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The impact of 85 years of coastal development on shallow seagrass beds (*Posidonia oceanica* L. (Delile)) in South Eastern France: A slow but steady loss without recovery

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ABSTRACT

Shallow *Posidonia oceanica* beds (0 to −15 m), the most common seagrass in the Mediterranean, were mapped from aerial photographs dating from the 1920's and from 2012 along 800 km of coastline in South-Eastern France (Provence-Alpes-Côte-d'Azur region). Changes in *P. oceanica* bed spatial distribution (limits and extent) during these 85 years were analyzed in terms of concordance (remaining areas), positive discordance (expanding areas) or negative discordance (lost areas). Lost areas were linked with direct or indirect impacts of coastal development (artificialized coastlines (namely harbours, ports of refuge, landfills, artificial beaches, groynes and pontoons, submarine pipelines and aquatic farms) visible on the photographs. The comparison showed that 73% of the shallow limits have declined. Considering spatial extent, remaining seagrass meadows areas accounted for the major part (85%), while lost areas accounted for 13% and expanding areas for 1.1%. Lost areas were mainly linked with artificial coastlines but 44% remained with undetermined causes (invisible pressures and/or mixed effects). The analysis of 96 coastal facilities creating the artificial (namely man-made) coastlines showed that the highest impact over the longest distance (5 km) was caused by harbours. Only artificial beaches had such a distant impact. Pontoons were the least surrounded by lost seagrass meadows areas. These quantitative data offer important information for marine conservation.

1. Introduction

With more than seven billion people on Earth (United States Census Bureau, 2014), human activities have global impacts on all oceans and seas (Jackson et al., 2001; Stachowitsch, 2003; Halpern et al., 2008). Coastal areas and coastal ecosystems are particularly affected as they concentrate rich marine biodiversity, an important human population and a wide range of human uses (Halpern et al., 2008). Population densities in coastal regions are now about three times higher than the average elsewhere, and the last 70 years with the industrial revolution and the population explosion were particularly demanding: rapid urban development, construction of new seaside resorts, marinas and extensions of existing ports (Small and Nicholls, 2003). However, marine ecosystems provide important and valuable goods and benefits (i.e. contributions that humans derive or create from ecosystem services (Millennium Ecosystem Assessment MEA, 2005; Haines-Young and Potschin, 2013)). For example, more than half of the total value of the world natural capital and services are considered to be related to a single marine ecosystem: seagrass beds (Costanza et al., 1997). In this context, marine conservation science needs to assess and understand the impacts of society on marine habitats in order to protect them. Approaches based on expert opinion (Halpern et al., 2007, 2008; Claudet and Fraschetti, 2010; Parravicini et al., 2012) are often used as a proxy for real impacts on habitats, but they are not as significant as quantitative assessments, and the critical lack of empirical knowledge about marine systems impedes the implementation of effective conservation measures (Claudet and Fraschetti, 2010). The knowledge of historical reference points

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(the state of conservation of marine ecosystems prior to large-scale human impacts), and observation of the consequences of past pressures on their current state remains the best approach to reducing human impacts and moving along a sustainable development path, but we are lacking this knowledge (Underwood, 1992; Pauly, 1995; Micheli et al., 2013).

Seagrasses are often considered as biological sentinels because any change in their distribution (e.g. a reduction in the maximum depth limit or a loss of covered areas) implies an environmental change (Orth et al., 2006). *Posidonia oceanica* L. (Delile) is the most common seagrass species in the Mediterranean Sea (Boudouresque et al., 2012). It forms extensive meadows from the surface to 30–40 m depth (depending on water transparency and temperature). Over time, this long-lived plant builds up a set of rhizomes and roots which interstices are filled in by sediment; this structure is called 'matte' (Boudouresque et al., 2012). The plant can reproduce both sexually and asexually but its growth is very slow (a few cm per year). After the death of the plant, the deterioration of rhizomes is very slow, leading to a dead matte that may persist for millennia (Boudouresque et al., 2012). Because of the important ecological (nursery, spawning, feeding, oxygenation) and economic roles (coastal protection and sediment trapping) (Borum et al., 2004; Boudouresque et al., 2012), *P. oceanica* is protected by EU legislation (Habitats directive), the Bern and Barcelona Conventions, national legislation and is classified Least Concern on the IUCN Red List (Pergent et al., 2010).

As with numerous seagrass species (Short and Wyllie-Echeverria, 1996; Spalding et al., 2003; Waycott et al., 2009; Selig et al., 2014), *Posidonia oceanica* meadows have known a widespread decline over the last decades (Boudouresque et al., 2009); a decline characterized by a decrease of shallow seagrass beds and/or by a reduction of the deeper limits and thus a loss of spatial extent. Ten percent is the global decline (loss of area) generally accepted for *P. oceanica* over the last 100 years (Boudouresque et al., 2012) but a recent paper claims a reduction by 50% of the density or biomass within the Mediterranean over the last 20 years (Marbà et al., 2014a). Actually, the magnitude of the overall *P. oceanica* area loss over the last century ranges from 0 to 50 % depending on the author (González-Correa et al., 2007; Boudouresque et al., 2009; Bonacorsi et al., 2013) but could reach 8% per year with possible functional extinction in 2059 according to others (Marbà et al., 1996; Jordà et al., 2012). The reality is difficult to assess because of a lack of reliable baseline data: quasi-absence of historical data, studies often only focusing on small spatial and temporal scales and/or using uncertain old maps (Montefalcone et al., 2013; Bonacorsi et al., 2013). These observed declines are mainly located near urban areas (Thomas et al., 2005; Boudouresque et al., 2012) and mostly associated with human activities even if they can sometimes be related to natural processes (e.g. colonization and erosion dynamics, climate change, sea level change, weather events, exceptional tectonic events or diseases) (Duarte, 2002; Boudouresque et al., 2009; Pergent et al., 2014; Tuya et al., 2014). A recent review of the literature showed that the *P. oceanica* decline is attributed to human physical impacts by two thirds (67.6%) of the studies (Marbà et al., 2014b). Main declines of *P. oceanica* meadows are related to coastline engineering (Ruiz and Romero, 2003; Boudouresque et al., 2012; Roca et al., 2014), aquaculture (Pergent-Martini et al., 2006; Holmer et al., 2008; Rountos et al., 2012), solid and liquid waste (Morena et al., 2001; Pergent-Martini et al., 2002; Boudouresque et al., 2012), pleasure boats and cruise tourism (Montefalcone et al., 2006; Okudan et al., 2011; Boudouresque et al., 2012) and to the introduction of exotic species (Boudouresque et al., 2012; Marbà et al., 2014a). However, the relative quantitative influence of each of these causes on the overall decline remains unknown.

