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Boat anchoring pressure on coastal seabed: quantification and bias estimation using AIS data

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Abstract (150 words)
Global shipping is economically important, but has many adverse environmental effects. Anchoring contributes greatly to this adverse impact, as it is responsible for mechanical disturbance of highly sensitive marine habitats. Recovery of these ecosystems is limited by slow regrowth. Anchoring pressure on coastal seabed habitats was estimated using AIS (Automatic Identification System) data along 1800 km of Mediterranean coastline between 2010 and 2015. A comparison with field observations showed that these results were most consistent for large boats (> 50 m). An analysis of AIS data coupled with a seabed map showed that around 30% of the habitats between 0 and -80 m exhibited anchoring pressure. \textit{Posidonia oceanica} seagrass beds were the most impacted habitat in terms of duration. This methodology efficiently estimates spatial and temporal anchoring pressure principally due to large boats and should interest managers of marine protected areas as much as coastline managers.

Key words: mooring impact; benthic habitats; ship; method; habitat vulnerability; resilience

INTRODUCTION
Global shipping (maritime transport and recreational boating) is an important sea use and has significant economic value. A recent review of maritime transport reported that “around 80% of global trade by volume and over 70% of global trade by value are carried by sea and are handled by ports worldwide” (United Nations Conference on Trade and Development (UNCTAD), 2015). The studied ships comprise commercial vessels (passenger and/or goods transport, service and assistance, professional use such as fishing, or research) and recreational vessels. Recreational boating represents a large number of users with 29% (34.2 million) of U.S. households having at least one member who boated in 2011 (USCG boating, 2011), and Europe having 36 million boaters and six million boats in its waters (European Boating Industry, 2010). There are numerous adverse environmental effects from this high number of boats: collision, pollution (e.g., ballast, oil, antifouling products), devoted buildings on land (harbours) and anchoring (Cappato, 2011). Anchoring is defined as the short-term deployment of a physical device to hold fast to the substrate by a vessel (Kininmonth et al., 2014). Anchoring is responsible for mechanical disturbance of highly sensitive marine habitats like seagrass meadows (Short and Wylie-Echeverria, 1996) and biogenic reefs (Ballesteros, 2006; Davis, 1977), whose recovery is limited by slow regrowth. Concentrated in shallow waters by its very nature, anchoring causes direct and indirect damage to some of the most valuable marine ecosystems (Costanza et al., 1997; Forrest et al., 2015) through deployment and retrieval of the anchor and the movement of the attached chain/rope (Milazzo et al., 2004; Walker et al., 2012). Concentrated on shallow waters by its very nature, anchoring causes direct and indirect damages to some of the most valuable marine ecosystems (Costanza et al., 1997; Forrest et al., 2015).
MATERIAL AND METHODS

1.1. Study area and existing seabed maps
This work considers the whole Mediterranean French coast including Corsica i.e., 1800 km coastline between 0 and -80 m. This area was chosen to take advantage of an existing seabed habitat map. This 1:10 000 seabed habitat map (between 0 and -80 m) was freely obtained from the “DONIA Expert” project, hosted by the cartographic platform Medtrix (www.medtrix.fr). This continuous map was built in 2014 using a combination of aerial pictures, Multi-beam echosounder data, side-scan sonar data and direct observations (“ground-truth points”) by divers (Holon et al., 2015; Holon, 2015). Eleven habitat classes were considered: *Cymodocea nodosa* seagrass, *Posidonia oceanica* seagrass, dead matte association, infralittoral shingle association, infralittoral soft bottoms, photophilous algae association, coralligenous reefs (= biogenic reefs), cirralittoral 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 (Boudouresque et al., 2012).

