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Dominique Calmet, Pierre Calmet, Charles-François Boudouresque. Does Beach Sand Nourishment Have a Negative Effect on Natural Recovery of a *Posidonia oceanica* Seagrass Fringing Reef? The Case of La Vieille Beach (Saint-Mandrier-sur-Mer) in the North-Western Mediterranean. *Water*, 2025, 17, <10.3390/w17152287>. <hal-05468767>

HAL Id: hal-05468767

<https://amu.hal.science/hal-05468767v1>

Submitted on 21 Jan 2026

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Article

Does Beach Sand Nourishment Have a Negative Effect on Natural Recovery of a *Posidonia oceanica* Seagrass Fringing Reef? The Case of La Vieille Beach (Saint-Mandrier-sur-Mer) in the North-Western Mediterranean

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Abstract

Posidonia oceanica seagrass, endemic to the Mediterranean Sea, provides ecological goods and ecosystem services of paramount importance. In shallow and sheltered bays, *P. oceanica* meadows can reach the sea surface, with leaf tips slightly emerging, forming fringing and barrier reefs. During the 20th century, *P. oceanica* declined conspicuously in the vicinity of large ports and urbanized areas, particularly in the north-western Mediterranean. The main causes of decline are land reclamation, anchoring, bottom trawling, turbidity and pollution. Artificial sand nourishment of beaches has also been called into question, with sand flowing into the sea, burying and destroying neighbouring meadows. A fringing reef of *P. oceanica*, located at Saint-Mandrier-sur-Mer, near the port of Toulon (Provence, France), is severely degraded. Analysis of aerial photos shows that, since the beginning of the 2000s, it has remained stable in some parts or continued to decline in others. This contrasts with the trend towards recovery, observed in France, thanks to e.g., the legally protected status of *P. oceanica*, and the reduction of pollution and coastal developments. The sand nourishment of the study beach, renewed every year, with the sand being washed or blown very quickly (within a few months) from the beach into the sea, burying the *P. oceanica* meadow, seems the most likely explanation. Other factors, such as pollution, trampling by beachgoers and overgrazing, may also play a role in the decline.

Keywords: fringing reef; overgrazing; *Posidonia oceanica*; Provence; sand nourishment of beaches; water quality



Academic Editor: José Luis Sánchez-Lizaso

Received: 13 May 2025

Revised: 22 July 2025

Accepted: 25 July 2025

Published: 1 August 2025

Citation: Calmet, D.; Calmet, P.; Boudouresque, C.-F. Does Beach Sand Nourishment Have a Negative Effect on Natural Recovery of a *Posidonia oceanica* Seagrass Fringing Reef? The Case of La Vieille Beach (Saint-Mandrier-sur-Mer) in the North-Western Mediterranean. *Water* **2025**, *17*, 2287. <https://doi.org/10.3390/w17152287>

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1. Introduction

The seagrass *Posidonia oceanica* (Linnaeus) Delile is endemic to the Mediterranean Sea, where it constitutes extensive meadows from the sea surface down to 30–40 m depth [1,2]. The *P. oceanica* ecosystem provides ecological goods and ecosystem services of paramount importance [3–14], a feature shared by most seagrass ecosystems worldwide [15,16]. For these reasons, it has been the subject of thousands of scientific studies (e.g., [17–26]).

An original feature of *P. oceanica* meadows is that the rhizomes are not easily degradable and are therefore preserved for millennia [27]. The structure constituted by the dead and living rhizomes, and by the sediment which fills the interstices, is called ‘matte’. Over

time, the living part of the matte, with living shoots, rises towards the sea surface; in shallow and sheltered bays, the meadow can reach the sea surface, with leaf tips slightly emerging, first forming fringing reefs, then barrier reefs where a lagoon occurs between the shore and the reef [6,17,28,29].

The remains of a previously unreported fringing reef of *P. oceanica* have been discovered in front of La Vieille beach, Saint-Mandrier-sur-Mer (eastern Provence, France) [30,31].

The *P. oceanica* meadows, including fringing reefs and barrier reefs, severely declined in many areas of the north-western Mediterranean from the early 20th century, e.g., near Genoa (Italy), Toulon and Marseilles (France), and Alicante (Spain), due mainly to coastal development, anchoring and bottom trawling (e.g., [32–41]). Pollution can also have a detrimental effect on *P. oceanica* [42–45], although its actual effect may have been overestimated [39,46,47]; the negative effect of pollution could be indirect, through overgrazing by fish and sea urchins attracted by nitrogen-enriched leaves and epibionts of *P. oceanica* [48,49]. Overgrazing by the sea urchin *Paracentrotus lividus* (Lamarck, 1816) and the fish *Sarpa salpa* (Linnaeus, 1758) has been considered as one of the key factors involved in the regression of the barrier reef of the Bay of Port-Cros (eastern Provence) [32,50–53]. Finally, artificial sand nourishment of beaches (also called ‘sand replenishment’) is often blamed for the decline of *P. oceanica*, as the sand washed away from the beaches buries the meadow and a layer of sand a few centimetres thick (from 4 cm), for three weeks to a few months, is enough to kill *P. oceanica* [54–63]. In addition, the washed sand increases the turbidity of coastal waters [22,64,65]. However, very little specific data exists on the subject of beach sand nourishment in the Mediterranean, showing impact or no impact [56,57,66]; the majority of references simply refer vaguely to sand nourishment. Beach nourishment is widely practiced worldwide, not only to combat the beach erosion but also to create artificial beaches [67,68]; it is a practice that is on the increase [68,69]. Beach replenishment is often considered a soft and environment-friendly solution, in any case preferable to the construction of groynes or riprap [70–72]. However, as in the Mediterranean, its effects on the beach and dune ecosystem as well as on subtidal ecosystems are conspicuous, although rarely considered or described [73–79].

