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STUDY OF THE *POSIDONIA OCEANICA* MEADOWS' UPPER LIMIT WITH GEOREFERENCED UNDERWATER PHOTOGRAMMETRY

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ABSTRACT. – Photogrammetry can be used to generate maps based on a large number of photographs and the tie points between them. Commonly used in terrestrial mapping with drones, georeferenced photogrammetry is currently seldom used in underwater studies. In order to obtain a centimetric positioning accuracy through direct georeferencing, we developed a floating platform encompassing two submerged cameras synchronized with a RTK GNSS at the surface. This device can be used from 1 m to 10 m depth in clear waters and the photographic views of the seafloor, with millimetric resolution, make it possible to map shallow habitats previously impossible to detect with classic methods such as acoustic sounding and aerial photographs. With this in mind, we used the platform to shoot 3 400 photos over a distance of about 500 m along the upper limit of the shallow *Posidonia oceanica* meadows of the Mugel, a creek in La Ciotat (France). The underwater photographs and the position data from the GNSS were synchronized to provide each picture with geographic coordinates. All the photos were then processed to build an orthomosaic of the meadow limit. Owing to its high resolution, the orthomosaic enabled the mapping of various features of the seascape such as the position of the limit with a centimetric accuracy, dead matte patches, litter detritus, artificial objects (moorings, wrecks) and marine organisms living on the seafloor.

INTRODUCTION

The meadows formed by the endemic seagrass *Posidonia oceanica* (Linnaeus) Delile constitute one of the most important marine habitats of the Mediterranean Sea due to the ecosystemic services (*e.g.*, shelter, nurseries, protection against coastal erosion, carbon sink, oxygen production) they provide (Boudouresque *et al.* 2012). Despite these key roles, they have been subject to anthropogenic impact resulting from human activities (*e.g.*, anchoring, trawling, coastal development, dredging) for decades. These activities lead to major changes and the fragmentation of the seascape formed by the meadows (Abadie *et al.* 2018a).

The shallowest extension of *P. oceanica* meadows, called the "upper limit", is the place where most interactions with human activities occur (*e.g.*, coastal development, tourism, leisure nautical activities). Due to the low depth of the upper limit – that may reach the surface in the case of barrier reef meadows – its mapping with conventional acoustic probes mounted on motorized boats is prohibited. Most of the time, the upper limit is mapped using aerial photographs with the disadvantage that *P. oceanica* meadows can be mistaken with rocks, dead matte and litter detritus.

Taking into account the limits of the classical mapping methods, the aim of this work was to develop a georeferenced photogrammetric technique to obtain underwater orthomosaics of *P. oceanica* meadows. Furthermore, this research involved the study of the information that can be extracted from photogrammetric products for ecosystem-based management purposes.

MATERIALS AND METHODS

The study took place at the Mugel Creek in the Bay of La Ciotat in the south of France within the Parc National des Calanques (Fig. 1A). Anchoring is forbidden in this small creek, which is characterized by shallow depths in its north-western part and an extensive *P. oceanica* meadow covering most part of the seafloor. Photogrammetric data (position and underwater photographs) were acquired on 27th August 2019 using the floating platform developed by Abadie *et al.* (2018b). Two hybrid cameras (Canon M50® and a Sony A6000®), equipped with 11-mm wide angle lenses in waterproof cases, were synchronized with a RTK GNSS (North RTKite®). The floating platform was operated at the surface above the western meadow limit over a distance of about 500 m by a snorkeller and 3 368 photos were taken in about 90 minutes.

After the image acquisition, the position data and the underwater pictures were synchronized by time, and XYZ attributes were written in the photographs' EXIF using ViewMap software developed by Seaviews. Photogrammetric processes, *i.e.*, the creation of a tie point cloud, the generation of a Digital Elevation Model (DEM) and finally the building of an orthomosaic were performed using the Metashape software from Agisoft. Finally, the orthomosaic was exported in ViewMap to generate

