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THE UNIQUE FEATURE OF A *POSIDONIA OCEANICA* REEF AND LAGOON ALONG THE FRENCH MEDITERRANEAN COAST

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BARRIER REEF
LAGOON
POSIDONIA OCEANICA
SEAGRASS REEF
ANTHROPIC PRESSURES

ABSTRACT. – *Posidonia oceanica* is a seagrass, which can build original reef structures. A unique emerging *P. oceanica* reef was encountered in the Le Brusc Bay on the French Mediterranean coast. Extending over 1,600 m in width, the reef appears to be one of the last remaining large *P. oceanica* reefs. This reef has two distinct profiles: a barrier reef on the eastern front and a fringing reef on the western front. Located on the outer section of the bay, the barrier reef limits water turnover in the bay, thus forming a lagoon. The presence of three small passes in the inner section of the bay has shaped an original current dynamic. The unique morphology of the Le Brusc lagoon makes it a site of high naturalistic value. To assess the health status of the Le Brusc reef, the present study precisely maps it for the first time using unmanned aerial vehicle imagery coupled with field observations. We also studied its evolution since 1950 using historic aerial photographs. Results indicate a regression of the reef, mainly due to the artificialization of the coastal area and the development of harbor facilities, causing the loss of 29.3 % of the reef's surface including the disappearance of more than two-thirds of the barrier reef's profile. In addition, 8,180 m of boat stranding marks were observed in the barrier reef.

INTRODUCTION

Posidonia oceanica (Linnaeus) Delile is a seagrass endemic to the Mediterranean Sea. Vertical growth of *P. oceanica* results in the progressive burial of roots, rhizome fragments and leaf sheaths in the sediment forming a rot-resistant powerful rhizome stratum called 'matte' (Boudouresque *et al*. 2012). This unique biostructure can grow up to several meters high (Molinier & Picard 1952). In conditions of calm and shallow water, *P. oceanica* meadows can near the sea surface and leaves may partly emerge (especially at low tide or during the spring and summer seasons when the leaves are the longest), resulting in the formation of a reef. Different profiles of *P. oceanica* reefs have been identified. Unlike fringing or plateau reefs, which respectively grow parallel and perpendicular to the coastline, barrier reefs have the distinctive feature of being located in inner bay areas (Bonhomme *et al*. 2015, Rouanet *et al*. 2019). The sheltered innermost waters bounded by the reef (*i.e*., the back-reef area) form an area with poor hydrodynamic and heavy sedimentation conditions. These lagoon-like conditions threaten the survival of *P. oceanica* and cause the regression of the reef in the lagoon and its spread towards the open sea (Molinier & Picard 1952, Boussard *et al*. 2019).

The Natura 2000 *Lagune du Brusc* site, located in the South of France near the city of Six-Fours-les-Plages, is a unique environment where *P. oceanica* forms a singular barrier reef structure. Unlike most barrier reef structures, located in the inner part of closed bays, the Le Brusc barrier reef grows on the outer edge of the lagoon on the northern side (Francour & Sartoretto 1991, Rouanet *et al*. 2008). The lagoon has the peculiarity of being delimited on its southern side by a string of small islands (Le Petit Gaou, Le Grand Gaou and Les Embiez Islands) allowing water renewal inside the lagoon through three passes. Despite its recognition as an exceptional natural site by several European and national management classifications – Natura 2000, special protected area of Mediterranean importance (SPAMI), Natural zone of ecological, faunal and floral value (ZNIEFF) and prefectural and municipal decrees – the Le Brusc lagoon suffers from major anthropogenic pressures (Holon *et al*. 2015). Since the beginning of the 21st century, major disturbances have been observed, such as the loss of the two species of seagrass meadows in the lagoon, *Cymodocea nodosa* (Ucria) Asch and *Zostera marina* Linnaeus (Couvray *et al*. 2020), compromising its fish nursery function (Kirchhofer *et al*. 2016). As the *P. oceanica* barrier reef plays a key role in the existence of the lagoon and the resulting ecosystem, assessing its present health status is crucial for the environmental management of this site.

