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# Relationship between the Evolution of the Shoreline and the *Posidonia oceanica* Meadow Limit in a Sardinian Coastal Zone

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## ABSTRACT

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Important environmental changes have been observed for some coastal processes in the Gulf of Oristano (west coast of Sardinia, Italy). With remote sensing as the principal tool, this study aims to assess littoral evolution over time (1977–2000) and to evaluate whether there is a relationship between the evolutionary trend of the shoreline and that of the upper limit of the *Posidonia oceanica* (L.) Delile meadow. Results show that some portions of the coastline, mainly located on the sandy part of the littoral, have encountered significant variations that can be partially related to the evolution of the upper limit of the *P. oceanica* meadow. Mainly of natural origins, this evolutionary trend has also been related to anthropogenic pressures put on the seagrass meadow. This finding confirms that *Posidonia* meadows significantly affect the littoral geomorphology, providing biogenic sediments, controlling beach slope, and acting as a “brake” on coastal water masses.

**ADDITIONAL INDEX WORDS:** *Gulf of Oristano, remote sensing, coastline evolution, seagrass meadow.*

## INTRODUCTION

Coastal zones, characterised by complex and fragile equilibria, are often coveted and, thus, subjected to strong anthropogenic pressures. As places of interaction of terrestrial and marine environments, they suffer from these disturbances of human origin in addition to those generated by the action of natural forces. There is no doubt that the management of this coastal fringe—with ecological, social, and economic issues of utmost importance—is a challenging and topical point. Nevertheless, appropriate management is possible only with the help of a precise knowledge of processes influencing coastal dynamics. In response to these various coastal processes, coastlines have changed at varying rates over years (EUROSION GROUP, 2004) and remote sensing techniques (*i.e.*, aerial photographs) have proved to be useful tools to trace and measure shoreline evolution. We therefore used this approach to study a portion of coastline partially included in the Sinis Peninsula and Mal di Ventre Island Marine Protected Area (Mediterranean Sea), which was established in 1997 by the Italian Ministry of the Environment.

The investigated area is located in the northern part of the Gulf of Oristano, on the western coast of Sardinia, Italy (39°51' N, 8°27' E; Figure 1). This shallow gulf has a surface of approximately 150 km<sup>2</sup>, is bounded to the northwest by the San Marco rocky cape at the end of the Sinis Peninsula, and

has a mostly sandy shoreline along an alluvial plain with several marshes and lagoons (DE FALCO *et al.*, 2000).

The analysis of the coastal evolution of this area was already made by Carboni but at a larger scale, all the Italian beaches being mapped and gathered in an atlas (CARBONI *et al.*, 1990). Figure 2 shows, for instance, a subset of the chart concerning the study area. In addition to the analysis of the shoreline evolution and using the ability of colour photography to map the shallow sea floor, cartography of the seagrass meadow was also realised. A lot of authors have conducted such kinds of research separately (*e.g.*, DURAND, 1998; PASQUALINI *et al.*, 1997), and others have been interested in the relationship between sediment and seagrass (*e.g.*, DE FALCO *et al.*, 2000; TERRADOS and DUARTE, 2000) or between seagrass and beach dynamics (*e.g.*, BASTERRETXEA *et al.*, 2004), but to our knowledge, few studies are available concerning the concomitant evolution of the shoreline position and of the seagrass meadow extent. We thus tried to examine whether there was a relationship between the evolution of the shoreline and that of the upper limit of the *Posidonia oceanica* meadow, which is here the principal ecosystem that largely covers the western part of the gulf (~15 km<sup>2</sup>), excepting a wide unvegetated breach (~0.9 km<sup>2</sup>) off Cape San Marco (CANCEMI *et al.*, 1997). This marine phanerogam endemic to the Mediterranean forms extensive underwater beds and is of major importance, not only because of the size of the covered area but also because of the role it plays in the equilibrium of the coastal environment (PASQUALINI, PERGENT-MARTINI, and PERGENT, 1998).