Degraded *P. oceanica* meadows can regenerate when the cause of regression has ceased, but the process is slow. The first studies on the subject estimated the progression of a meadow margin at 3–6 cm/year on average [1,34,80–83]. More recent work suggests a faster actual progression: up to 20 cm/year [84–88]. In addition, new patches of *P. oceanica* may come from cuttings [83,89–92] and seed germination [91,93].

Here, we describe in detail the fringing reef of *P. oceanica* at Saint-Mandrier-sur-Mer (north-western Mediterranean). Using a set of aerial photos, the oldest dating from 1953, we try to trace its changes over time: continued degradation, stability, or beginning of recovery. We analyse the possible links between this process, the changes in water quality and the management practices on the adjacent beach, and offer a comparison with the kinetics of *P. oceanica* in other Mediterranean regions. The objective is to draw attention to the effects of beach sand nourishment on the seagrass, an issue of growing concern on which there is little data in the case of the Mediterranean Sea. The discussion will focus on protection measures for a *P. oceanica* fringing reef in an area subject to multiple anthropogenic impacts.

2. Materials and Methods

The Saint-Mandrier-sur-Mer (hereafter ‘Saint-Mandrier’) Peninsula is located south of the city of Toulon (Provence, France). It closes the Bay of Toulon to the south (Figure 1). Its coast formerly presented an alternation of cliffs and small pebble beaches. However, from the 20th century onwards, its coastline has been profoundly altered by humans. This transformation was linked first to the construction of extensive naval facilities, then

to tourism development with the creation of marinas. In total, 22% of shallow coastal habitats between the sea level and 10 m depth have been artificialized [94]. The coastline of the peninsula located within the *Petite Rade* has been completely artificialized by port construction, land reclamations, riprap and artificial beaches such as that of La Vieille.

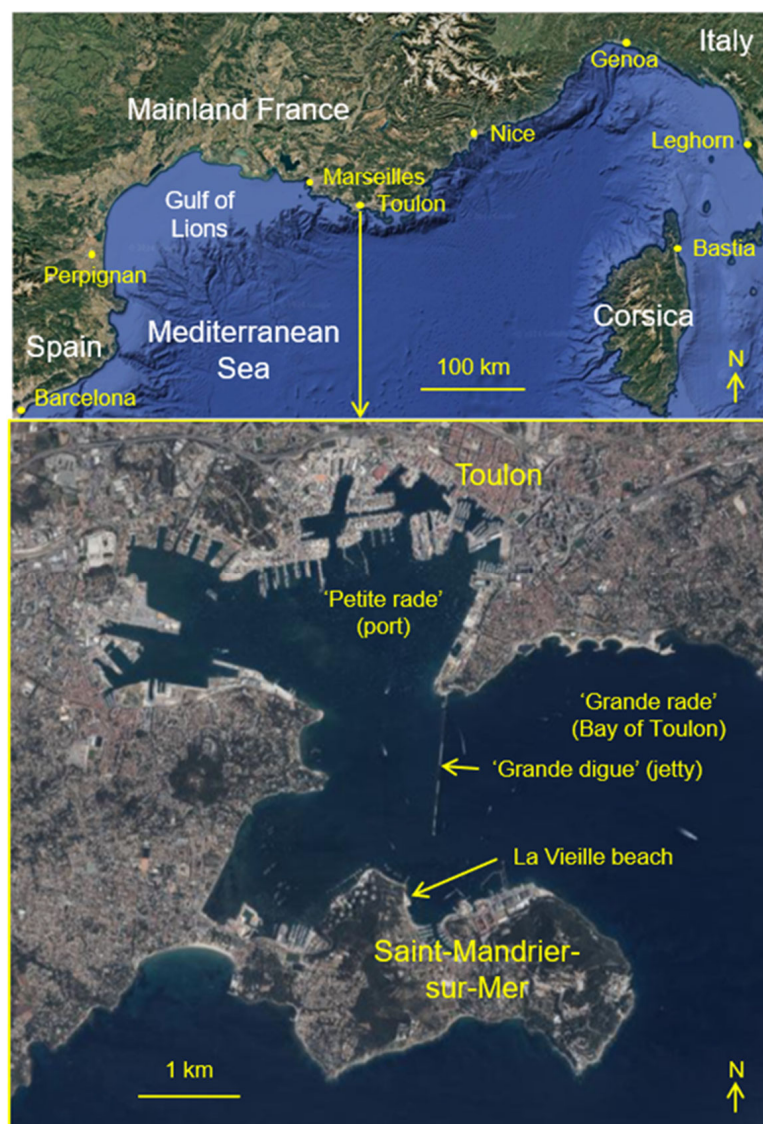


Figure 1. The study area in southern France, and location of the fringing reef of *Posidonia oceanica* off the beach of La Vieille (Saint-Mandrier-sur-Mer). Maps from Google Earth®.