We used an unmanned aerial vehicle (UAV) combined with orthophotography, field observations by snorkeling and hydroacoustic surveying to map the *P. oceanica* reef and Le Brusc lagoon. This work enabled us to produce an accurate representation of the Le Brusc *P. oceanica* reef and assess the direct impacts of boat stranding marks and harbor facilities on the reef, and supports the hypothesis of the indirect impact of water flow dynamic on the barrier reef health.

MATERIALS AND METHODS

Area mapping: The study area is located on the Mediterranean coast, in the South of France near the city of Six-Fours-les-Plages. Images of the Le Brusc lagoon site were taken in August 2019 and January 2020 using a Phanton 4 unmanned aerial vehicle (UAV). Up to 737 pictures were used for each photogrammetry. Orthomosaics were prepared using the DroneDeploy software program. Historic aerial photographs (source: National Geographic Institute, IGN) and, in particular the IGN 1950 aerial photograph, were used along with French administrative documents relative to the area to assess the development of anthropic facilities. Georeferencing and cartography analysis were performed using a Geographic Information System (QGIS 3.8, projection Lambert 93). *In situ* observations enabled us to validate the interpretation of the aerial photographs.

Bathymetry mapping: A hydroacoustic survey of the barrier reef and of the southern passes was carried out in 2018 by the engineering service SEMANTIC TS using a multi-beam R2SONIC 2020 echosounder. In very shallow areas, a mono beam eBEEM echosounder was used instead. Data collected with both sounders was merged to obtain the bathymetric chart of the Le Brusc lagoon and barrier reef with 0.25-meter precision. A previous hydroacoustic survey from 2006 conducted all around Les Embiez Island with 1-meter precision was used to determine the bathymetry of the full *P. oceanica* reef (fringing and barrier reefs).

Posidonia reef mapping: The Le Brusc *P. oceanica* reef was mapped according to the method detailed above. Visual differentiation of dead matte and living *P. oceanica* beds was possible for the barrier reef (north), but not for the smaller *P. oceanica* reef (westernmost southern pass) growing on rocky substrate. To fix the external limit of the fringing reef (north-west), 3 criteria were used: 1) absence of *P. oceanica*, or 2) presence of a vertical structure (*i.e.*, reef drop-off), or 3) closest to the 1-m depth limit (determined by the bathymetry mapping) following the natural topography of the meadow. The same criteria were used to fix the external limit of the barrier reef (north-east), except that the 0.75 m-depth bathymetry contour was followed to be in accordance with the depth of the reef's inner profile. To assess the global morphology of the barrier reef, we virtually separated the reef into 4 longitudinal and 5 transversal evenly distributed sections.

RESULTS

Lagoon and reefs

A fringing reef extends on the west side of the great barrier reef along the Les Embiez Islands, forming together a 1,600 m long *P. oceanica* reef from Le Brusc harbor to Les Embiez harbor (Fig. 1). In 2020, 18.7 ha were covered by the reef versus 26.4 ha in 1950. The lagoon covers 44 ha and the 3 southern passes maximum depths measured in the narrowest point are respectively, from west to east, 0.7 m, 0.8 m and 0.5 m. A second smaller *P. oceanica* barrier reef grows in the westernmost southern pass. It covers a total surface of 6,270 m^2 for 2,800 m^2 of living *P. oceanica* beds. From 1950 to 2020, we observe