The present work estimates the changes that the shallowest part of *Posidonia oceanica* meadows have undergone in connection with coastal human activities over a large spatial (800 km) and temporal (85 years) scale. The objectives are thus: a) to assess old and present *P. oceanica* meadows (limits and spatial extent) using a unique methodology, b) to link the loss observed with human activities in order to estimate their direct and indirect impacts on the meadows, and c) to quantify the spatial scale of the impacts on adjacent seagrass meadows. Considering the available literature and the plant characteristics (slow growth, long-term persistence, high sensitivity) we expect to observe a decline of a large part of the shallow limits (an average loss of 10% of the initial area is expected) mostly located near urban areas, but also to highlight an overall stability of the meadows general spatial extent and small expanded areas.

2. Materials and methods

2.1. Study area

This study is of 800 km of the coastline of Provence-Alpes-Côte-D'Azur (PACA), the French Mediterranean region where the highest reclamation area from the sea was observed between 1920 (1643.19 ha) and 2010 (3945.56 ha) (MEDAM, 2014). The man-made (artificial) coastline went from 45.10 km in 1920 (mainly harbours) to 156.39 km (=19.05%, mainly harbours, landfills, artificial beaches and ports of refuge) in 2010 (MEDAM, 2014). This region regroups three French departments (Bouches du Rhône, Var and Alpes Maritimes) and represents 26 coastal water bodies, namely geographical units of homogeneous waters according to the Water Framework Directive (WFD,2000/60/EC).

2.2. Photographs used

This study used several geo-referenced mosaics of historical aerial photographs (1922, 1924, 1927 and 1944, depending on the area) made available by the 'Région Provence-Alpes-Côte d'Azur © SHOM, IFREMER et Photothèque nationale (2008)' consortium. Only one picture (the oldest one) was kept per place with the following proportions: 6% of the study area was based on photographsdating from 1922, 53% from 1924, 34% from 1927 to 7% from 1944 (Fig. 1). All of these photographs were there after called 'old pictures' without distinction in order to simplify the message. They were provided after undergoing geometric corrections allowing to eliminate image distortions with BD-ORTHO® ©IGN. Present aerial geo-referenced photographs were mostly (94%) taken in 2012 (IGN, 'Ortho Littorale V2 – MEDDE'). Four year older photographs (2008) were used when those taken in 2012 were not usable. Thus, according to the areas involved, this study considered a mean time frame of 85 years and a median time frame of 68 years. Photographs were exported with a 5 × 5 km grid into a CAD software at 1/20 000 with a 1000 dpi resolution. They were then processed for quality improvement: colors, contrast, sharpness and noise filtration.

2.3. *Posidonia oceanica* meadow charts

Aerial photographs generally permit a mapping of *Posidonia oceanica* distribution up to 20 m depth (Pasqualini et al., 1998). Shallow seagrass beds (0 to −15 m) of *P. oceanica* were mapped from old and present aerial photographs along the PACA coastline (Fig. 2). The present coastline geographical information was provided by IGN and SHOM; it was modified according to the old aerial pictures in order to draw the old coastline. The deep delimitation was based on the SHOM −15 m isobath improved by fine-scale bathymetric data obtained from a multi-beam echosounder

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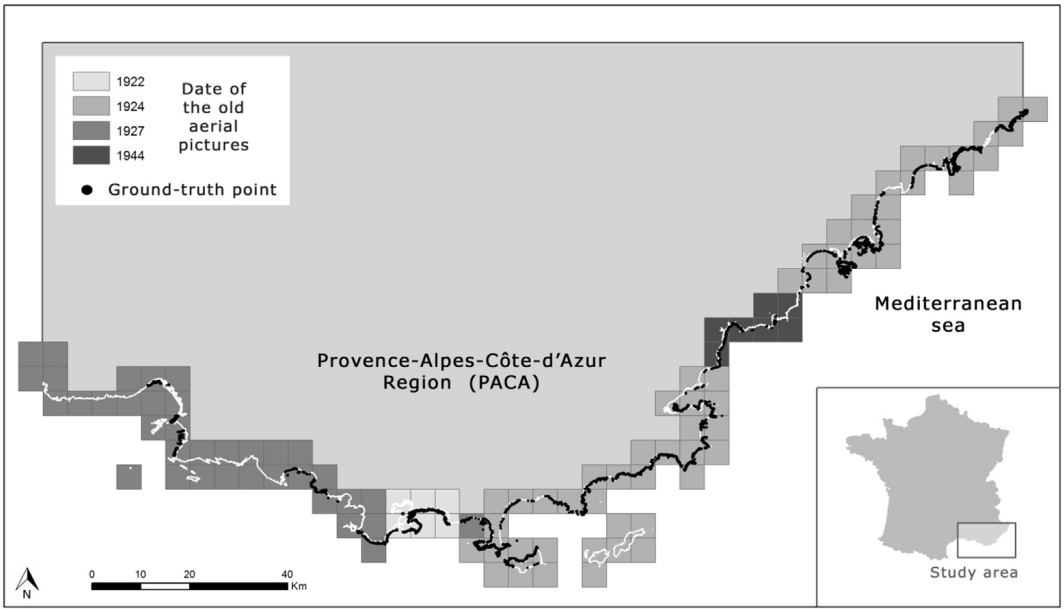

Fig. 1. Location of the old pictures and of the ground-truth points (observations from a rubber dinghy with an aquascope, one-off scuba dives and transect dives) used to map *P. oceanica* beds along the Southern-East (Provence-Alpes-Côtes-d'Azur region) coastline (in white) at a 0 to −15 m depth.

