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Anchoring pressure and the effectiveness of new management measures quantified using AIS data and a mobile application

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Abstract :

Large boats can have a major impact on sensitive marine habitats like seagrass meadows when anchoring. The anchoring preference of large boats and their impacts can be mapped using Automatic Identification System (AIS). We found a constant increase in the number of anchoring events with, until recently, a large part of them within the protected Posidonia oceanica seagrass meadows. French authorities adopted a new regulation in 2019 forbidding any anchoring within P. oceanica seagrass meadows for boats larger than 24 m. The number of large ships (>24 m) anchoring in P. oceanica meadows significantly decreased after the enforcement of the regulation. The surface of avoided impact thanks to the new regulation corresponds to 134 to 217 tons of carbon sequestered by the preserved meadow in 2022. This work illustrates that a strict regulation of anchoring, based on accurate habitat maps, is effective in protecting seagrass meadows.

Highlights

► AIS data allows to measure regulation effectiveness. ► The number of large ships anchoring events within French *Posidonia oceanica* meadows is decreasing. ► New French anchoring regulation is effective in preserving *Posidonia oceanica*. ► Mobile applications can help promote sustainable environmental practices at sea.

Keywords : Anchoring, Posidonia oceanica, Boating, Marine habitat conservation, Regulation, Seagrass, Blue carbon

1. Introduction

Marine ecosystems and especially coastal ecosystems are severely threatened at the global level by human activities (Díaz et al., 2019; Halpern et al., 2019, 2008). In the European Union (EU), a legal framework has emerged to face the challenge of maintaining good ecosystem health while allowing sustainable economic development in coastal areas. The European Water Framework Directive (2000/60/EC) and the Marine Strategy Framework Directive (2008/56/EC) both aim at achieving a good ecological status for all surface waters in the EU. Achieving this objective first required to implement multiple measures among them to define the "good ecological status", then to limit the impacts and finally to evaluate the ecological status in the concerned water bodies. At the regional scale, the Mediterranean Action Plan works toward a healthy Mediterranean Sea and a sustainable development in the area, within the framework of the Barcelona Convention (UNEP, 2022). Evaluating the efficiency of management measures is crucial in the management process and requires adapted indicators based on reliable and accessible datasets (European Environment Agency, 2020; OFB, 2021). Quantifying human pressures and their impacts is a major challenge in the marine environment (Holon et al., 2018, 2015; Micheli et al., 2013; Quemmerais et al., 2020; Saeedi et al., 2019) and it is crucial when trying to evaluate the effectiveness of the regulations in place (Iglesias and Buono, 2009; Stelzenmüller et al., 2018).

Marine traffic is a priority human activity in our globalized society, currently using the sea for 90 % of its exchanges ("OECD ocean shipping," 2022). Nevertheless, its impact on the environment is high (Walker et al., 2018), in particular on sensitive marine habitats. The Automatic Identification System (AIS (IMO, 2022), communicating information of position and identification between ships to avoid collisions) while initially developed as a security tool, reveals an interesting asset in quantifying marine traffic pressure and impacts. AIS data was used in the past for evaluating vessel density, navigation route, underwater anthropogenic noise, interactions with whales, non-native species introduction, and compliance with protected areas (Robards et al., 2016), or mapping fishing activity (Ferrà et al., 2018). It was also previously used to map anchoring pressure and its impact on marine habitats including seagrass beds (Deter et al., 2017; Pergent-Martini et al., 2022). Mobile applications for navigation (e.g. NAVIONICS, DONIA, NAVILY), helping boaters in their journey by providing them information on local regulations, bathymetric maps, weather forecasts and more, are becoming more and more popular within the boating community (e.g. the number of DONIA users was multiplied by approx. 20 between the beginning of 2019 (approx. 2,200) and the end of 2022 (approx. 46,000)). These tools, together with participatory data and social networks, can provide valuable data on human activities to marine managers (Goldberg and McClintock, 2016). Among them, DONIA (Andromède océanologie, 2022a), specifically aims at saving *Posidonia oceanica* and other seagrass beds (Cymodocea, Zostera) from anchoring in several Mediterranean countries (France, Spain, Italy, Tunisia).

Posidonia oceanica (Linnaeus) Delile, 1813, is an endemic species that forms large meadows between the surface and approximately 40 meters deep in the Mediterranean Sea. *P. oceanica* is very sensitive to anchoring pressure (Figure S1) (Abadie, 2016; Andromède océanologie, 2022b; Boudouresque et al., 2012) and shows a very slow recolonization speed once damaged (Boudouresque, 2006). Major declines of *P. oceanica* were observed in the Mediterranean Sea in the last century (Marbà et al., 2014; Telesca et al., 2015). *P. oceanica* meadows build deep mattes structures, made of an accumulation of underground non putrescible roots sequestering carbon over thousands of years (Boudouresque, 2006). They were recently recognized as major carbon sinks (Leduc et al., 2023; Monnier et al., 2021) with average sequestration rates ranging from 0.278 t of Carbon/ha/yr (Pergent-Martini et al., 2021) to 0.45 t of Carbon/ha/yr (Monnier et al., 2020). This rate has been shown to be greater in shallower areas and can be estimated as a function of depth (Pergent-Martini et al., 2021).