La Vieille beach is a small, relatively recent artificial beach: 95 m long, 2500 m² in surface area, and supplied with quarry sand (Table 1). It was created during the period 1970–1971, to promote the development of tourism at Saint-Mandrier, a town devoid of natural sand beaches (Figure 2). La Vieille beach is under the influence of easterly gales which generate waves that erode the northern part by washing the sand located at the bottom of the beach out to sea. When it rains, the gully of rainwater from the path bordering the top of the beach also carries sand into the sea. The northwest wind (known as '*mistral*') carries sand from the beach onto the access road, right up to the buildings located on the Quai Séverine; during rains, this sand is then carried by runoff water to the sea via the rainwater drainage network.

Table 1. Granulometric analysis of quarry sand deposited on La Vieille beach, in May 2022 [95], according to the Wentworth scale [96].

Grain Size	Percentage
<63 μm	2%
<125 μm	4%
<250 μm	21%
<500 μm	48%
<1000 μm	81%
<2000 μm	95%
<4000 μm	98%
<8000 μm	100%

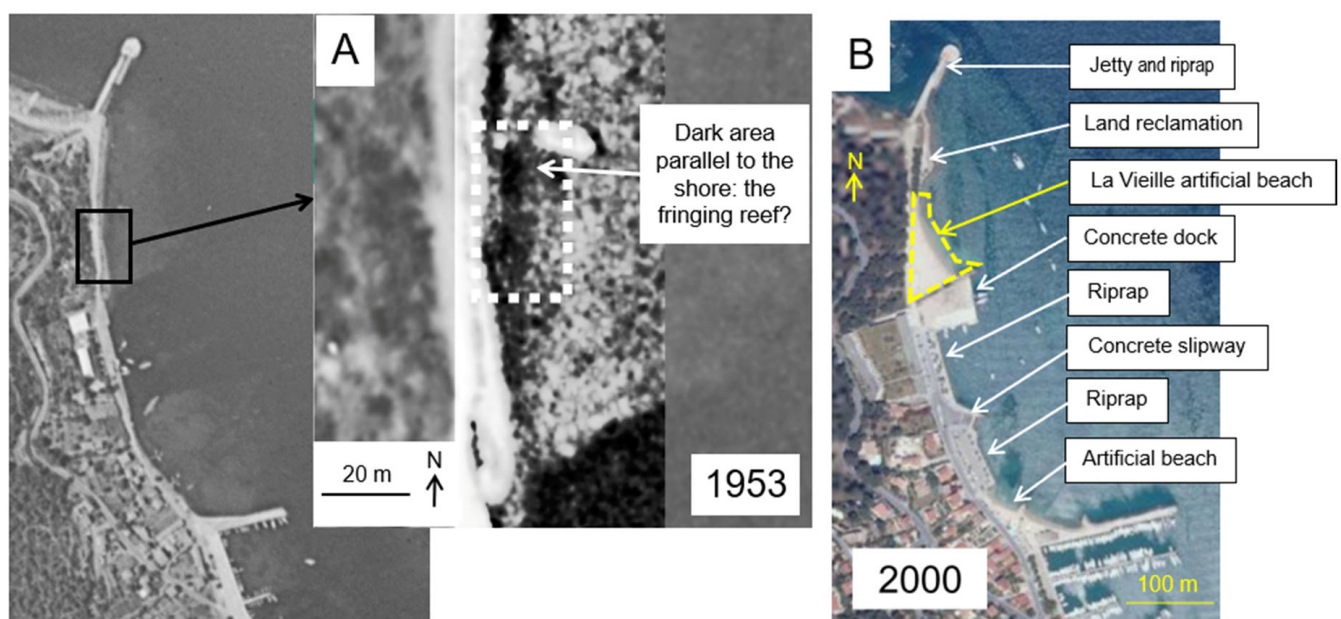


Figure 2. Comparison between aerial images from 1953 (A) and 2000 (B). The zoomed-in image (A) of the 1953 photograph shows a darker area parallel to the shore that can be interpreted as the fringing reef. The 2000 image (B) shows La Vieille beach demarcated by a yellow dotted line. From IGN.

The use of aerial photographs makes it possible to map the limit of the *P. oceanica* meadows and their changes where they are shallow, which is the case at the study site: the fringing reef is less than 1 m depth. Ground truth surveys via snorkelling provide verification that the colours and their nuances are correctly interpreted. Comparison of diachronic photos does not reveal changes of the order of a few centimetres or decimetres; on the other hand, changes of one metre or more can be highlighted [46,97–100].

The aerial georeferenced (Lambert-93 Projection—RGF 1993) orthophotographs used are those available on the IGN (French National Geographic Institute) internet portal La BD ORTHO® (<https://geoservices.ign.fr/bdortho#telechargementanc>, accessed on 15 February 2025) and ‘Remonter le temps’ (<https://remonterletemps.ign.fr/>, accessed on 15 February 2025) which were not blurred for reasons of military security. They were selected according to their high resolution (50 cm), the absence of waves and swell, the absence of iridescence and reflectivity of the sun on the surface of the sea, the transparency of the water column and the visibility of bottom structures such as seagrass beds.