(Andromède Océanologie, 2013). Seagrass meadows were interpreted from sudden changes in hue and lightness in a semi-automatic way. At a 1:5000 scale, the image was automatically segmented and the technician validated every single segment of seagrass patch within polygons. Additional polygons were sometimes manually delineated when they were visible but not recognized by the segmentation tool. The more or less good quality of photographs (objects, paper defaults, bad digitalization of silver

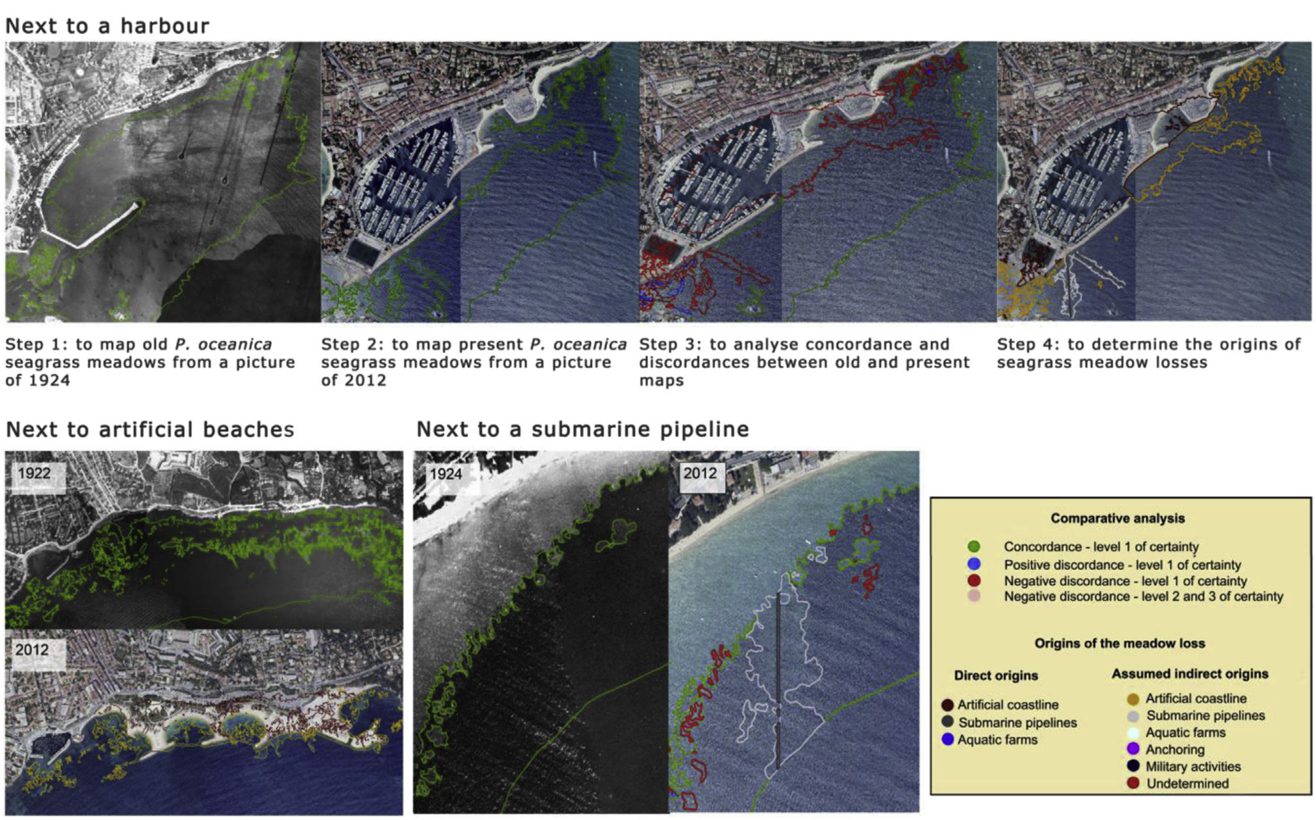

Fig. 2. Three examples are taken in order to illustrate the methodology. Old and present aerial photographs were used to map old and present *P. oceanica* seagrass beds (steps 1 and 2), then the two maps were compared and analyzed in terms of concordances and discordances (step 3) and finally the negative discordances were attributed to the coastal settlements (step 4). Three levels of certainty were defined in order to qualify our confidence in the interpretation of the old pictures. Level 1 of certainty qualified seagrass beds with distinct contours, growing on identified substrates. Level 2 qualified areas with a more difficult but reliable interpretation (water turbidity, swell, shadows) resolved thanks to the lab technician's experience of the area and the help of external data. Level 3 concerned subjective interpretations and/or an absence of data. Only the most reliable maps (level 1 of certainty) were used to analyze direct and indirect origins of lost meadows (areas in negative discordance).

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shots) and of the shooting conditions (reflections, luminosity, waves, silver shot quality) makes the photographs more or less suitable for use. Three levels of certainty were thus defined in order to qualify our confidence in the interpretation of the old photographs. Level 1 of certainty qualified seagrass beds with distinct contours, growing on identified substrates. Level 2 qualified areas with a more difficult but still reliable interpretation (water turbidity, swell, shadows) solved because of the technician experience of the area and the help of external data. Level 3 concerned subjective interpretations and/or an absence of data. Ground truth points (observations from a rubber dinghy with an aquascope, one-off scuba dives and transect dives) were performed between 0 and −15 m at 3861 points of questionable interpretation identified on the present pictures (Fig. 1).

