Spatial, temporal and structural variations of a *Posidonia oceanica* seagrass meadow facing human activities

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Abstract

The Bay of Saint-Cyr (Provence, France, Mediterranean Sea) is the site of two harbours, coastal urban development, trawling, boat anchoring and a sewage outfall. The *Posidonia oceanica* seagrass distribution was mapped with the help of aerial photographs, side scan sonar and GIS. In addition, the temporal variations of its distribution were studied by aerial photographs and GIS from 1955 to 2000. Finally, coverage and shoot density were measured via scuba-diving. This work reveals (i) the regression of the *P. oceanica* meadow at sites where harbours have been built, (ii) the occurrence of spaces within the meadow free of live *P. oceanica* (“intermattes”), which account for 8% of its surface area, (iii) a deep area where *P. oceanica* coverage and shoot density are low and (iv) evidence of regression, although modest, of the meadow at its lower limit. Nevertheless, the study site also exhibits an extensive and on the whole relatively healthy meadow whose limits have changed little over time.

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1. Introduction

The coexistence of various commercial and urban activities disrupts the stability of littoral ecosystems (UNEP, 1996). The regression of littoral seagrass beds recorded over the last few decades provides an illustration of this phenomenon (for review see Short and Wyllie-Echeverria, 1996). The management of seagrass meadows is an increasing priority in the light of the essential role they play from an ecological and sedimentary point of view (Kuo et al., 1996). In order to implement management measures, assessment of seagrass dynamics under the impact of human activities must be undertaken.

Among the different methods used to map seagrasses, aerial photography has been demonstrated to be the best method to map shallow meadows (Green et al., 1996; Ward et al., 1997; Pasqualini et al., 1998; Kendrick et al., 2002; Frederiksen et al., 2004) while side scan sonar appears to be particularly suitable for deeper ones (Siljeström et al., 1996; Pasqualini et al., 1999, 2000; Piazza et al., 2000). These methods associated with Geographical Information System (GIS) constitute an efficient tool for seagrass management (Ferguson and Korfmacher, 1997; Robbins, 1997; Douven et al., 2003).

Although numerous studies have already focused on the dynamics of seagrasses under the impact of human activities, few have associated spatial, temporal and structural data. The aim of the present study is to assess the spatial, temporal and structural variations of a *Posidonia oceanica* (Linnaeus) Delile meadow at a site presenting a variety of human activities then to attempt to link the variations observed with the impact of these activities. *P. oceanica*, endemic to the Mediterranean, is by far the most abundant seagrass there, constituting vast meadows from the surface to a depth of 40 m (Duarte, 1991). Investigations were performed through (i) the present day cartography of the seagrass meadow via aerial photography, side scan sonar and GIS, (ii) the change of seagrass extension from 1955 to 2000, using ancient aerial photographs and GIS and (iii) two parameters suitable for plant vitality assessment, namely coverage and shoot density.

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2. Material and methods

2.1. Study site

The study site (Bay of Saint-Cyr, Provence, France, Mediterranean Sea; approximately 4 km²) is located to the east of Marseilles, at a latitude between 43.155°N and 43.180°N and a longitude between 5.670°N and 5.690°N. In addition to a vast *P. oceanica* meadow, the area harbours some underwater cliffs with gorgonians and the precious red coral *Corallium rubrum*, subtidal reefs with photophilous algae and sand bottoms. Ecosystems of this site, in particular the *P. oceanica* meadow, are considered as subject to a level of anthropogenic pressure which is intermediate between that of pristine areas of the Port-Cros National Park (French Riviera) and that of the Marseilles harbour and sewage outfall area (Pergent-Martini and Pergent, 1996).

Human impact at the study site takes the form of the port facilities of La Ciotat (5 km westwards), two small pleasure boat harbours (Les Lecques with 431 boat places and La Madrague with 240 boat places), marine leisure activities (scuba-diving, recreational fishing, boating, cruising boats), trawling and coastal urbanisation. The percentage of man-made facilities of La Ciotat (5 km westwards), two small pleasure boat harbours of La Madrague and Les Lecques were made using (Pergent-Martini and Pergent, 1996).

