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Use of remote sensing for the characterization of the Mediterranean coastal environment – the case of *Posidonia oceanica*

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Abstract. The beds of *Posidonia oceanica*, a marine vascular plant species endemic to the Mediterranean, form a major Mediterranean marine ecosystem. These beds are well-developed along the sandy east coast of Corsica, where the continental shelf is wide and extends for ca. 100 km. The upper limit of this ecosystem has been mapped by means of a computer image processing technique using 1 / 20 000 colour photographs. One of the major problems for image processing in the marine environment is the impact of the water layer (of variable thickness and quality), which can result in variations of the spectral signature for a particular vegetation or bottom type. In an attempt to reduce the impact of this artefact, a processing technique that takes into account bathymetric factors has been tested. Cartographical data obtained for an area extending from Bastia to Solenzara are presented. In the vicinity of the mouths of coastal rivers, a systematic indentation of the upper limit of the seagrass beds has been revealed. On the basis of these results, local variations in the quality of the marine environment can be detected, in particular with regard to salinity, turbidity and/or the impact of sedimentation. The overall surface area of the *Posidonia oceanica* beds has also been calculated.

Keywords: Aerial photography; Continental shelf: Image processing; Mediterranean Sea; *Posidonia oceanica*; Surface.

Introduction

The Mediterranean coast is a vulnerable and endangered environment, since it is under increasingly intensive pressure from industrial, economic, touristic and urban development. It is subjected to concentrations of industrial waste, oil spills and untreated waste, amounting to almost 70 % of the domestic sewage (Ramade 1993). The alteration or disappearance of many marine biotopes is undoubtedly linked to these factors (Bourcier 1982; Vicente 1983).

Posidonia oceanica (L.) Delile, a marine phanerogam endemic to the Mediterranean, occupies most of the coastal sea-bed between the surface and 40 m depth. This plant forms extensive underwater beds and is one of the bases for the richness of the coastal waters (Boudouresque & Meinesz 1982). *Posidonia oceanica* is of major importance, not only because of the extensiveness of the areas it occupies (1 to 2% of the entire Mediterranean sea-bed), but also because of the role it plays in the ecology (Boudouresque & Meinesz 1982) and the equilibrium of the coastal environment (Jeudy de Grissac & Boudouresque 1985). Because of the bathymetric range, this seagrass is directly exposed to natural and human pressure, with the result that over recent decades, a marked regression of the *Posidonia* beds has been observed, mainly in the vicinity of industrial and port facilities, but also in certain relatively secluded areas (Peres & Picard 1975; Boudouresque & Meinesz 1982). *Posidonia oceanica* has therefore been listed as a protected plant species in France (ÔArr•tŽÕ of 19 July 1988, confirmed by the ÔDŽcretÕ of 20 September 1989).

In view of the regression of the seagrass beds, environmental protection measures are increasingly urgent. A prerequisite for any attempt to protect the *Posidonia* beds is the availability of a proper survey of the current knowledge of the resources to be managed. The production of thematic survey maps displaying the data in a comprehensive form, is often an essential first step towards creating a basis for a sound diagnosis.

Among the various cartographical techniques available today (Meinesz et al. 1981; Pergent et al. 1995), aerial or satellite remote sensing has recently made considerable progress. Computer image processing, which is widely used in satellite remote sensing, is increasingly applied for the interpretation of aerial photographs (Mani•re & Jaubert 1985; Courboules et al. 1988; Welch et al. 1991). The plant assemblages of the surface waters of the infralittoral zone are clearly visible on these photographs (Kelly 1980; Meinesz et al. 1988). On the basis of this kind of data, it is possible to determine the distribution, monitor the dynamics and even estimate the biomass of the benthic plant assemblages

(Cambridge & Mc Comb 1984; Meulstee et al. 1986). It is thus an indispensable tool for managing the coastal environment and development.

However, in the marine environment, computer image processing of aerial remote sensing data comes up against the problem of the impact of the water layer (of variable depth and quality), which gives a variable definition of the marine assemblages according to the depth. In the present study, we have simultaneously tested three processing techniques in an attempt to reduce the impact of this artefact. The overall surface area covered by *Posidonia oceanica* beds has also been estimated for the entire study site.