2.4. Comparative analysis and origins of meadow loss

Comparative maps were obtained after superposition of the layers containing the old and present *Posidonia oceanica* beds distributions using a CAD software (Fig. 2). They were then given vectors within the GIS software. Polygons were automatically drawn from the raster (image) representing *P. oceanica* meadows. Changes between old and present sub-marine meadows were analyzed in terms of concordance (remaining areas), positive discordance (expanding areas) and negative discordance (lost areas). The proportion of declining shallow limits (in length) was estimated from the projection on the coastline of the negative discordant areas. Only meadows drawn with a level 1 of certainty were considered for these calculations. According to the working scale used (1:15 000, see above), we estimate that we were able to detect a 5 m minimum difference between old and present pictures/maps.

Where negative discordances (loss in spatial extent) were observed, the comparison of old and present pictures also allowed us to draw three types of coastal developments directly or indirectly impacting seagrass beds: artificialized coastlines (namely harbours, ports of refuge, landfills, artificial beaches, groynes and pontoons), submarine pipelines and aquatic farms. These types of developments were chosen according to MEDAM (2014). Their direct influence on the loss of *Posidonia oceanica* meadow areas (level 1 of certainty) was acknowledged when former meadows have been physically replaced by these developments. Indirect impacts were assumed when losses were observed around these developments. We also considered the effects of anchoring and military activities when they were obvious (visible trails and bomb impacts on the meadows). As the responsible factors (boats, bombs …) were not observed on the pictures, no difference was made between direct and indirect impacts for those. The remaining losses, for which the origin could not have been determined, were classified as 'undetermined origin.

2.5. Impact distances

The impact magnitude of all different types of coastline settlements (harbours, ports of refuge, landfills, artificial beaches, groynes and pontoons) that caused losses (level 1 of certainty) were analyzed. The area (in m^2;) of every settlement of each type was calculated and the total (direct + indirect) area of meadow loss was estimated within a 200 m, 500 m, 1000 m, 2000 m, 5000 m and 10 000 m radius from them. The magnitude of the impact (area of meadows destroyed for 1 m^2; built) was calculated as the ratio between the seagrass loss area and the settlement area within each radius. The maximal distance of impact was the distance from the impacting source where the increment of accumulated seagrass loss with increasing distance was equal to zero. Only settlements that were clearly identifiable owing to their remoteness were considered in order to avoid mixed effects. In the case of big principal buildings that necessitated other secondary constructions (harbour/landfills for example), the loss was assumed to be due to the principal building.

3. Results

The 1920's *Posidonia oceanica* beds area along the coastline, between 0 and 15 m depth, was over 14 528.3 ha (considering the three levels of uncertainty). Around 36% of this mapped area was dependent on the technician subjectivity (level 3 of certainty) because of the poor quality of data. Present pictures revealed 13 111.8 ha of seagrass meadows (Table 1). Former meadows represented 14 528.3 ha among which 7696.8 ha corresponded to level 1 of certainty; these 7696.8 ha were entirely covered by the present map. All the following results were based on data qualified by level 1 of certainty; it represented 53% of the study site. The general map (with several zooms in order to make the visualization easier) used to obtain the quantitative data is presented in Fig. 3. The high resolution entire map may be freely (with login) consulted online on www.medtrix.fr within the SURFSTAT project.

The comparison between old and recent maps showed that 73% of the shallow seagrass limits have declined. *Posidonia oceanica* spatial extent were essentially concordant: 6583.7 ha remained at the exact same place after 85 years, thus the 85.5% of remaining areas (Table 1). The Var French department presented the highest part of remaining areas (92%) compared to Alpes-Maritimes (73%) and Bouches-du-Rhône (70%) (Fig. 4). Positive discordance was poor with only 83.2 ha (1%): this represents on average an expanding of 0.97 ha per year. This expanding occurred through small patches here and there, mostly in place of old bomb impacts or other past damages. In contrast, negative discordance accounted for 1029.9 ha (13.4%); this represents a loss of 12.1 ha per year or 332 ^{2}; per day (Table 1). The loss was the highest in the Bouches-du-Rhône French department (29%) mainly around major cities. In the Alpes-Maritimes, the loss essentially occurred around Cannes, Cagnes-sur-mer and Nice. In the Var French department, the spatial loss was concentrated around Toulon, Sainte Maxime and Fréjus (Fig. 4).

The coastal facilities (physical holdings) under consideration were clearly linked to 55.5% of the spatial loss. The meadow loss mainly corresponded to artificial (man-made) coastlines (48.7%), with a weak disequilibrium in favor of indirect impacts (i.e. due to changes in water quality, turbidity or currents (hyper-sedimentation or erosion) during and/or after the installation) compared to direct ones (Table 1). The principal causes were harbours (83.8%) and artificial beaches (10.3%) (Fig. 5). The second most important identified origin of loss were submarine pipelines (4.8%). Other identified activities i.e. aquatic farms, military activities and anchoring represented less than 1%, respectively 0.9, 0.7 and 0.3%. After the analysis, 44.5% of the losses remained undetermined (Table 1).

In total, 96 settlements were analyzed in the light of their impact distances on seagrass meadows: 5 groynes, 6 pontoons, 9 artificial beaches, 13 landfills, 21 ports of refuge and 42 harbours (Fig. 6). No meadow loss could be clearly linked to a given settlement beyond 5 km. The highest impact at the longest distance from its point of origin was caused by harbours: 2.9 ^{2};± 5.2 destroyed for 1 m^2; built at 5 km, the high variability being linked to the harbour size. Only artificial beaches presented such a distant impact (5 km) but with a lower strength (0.7 ^{2}; ± 0.7 destroyed for 1 m^2; built). Meadow losses caused by ports of refuge and landfills were visible on a shorter distance: respectively 2.2 m^2; destroyed at 1 km and 2.3 m^2; at 500 m. Groynes presented the shortest impact: 200 m (0.6 m^2;). Pontoons were the least surrounded by areas of lost

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Table 1
Synthesis of seagrass beds mapped from present and old pictures. Three levels of certainty were defined in order to qualify our confidence in the interpretation of the old pictures. Level 1 of certainty qualified seagrass beds with distinct contours, growing on identified substrates. Level 2 qualified areas with a more difficult but reliable interpretation (water turbidity, swell, shadows) solved thanks to the lab technician experience of the area and the help of external data. Level 3 concerned subjective interpretations and/or an absence of data. The comparison between old and present seagrass spatial extent was based only on very reliable data (level 1 of certainty). Changes between old and present meadows were analyzed in terms of concordance (remaining areas), positive discordance (expanded areas) and negative discordance (lost areas). The assumed direct (physical replacement) or indirect (nearby coastal settlements) origins of negative discordances are indicated. All data are presented in terms of areas (ha) and percents (%).