In total, eight aerial photographs were selected for further analysis, corresponding to the years 1953, 1972, 2000, 2011, 2013, 2015, 2020 and 2023. The month chosen for photographing matters, as the leaves can be very short in winter, and more than 1 m long (up to 142 cm) in spring-summer [101–103]; when the leaves are flattened by the current, the apparent surface area of meadow patches is increased. Some of the photographs have been digitally processed to enhance the contrast and reduce iridescence. The digital processing of each photograph was carried out by selecting the panchromatic bands (shades of black and white) to increase the contrast between the different areas of the image. The effectiveness of the processing was visually assessed when the boundaries of the patches of naturally dark green *P. oceanica*, which appear in varying shades of grey on the image, were clearly distinguished from the surrounding sand areas, which appear in white and light grey. The seagrass patches were then selected and their surface area calculated using a Geographic Information System (QGIS). From the 2023 photograph, the structures assumed to correspond to living *P. oceanica*, to dead *P. oceanica* ('dead matte') not covered with sediment, and to the sediment area, were confirmed by a ground truth survey via snorkelling and scuba diving, with an accurate GPS positioning of the boundaries. Finally, we have drawn up a very precise GPS map of the fringing reef to enable finer future monitoring of its kinetics and state of health.

3. Results and Discussion

3.1. Change over Time of the La Vieille Fringing Reef

The oldest available IGN photograph of the La Vieille fringing reef dates from 1953. A darker area, at the current location of the reef, could correspond to it (Figure 2A). All subsequent photographs show the main part of the fringing reef, north of La Vieille beach, and an alignment of reef fragments towards the south, in front of the beach (Figure 3A–F).

The 1972 photo (Figure 3A) shows the first sand nourishment of the beach following its creation in 1970. That year, the shore was filled with various materials mixed with pebbles that were covered with sand in 1971. The beach width ranged from 15 m in the northern part to 40 m in the southern part. The fringing reef was constituted of 5 patches of different size that were oriented along a north-south axis. The western limit of the patches was in contact with the sand of the beach showing that a large amount of sand had been added that certainly covered the western limit of the initial fringing reef. The total surface of the patches can be estimated as 251 m².

The 2000 to 2023 photos (Figure 3B–F) show major changes in the beach sand surface area as well as the fringing reef structure. In the northern part of the beach, the shoreline has permanently receded since the replenishment of 1972 with a width of less than 10 m. This is the beach area that is the most eroded during storms and is the site of the main annual sand nourishment operation.

Since 2000, the two patches in the north of the fringing reef have disappeared (Figure 3B). The two central patches are aggregated in a single main part and the southern patch has narrowed and been broken up into small patches. In the main part of the reef, two patches of 'dead matte' can be seen: the dead rhizomes of *P. oceanica* do not bear shoots of leaves; the first, to the north, is more or less circular (DM N); the second, to the south, is trefoiled (DM S) (Figure 4). We can also distinguish two indentations on the edge of the reef, one to the north (Ind N), the other to the south (Ind S).