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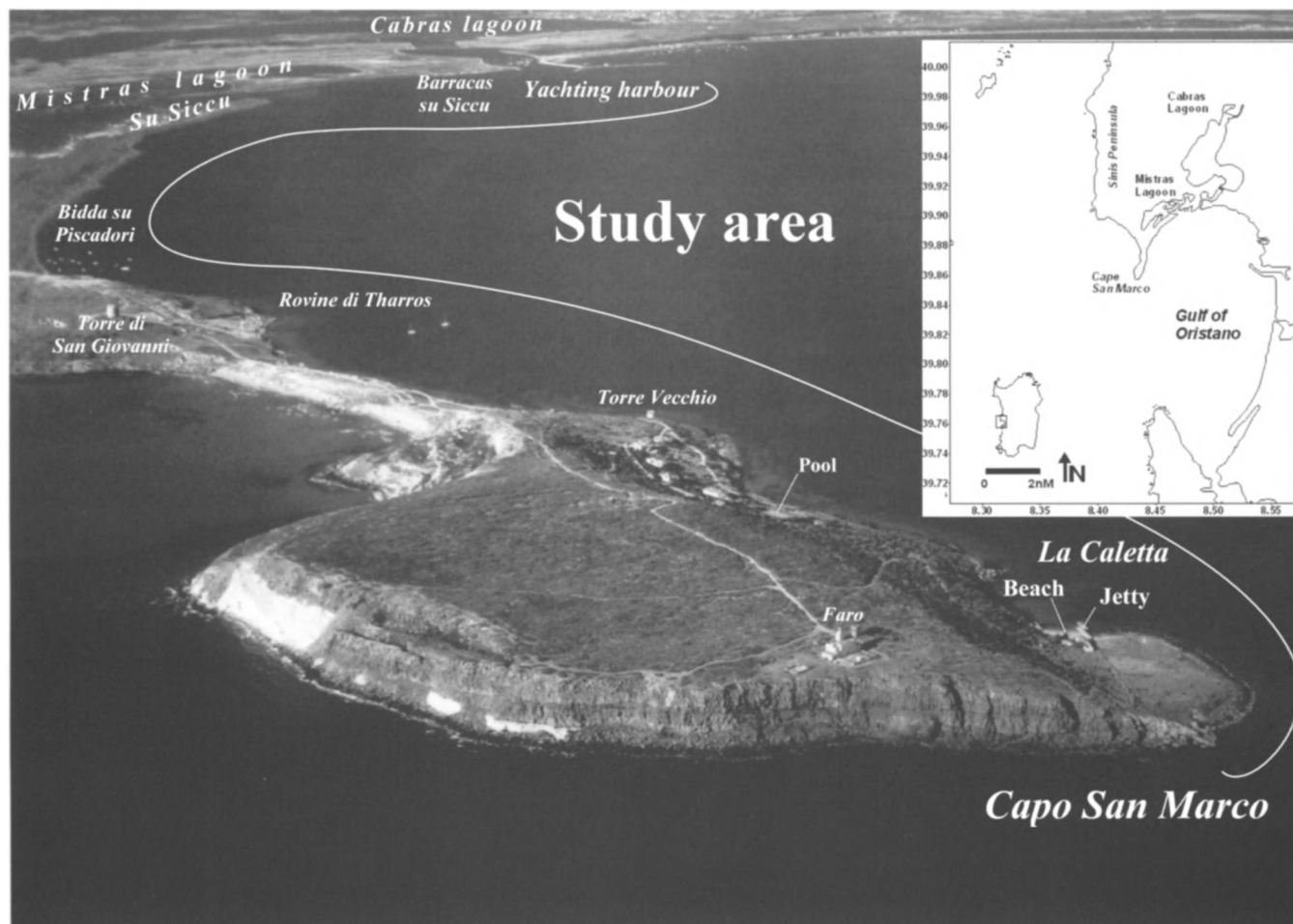


Figure 1. Study area, northern part of the Oristano Gulf (Sardinia, Italy) stretching from the southern end of Cape San Marco to the marina on more or less 8 km. The study area comprises various types of coastline and is part of an "Area Marina Protetta." From the cape up toward the north, one meets, successively, cliff, rocky portion, sandy portion, dune belt (Biddu su Piscadori), and, finally, the old beach lobe of Su Siccu.

