Journal of Sea Research
October 2022, Volume 188 Pages 102258 (13p.)
https://doi.org/10.1016/j.seares.2022.102258
https://archimer.ifremer.fr/doc/00787/89931/

Major regression of *Posidonia oceanica* meadows in relation with recreational boat anchoring: A case study from Sant'Amanza bay

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Abstract :

The anchoring of large recreational craft constitutes one of the main threats in shallow marine habitats. In the Mediterranean, this activity has seen constant development during the last decades, causing major physical disturbances in Posidonia oceanica meadows and associated ecosystem services. In this context, the main aims of the present study are to estimate the impact of this anchoring on P. oceanica meadows surface areas and carbon fixation and sequestration capacities, in a particularly highly-frequented area (Sant'Amanza bay, Corsica Island). Accurate benthic marine habitats mapping was performed yearly (2019–2021) using a drone coupled with ground-truthing data. The evaluation of carbon fixation and sequestration by the plant was measured at 12 stations within the bay (−5 m to −30 m). The maps of the marine habitats reveal an extensive regression of P. oceanica meadows (7.5 ha) between 2019 and 2020. This destruction represents a 9% decline in the total carbon fixation and sequestration performed each year by P. oceanica meadows within the bay. The related ecosystem services loss is estimated at 4.72 million € yr−1. Although an overall decline of boat anchoring in the seagrass meadow has been observed (e.g. recent enforcement of anchoring regulations), other solutions should be experimented to manage this major carbon sink.

Highlights

► Mapping exhibited major loss of seagrass beds coverage (72.9 ha) in Sant'Amanza bay. ► Drone-imagery highlighted high meadows regression between 2019 and 2020 (−7.5 ha). ► Vitality of seagrass meadows decline in areas highly-impacted by vessels anchoring. ► Carbon capture and sequestration rate of meadows declined with boat anchoring. ► Loss of ecosystem services associated with boat anchoring were estimated.

Keywords : Anthropogenic impact, Anchoring, Seagrass, Posidonia oceanica, Ecosystem services, Mediterranean Sea

1. Introduction

At the 21st meeting of the Conference of the Parties (COP 21) of the Climate Change Convention, participants underlined the importance of sinks and reservoirs of greenhouse gases (on land and in the ocean) and recommended actions to conserve and enhance these sinks with the aim of reducing the impact of climate change (UNFCCC, 2015). Even if the absorption of CO_2 by these sinks is likely to increase, the ocean and land carbon sinks are projected to be less effective, and their overall contribution could be reduced under scenarios with increasing CO_2 emissions (IPCC, 2021a). Furthermore, the effective management of coastal 'blue carbon' ecosystems (mainly salt marshes, mangroves, and seagrass meadows) is essential to enhance their carbon sink capacity and to avoid emissions from the degradation or loss of their existing carbon stocks (IPCC, 2021b).

In the Mediterranean Sea, the endemic seagrass *Posidonia oceanica* (L.) Delile forms extensive meadows from the surface to more than 40 m depth. The *P. oceanica* meadows play a major role in coastal areas by providing ecosystem functions and services notably in climate change mitigation associated with the formation of a specific biogenic structure, the matte (Molinier and Picard, 1952; Mateo *et al.*, 1997; Monnier *et al.*, 2021). This belowground formation, composed of intertwined rhizomes, roots and leaf sheaths embedded in the sediment, exhibits a very low decay rate in relation with the highly refractory nature of the organic matter and the anoxic conditions (Romero *et al.*, 1992; Mateo *et al.*, 1997, 2006; Kaal *et al.*, 2018). The accretion of organic material in coastal sediments beneath the *P. oceanica* meadows constitutes one of the largest carbon sinks in coastal areas worldwide and can reach several meters in height and remain over millennia (Lo Iacono et al., 2008; Serrano et al., 2012; Monnier *et al.*, 2021, 2022).

Although this species is one of the main targets of conservation actions, the regression of *P. oceanica* meadows is well-documented over the whole Mediterranean basin (Boudouresque *et al.*, 2009; Marbà *et al.*, 2014; De Los Santos *et al.*, 2019). As for other seagrasses worldwide (Collins *et al.*, 2010; Sagerman *et al.*, 2020), among the anthropogenic impacts undergone by *P. oceanica* meadows, mechanical impacts, particularly related to anchoring by large recreational vessels, are of increasing importance (Ceccherelli *et al.*, 2007; Montefalcone *et al.*, 2008; Abadie *et al.*, 2016; Deter *et al.*, 2017; Carreño and Lloret, 2021) due to the development of recreational boating over the past decades (Cappato *et al.*, 2011; Carreño and Lloret, 2021). Despite the relatively small size of the Mediterranean Sea (less than 1% of the surface area of the world's seas and oceans), more than half of the world fleet of large recreational vessels (>24 m in length) frequent Mediterranean waters for at least eight months per year (Cappato *et al.*, 2011; Carreño and Lloret, 2021), mainly in the western Mediterranean basin (*e.g.* Côte d'Azur, Liguria, southern Corsica and northern Sardinia). In Corsica, an increase of this activity has been recorded during the last decade (Figure 1a; Figure 1b). Out of nearly 2,000 of these large vessels counted in 2018 around the coasts of Corsica, 44% of them anchored in the southern part of the island, in Bonifacio Strait, and 77% of them on the *P. oceanica* meadows (Fontaine *et al.*, 2019).

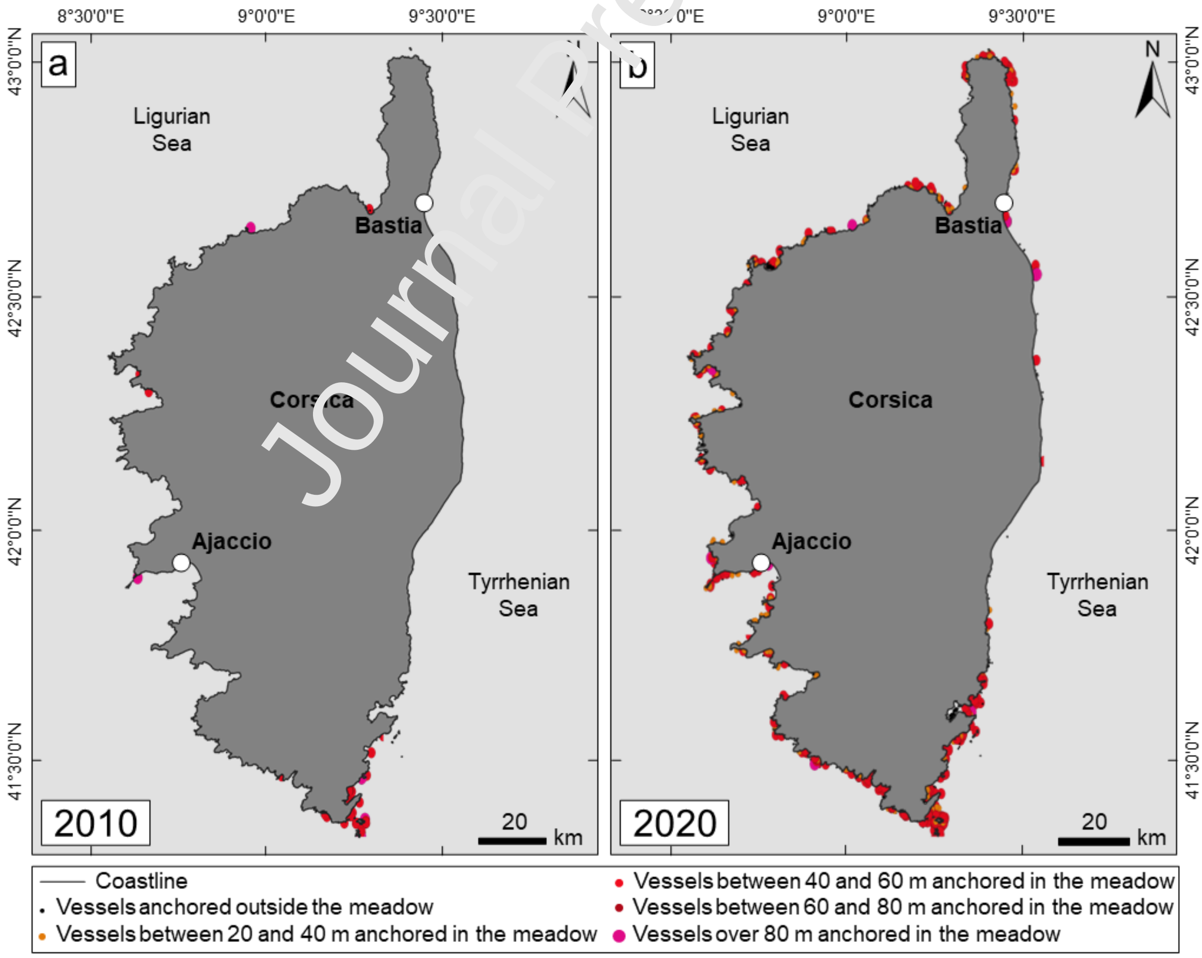

Figure 1. Location of large vessel units (>20 m) anchored on *P. oceanica* meadows around the coastline of Corsica in 2010 (a) and 2020 (b) based on Automatic Identification System (AIS) data from the Marine Traffic platform; www.marinetraffic.com). **(1.5-column)**

While some recent studies have reviewed the main consequences of recreational boating for seagrasses (Carreño and Lloret, 2021; Sagerman *et al.*, 2020), their authors stressed that in order to look beyond the general conclusion that recreational boating can have an impact on seagrass meadows, there is a need for more quantitative studies and a greater research effort is required to better assess the ecological impacts and to devise management measures to mitigate them.