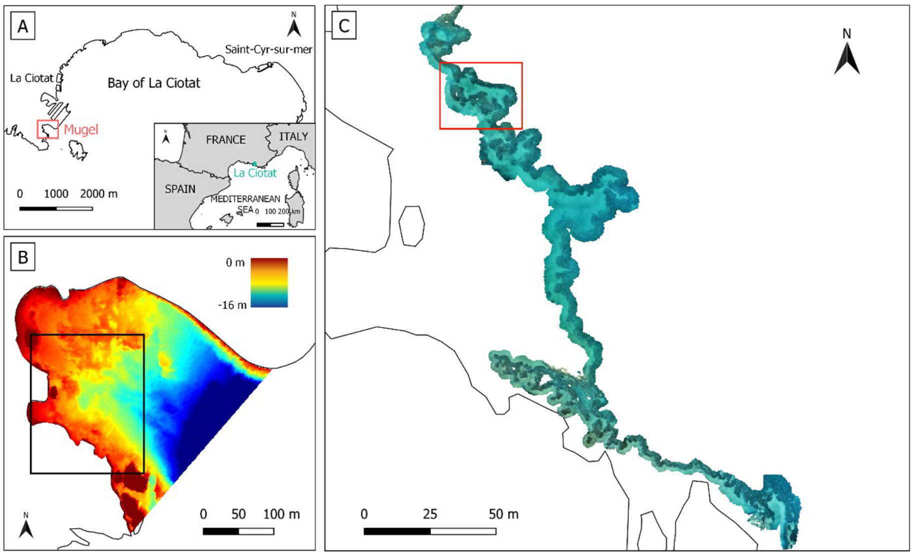

Fig. 1. – **A**: Study site (red frame) in the Bay of La Ciotat. **B**: Bathymetric map of Mugel Creek (data from the Litto3D program of the Hydrographic Service of the French Navy). The black frame represents the area where the meadow upper limit was mapped. **C**: Underwater orthomosaic of the meadow limit.

photographic tiles that allowed a better visualization to detect and map the various elements of the seafloor (*e.g.*, meadow, dead matte, moorings, rocks, wrecks, litter, sediments).

All the individuals of the fauna within the meadow and on the nearby various substrates were identified up to the species when possible. Their location was pinpointed and stored in a georeferenced computer file exploitable in a Geographic Information System (GIS). In order to investigate the potential of the biological data that can be extracted from the orthomosaic, all the substrates and habitats were manually mapped in ViewMap on a restricted portion of the whole orthomosaic, corresponding to a 350 m^2 surface area with depths ranging from 2 m to 7 m (Fig. 1B, C).

RESULTS

The orthomosaic clearly showed the *P. oceanica* meadow's limit that was very contrasted with the fine sediments at its edge (Fig. 1C). The pixel resolution obtained was 1 mm for a positioning precision of 7 cm over the whole area mapped. The high resolution allowed detection of dead matte and litter detritus areas as well as *P. oceanica* meadows, fine sediments and rocks (Fig. 2A). Artificial substrates were also identified such as old concrete blocks, tyre mooring systems (Fig. 2A), and small wrecks.

Five different sessile species were identified with various abundances: two snakelock anemones *Anemonia viridis* Forsskål, 1775, 285 sea-cucumbers *Holothuria* sp., two red starfishes *Echinaster sepositus* (Retzius, 1783), 57 brown sea-urchins *Paracentrotus lividus* (Lamarck, 1816) and eight fan mussels *Pinna nobilis* Linnaeus, 1758 (living and dead individuals). Most of the detections occurred on bare substrates, *i.e.*, rocks and sediments, and at the edge of the meadow. *Holothuria* sp. was mainly detected on the dead matte at the edge of the meadow. *P. lividus* individuals were observed in the cracks of shallow rocky bottoms. Dead *P. nobilis* were found lying on the dead matte while the erect ones were situated within the *Posidonia oceanica* meadow near the edge.

