of Fernando de Noronha (Brazil) by geostatistical interpolation of surface acoustic density s_A (see MCLENNAN *et al.*, 2002 for definition of acoustic quantities).**

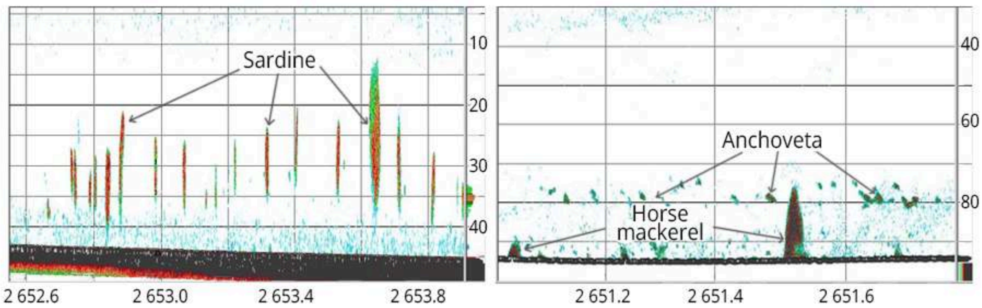


The 50 m isobath is indicated by the black dotted line.
Source: SALVETAT *et al.* (2022)

15 Stock assessment is ideally done by species. Within the share of energy returned by "fish" in the detection, this energy is divided according to the species present, some of which are exploited by fisheries, others not. Determining the distribution of energy between species is aided by identification trawls carried out using different types of

detection and the expertise of the scientific team on the pattern of detections by species in a given geographical area and season (fig. 6).

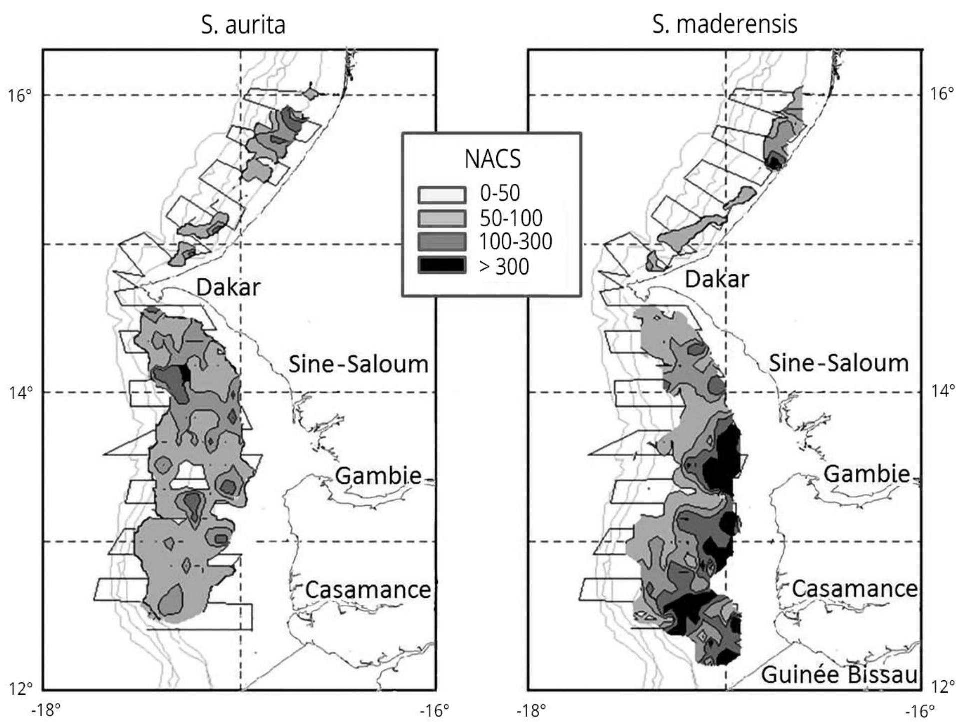
Figure 6. **Detection of typical fish schools in the Bay of Biscay (France) in spring: sardines (left), anchovies and horse mackerel (right), confirmed by identification trawls. The acoustic energy of each school is calculated and assigned to the corresponding species.**



Source: Noël Diner, pers. comm.

16 The distribution of each species is thus mapped in terms of surface acoustic density (SAD) (expressed in $m^2.nmi^{-2}$, MCLENNAN *et al.*, 2002) (fig. 7). Based on the size distribution from the trawls, the equations relating the individual echo of a fish to its size or to its size and mass make it possible to estimate the mass of the species per unit area. This mass, assigned to the distribution area of the species, ultimately provides an estimate of the total biomass of the species.