		Area (ha)	Percent (%)
	Total - Present meadows	13 111.8	
	Total – Old meadows	14 528.3	
	Level 3 of certainty	5 216.6	35.9
	Level 2 of certainty	1 614.9	11.1
	Level 1 of certainty	7 696.8	53.0
Comparison between old and present meadows	Concordance	6 583.7	85.5
	Positive discordance	83.2	1.0
	Negative discordance	1 029.9	13.4
Origins of negative discordances	Man-made coastline - direct	220.8	21.4
	Man-made coastline - indirect	281.2	27.3
	Submarine pipeline - direct	3.9	0.4
	Submarine pipeline- indirect	45.8	4.4
	Aquatic farms - direct	9.6	0.9
	Military activities	7.2	0.7
	Anchoring	2.7	0.3
	Undetermined	458.7	44.5

meadows: 0.3 m^2; at 200 m and 0.5 m^2; at 500 m, the maximal distance of impact.

4. Discussion

4.1. *Posidonia oceanica* meadows: declining limits and lost areas

As expected, *Posidonia oceanica* seagrass beds have disappeared through a regression of their limits. Most of *P. oceanica* shallow limits (73%) have declined over the last 85 years. With a loss of 13.4% of the initial (1920's) meadow areas, this study confirms the overall loss (between 13 and 38%) recently estimated by Marbà et al. (2014b) and the 10% generally assumed (see the introduction). Unfortunately, these values mostly concern the North Western Mediterranean while a lack of data regarding the Eastern and Southern Mediterranean makes it difficult to generalize to the entire basin.

Coastal settlements that we considered to explain this spatial loss represent 55.5%. At the same time, the cause of 44.3% of lost meadow areas remains undetermined meaning that a) either no obvious single pressure (role of varied pressures), or b) no visible pressure (invisible pressures or pressures considered to be not visible) could be observed next to these losses. a) Numerous regions locally concentrate varied pressures such as coastal-based impacts, ocean-based pollution and maritime activities (Halpern et al., 2008; Coll et al., 2011). Marbà et al. attributed 39% of seagrass loss to more than one single pressure (Marbà et al., 2014b). Undetermined losses could thus be due to a mix of close visible factors. b) Invisible and factors that were not considered are: former settlements not visible on pictures anymore, hardly identified activities like anchorage, private swimming pool and rainwater discharges, but also changes in water characteristics (turbidity and sediment in deficit or in excess, salinity, temperature, chemical substances, pollution; see introduction) due to wastewater discharges, soil leaching, and rivers. Marbà et al. (2014a,b) showed for example that 30% of the meadows are impacted by water eutrophication. Almost 98% of the contaminants found in the French part of the Mediterranean sea come from the rivers (the Rhône river alone is responsible for almost 75% of them) (DIRM Méditerranée 2013) and 80% of urban sewage discharged into the Mediterranean is not treated. At a global level, 80% of the pollution of the marine environment comes from the land, the most important source being ‘non point-source pollution’, which occurs as a result of runoff (septic tanks, cars, trucks, boats, farms, ranches, and forest areas) (WWF, 2014). The presence of exotic invasive macrophytes may also be counted as invisible factors (not visible on the maps). Exotic invasive species (in particular *Caulerpa* spp) are *a priori* not able to eliminate a healthy *Posidonia oceanica* meadow (but see *Lophocladia Lallemandii* impact on healthy meadows (Marbà et al., 2014a) and the meadows impacted by biological invasions (=2.4%, Marbà et al., 2014b)) but they can amplify the decline of stressed and degraded seagrass meadows that offer a favorable environment for their development (Boudouresque et al., 2009). Finally, the observed loss of seagrass may also be due to global warming (higher water temperatures and rise in sea level). Indeed, *P. oceanica* is sensitive to high sea surface temperatures in summer (Mayot et al., 2005; Celebi et al., 2006; Marbà and Duarte, 2010; Pergent et al., 2014). Shallow water (0–80 m depth) warming in particular at −20 m (+1.4 °C for the Spanish Catalan coast for example) was demonstrated for over last 30 years along the NW Mediterranean basin coasts (Prieur, 2002; Salat and Pascual, 2002; Vargas-Yáñez et al., 2008; Boudouresque et al., 2009; Pergent et al., 2014) and especially after 2000 (Marbà and Duarte, 2010; Pergent et al., 2014).

