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COUPLING THE MAP OF MARINE HABITATS AND FISH ACCUMULATION ZONES: A THREE-DIMENSIONAL SPATIAL APPROACH FOR THE MANAGEMENT OF HALIEUTIC RESOURCES

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MAPPING
MARINE HABITATS
3D
MULTIBEAM ECHO SOUNDER
WATER COLUMN
HALIEUTIC
MEDITERRANEAN

ABSTRACT. – The spatialization of halieutic data is an essential element to define and create efficient protected and managed areas. Moreover, the distribution of fish schools is not homogeneous in the water column and is strongly linked with marine habitats. It is thus necessary to develop techniques allowing a spatial evaluation of halieutic resources. Multibeam echo sounders (MBES) provide acoustic data of the seafloor and the water column with a high accuracy and resolution. A single acquisition gives the bathymetry, a backscatter mosaic of the sea bottom and an acoustic imagery of the water column. The bathymetric data processing highlights the seafloor rugosity using several metric indices. A semi-automated classification including depth, rugosity indices and backscatter values provides maps of marine habitats, which are finally validated with ground truth. Data from the water column are analyzed using an algorithm that detects acoustic targets corresponding to fishes. A georeferenced scatter graph of fish schools is thus automatically created. The 3D model of the seafloor obtained from the bathymetry is textured with the map of marine habitats. Points corresponding to fish detection are then added on the 3D model to provide a complete map. Through this process managers can access to a clear visualization of fish accumulations and the key marine habitats within their areas of interest.

INTRODUCTION

Marine ecosystems are among the most rich and complex biological systems of our planet but remain difficult to study when compared with terrestrial habitats (Appeltans *et al*. 2012). To integrate and assess marine ecosystems' complexity in governmental efforts to protect them against anthropogenic influences, an ecosystem-based management theory was produced (Slocombe 1993). More and more applications based on this approach are currently developed to consider the resilience and robustness of marine systems (Curtin & Prellezo 2010). These approaches rely on the understanding of ecosystems functioning by associating marine species in functional groups according to their ecosystemic roles (Buchmann & Roy 2002). They are especially suitable to respond to the European directives, such as the Marine Strategy Framework Directive (MSFD), aiming to reach a good ecological status of marine areas.

Due to complexity and the difficult access to the marine environment, most of the survey techniques classically used are based on discrete samplings and observations focusing on a single or few functional compartments. A good example of the paradigm evolution concerning the survey of marine ecosystems is the study of *Posidonia oceanica* (L.) Delile seagrass meadows that previously focused on the plant morphology (Pergent-Martini *et al*. 2005) while, nowadays, ecosystem-based approaches are developed (Personnic *et al*. 2014). Although this shift in paradigm provides a better evaluation of ecosystem status, the data on which it relies are still discrete and random measurements upscaled to large areas. Complementary spatial data are thus required to fulfill an effective ecosystem-based management of the marine environment.

The most effective tool to acquire spatial information on the seafloor and the water column above – with a high resolution and positioning accuracy – is currently the multibeam echo sounder (MBES) (Abadie & Viala 2018). This type of acoustic probe is able to provide simultaneously bathymetric data, backscatter images and the water column imagery (WCI) on a large swath (increasing with the depth). Recent signal processing methods for bathymetric data allow to generate maps of marine habitats using various rugosity indices (Abadie *et al*. 2018). Likewise, innovative algorithms are able to detect various acoustic targets on the WCI among which the fish schools and the individuals composing them (Lamouret *et al*. 2019).

In order to pave the way for a spatial approach of the ecosystem-based management, we investigated the capacity of MBES to provide exploitable two and three-dimensional information on several functional compartments of key marine ecosystems of the Mediterranean Sea. With this main target in mind, we studied the inter-seasonal and inter-annual characteristics of fish accumulations on various habitats. We also experimented different environmental indicators in an attempt to describe the link between marine habitats' features and fish distribution.