The French Mediterranean coastal area is a hotspot for tourism and recreational boating (UNEP/MAP, 2017) and is home to large areas of *Posidonia oceanica* meadows (Traganos et al., 2022). *P. oceanica* indeed covers 79,131 ha in the French Mediterranean sea (Deter et al., 2022), 5% of which are subject to anchoring pressure (Deter et al., 2017). *P. oceanica* has been protected in France for many years (19/07/1988 decree) and many pressures have been regulated (wastewater policy of the French Water Agency, "loi littoral" in 1986 for coastal constructions). In addition, new strict regulations have recently been adopted (Prefectoral decrees n°155/2016 (abrogated by n°131/2022) and n°123/2019) (Deter et al., 2022), first regulating and then forbidding any anchoring in *P. oceanica* meadows for boats larger than 24 m. This change in the regulation was accompanied by adapted training of concerned state services (legal and surveillance actors), and led to multiple controls and court sentences (Deter et al., 2022).

The objective of this paper is to show how AIS data and mobile applications can be useful in managing and protecting marine habitats. In particular, we aimed to (1) use AIS data to assess the effectiveness of the new regulation on *Posidonia oceanica* meadows in France, (2) show how a mobile application such as DONIA can help to better understand anchoring patterns of small boats not equipped with AIS and even influence anchoring preference.

2. Materials and methods

The study area encompassed the entire Mediterranean French coast including Corsica (i.e. 1,800 km of coastline) between 0 and 80 m deep, containing the entire anchoring depth range. The study period spanned from January 2010 to December 2022.

2.1 AIS positions

AIS data were collected from two different sources. AIS data from 2010 to 2018 came from Marine traffic database (www.marinetraffic.com) (Figure S3a). Those AIS positions correspond to positions of declared anchoring activity, received by terrestrial AIS stations, with an hourly frequency. AIS data from 2019 to 2022 came from the terrestrial receiving stations of AIShub network (www.aishub.net) (Figure S3b). those AIS data are raw positions that were collected with a frequency of one position every two minutes. All AIS data contain information on boat identification, time of detection, geographic coordinates, heading direction, speed, dimensions, type, and destination (when declared). All AIS positions were combined in a unique database independently of source or frequency.

2.2 DONIA (application) positions

The DONIA mobile application (Andromède océanologie, 2022a) was created in 2013 and developed in its last version in 2018; it counted more than 45,000 users in December 2022. It aims to provide sea users with a free of charge and continuous map of the French Mediterranean Sea marine habitats at a depth between 0 and 80 m, in order to encourage good anchoring practices. The anonymized data from the DONIA application contain information on boat position, time, speed and dimensions, with a frequency of one position every two minutes. In total about 100 million positions were available.

2.3 Anchoring positions

The methodology used to obtain the anchoring positions from AIS (approx. 55,000 between 2010 and 2018 and approx. 160,000 between 2019 and 2022) and from DONIA (approx. 9,900 between 2019 and 2022) was derived from the work of Deter et al. (2017). AIS data were filtered with the following conditions: speed < 1 knot, distance between the hourly AIS points ≤ 600 m, contiguous AIS points per vessel ≥ 4, no anchoring within harbors or equipped mooring areas, and anchoring time greater than 2 hours. A regression circle was then fitted to the AIS positions and its center was defined as the position of the anchor. In case of a calculated radius higher than 600 m, the centroid of AIS positions was considered as the position of the anchor. The anchoring zone was finally defined as a polygon including the anchoring position of a vessel and its AIS points and reduced by one third in a concentric manner to obtain the anchoring impact area. The theoretical surface of degraded *Posidonia oceanica* was obtained by overlaying anchoring polygons and the habitat map. This surface under anchoring pressure is considered as potentially degraded, and the term of "impacted surface" is therefore used in this work.

Data analysis was performed using R version 4.1.2 (R Core Team, 2022). The computation challenges posed by the large number of AIS positions, due to the use of raw AIS data, were addressed using Postgresql 9.6 and Postgis 2.4 (PostgreSQL Global Development Group, 2022) spatial database management tools.

All the anchoring positions are freely available for visualization in the cartographic platform Medtrix (Andromède océanologie, 2022c) (a free registration is requested) within the "Suivi du mouillage" project.

2.4 Seabed habitat maps

We used a 1:10,000 seabed habitat map (between 0 and 80 m) covering the entire study area. This continuous map was first built in 2014 (and locally updated almost yearly ever since) using a combination of aerial pictures, multi-beam echosounder data, side-scan sonar data and direct observations ("ground-truth points") by divers (Andromède Océanologie, 2014). This map is composed of eleven habitat classes: *Cymodocea nodosa* seagrass, *Posidonia oceanica* seagrass, dead matte association, infralittoral shingle association, infralittoral soft bottoms, photophilous algae association, coralligenous reefs (= biogenic reefs), circalittoral soft bottoms, artificial habitats, offshore rocks and the bathyal zone. Dead matte association is the habitat resulting from the death of *P. oceanica* seagrass beds building matte (Boudouresque et al., 2012). The seabed habitat map is freely available for visualization on Medtrix, within the "DONIA expert" project. For the purpose of this study, habitat data was grouped into four classes: *P. oceanica* seagrass, dead matte association, soft bottom (infralittoral soft bottoms, circalittoral soft bottoms) and other.