Figure 7. **Acoustic density distribution (NASC, in $m^2.nmi^{-2}$) of two Senegalese sardinella species (*Sardinella aurita* and *S. maderensis*) obtained by the acoustic campaigns of the research vessel Itaf Deme 2005-2006-2007 (Senegal)**



Source: SARRÉ *et al.* (2018)

17 There are a number of uncertainties associated with this assessment method (SIMMONDS and MACLENNAN, 2005). Weather plays an important role: bad weather (wind, swell) generates surface bubbles that attenuate the propagated signal to an extent that is difficult to quantify, and induces vessel movements that prevent the correct detection of echoes (if the orientation of the vessel changes between the time of transmission and reception). The classification of species based on acoustic detection is also a source of potential error: the assignment of detection to a given species (e.g. fig. 6) is done with an "expert eye" in an area and season for which the types of aggregation of species are known. Yet this assumes their stability, an assumption that may be challenged in the event of a strong wind event, for example.

18 In poorly documented, multi-species regions, trawling often identifies assemblages of species, and it is difficult to be more precise than the assemblage itself in the distribution of acoustic energy. The factor for converting acoustic density into a quantity and then mass of fish is not known for all species, particularly in tropical environments; equations from the literature are therefore used, which are not necessarily optimal for the environment studied. Fish behaviour is another important factor: the noise caused by vessels, depending on the depth of the organisms targeted and the frequency of use of the areas studied, may cause fish to avoid the vessel and no longer be detected by the vertical sounder. Devices such as omnidirectional sonars can detect schools of fish around the boat, but they do not allow for the quantitative analysis of observations, which is necessary for evaluation. They do, however, provide information on the presence of schools not detected by the vertical sounder under the boat. Despite these (studied and known) uncertainties and biases, the assessment of pelagic fish stocks with the acoustic approach is at least as good as – and probably better than – other existing methods (SIMMONDS and MACLENNAN, 2005). A combination of methods is, in any case, preferable.

Other applications of interest to MSP

Ecosystem approach

19 The ecosystem approach to resource management is currently considered the most relevant for achieving sustainable development, and is thus one of the key elements in marine spatial planning (ANSONG *et al.*, 2017).

20 In the case of active acoustics, moving from a fisheries approach to an ecosystem approach is a fairly simple choice. Indeed, as shown in figure 4, lowering the threshold for the visualisation and analysis of acoustic data allows the biotic environment of the fish to be taken into account. The latter, which is made up of planktonic layers, has a distribution that is much more constrained by the physical conditions of the environment (waves, stratification, currents, etc.) than the nekton, which is much more mobile, except when the environmental conditions include parameters that limit its survival. Acoustic observation of the distribution of organisms thus makes it possible to extract information on the hydrodynamic characteristics of the water column, provided that a low enough threshold is used. In the case of Peru, for example, the vertical distribution of anchovies (*Engraulis ringens*) is particularly constrained by oxygen availability. Acoustic detection of anchovy schools provides information on the depth of the oxycline (where the oxygen level drops rapidly relative to the surface

layer of the ocean), with the very fine resolution of the acoustic data (fig. 9A, BERTRAND *et al.*, 2010).

21 In addition to the data provided by acoustics on the distribution of fish and their biotic or even abiotic environment and its hydrodynamic structure, the ecosystem approach also takes into account primary production, currents, topography, etc., from other sensors (see Box 1 on biologging in marine megafauna) and aims to understand their interactions.

Box 1. How can megafauna biologging data be used for marine spatial planning?

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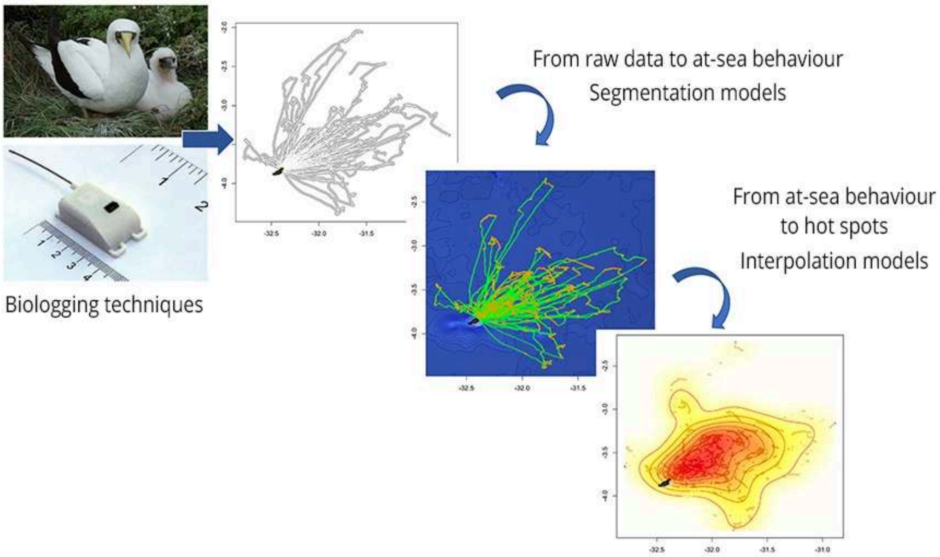
Marine systems have a number of attributes that make them particularly difficult to delineate for management purposes. They are inherently three-dimensional, opaque compared to terrestrial systems, and many systems (such as fronts and eddies) are dynamic in space and time. Fusion and scaling of oceanographic and ecological data are required to observe, dynamically manage and conserve species embedded in a dynamic mosaic of seascapes.