MATERIALS AND METHODS

Study site and data acquisition: This study took place in the Bay of La Ciotat in the south of France off the Ile Verte (Fig. 1) on a site renowned for the richness of its habitats and biodiversity. The site covers an area of 0.83 km^2. An exhaustive acoustic data acquisition was performed two times in June and August 2016 to consider the increase of the water temperature linked with fish observations. These two acquisitions were realized in similar conditions: a two hours work done in the morning to collect the data along the same lines north-south oriented. Another acoustic dataset was obtained in June 2019, allowing an inter-annual comparison.

Acoustic data were acquired by using a R2Sonic 2022 MBES fixed on the hull of a 6 m long survey boat. Position and attitude were recorded by an Applanix I2NS, an inertial system equipped with a RTK GNSS positioning device providing 0.015° roll/pitch precision as well as a horizontal accuracy of 1 cm and a vertical one of 1.5 cm. Acoustic data were acquired at a frequency of 450 kHz with an individual beam width of 0.9° × 0.9° for a maximum swath sector of 160° and 1024 soundings per swath. Transects were defined prior to the data acquisition and the navigation was operated by a Raymarine ACU 200 autopilot synchronized with the RTK GNSS using ViewMap, a Geographic Information System (GIS) and navigation software developed by Viala (2015a). The underwater sound velocity was constantly checked using a Valeport Ltd miniSVS sound velocity sensor mounted on the MBES. Additional underwater sound velocity profiles were performed with another miniSVS to detect the possible presence of a thermocline or fresh water layers impacting the sound propagation. Water temperature profiles were computed from the sound velocity data. Ground truth data were performed by scuba diving to validate the seafloor classification.

Acoustic data treatment and generation of habitat maps: R2Sonic 2022 bathymetric soundings were processed using the ViewSMF computer program developed by Viala (2015b) for the visualization and processing (automatic or manual) of MBES acoustic data and metadata. False echoes were removed using filters to isolate one or several soundings. A rugosity index, named Bathymetric Automated Treatment for the Classification of the Seafloor (BATCLAS), is then computed from bathymetric soundings to highlight the underwater landscape according to the method developed by Abadie *et al*. (2018). The noise on the backscatter imagery was reduced using a time variable gain and snippets. A digital elevation model (DEM) encompassing a bathymetric map, the treated backscatter imagery and the BATCLAS index was generated. Finally, data from the DEMs and ground truthing were computed in ViewMap using a decision tree to classify marine habitats and build polygons exploitable in Geographical Information System (GIS) for further analysis. The final maps take the shape of 2D and 3D maps of marine habitats.

Water column processing and environmental indicators: The WCI was analyzed following the technique developed by Lamouret *et al*. (2019). This method utilizes an algorithm that automatically detects and identifies acoustic targets corresponding to fishes on the WCI. For each detection, the localization, the dimensions and the energy are computed and stored in computer files. The halieutic data set is finally exported under the shape of a scatter plot for 2D and 3D analyses, as well as for investigating the relationships between fish distribution and marine habitats.

In order to compare the density between the different dataset, the fish density is computed from the scatter plot for the whole area and for several sub-areas of interest of the marine habitat map. The density is given in fishes/m^2, corresponding to the number of fishes in a column of 1 m^2 and of height given by the bathymetry. The density by subzone is then easily comparable

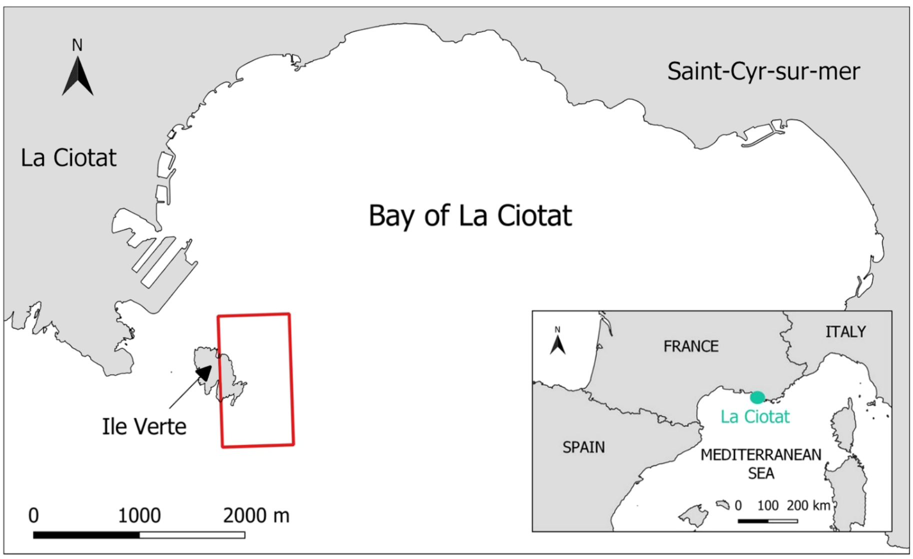

Fig. 1. – Study site (red frame) in the Bay of La Ciotat.