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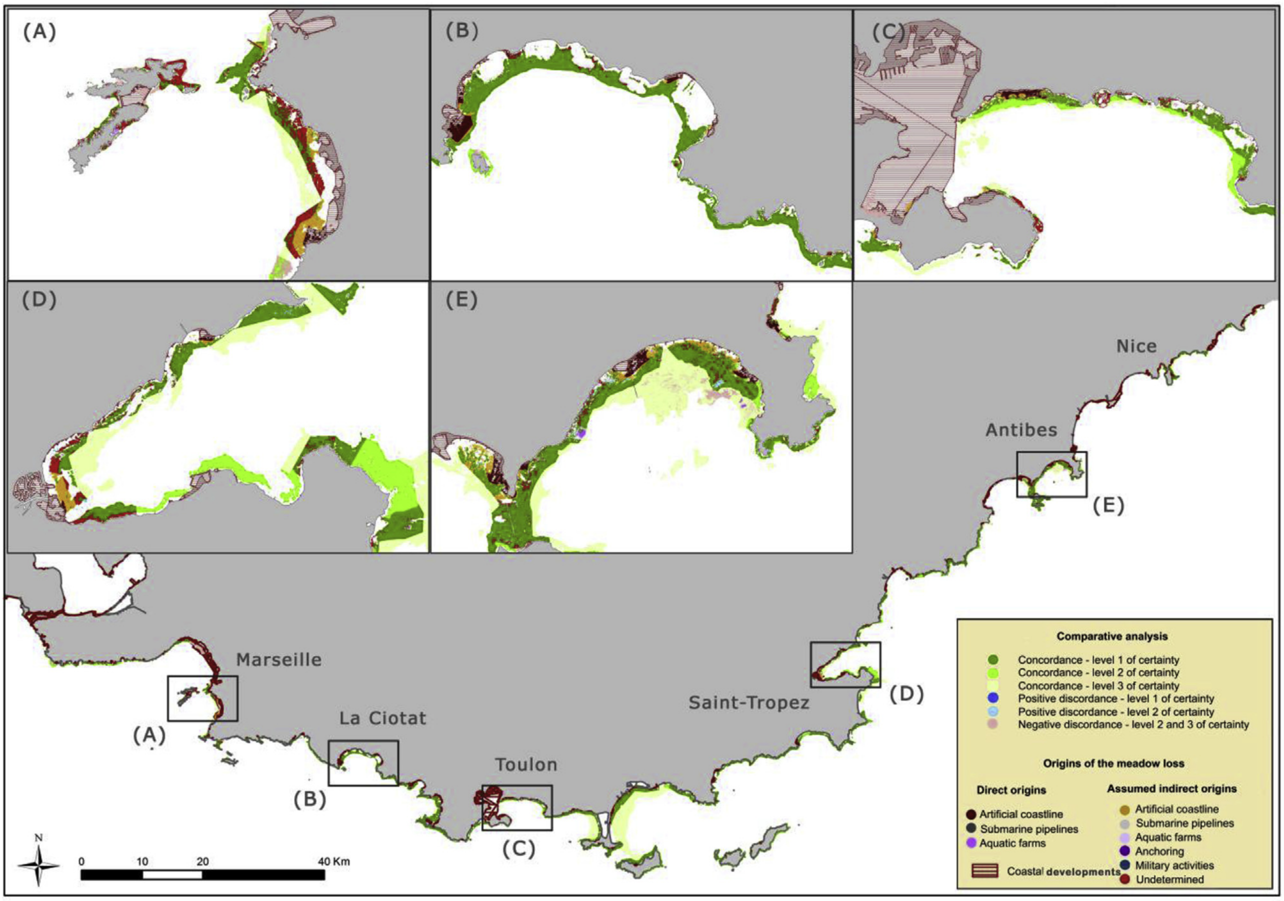

Fig. 3. Overall comparative map showing changes (concordance, positive discordance or negative discordance) in *Posidonia oceanica* meadows distribution over 85 years of coastal development. Five sites (A, B, C, D, E) are taken as examples in order to better visualize local data. Three levels of certainty were defined in order to qualify our confidence in the interpretation of the old pictures. Level 1 of certainty qualified seagrass beds with distinct contours, growing on identified substrates. Level 2 qualified areas with a more difficult but reliable interpretation (water turbidity, swell, shadows) solved by the technician experience of the area and the help of external data. Level 3 concerned subjective interpretations and/or an absence of data. Only the most reliable maps (level 1 of certainty) were used to analyze direct and indirect origins of lost meadows (areas in negative discordance). Coordinate system: RGF Lambert 93/IAG GRS 1980.

4.2. Relative influence of the different coastal engineering on seagrass meadows

Coastal engineering is involved in half of the seagrass losses. The most important loss occurred around the largest coastal cities, especially in line with man-made coastlines (mainly harbours and to a lesser extent artificial beaches). This means that without considering wastewaters (counted with the pipelines) major cities play an important part in *Posidonia oceanica* loss, mainly because of commercial, leisure and tourist activities. Man-made coastlines destroy areas a little more indirectly than directly according to previous local studies (Astier, 1984; Boudouresque et al., 2012). *P. oceanica* meadows were thus either buried by some coastal development or the related construction work, or died later because of the new conditions created close to a harbour (hydrodynamism, nutrient-epiphytes, grazers, siltation, pollution) (Ruiz and Romero, 2003). The ones that did not die generally present a reduced productivity and abundance (Ruiz and Romero, 2003). However, harbours are often old facilities thus their means of action are limited. Focus can be made on containing the potential extension of their indirect impacts, by monitoring the frequency, the water quality and the quality of the products used or inventing new ways of transportation (clean energy) and new ways of using ports. Even small settlements may have great impacts as for example pipelines directly involved in 4.8% of the losses, mostly indirectly. In contrast, the impact of anchoring is weak (0.3%) but might be underestimated for three reasons: a) it is hard to identify the impacts of anchoring on the meadows using only aerial pictures, b) the method consisted in matching the meadow loss around harbours first, implying artificial coastlines leaving little possibilities to anchor, and c) the impact of anchoring is far greater beyond 10 m depth where the matte is less compact, the meadow more sensitive and the anchor chain longer (Andromède Océanologie, 2014).