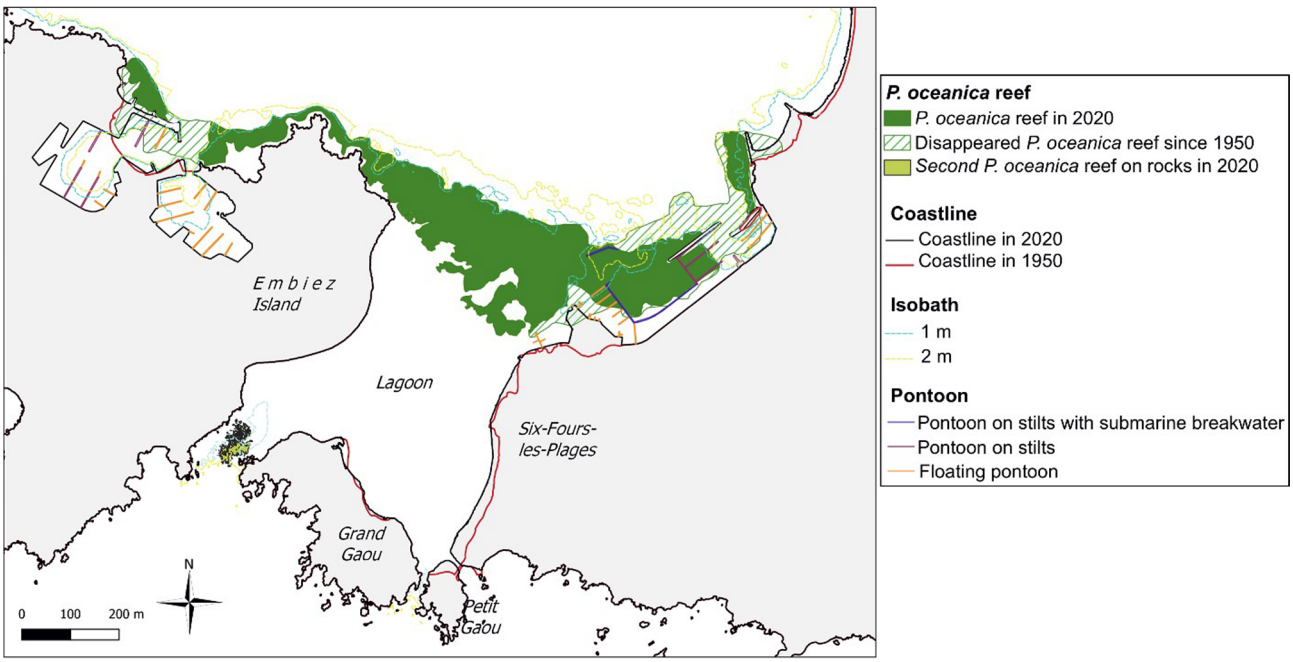

Fig. 1. – Le Brusc lagoon and *Posidonia oceanica* reefs, including harbor facilities and changes in the coastline between 1950 and 2020. The main reef in the north includes living *P. oceanica*, dead matte and natural passes. The second reef in the south includes only living *P. oceanica*.