1.2. AIS ship data pre-treatment
For this work, AIS data were purchased from MarineTraffic.com for a six-year period from 2010 to 2015 along the Mediterranean French coastline. No data prior to 2010 were available. Our request concerned data received by terrestrial AIS bases with an hourly frequency for vessels declared as “anchored”. The dataset contained the following fields for over two million (2145523) AIS positions: vessel identity (Maritime Mobile Service Identity – MMSI), speed, position (longitude and latitude), course, heading, timestamp and vessel length. Vessel length was found to be unusable because of a high number of null, missing or incorrect data because this field is manually recorded when AIS is installed. First, anchoring positions were localised and vessels that were not anchored (false positives) were removed if they did not meet the following conditions: speed < 1 knot, distance between the hourly AIS points ≤ 600 m (300-meters-long vessels are now common in maritime transport) and AIS points per vessel ≥ 4. Anchored vessels are generally not totally immobile and often drift with current, wind and/or swell around the anchor according to a circle or an arc of a circle pattern (Figure 1). A regression
circle and its centre were defined as the anchoring position for each vessel using the “lsfit.circle” function of the *Circular v.0.4-7* package (Agostinelli and Lund, 2013) with R version 3.2.4 (R Core Team 2015). In the case of the radius being higher than 600 m (highly clustered points or aligned points) or when the centre was positioned on land or within harbours (“harbour” layer obtained from (Meinesz et al., 2010)), the centroid, instead of the centre of the circle, was taken as the anchoring position. It was also verified that no anchoring points were identified within the 27 equipped mooring areas declared and controlled by prefectural decrees.
Figure 1. Examples of anchoring zones (grey) and anchoring impact areas (yellow). a) Anchoring areas (grey) are determined from AIS data. Each colour represents a different anchoring. Estimated anchoring positions are
presented in red. b) Anchoring zone was reduced of one third in a concentric manner to define anchoring impact areas.

1.3. Anchoring impact analysis
An anchoring zone was defined as a polygon including the anchoring position of a vessel and its AIS points. Anchoring zones partly covering land or harbours were removed from the dataset. The area of each anchoring zone was reduced by one third in a concentric manner to remove the chain length placed in the water column and to define the anchoring impact area (Figure 1) (Boudouresque et al., 2012). Anchoring duration was calculated based on the first and last AIS points (date and time) used to define the area. A grid composed of 20 x 20 m cells was applied and the duration was divided by the area of the anchoring zone and multiplied by the area of cell occupied by the anchoring zone polygon to determine a proportional anchoring duration per cell (400 m²). Anchoring density was studied through the number of anchored vessels per cell and per year as well as the time interval between two anchorings. Combining this with the seabed habitat map allows studying the impact of anchoring (range, duration, seasonality) on these habitats. This part of the work was performed using ArcMap version 10.0 and Qgis 2.13.3.

1.4. Comparison between AIS and observation data
To estimate the bias of AIS data, it was compared with existing field observations. Anchored vessels were counted and their length estimated in the framework of two studies: i) from the coastline at 12h00 UTC over 21 days (15 May - 30 September) in 2014 between the capes of Nice and Ail (Meinesz and Miranda, 2014) and ii) from a plane over three days (26 July 12h55 pm to 1h20 pm, 10 August 11h14 am to 11h22 am UTC and 25 September 09h52 am to 09h56 am UTC) in 2014 (MEDOBS project, http://medtrix.fr). These data were compared with AIS data obtained from the same days, within the same areas and time slots through analyses of variance (ANOVAs).

2. RESULTS
The database obtained from Marine Traffic contained data from 12447 different vessels (around 2000 different vessels per year over six years). After the pre-treatment, and after removing any anchoring zones partly covering harbours or land, 60097 anchoring impact areas were analysed for a total cumulated impact area of 79214.99 ha (median = 3964.33 m²). This corresponded to 5868 different vessels (around 1 800 per year) for 2065457 AIS positions (Table 1). During the study (2010-2015), the highest number of anchored vessels was observed between May and September with maximal values in July (12623) and August (12770) (Figure 2). Anchoring lasted for an average of 27.63 hours (median = 14.55 ±47.07) and was observed at an average of -20 m. Most of the anchored time was spent during the night (883530 hours compared with 779401 hours during the daytime). The annual cumulated anchoring durations were similar each year (Anova: F=0.73; P=0.60), in contrast to cumulated anchoring impact areas which varied by year (F=198.87; P<0.001) with the total highest impact area found in 2010. Each grid cell hosted an average of 1.15 anchored vessels per grid cell (20 x 20 m) per year (no significant variation between years; F=651.23, P<0.001) with a maximum of 26 vessels per cell observed in 2015. The interval between two anchorings within one grid cell varied from 0.04 h to 8886.71 h (370 days) with a mean interval of 1350.56 h (median =997.62 ±1284.42 h), i.e., 56 days.