### PHYSICAL PROCESSES

The general circulation of surface and subsurface water masses in the western Sardinian sector that constrains the coastal dynamics is meant to be more or less oriented south to north, as indicated by numerical models (e.g., EUROMODEL GROUP, 1995), and is subject to a seasonal and interannual variability. Mesoscale circulation in the surface layer off western Sardinia is influenced by the Algerian basin hydrodynamic in which the inflowing surface Atlantic water forms along the African coast the so-called Algerian current (MILLOT, 1999), which rapidly becomes unstable and generates large anticyclonic eddies. Some of them follow the Sardinian slope northward and drive, or strongly disturb, the circulation over the slope and onto the shelf (RIBOTTI *et al.*, 2004). Their characteristic velocity varies between 15 and 55 cm/s (RIBOTTI *et al.*, 2004), and their influence inside the gulf is expected to be rather weak because they are open sea eddies.

In addition to general and regional hydrodynamics, one has to stress here the very important role played by the winds in

such microtidal Mediterranean coastal zones. On the one hand, they are responsible for the dynamics of the surface mixed layer and, in very shallow areas, of an enhanced bottom turbulence and associated erosional power. On the other hand, they induce more or less strong drift currents, as well as vertical upwelling/downwelling motions in the case of favourable alongshore air flows. At larger scale, they control the wave/swell system. Although several studies have been conducted further to the north along the west coast of Corsica (e.g., DJENIDI, 1985; SKLIRIS, LACROIX, and DJENIDI, 2004), very few or no data are unfortunately available for the region of interest.

Prevailing winds in this zone throughout the year are mainly from the northwest (Mistral) and are light or moderate, sometimes rising to gale force during winter. However, our study area is quite sheltered by the Sinis Peninsula, thus decreasing the effects of these winds. In autumn and winter, the southwestern Libeccio is also important, with variable fetches (PINNA, 1998). It generates the recorded clockwise



Figure 2. Subset of the map from the “Atlante delle spiagge italiane.” Map of our study area, showing the evolutionary trends of the coastline (–, stability; >, progradation; <, erosion).

alongshore drift current in the northern part of the gulf. These strong winds expose the investigated site to very high waves, among the highest in the Mediterranean Sea (Istituto Studio Dinamica Grandi Masse and European Centre for Medium-Range Weather Forecasts in DE FALCO *et al.*, 2003), that affect the littoral geomorphology. Indeed, wave and wind approaches determine the primary direction of sediment transport over intermediate timescales, and the bottom topography and shoreline orientation dictate wave refraction patterns, the resulting wave energy gradients, and wave-driven currents (STORLAZZI and FIELD, 2000).

## METHODS

Aerial colour photographs of the northern part of the Oristano Gulf (1977–1/13 000; 1995 and 2000–1/20 000) were digitised in “true colors RGB” by means of a colour scanner, and the resolution was adjusted according to the scale of the picture such that a pixel size of 1 m was obtained. The data analysis was performed by Multiscope 2.4 software (Matra Cap Systems). Data processing involved specific geometric corrections with the use of ground control points chosen on a reference map (Carta Tecnica dell’Italia Meridionale, ISTITUTO GEOGRAPHICO MILITARE, 1973–1/5 000), digitised in the same way as the photographs, to eliminate the distortions related to the conditions of taking pictures. After this, a contrast stretch that allows a better visualisation was applied, and a mosaic was built with obtained colour composites to digitise the shoreline. For the upper limit of the seagrass meadow, the ground-masked images were subjected to a principal components analysis to decorrelate the planes (red, green, blue) and to exploit a maximum amount of data (BALLESTA *et al.*, 2000). Colour composites were then created, allowing a better discrimination of the marine assemblages. A classification supervised by generalised hypercubes (fuzzy entity theory) was then applied to these colour composites (PAS-

QUALINI *et al.*, 1997) and then controlled by *in situ* field observations. Two ground truth surveys conducted in 1995 and 2000 comprising eight and five scuba transects, respectively, ranged from 300 to 900 m in length with a beach-to-offshore orientation. In addition, a field survey by boat was made in 2002 to identify shore nature and coastal botanic marine assemblages. Finally, superpositions were made to obtain synthesis images showing diachronic evolution. The complete image processing workflow is presented in Figure 3.

## RESULTS

### Shoreline Evolution

After achieving the superimposition of the various coastlines on the reference map and measuring the interannual distances, we obtained a chart that shows the diachronic evolution of the shoreline between 1977 and 2000. An extract of this chart is presented in Figure 4 and shows results on a portion of the studied zone. Because of certain distortions noticed on the borders of the “Technical Map,” the latter was used here only to locate places, whereas shore evolution was deduced by comparison between the different positions of the coastlines (1977, 1995, and 2000).