Material and Methods

Corsica is one of the seven major Mediterranean islands. *Posidonia oceanica* appears to be particularly widespread around Corsica (Meinesz et al. 1990); as a result of the transparency of the water, it extends down to a depth of 43m (Boudouresque & Bianconi 1986). Little research has been carried on the Corsican seagrass beds, and the available data are either relatively old, or limited to certain areas. The coastline on the western side of the island is steep and jagged, while that of the eastern side is low-lying and straight (Fig. 1). The coastline studied here, from Bastia to Solenzara, extends for a little over 100 km, is characterized by a very wide continental shelf and forms the sandy east coast of Corsica.

30 aerial colour photographs, scale 1/ 20 000, taken in June 1994, cover the whole of the site studied, except for the area around the Solenzara military base (Fig. 1). The latter area could be covered by four aerial colour photographs, scale 1/25000, taken at the military base area in June 1990.

Field data acquired on the ground are an indispensable addition to any cartographical work involving aerial photographs, to solve specific problems of interpretation (Lefevre & Valerio 1981). Therefore 17 field sites were investigated (Fig. 2). There are two techniques for observing the assemblages *in situ*: (1) occasional observation, with the position determined by a Global Positioning System (GPS) with an accuracy of 20m (GPS PRONAV 100¨) or (2) the transect method (Meinesz et al. 1981).

The aerial photographs are digitised by means of a colour scanner (Canon CLC 10, driven by a Pentium 100 microcomputer), using the IMAGE-IN SCAN & PAINT software (Image In¨), in 16.8 million colours. Each pixel in the photograph corresponds to a property vector resulting from the reflectance values for each primary colour or colour plane in the visible spectrum

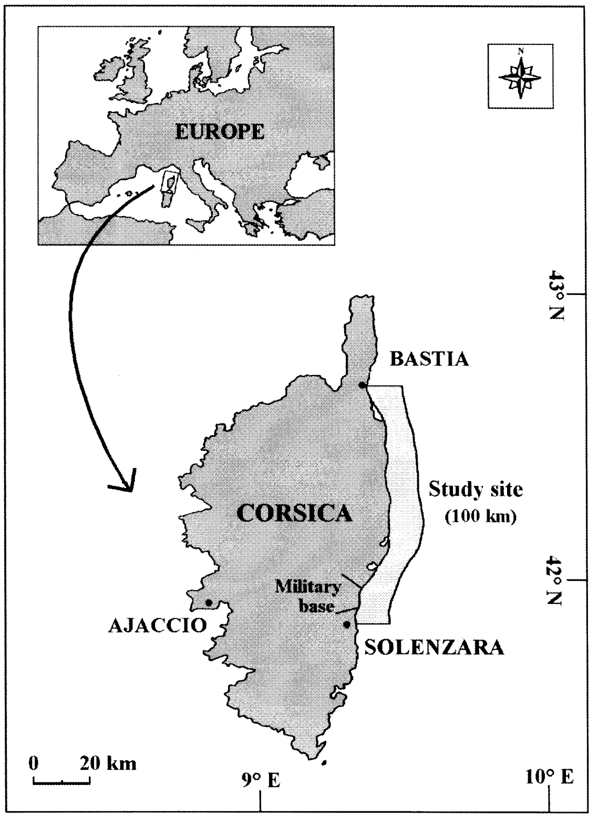


Fig. 1. Geographical location of the study site.

(red, green, blue; RGB). The photographs were scanned at 101 dpi to give a pixel resolution of 5 m × 5m. The data are analysed on the basis of the three planes (R, G, B), using the MULTISCOPE software (version 2.3, Matra Cap System¨). The preprocessing first involves the application of a specific geometrical rectification in order to eliminate distortions in the photographs. This technique involves adjusting the coordinates of reference points on the working image to those reference points on a map (1/ 25000 scale IGN maps or 1 / 50 000 scale SHOM charts) using a polynomial model. The algorithm is applied to each point on the working image (Meaille et al. 1988). The terrestrial domain is eliminated on the raw image by delimiting the land-sea boundary with closed polygons. The readjustment of the dynamics consists of enhancing the contrast of the image, and thus gaining in precision and clarity (Castan 1979).