Marine megafauna (seabirds, marine mammals, large fish, etc.) are highly mobile animals that move over large areas of the sea to feed, breed, rest or migrate. Thus, a comprehensive understanding of the causes, patterns, mechanisms and consequences of megafaunal movements is essential to manage human activities in seascapes under multiple pressures: for example, through marine spatial planning. Yet measuring habitat use at sea and defining critical niches and corridors has long been a challenge.

In recent decades, considerable progress has been made with a range of recording technologies. Biologging refers to the use of miniaturised tags attached to animals to record and/or transmit data on an animal's movements, behaviour, physiology and/or environment. Today, ecologists have access to an arsenal of sensors (triaxial accelerometers, magnetometers, global positioning systems, cameras, diving sensors, etc.) that can continuously measure most aspects of an animal's condition (e.g. location, behaviour, caloric expenditure, interactions with other animals) and its external environment (e.g. temperature, salinity, depth). These technologies allow ecologists to obtain new answers about the physiological performance, energy, foraging, migration, habitat selection and sociality of wild animals, as well as to collect data about the environments in which they live. Combined with state-of-the-art statistical modelling in movement ecology, biologging technologies provide essential information on the dynamic ecological niches of megafauna species. This is a key step in delineating biodiversity hotspots and coldspots, which can help to better define conservation issues in a marine spatial planning framework (fig. 8).

Figure 8. **Biologging data collected on seabirds (*Sula sula*) from the Fernando de Noronha archipelago (Brazil) in the framework of the Paddle project**

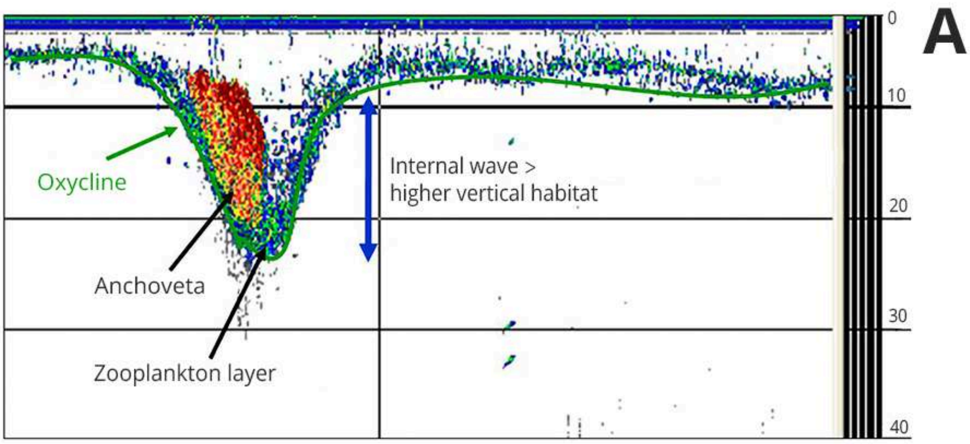


The raw GPS data was processed by different statistical models to identify feeding areas and deduce critical areas (hotspots) for this species.

Potential habitat and habitats to be preserved

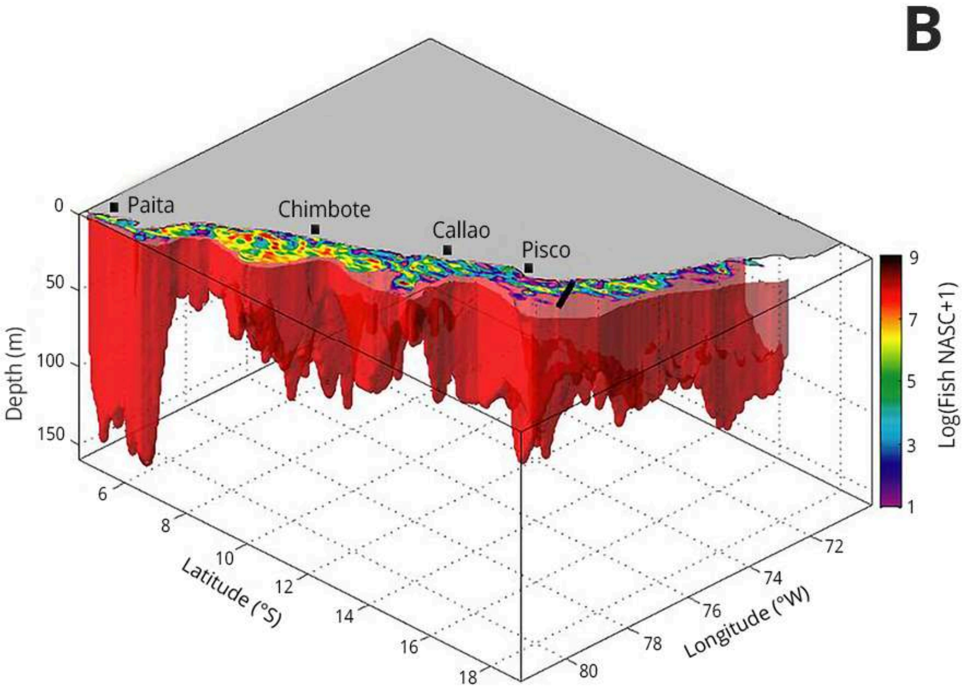
22 In the example of Peru, the resolution of the acoustic data allows the depth of the oxygen minimum zone to be mapped in three dimensions. From this, we can determine a volume of potential anchovy habitat, in which they have sufficient oxygen for their survival (fig. 9B, BERTRAND *et al.*, 2010).