As might be expected, the synthesis of this evolution (Figure 5) shows that the rocky portion is, overall, rather stable and that the significant variations—changes of position of more than 3.5 m (value estimated in accordance with the method explained by DURAND [1998])—are mainly located on the sandy part. These shoreline changes range from 3.5 to 58 m. Obviously, such variations were mostly recorded between 1977 and 1995 (the longer period). Indeed, what can be observed is a fair conformability between the position of the coast in 1995 and 2000, except where strong erosion occurs. In these places, the retreat is spread out throughout the whole period under consideration.

Considering these variations, modifications have been made in the map from the “Atlante delle spiagge italiane.” The comparison between Figures 2 and 5 leads first to the statement that the coastline evolution is more accurately defined and that new trends appear in some zones (Bidda su Piscadori, Barracas su Siccu, Mistras lagoon mouth). The evolution of the old beach lobe of Su Siccu is also more precisely and differently described in our study. The beginning of this lobe, which was noticed under erosion on the map of CARBONI *et al.* (1990), is now experiencing a net progradation. Likewise, the second part of the lobe is under strong erosion, except the extreme end, which is in progradation.

### Seagrass Meadow

By superimposition of the two supervised classifications from 1995 and 2000, with the use of the mean radiometry of the pixels, we have obtained a chart (Figure 6) showing the variations of the surfaces covered by the seagrass meadow. Considering the characteristics of the studied zone (*e.g.*, weak water turbidity), the quality of aerial photographs, and the large scale of the map used for geometric rectification, and according to the reliability assessment method established by PASQUALINI *et al.* (1997), we can estimate the reliability of

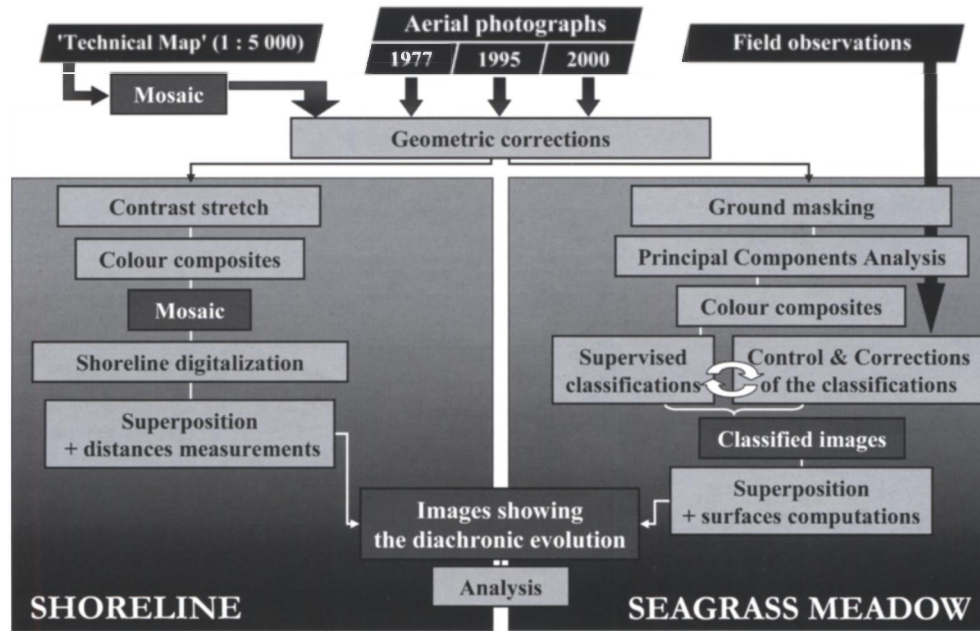


Figure 3. Image processing procedure.

these classifications at the 90% level. The obtained chart exhibits a lot of changes around Cape San Marco and the small harbour of La Caletta. Likewise, the upper limit of the seagrass bed along the coast and the channel leading to the sandy discontinuity show some variations. After the analysis of this map, coupled with a meticulous examination of both classifications, we noted that all these changes are mainly

ascribable to a regression that occurred between 1995 and 2000. Moreover, the structure of the upper limit of the meadow became more irregular.

