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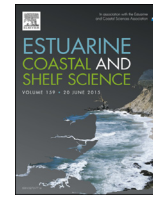

The impact of 85 years of coastal development on shallow seagrass beds (*Posidonia oceanica* L. (Delile)) in South Eastern France: A slow but steady loss without recovery

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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 pictures dating from 1922, 53% from 1924, 34% from 1927 to 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 × 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 pictures 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 pictures 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 (Andromède

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