Figure 9 A. Extract from an echogram showing a school of anchovies concentrated above a layer of plankton aggregated along the oxycline, at which the oxygen level drops sharply in relation to the surface layer of the ocean.



The presence of an internal wave in the water column causes the oxycline to sink and thus provides a higher volume of habitat for the anchovies. Example taken along the coast of Peru.
Source: BERTRAND *et al.* (2008)

Figure 9 B. Potential anchovy habitat (in red) from the position of the oxycline provided by acoustic data from the small pelagic assessment campaign carried out by the Instituto del Mar del Perú (IMARPE) (Lima, Peru, February–April 2005)



The acoustic abundance of anchovy is shown in a logarithmic scale above the volume of anchovy.
Source: BERTRAND *et al.* (2010)

23 Tropical offshore environments, which are essentially oligotrophic (poor in nutrients and resources), are still very poorly understood. However, in such areas, the presence of oceanic islands or seamounts locally modifies the flow of currents, forming more productive oases (MARSAC *et al.*, 2019). Large predators are present in these areas, such as tuna, dolphinfish, marine mammals, etc., which feed on organisms 2 to 20 cm in size (macrozooplankton and micronekton). These organisms are acoustically detectable (crustaceans, jellyfish, squid and other syphonophores in figure 2). Studying the distribution of organisms around certain topographical structures in offshore environments makes it possible to determine their interest as distribution areas for mammals or large fish and the prey of these large predators. Concentrations of organisms have been found on the flanks and tops of seamounts, particularly at night in the example of Cross Mountain in the central Pacific, a few hundred kilometres from the Hawaiian Islands (JOHNSTON *et al.,* 2008). Species may be associated with mountaintops or flanks, such as the potential prey of large predators associated with the summit and flanks of MAD-Ridge, south of Madagascar in the Indian Ocean (ANNASAWMY *et al.*, 2019; fig. 10 A and B). Combining active and passive acoustics (listening to the sounds of marine animals) can help link the presence of large predators and their prey concentrations (JOHNSTON *et al.*, 2008), and thus provide quantitative spatial observations that are critical to decisions on whether to protect an area.

24 The presence of strong vortex structures, such as exist in the Mozambique Channel, may have a greater enriching effect than topographic structures (ANNASAWMY *et al.*, 2020).

Figure 10A. Acoustic detections at the top of the MAD-Ridge seamount in southern Madagascar, at night