Table 1. Anchoring data analysis per year. Areas were calculated using a 20 x 20 m grid cell.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of anchored vessels</th>
<th>Number of different vessels</th>
<th>Cumulated anchoring impact area in ha</th>
<th>Anchoring mean duration in hours (standard error)</th>
<th>Cumulated anchoring duration in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>7239</td>
<td>1822</td>
<td>6893.44</td>
<td>1.51 (2.03)</td>
<td>259527.43</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Year</th>
<th>Anchored Vessels</th>
<th>Anchored Days</th>
<th>Average Impact Area (km²)</th>
<th>Total Impact Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>9395</td>
<td>1841</td>
<td>5820.80</td>
<td>247846.09</td>
</tr>
<tr>
<td>2012</td>
<td>10358</td>
<td>1790</td>
<td>6238.08</td>
<td>269215.95</td>
</tr>
<tr>
<td>2013</td>
<td>11219</td>
<td>1818</td>
<td>6846.68</td>
<td>280130.79</td>
</tr>
<tr>
<td>2014</td>
<td>10888</td>
<td>1860</td>
<td>6664.24</td>
<td>268313.16</td>
</tr>
<tr>
<td>2015</td>
<td>10998</td>
<td>1899</td>
<td>6553.48</td>
<td>256112.12</td>
</tr>
<tr>
<td>Total</td>
<td>60097</td>
<td>5868</td>
<td>15219.88</td>
<td>1581145.52</td>
</tr>
</tbody>
</table>

Figure 2. Anchoring seasonality based on AIS data (all years from 2010 to 2015 were considered).

Most of the anchoring density was located east of the mainland coastline (99% of the total impact area) with four zones having 80.7% of the total impact areas: Fos-sur-mer, Cannes/Golfe-Juan/Antibes, Beaulieu / Villefranche-sur-mer and Saint-Tropez (Figure 3 Erreur ! Source du renvoi introuvable.).
Figure 3. Anchoring pressure density (all the anchoring impact areas are overlaid) along the Eastern Mediterranean French coastline between 2010 and 2015. The four zoomed areas show the most impacted seabeds. The scale varies between 0 and 100 where 100 corresponds to the maximal number of overlaid areas.

Between 0 and -80 m, almost one third (29.49%) of the seabed habitats were subjected to anchoring pressure between 2010 and 2015 (Table 2). The most impacted habitats (in terms of areas) were circalittoral soft bottom (6 022 ha), infralittoral soft bottom (4 488 ha) and *P. oceanica* seagrass (3 772 ha). Proportionally to its presence along the coastline, *P. oceanica* dead matte association was the most impacted habitat (11.13%) followed by *C. nodosa* seagrass (5.27%) and *P. oceanica* seagrass (4.52%). In terms of duration, *P. oceanica* seagrass beds were also the most occupied habitats (36.40 hours of anchoring/ha/year) (Table 2).
Table 2. Anchoring pressure analysis of seabed habitats. Areas were calculated using a 20 x 20 m grid cell.

<table>
<thead>
<tr>
<th>Marine habitats</th>
<th>Total habitat area (ha)</th>
<th>Area subjected to anchoring (ha)</th>
<th>Percent of habitat impacted by anchoring (%)</th>
<th>Anchoring duration during the 6-year study (hours)</th>
<th>Anchoring duration / ha of impacted habitat / year (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infralittoral soft bottom</td>
<td>117576.16</td>
<td>4487.84</td>
<td>3.82</td>
<td>669857</td>
<td>24.88</td>
</tr>
<tr>
<td>Circalittoral soft bottom</td>
<td>446530.61</td>
<td>6021.88</td>
<td>1.35</td>
<td>484191</td>
<td>13.40</td>
</tr>
<tr>
<td>Coralligenous reefs</td>
<td>4787.81</td>
<td>69.72</td>
<td>1.46</td>
<td>5910</td>
<td>14.13</td>
</tr>
<tr>
<td>Artificial habitats</td>
<td>279.25</td>
<td>0.64</td>
<td>0.23</td>
<td>43</td>
<td>11.20</td>
</tr>
<tr>
<td><em>P. oceanica</em> seagrass association</td>
<td>83534.30</td>
<td>3771.84</td>
<td>4.52</td>
<td>262010</td>
<td>11.58</td>
</tr>
<tr>
<td><em>P. oceanica</em> dead matte association</td>
<td>5980.48</td>
<td>665.68</td>
<td>11.13</td>
<td>145397</td>
<td>36.40</td>
</tr>
<tr>
<td>Photophilous algae association</td>
<td>15339.39</td>
<td>149.72</td>
<td>0.98</td>
<td>10453</td>
<td>11.64</td>
</tr>
<tr>
<td>Offshore rocks</td>
<td>858.62</td>
<td>2.72</td>
<td>0.32</td>
<td>201</td>
<td>12.32</td>
</tr>
<tr>
<td>infralittoral shingle association</td>
<td>207.33</td>
<td>0.84</td>
<td>0.41</td>
<td>29</td>
<td>5.75</td>
</tr>
<tr>
<td><em>C. nodosa</em> seagrass</td>
<td>498.28</td>
<td>26.28</td>
<td>5.27</td>
<td>2942</td>
<td>18.66</td>
</tr>
<tr>
<td>Bathyal zone</td>
<td>121559.02</td>
<td>22.68</td>
<td>0.02</td>
<td>112</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>797151.26</strong></td>
<td><strong>15219.84</strong></td>
<td><strong>29.49</strong></td>
<td><strong>1581145</strong></td>
<td><strong>160.77</strong></td>
</tr>
</tbody>
</table>