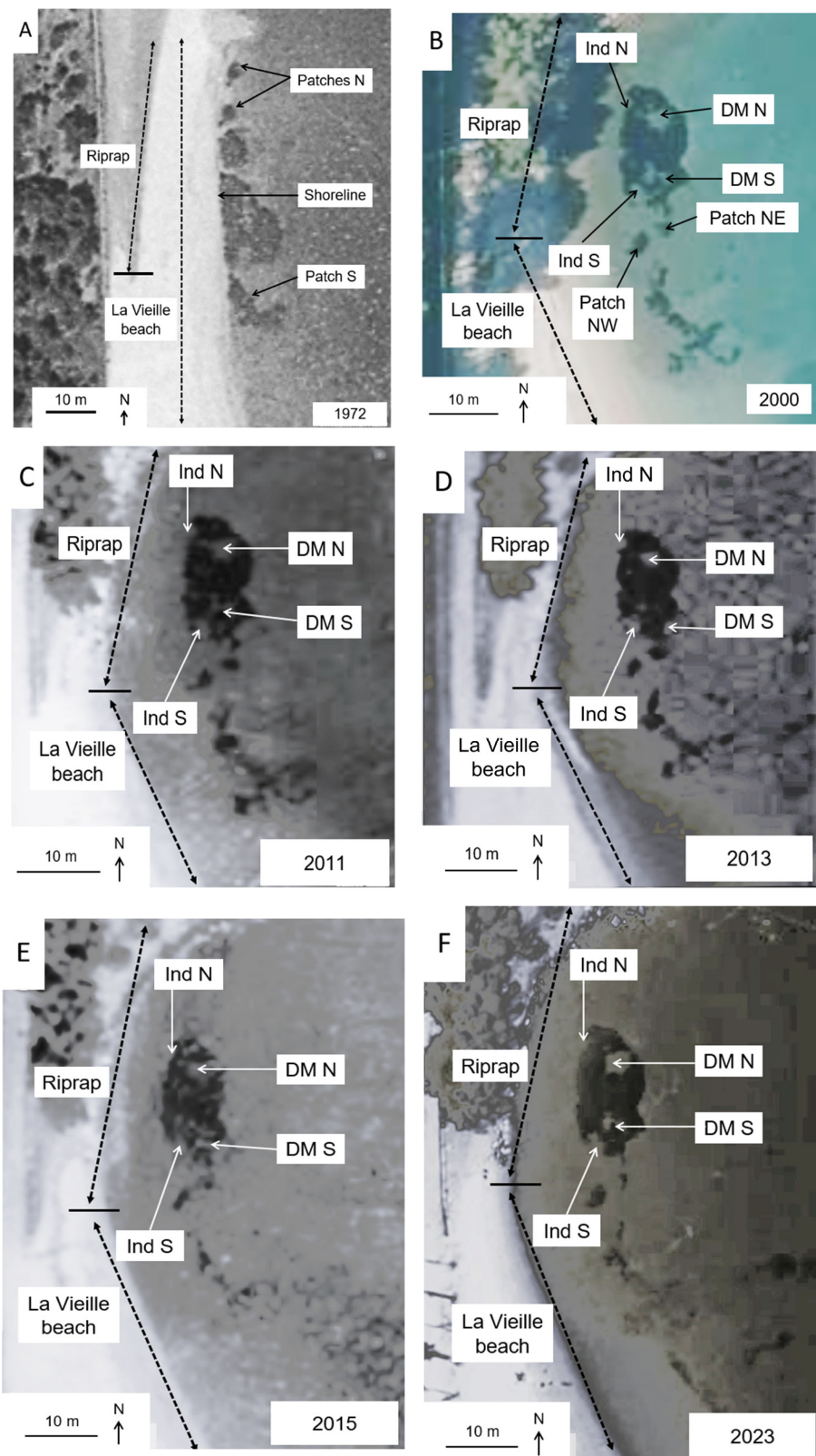


Figure 3. Maps of the fringing reef of La Vieille beach, from aerial photographs: 1972 through 2023 (A–F). Dotted arrows indicate the extent of the riprap and the beach, and the black line marks their limit. Ind N: Indentation North; Ind S: Indentation South; DM N: patch of dead matte North; DM S: patch of dead matte South. The pictogram (sea, sun and arrow), at the bottom right of F, indicates the direction of the sun's rays, deduced from the shadows on the beach.

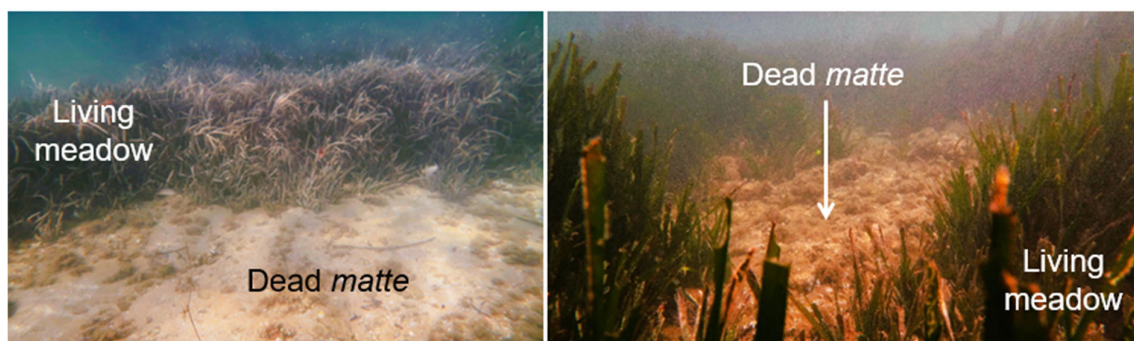


Figure 4. Patches of dead matte within the main part of the fringing reef. **(left)** Patch DM N (see Figure 3); dead rhizomes (with no shoots of living leaves) are partly buried by a layer of sand. **(right)** Patch DM S (see Figure 3); the tips of dead rhizomes are clearly visible. Photos August 2023 © Dominique Calmet.

The quality of the photographs is highly contrasting over the last 24 years, the latest from 2023 being the best (IGN aerial infrared photos) and that of 2015 the worst. Despite these differences in quality, between the early 2000s and 2023, the main part of the reef does not show changes, either in its general shape and surface area, or in identifiable details (Ind N, Ind S, DM N and DM S). Its surface area estimated from the 2023 photograph is 127 m² but this may be an overestimation of the area due to the length of the leaves and their shadow as the photo was taken in summer, early in the morning. In contrast, the reef patches of the southward alignment seem to have lost surface area mainly between 2015 and 2023, some fragments being even difficult to observe in situ (Figure 5); their total surface area is assessed from the 2023 photo to be 36 m².