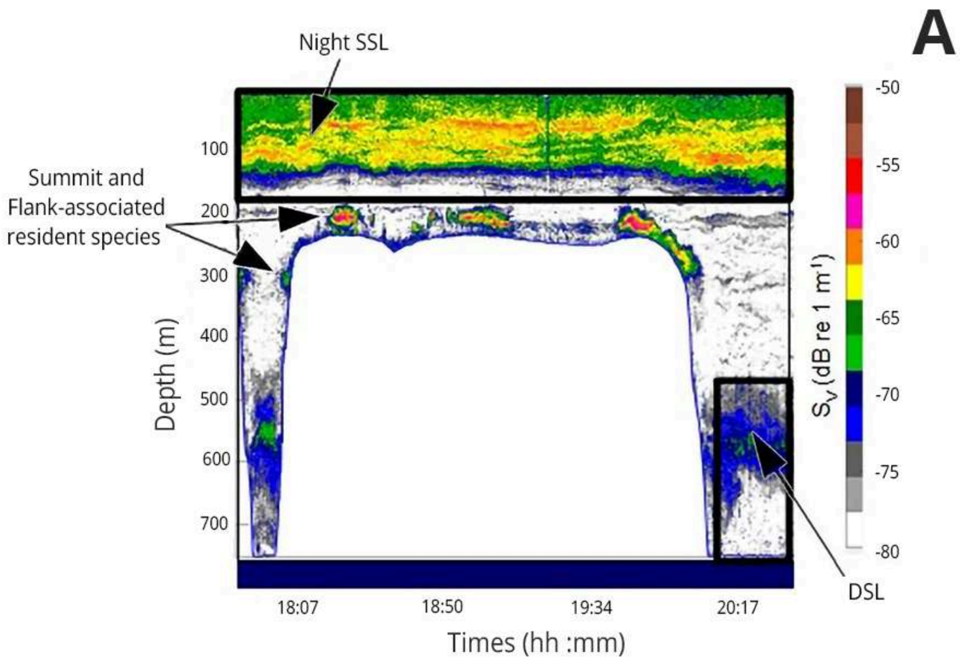
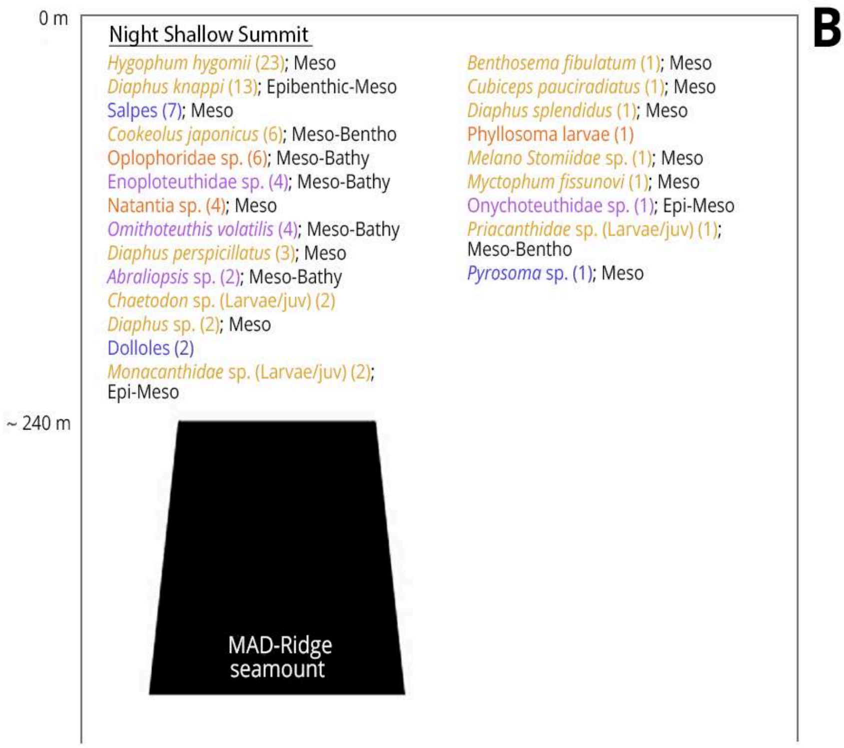


Figure 10B. Dominant species associated with the mountaintop according to trawls



Habitat categories: Epi: epipelagic; Meso: mesopelagic; Bentho: benthopelagic; Bathy: bathypelagic; epibenthic or the combination of several habitats
Source: ANNASAWMY *et al.* (2019)

25 At the scale of the exclusive economic zone (EEZ) around New Caledonia, for example, the pelagic zone has been fully integrated into the Coral Sea Natural Park since 2014; strict reserves were established in 2018 around some remote reefs, but the protected areas remain limited. A series of surveys covering the EEZ provided acoustic density and its horizontal and vertical distribution. Statistical models to study this set of densities in relation to environmental parameters and to the distribution of large predators may help to delimit other areas of priority interest to be preserved, for the conservation of species or the ecosystem in general (RECEVEUR *et al.*, 2020, 2021).

Long-term observations in shallow environments

26 Taking stock of an ecosystem at a given time provides initial synoptic knowledge. However, the effects of new uses or of the implementation of conservation measures must be assessed through medium- or long-term monitoring. In the case of marine protected areas (MPAs), monitoring is carried out and experimental sampling provides information on changes in species diversity, size, age at first maturity, trophic levels, etc. The study carried out in the Bamboung MPA in Senegal in the Sine-Saloum estuary (ECOUTIN, 2013) is an example. Determining the density of organisms by vertical acoustics here is difficult due to the very shallow depth of the environment. Indeed, the operation of the equipment does not allow the first two metres below the surface to be exploited. Moreover, the echo off the bottom is much stronger than that of the biological organisms, which can only be detected if they are about 50 cm above the

bottom. However, this method provides additional insight (BÉHAGLE *et al.*, 2018), and without the bias of the selectivity of experimental nets. In the case of the study in Senegal, the variability of the environment, the small size of the MPA and practical difficulties in ensuring a perfectly regular protocol over the time series made it difficult to clearly summarise the results, highlighting the need for another methodology based on fixed stations over relevant periods (nychthemeral, seasonal, tidal, annual cycles) to monitor the dynamics of the fish at strategic points in the study environment. Fixed stations were used in a study conducted in northern Brazil in the Bragança region, combining acoustic and biological sampling. The results describe the migration patterns of mangrove fish, according to their size, in relation to the tide. This study also points to the interest of combining data from sounders used vertically and horizontally (KRUMME and SAINT-PAUL, 2003) to better quantify passing fish when the environment is vertically homogeneous and dominated by epibenthic species (KRUMME, 2004).