Sewage treatment plant (23 000 population equivalent) has been existing since 1988, with a pipe discharging treated water at 40 m depth. Before that, a PCV pipe discharging untreated water.

2.2. Spatial data

The map of *P. oceanica* distribution was established using aerial photography (shallow areas, i.e. <10 m depth) and side scan sonar (deeper areas). The aerial color photograph (1/15 000) was taken on July 2001 from a plane equipped for vertical photography flying at 325 m, with a photogrammetric Zeiss camera (23 cm × 23 cm, focal 152 mm; film AGA P 200), according to a standardized protocol (Lefèvre et al., 1984). It was digitised (800 dpi; pixel of 0.5 m × 0.5 m) with an Agfa SnapScan 600® color scanner using Corel Photo Paint 8® software in 16.7 million colors. Pre-processing involved specific geometric correction in order to eliminate distortions in the photograph (Pasqualini et al., 1998). This correction was achieved by means of the extension Géoref-Image® Version 2.2b of the Geographic Information System (GIS) ArcView 3.2® software, from “orthophotoplans” (photographs adjusted from two color negatives taken with different optical axes with a geographical referencing accuracy of 1 m) of the Bd-ortho® (Institut Géographique National, France). Reference points were taken from the terrestrial parts of the photograph. Patches of seagrass were delimited by feature extraction process by means of ImageAnalysis® (extension of Arc view 3.2). Some pixels are selected within a homogeneous region identified as *P. oceanica*. These pixels are used to define the classification rule in each color band of the photograph. Pixels around these selected pixels are classified step by step. The classifier looks at the pixel values of the additional pixel to see if they fall within the determined range. If this is the case, they are included in the closed polygon which delimits the patch of seagrass. Additional polygons were delimited manually when they were visible, although not taken into account by Image-analysis. Side scan sonar images (EdgeTech DF 1000 DCI®) were obtained during the oceanographic campaign Posicart I of the vessel Théys II in June 2000 (for rationale and principles of side scan sonar, see Pasqualini et al., 1998; Brown et al., 2002). The numerical data acquisition system is of the TEI ISIS type on a PC platform under Windows. The images obtained (sonograms) indicate the distribution and boundaries of the different substratum, sediment and seagrass bottoms which are characterised by different shades of grey. The sonograms were rectified with reference to a map indicating the location of the vessel’s route. The information obtained from the sonograms was manually transferred to the map. This map was then digitised using a color scanner. Possible misinterpretation of both the aerial photographs and the sonograms (e.g. patches of drifting dead *P. oceanica* leaves lying on a sand bottom) and doubtful points of interpretation were resolved by scuba ground truthing; 18 pinpointns and 7 transect dives were performed. Exact location of the dives was obtained by means of a Global Positioning System (GPS, Magellan 315®).

2.3. Temporal data

With the aim of assessing the dynamics of the *P. oceanica* meadow, the geographical database on ArcView 3.2® software was completed with earlier aerial photographs (dating from 1955, 1974 and 1979; Institut Géographique National) which were processed in the same way as the present aerial photograph, except for the resolution (according to scale with the aim of obtaining a pixel of 0.5 m × 0.5 m). Maps of changes in spatial distribution of *P. oceanica* near the two harbours of La Madrague and Les Lecques were made using Spatial Analyst® by multiplication of raster data. A more ancient photograph, dating from 1944 (US Air Force) was also used, but is not accurate enough for processing in the same way as the others.

2.4. Structural data

Structural data concerning the cover and the shoot density of *P. oceanica* were obtained via scuba-diving. The coverage corresponds to the percentage of the substrate covered by live *P. oceanica* in relation to the whole surface area. The coverage was measured by means of a 30 cm × 30 cm see-through plastic slide divided into nine 100 cm² squares. The diver, swimming 3 m above the bottom and holding the slide at arm’s length, counted the number of squares occupied (more or less totally) by *P. oceanica*. At each sampling site, 30 measurements were performed at similar distance intervals (the same number of flipper strokes). The shoot density is the mean number of living *P. oceanica* shoots per surface area unit. At least five measurements were performed within a 20 cm × 20 cm frame...
at each sampling point (Pergent et al., 1995; Marcos-Diego et al., 2000). Measurement of coverage and shoot density was performed at 34 pinpoint in the study area (Fig. 1a and b). The category limits of coverage and shoot density were delimited with “smart quantiles” method of the software ArcGis, which constitute a trade off between equal intervals and quantiles methods.