In this context, the main aim of this case-study is (i) to provide a detailed assessment of the impact of this activity over an area particularly exposed to large boat anchoring through an analysis of the spatial distribution of vessels, an assessment of the surface area of seagrass meadows destroyed, and the losses in terms of carbon fixation and sequestration, and (ii) to put these results into perspective in a broader context, and in particular at the scale of the Mediterranean Sea.

2. Materials and Methods

2.1. Study site

The study site is located in the south-eastern part of Corsica in Sant'Amanza bay (41.436698°N, 9.246421°E), an area included in the Marine Protected Area Natural Reserve of the Strait of Bonifacio (Figure 2). The site, covering a surface area of 1 466 ha, is notably frequented during the summer season by recreational boats due to its orientation, which makes it a sheltered site (Sorba *et al.*, 2018).

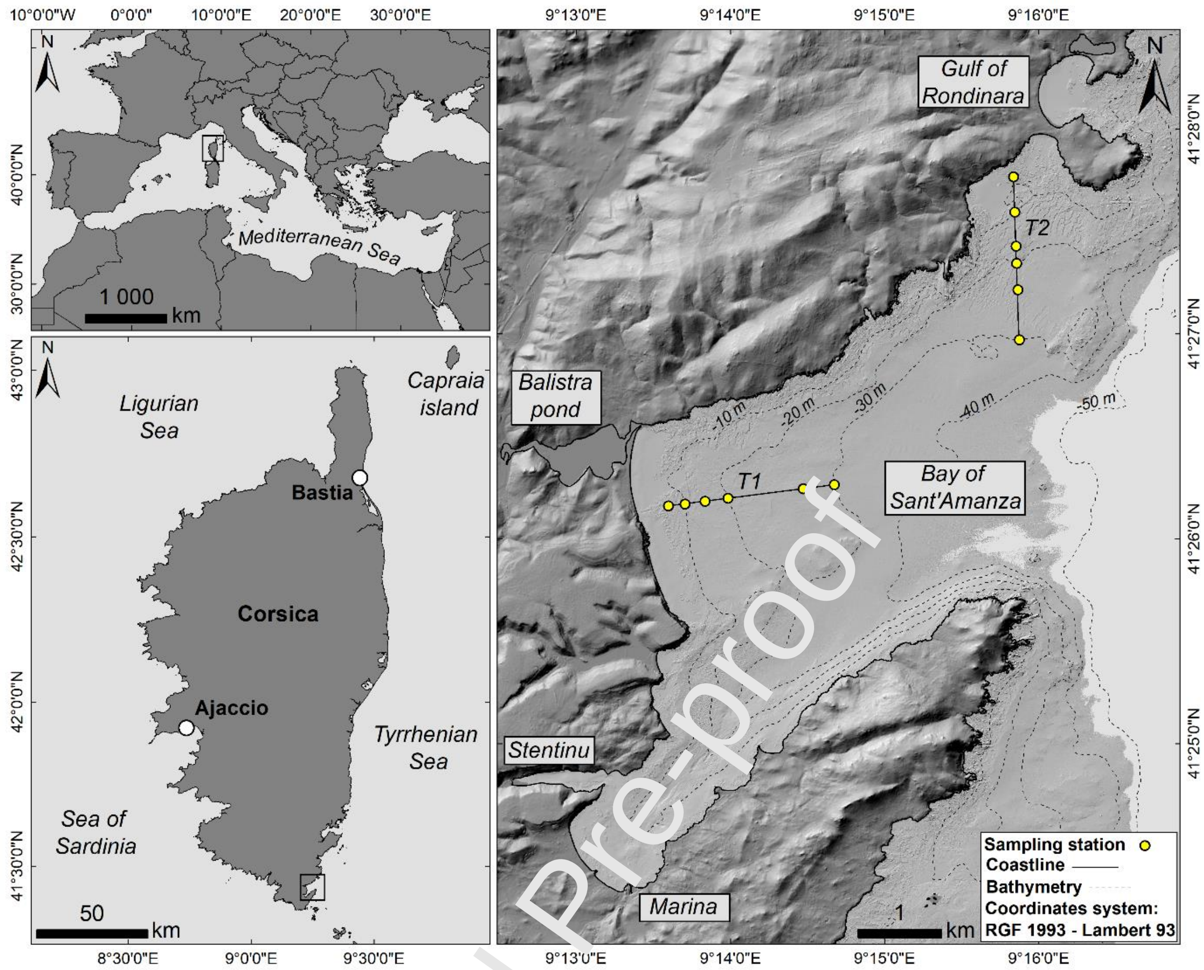

Figure 2. Location of Sant'Amanza bay and sampling stations (yellow dots) along the transects T1 and T2. **(1.5-column)**

2.2. Analysis of boat frequentation

The information concerning the identification, movements and location of boats was based on Automatic Identification Systems (AIS) data from the Marine Traffic website (MarineTraffic, 2022), covering the period between April 2019 and September 2021. The dataset contained 14 fields but only 8 were used: Maritime Mobile Service Identity (MMSI), ship name, length, status (anchored = 1; moored = 5), speed, latitude, longitude, date, and time. Incorrect data (*e.g.,* anchored with moving speed) were removed according to Deter *et al.* (2017) and classification was based on vessel length (20-40 m, 40-60 m, 60-80 m and >80 m). The location of each vessel was reported on a Geographical Information System (GIS; ArcGIS 10.8® software) to perform a spatial analysis.

The anchoring pressure of recreational craft units in Sant'Amanza bay was estimated from AIS data covering the period between 1st April and 30th September, because this corresponds to the main period of frequentation of the site with 96.9% (2019) and 98.7% (2020) of the vessels present over the year.

2.3. Mapping of marine benthic habitats

The mapping was achieved over 1 466 ha between 0 and 50 m depth in Sant'Amanza bay. The identification of the main marine benthic biocenoses and bottom types was based on the typology of benthic biocenoses in the Mediterranean of the National Museum of Natural History of Paris (Michez *et al.*, 2011).

The shallow area (<15 m depth; 627 ha) was mapped using a complete photographic coverage (RGB-colored and georeferenced aerial photographs at 1/5 000th, from the BD ORTHO® 2016 – French National Geographic Institute (IGN)) with a 50 cm pixel resolution. Three aerial imagery campaigns by drone were also carried out annually (12th June 2019, 16th February 2020 and 24th February 2021) in order to identify the spatio-temporal evolution of marine benthic habitats in an area particularly exposed to large boat anchoring (Balistra beach; Sorba *et al.*, 2018). These aerial photographs, covering about 117.5 ha of the shallow waters (0-20 m depth), were acquired with a DJI Phantom 4 Pro 2.0 unmanned aerial vehicle (UAV) flying at an altitude of 30 m above sea level. The data were georeferenced with a GNSS RTK Spectra® SP 60 system (Lepont Instruments), offering centimeter level accuracy positioning, and compiled to obtain an orthomosaic with a 5 cm pixel resolution (Agisoft Metashape Professional 1.7 software). All the aerial images were processed using Envi 4.7® software following the method described by Bonacorsi *et al.* (2013): (i) optimization of imagery (contrast and dynamic adaptation), (ii) selection of training areas corresponding to the different marine benthic habitats, (iii) application of a supervised maximum likelihood classification (extrapolation of the information), (iv) filtration (elimination of isolated or misclassified pixels), and (v) vectorization for integration into ArcGIS 10.8® software.

The deeper area (>15 m depth, 839 ha) was mapped using exhaustive acoustic coverage acquired by side-scan sonar Klein 3000™ during the Carbonsink oceanographic survey on board the oceanographic vessel *L'Europe* (Ifremer) in August 2018. The vessel's absolute decimetric position was determined using a DGPS (Differential Global Positioning System). The dataset, processed using the Caraibes 4.4® software from Ifremer, enabled us to develop a georeferenced sonar mosaic (50 cm resolution) integrated in ArcGIS 10.8® for processing.

Ground-truth data (n = 560) were acquired during the 2018-2021 period using various tools according to depth (bathyscope: 419; Remotely Operated Vehicle imagery: 13; underwater photo quadrat: 93, scuba diving: 30; Van Veen grab samples: 5). These *in situ* observations were reported on ArcGIS 10.8® (projection system WGS 1984 Mercator) (i) to validate the interpretation of the aerial photographs and sonar mosaics, and (ii) to build the confusion matrix. An assessment of the reliability of the maps was carried out by applying the scale of Valette-Sansevin *et al*. (2019) taking into account the various stages of the mapping process: (i) acquisition of raw data, (ii) acquisition of ground-truthing data, and (iii) data processing. The maps of marine benthic habitats were established on the basis of the most relevant information (*i.e.* with the highest reliability level). The estimation of the surface areas occupied by the different marine benthic habitats in Sant'Amanza bay was determined using the RGF 1993 – Lambert-1993 projection system (EPSG: 2154).

2.4. Carbon fixation and sequestration

Carbon fixation and sequestration estimates were performed at 12 stations located along two transects oriented perpendicular to the coast (Figure 2). The transects were located in the middle part (transect T1) and in the entrance of the bay (transect T2) from the upper limit (shallowest part) to the lower limit (deepest part) of the *P. oceanica* meadows (Figure 2). At the following depths (-5 m, -10 m, -15 m, -20 m, -25 m, -30 m), shoot density was measured using a 40 cm x 40 cm quadrat (5 replicates randomly distributed within the seagrass meadow) and orthotropic (vertical) shoots (n = 10) were collected in June 2020.