through times on 2D maps. The study area was divided in three main sub-areas: (1) the Ile Verte walls, (2) the rocky reefs, (3) the sedimentary plains. Moreover, the rocky reefs were subdivided one by one.

RESULTS

Depths varied from a few meters (< 10 m) on the shallowest cost of the Ile Verte to 66 m in the south-east corner (Fig. 2A). In the extension of the island towards the south-east an uneven seascape was clearly visible, composed of vertical walls and plateaus. The backscatter imagery (Fig. 2B) highlights the relief seen on bathymetric data.

Table I. – Areas covered by each marine habitat and their proportion.

Habitat	Area (m²)	Proportion (%)
Coralligenous communities	27,838	3.9
P. oceanica meadows	7,225	1.0
Algal cover on rocky substrate	39,151	5.7
Soft sediments	624,502	89.4
Total	**698,716**	**100.0**

Apart from these irregularities, the seabed was even with two ranges of backscatter intensity: a high value on the northern part and a lower one in the south, indicating two types of sediments with contrasted granularities. The

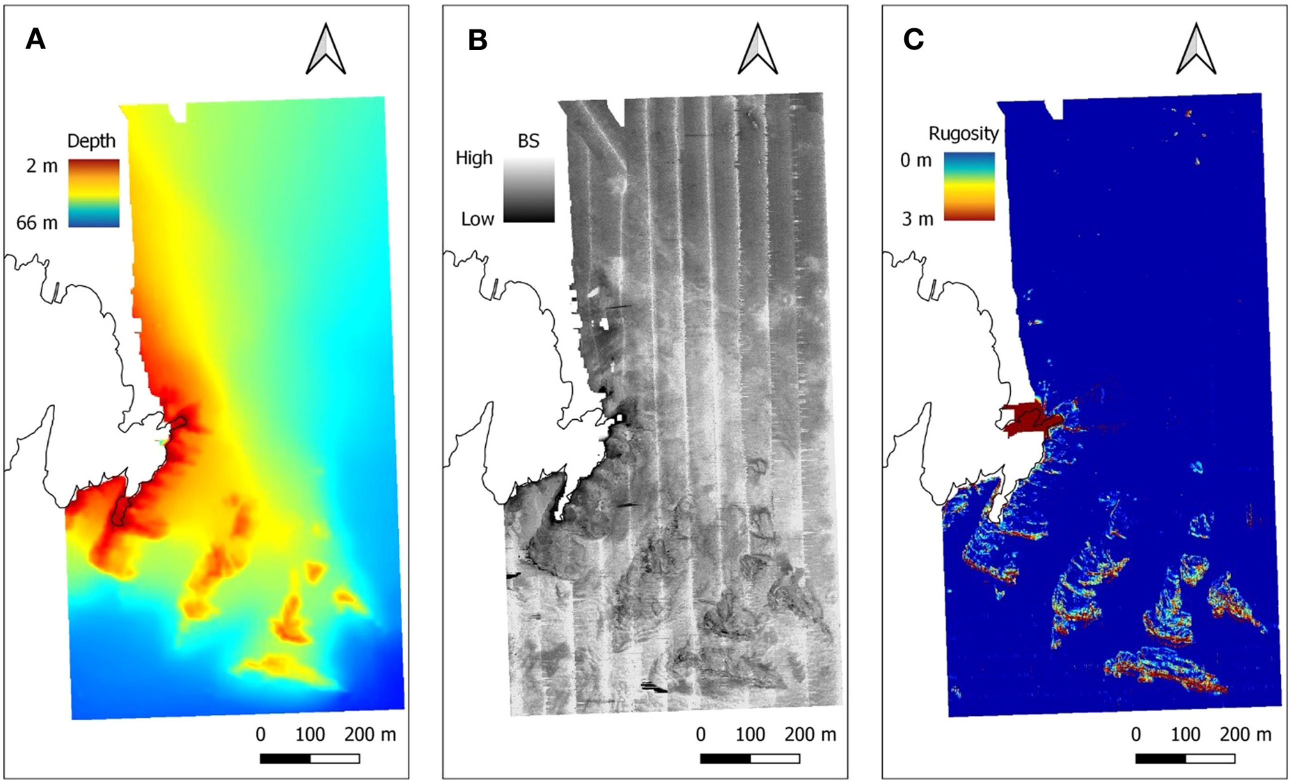

Fig. 2. – Multibeam echo sounder data products. **A**: Bathymetry; **B**: Backscatter imagery; **C**: Rugosity.

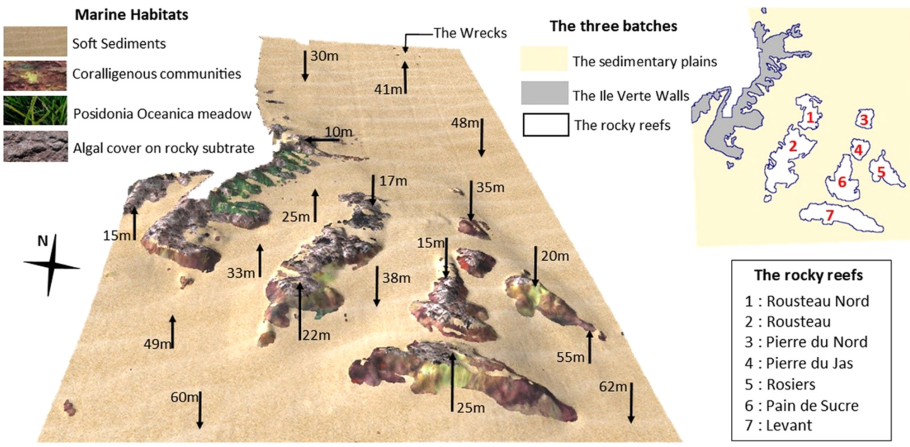

Fig. 3. – 3D representation of the seabed topology with marine habitats and details of the three batches studied with reefs names for fish density studies.

unevenness were highlighted again and well delimited on the rugosity index map (Fig. 2C). The rest of the seabed appeared smooth, except for small spots in the north east of the zone corresponding to known ship wrecks.