Image processing was conducted on the set of photographs taken in 1994 with the primary objective of extracting the maximum information from the data. Principal Component Analysis (PCA), a technique widely used in satellite and aerial image processing (Belsher et al. 1988), is applied to the green and blue planes. The first component, plane P1, resulting from

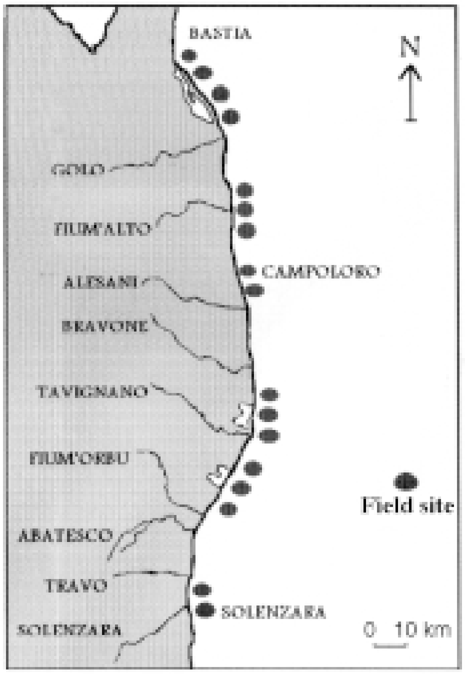


Fig. 2. Location of the field sites near the river mouths along the entire sandy east coast of Corsica.

this PCA is crossed with the red and blue planes (coloured composition) in order to distinguish formations down to a depth of 20 m. A classification supervised by hypercube is applied to the coloured composition (Mani•re et al. 1994); it involves positioning polygons assumed to contain pixels belonging to the same assemblage and bottom type (Courboules & Mani•re 1992). Four assemblages and bottom types are thus taken into account: (1) soft sediment (mud and sand); (2) photophilous algae on rock (including scree and pebbles); (3) decayed or patchy seagrass beds (on sandy rock); (4) continuous seagrass beds (cover > 50%). The positioning of the polygons is therefore based on *in situ* field observations. Homogenization is carried out to eliminate isolated or wrongly classified points. Occasional corrections can be made on the final images on the basis of field data.

Direct interpretation was used for the 1990 photographs of the Solenzara military base area, since the occurrence of reflection precluded computer processing. The limits of the benthic structures were determined; they correspond to changes in shades of colour or light intensity on either side of a more or less regular contour. These contours correspond to the assumed position of the various assemblages (photophilous algae on rock, sand and *Posidonia oceanica* beds).

The images processed were assembled to form a mosaic-like covering of the whole of the area studied.

In order to quantify the surface area occupied by the *Posidonia* beds from the upper to the lower limit, an extrapolation was used for the depth range from 20 m down to the lower limit of occurrence. This was done on the basis of occasional field observations and bibliographical data. In some photographs, underwater formations below 20m depth can be detected visually. All these data were taken into account for the extrapolation. Given the number of pixels, and the surface area of each pixel, the overall surface area of the *Posidonia* beds was calculated.

Results and Discussion

Image processing by depth range

First, the image processing technique was applied to photograph n¡ 3080 (1994), sited at the mouth of the FiumÕAlto (Fig. 2). The raw image coupled with the field data provides evidence of the occurrence of a indentation of the upper limit of the *Posidonia oceanica* bed down to a depth of ca. 20 m. To the north and south of this sandy beach, two arms of seagrass bed extend almost up to the shoreline, with the occurrence of photophilous algae on rock and pebbles.

Processing is carried out for the whole photograph by positioning a series of polygons that are characteristic of each of the assemblages and bottom types considered (sand, continuous seagrass bed, patchy seagrass bed and photophilous algae on rock). The final result (Fig. 3A) shows several problems of interpretation with regard to the classification of the pixels. This can probably be explained by the fact that a given assemblage may give different spectral signatures according to the depth (Pirazzoli 1982; Belsher et al. 1988). In fact, sandy bottoms present colour tones that vary considerably with depth.

