# 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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Original research paper submitted to **Estuarine coastal shelf science**

# 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 pictures 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* beds spatial distribution (limits and areal extents) 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 pictures. The comparison showed that 73 % of the shallow limits have declined. Considering areal extents, 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 artificialized coastlines but 44 % remained with undetermined causes (invisible pressures and/or mixed effects). The analysis of 96 coastal facilities participating to the artificialized (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.

Key words: seagrass meadows decline; consequences of urbanization; large-scale decrease of seagrass meadows; loss of marine meadows; human-driven impacts; anthropogenic pressures

## 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 seventy 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 human beings on marine habitats in order to protect them. Approaches based on expert's opinions (Halpern et al 2007; Halpern et al 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 (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 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 centimetres 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 (Habitat directive), the Bern and Barcelona Conventions, national legislation and is classified Least Concern on the IUCN Red List (Pergent et al 2010).

Like numerous seagrass species (Short and Wyllie-Echeverria 1996; Spalding et al 2003; Waycott et al 2009; Selig et al 2014), *P. 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 areal 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* are a loss over the last century that ranges from 0 to50 % 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 responsibility of *P. oceanica's* 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 consists in estimating the changes that the shallowest part of *P. 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 i) to make an assessment of old and present *P. oceanica* meadows (limits and areal extent) using a unique methodology, ii) to link the loss observed with human activities in order to estimate their direct and indirect impacts on the meadows and iii) to quantify the spatial scale of the impacts on adjacent seagrass meadows. Considering the available literature (see introduction above) 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 areal extent and small expanded areas.

## MATERIALS AND METHODS

### Study area

This study was led along 800 km of coastline. It represents 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 (artificialized) 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).

### Pictures used

This study used several geo-referenced mosaics of historical pictures (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 pictures dating from 1922, 53 % from 1924, 34 % from 1927 and 7 % from 1944 (Fig. 1). All of these pictures 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 pictures were mostly (94 %) taken in 2012 (IGN, "Ortho Littorale V2 – MEDDE"). Four year older pictures (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. Pictures were exported with a 5 x 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.

### *Posidonia oceanica* meadows charts

Aerial pictures generally permit a mapping of *P. oceanica's* 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 pictures along the PACA coastline (Fig. 2). The present coastline geographical informations were 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 (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 lab 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 pictures (objects, paper defaults, bad digitalization of silver shots) and of the shooting conditions (reflections, luminosity, waves, silver shot quality) makes the pictures 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 pictures. 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 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. 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 3 861 points of questionable interpretation identified on the present pictures (Fig. 1).

### Comparative analysis and origins of meadow loss

Comparative maps were obtained after superposition of the layers containing the old and present *P. oceanica* beds distributions using a CAD software (Fig. 2). They were then vectorized within a 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 areal extents) were observed, the comparison of old and present pictures also allowed 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 *P. 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".

### 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 m²) 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, 1 000 m, 2 000 m, 5 000 m and 10 000 m radius from them. The magnitude of the impact (area of meadows destroyed for 1 m² 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.

RESULTS

In the 1920's *P. 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 lab technician's subjectiveness (level 3 of certainty) because of the bad quality of data. Present pictures revealed 13 111.8 ha of seagrass meadows (Table 1). Former meadows represented 14 528.3 ha among which 7 696.8 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 Figure 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. *P. oceanica* areal extents 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. On the contrary, negative discordance accounted for 1029.9 ha (13.4 %); this represents a loss of 12.1 ha per year or 332 m² 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 areal 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 areal loss. The meadow loss mainly corresponded to artificialized (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 m²± 5.2 destroyed for 1 m² 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 m² ± 0.7 destroyed for 1 m² built). Meadow losses caused by ports of refuge and landfills were visible on a shorter distance: respectively 2.2 m² destroyed at 1 km and 2.3 m² at 500 m. Groynes presented the shortest impact: 200 m (0.6 m²). Pontoons were the least surrounded by areas of lost meadows: 0.3 m² at 200 m and 0.5 m² at 500 m, the maximal distance of impact.

## DISCUSSION

### *P. oceanica* meadows: declining limits and lost areas

As expected, *P. 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 areal loss represent 55.5 %. At the same time, the cause of 44.3 % of lost meadow areas remains undetermined meaning that i) either no obvious single pressure (role of varied pressures) ii) or no visible pressure (invisible pressures or pressures considered to be not visible) could be observed next to these losses. i) Numerous regions locally concentrate varied pressures like 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. ii) 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, rivers... Marbà et al (2014) 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 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 *P. 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 favourable 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).