Intermattes are spaces without live *P. oceanica* within the meadow. They are occupied by sand or more generally by dead matte. When *P. oceanica* dies, the rhizomes decay very slowly and may persist for centuries or even millennia: dead matte is constituted by the intertwined dead rhizomes the interstices of which are filled with sediment.

### 3. Results

A continuous *P. oceanica* meadow occupies most of the bay from the surface to 32–34 m depth, with the exception of a vast and shallow sandy area in the centre of the bay, that it to say a total surface area of approximately 191 ha (Fig. 2). On the basis of the structure and the vitality of the *P. oceanica* meadow, three geographic sectors can be defined within the area:

1. In sector 1 (Fig. 2, S1), in the northern part of the bay, the *P. oceanica* meadow exhibits high coverage with few intermattes. Most of these intermattes, occupied by dead matte (15 intermattes, 1.5–1797 m² of surface area) are located close to the harbour of Les Lecques (Fig. 2, i). Fig. 3a and b shows the disappearance of *P. oceanica* from the area nowadays occupied by the harbour and the appearance of many intermattes between 1974 and 1979. This decline continues between 1979 and 2000 but is less marked. In the north-western part of the sector (Fig. 2, ii),
from 2 to 16 m depth, *P. oceanica* grows on exposed hard bottom with local coverage values of 40–45% (typical values for meadows on rock) and, according to the classification of Pergent et al. (1995), normal shoot density (Fig. 1a and b). With the exception of the latter zone, the meadow develops on sandy substrate with high coverage values of 80–90% and normal shoot density. The upper limit of the meadow is located at 14 m depth in the centre of the bay (Fig. 2, iii).

(2) The *P. oceanica* meadow in sector 2 (Fig. 2, S2) grows on sandy substrate between 14 and 32 m depth and exhibits lower coverage and many large intermattes of dead matte (about a hundred patches from 26 m² to about 1 ha of surface area). In contrast to sector 1, where most of the meadow exhibits high coverage values, in particular between 20 and 30 m depth, coverage values at these depths in sector 2 may be as low as 4–16% (Figs. 1b and 2, iv), where *P. oceanica* only subsists as patches within a dead matte area. The deeper limit of the meadow is sinuous and also exhibits, in particular in its northern part (Fig. 2, v), some dead matte areas with patches of *P. oceanica*.

(3) In sector 3 (Fig. 2, S3), the *P. oceanica* meadow grows on rock and small blocks down to 25 m depth and on sandy bottom below this depth. Along the southern coastline of the bay (between La Madrague harbour and cape Grenier), the meadow grows very close to the shore and exhibits high

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**Fig. 3.** Changes in spatial distribution of the *P. oceanica* meadow near Les Lecques harbour (a) between 1974 and 1979, (b) between 1979 and 2000, and near La Madrague harbour (c) between 1955 and 1974 and (d) between 1974 and 2000.
4. Discussion

The P. oceanica meadow occupies most of the Bay of Saint-Cyr, locally from close to sea level down to 32–34 m depth. The depth of the lower limit of the P. oceanica meadow is close to that of meadows dwelling in very pristine waters, e.g. in the Port-Cros National Park, French Riviera, 34–38 m (Harmelin and Laborel, 1976) and in Corsica, 30–38 m (Marion, 1883; Blanc, 1975; Bourcier, 1980). In addition, there is no evidence of dead matte below the sand layer. It can thus be supposed that the lack of P. oceanica in this area is not due to the disappearance of the seagrass but to the existence of natural non-suitable conditions in this part of the bay, e.g. water movement generating sand waves (sediment input above 70 dm$^3$ m$^{-2}$ a$^{-1}$ results in the death of P. oceanica; Boudouresque and Jeudy de Grissac, 1983; Boudouresque et al., 1984), erosion by undertow currents (Blanc and Jeudy de Grissac, 1978) or resurgence of fresh water from the phreatic layer (P. oceanica is reportedly very sensitive to low salinity; Ben Alaya, 1972). The fact that P. oceanica is only present on a rocky outcrop (Fig. 2, vii) in this area suggests that sand movements may be responsible for this area being almost devoid of seagrass. In any case, the limits of this area do not seem to have changed conspicuously since at least 1944.