In order to try to reduce the effect of this artefact, the polygons corresponding to this object were defined according to each of the three depth ranges at the site: shallow sand (0 to 5 m), intermediate sand (5 to 10 m) and deep sand (10 to 20 m) (Fig. 3B). The image processing was generalized for the whole of the photograph. This technique offers a better recognition of sand according to depth, but does not solve the problem of the overlap of categories with other neighbouring assemblages and bottom types. The intermediary pixels are attributed arbitrarily to an object, which is not necessarily the one they actually belong to. Confusions of interpretation occur between photophilous algae between 0 and 5 m depth and sand between 5 and 10 m.

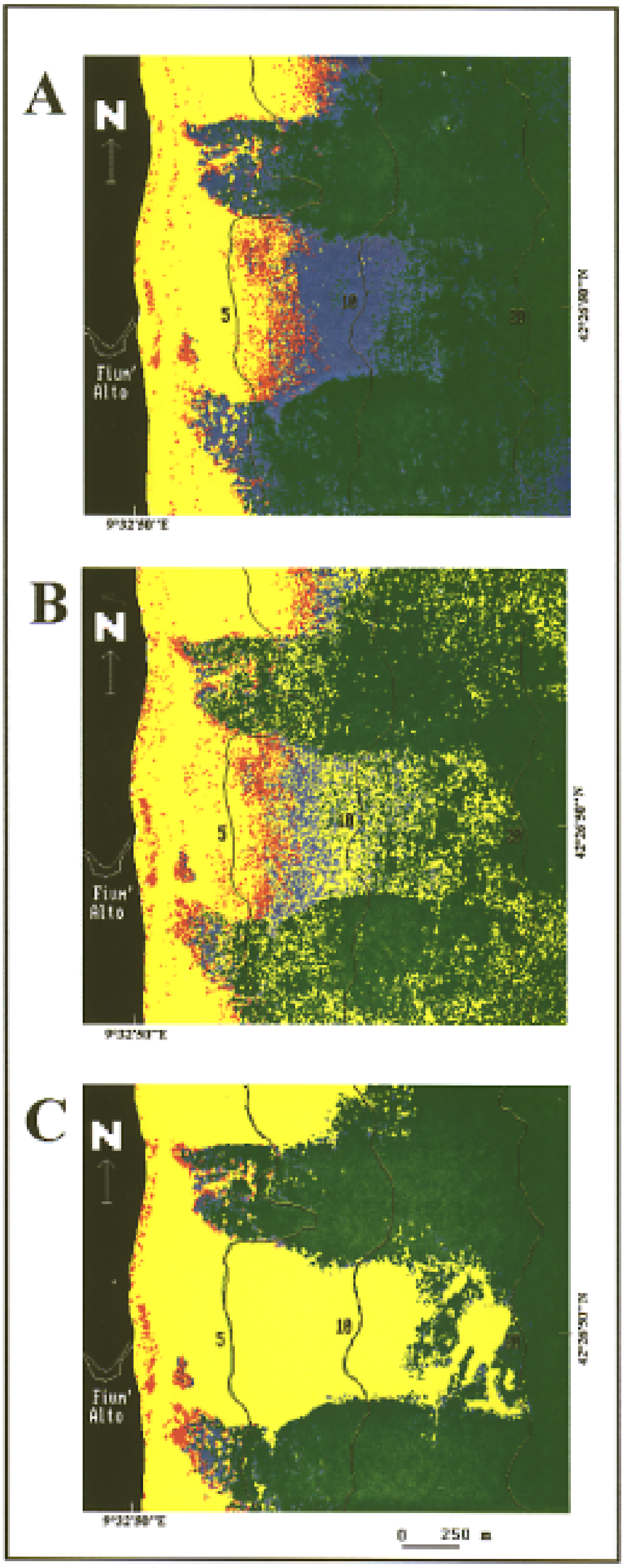
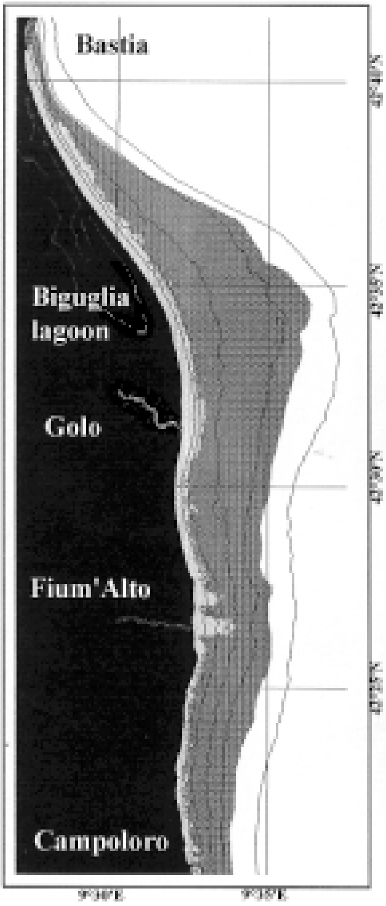