Ground truthing confirmed the existence of the spots that were three very dilapidated wrecks – a wooden trawler and two sailing ships – playing the role of artificial reefs on the sandy plain. Ground truths also established the main habitats, *i.e.*, rocky substrate with algal cover (39,151 m²), *P. oceanica* (L.) Delile meadows (7,225 m²), coralligenous communities (27,838 m²) and soft sediments (624,502 m²; Table I). The *P. oceanica* meadows were not found on sediments, but rather on hard substrates (Fig. 3). Sparse meadows were observed on the top of the rocky reefs too; however, they were not represented due to their small size. The coralligenous communities were present on each rocky substrate from around 25 m depth while rocks covered by algal communities were found above this limit.

The temperature profiles of the two June acquisitions did not present a clear thermocline, but rather two main temperature gradients (Fig. 4). The greatest temperature decreasing of 1.5 °C was found in the twenty-first meters in June 2016 (from 19.0 °C to 17.5 °C), and in the ten first meters in June 2019 (from 23 °C to 21.5 °C). Beyond 20 m depth, the temperature decreased more slowly to stabilize at 17.2 °C and 19.0 °C in June 2016 and June 2019, respectively. The August 2016 profile showed a thermocline at 5-10 m depth where temperature dropped from 25 °C to 21 °C and then declined more slowly to 19 °C deeper (Fig. 4).