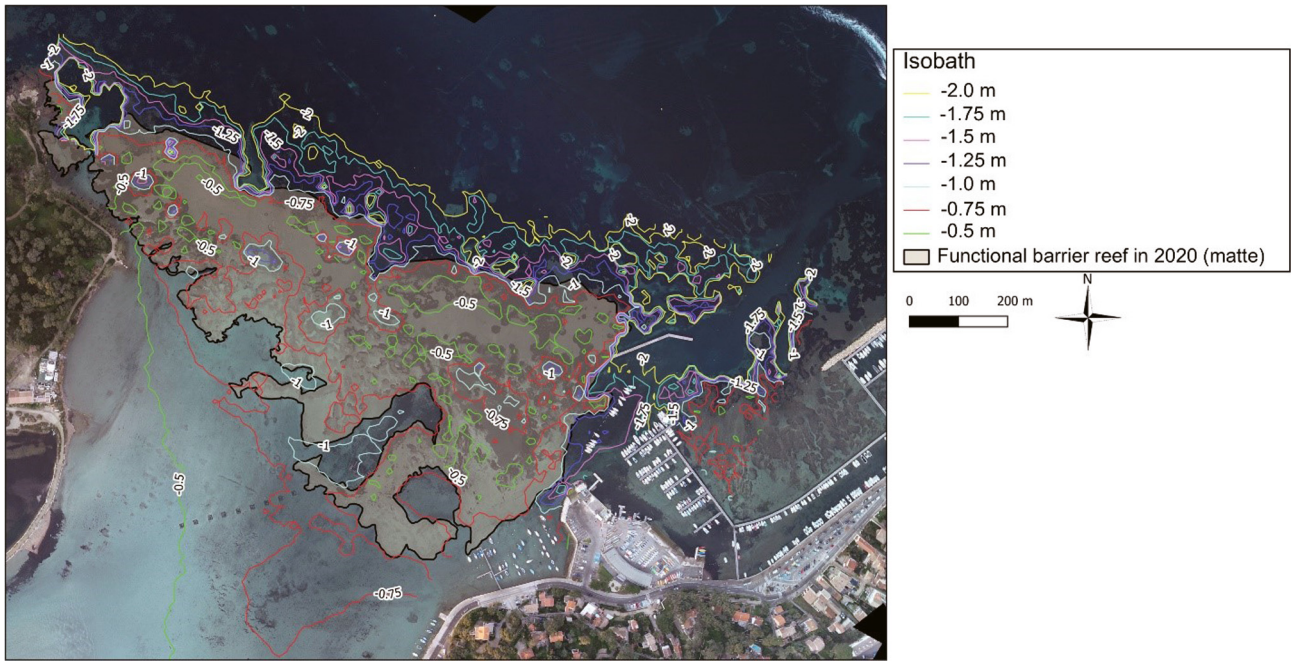

Fig. 2. – Functional barrier reef of the Le Brusc Lagoon and associated bathymetry. The functional barrier reef includes living *P. oceanica* and dead matte of the reef not directly impacted by the harbor facilities.