Fig. 3. Maps of the main benthic assemblages at the mouth of the FiumÕAlto, obtained by image processing. **A.** General processing; **B.** General processing by subdivision by assemblage and bottom type according to depth range; **C.** Processing by depth range.
yellow = sand;
green = continuous seagrass bed;
red= photophilous algae on rock;
blue = patchy seagrass bed;
black = land.



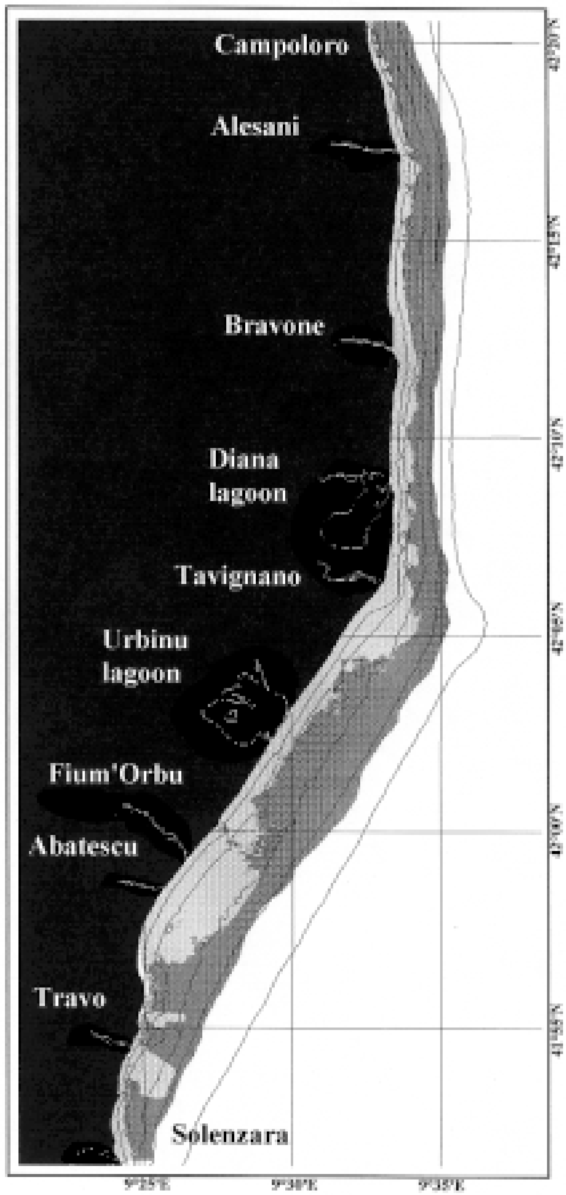


Fig. 4. General map of benthic assemblages from Bastia to Solenzara (Light grey = sand; Grey = continuous seagrass bed; Middle grey = photophilous algae on rock; Dark grey = patchy seagrass bed; Black = land). The photophilous algae on rock and patchy seagrass bed are poorly represented, but are not visible at this scale.