A phenological analysis (Giraud, 1979) and a lepidochronological study (Pergent, 1990) were carried out. Net primary production was estimated using the lepidochronological cross method (Vela *et al*., 2006), derived from Pergent and Pergent-Martini (1990), taking into consideration the biomass of foliar tissues (removal of epiphytes with a glass slide) produced during a one-year period. A correction coefficient was applied to the length of the blades and petioles collected in June to determine their average value over a year (Valette-

Sansevin, 2018). Rhizome production was evaluated from segments of the rhizome, with roots inserted, between two scales (dead sheath) with a minimum thickness (corresponding to the tissue produced during a one-year period) cut and then dried for 48 h at 70 °C, up to constant weight. The segments corresponding to the two most recent years were not considered because their growth was not yet complete (Boudouresque *et al.*, 1984). The carbon content (%C) of leaf blades, sheaths, and rhizomes, expressed as a percentage of dry weight (DW), was determined for each sample using elemental analysis (Elementar Vario Micro Cube®, Elementar Analysen systeme GmbH). The carbon fixation (g C m^{-2} yr^{-1}) was calculated by multiplying the net primary production per shoot (carbon content in blade, sheaths and rhizomes; mg C $shoot^{-1}$ yr^{-1}) by the shoot density (shoots m^{-2}). The carbon sequestration (g C m^{-2} yr^{-1}) was calculated by multiplying the carbon content in sheaths and rhizomes by the shoot density.

The global estimates of carbon fixation and sequestration of the *P. oceanica* meadow in Sant'Amanza bay were achieved by fitting logarithmic regression curves using the mean carbon fixation (n = 12) and sequestration (n = 12) values determined at each depth interval along the two transects. The corresponding equations were integrated into a morpho-bathymetric Digital Terrain Model (DTM) using the Spatial Analysis toolbox (Map Algebra – Raster Calculator functions) in ArcGIS 10.8®. The DTM raster mosaic was performed from the compilation of LiDAR data (1 km^2-slabs) with a spatial resolution of 1 m x 1 m and a vertical accuracy of 0.2 m (SHOM-CDC-DREAL Corse, 2021). The changes in the carbon fixation and sequestration capacity of *P. oceanica* were estimated off Balistra beach applying this procedure and using 2019 and 2021 seagrass meadows extent.

2.5. Statistical analysis

In order to assess the impact of recreational boat anchoring on *P. oceanica* meadows, a grid (50 m x 50 m cells, n = 347) was overlayed on the 2019 and 2021 marine benthic habitats maps off the coast of Balistra beach. In each cell, the cumulative number of anchored vessels and the percentage of surface covered by *P. oceanica* meadow, dead matte and different types of patches (natural and anthropogenic) were measured on ArcGIS 10.8®. The patches of dead matte and sandy areas were classified as natural or anthropogenic following the classification of Abadie *et al.* (2015). These measurements were used to determine the

Conservation Index (CI; Moreno *et al.*, 2001) and the Patchiness Source Index (PaSI; Abadie *et al.*, 2015) which reflect the state of conservation of the meadow and the cause of the meadow patchiness (natural or anthropogenic), respectively. The anchoring-induced changes in carbon fixation and sequestration capacity of *P. oceanica* meadow were also estimated calculating the difference in each cell between 2019 and 2021. Statistical analyses and graphical representations were performed using XLSTAT® software. Prior to analysis, homogeneity of variances was tested by Shapiro-Wilk test. When necessary, data were log-transformed to satisfy the conditions of application of the parametric tests (data normality and homogeneity of variances). Paired *t*-tests were used to check for significant differences in *P. oceanica* meadow and dead matte coverage, natural and anthropogenic patches, and PaSI and CI between 2019 and 2021 in control (0 boat cell^{-1}; n = 28), and anchored areas (>3 boats cell^{-1}; n = 28). The relationships between cumulative number of anchored vessels per cell and the difference in *P. oceanica* meadow and dead matte coverage, natural and anthropogenic patches, PaSI and CI, carbon fixation and sequestration capacity between 2019 and 2021 were analyzed by performing Pearson correlation tests. The correlation coefficient was calculated together with p-values to determine the significance and strength of each relationship. A significant difference is considered as a p-value ≤ 0.05.

3. Results

The anchoring pressure of recreational craft units in Sant'Amanza bay was estimated from AIS data covering the period between 1st April and 30th September, because this corresponds to the main period of frequentation of the site with 96.9% (2019) and 98.7% (2020) of the vessels present over the year. Vessel lengths between 20 and 40 m and between 40 and 60 m were mostly anchored off Balistra beach, on bottoms of -5 m to -20 m depth (Figure 3a; Figure 3b). There is also a second preferential anchoring zone a little further south (at the base of the cliffs), and further east on the other side of the bay. Vessels of 60 to 80 m length were distributed between these three sites, with, for the year 2021, preferential anchoring in the sector reserved for large vessels (Figure 3c). Finally, vessels over 80 m were mainly anchored in the area reserved for them with the exception of one boat, the same, in 2019 and 2020 (Figure 3d).

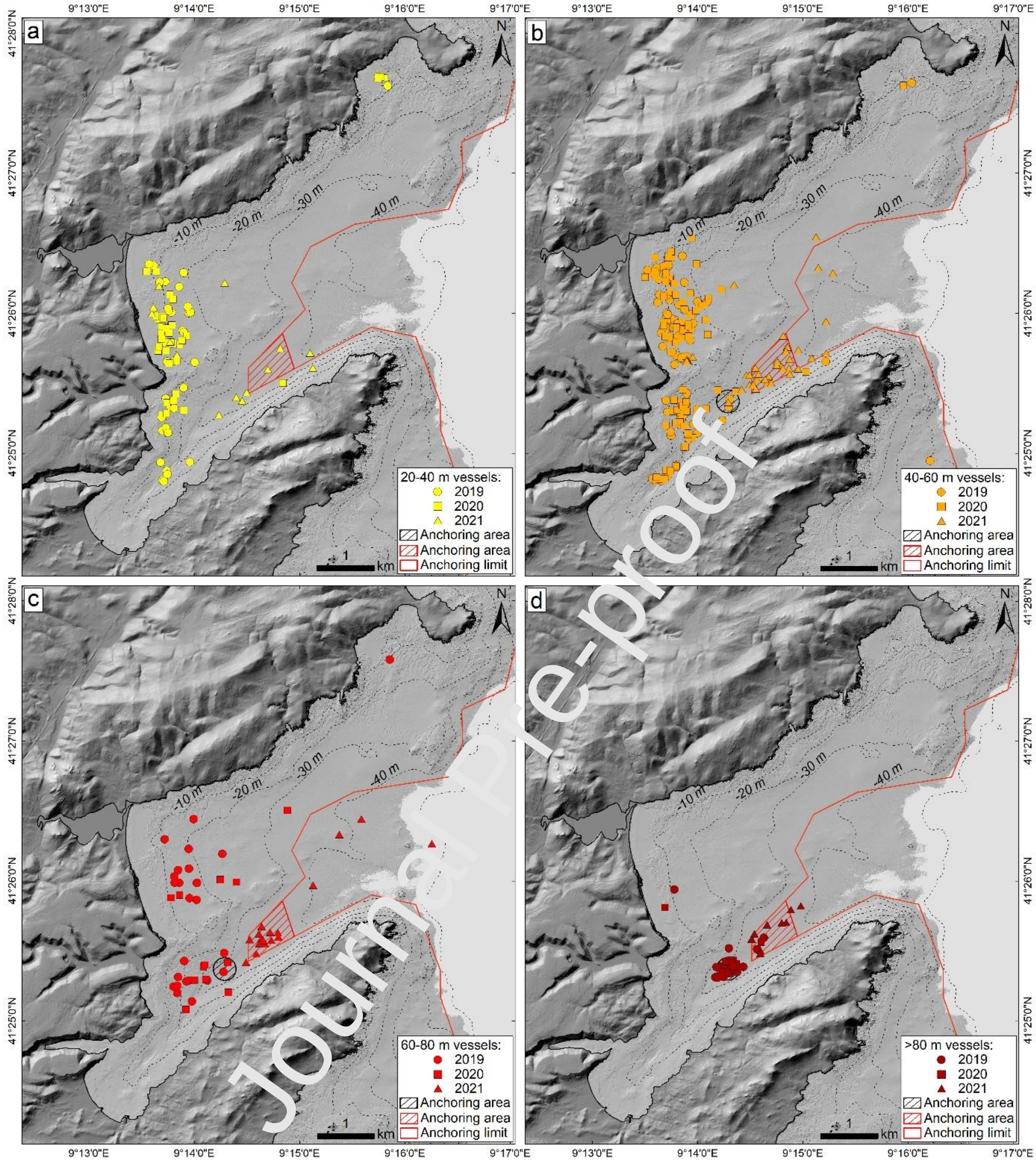

Figure 3. Distribution of the anchoring pressure of vessels from 20 to 40 m (a), from 40 to 60 m (b), from 60 to 80 m (c) and >80 m (d) in Sant'Amanza bay. Authorized anchoring area in 2016-2020 (black hatched) and since 2021 (red hatched) for the vessels >80 m. Data from MarineTraffic (2022). **(1.5-column)**

The total number of vessels anchored in Sant'Amanza bay during the summer season decreased during these three years, with 160 vessels in 2019 (Figure 4a), 134 in 2020 (-16%; Figure 4b) and 81 in 2021 (-40%; Figure 4c), *i.e.*, a decrease of 49% for the entire period. The 20 to 40 m units showed the greatest decrease between 2019 and 2021 with -67%. Conversely, units between 60 and 80 m exhibited the smallest decrease (-32%). The peak in attendance was also increasingly late with a peak in the first week of August in 2019 (24 vessels) and in the third week of August in 2020 (27 vessels) and in 2021 (12 vessels).