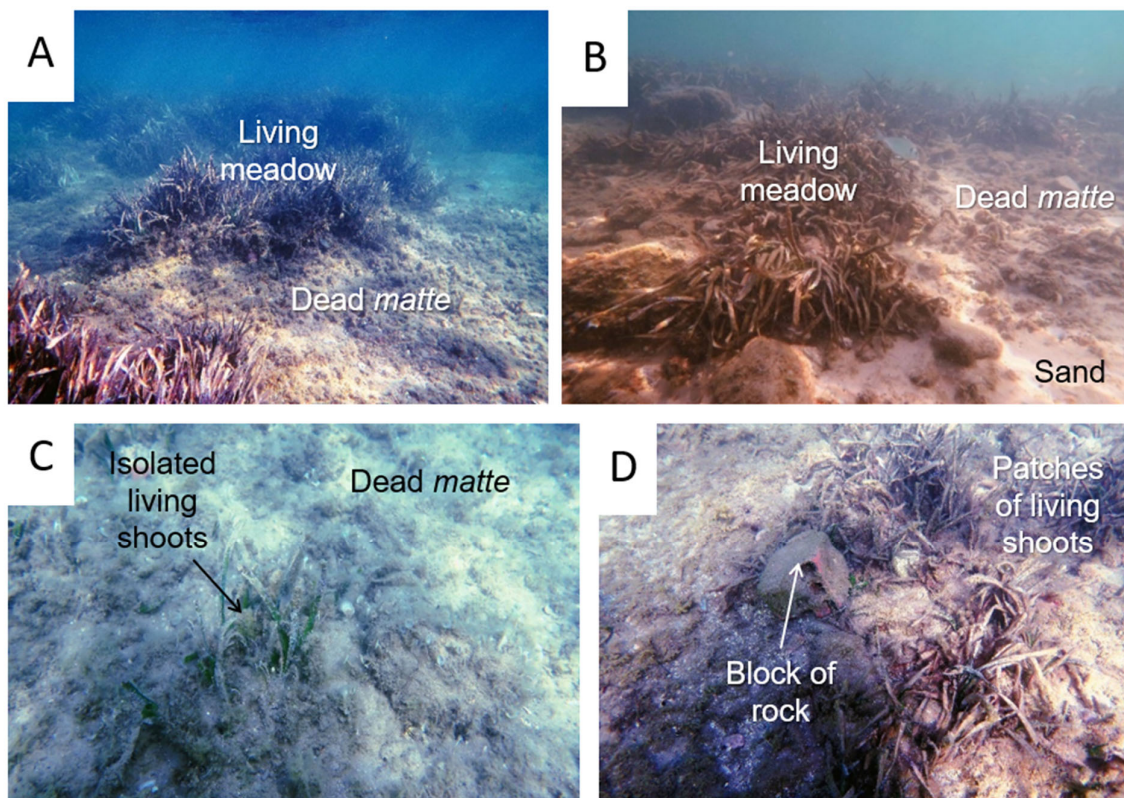


Figure 5. (A–C) Patch NE (see Figure 3B) with living *Posidonia oceanica* and dead matte. (D) Patch NW (see Figure 3B), with a few remaining living shoots of leaves. Photos August 2023 © Dominique Calmet.

Thus, the total surface area of the fringing reef is estimated at 163 m² in 2023, showing a regression in the order of 35% since 1972.

Based on the annual average rate of marginal expansion mentioned above (between 3 and 20 cm per year), between 1972 and 2023, the putative progression of the margins of the main part of the reef would have been in the order of 1.5 m [51 years × 3 cm] to 10.2 m [51 years × 20 cm], which would have been visible in the photos. This is obviously not the case (Figure 3); thus the hypothesis of its stability cannot be rejected.

Based on the date (summer) of the 2023 photograph (the most recent), a season when the leaves are longest, the small patches of the southward alignment should have been clearly visible, which is not the case. The 2024 ground truth confirms the absence of some of these patches. The hypothesis of their regression is therefore plausible.

3.2. Possible Reasons for the Lack of Recovery of the La Vieille Reef

The stability of the northern part of the *P. oceanica* fringing reef for more than 20 years, and the continued degradation of what remains of its southern part, raises questions. Recent decades have been characterized, along all the coasts of the French Mediterranean, as well as in the other countries of the European Union (EU), by an improvement in water quality, thanks to national legislation and EU directives, such as the Habitat Directive (HD), the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD), despite their obvious limitations (e.g., [104–113]). The drastic reduction of the multiple domestic and industrial discharges of polluted water, scattered all along the coasts, the establishment of wastewater drainage networks, the treatment of most of this sewage in treatment plants, the improvement of the management of ports and marinas, the use of antifouling paints with less harmful effects on flora and fauna than the earlier antifouling paints, the slowing down of the artificialization of the coastline thanks, in France, to the French *Loi Littoral*, the regulation of anchoring, etc., have had positive results on the state of health of marine ecosystems, including the *P. oceanica* meadow (e.g., [94,114–123]).

Along the coasts of France and other EU countries, including near the discharge point of sewage treatment plants, the *P. oceanica* meadows are often progressing, more quickly than expected [86,87,124,125], thanks to expansion at the margins, cuttings and seeding [91,93,126,127]. This has been reported, e.g., at Marseilles [84,88] and Hyères [85] (France), and at Bergeggi [23], Ischia [128] and Sicily [129] (Italy). This trend reversal concerns not only *P. oceanica*, but also most other seagrass species, across all European coasts, both Mediterranean and Atlantic [130].

In this context, the poor state of the La Vieille fringing reef, at Saint-Mandrier, is surprising. Several reasons could explain this state of health: a level of pollution that might still be too high, overgrazing, the surf and the turbidity generated by the frequent passage of large vessels, including warships and car ferries, trampling by beachgoers and the quarry sand coming from the beach.

Saint-Mandrier is located in the *Petite Rade* surrounded by a conurbation of ~600,000 inhabitants of which Toulon is the central city (Figure 1). The *Petite Rade* is the site of the largest French naval port as well as three commercial ports and four marinas. La Vieille beach is less than 4 km, as the crow flies, from Toulon. One of the marinas and a shipyard are located a few hundred metres south of La Vieille beach (Figure 6). The water quality in harbours has improved in recent decades, but less than that of domestic and industrial wastewater; the latter now passes through efficient wastewater treatment plants (WTPs). Among the six WTPs in the Toulon area, the Amphora WTP treats the wastewater of 100,000 inhabitants before discharging the treated water 1800 m offshore of the Toulon *Petite Rade* (Figure 1) at a depth of 54 m. Biological indicators, e.g., the CARLIT index, show a relatively good state for the Bay of Toulon water body [120,131]. However, there are nearly 80 rainwater and