The same problem occurs for the shallow patchy seagrass bed which presents a spectral signature that is very similar to that of intermediate sand. In the deep zone, the sand and seagrass bed take on an increasingly monochrome tone that makes it difficult to distinguish between them. In order to improve the data obtained, the polygons corresponding to each of the assemblages and bottom types studied (sand, continuous seagrass bed, patchy seagrass bed and photophilous algae on rock) were defined on the basis of each depth range (0 to 5 m, 5 to 10 m and below 10 m).

The processing technique gives results that are much closer to the field data. Nevertheless, a few discrepancies of interpretation between sand and deep seagrass bed persist in places. These errors are corrected manually by individual adjustment on the basis of field data (Fig. 3C).

Table 1. Surface area (ha) occupied by the various assemblages and bottom types occurring in the study area.

Legend	Surface area			
	0 - 20 m deep		from surface to lower limit	
	ha	%	ha	%
Photophilous algae on rock	100	0.6	100	0.3
Continuous seagrass bed	7 416	44.2	21838	68.6
Patchy seagrass bed	369	2.2	398	1.2
Sand	8893	53	9470	29.7
Seabed surface area	16779	100	31806	100
Surface area occupied by seagrass bed	7601	45.3	22036	69.2

Application at the sandy east coast of Corsica

Image processing was applied to the whole 1994 set of photographs, with the addition of the direct interpretation of the 1990 photographs. On this basis, the marine assemblages or bottom types between 0 and 20 m depth have been mapped. An estimation of the position of the lower limit of the seagrass beds has been provided on the basis of the available bibliographical data, with the addition of occasional field data obtained by divers. It appeared that the lower limit ranges from 17m depth south of Bastia to 38 m depth south of Campoloro, with a mean depth of 32 -35 m over the whole coastline. On the basis of these findings, it has been possible to map the location of the *Posidonia oceanica* beds over the whole area (Fig. 4).

The distribution of the seagrass beds between Bastia and Solenzara is relatively homogeneous, except at the mouths of rivers, where the upper limit is systematically lower. The seagrass mainly occurs on sandy bottoms; on rocky bottoms or matte, it is patchy in form. The distribution of the photophilous algae, which are largely localised on rocky or pebble substrates, is heterogeneous and weak along the whole of this sandy coast. The abundance of pebbles that are found near the shore are washed down by the numerous rivers that flow into the sea in this area. The systematic indentation of the upper limit of the *Posidonia oceanica* beds at the mouths of the rivers is probably the result of the sensitivity of the plant species to reduced salt contents (Boudouresque & Meinesz 1982). However, the extent of the lowering of the upper limit is not systematically related to the flow rate of each river. Whereas the flow rate of the Golo is 16 × higher than that of the FiumÕAlto (Binet 1989), the mapped degree of indentation for the latter is distinctly greater. Other environmental factors certainly influence the degree of indentation of the seagrass beds at the river mouths. At the mouths of the Tavignano, the FiumÕOrbu and the Albatesco (Fig. 4), the upper limit of the seagrass beds is strongly indented. In this region, there is a considerable concentration of agricultural land. The enrichment of the sea water with organic matter forms a screen against the light, which inhibits the development of *Posidonia oceanica* beds (Boudouresque & Meinesz 1982). It should be pointed out that the exact location of the indentation of the upper limit of the seagrass beds is generally slightly to the south of the river mouths. This observation confirms the north-south flow pattern of the currents along the sandy eastern seaboard of Corsica.

Comparison of the 1990 and 1994 photographs does not reveal any significant alteration in the position of the *Posidonia oceanica* beds.