### 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 harbors and to a lesser extent artificial beaches). This means that without considering wastewaters (counted with the pipelines) major cities play an important part in *P. oceanica's* loss, mainly because of commercial, leisure and touristic 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 means of action are limited. Focus can be made on containing the potential extension of their indirect impacts, by monitoring the frequentation, the water quality and the quality of the products used or inventing new ways of transportation (clean energy) and new ways of doing in ports. Even small settlements may have great impacts as for example pipelines directly involved in 4.8 % of the losses, mostly indirectly. On the contrary, the impact of anchoring is weak (0.3 %) but might be underestimated for three reasons: i) it is hard to identify the impacts of anchoring on the meadows using only aerial pictures, ii) the method consisted in matching the meadow loss around harbours first, implying artificialized coastlines leaving little possibilities to anchor and iii) 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 artificialized coastlines helps to assess the relative impact of the different settlements on the meadow loss. Although no impact was detected beyond 5 km, but 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 m² destroyed for 1 m² built over 5 km). Only beaches present such a distant impact (5 km) but with a lower strength (0.7 m² ± 0.7 destroyed for 1 m² built). Compared to these values, the “500 m safety distance” generally used for seagrass meadows seems ridiculous (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 recent work has identified 25 ecosystem services provided by *P. 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 (3.5 million ha for now (Laffoley and Grimsditch 2009)) would represent a minimal loss ranging between 128.7 and 233.4 € per year in the contribution to human beings 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.

Large remaining seagrass areal extents

Although most of the shallow limits have declined, remaining *P. oceanica* meadows areas are predominant (85.5 %), confirming there by former long-term studies led at smaller spatial scale (Pasqualini et al 2001; Bonacorsi et al 2013). Similarly, compiled published data analyzed by Marbà and her colleagues estimated the overall remaining areas ranging between 62 and 87 % since 1960 within the Mediterranean (Marbà et al 2014b). The restriction of the present work to shallow limits (0 to 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 areal extents must also be adjusted with three biases of the study. i) the methodology does not detect any change inferior to 5 m (work scale = 1:5 000), ii) only the shallow part of the meadow that is expected to decline slower than the deepest (see above) is considered, iii) the value “85.5 % of remaining areas” only considers extents 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 points out the fact that P*. 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 a bio-indicator (see introduction). Besides, resilience of *P. oceanica* is largely recognized as almost null (Boudouresque et al 2009; Boudouresque et al 2012; Pergent et al 2014).

The quasi-null resilience of *P. 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 areal extent of *P.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 to 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.

CONCLUSION

This work is the first on *P. oceanica* led at such a large spatial and temporal scale in Mediterranean Sea; the results obtained are thus important for stakeholders, managers and environmentalists. Not with standing large remaining areas, most shallow limits have declined and shallow *P. oceanica* meadows have lost 13.4 % of their areal extent, i.e. 332 $m^2$ every day over the last 85 years. Decline is note worthy because once disappeared, recolonization is almost impossible. The influence of anthropogenic pressures is obvious especially of 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).

ACKNOWLEDGEMENTS

The data used for this work were made available by the consortium « Région Provence-Alpes-Côte d'Azur © SHOM, IFREMER et Photothèque nationale (2008) »,IGN, ortho littoral V2« Ortho Littorale V2 – MEDDE », SHOM, and Oeil d'Andromède. We thank The French Water Agency (Agence de l'Eau Rhône Méditerranée Corse) for its support. Florian is a PhD student funded by LabEX CeMEB and Andromède Océanologie. Our work is catalogued by the ISEM Steering Committee as ISEM xxxx (http://www.isem.cnrs.fr)).We are grateful to two anonymous reviewers and the editor Mike Eliott for their conscientious work which has greatly helped to improve the manuscript. Many thanks to Benoit Jullian for his advices during the analysis and to Sibylle Cazacu who has corrected the English version of the manuscript.

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TABLES AND FIGURES

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's 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 areal extents 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 |

Figure 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.