A comparison with observation data allowed the estimation of the bias of the method (Figure 4). In total, 5572 vessels were observed by counting from the coast (Meinesz and Miranda, 2014) while 299 vessels were counted from AIS data at the same place and during the same period, i.e. a number 19 times lower. However, the number of large vessels (>50 m) observed was similar with the number of vessels counted from AIS data (Anova: F=0.34; P=0.56). The number of vessels estimated from AIS was also much lower than the number counted by aerial observation (Anova: F = 38.65; P<0.01).
Figure 4. Comparison between the number of anchored vessels estimated from AIS data and vessels counted from the coastline (Meinesz and Miranda, 2014) with a length estimation, and vessels counted from a plane (MEDOBS project, http://medtrix.fr). No length is given for vessels obtained from AIS data or from aerial observation. Data were recorded within the bay of Villefranche-sur-mer and the Cap Ferrat Natura 2000 area.

3. DISCUSSION

This paper presents, step by step, an effective methodology using AIS data to localise and quantify anchoring pressure in several ways (number of anchored vessels, anchoring impact areas, duration, intervals between anchoring) along a large coastline (1800 km). AIS produces good quality data for its cost; it allows an automatic pre-treatment and analysis of a large amount of quantitative and accurate data to estimate anchoring positions and impact areas. Contrary to the analysis of satellite imagery, there is no risk of false positives (Pieralice et al., 2014). Based on the present results, there are several possibilities of use: to estimate anchoring pressure from a temporal viewpoint, i.e., time of day, season, year (anchoring was higher during the night and summer) or a spatial viewpoint (several concentration areas were localised to the east of the study zone), and/or in investigating seabed habitats by coupling the results with a seabed habitat map. Anchoring density and time intervals between anchor deployments may also be coupled with the biological resilience of the habitats to better estimate the impact of anchoring pressure. Another huge advantage of our method is that it allows identification of boats, and thus the owners (and captains), origin harbours and frequently used harbours. This is useful information for coastline management as it gives an answer to the question of “where and when to act?”. It also provides information for awareness campaigns aimed at changing habits. This type of result might also help influence stakeholders in balancing the economic value brought by boating with the environmental cost. The abundant literature devoted to these questions confirms the interest of managers of marine protected areas (MPA) and coastline managers (Giakoumi et al., 2015; La Manna et al., 2015; Venturini et al., 2016).