sewage outlets in the Toulon *Petite Rade* that are potential sources of pollutants, especially during heavy rainwater periods. Lazaret Bay, situated in the *Petite Rade*, west of La Vieille beach, houses mussel and oyster culture facilities but, due to periodic bacteriological contamination, a decontamination stage for the time necessary to allow them to eliminate microbiological contaminants and to render them suitable for direct human consumption is mandatory. Sediments of the *Petite Rade* are still characterized by high levels of trace metals (e.g., Pb, Hg, Zn), polycyclic aromatic hydrocarbons (PAHs) and tributyltin [132–138]. Contaminated sediments in the first 20 cm are considered a potential source of contamination of the water column; while the diffusion of metallic contaminants in water from sediments is normally low, resuspension due to storms, maritime traffic and dredging can lead to fairly significant remobilization for elements such as cadmium, copper and lead, leading to significant contamination of the water column [134]. Contamination from the *Petite Rade* is exported by currents to the *Grande Rade* [139]; La Vieille beach is located exactly on the boundary between these two basins. Overall, although the contamination of the study site is undoubtedly significant, and may play a role in the state of health of *P. oceanica*, this seagrass is relatively resistant to chemical contaminants, at the concentrations actually observed in the natural environment (e.g., [39,47,140,141]), so that contamination of the study site is unlikely to constitute the main explanatory factor.



Figure 6. (left) The marina located south of La Vieille beach and the southern part of its fringing reef. (right) Beachgoers on La Vieille beach, anchored recreational boats and in the background a car ferry from Corsica, sailing towards the entrance of the port of Toulon. Photos © Dominique Calmet.

The water is frequently turbid off La Vieille beach. This is due to the resuspension of sediment by waves, particularly during the passage of large ships (Figure 6), the washing away of sand from the beach, and trampling by bathers. The seagrass *P. oceanica*, a photosynthetic plant, is very negatively impacted by turbidity and shading, but this mainly concerns deep areas rather than a very shallow fringing reef [1,140,142–144]. Turbidity is therefore unlikely to have a significant impact at such a shallow site.

Trampling of the fringing reef, a very shallow habitat, by bathers (Figure 6) is likely detrimental. As far as we know, no study has dealt with this issue, although trampling is mentioned by several authors (e.g., [29]). Following the notification of the occurrence of the fringing reef to the municipality of Saint-Mandrier [30,31], in July 2024, marker buoys were set up on the northern part of the fringing reef in order to prevent trampling.

Macro-herbivores are present on the la Vieille fringing reef. The edible sea urchin *Paracentrotus lividus* is currently not very abundant; however, its abundance is known to fluctuate greatly from year to year, depending on disease, climatic events, predation pressure, overfishing of its predators and human harvesting for consumption (e.g., [145–151]). On the other hand, the salema *Sarpa salpa* is relatively abundant all year round, as evidenced by the leaves of *P. oceanica*, which are relatively short and show numerous fish bite marks (Figure 7). Overgrazing by *S. salpa* has been widely observed in the Mediterranean, including in Marine Protected Areas, although the reasons are not clearly understood [52,53,152–154]. Small isolated patches of *P. oceanica* are more grazed by *S. salpa* and vulnerable than extensive

meadows [155]; furthermore, sea water warming increases grazing [156]. With the disappearance of all *P. oceanica* meadows in the *Petite Rade*, La Vieille is the only area for *S. salpa* to feed on *Posidonia* leaves, which could be conducive to their overgrazing by *S. salpa*, and thus a possible cause of the lack of recovery or the decline of the Saint-Mandrier fringing reef.

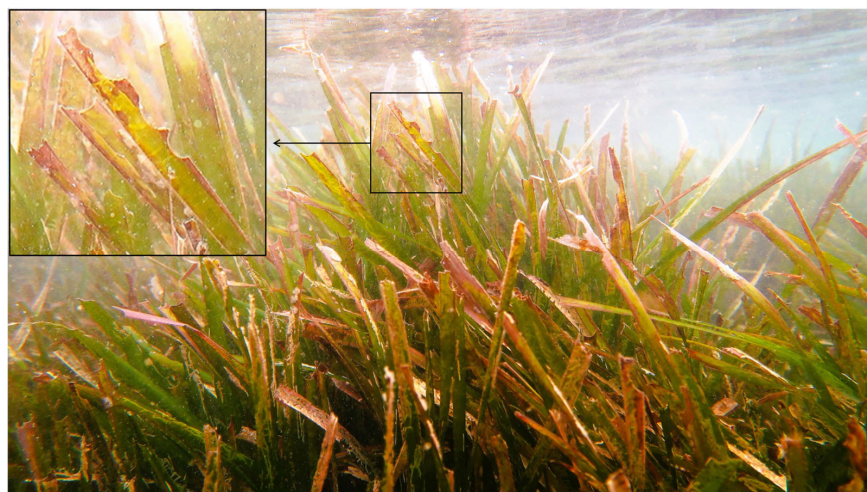


Figure 7. Grazed leaves of *Posidonia oceanica* showing *Sarpa salpa* bite marks. Top left: Enlargement of a part of the photo. La Vieille beach, May 2024. Photo © Dominique Calmet.

Finally, the nourishment of the La Vieille artificial beach with sand could be a major reason for the poor state of health of the fringing reef. The beach is replenished with 20 m³ of quarry sand every year, in early summer, less than two metres from the landward limit of the reef (Figure 8). The sand is then quickly washed away and leaves the beach (Figure 9). We observe that the rhizome tips are never bare, outside the sediment; on the contrary, they are always covered by sediment, which often covers the growing points of the leaf shoots (Figure 10). We did not observe deeply buried growing points, perhaps because we did not dive at the time when the beach is replenished with sand; we know that a few weeks of burial are enough to kill the growing points [55,58]; furthermore, burial and mortality events may not occur every year, while their consequences are long-lasting. Sand nourishment has often been blamed for the degradation of *P. oceanica* meadows lying off beaches; as seagrass meadows contribute to wave and swell attenuation, they protect beaches against erosion. Beach nourishment could thus be seen as a kind of vicious circle: policy makers replenish beaches with sand to counteract beach erosion, washed away sand buries and kills *P. oceanica* meadows, so that beach erosion increases [6,7,39,55–59,157–159].