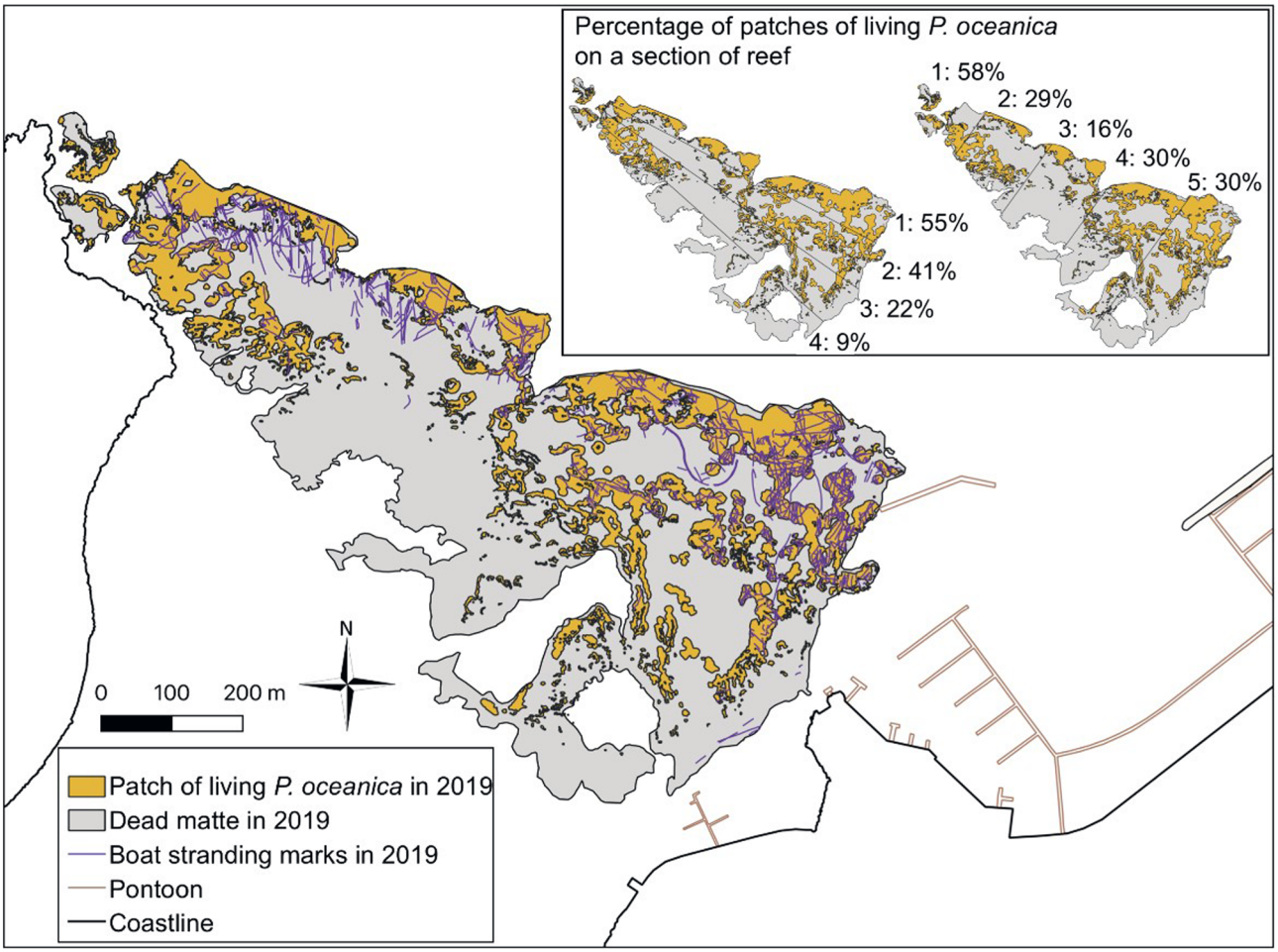

Fig. 3. – Patches of living *Posidonia oceanica* and dead matte in the functional barrier reef (*i.e.*, part of the reef not directly impacted by the harbor facilities) in 2019, including boat-stranding marks.

a regression of the lagoon surface and of the living *P. oceanica* mainly on the east side due to artificialization of the coastal area and the development of harbor facilities.

Great barrier reef

The cartographic analysis of the study site reveals the loss of the easternmost part of the barrier reef due the construction of the Le Brusc harbor facilities on it. In this area, only a few areas of silted dead matte and small patches of silted living *P. oceanica* remain. We therefore assume that the reef in this area no longer plays the role of a functional barrier reef for the lagoon. What remains of the barrier reef covers 10 ha and is delimited by two small passes. We consider this area as the functional barrier reef for the lagoon (Fig. 2). The morphology of the western pass resembles more that of a small water hole. The eastern pass is partly blocked by a boat launch ramp, pontoons on stilts and underwater breakwaters (Fig. 1). In 2019, our map revealed that patches of living *P. oceanica* only made up 29 % of the functional barrier reef. The patches were overall small and fragmented. We used the percentage of living *P. oceanica* on the reef surface as an indicator of the reef's vitality. We observed a difference in the proportion of the patches between the outer and inner areas of the barrier reef. The patches of living *P. oceanica* accounted for 55 % of the reef's total surface at the outer limit versus 9 % at the inner limit. We also observed a higher proportion of patches in the eastern and western peripheral sections of the reef in comparison with the centre (Fig. 3).

DISCUSSION

The Le Brusc reef, made up of both a fringing and a barrier reef, has been precisely mapped for the first time in this study. We have shown that this reef was continuous between the present Embiez harbor in the west and Brusc harbor in the east in 1950 (Fig. 1). Since then, Embiez harbor, built in 1962, and the construction of the main jetty and the digging of the channel, broke the continuity of the reef, isolating its westernmost section. On its eastern side, the successive developments until 2019 of the old Le Brusc traditional fishing harbor induced the destruction of part of the barrier reef. The reef suffered its greatest damage after the construction of the nautical base and the boat launch ramp in 1970. The artificialization of the beach just north of the Le Brusc harbor most likely also enhanced the degradation of the eastern part of barrier reef. In addition, successive coastline modifications to the east of the lagoon may also have had an indirect impact on the reef. As a consequence, the reef lost 29.3 % of its surface between 1950 and 2020.