For the large sandy breach, the superposition of obtained classifications did not enable the analysis of the evolution of the meadow along this discontinuity. This is because of the distortion resulting from the lack of control points in the sea at the time of the computation of the polynomial used by the software for the geometric correction. Nevertheless, Figure 6b (manual fittings of small portions of the chart) helps to

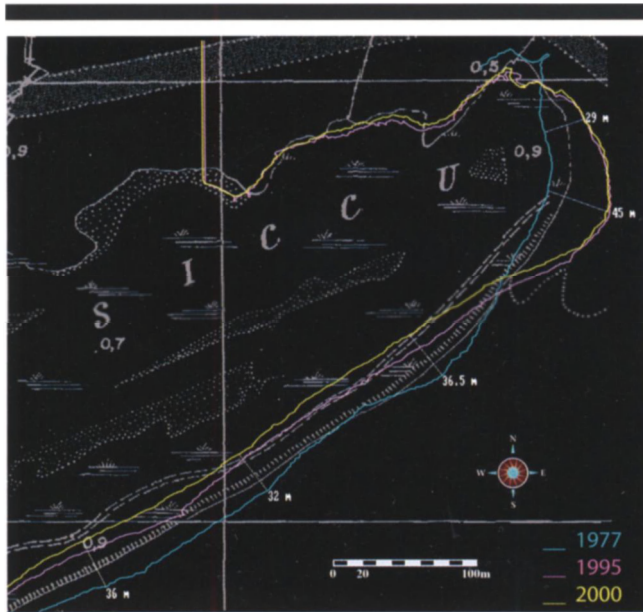


Figure 4. Diachronic evolution of the beach lobe of Su Siccu between 1977 and 2000.

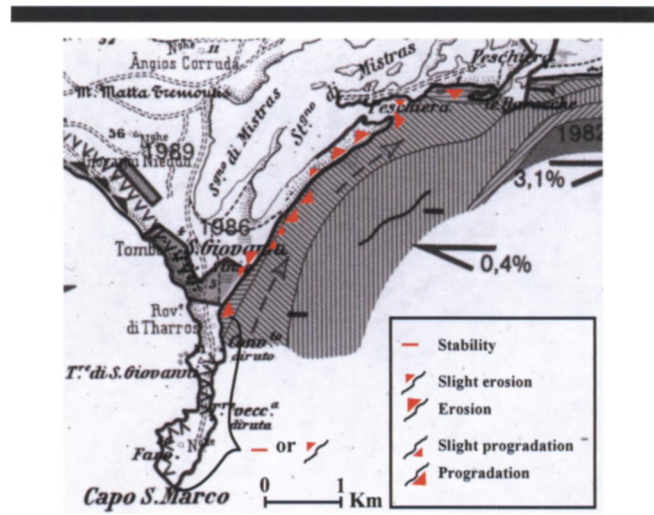


Figure 5. Synthesis of shoreline evolutionary trends along the studied zone.