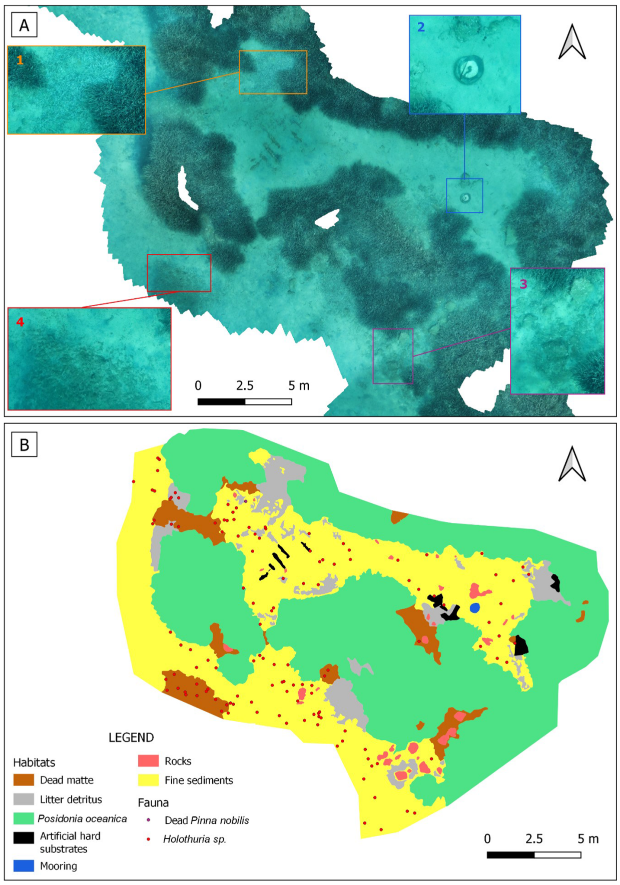

Fig. 2. – **A**: Orthomosaic of the focused area with zooms on special habitat patterns: 1: detritus litter at the edge of the *P. oceanica* meadow; 2: mooring system; 3: rocks and detritus litter; 4: dead matte with *Holothuria* sp. individuals. **B**: Map of the marine habitats and the identified fauna.

The map of the restricted area showed a distribution of the litter detritus and the dead matte at the edge of the *P. oceanica* meadow (Fig. 2B). Artificial concrete blocks were visible at the edge of the meadow, the latter covering them partially. A mooring system (an old tyre filled with concrete) and an assemblage of metallic structures were found on the main fine sediment patch (Fig. 2A). The spatial data showed that *P. oceanica* (living and dead parts) covered 63.7 % of the zone while fine sediments occupied 35.5 % and artificial substrates 0.8 % (Table I). When focusing on *P. oceanica* only, the dead parts of the plant (dead matte and litter detritus) represented 17.2 % of the total surface (Table I).

DISCUSSION

The aim of this research was to investigate the potential of orthomosaics generated by underwater georeferenced photogrammetry to study several functional compartments of the *P. oceanica* ecosystem in the framework of an ecosystem-based management strategy.

When compared with other mapping techniques, georeferenced underwater photogrammetry shows several key advantages. Acoustic sounders and airborne lidar are designed for bathymetric study and habitat mapping. They do not provide data allowing sessile fauna detection unlike underwater photogrammetry. Airborne photogrammetry is able to map near-surface marine habitats (up to 2 m depth) such as coral reefs and seagrass meadows (Casella *et al.* 2017) but requires still water. Moreover, their flying altitude – around 30 m – provides orthomosaics with a centimeter or decimeter resolution. The underwater photogrammetric technique deployed in the present study, with its millimeter resolution, allows the detection and identification of the sessile fauna of centimetric size. Its two main drawbacks are the range of the mapping efficiency, *i.e.*, the size of the mapped area, which is far lower than that of acoustic and lidar techniques; and its range, which depends on the water transparency since the photographs are shot from the surface. In the clearest Mediterranean water, its maximum range is around 10 m.

This work focused on the upper limit of the Mediterranean seagrass meadow, a place where many natural (*e.g.*, hydrodynamics, interaction with land ecosystems) and anthropogenic (*e.g.*, boating, fishing, tourism, coastal development) influences occur (Holon *et al.* 2015). Over the last decades the meadow's upper limit has been mainly mapped using aerial orthophotographs, with the drawback that dead matte, litter detritus and rocks can be mistaken for living *P. oceanica*. Underwater photogrammetry removes this uncertainty because of the photographic view that allows the mapping of the different habitats and substrates with virtually no erroneous identification (Rende *et al.* 2015). As highlighted in the results of this research, this technique also makes possible a spatial analysis of the different living and dead parts of *P. oceanica* meadows, the litter detritus and the dead matte representing about 20 % of the surface covered by the plant. Due to their important ecological role (*e.g.*, habitat, source of food, carbon sink), these areas should be taken into account in an ecosystem-based approach for the *P. oceanica* system (Boudouresque *et al.* 2015).

Underwater photogrammetry is also a powerful tool to detect and map artificial structures and more specifically illegal mooring systems composed of concrete blocks with a chain linked to a surface buoy. This system can be very harmful for *P. oceanica* meadows at shallow depth by pulling off the leaves, resulting in the generation of a dead matte area within the range of the length of the chain (Montefalcone *et al.* 2008). The capacity of photogrammetry to detect them paves the way for studying the impact of mooring systems on seagrass meadows with a spatial approach linking anthropogenic pressure and the ecological status of the seafloor surrounding them.