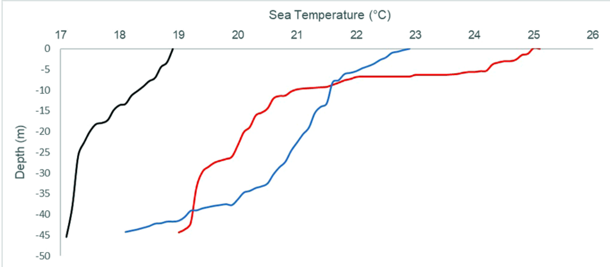

Fig. 4. – Temperature profile in June 2016 (black); August 2016 (red); June 2019 (blue).

For each acquisition, fish accumulations were well focused on the Ile Verte walls and on the rocky reefs (Fig. 5). They appeared as large continuous and dense schools rather than numerous medium schools. The accumulation on the wrecks was worth more noteworthy than the surroundings, except in August 2019 where a large fish school was observed (Fig. 5C). With the exception of the north-west boundary of the site, there were no major fish schools on the sedimentary plains (Fig. 5). Numerous single detections were pointed on this habitat, however. Fish detection were more numerous in June 2016 (38,498 detections) than in August (23,268 detections), while the number of fishes in August 2019 reached 57,472 detec-

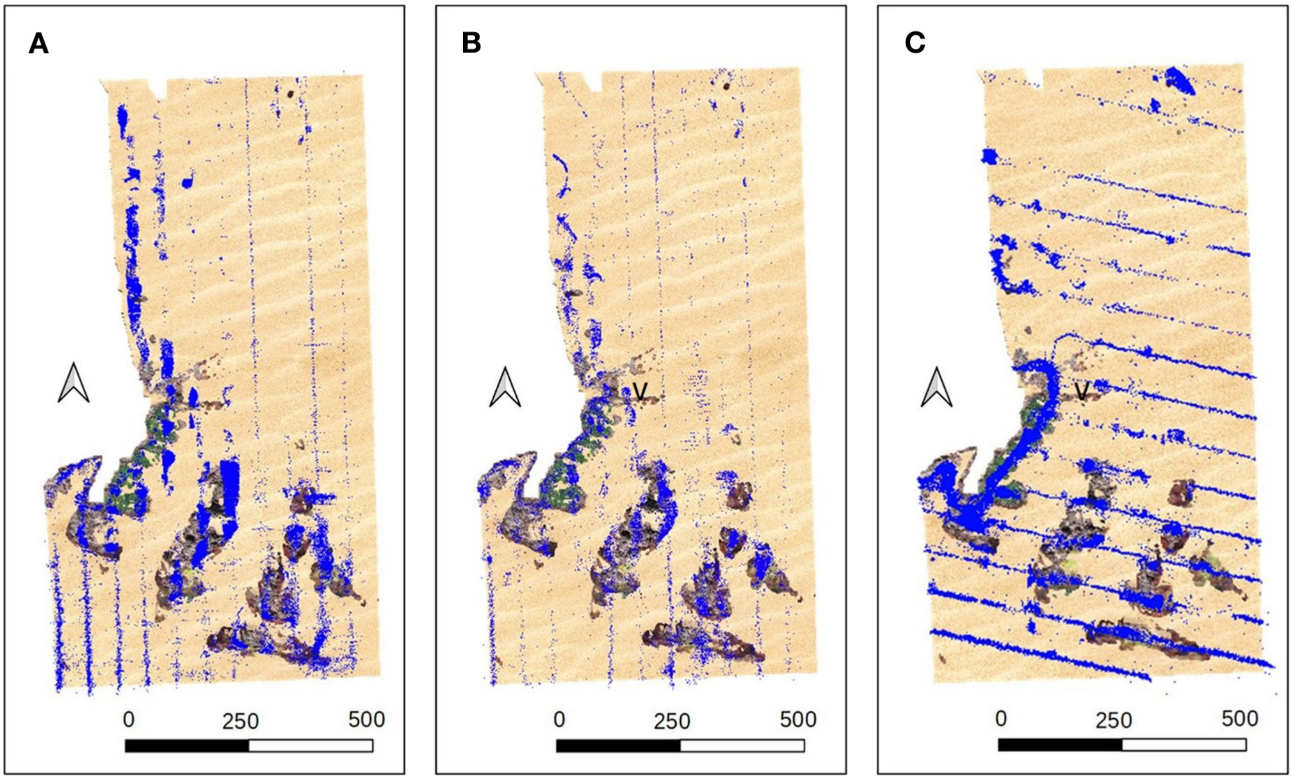

Fig. 5. – Scatter plots representing fishes in **A**: June 2016; **B**: August 2016; **C**: June 2019. Each blue dot represents a detected fish whatever its size.