2.5 Anchoring regulation

The two recent French Prefectoral decrees (n°155/2016 (abrogated by n°131/2022)) and in particular n°123/2019) (Table 1 Description of the French prefectoral decrees n°155/2016 and n°123/2019Table 1) have been locally translated in 18 decrees (2 abrogated) between 2019 and 2022 with the definition of forbidden anchoring areas (Table S2). A small part of the coastline still must provide a local declination of the decree n°123/2019, that should enter in force in 2023. A regulation database was created regrouping all polygons of anchoring interdiction. This regulation database is freely available for visualization on Medtrix (Andromède océanologie, 2022c) within the "DONIA" project.

Table 1 Description of the French prefectoral decrees n°155/2016 and n°123/2019

	French Prefectoral decree 155/2016	**French Prefectoral decree 123/2019**
Publication date	24/06/2016 (abrogated by n°131/2022)	03/06/2019
Application date	2016	2020 to 2022 depending on areas (see Appendix 1)
Target	Pleasure boats longer than 80 m, and other boats longer than 45 m	Boats longer than 24 m

Content	Captains must ask permission for anchoring to the nearest semaphore	Anchoring is forbidden in *Posidonia oceanica*
URL	https://www.premar-mediterranee.gouv.fr/uploads/mediterranee/arretes/7faf64e16548a431e40cfa183d8cb167.pdf	https://www.premar-mediterranee.gouv.fr/uploads/mediterranee/arretes/eec503812bac663e9c5536c6d5a59ee1.pdf

2.6 Data analysis

The proportion of anchoring events per marine habitat (four categories) and the total number of anchoring events, during the summer (July and August), according to the boat size and period (before/after regulation), were analyzed to investigate the effect of the regulation. This analysis was first realized for the boats longer than 80 m (hereafter named "very large boats") between 2010 and 2022, then for the boats longer than 24 m (hereafter named "large boats") over the same period, and finally for the boats smaller than 24 m (hereafter named "small boats") between 2019 and 2022:

- For very large boats, the change of anchoring preference was investigated after the new regulation in 2016 (Decree n°155/2016). This was done by testing if the proportion of anchoring on *Posidonia oceanica* beds was different before and after 2016 using a χ^2 test. A second test was performed on the boats smaller than 80 m to control the effect of the regulation; the dataset stopped in 2020 for this control group in order to avoid an effect of the second decree applied in 2020.
- For large boats, the change of anchoring preference was investigated after the application of the regulation in 2020 (n°123/2019). This was done by testing if the proportion of anchoring on *Posidonia oceanica* beds was different before and after the decree application date (2020 in most cases) using a χ^2 test, on the water bodies concerned by the decree. A second test was performed on boats of the same size class but on the water bodies not yet concerned by the decree to control this effect. The year 2020 was chosen as the decree application date for the control group.
- For small boats that were not concerned by any of the decrees n°155/2016 or n°123/2019, the change of anchoring preference was investigated with or without the use of the DONIA application. This was done by testing the relationship between the use of DONIA (users or non-users) and the habitat (in or out of *Posidonia oceanica* beds) using a χ^2 test. This analysis was performed from 2019 (first complete year of DONIA anchoring positions) to 2022. When a boat anchoring position was detected with both DONIA and AIS, it was only considered as a DONIA user.

The surface of *Posidonia oceanica* preserved by both the regulation (decrees n°155/2016 and n°123/2019) and the DONIA application (for small boats) was calculated separately. The surface preserved by the regulation was calculated as the difference between the current scenario and a scenario without implementation of the decrees, considering a constant surface of *P. oceanica* degraded from the year before each decree until 2022 (2016 for very large boats and 2019 for large boats respectively). The surface preserved by the DONIA application for small boats (S_p) was calculated by multiplying the total surface of anchoring on *P. oceanica* seagrass by DONIA users each year (S_a) by the difference of the ratio of anchorings on *P. oceanica* between DONIA users (R_d) and non-users (R_{nd}) ($S_p = S_a * (R_{nd} - R_d)$). An estimation of the equivalent quantity of carbon sequestered by the seagrass preserved by both the regulation and the DONIA application was also evaluated based on the literature (Monnier et al., 2020; Pergent-Martini et al., 2021). These estimations used sequestration rates averaged over the depth range of *P. oceanica* (Monnier et al., 2020; Pergent-Martini et al., 2021) or as a function of depth (Mean C sequestration (g $C.m^{-2}$ yr^{-1}) = -40.46 x ln(depth) + 145.53) (Pergent-Martini et al., 2021).

3. Results

The estimated total surface impacted by anchoring between 2010 and 2022 was about 58,000 ha (12 % on *Posidonia oceanica*, 11 % on dead matte, 76 % on soft bottoms and 1 % on other habitats; 12 % between 0 and 10 m deep, 24 % between 10 and 20 m deep, 37 % between 20 and 40 m deep, and 27 % deeper than 40 m). In 2022 more than 800 ha of *P. oceanica* meadows were still impacted by anchoring, with more than 250 ha due to large boats, and more than 500 ha due to small boats.