This thorough analysis of artificial coastlines helps to assess the relative impact of the different settlements on the meadow loss. Although no impact was detected beyond 5 km, most probably because of a doubtful detection (mixed effects) than an absence of impact, the present study shows that harbours are the most damaging man-made coastal developments (2.9 ± 5.2 m^2; destroyed for 1 m^2; built over 5 km). Only beaches present such a distant impact (5 km) but with a lower strength (0.7 m^2; ± 0.7 destroyed for 1 m^2; built). Compared to these values, the '500 m safety distance' generally used for seagrass meadows seems untenable (Pergent-Martini et al., 2006; Cabaço et al., 2008; Tuya et al., 2014). These data will be very useful for the modeling of anthropogenic pressure impacts and the prediction of the possible ecosystem services loss after construction works. For this protected plant which loss can hardly be compensated, the sequences 'avoid' and 'reduce' must be seriously taken into account. It is all the more important because estimating the real cost of these losses is hard. A

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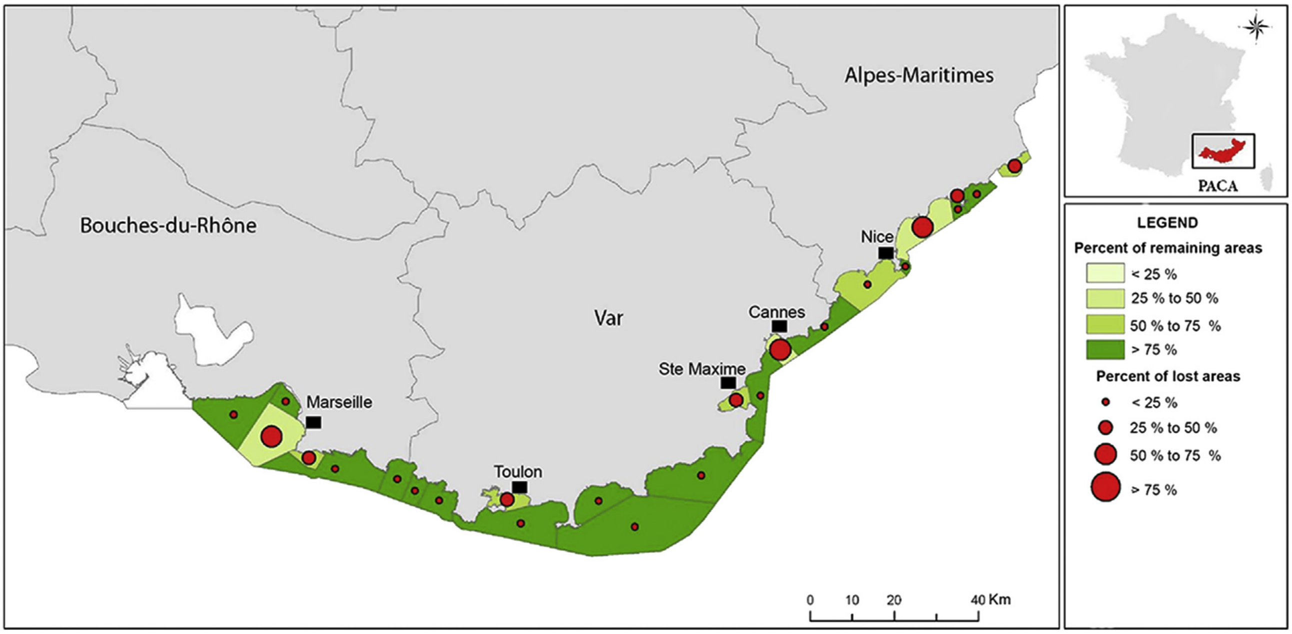

Fig. 4. Percentage of concordance and negative discordance between old and present mapped meadows, interpreted as remaining and lost areas of *Posidonia oceanica* meadows (between 0 and −15 m) observed per water body within the study site (PACA = Provence-Alpes-Côte-d'Azur region). Only maps with level 1 of certainty (=seagrass beds with distinct contours, growing on identified substrates) were used to define former meadows distribution. Coordinate system: RGF Lambert 93/IAG GRS 1980.

recent work has identified 25 ecosystem services provided by *Posidonia oceanica* meadows, among which eleven have been evaluated for their seven goods and benefits (Campagne et al., in press). The total value ranged between 283 and 513 € ha^{-1}/yr^{-1} which equates to 25.3 to 45.9 million € per year for the species. Under these conditions, a decline of 13% generalized to the entire Mediterranean (currently 3.5 million ha (Laffoley and Grimsditch, 2009)) would represent a minimal loss ranging between 128.7 and 233.4 € per year in the contribution to humans and their well-being. In addition to this annual economic loss, the destruction of *P. oceanica* represents a long-term decline in some ecosystem services usually provided, like the release of carbon, heavy metals and sediment sequestered until destruction in the matte.

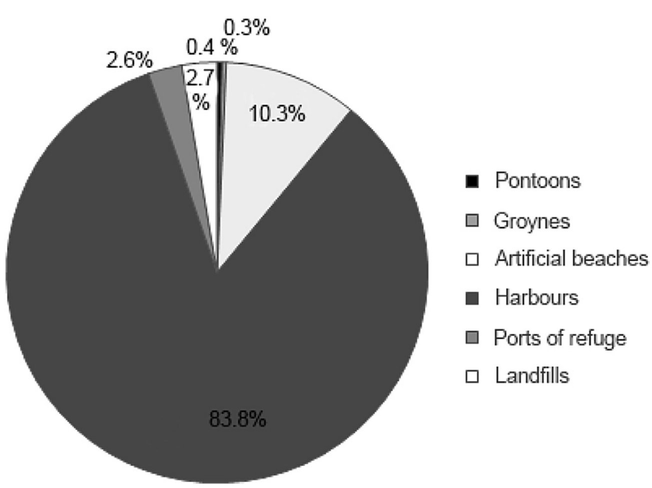

Fig. 5. Relative importance (in %) of the different types of man-made coastline developments responsible for the direct loss (in spatial extent) of *Posidonia oceanica* meadows (between 0 and −15 m) within the study site. Direct losses assessment was obtained from the comparison between old meadows mapped with level 1 of certainty (=seagrass beds with distinct contours, growing on identified substrates) and present meadows.