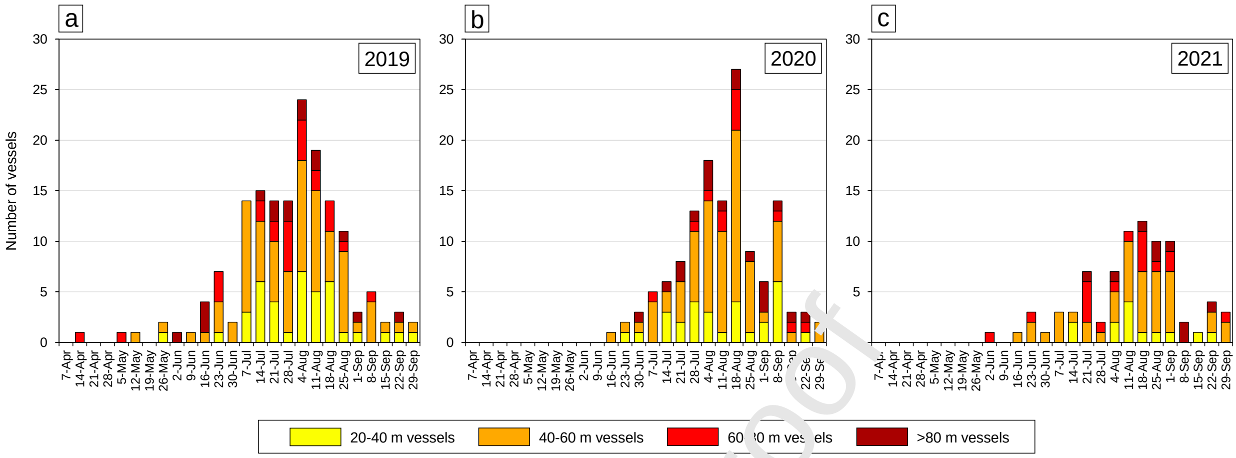

Figure 4. Recreational boating frequency in 2019 (a), 2020 (b) and 2021 (c) in Sant'Amanza bay during the summer seasons (1st April – 30th September). **(2-column)**

The cartography of biocenoses and bottom types of Sant'Amanza bay reveals a *P. oceanica* meadow which develops preferentially between 5 and 30 m depth, that is to say 45% of the surface area of the bay (649.7 ha), but also large areas of dead matte which attest to the pressures impacting the site (Figure 5a; Figure 5b). This dead matte (158.7 ha) is present (i) in the southern part of the bay and at the outlet of a small coastal river (Stentinu; Figure 2), and (ii) in the central area of the bay, off Balistra beach, mainly associated with anchoring (72.9 ha, 11%).

The three maps produced off Balistra beach, between 2019 and 2021, show a major regression of the seagrass meadows which reached 7.5 ha between 2019 and 2020, *i.e.,* nearly -14.7% of the surface area covered by *P. oceanica*, with a stabilization the following year (-0.3%; Figure 6; Table 1). During the 2019-2021 period, the *P. oceanica* meadows impacted by recreational boat anchoring exhibited a significant loss of coverage (Student *t*-test: -9.8 ± 0.5%; Table 2) and decrease in their state of conservation (-0.3 ± 0.0; Pearson correlation test: r = -0.86, p < 0.05; Figure 7) whereas no major change was denoted in control areas. Conversely, the surface areas of dead matte increased significantly with boat anchoring pressure (r = 0.98, p-value < 0.1; Figure 7). Even though dead matte coverage showed a significant increase in both control and anchored areas, the most significant changes were observed in highly-impacted areas (+27.6 ± 1.1%; Table 2). At the same time, an increase in anthropogenic patches surfaces (+30.1 ± 1.1%) and decrease of PaSI values (-0.2 ± 0.0) have been highlighted in anchored areas (Table 2) and proved to be highly related to boat anchoring pressure (Figure 7).

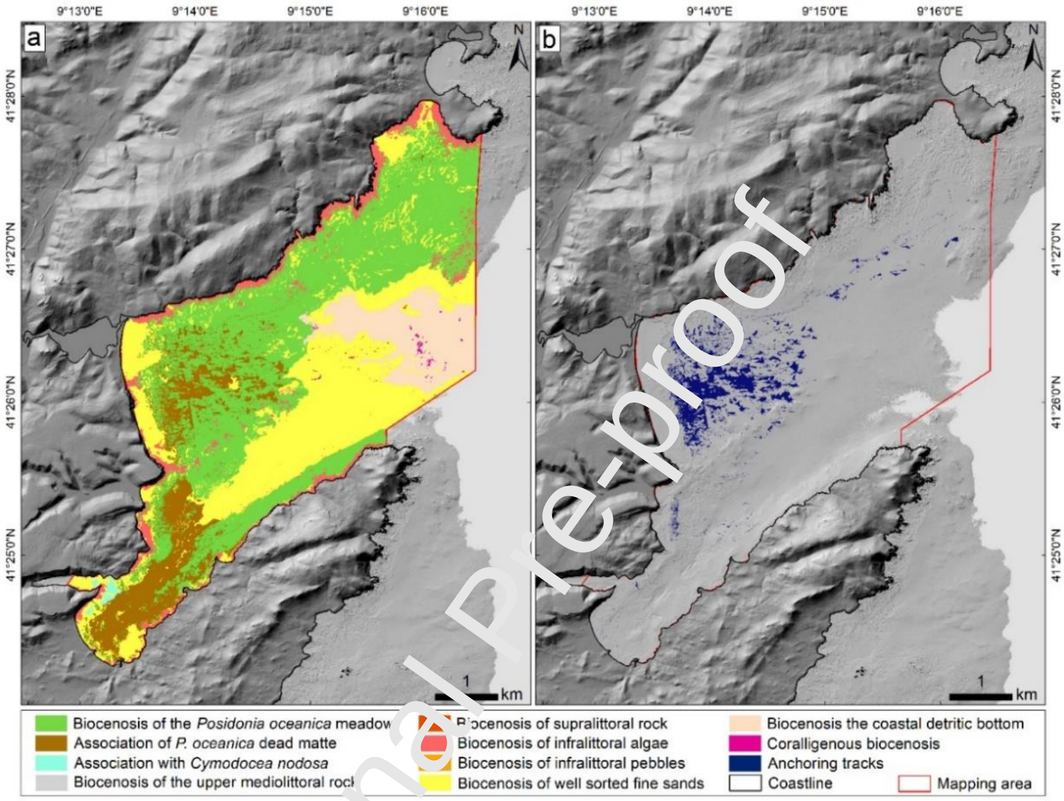

Figure 5. Distribution of main biocenoses and associations (a) and location of the main anchoring tracks (b) in Sant'Amanza bay. **(1.5 column)**

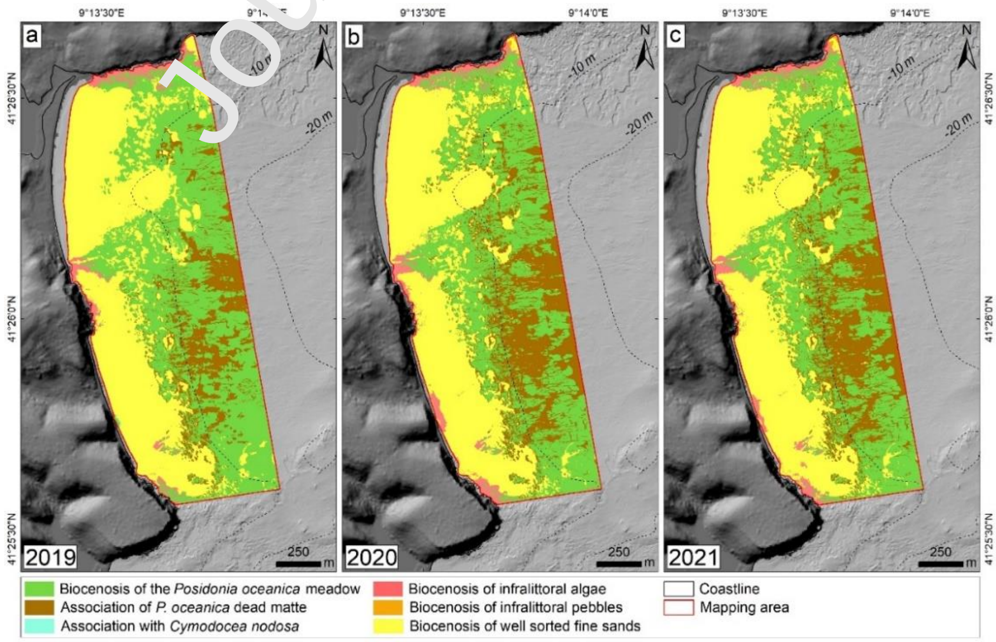

Figure 6. Distribution of main biocenoses and associations in 2019 (a), 2020 (b) and 2021 (c) off Balistra beach. **(1.5-column)**

Table 1. Surface area (in ha) covered by the main biocenoses and associations off Balistra beach (see area in Figure 6) between 2019 and 2021 and the reliability of the maps (Valette Sansevin *et al.*, 2019).