The number of anchoring positions per marine habitat highlighted contrasting results for the different boat size categories:

- For very large boats (Figure 1), the proportion of anchoring positions within *Posidonia oceanica* beds significantly decreased (χ^2 = 69, N = 4,869, p-value < 0.001) from the period before 2016 (422 positions, i.e. 16 % of total anchoring positions) to the period after 2016 (179 positions, i.e. 8.1 % of total anchoring positions). The control group (boats smaller than 80 m) showed however a reversed trend (before 2016: 5,587, i.e. 9.5 % of total anchoring positions; after 2016: 15,876, i.e. 27 % of total anchoring positions; χ^2 = 74, N = 59,126, p-value < 0.001). An almost constant increase in the number of very large boats anchoring positions was observed between 2010 and 2022 (Figure S3), except for a reduction in 2020 (-45 %), mainly concerning foreign boats sailing under flags of convenience (-54 %) (i.e. registered under a national jurisdiction different from that of the owner(s)).
- For large boats (Figure 1), the proportion of anchoring positions within the seagrass *Posidonia oceanica* significantly decreased ($\chi 2$ = 2,756, N = 55,487, p-value < 0.001) between the period before the decree application (13,630 positions, i.e. 34 % of total anchoring positions) and the period after the decree application (1,955 positions, i.e. 12 % of total anchoring positions), when looking at the water bodies concerned by the local translations of the Prefectoral decree n°123/2019. The control group (water bodies not concerned by the local translations of the Prefectoral decree n°123/2019), although lighter, showed a similar trend (before 2020: 930, i.e. 14 % of total anchoring positions; after 2020: 344, i.e. 12 % of total anchoring positions; χ^2 = 5.9, N = 9,361, p-value < 0.05). An almost constant increase in the number of large boats anchoring positions was observed between 2010 and 2022 (Figure S3), except for a reduction in 2020 (-9%), mainly concerning foreign boats sailing under flags of convenience (-18 %).
- For small boats (Figure 1), the proportion of anchoring positions within the seagrass *Posidonia oceanica* slightly decreased for both DONIA users and non-users between 2019 (DONIA users: 117 positions, i.e. 36 % of total anchoring positions; DONIA non-users: 2,532 positions, i.e. 43 % of total anchoring positions) and 2022 (DONIA users: 516 positions, i.e. 31 % of total anchoring positions; DONIA non-users: 5,454 positions, i.e. 40 % of total anchoring positions). During this period, the proportion of anchoring positions within the meadows was lower for DONIA users compared to non-users (χ^2 = 86, N = 51,107, p-value < 0.001). A strong increase was observed

between 2019 and 2022 in the number of anchoring positions for small boats using DONIA (+ 414 %). The number of anchorings not using DONIA also increased during this period (+ 136 %).

The total surface of anchoring within *Posidonia oceanica* decreased on average between 2019 and 2022 for large boats (- 72 %), and increased for small boats (+ 67 %). A small decrease was however observed between 2021 and 2022 in the total surface of anchoring within *P. oceanica* for boats between 10 and 24 m length (- 17 %) (Figure 2). The surface of *P. oceanica* preserved by the anchoring regulation (both decrees) and the DONIA application ranged from 0.74 ha in 2017 to 490 ha in 2022 for a total surface of 894 ha from 2017 to 2022 (Figure 2). These surfaces corresponded to a yearly carbon sequestration ranging from 0.21 to 0.33 tons (0.24 when taking into account depth) in 2017 and to 136.14 to 220.37 tons (212 when taking into account depth) in 2022 (98 % thanks to the regulation for large boats and 2 % thanks to the DONIA application for small boats).