In contrast to several coastal areas in the Mediterranean (e.g. Augier and Boudouresque, 1970; Meinesz et al., 1991; Ramos-Esplá et al., 1994; Boudouresque, 2004), the Bay of Saint-Cyr did not exhibit a dramatic loss of P. oceanica despite the enlargement of the two harbours of Les Lecques and La Madrague. If the surface area directly covered by these harbours is not taken into consideration, intermattes cover a total area which represents 8% of the overall surface area of the meadow; this percentage is relatively weak when compared with strongly degraded meadows in the vicinity of large cities and commercial port facilities (Blanc, 1975; Blanc and Jeudy de Grissac, 1978; Boudouresque, 2004). Three decades after the extension of the Les Lecques harbour, P. oceanica persists in proximity to the port and even up against the very base of the seawall (Fig. 3a and b). This is a rather uncommon feature: many harbours have an indirect negative impact on surrounding seagrass meadows (Ruiz and Romero, 2003). In addition, no new intermatte has appeared between 1979 and 2000 (Fig. 3b) and shoot density and coverage values are high in the vicinity of the Les Lecques harbour. In the vicinity of La Madrague harbour, together with evidence of loss (see below), the meadow exhibits high values of shoot density (Fig. 1a) and zones where P. oceanica recolonises intermattes (Fig. 3c and d).

Nonetheless, the possibility that the intermattes within the Saint-Cyr meadow may be of natural origin is definitely invalidated for many of them. Most intermattes located close to the Les Lecques harbour appeared subsequently to the enlargement of the harbour (Fig. 3a). Concerning the area near the La Madrague harbour (Fig. 2, vi), a strong regression occurred between 1955 and 1974 (Fig. 3c). Few years later, Blanc and Jeudy de Grissac (1978) still observed the regression of P. oceanica meadow in this sector down to 10 m depth. Even if the phenomenon seems to be less marked at the present time, the map of changes in spatial distribution of P. oceanica between 1974 and 2000 (Fig. 3d) shows the appearance of new intermattes and the extension of those already existing. Three elongated sandy zones (Fig. 2, ix) clearly originated from anthropogenic activities such as trawling (which, though prohibited less than three nautical miles from the shore, is very commonly done along most of the Mediterranean shores; Ardizzone and Pelusi, 1984; Ramos-Esplá, 1984; Pasqualini et al., 2000), anchoring of large cruise boats or pleasure boats (Paillard et al., 1993; Ramos-Esplá et al., 1994; Martín et al., 1997; Francour et al., 1999).

As for a number of other areas in the Mediterranean Sea (Boudouresque et al., 2000), the lower limit of the P. oceanica meadow appears to be regressive in some parts of the Saint-Cyr bay. This regression is particularly marked in the northern part of the bay (Fig. 2, v), with the survival of only few patches of P. oceanica within a dead matte area. In the southern part of the bay (Fig. 2, x), a 1.1 ha strip of dead matte and large shallower intermattes located in the same area (Fig. 2, vii) may be linked to the proximity of the outfall of a sewage treatment plant, located at 40 m depth (Pergent-Martini and Pergent, 1996; Pergent-Martini et al., 1996; Argyrou et al., 1999).

In conclusion, in the Bay of Saint-Cyr, which harbours two small ports, a sewage outfall, trawling, boat anchoring and coastal urban development, the P. oceanica meadow occupies most of the suitable bottoms. The upper limit seems stable over time. In contrast, losses were observed at its lower limits though of weak importance when compared with other Mediterranean coastal areas. With the exception of the lower limit and the area which was directly covered by the harbours, the dead matte surface area is relatively modest. The results presented here give an indication of a possibly uncommon feature, a relatively...
healthy meadow which coexists with a variety of human activities.

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