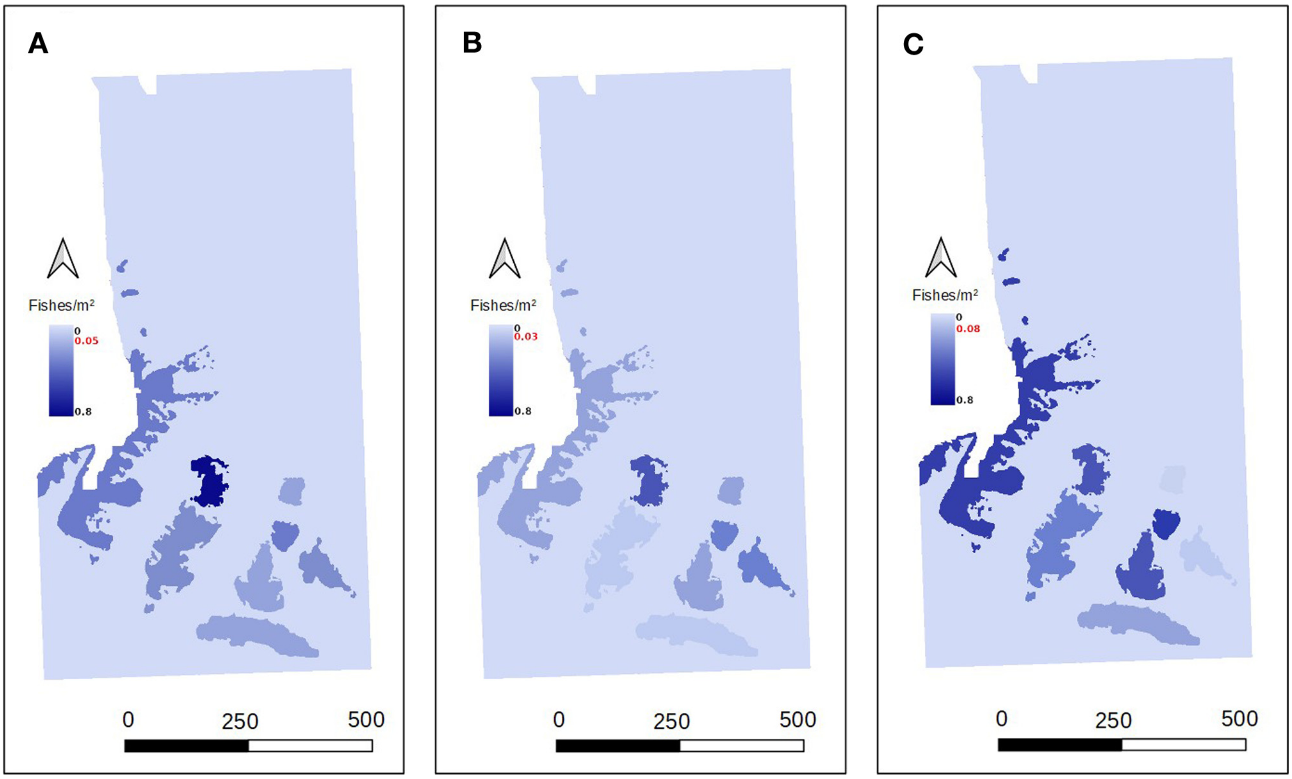

Fig. 6. – Local fish density in fishes/m² in **A**: June 2016; **B**: August 2016; **C**: June 2019. The red value corresponds to the mean number of fishes/m².

Table II. – Number of fish detections and proportions per depth categories.