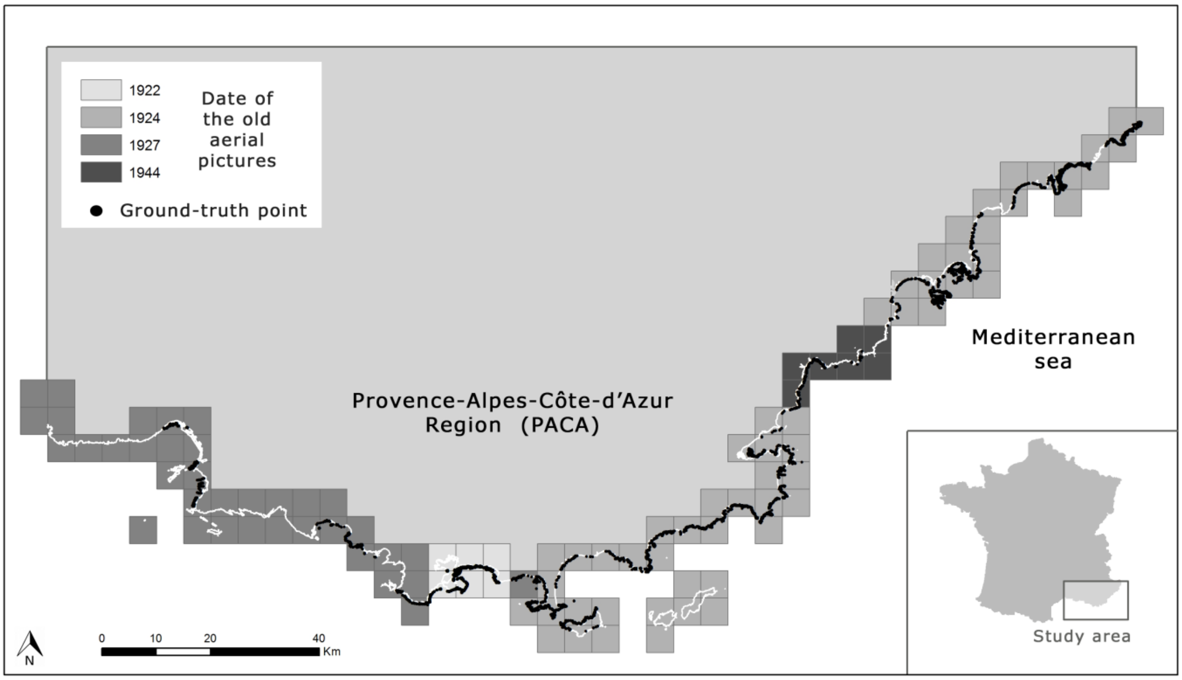

Figure 2. Three examples are taken in order to illustrate the methodology. Old and present aerial pictures were used to map old and present *P. oceanica* seagrass beds (steps 1 and 2), then the two maps were compared and analyzed in terms of concordances and discordances (step 3) and finally the negative 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).