Marine biocenoses and association	2019	2020	2021
Biocenosis of the *Posidonia oceanica* meadow	50.91	43.43	43.28
Association of *P. oceanica* dead matte	14.73	23.30	23.28
Association with *Cymodocea nodosa*	0.02	0.00	0.00
Biocenosis of infralittoral algae	3.01	3.85	3.47
Biocenosis of infralittoral pebbles	0.00	0.08	0.08
Biocenosis of well sorted fine sands	48.79	46.79	47.35
Total surface area	117.46	117.45	117.46
Reliability	79.5%	96.7%	96.7%

Table 2. Mean (± S.E.) surface area covered by *P. oceanica* meadows and dead matte (%), natural and anthropogenic patches (%), and Conservation Index (CI) and Patchiness Surface Index (PaSI) values calculated in control (0 boat cell^{-1}; n = 28) and anchored areas (≥3 boats cell^{-1}; n = 28) between 2019 and 2021. [a] Significant difference (Student *t*-test, p value < 0.05).

	Surface *P. oceanica* meadows (%)		Surface dead matte (%)		CI	
	2019	**2021**	**2019**	**2021**	**2019**	**2021**
Control	68.9 ± 0.9	71.3 ± 0.8	0.0 ± 0.0	1.9 ± 0.1[a]	1.0 ± 0.0	1.0 ± 0.0
Anchored	64.1 ± 0.8	54.3 ± 0.9[a]	9.6 ± 0.5	37.3 ± 1.0[a]	0.9 ± 0.0	0.6 ± 0.0[a]
	Surface natural patches (%)		**Surface anthropogenic patches (%)**		**PaSI**	
	2019	**2021**	**2019**	**2021**	**2019**	**2021**
Control	20.0 ± 0.8	17.2 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0
Anchored	8.0 ± 0.4	6.0 ± 0.4	9.6 ± 0.5	39.7 ± 1.0[a]	0.4 ± 0.1	0.2 ± 0.0[a]

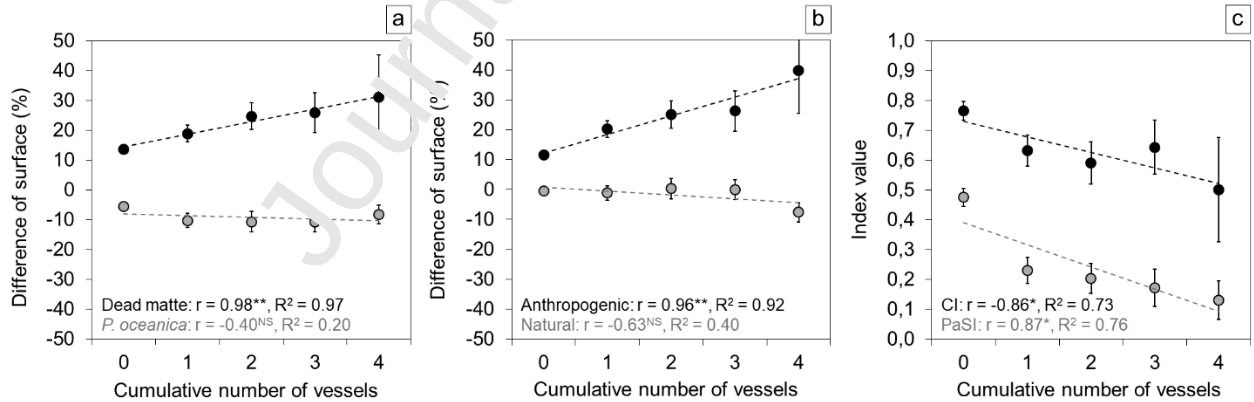

Figure 7. Relationship between the cumulative number of vessels (boats cell^{-1}) measured during the 2019-2021 period and the changes in surface areas covered by *P. oceanica* and dead matte (a), natural and anthropogenic patches (b) and, Conservation Index (CI) and Patchiness Surface Index (PaSI) values in 2021 (c). Levels of significance: *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001, NS, p > 0.05. **(2-column)**

The mean density of *P. oceanica* meadows classically decreases with depth but apart from the -5 m station, it was, on average, always lower in the central part (351.0 ±

194.4 shoots m^{-2} – T1 transect) than at the entrance to the bay (422.5 ± 186.4 shoots m^{-2} – T2 transect; see Table S1 in Supplementary material).

For the T1 transect, the mean number of leaves produced annually varied between 6.4 ± 1.3 (-25 m) and 8.2 ± 1.6 (-20 m), while the average length of the blades and the petioles, showed maximum values at the level of the shallower station (-5 m). The density of the leaves (dry weight per unit area; see Table S2 in Supplementary material) and their carbon content (see Table S3 in Supplementary material) offered a basis for assessment of the primary production for the different stations (Table 3).

Carbon fixation by the leaves of *P. oceanica* decreased with depth and varied between 880.3 mg C shoot^{-1} yr^{-1} (-5 m) and 345.3 mg C shoot^{-1} yr^{-1} (-30 m). The part of primary production devoted to the elongation of the rhizomes and roots followed the same pattern (Table 3). The annual carbon fixation by the meadow varied between 646.1 g C m^{-2} (-5 m) and 63.7 g C m^{-2} (-30 m; Figure 8a), reaching on average (± S.E.) 212.6 ± 88.5 g C m^{-2}. The annual carbon sequestration in the matte, corresponding to the sheaths, rhizomes, and roots, varied between 139.9 g C m^{-2} (-5 m) and 12.9 g C m^{-2} (-30 m), or on average 48.4 ± 19.1 g C m^{-2} (22.9% of total fixation; Figure 8b).

Table 3. Number of leaves produced annually, average annual length of leaf blades and petioles, primary leaf production per shoot (mg dry weight yr^{-1}) and carbon fixation (mg C yr^{-1}), at the different depths along the transects studied. B3 = Blade rank 3; S1 = Sheath rank 1; cor. = value observed in June, corrected to determine the annual value; sh = Shoot; PP = Primary Production; DW = Dry weight; Rh = Rhizome; Ro = Roots.

Depth	Transect	Nb leaves yr^{-1}	Length B3 cor. (mm)	PP Blades (mg DW / C sh^{-1})	Length S1 cor. (mm)	PP Sheaths (mg DW / C sh^{-1})	PP Rh/Ro (mg DW / C sh^{-1})
-5 m	T1	7.7	484.0	1 745.8 / 714.2	41.2	406.1 / 166.1	74.8 / 31.3
	T2	8.0	513.5	1 904.6 / 779.1	48.7	626.0 / 256.1	106.8 / 44.7
-10 m	T1	7.5	379.8	896.2 / 374.1	39.3	262.3 / 109.5	71.0 / 30.3
	T2	7.4	435.9	1 382.0 / 577.0	49.4	459.6 / 191.9	97.3 / 41.5
-15 m	T1	7.4	270.0	725.9 / 299.6	31.7	186.2 / 76.8	52.3 / 22.0
	T2	7.3	412.8	1 123.4 / 463.7	36.1	298.8 / 123.3	51.6 / 21.7
-20 m	T1	8.2	301.5	894.9 / 370.1	28.7	239.5 / 99.1	51.6 / 22.0
	T2	8.5	295.1	1 352.5 / 559.3	40.6	367.8 / 152.1	63.0 / 26.9
-25 m	T1	6.4	399.6	938.8 / 385.2	36.9	174.0 / 71.4	43.6 / 18.4
	T2	7.1	303.7	1 095.4 / 449.4	36.4	221.6 / 90.9	46.9 / 19.8
-30 m	T1	6.6	336.9	695.7 / 284.0	30.3	150.3 / 61.4	25.3 / 10.7
	T2	7.2	357.1	801.8 / 327.3	31.6	136.2 / 55.6	29.5 / 12.4

For the T2 transect, the number of leaves produced annually varied between 7.1 (-25 m) and 8.5 (-20 m) while the average length of the blades and the petioles, showed maximum values at the level of the shallower stations (respectively -5 m and -10 m).

Carbon fixation by the leaves of *P. oceanica* decreased with depth and varied between 1 035.2 mg C shoot^{-1} yr^{-1} (-5 m) and 382.9 mg C shoot^{-1} yr^{-1} (-30 m). The part of primary production devoted to the elongation of the rhizomes and roots followed the same pattern (Table 3). The annual carbon fixation by the meadow varied between 726.2 g C m^{-2} (-5 m) and 95.4 g C m^{-2} (-30 m; Figure 8a), reaching on average (± S.E.) 325.8 ± 95.8 g C m^{-2}. The annual carbon sequestration in the matte varied between 202.3 g C m^{-2} (-5 m) and 16.4 g C m^{-2} (-30 m) and was on average 84.4 ± 29.1 g C m^{-2} (23.6% of the total carbon fixation; Figure 8b).

However, it should be noted that the carbon fixation values per shoot were much lower, between -10 and -20 m, for the T1 transect (between -52 and -59%) compared to those recorded along the T2 transect at equivalent depths. This difference was smaller for the other depths (-11 to -18%).