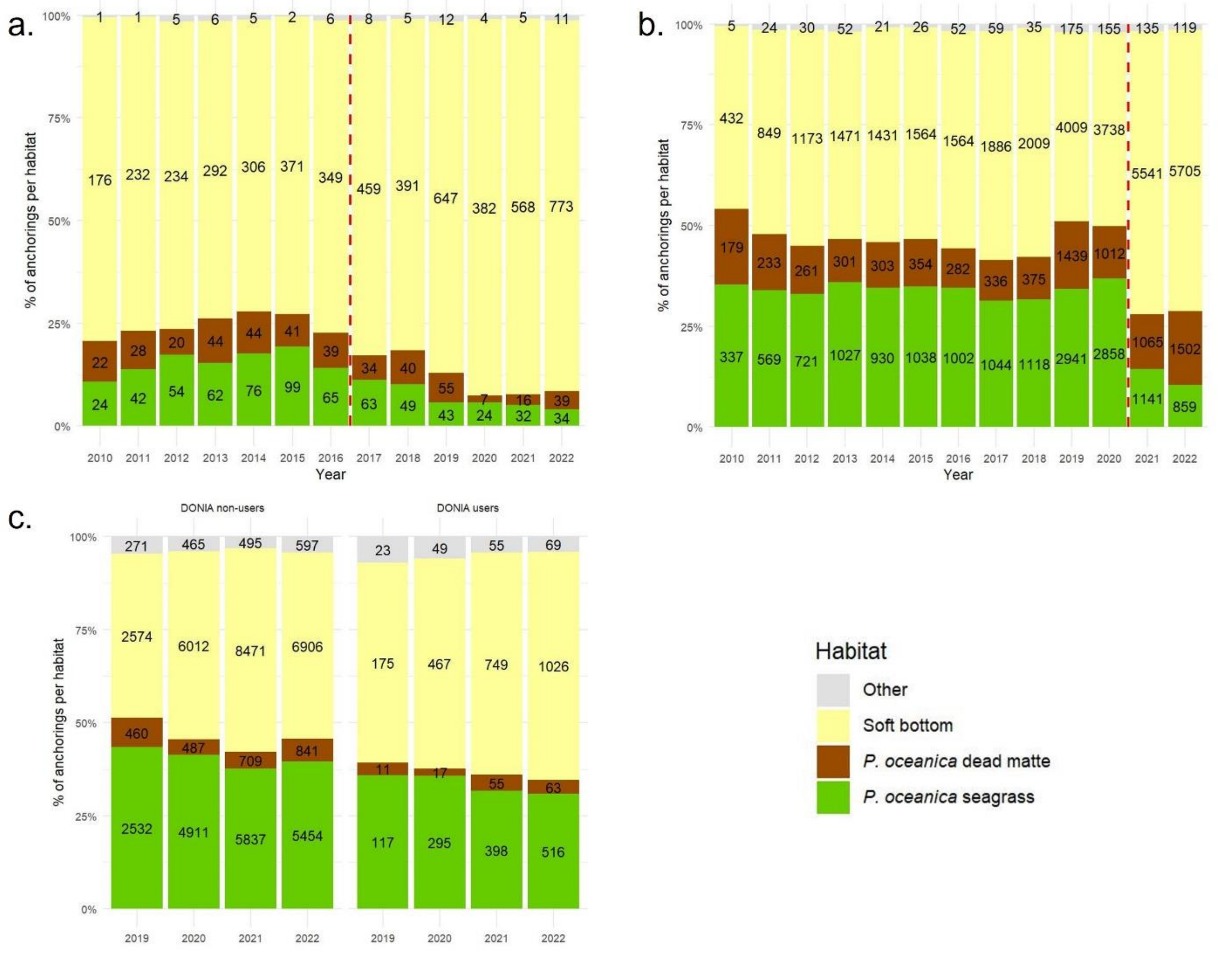

Figure 1 Percentage of anchoring positions per year and habitat. a. during the summer between 2010 and 2018 ("declarative" anchorings) and between 2019 and 2022 ("calculated" anchorings) for very large boats (> 80 m). The dashed red line shows the limit used to test the effect of the decree (2016). b. during the summer between 2010 and 2018 ("declarative" anchorings) and between 2019 and 2022 ("calculated" anchorings) for large boats (> 24 m), within water bodies concerned by the local declinations of the Prefectoral decree n°123/2019. The dashed red line shows the limit used to test the effect of the decree (2020). c. for DONIA users and non-users during the summer between 2019 and 2022 ("calculated" anchorings) for small boats (< 24 m). Number of anchorings per category inside the bars.