Intended for color reproduction on the Web and in print

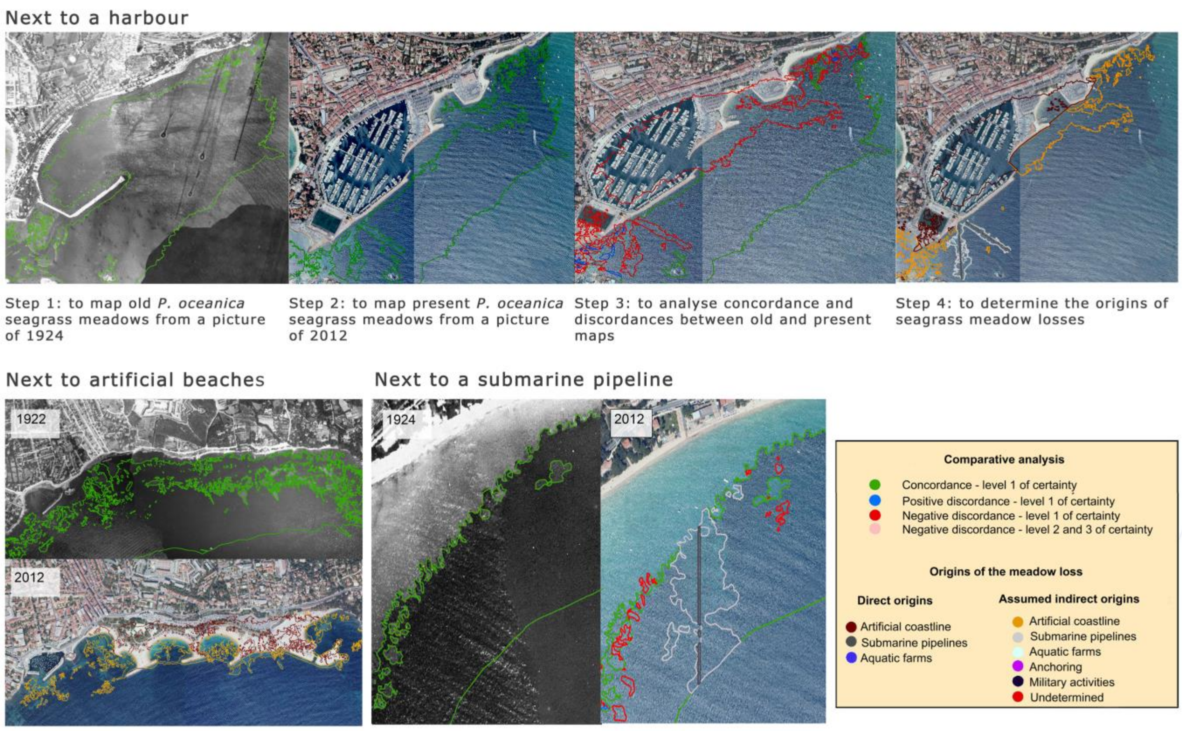

Figure 3. Overall comparative map showing changes (concordance, positive discordance or negative discordance) in *Posidonia oceanica* meadows distribution over 85 years of coastal development. Five sites (A, B, C, D, E) are taken as examples in order to better visualize local data. Three levels of certainty 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 thanks to the 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). Coordinate system: RGF Lambert 93 / IAG GRS 1980.

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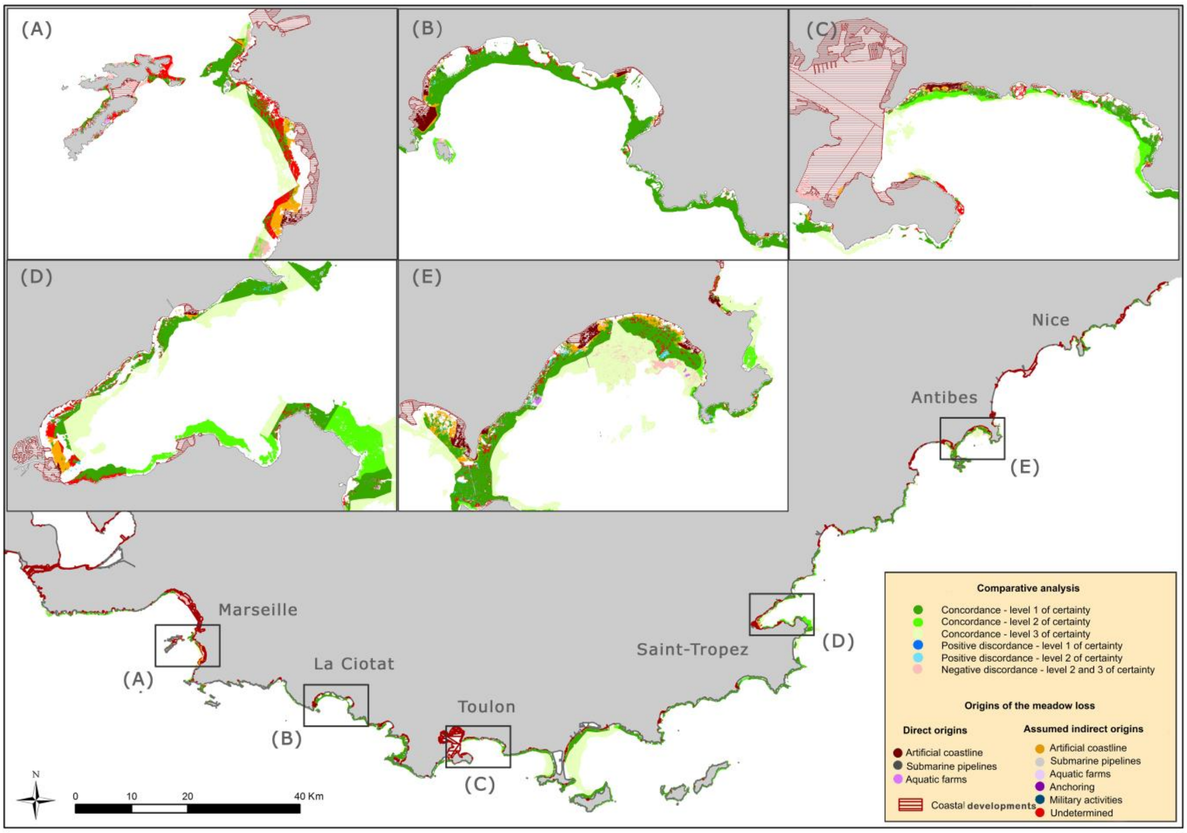

Figure 4. Percents of concordance and negative discordance between old and present mapped meadows, interpreted as remaining and lost areas of *Posidonia oceanica* meadows (between 0 and -15 m) observed per water body within the study site (PACA = Provence-Alpes-Côte-d'Azur region). Only maps with level 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.