Position in the water column and depth range (m)	June 2016		August 2016		June 2019	
Near surface [0, 20[	25,695	66.8 %	14,316	61.5 %	29,590	51.5 %
Mid-depth [20, 40[	10,892	28.3 %	6,979	30.0 %	23,653	41.1 %
Deep [40, max]	1,903	4.9 %	1,971	8.5 %	4,253	7.4 %
Total	**38,492**		**23,268**		**57,472**	

tions (Table II). Concerning fish densities, soft sediments showed low fish densities (from 0.01 fishes/m² in June and August 2016 to 0.03 fishes/m² in June 2019), however close to the average value (Fig. 6). On average over the three acquisitions, the Ile Verte walls had a higher fish abundance (0.31, 0.14 and 0.38 fishes/m² in June, August 2016 and June 2019, respectively) than the rocky reefs (0.25, 0.15 and 0.24 fishes/m² in June, August 2016 and June 2019, respectively; Fig. 6). Among the reefs, Rousteau Nord and Pierre du Jas showed the highest fish abundances, while the largest reefs – Rousteau and Levant – were among the poorest (Fig. 6).

Whatever the time of acquisition, fishes were mainly detected in the twenty-first meters, representing more than 50 % of all detections in general and up to 66.8 % in June 2016 (Table II). By averaging the three acquisitions, about a third of detections were located in the mid-depth waters, between 20 and 40 m. Finally, less than 10 % of the fishes detected were found in the deepest waters of the study site (Table II).

DISCUSSION

This work was aimed at studying the capacity of a compact MBES to provide a precise map of marine habitats along with fish accumulations, with the final purpose of providing a spatial ecosystem-based approach to managers and stakeholders.

MBES advantages and operability

The main original outcome of this research effort is to put into light the possibility to have a global spatial review of an area with a single acoustic acquisition. Modern MBES are able to collect both bathymetry, backscatter and WCI without compensation of data quality and quantity. The WCI alone is used in various fields of research, such as biology, archeology, physical oceanology (Colbo *et al*. 2014), and reveals its full potential when combined with the other MBES outputs. The versatility of the MBES used in this study (a R2Sonic 2022) is an advantage, on the condition of having the capacity to properly collect, store and process all the acoustic data, without forgetting GPS and Navigation information. However, this MBES is commonly dedicated to bathymetry and seafloor imagery acquisition, it is not a fishery-dedicated tool. Moreover, the system is adjusted and calibrated for the seafloor measurement and not for the water column observation. This implies several consequences: (1) acoustic noises can alter the WCI and hinder their processing; (2) only the pelagic fishes can be seen, the demersal and benthic ones are mingled with the seabed noise; (3) When compared to fishery MBES, the one used in this work is installed under the hull at mid-length of the boat and not in the bow as a forward-looking MBES. Thus, the WCI is a vertical cut of the fish schools, and not a fish school seen as a whole; (4) as the MBES is used to map the seabed, the acoustic signals are emitted towards the nadir. There is also a good cover of the seabed, but the water column is not entirely scanned. This explains why the scatter plot is composed of bands North-South oriented.

The place on the hull and the looking direction of the MBES become important when the avoiding-boat behavior of schools is considered. In a previous study on fish behaviors regarding MBES acquisition, Soria *et al.* (1996) explained that a fish school feels the vessel coming far away. From this moment, a first part of the school avoids laterally the vessel and is not seen. Then, when the disturbance, *i.e.*, the boat, arrives above the school, another part of the school also avoids it laterally and can only be seen on the edge of the WCI. What remains of the school is the little part recorded by the MBES while fishes are avoiding the disturbance by diving. That is why Soria *et al.* (1996) and Paramo *et al.* (2010) used a MBES with a 45° tilt from the nadir. Nevertheless, it is hard to say how many fishes are missed in the detection process.

Processing of the WCI

Although the algorithm developed to extract fish information from the WCI is able to automatically detect fish targets without human intervention, this type of processing has currently several drawbacks. In this line of thought, wherever in the area, several fishes are not detected because they do not pass the filters. Some false alarms exist too. This is not disturbing the scatter plot and it does not influence so much the local density as well. However, it is more troublesome on the vast soft sedimentary seafloor where it seems that too much detections were performed. Thus, all these points are lonely, close to the seabed and around the nadir and could correspond to some acoustic noise. However, when looking the WCI at great depths, these points look like fishes for the algorithm as well as the human eyes. On the one hand, should these detections might be noises, then the sedimentary seafloor is really deserted by pelagic fishes. On the other hand, they could be true detections and these vast areas might be more populated than expected, while remaining very sparsely populated. We decided to display them, at least so that the reader may view the boat trajectories and assess the difficulty to validate fish detections.