27 In very shallow environments, as mentioned above, the possibilities of depth sounders are limited, even when used horizontally: as soon as the single detection beam (cone small aperture, typically ~7°, or elliptical 2° x10°) meets the surface or the bottom of the water, other weaker detections are masked. Acoustic cameras, which consist of a set of much finer beams in both directions and which work like medical ultrasound scanners, provide other possibilities in these environments: if part of the beam hits the bottom or the surface, the other beams, which are oriented differently, can detect the biological targets of lower levels. In addition, the image resolution provided by the use of very high frequencies and the visualisation of the swimming movement of the targets allow in some cases the recognition of target types. These characteristics make it well suited to assessing individual targets in shallow environments, particularly for monitoring fish migrations (fig. 11, MARTIGNAC *et al.*, 2013).

Figure 11 A. Schematic presentation of the beams of an acoustic camera (DIDSON)

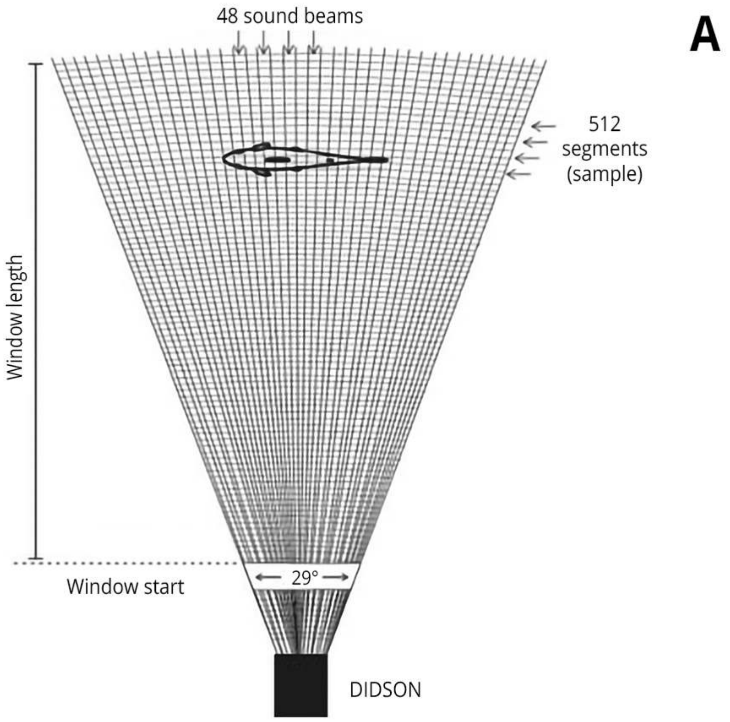
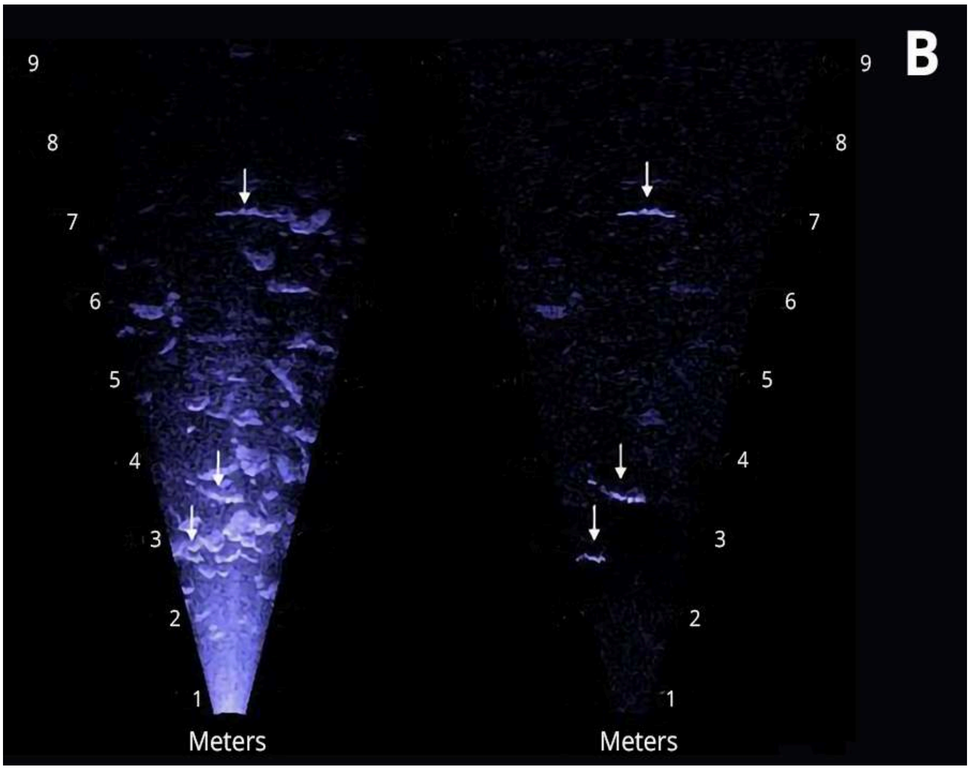