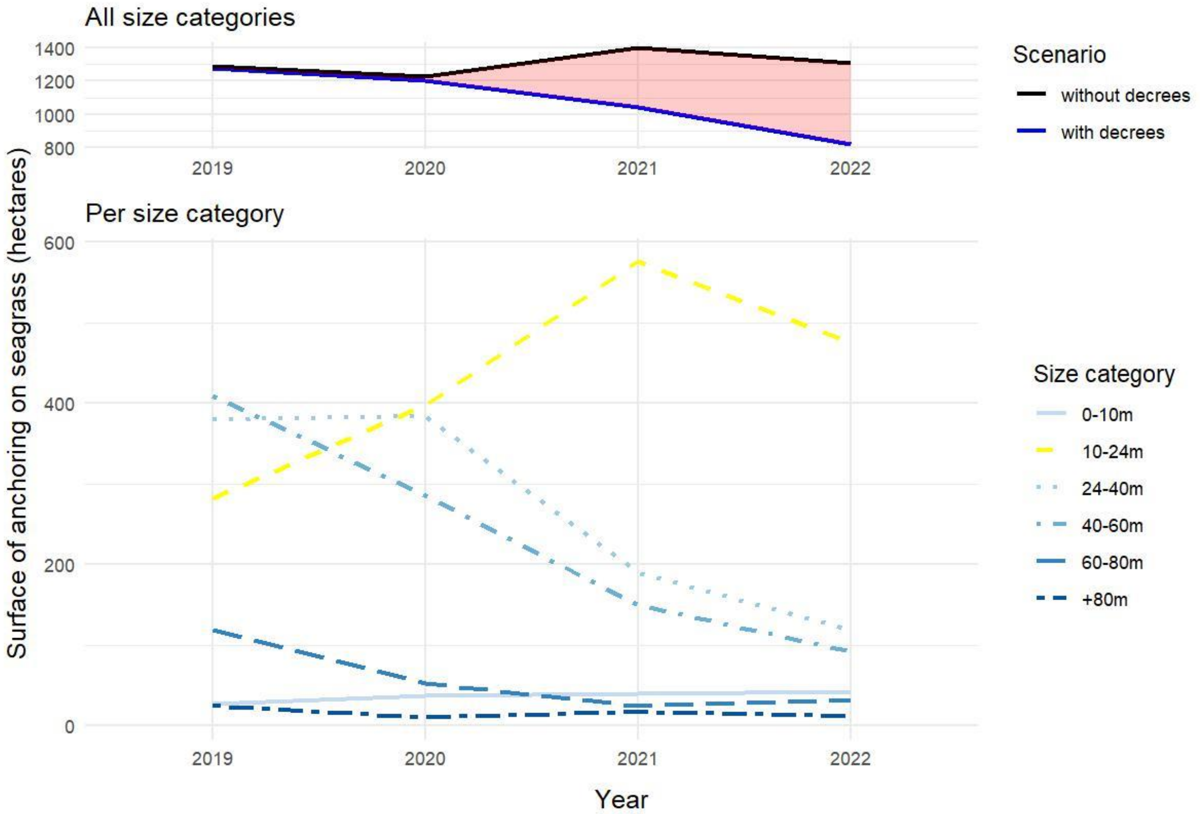

Figure 2 Top: Total surface of anchoring within Posidonia oceanica between 2019 and 2022 per year. The blue line represents the evolution of the total surface of anchoring on P. oceanica. The black line represents the evolution of the surface of anchoring on P. oceanica in a scenario without anchoring regulation and without the DONIA application. The red transparent area represents the surface of P. oceanica preserved by the regulation and by the DONIA application. Bottom: Surface of anchoring on P. oceanica between 2019 and 2021 per boat size category and per year. The yellow line represents the boats between 10 and 24 m length.

4. Discussion

This study aimed at testing the ability of AIS and mobile application data to assess the anchoring behavior of boats and their subsequent pressure on *Posidonia oceanica* meadows over the period 2010-2022. By comparing the number of anchoring events within the seagrass per boat size class through time, this study also assessed the change in anchoring preference after the introduction of new regulations.

This work confirmed that AIS data are effective to monitor anchoring pressure distribution and its variation in time and also highlights its usefulness in regulation effectiveness evaluation. While the total number of anchoring keeps increasing, the total surface of anchoring within *P. oceanica* is indeed decreasing since 2019 thanks to the application of the new regulation.

The evolution of anchoring events in *Posidonia oceanica* detected from AIS data well reflects the restrictions enforced by decree n°155/2016 and n°123/2019 regarding very large boats and large boats respectively. The control group did not confirm the effect of the decree n°123/2019, most probably because the general decree caused fear and induced a change of behavior even on waterbodies where it was not yet locally translated (used as control group), and because of side actions combined to the new regulation. Side actions can indeed help conservation (Bickford et al., 2012; Bruner et al., 2001), and include here communication and sensibilization in the recent years towards boat captains and boaters on *P. oceanica* ecological importance and sensitivity to anchoring, control by local managers and national custom services, sometimes followed by court sentences, and an increasing number of mooring buoys or areas with regulated mooring outside harbors (sometimes also as a consequence of the regulation).

Data obtained from the DONIA application allowed to better detect a small portion of small boats that did not use AIS (only approx. 5% of boats < 24 m are equipped with AIS (Deter et al., 2017)). The DONIA application, based on a unique mapping dataset of marine habitats in the French Mediterranean sea, was developed to help boaters anchor outside of *Posidonia oceanica* meadows. The first version of the DONIA application was released in 2013, hence before the regulation forbidding anchoring on *P. oceanica* meadows. The proportion of DONIA users' anchorings in *P. oceanica* was lower than non-users (31 % for DONIA users' and 40 % for non-users in 2022), showing the effectiveness of DONIA and more generally the role such applications can have in promoting good practices in order to preserve marine ecosystems.
While a slight decrease in the proportion of anchorings within *Posidonia oceanica* was also observed for small boats not using DONIA, their anchoring behavior remained impacting with more than 1/3 of the anchoring events within *P. oceanica* in 2022. In the absence of regulation, small boats owners might think they do not impact the seagrass when anchoring. All anchorings however impact the seafloor, although differing in intensity according to the boat size (Griffiths et al., 2017; Rouanet et al., 2013). While the anchoring of these small boats is not damaging the entire polygon of anchoring, the scars created in the meadow can expand in the long term under the effect of hydrodynamic erosion (Abadie, 2016). The anchoring surface within *P. oceanica* of small boats is moreover very important (especially for boats between 10 and 24 m length, see results) although underestimated when using AIS data (Deter et al., 2017). More studies are therefore needed to better localize and characterize the impact of small boats anchoring within *P. oceanica* meadows using innovative monitoring tools including satellite or drone images analysis with artificial intelligence (Goswami et al., 2020; Kanjir et al., 2018) that are currently under development.