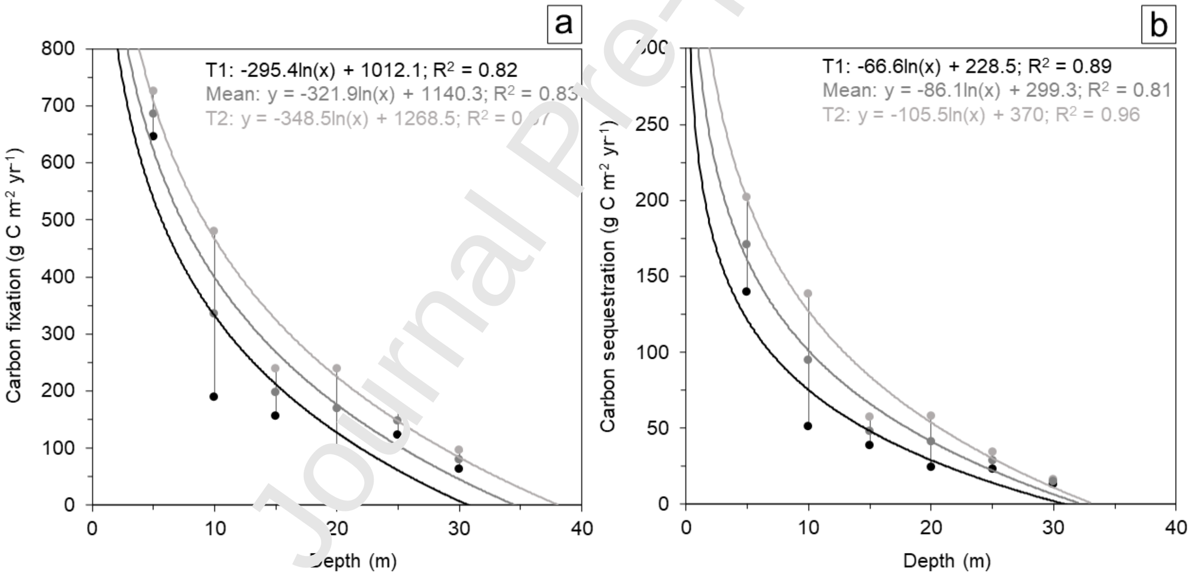

Figure 8. Carbon fixation – net primary production (a) and sequestration – part of the net primary production (b) by the *P. oceanica* meadows measured at the different stations of Sant'Amanza bay. The continuous lines correspond to the trend curves associated with T1 transect values (black), T2 transect values (light grey) and mean values (dark grey). Mean (± S.E.) values at each depth represent the average values calculated from T1 and T2 transects. **(1.5 column)**

The integration of the carbon fixation (R^2 = 0.83; Figure 8a) and sequestration (R^2 = 0.81; Figure 8b) equations over the entire bathymetric range of the *P. oceanica* meadow at the study site provided a basis for estimation of the total fixation rate at 1 531.4 ± 349.3 t C yr^{-1} for the entire bay in 2021 (5 620.2 ± 1 281.9 t eqCO_2), *i.e.,* on average 2.4 ± 0.5 t C ha^{-1} yr^{-1}

(Figure 9). The quantity of carbon sequestered reached 373.2 ± 104.1 t C yr^{-1} (1 369.6 ± 382.2 t $eqCO_2$), or on average 0.6 ± 0.2 t C ha^{-1} yr^{-1}. Off Balistra beach, between the surface and 15 m depth (Figure 6), carbon fixation decreased between 2019 and 2021, from 204.3 to 182.6 t C yr^{-1}; *i.e.,* an estimated loss of fixation capacity of 25.7 t $eqCO_2$ yr^{-1} and the sequestration capacity has been reduced of 6.6 t $eqCO_2$ yr^{-1} in average. At the same time, the analysis of relationship between the changes in carbon fixation and sequestration capacity of *P. oceanica* meadow and the boat density revealed a significant negative correlation between carbon fixation and sequestration with anchoring pressure (Pearson correlation test: r = -0.99; R^2 = 0.76; p-value < 0.05; Supplementary material). Thus, the carbon fixation and sequestration capacity in areas with boat anchoring (*i.e.,* 1 to 4 boats $cell^{-1}$) declined about -14.4 ± 2.5% and reached only -0.8 ± 3.9% for non-impacted areas (0 boat $cell^{-1}$).

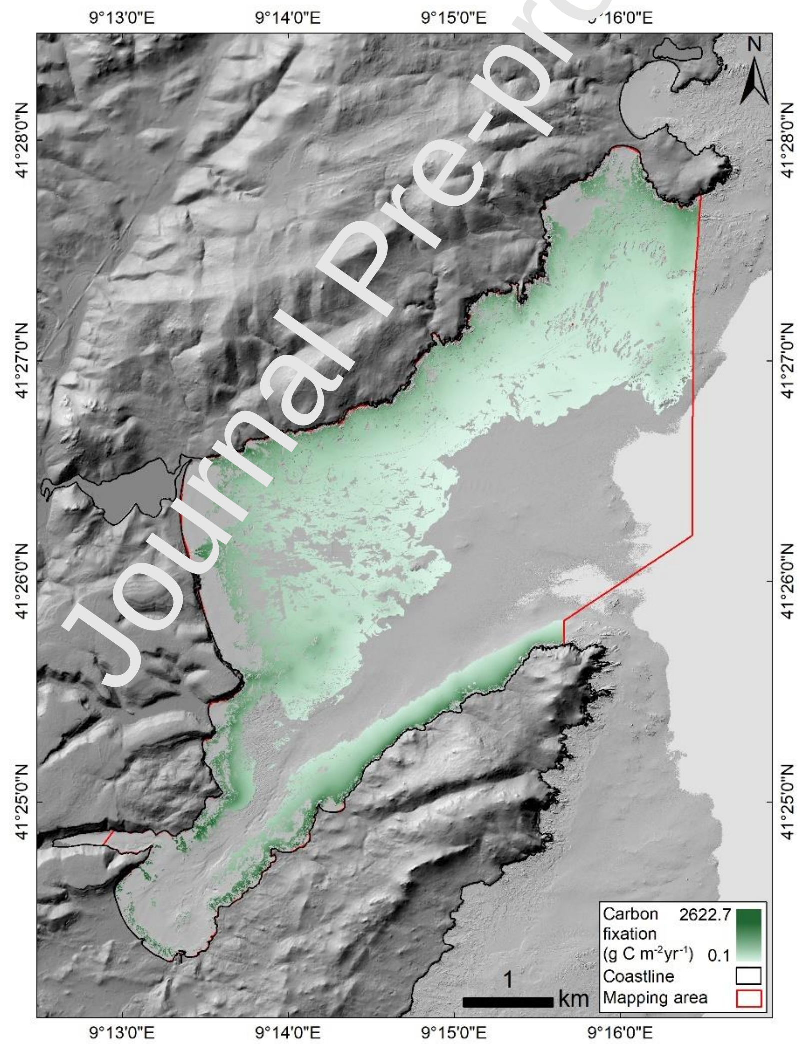

Figure 9. Carbon fixation in the *P. oceanica* meadow in Sant'Amanza bay. **(1.5-column)**

4. Discussion

In general, the bibliographic data (Francour *et al.*, 1999; Milazzo *et al.*, 2002; Broad *et al.*, 2010; Diviacco *et al.*, 2012; Serrano *et al.*, 2016) indicate that anchoring generates various physical pressures, such as crushing and/or tearing of the canopy, compaction of the substrate under the action of the weight of the anchor, abrasion of the bottoms by the chain, or even their alteration. In addition, anchoring can also lead to an increase of the particle load in the water column (resuspension of organic matter and fine particles in particular), which gives rise to material deposits (localized siltation occurring during the re-deposition; Diviacco *et al.*, 2012; Collins *et al.*, 2010; Colomer *et al.*, 2017).

With 72.9 ha destroyed in the northern part of the bay (Figure 9b), including 7.5 ha between 2019 and 2020 at Balistra beach, anchoring represents a major impact in Sant'Amanza bay. According to the classification of Abadie *et al.* (2015), the main types of patches, identified inside the *P. oceanica* meadow located near Balistra beach, are (i) anchoring tracks, corresponding to corridors of dead matte approximately 50 to 500 m long and 2 m wide, and (ii) 'funnel' shape dead matte areas with a length ranging from 50 to 150 m observed from 10 m to 35 m depth, which are probably due to the anchoring of large vessels (Figure 3; Demers *et al.*, 2013; Glasby and West, 2018).

The abrasion areas scraped by the chain during anchoring were estimated by the method of Griffiths *et al.* (2017), on the basis of the location of the units (AIS data), their size and the anchoring depth. It was thus possible to determine the surface area impacted by the vessels anchored off Balistra beach during the 2019 and 2020 summer seasons. The superimposition of these abrasion areas onto the 2020 and 2021 marine benthic habitat map highlights alterations (Figure 10). Thus, a modification in the surface area of dead matte at the expense of living meadow and soft bottoms was observed in 2020 and 2021, with -4.54 ha and +0.03 ha, respectively.