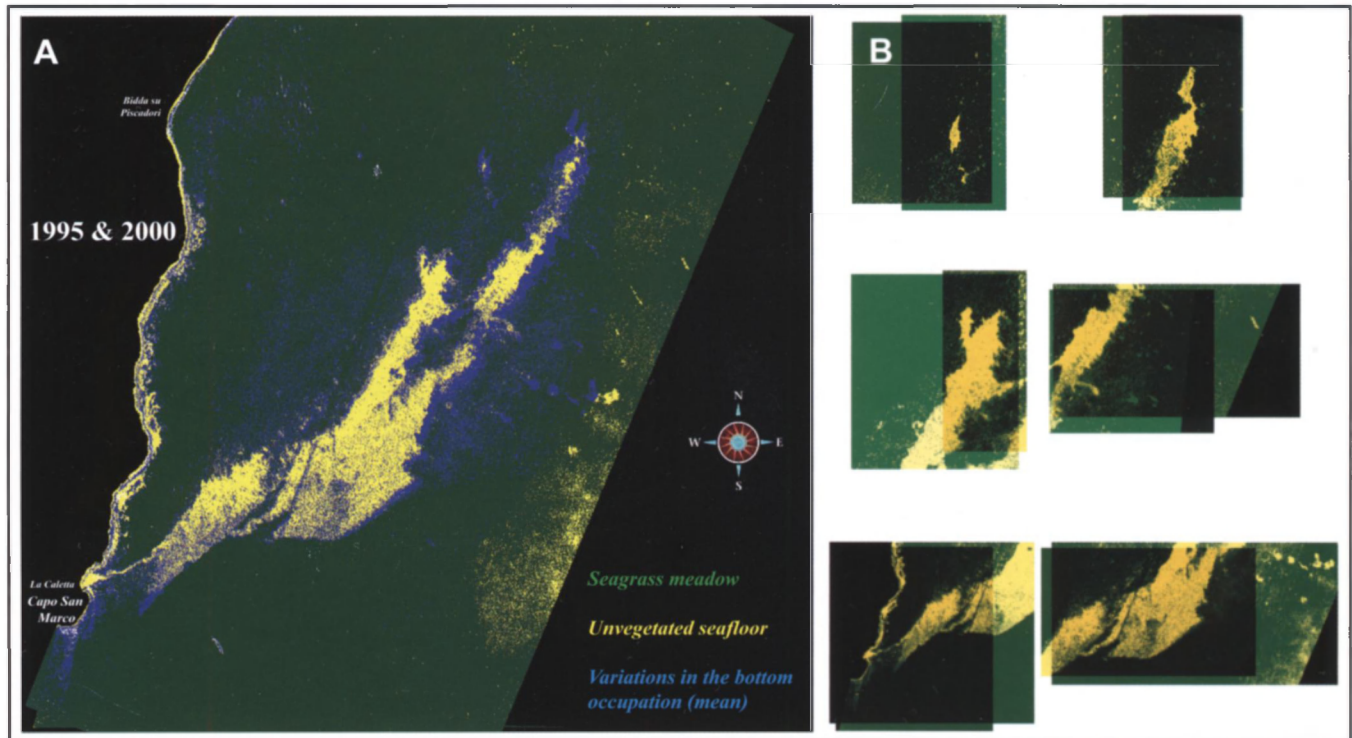


Figure 6. Evolution of the seagrass meadow. (A) Superposition of supervised classifications. (B) Manual fittings of parts of the supervised classifications in the sandy breach area.

solve this problem and shows that only a few significant changes occurred during that period.

Examining the classification published by CANCEMI *et al.* (2000) in the northern part of the Gulf of Oristano, we noted that the meadow facing the end of the beach lobe of Su Siccu, which was identified by us as in net erosion, is highly degraded and comprises a mixture of *Cymodocea nodosa* (Ucria) Ascherson and *P. oceanica*. Moreover, our field observations lead to the same statement.

Thus, we think that a relationship could exist between the evolution of the upper limit of the meadow and that of the position of the facing coast.

## DISCUSSION

Observed variations of the shoreline position result from various factors, such as natural erosion, littoral drift, and human activities. Consider, for instance, the old beach lobe of Su Siccu, which according to the update of the map of Carboni *et al.* (1990) (Figure 5) shows the most important changes. It exhibits a classical evolution of beach lobe with erosion, linearisation of the shoreline, and accumulation of sediments at the end of the lobe. This typical evolution is probably due not only to the littoral drift that transports and distributes sediments along the lobe, but also to the disappearance of the seagrass bed in this zone.

The progradation at Barracas Su Siccu (Figures 1 and 5) is probably due to the shoreline changes related to the ex-

cavation of an artificial channel, dredged in the late 1970s, that connects the Cabras lagoon to the sea (Figure 1). A low dam rising up the high tide level was created inside the channel to allow the flushing of excess water in case of flood. This dam traps the sediments inside the lagoon (DE FALCO, MAGNI, and TERASVUORI, 2004); consequently, the sediment discharge into the gulf from Cabras lagoon can be considered negligible.

Mistras lagoon is characterised by the absence of fresh water input from rivers, and exchange with the sea is mainly due to microtidal variations. Consequently, the discharge of sediments from the lagoon to the sea can be considered irrelevant.

Changes in other places (*e.g.*, Bidda su Piscadori) seem to have been caused by beach replenishment.