The regulation protecting *Posidonia oceanica* in France, and to a smaller extent the DONIA mobile application, allowed a relatively "low-cost" blue carbon sequestration, particularly interesting in the context of climate change, with the sequestration in 2022 of 136.14 to 220.37 tons of carbon (98 % thanks to the regulation for large boats and 2 % thanks to the DONIA application for small boats). It should here be emphasized that the role of the DONIA application in the protection of *P. oceanica* cannot be limited to those numbers (concerning only small boats), the mapping database behind the application being one of the cornerstones of the new regulation (concerning large and very large boats). Carbon labels should moreover be investigated in the future to finance such tools as well as mooring buoys, as is currently the case in France with the "Prométhée – Med" project (EcoAct, 2022) aiming to certify marine seagrass conservation measures in the framework of the French low carbon label.

Between 2010 and 2022, more than 6,500 ha of *Posidonia oceanica* seagrass were impacted by anchoring in the French Mediterranean territorial waters. The constant increase in the number of anchorings in the seagrass had to be tackled by the French authorities, and the decrees recently applied by the French Maritime Prefect have proved effective in protecting *P. oceanica*. However, more than 800 ha of *P. oceanica* meadows were still impacted by anchoring in 2022, with more than 250 ha due to large boats despite an ambitious and effective regulation in place, and more than 500 ha due to small boats for which there is no specific regulation yet (although *P. oceanica* is a protected species (19/07/1988 decree) and its degradation remains forbidden). *P. oceanica* is also considered as a threatened species at the Mediterranean scale by the Barcelona convention (UNEP, 2022), and such impact assessment could therefore be relevant for the whole Mediterranean sea. In France, as a consequence of the new regulation, large boats' anchoring pressure was then transferred to other habitats, mostly sandy bottoms (more than 6,000 hectares in 2022) and dead matte (more than 900 hectares in 2022). While considered less ecologically important, sandy bottoms are still poorly known and are subject to growing attention of the scientific community (Jac et al., 2022, 2021). In addition, *P. oceanica* dead matte is not actually dead in terms of biodiversity (Borg et al., 2006) and is known as a favorable substrate for natural recolonization and restoration (Boudouresque et al., 2021; Calvo et al., 2021; Pansini et al., 2022) and the idea of its protection against anchoring should also be studied, at least partially on limited time periods and/or areas, and/or based on acceptable thresholds of pressures to be defined (Holon et al., 2018). The European commission adopted in 2022 the Nature Restoration Law, aiming to restore ecosystems, habitat and species across the EU. A similar initiative is needed at the European level to better protect seagrass meadows from anchoring.

5. Conclusion

Posidonia oceanica seagrass covers a total of 19,020 km² in the Mediterranean Sea, almost 5 % of which being present in the French waters (Traganos et al., 2022). *P. oceanica* has been protected in France for many years and the strict regulations recently adopted (Prefectoral decrees n°155/2016 (abrogated by n°131/2022) and n°123/2019) allowed to significantly decrease the anchoring pressure on its meadows. This work showed that French *P. oceanica* meadows can be an inspiring case study for other countries, proving that ambitious regulation, combined with adapted and intelligent monitoring and control efforts, are effective in preserving protected habitats and associated carbon stocks without a priori negatively impacting touristic frequentation. Mobile applications might also bring a serious added value in actions as wide as communication, sensibilization, monitoring, control, and behavior influence.

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Contributors
T.B., F.H. and J.D. designed the study. T.B., G.M., G.D. and A.B. collected the data. T.B. analyzed the data. G.M., P.B. and N.M. helped in interpreting the results and drafting the article. All authors contributed to the final manuscript.

Declaration of interests
Donia is a tablet and smartphone application created by Andromede océanologie and made freely available thanks to the funding / collaboration with Agence de l'eau Rhône Méditerranée Corse and Naos. Therefore, the results of this publication have no commercial impact.

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Supplementary material for

Anchoring pressure and the effectiveness of new management measures quantified using AIS data and a mobile application

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Figure S1. Anchor of a large ship (> 24 m in length) in the *Posidonia oceanica* meadow with clear evidence of the related physical disturbance and impact (source: Laurent Ballesta©)

Table S2. Description of the local translations of the French prefectoral decree n°123/2019

Decree	Date	Boat length	Area
204/2020	14/10/2020	more than 20m	Var river output to the limit of French, Monaco and Italian waters
205/2020	14/10/2020	more than 24m	"pointe de l'Aiguille" to the Var river output
206/2020	14/10/2020	more than 24m	Bonifacio marine reserve
221/2020 (abrogated)	05/11/2020	more than 24m	Off the Pyrénées-Orientales department
249/2020	15/12/2020	more than 24m	Saint-Raphaël old port to "pointe de l'Aiguille"
245/2020	15/12/2020	more than 24m	"pointe Fauconnière" to cap Cépet
246/2020	15/12/2020	more than 24m	Cap Carqueiranne to Cap Bénat
247/2020	15/12/2020	more than 24m	Cap Bénat to "pointe de la Bonne Terrasse"
248/2020	15/12/2020	more than 24m	Cap Pinet to "pointe de Saint Aygulf"
20/2021	05/02/2021	more than 24m	Off the Herault department
095/2021	18/05/2021	more than 24m	Cap Corse marine natural parc
099/2021	20/05/2021	more than 24m	Calanques national parc
100/2021 (abrogated)	20/05/2021	all	Marseille
101/2021	20/05/2021	all	Cassis
197/2022	24/06/2022	more than 24m	Off the Pyrénées-Orientales department
250/2022	05/08/2022	all	Marseille
252/2022	08/08/2022	all	Villefranche sur mer
319/2022	17/10/2022	more than 24m	East Corsica (Bastia to Porto-Vecchio)