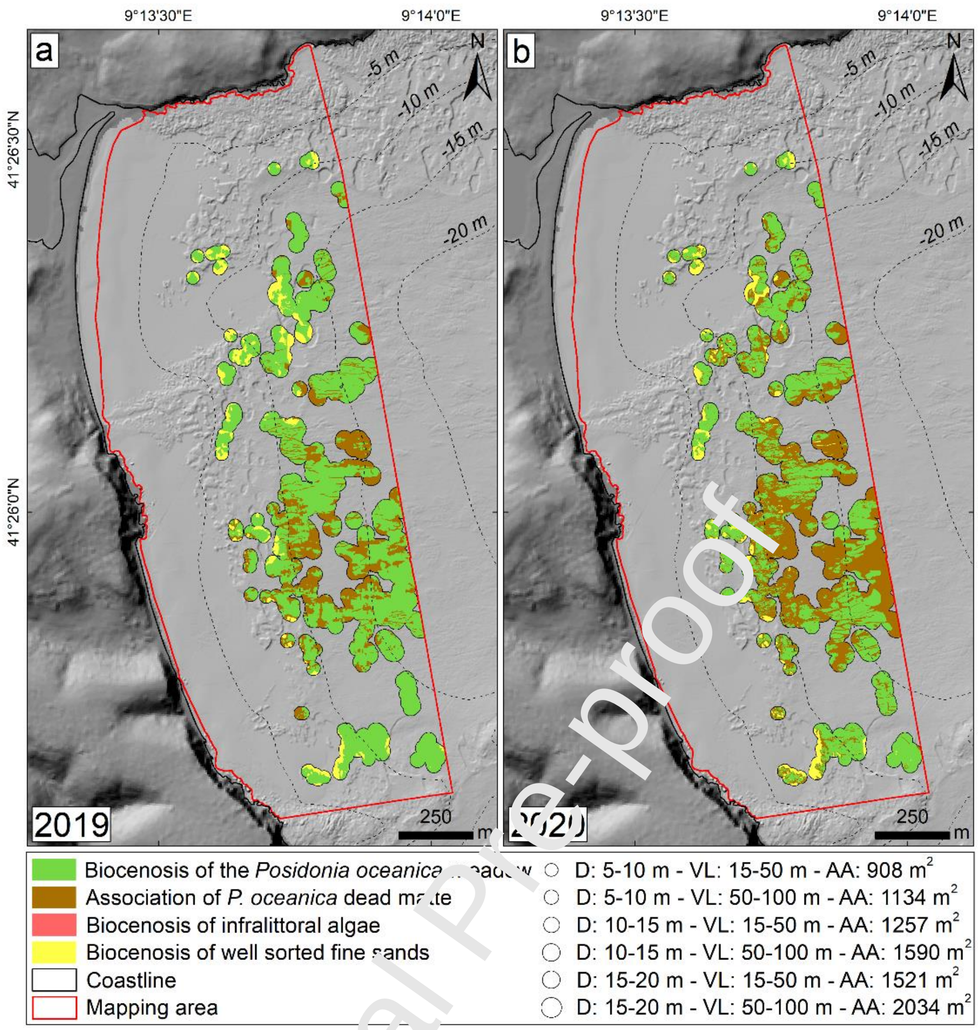

Figure 10. Patterns of change in the biocenoses between 2019 (a) and 2020 (b), in abrasion areas of vessels anchored in the *P. oceanica* meadow off Balistra beach after the summer seasons 2019 and 2020 (1st April – 30th September). D: depth range; VL: vessels length; AA: abrasion area (from Griffiths *et al*., 2017). **(1.5-column)**

Nevertheless, part of the decrease in the surface area occupied by *P. oceanica* meadows between June 2019 and February 2020 (7.5 ha) could also be explained by the acquisition period of drone images. The coverage of the adjacent substrate by *P. oceanica* leaves is higher at the beginning of the summer season due to the plant's vegetative cycle, with a maximum leaf length between June and August, and a minimum between December and February (Giraud, 1977; Peirano *et al*., 2011). The comparison of 12 'control areas', covering an area of one hectare each (see Figure S1 in Supplementary material), with little or no impact of large unit anchoring (AIS data) between June 2019 and February 2020, shows an average overestimation of meadow areas of 1.9 ± 1.2 ha in the summer season (see Table S4 in Supplementary material).

The density of the meadow showed a substantial decline in the sectors where the anchoring was the most intensive. It was thus lower along the T1 transect, with notably poor (-10 m) to moderate (-20 m) values, compared to the T2 transect where these values were good to very good (UNEP/MAP-RAC/SPA (2015) classification). In 2019 and 2020, nearly 30% of the boats anchored in the meadow (Table 4), with a majority of units 40 to 60 m long (n = 47). The degradation of this meadow vitality descriptor has already been observed at sites impacted by anchoring of large vessels (UNEP/MAP-RAC/SPA, 2015).

Table 4. Number and percentage of vessels, according to length, anchored in the *P. oceanica* meadow in Sant'Amanza bay, between 2019 and 2021.

Year	Vessels in the bay	20-40 m	40-60 m	60-80 m	>80 m	Total
2019	160	16 (10.0%)	21 (13.1%)	6 (3.8%)	1 (0.6%)	44 (27.5%)
2020	134	8 (6.0%)	26 (19.4%)	6 (4.5%)	0 (0.0%)	40 (29.9%)
2021	81	2 (2.5%)	4 (4.9%)	0 (0.0%)	0 (0.0%)	6 (7.4%)

The destruction of the *P. oceanica* meadow and its replacement by dead matte was accompanied by a drastic loss of ecosystem services associated with this biocenosis. Thus, in the Balistra area, the loss of ecosystem services (L_{ES}; in € Emergy) has been assessed at 4.72 million € yr^{-1} corresponding to the difference between the value of *P. oceanica* ecosystem services (79 200 € ha^{-1} yr^{-1}; Rigo *et al.*, 2021), and the value of *P. oceanica* dead matte ecosystem services (14 400 € ha^{-1} yr^{-1}; Rigo *et al.*, 2020). As regards more specifically the loss of ecosystem services relating to the role of carbon sinks provided by *P. oceanica* meadows, the impact can be subdivided into two main categories:

- A reduction in living meadow areas due to the anchoring of large vessels, which directly leads to a loss of carbon fixation and sequestration capacity. Taking into account (i) the surface areas impacted by the anchoring of large vessels in Sant'Amanza bay (72.9 ha; Figure 5b), and (ii) the values of carbon fixation and sequestration by the *P. oceanica* meadow at the corresponding depths (Figure 9), the annual fixation and sequestration losses can be estimated respectively at 141.3 ± 37.1 t C and 33.0 ± 9.8 t C, or 9% of the total fixation and sequestration from the meadows in the bay.
- The destruction of the matte, under the combined action of anchors and chains, results in a remineralization of carbon accumulated for thousands of years in the sediments of seagrass meadows (Serrano *et al.*, 2016). In addition, marine currents

and hydrodynamic forces can accelerate matte erosion and the exposure of carbon stocks to aerobic conditions (Burdige, 2007). The measurements carried out within the anchor tracks show a furrowing of the matte of 20 to 30 cm, over a width of 1 to 2 m, that is to say a volume of lost matte estimated on average at 0.37 m^3 per linear meter. Considering (i) the average amount of carbon stored in the first 30 centimeters of *P. oceanica* matte (107 ± 5 t C ha^{-1}; Monnier, 2020; Monnier *et al.*, 2020, 2022), and (ii) the surface areas destroyed within the bay (72.9 ha), boat anchoring would be responsible for the loss of more than 7 800 ± 365 t C (28 627 ± 1 338 eqCO_2), *i.e.* all of the carbon sequestered by the *P. oceanica* meadow of Sant'Amanza bay over the past 20 years.

The decline in the number of vessels observed in Sant'Amanza bay (Figure 4), as well as the shift in peak traffic between 2019 (week of August 4) and 2020/2021 (week of August 18), which reflects a later start in the summer season, may undoubtedly be explained by the COVID-19 pandemic and the corresponding spring lockdowns (March 17 to May 11 in 2020 and April 3 to May 3 in 2021), as observed both in the Mediterranean basin and worldwide (Plan Bleu, 2022). The monitoring of vessels over 80 m length anchoring in Sant'Amanza bay shows an increase in their number between 2019 (n = 16) and 2020 (n = 18), probably linked to a reorientation towards the Mediterranean of some cruise organizers (*e.g.* Ponant), due to the COVID-19 pandemic, then a sharp decline in 2021 (n = 9).

At Mediterranean scale, more than 2 million hectares of *Posidonia oceanica* meadow have been identified with regressions that can be significant (Telesca *et al.*, 2015; Traganos *et al.*, 2018; Boudouresque *et al.*, 2021; Pergent-Martini *et al.*, 2021). More than 90% of these seagrass beds are located in six countries (Spain, France, Italy, Croatia, Greece and Tunisia) where recreational boating is highly developed, particularly for the five northern Mediterranean countries (Desse and Charrier 2017; Plan Bleu, 2022).

The recent regulations relative to the anchoring of the largest vessels (>80 m), in force since 2016 (French Naval Prefecture, Decree No. 155/2016), completed in June 2019 (French Naval Prefecture, Decree No. 123/2019), set out the general framework for anchoring and stopping by ships and, in particular, dictates a ban on anchoring in an area where protected marine plant species are present. It refers to local decrees to identify the areas where anchoring on *P. oceanica* meadows is prohibited (*i.e.,* French Naval Prefecture, Decree No. 206/2020 for Sant'Amanza bay) for all vessels (>24 m) and designating the authorized anchoring area for vessels over 80 m. The analysis of the AIS data seems to indicate that this regulation is rather well respected by the largest vessels, with a very small number of them positioned on the meadows (n = 1 in 2019; Table 4). For smaller vessels (20 to 80 m), anchoring on the meadows also shows a strong decrease in 2021 due to (i) the reduction in the number of vessels present in the bay, and (ii) their positioning mainly outside the meadows (Table 4). Thus, in view of these factors, it appears that these regulations have been mostly respected and constitute an effective measure to limit the impact of large vessel recreational boating on *P. oceanica* meadows.

However, such regulations are still almost non-existent at the scale of the Mediterranean with the exception of France, Croatia and Spain – Balearic Islands (Pergent-Martini *et al.*, 2022). The Balearic Islands have a decree that regulates the protection of *P. oceanica* meadows with respect to anchoring, explicitly indicating that anchoring is strictly prohibited for boats of any size and tonnage on seagrass beds and that mooring is only permitted on environment-friendly buoy systems with a low impact on the seabed (Official Bulletin of the Balearic Islands, Decree No. 25/2018 of the 29th of July 2018).

On the other hand, the creation of a 60 ha mooring area (ZMEL) off Balistra beach, where anchoring will be prohibited for all vessels, whatever their size, should provide additional protection for *P. oceanica* meadows in this region. While several studies have reported a lower impact for the anchoring of boats (Boudouresque *et al.*, 1995), the repetition of anchoring cycles is likely to cause significant damage (Ruitton *et al.*, 2020). Finally, the arbitrary limit of 24 m will need to be reviewed later, depending on new knowledge, and in particular for boats between 10 and 24 m length.