Despite all these drawbacks, the processing method is fast enough to provide quick results, meaning with a mid-powerful computer, one hour of acquisition is processed in one hour of computer calculation. Moreover, improvements are under study in order to obtain a higher precision in target detection while decreasing the processing time. Another enhancement under progress concerns the pre-processing of the WCI to reduce the noise or calibrate the background noise.

Contribution to the ecosystem based management

This research work suggests a new approach to evaluate the ecological status of an area of interest with different levels of analysis that can be adapted according the characteristics of the managed zone (*e.g.*, large areas, complex patchwork of marine habitats, extensive seagrass meadows), and the final aim of the study (*e.g.*, MSFD, seascape analysis, halieutic research). It also allows to obtain spatial data for several functional compartments of the Mediterranean ecosystems *P. oceanica* meadows, algae-dominated rock reefs and coralligenous communities (Table III), according to the conceptual representa-

Table III. – Functional compartments of the Mediterranean ecosystems investigated by coupling marine habitat maps and fish detection in the water column.

Ecosystem	Functional compartments	Type of data
Posidonia oceanica meadows	*Posidonia* leaves	Area covered
	Planktivorous teleosts Piscivorous teleosts Predatory teleosts Herbivores 1	Fish number
Algae-dominated rock reefs	Multicellular photosynthetic organisms	Area covered
	Herbivorous teleosts Piscivorous teleosts Omnivorous teleosts Invertivorous teleosts Planktivorous teleosts	Fish number
Coralligenous communities	Builders	Area covered
	High-level predators Predatory teleosts Planktivorous teleosts	Fish number

tion of Personnic *et al*. (2014), Thibaut *et al*. (2017) and Ruitton *et al*. (2014), respectively. Obviously, this spatial approach does not replace the qualitative and quantitative assessment made by scuba diving but rather intervenes as a complementary tool allowing cross-validation. It may also be used to produce a first investigation of an area with few data on fish accumulations and benthic habitats for a more efficient scuba diving evaluation later.

One of the limits of a spatial approach through discrete acquisitions relies on the instantaneousness of the maps produced. Moreover, the pelagic fish distribution depends of numerous biotic and abiotic parameters that are virtually impossible to wholly assess such as marine habitats, sea temperature, salinity currents, day period, light intensity (Saraux *et al*. 2014). This difficulty is illustrated in this study where the combination of sea temperature, seascape and marine habitats are not sufficient to explain the fish distribution observed. In fact, if the fish biomass is increasing with sea temperature, the August 2016 acquisition should have been the survey with the most detections in total and especially within the twenty first meters where temperatures were the highest. On the contrary, this acquisition shows about two times less fish detections than in June 2016 and 2019 (Table II). The same observation is made for the June acquisitions, due to the sea surface temperature, the 2019 one should have presented a higher fish abundance than the 2016 one.

Although this first application is promising for an effective evaluation in a management purpose, further developments are still required for a deeper investigation of the link between marine habitats and fish accumulations. Moreover, the anthropogenic impacts and abiotic factors must be included in the analysis for a sharper ecological assessment. For instance, the fish densities need to be calculated per habitat and not only by area. Likewise, the vertical dimension should be more exploited with volumetric analysis rather than the only study of the vertical repartition of fish schools. An important research effort is also required to link the size of the WCI acoustic targets with the one of actual fishes to produce an evaluation of the biomass per surface and/or volume (even with a relatively large margin of error). At last, an ecological index can be built on the comparison between different sites (impacted and protected) at various seasons to link anthropogenic impacts with the ecological status.

This research effort clearly highlights the capacity of spatial acoustic data obtained with a MBES to provide quantitative information on the marine habitats and fish distribution. This work aimed at paving the way to further developments to provide managers with effective spatial tools to evaluate the ecological status of key Mediterranean marine ecosystems. If coupled with *in situ* underwater observations, this spatial approach has the potential to give a complete view of underwater key biological systems as never been before.

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