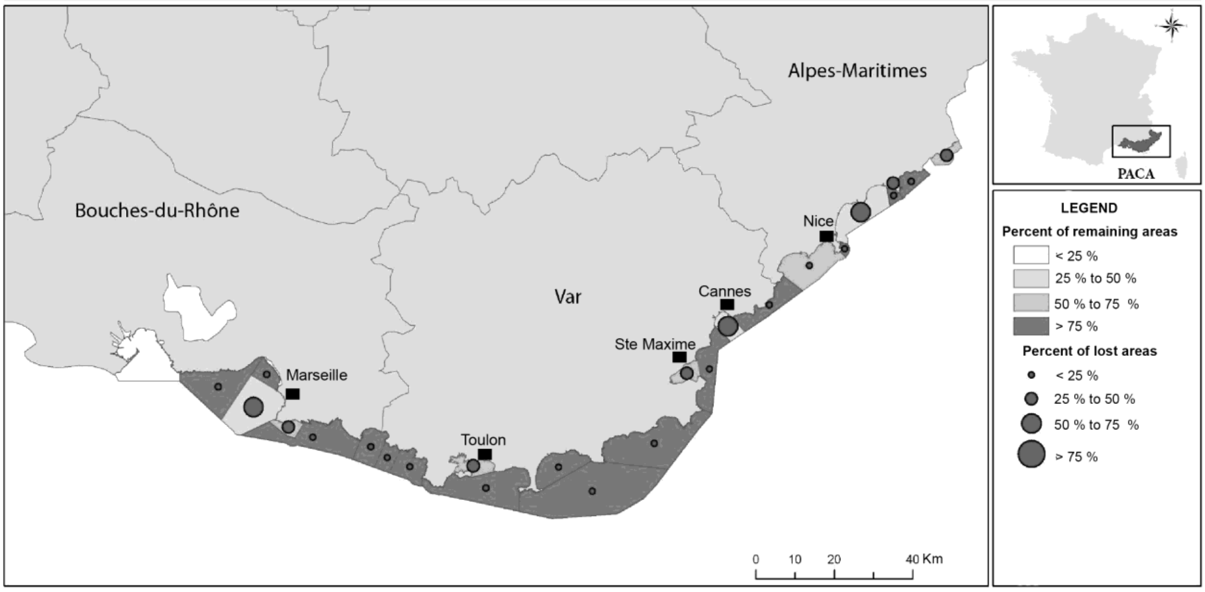

Figure 5. Relative importance (in percents) of the different types of man-made coastline developments responsible for the direct loss (in areal extents) of *Posidonia oceanica* meadows (between 0 and -15 m) within the study site. Direct losses assessment was obtained from the comparison between old meadows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

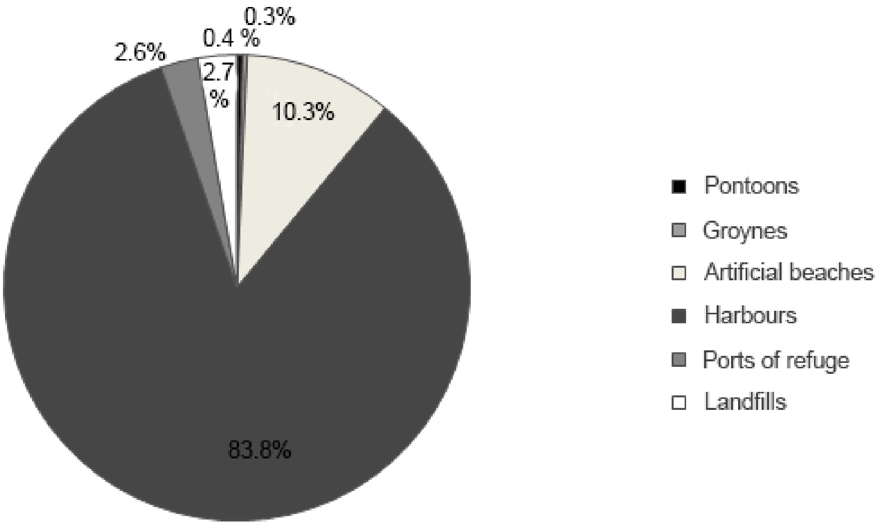


Figure 6. Lost *Posidonia oceanica* areas (in m²) according to the distance to different types of man-made coastline developments (96 facilities precisely) in meters. Results are presented for 1 m² of each type of development.