Due to the protection it enjoys, the *P. oceanica* meadow in Sant'Amanza bay should naturally be able to recolonize the seabed covered today by dead matte. However, the low growth rate of *P. oceanica* rhizomes (a few centimeters per year; Caye, 1980) and the large areas of dead matte to colonize (several tens of hectares) will require a colonization period of several decades to several centuries (Meinesz and Lefevre, 1984; Pergent-Martini *et al.*, 1995; Cotugno *et al.*, 2019). In addition, the use of transplantations of cuttings of *P. oceanica* could be considered to restore this habitat and the associated ecosystem services more quickly. To date, many techniques are available (van Katwijk *et al.*, 2009; Boudouresque *et al.*, 2021; Calvo *et al.*, 2021) and their application on the scale of this bay would be of interest.

Acknowledgments

This work would not have been possible without the participation of the oceanographic research vessel L'Europe (Ifremer) and the crew (GENAVIR), provided by the Flotte Océanographique Française for Carbonsink survey. This research was part of the regional Carbonsink program (2018-274 N°SIREPA AFB: 3915), the national CANOPé program (AERMC-721 2017 011, PACA-2017_09438, OEC-2018/047) and the Interreg Italy-France Marittimo 2014-2020 cooperation program – GIREPAM project (E76J16001050007). We are grateful to GIS Posidonie staff for the 2019 drone campaign, Eric Janaudy (Costa Verde Loisirs) for help during the field mission and M. Paul for proofreading the manuscript.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Figure 1. Location of large vessel units (>20 m) anchored on *P. oceanica* meadows around the coastline of Corsica in 2010 (a) and 2020 (b) based on Automatic Identification System (AIS) data from MarineTraffic platform; www.marinetraffic.com). **(1.5-column)**

Figure 2. Location of Sant'Amanza bay and sampling stations (yellow dots) along the transects T1 and T2. **(1.5-column)**

Figure 3. Distribution of the anchoring pressure of vessels from 20 to 40 m (a), from 40 to 60 m (b), from 60 to 80 m (c) and >80 m (d) in the bay of Sant'Amanza. Authorized anchoring area in 2016-2020 (black hatched) and since 2021 (red hatched) for the vessels >80 m. Data from MarineTraffic (2022). **(1.5-column)**

Figure 4. Recreational boating frequency in 2019 (a), 2020 (b) and 2021 (c) in the bay of Sant'Amanza during the summer seasons (1st April – 30th September). **(2-column)**

Figure 5. Distribution of main biocenoses and association (a) and location of the main anchoring tracks (b) in the bay of Sant'Amanza. **(1.5-column)**

Figure 6. Distribution of main biocenoses and association in 2019 (a), 2020 (b) and 2021 (c) off the Balistra beach. **(1.5-column)**

Figure 7. Relationship between the cumulative number of vessels (boats cell^{-1}) measured during the 2019-2021 period and the changes in surface areas covered by *P. oceanica* and dead matte (a), natural and anthropogenic patches (b) and, Conservation Index (CI) and Patchiness Surface Index (PaSI) values in 2021 (c). Levels of significance: *p ≤ 0.05, **p ≤ 0.01, ***p ≤ 0.001, NS, p > 0.05. **(2-column)**

Figure 8. Carbon fixation – net primary production (a) and sequestration – part of the net primary production (b) by the *P. oceanica* meadows measured in the different stations of the bay of Sant'Amanza. The continuous lines correspond to the trend curves associated with T1 transect values (black), T2 transect values (light grey) and mean values (dark grey). Mean (± S.E.) values at each depth represent the average values calculated from T1 and T2 transects. **(1.5 column)**

Figure 9. Carbon fixation in the *P. oceanica* meadow in the bay of Sant'Amanza. **(1.5-column)**

Figure 10. Patterns of change in the biocenoses between 2019 (a) and 2020 (b), in abrasion areas of vessels anchored in the *P. oceanica* meadow off Balistra beach after the summer seasons 2019 and 2020 (1st April – 30th September). D: depth range; VL: vessels length; AA: abrasion area (from Griffiths *et al*., 2017). **(1.5-column)**

- Mapping exhibited major loss of seagrass beds coverage (72.9 ha) in Sant'Amanza bay
- Drone-imagery highlighted high meadows regression between 2019 and 2020 (-7.5 ha)
- Vitality of seagrass meadows decline in areas highly-impacted by vessels anchoring
- Carbon capture and sequestration rate of meadows declined with boat anchoring
- Loss of ecosystem services associated with boat anchoring were estimated

Table 1. Surface area (in ha) covered by the main biocenoses and association off the Balistra beach (see area in Figure 7) between 2019 and 2021 and the reliability of the maps (Valette Sansevin *et al.*, 2019).

Marine biocenoses and association	2019	2020	2021
Biocenosis of the *Posidonia oceanica* meadow	50.91	43.43	43.28
Association of *P. oceanica* dead matte	14.73	23.30	23.28
Association with *Cymodocea nodosa*	0.02	0.00	0.00
Biocenosis of infralittoral algae	3.01	3.85	3.47
Biocenosis of infralittoral pebbles	0.00	0.08	0.08
Biocenosis of well sorted fine sands	48.79	46.79	47.35
Total surface area	117.46	117.45	117.46
Reliability	79.5%	96.7%	96.7%

Table 2. Mean (± S.E.) surface area covered by *P. oceanica* meadows and dead matte (%), natural and anthropogenic patches (%), and Conservation Index (CI) and Patchiness Surface Index (PaSI) values calculated in control (0 boat cell^{-1}; n = 28) and anchored areas (≥3 boats cell^{-1}; n = 28) between 2019 and 2021. [a] Significant difference (Student *t*-test, p value < 0.05).

	Surface *P. oceanica* meadows (%)		Surface dead matte (%)		CI	
	2019	2021	2019	2021	2019	2021
Control	68.9 ± 0.9	71.3 ± 0.8	0.0 ± 0.0	1.9 ± 0.1[a]	1.0 ± 0.0	1.0 ± 0.0
Anchored	64.1 ± 0.8	54.3 ± 0.9[a]	9.6 ± 0.5	37.3 ± 1.0[a]	0.9 ± 0.0	0.6 ± 0.0[a]
	Surface natural patches (%)		**Surface anthropogenic patches (%)**		**PaSI**	
	2019	**2021**	**2019**	**2021**	**2019**	**2021**
Control	20.0 ± 0.8	17.2 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0
Anchored	8.0 ± 0.4	6.0 ± 0.4	9.6 ± 0.5	39.7 ± 1.0[a]	0.4 ± 0.1	0.2 ± 0.0[a]

Table 3. Number of leaves produced annually, average annual length of leaf blades and petioles, primary leaf production per shoot (mg dry weight yr^{-1}) and carbon fixation (mg C yr^{-1}), at the different depths along the transects studied. B3 = Blade rank 3; S1 = Sheath rank 1; cor. = value observed in June, corrected to determine the annual value; sh = Shoot; PP = Primary Production; DW = Dry weight; Rh = Rhizome; Ro = Roots.

Depth	Transect	Nb leaves yr^{-1}	Length B3 cor. (mm)	PP Blades (mg DW / C sh^{-1})	Length S1 cor. (mm)	PP Sheaths (mg DW / C sh^{-1})	PP Rh/Ro (mg DW / C sh^{-1})
-5 m	T1	7.7	484.0	1 745.8 / 714.2	41.2	406.1 / 166.1	74.8 / 31.3
	T2	8.0	513.5	1 904.6 / 779.1	48.7	626.0 / 256.1	106.8 / 44.7
-10 m	T1	7.5	379.8	896.2 / 374.1	39.3	262.3 / 109.5	71.0 / 30.3
	T2	7.4	435.9	1 382.0 / 577.0	49.4	459.6 / 191.9	97.3 / 41.5
-15 m	T1	7.4	270.0	725.9 / 299.6	31.7	186.2 / 76.8	52.3 / 22.0
	T2	7.3	412.8	1 123.4 / 463.7	36.1	298.8 / 123.3	51.6 / 21.7
-20 m	T1	8.2	301.5	894.9 / 370.1	28.7	239.5 / 99.1	51.6 / 22.0
	T2	8.5	295.1	1 352.5 / 559.3	40.6	367.8 / 152.1	63.0 / 26.9
-25 m	T1	6.4	399.6	938.8 / 385.2	36.9	174.0 / 71.4	43.6 / 18.4
	T2	7.1	303.7	1 095.4 / 449.4	36.4	221.6 / 90.9	46.9 / 19.8
-30 m	T1	6.6	336.9	695.7 / 284.0	30.3	150.3 / 61.4	25.3 / 10.7
	T2	7.2	357.1	801.8 / 327.3	31.6	136.2 / 55.6	29.5 / 12.4

Year	Vessels in the bay	20-40 m	40-60 m	60-80 m	>80 m	Total
2019	160	16 (10.0%)	21 (13.1%)	6 (3.8%)	1 (0.6%)	44 (27.5%)
2020	134	8 (6.0%)	26 (19.4%)	6 (4.5%)	0 (0.0%)	40 (29.9%)
2021	81	2 (2.5%)	4 (4.9%)	0 (0.0%)	0 (0.0%)	6 (7.4%)

Table 4. Number and percentage of vessels, according to length, anchored in the *P. oceanica* meadow in the bay of Sant'Amanza, between 2019 and 2021.