However, there is a limitation to AIS, hindering its potential. AIS data only give access to around 1/20 of boat anchorings with a bias in favour of larger ones. These vessels represent a minority of the maritime transport and recreational vessels registered along this coastline (Direction générale des infrastructures, des transports et de la mer, 2015; Ministère de l’Ecologie, du Développement Durable et de l’Energie, 2013). For example in 2015, French Mediterranean coastline counted 404...
854 registered pleasure (motor and sailing) boats, most of them (86 %) were shorter than 8 m
(Direction générale des infrastructures, des transports et de la mer, 2015). However, we envisage
that use of AIS will increase and that increasing numbers of ships will be equipped with it in the
future, since it provides useful information to vessel captains. In the absence of a global regulation
requiring the use of AIS, the data will only be improved by the modernisation of vessels and the
goodwill of captains and owners. Large vessels (here high standing pleasure boats and commercial
vessels) represent the most important economic value but they also have the biggest anchors and
the longest chains and are thus able to produce the greatest damage to seabed habitats. For
example, a large (50 m) vessel anchored overnight on a coral reef caused rapid losses of coral and
reef structural complexity, equal to the cumulative decline over 23 years observed at an adjacent site
(Forrester et al., 2015). Another limit of this work is that it does not consider the type of anchor and
the resulting potential difference to the impact on the seabed (Milazzo et al., 2004). However, the
type of anchor and the location of small vessels not equipped with AIS could be provided in the
future by smartphone applications like the free DONIA® and Anchor Watch® smartphone applications
or others that are provided for a payment like Navionics®.

Finally, this present work provides important data for seabed habitat conservation. One-third of the
coastal seabed (0 to -80 m) is used for anchoring by big vessels, with more than 80 % of these impact
areas distributed among four small zones in the east. Three of these zones contain tourist activities
while the last zone (Fos-sur-mer) contains commercial boats waiting to unload. Despite this localised
intense “parking” use, no regulations or mooring equipment do exist within these areas. However,
this is beginning to change with, for example, a lighted buoyed mooring area project near St Tropez
(Commune de Ramatuelle, 2016) and the new prefectoral decree N°155/2016 that controls the
mooring of vessels longer than 45 m in French inshore and territorial waters (Préfecture maritime de Méditerranée, 2016). The latter falls within three European Framework directives (Marine Strategy
the “Habitats” directive (92/43/CEE)) aimed at preserving habitats and species of community
interest, including P. oceanica. Our results show that P. oceanica seagrass beds are the most
impacted habitat in terms of duration (36.40 hours of anchoring/ha/year) and also one of the three
most impacted habitats in terms of area proportional to their seabed cover (4.52 %). Seagrass beds
are, proportional to their presence, the most impacted habitat: around 10 % of impacted areas
consisted of living seagrass beds and around 11 % consisted of dead seagrass beds (dead matte). The
impact of anchoring on seagrass beds has already been highlighted by less accurate global analysis of
aerial images (Florian Holon et al., 2015). This highly fragile habitat has been greatly studied for its
sensitivity to anchoring pressure (Boudouresque et al., 2012; Francour et al., 1999; Milazzo et al.,
2004; Montefalcone et al., 2008) and the consequences of anchors and anchoring chain systems
during boat drift means dead matte lines and ‘furrows’ are visible underwater by sonar and aerial
views (Abadie et al., 2016, 2015; Holon et al., 2015). Our study shows that a grid cell (400 m²)
receives an anchor deployment every 56 days on average and 370 consecutive days was the maximal
period free from anchoring. These are minimal values as small vessels are largely underestimated
and generally anchored at shallower depths than large vessels. This is insufficient to permit a habitat
to recover, especially in the case of P. oceanica meadow (a protected habitat and plant) whose
average horizontal progression is no more than 3-4 cm per year (Boudouresque et al., 2012). For
example, meadows destroyed during the second world war are still not completely recolonised 80
years later (Holon et al., 2015). This sensitive habitat faces other stressors (e.g., climate change and
pollution from waste waters) and how synergistic, antagonistic or additive the combined effects of
these stressors are remains undetermined. In the meantime, it is important to improve human
behaviours as this study shows that large boats still anchor within highly sensitive habitats, despite
equipment that could help them to avoid these areas. The problem could be that captains either do
not know which seabed habitat they occupy during the mooring and that seabed habitats are not
similarly sensitive (and that some of them are even protected), or are uninterested in seabed habitat
sensitivity (Balaguer et al., 2011; Lloret et al., 2008) because they do not risk anything if they damage
a protected habitat by using their anchor. Enhancing the broadcast of seabed habitat maps to sea users (see a first initiative through the free DONIA® application) and well-adjusted awareness campaigns could help to improve these points. Even if it is not their aim, AIS data may help to detect and identify, at the time or afterward, vessels that do not respect the law and damage protected habitats. These vessels could be targeted for education actions.

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References