Figure 8. The La Vieille beach is annually replenished with quarry sand. (left) Late June 2023, just after replenishment. (right) Late summer (September) 2023. Photos © Dominique Calmet.

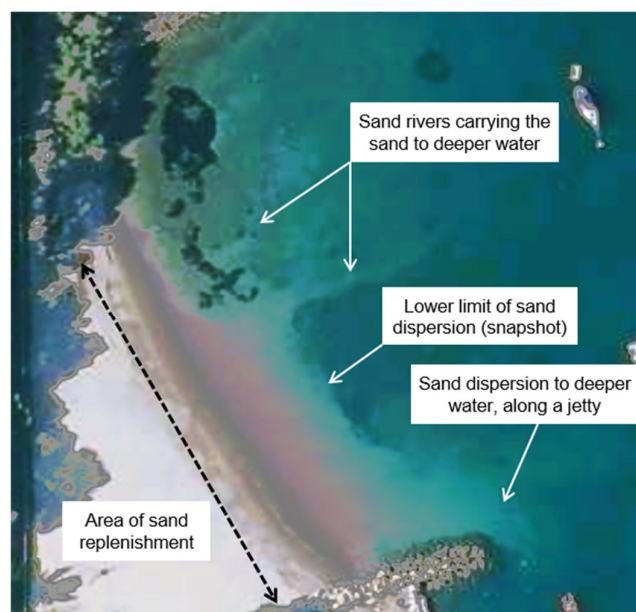


Figure 9. Dispersion of the sand from the La Vieille beach to deeper water. The photo is just a snapshot of the upper layer of the water column (3 m at best); sand can go elsewhere and deeper, according to time and weather. Image in 2020 from IGN.



Figure 10. A patch of *Posidonia oceanica* in the southward alignment. The growing points of the leaf shoots are more or less buried under the sand. May 2024. Photo © Dominique Calmet.

In order to weigh up the possible causes of the poor health status of the La Vieille *P. oceanica* fringing reef (pollution, turbidity, trampling, overgrazing, beach nourishment), and possibly to confirm the primary responsibility of beach nourishment, the use of high precision marking tools, enabling the measurement of centimetric progression or regression, is necessary. Several methods are available: (i) Cement markers or metal stakes [160–164]; (ii) Acoustic telemetry [165–169]. Whatever the method, it should concern not only the fringing reef of La Vieille beach, but also shallow *P. oceanica* meadows located in the vicinity of the study area, i.e., subject to the same set of anthropic pressures, but not directly impacted by beach nourishment.

4. Conclusions

The *Posidonia oceanica* fringing reef at La Vieille beach (Saint-Mandrier, near Toulon), is severely degraded. While regional trends in the northwestern Mediterranean show recovery of degraded *P. oceanica* meadows in some cases at a faster rate than expected [87,130], thanks to protection measures in France since 1988 and in the EU since the Habitats Directive of

1992 [170–173], and then improved wastewater treatment, no such recovery has occurred at this site.

On the contrary, a continued retreat is observed, particularly in the southern part of the fringing reef. Localized factors can counteract general trends. At La Vieille, the most plausible cause of ongoing decline is annual beach sand nourishment. Sand is quickly washed down into the sea, burying and smothering the seagrass meadow. Other contributing factors (e.g., pollution, turbidity, overgrazing, trampling) likely act in combination, although their relative contribution remains uncertain.

The severity and persistence of decline are likely site-specific, influenced by the proximity of the meadow to the shore and sand nourishment methods. This case highlights the importance of localized assessments when managing seagrass meadows.

The fringing reef of La Vieille can be regarded as a workshop-site, given its highly reduced remnant area, allowing for the detection of potential changes, either further decline or recovery, in response to improved conditions such as the prevention of trampling and cessation of beach nourishment, or ongoing habitat deterioration.

Protection against trampling was implemented this year; its impact on the fringing *P. oceanica* fringing reef will be monitored over the coming years. In parallel, sand nourishment operations are expected to cease in the near future, which could allow for the assessment of natural recovery processes in the absence of recurrent sediment input.

The methods and finding of this study may serve as a valuable model for similarly exposed coastal sites, where comparable hydrodynamic and morphodynamic conditions significantly influence sand dispersion from the beaches, leading to the burial of seagrass meadows.

Author Contributions: Conceptualization, D.C.; investigation, D.C. and P.C.; original draft preparation, C.-F.B.; writing, review and editing, D.C., P.C. and C.-F.B. All authors have read and agreed to the published version of the manuscript.

Funding: This study is being conducted as part of the Moana “shallow coastal waters” project funded by FNE (France Nature Environnement) with the support of the “Superpowers of the Ocean” operation organized by France TV.

Data Availability Statement: Most data are contained within the article. The map of the fringing *Posidonia oceanica* reef with GPS positioning will be communicated upon request.

Acknowledgments: The authors acknowledge with thanks, the three anonymous reviewers and the editor for their highly valuable comments and suggestions and Michael Paul, a native English speaker, for proofreading the text.

Conflicts of Interest: The authors declare no conflicts of interest.

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