The identification and detection of sessile species is another advantage of underwater photogrammetry, thus allowing further investigations of the spatial distribution of marine organisms according the seascape characteristics (Abadie *et al.* 2018b). In the framework of this study, the key species *Paracentrotus lividus* of the *P. oceanica* ecosystem was detected, although not within the meadow but at its edge on a rocky substrate. The endemic – and currently under threat of extinction – species *Pinna nobilis*

Table I. – Area covered by marine habitats and their proportion in the focused area.

Habitat	Area (m^2)	Relative proportion (%)	Overall proportion (%)
Posidonia oceanica			
Living meadow	183.6	82.8	52.0
Dead matte	17.8	8.0	5.0
Litter detritus	20.3	9.2	5.7
Other habitats/substrates			
Fine sediments	125.3	–	35.5
Rocks	3.6	–	1.0
Artificial hard substrates	2.3	–	0.7
Mooring device	0.2	–	0.1

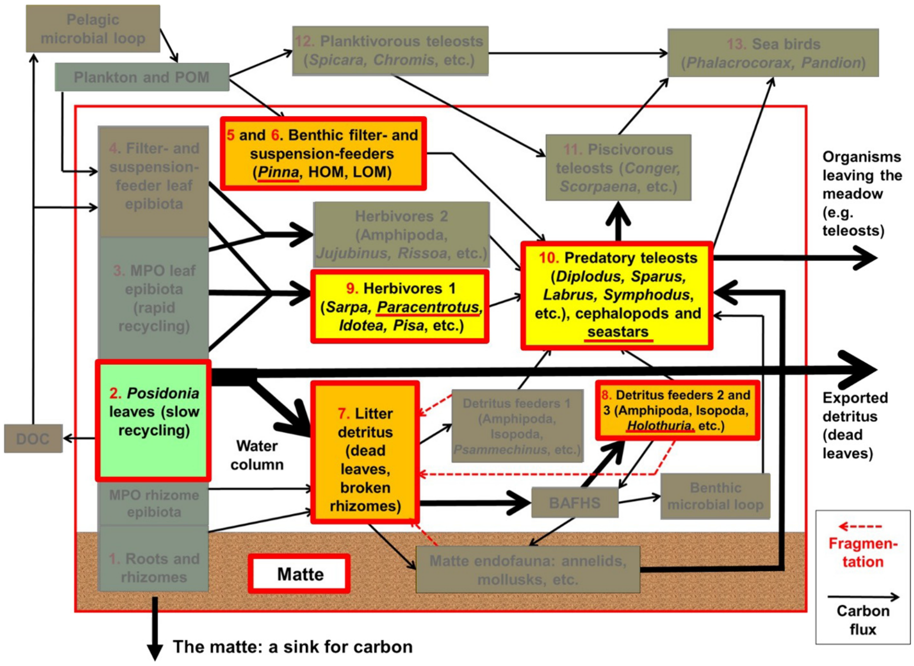

Fig. 3. – Conceptual representation of the *Posidonia oceanica* ecosystem composed of functional compartments and the interactions between them. Compartments framed in red are the ones investigated with photogrammetry in this study. Modified from Personnic *et al*. (2014).

was also detected. Unlike *P. lividus*, individuals of *P. nobilis* were found within the meadow near its edge. It was impossible to tell which ones were living and which ones were dead however, except for two individuals that were lying on their side on dead matte. These observations on *P. nobilis* distribution corresponds to that made by Coppa *et al*. (2010) who found that this bivalve settles mainly on dead matte and within the meadow close to the edge. The difficulty of detecting sessile species within the canopy is mainly due to the length of the leaves at the moment of the data acquisition (August). In order to increase the detection capacity of sessile species within the meadows, we recommend performing the data acquisition at the end of autumn or during winter when *P. oceanica* leaves are shorter and meadows are sparser.

It is clear that underwater photogrammetry is suited to the study of both spatial features of marine habitats and the distribution of several benthic species. In the framework of an ecosystem-based management strategy for the *P. oceanica* ecosystem, this method can be used to investigate several functional compartments (Fig. 3) of the conceptual model suggested by Personnic *et al*. (2014). It is obvious that photogrammetric mapping is not able to replace scuba diving data sampling. It is rather a low cost and effective tool to obtain additional spatial data on an area of interest.

Recent innovations in the acquisition of spatial data have the potential to provide new insights on the spatial heterogeneity of seagrass meadows and the organisms that live within or near them. The approach presented in this work thus appears relevant in the framework of an ecosystem-based management strategy for *P. oceanica* meadows. More work remains to be done on the analysis of the photogrammetric products to apprehend their true capacity in terms of the exploitable information. Furthermore, the spatial analysis of orthomosaics still requires automatization for more objective and effective study.

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