Figure 11 B. Detection of three fish (indicated by arrows) swimming over a rocky bottom (left) and the same fish after removal of the static bottom by post-processing (right) (MAXWELL and GOVE, 2004)



Source: MARTIGNAC *et al.* (2013)

Conclusion

28 This chapter presents an overview of the scope of information provided by active acoustics, as well as some of the applications for which this approach is essential. Stock assessment of exploited resources was one of the first concerns of its users, but its purposes have been greatly extended since the end of the 1990s with technological advances in the equipment. Today, acoustics has become a vital tool in an ecosystem approach: it provides quantitative and qualitative information on the various biotic components of an ecosystem, plankton and nekton, and sometimes on its physical structure. It is a preferred approach for studies in protected environments, as it is non-destructive and non-intrusive. The diversity of equipment available means that it can be used in turbid or obstructed environments, etc. or, conversely, in offshore environments where it is the only method that provides a cross-section of the water column from the surface to the bottom. The spatialized ecological knowledge obtained with high-resolution acoustic data is valuable for planning in liquid environments.

BIBLIOGRAPHY

ANNASAWMY P., TERNON J.-F., COTEL P., CHEREL Y., ROMANOV E., ROUDAUT G., LEBOURGES-DHAUSSY A., MÉNARD F., MARSAC F., 2019
Micronekton distributions and assemblages at two shallow seamounts of the south-western Indian Ocean: insights from acoustics and mesopelagic trawl data. *Progress in Oceanography*, 178: 102161.

ANNASAWMY P., TERNON J.-F., LEBOURGES-DHAUSSY A., ROUDAUT G., COTEL P., HERBETTE S., MÉNARD F., MARSAC F., 2020
Micronekton distribution as influenced by mesoscale eddies, Madagascar shelf and shallow seamounts in the south-western Indian Ocean: an acoustic approach. *Deep-Sea Research II*, 176: 104812.

ANSONG J., GISSI E., CALADO H., 2017
An approach to ecosystem-based management in maritime spatial planning process. *Ocean & coastal management*, 141: 65-81.

BALLÓN M., BERTRAND A., LEBOURGES-DHAUSSY A., GUTIÉRREZ M., AYÓN P., GRADOS D., GERLOTTO F., 2011
Is there enough zooplankton to feed forage fish populations off Peru? An acoustic (positive) answer. *Progress in Oceanography*, 91 (4): 360-381.

BÉHAGLE N., GUILLARD J., ECOUTIN J.-M., LAË R., SOW I., TITO-DE-MORAIS L., LEBOURGES-DHAUSSY A., 2018
Acoustic survey of an estuarine marine protected area and of its close vicinity: analysis and monitoring prospective. *Journal of Aquaculture and Fisheries*, 2 (2): 011.

BENOIT-BIRD K., LAWSON G., 2016

Ecological insights from pelagic habitats acquired using active acoustic techniques. *Annual Review of Marine Science*, 8: 463-490.

BERTRAND A., BALLON M., CHAIGNEAU A., 2010

Acoustic observation of living organisms reveals the upper limit of the oxygen minimum zone. *PLoS ONE*, 5 (4): e10330.

BERTRAND A., GERLOTTO F., BERTRAND S., GUTIÉRREZ M., ALZA L., CHIPOLLINI A., DÍAZ E., ESPINOZA P., LEDESMA J., QUESQUÉN R., PERALTILLA S., CHAVEZ F., 2008

Schooling behaviour and environmental forcing in relation to anchoveta distribution: an analysis across multiple spatial scales. *Progress in Oceanography*, 79: 264-277.

ECOUTIN J.-M. (ed.), 2013

The Bamboung Community Marine Protected Area (Sine-Saloum): synthesis 2003-2011. Dakar, IRD, 157 p. https://www.documentation.ird.fr/hor/fdi:010060105

FERNANDES P. G., 2009

Classification trees for species identification of fish-school echotraces. *ICES Journal of Marine Science*, 66: 1073-1080.

JOHNSTON D. W., MCDONALD M., POLOVINA J., DOMOKOS R., WIGGINS S., HILDEBRAND J., 2008

Temporal patterns in the acoustic signals of beaked whales at Cross Seamount. *Biology Letters,* 4: 208-211.

JUHEL P., 2005

History of underwater acoustics. Paris, Vuibert, coll. Inflexions.

KORNELIUSSEN R. J. (ED.), 2018

Acoustic target classification. *ICES Cooperative Research Report*. 344. 104 p.

KORNELIUSSEN R. J., HEGGELUND Y., MACAULAY G. J., PATEL D., JOHNSEN E., ELIASSEN I. K., 2016

Acoustic identification of marine species using a feature library. *Methods in Oceanography*, 17: 187-205.

KRUMME U., 2004

Patterns in tidal migration of fish in a Brazilian mangrove channel as revealed by a split-beam echosounder. *Fisheries Research*, 70: 1-15.

KRUMME U., SAINT-PAUL U., 2003

Observations of fish migration in a macrotidal mangrove channel in Northern Brazil using a 200 kHz split-beam sonar. *Aquatic Living Resources*, 16: 175-184.