The stretch of coastline mapped represents exactly 105.8 km, according to Meinesz et al. (1990). On the basis of field data, it would appear to be reasonable to assume that only half of the patchy seagrass bed is in fact occupied by the seagrass bed. On the basis of surface area calculations from the cartographical data (Fig. 4), the area covered by *Posidonia oceanica* beds may be estimated at 22036 ha (Table 1). In 1990, Meinesz et al. estimated the potential surface area of the *Posidonia oceanica* beds at 26150 ha for the same coastal sector, solely on the basis of the distribution of the seagrass beds in the 5 to 35 m depth range. This underestimate would appear to be reasonable. Our own observations show that the upper limit of the seagrass beds ranges from 5 to 10 m depth, and sometimes drops to 20 m depth at the mouths of rivers (Fig. 3). The extent of the areas covered by the seagrass beds (22036 ha over 100 km) confirms the exceptional value of this coast in terms of the environmental patrimony. The coverage area figure is comparable with that reported by Meinesz et al. (1990) for the whole of the Provence-Alpes-C™te dÕAzur coast (20 000 ha over 750 km). In addition to the topography of the sea bottom (shallow water), the extent of the seagrass beds perhaps reflects the low rate of urban coastal development along the coast between Bastia and Solenzara (0.5%). These authors (Meinesz et al. 1990) report that the potential surface area of *Posidonia oceanica* around the whole of the Corsican coast (about 950 km of coastline) amounts to 75 592 ha. The area studied here, 22 036 ha, which only represents 10% of the total coastline, would thus account for around 30% of the seagrass beds in Corsica.

Accuracy

With regard to the accuracy of our estimations, it should be pointed out that the degree of reliability differs according to the depth range considered. In shallow water (0 to 20 m deep), the image processing procedure offers relatively reliable results. On the other hand, the data for depths in excess of 20 m are based on an extrapolation, and correspond therefore to the potential surface area of the seagrass beds. The deep seagrass bed between 20 m deep and the lower limit (14436 ha) occupies a greater surface area than the shallow seagrass bed (7600 ha). The results may seem somewhat surprising but can most probably be explained by (1) the difference in cartographic methods used, and/or (2) the fact that the factors responsible for the regression of seagrass beds (hydrodynamic forces, fresh water input, human pressure, etc.) have a more pronounced effect in shallow waters.

Conclusions

This initial study of an area for which little data are available necessitates the use of large scale cartographical techniques. This is an essential stage for the preparation of a properly coordinated plan for the management of the coastal environment at the country or the regional level (the latter can be ÔDŽpartementÕ or a ÔRŽgionÕ in the French administration). Aerial remote sensing, in association with computer image processing, has made it possible to map the main benthic assemblages along 100 km of the Corsican coastline. In view of the fact that previously, biocenotic cartography had been carried out for less than 10% of the coastline, this preliminary study must be considered as an essential step.

The results obtained during the course of the present study confirm the potential of aerial remote sensing for the marine environment. The methodology tested here (image processing by depth range) has considerably improved the preliminary attempts at establishing a cartography of the benthic assemblages. The degree of resolution used here (5m pixel) would appear to be a satisfactory compromise between the extent of the surface area under investigation and the objectives of the study. Nevertheless, it should be borne in mind that, since the position of the lower limit is based on extrapolations, the final version of the map can only indicate the potential position of the seagrass beds.

The production of thematic survey maps means that the natural resources that occur at the site can easily be quantified. The estimation of the area occupied by *Posidonia oceanica* beds between Bastia and Solenzara amounts to 22036 ha . This finding provides an interesting basis for comparison with the data available for the whole of the Provence-Alpes-C™te dÕAzur coastline. For a stretch of coast nearly seven times longer than that studied here, the overall surface area of occupation by the *Posidonia oceanica* beds is virtually identical. In addition to the topography of the sea-bed (shallow water), the extensiveness of the Corsican seagrass beds is probably due to the low rate of occupation by coastal developments Ð 1.8 % on average for the Corsican coast, as against 16% for the coast of Provence-Alpes-C™te dÕAzur (Meinesz et al. 1993). These features confirm the outstanding ecological and economic value of the Corsican coasts. It is clear that this area is a priority case for environmental protection and management. The maps presented here provide a basis for assessing variations in the quality of the marine environment along the eastern seaboard of Corsica, notably the salinity and / or turbidity of the water and the impact of sedimentation.

The mapping of the benthic assemblages can offer a useful decision basis for those responsible for the management of the coastal environment, both with regard to development projects, whether for aquaculture, industry or tourism, and for the conservation of the most vulnerable or most outstanding sites. The final objective is to make available a set of data that is easily accessible and open-ended (current patterns, types of bottom, bathymetry, assemblages, coastal developments, patterns of use, etc.), which would contribute to the development of a complete Geograph Information System.

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