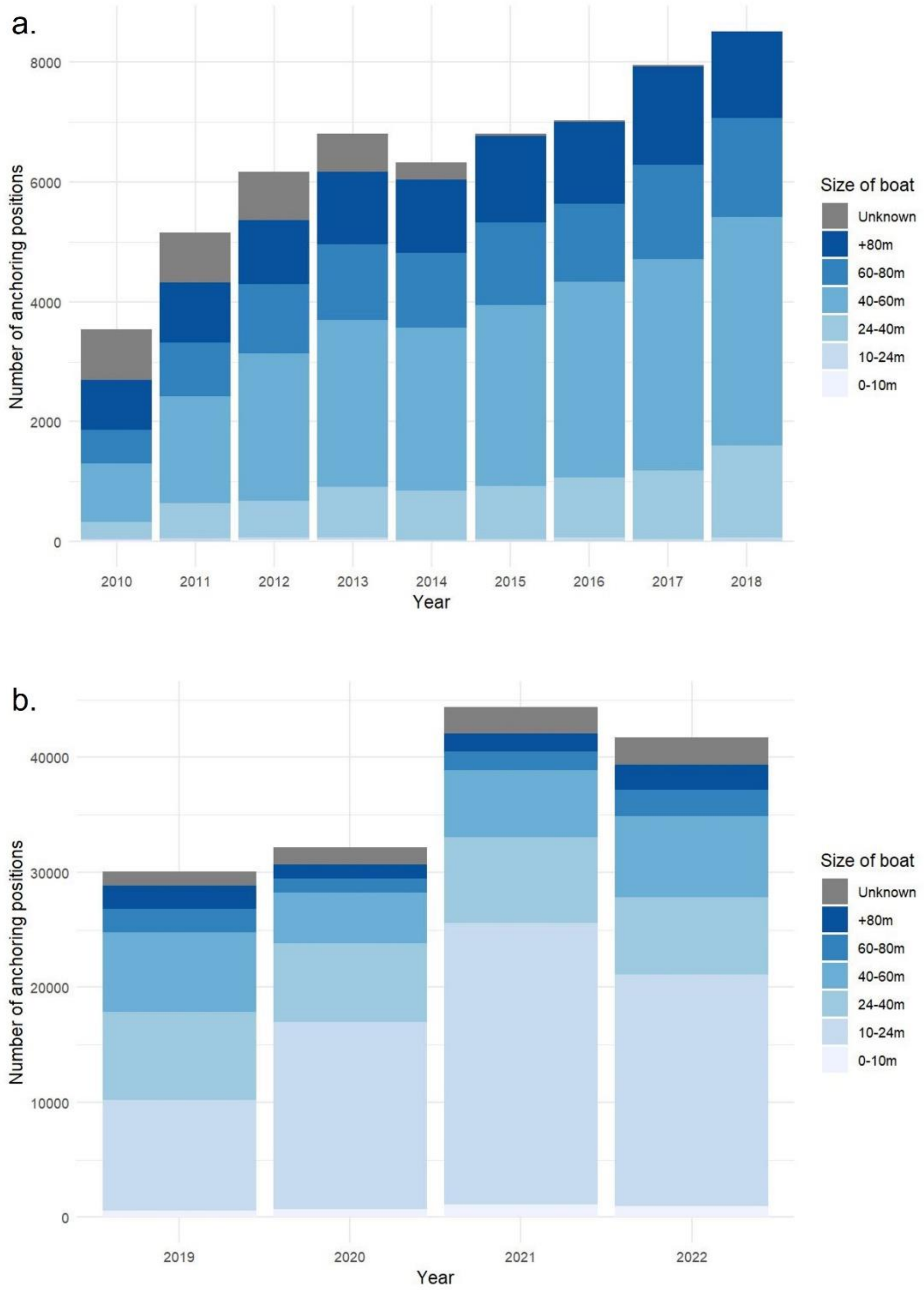

Figure S3. Number of anchoring positions per year and size category a. between 2010 and 2018 (Marine traffic dataset) and b. between 2019 and 2022 (AIShub dataset)

An almost constant increase in the number of anchoring positions was observed between 2010 and 2022. This trend seems particularly important for small boats and could be explained by an increased frequentation and/or by a wider equipment with the AIS system among boaters (increase of more than 10,000 units per year in the number of pleasure boats registrations in France (Secrétariat d'état chargé de la mer, 2022)). A reduction was observed in 2020 in the number of anchoring events for large boats and especially for very large boats. It mainly concerns foreign boats including boats sailing under flags of convenience. This is probably due to the COVID pandemic, which strongly impacted the worldwide travel and the tourism industry (Škare et al., 2021). A small reduction was also observed in the number of anchoring events for small boats in 2022, that could be linked to the strong inflation that year (including particularly the increase of fuel cost (inflation.eu, 2022)) and reduction of leisure activities during this period.

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