4.3. Large remaining seagrass spatial extent

Although most of the shallow limits have declined, remaining *Posidonia oceanica* meadows areas are predominant (85.5%), confirming the former long-term studies at smaller spatial scale (Pasqualini et al., 2001; Bonacorsi et al., 2013). Similarly, compiled published data analyzed by Marbà et al. (2014b) estimated the overall remaining areas ranging between 62 and 87% since 1960 within the Mediterranean. The restriction of the present work to shallow limits (0–15 m depth) generally presenting slower losses explains the highest proximity found with the maximal remaining value. Actually, while the shallowest depth limits generally go deeper according to an absolute rate of 0.04 ± 0.1 m yr^{-1}, the deepest limits decrease more than 10 times faster (0.61 ± 0.29 m yr^{-1}) (Marbà et al., 2014b). However, most of *P. oceanica* shallow limits have declined (73%) and this relative impression of stability considering the spatial extent must also be adjusted with three biases of the study. a) the methodology does not detect any change <5 m (work scale = 1:5000), b) only the shallow part of the meadow that is expected to decline slower than the deepest (see above) is considered, c) the value '85.5% of remaining areas' only considers extent in areas and does not take into account the shoot density within this area while the average loss in shoot density was recently estimated to 27.51 shoots m^{-2}; yr^{-1}(Marbà et al., 2014b).

The largest remaining areas were observed where the coastline is the least man-made and where changes in the coastlines had occurred previously to the beginning of the study and thus impacted the meadows a long time ago without any recolonization afterwards. This indicates that *Posidonia oceanica* meadows are little resistant and not resilient. Actually, ecosystem stability is generally defined by two dynamics: resistance, as the ability to with stand disturbance, and resilience, as the ability to recover from disturbance (Pimm, 1984). Seagrass meadows do not generally face important declines in sectors characterized by null or poor anthropogenic impacts (Boudouresque et al., 2009) and its relatively quick response to disturbance has been extensively demonstrated (Ruiz and Romero, 2003; Leoni et al., 2006), hence its use as

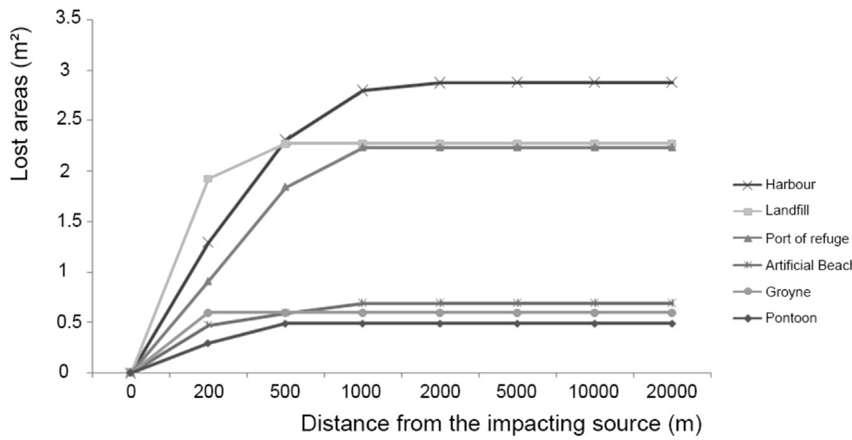

Fig. 6. Lost *Posidonia oceanica* areas (in m^2) according to the distance to different types of man-made coastline developments (96 facilities precisely) in m. Results are presented for 1 m^2 of each type of development.

a bio-indicator (see introduction). In addition, resilience of *P. oceanica* is largely recognized as almost null (Boudouresque et al., 2009, 2012; Pergent et al., 2014).

4.4. The quasi-null resilience of Posidonia oceanica meadows

Over 85 years, a very small expanded area has been observed: 0.9 ha yr^{-1}representing only 1%. This result was obtained from a large continuous area but a relatively small area compared to the estimated potential spatial extent of *Posidonia oceanica* in the Mediterranean (0.15% for 76.97 km^2; analyzed from 50 000 km^2; of covered coastal seafloor estimated in the past, (Bethoux and Copin-Montégut, 1986)). However, it confirmed the value (0.69 ha yr^{-1} = 1.31%) obtained from a pool of 519 small studies covering in the end an area only a little larger (1%) at the scale of the Mediterranean (Marbà et al., 2014b). This very weak progression and resilience is a characteristic of climax ecosystems. *P. oceanica* meadows are a climax ecosystem found on most Mediterranean subtidal bottoms (Boudouresque et al., 2012). Its clonal spread mode has allowed *P. oceanica* to maintain highly competitive clones over more than 100 000 years (it is the oldest living organism (Arnaud-Haond et al., 2012)), and to develop extensive monospecific meadows protected from native competitors and major predators (Hemminga and Duarte, 2000). However, 70 years old traces of bombs are still visible even in the middle of healthy growing meadows. The colonization of new areas and the recolonization of lost areas, via seeds, vegetative fragments or marginal spread of the meadow are extremely slow (horizontal growth is on average 1–6 cm/year (Marbà et al., 1996; Marbà and Duarte, 1998; Pergent-Martini and Pasqualini, 2000; Boudouresque et al., 2012)). Each loss being almost irreversible, this highlights the importance of combining all available means to prevent damage to the protected *P. oceanica* meadows.

5. Conclusions

This work is the first on *Posidonia oceanica* at such a large spatial and temporal scale in the Mediterranean Sea; the results obtained are thus important for stakeholders, managers and environmentalists. Notwithstanding large remaining areas, most shallow limits have declined and shallow *P. oceanica* meadows have lost 13.4% of their spatial extent, i.e. 332 m^2; per day over the last 85 years. Decline is noteworthy because once disappeared, recolonization is almost impossible. The influence of anthropogenic pressures is obvious especially on man-made coastlines. The quantitative impact of different types of costal settlements was highlighted but a large part of the loss remained undetermined. From now, it is a question of statistically testing the relative influence of each anthropogenic factor (including physical impacts and water eutrophication) but also of the environment of the undetermined losses. This will be done at a larger scale by considering the entire *P. oceanica* and dead matte distribution along the French coast. However, it is now also time to analyze human-driven impacts at a finer scale than the usual, namely a scale that would really allow designing management measures for marine key ecosystems. Indeed, an efficient conservation program relies on understanding the relationships between major threats and the ecological status of those ecosystems (Coll et al., 2011).

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