LAVERY A. C., WIEBE P. H., STANTON T. K., LAWSON G. L., BENFIELD M. C., COPLEY N., 2007

Determining dominant scatterers of sound in mixed zooplankton populations. *J. Acoust. Soc.* 122 (6): 3304-3326.

LE PAPE O., DELAVENNE J., VAZ S., 2014

Quantitative mapping of fish habitat: a useful tool to design spatialized management measures and marine protected area with fishery objectives. *Ocean & Coastal Management*, 87: 8-19.

LILJA J., ORELL P., 2011

Use of Didson to estimate spawning run of Atlantic salmon in the River Karasjohka, the tributary of the River Tana. *Finnish Game and Fisheries Research Institute*, 25 p.

MARSAC F., GALLETTI F., TERNON J.-F., ROMANOV E. V., DEMARCQ H., CORBARI L., BOUCHET P., ROEST W., JORRY S., OLU K., LONCKE L., ROBERTS M. J., MÉNARD F., 2019

Seamounts, plateaus and governance issues in the southwestern Indian Ocean, with emphasis on fisheries management and marine conservation, using the Walters Shoal as a case study for implementing a protection framework. *Deep-Sea Research II-Topical Studies in Oceanography*, 176: 104715.

MARTIGNAC F., DAROUX A., BAGLINIERE J.-L., OMBREDANE D., GUILLARD J., 2013

The use of acoustic cameras in shallow waters: new hydroacoustic tools for monitoring migratory fish population. A review of Didson technology. *Fish and fisheries*, 16 (3): 486-510.

MAXWELL S. L., GOVE N. E., 2004

The feasibility of estimating migrating salmon passage rates in turbid rivers using a dual frequency identification sonar (Didson). Regional Information Report1, No. 2A04-05, Alaska Department of Fish and Game Division of Commercial Fisheries. 88 p.

MCLENNAN D.N., FERNANDES P. G., DALEN J., 2002

A consistent approach to definitions and symbols in fisheries acoustics. *ICES Journal of Marine Science,* 59 (2): 365-369.

MORENO G., JOSSE E., BREHMER P., NØTTESTAD L., 2007

Echotrace classification and spatial distribution of pelagic fish aggregations around drifting fish aggregating devices (DFAD). *Aquatic Living Resources*, 20: 343-356.

RECEVEUR A., MENKES C., ALLAIN V., LEBOURGES-DHAUSSY A., NERINI D., MANGEAS M., MÉNARD F., 2020

Seasonal and spatial variability in the vertical distribution of pelagic forage fauna in the Southwest Pacific. *Deep-Sea Research Part II-Topical Studies in Oceanography*, 175: 104655.

RECEVEUR A., ALLAIN V., MÉNARD F., LEBOURGES-DHAUSSY A., LARAN S., RAVACHE A., BOURGEOIS K., VIDAL E., HARE S., WEIMERSKIRCH H., BORSA P., MENKES C., 2021

Modelling marine predator habitat using the abundance of its pelagic prey in the tropical south-western Pacific. Ecosystems. https://doi.org/10.1007/s10021-021-00685-x

SALVETAT J., LEBOURGES-DHAUSSY A., TRAVASSOS P., GASTAUER S., ROUDAUT G., VARGAS G., BERTRAND A., 2019

In situ target strength measurement of the black triggerfish *Melichthys niger* and the ocean triggerfish *Canthidermis sufflamen*. *Marine and Freshwater Research*, 71 (9): 1118-1127.

SALVETAT J., BEZ N., HABASQUE J., LEBOURGES-DHAUSSY A., LOPES C., ROUDAUT G., SIMIER M., TRAVASSOS P., VARGAS G., BERTRAND A., 2022

Comprehensive spatial distribution of tropical fish assemblages from multifrequency acoustics and video fulfils the island mass effect framework. *Scientific Reports,* 12: 8787. https://doi.org/10.1038/s41598-022-12409-9

SARRÉ A., KRAKSTAD J.-O., BREHMER P., MBYE E. M., 2018

Spatial distribution of main clupeid species in relation to acoustic assessment surveys in the continental shelves of Senegal and The Gambia. *Aquatic Living Resources*, 31 (9).

SIMMONDS J., MACLENNAN D., 2005

Fisheries acoustics. Theory and practice. Second edition. New Jersey, Wiley-Blackwell, 456 p.

STANTON T. K., CHU D., JECH J. M., IRISH J. D., 2010

New broadband methods for resonance classification and high-resolution imagery of fish with swim bladders using a modified commercial broadband echosounder. *ICES Journal of Marine Science*, 67: 365-378.

SUND O., 1935

Echo sounding in fishery research. *Nature*, 135 (3423): 953.

TRENKEL V. M., RESSLER P. H., JECH M., GIANNOULAKI M., TAYLOR C., 2011
Underwater acoustics for ecosystem-based management: state of the science and proposals for ecosystem indicators. *Marine Ecology Progress Series*, 442: 285-301.

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