Extreme temperature and salinity conditions (compared to those in open waters) arise in bodies of water enclosed by barrier reefs, generating stress for *P. oceanica* (Molinier & Picard 1952, Boussard *et al*. 2019). According to theoretical *P. oceanica* barrier reef dynamics (Molinier & Picard 1952), reefs tend to regress in the lagoon area and expand towards the open sea. Consequently, the presence of dead matte in a *P. oceanica* reef is common and not necessarily a sign of a declining health. At first glance, we can consider the decreasing outer to inner gradient of living *P. oceanica* observed in the Le Brusc barrier reef as not alarming (Fig. 3). However, the Le Brusc lagoon has the unique feature of receiving seawater through three inlets in the South. The reduced size and shallow depth of these passes, as well as the presence of a second *P. oceanica* reef in the main pass, reduces swell and wave action in the lagoon while allowing the water to circulate. The specificities of the Le Brusc barrier reef is its location on the outer part of the bay, which allows it to benefit from the rate of water-turnover made possible by the passes. Historically, the water flow used to enter the lagoon through the main southern pass, flowed along the eastern coastline of the lagoon and exit the lagoon through a natural pass east of the barrier reef (Blanc 1958). We can assume that the environmental conditions were suitable enough for *P. oceanica* due to the sufficient water-turnover. Nowadays, this large pass on the barrier reef is blocked by the nautical base of the Le Brusc harbor. Only two narrow inlets remain, one on the western end of the barrier reef and the other close to the former large pass in the east. The recent construction of new pontoons equipped with underwater breakwaters near this second inlet will most likely further reduce the water flow (Figs 1, 2). As described above, we observed an outer to inner gradient of the reef's vitality, which could be consistent with theoretical *P. oceanica* barrier reef dynamics (Molinier & Picard 1952). However, due to recent developments in the Le Brusc harbor, short-term changes in the vitality pattern should be assessed in the years to come. We also observed a higher vitality on both sides of the *P. oceanica* barrier reef, certainly linked to the presence of the passes, which favor water renewal. However, there were more patches of living *P. oceanica* on the western side of the reef than on the eastern side (respectively 58 and 30 %) (Fig. 3) even if the main flow was historically on the east side of the barrier reef (Blanc 1958). These results suggest the possible indirect effects of harbor facilities on the water flow and on the vitality of *P. oceanica* barrier reefs. Additional research on the hydrodynamics of the lagoon should be performed to complete our observations.

Francour & Sartoretto (1991) observed an abnormally high mortality rate of the Le Brusc barrier reef in the decades prior to their study. In line with their observations, our study showed that less than a third of the 1950 barrier reef surface area remained in 2019 (Fig. 3). We therefore hypothesize that a high level of human activity in this area (Holon *et al*. 2015) is a strong factor to explain the observed decline of living *P. oceanica* on

the Le Brusc barrier reef. For instance, increasing boating activities increase the stress on the reef. In 2019, we recorded 8,180 meters of boat stranding marks on the barrier reef. Despite sailing and motorboats being prohibited in this area, several boat strandings are observed each year on the reef (personal observations). Such erosion of the barrier reef has also been observed at Port-Cros Island (Augier & Boudouresque 1970). Considering the very slow elongation rate of *P. oceanica* rhizomes, these marks accumulate year after year and fragilize the reef. Damaging or altering the vitality of such reefs is therefore irreversible on a human time scale.

The Le Brusc reef is one of the last remaining large *P. oceanica* reefs on the French Mediterranean coast. The goods and services provided by such ecosystems, such as climate change mitigation (Boudouresque *et al*. 2016), give grounds for their immediate protection. The barrier reef is vital to the Le Brusc lagoon ecosystem and is a part of our natural heritage. Although the lagoon is now closed to swimmers and sailing and motor boats to protect its nursing grounds, constant direct and indirect anthropogenic pressures continue to threaten the barrier reef and the lagoon on short time scales.

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