The apparent regression of the extent of the meadow between 1995 and 2000 along the coast could be caused by the presence of dead seagrass leaves masking the sandy bottom on the 1995 photograph. However, the field data collected in 1995 allows us to exclude this hypothesis because the distance of the meadow upper limit from reference points along the coastline was measured by a metric line and used to validate the photo analysis interpretation (CANCEMI *et al.*, 1997). The same method was adopted in 2000. Consequently, the variation of the position of the upper limit from 1995 to 2000 could be ascribed to meadow regression.

The patchiness of the upper limit of the meadow is a stage

in evolution toward its disappearance and is meant to be caused by the rise of the intermatte channel widths. For the sandy discontinuity, observed variations are probably related to the classification process and the lack of sufficient ground truth data in this area. Because of the distance from the coast, it was not possible in 1995 to collect precise reference ground points in the sandy discontinuity, and the field observation points were positioned by the Global Positioning System (CANCEMI *et al.*, 1997).

The presence of a mixed meadow at the end of the beach lobe represents a step in the process of ecological succession (CANCEMI *et al.*, 2000) leading to the complete disappearance of *P. oceanica*, which has been identified by DE FALCO *et al.* (2003) as a clear provider of biogenic material that is exported to the shore, contributing thus toward the sustainability of its sediment budget. Moreover, the meadow canopy acts like a brake for the coastal water masses because of the high shear stress it generates, and it also has a wave attenuation action (*e.g.* FONSECA and CAHALAN, 1992; JEUDY DE GRISAC, 1984). In addition, the frequent presence of floating fragments of dead *Posidonia* lead to an increase in water viscosity that reduces wave energy and thus protects the beach from erosion. The combined effect of all these actions explains the relationship between the evolution of the upper limit of the meadow and that of the position of the facing coast. In addition, *P. oceanica* meadow acts as a reef, and the meadow upper limit regression could cause a decrease of beach slope and shoreline retreat (BASTERRETXEA *et al.*, 2004).

Through the decrease of the positive effect it exerts, the regression of the meadow enhances beach erosion.

Different factors could be responsible for the meadow withdrawing, but we state here that, in this zone, they are mainly anthropogenic. The building of a yachting harbour in 1982 has generated a clear increase of the anchorage—well known for its negative effects on the seagrass beds (FRANCOUR, GANTEAUME, and POULAIN, 1999)—inside the gulf and along its northern coast, as well as frequent resuspension of bottom sediments. In addition, the lagoon of Cabras has been affected in the last decades by strong eutrophication phenomena (a dystrophic crisis in 1999 caused massive fish mortality; DE FALCO, MAGNI, and TERASVUORI (2004)). Those phenomena could reduce the water quality in the sector of the lagoon mouth, particularly by increasing turbidity, which might be a cause for the regression of *P. oceanica* meadow in this sector (CANCEMI *et al.*, 2000).

## CONCLUSION

This study has allowed us to bring up to date and especially to refine the map from the “Atlante delle spiagge italiane” frequently used by coastal sites managers. Mainly of natural origins, variations noticed in the shoreline position within our study area are explained by some terrestrial processes, by interactions with the seagrass meadow, and by local hydrodynamics. Regarding the evolution of the seagrass bed extent, the unusual availability of a large-scale reference map coupled with the physical characteristics of the gulf (*e.g.*, weak water turbidity, shallow seafloor) has permitted us to here obtain good reliability for the supervised classification.

Comparison between available maps leads us to conclude that a correlation can be observed between the position of the upper limit of the seagrass meadow and that of the facing coast. Indeed, the seagrass meadow significantly affects the littoral geomorphology, being, among other things, an important provider of biogenic sediments, a control on the beach profile, and a brake on coastal water masses.

Considering the observed changes in the shoreline positions and taking into account their origins, a few protection measures are conceivable. Nevertheless, relationships resulting from the meadow extension process and the coastline evolution imply a necessity to sustain the ongoing efforts made in this protected area aimed at preserving its ecosystem.

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## □ RÉSUMÉ □

Cet article concerne l'étude de processus côtiers dans le Golfe d'Oristano (Sardaigne occidentale, Italie) où d'importants changements environnementaux ont été observés. Cette recherche, utilisant comme principal outil la télédétection, vise à évaluer l'évolution du littoral au cours du temps, sur la période allant de 1977 à 2000, et à examiner s'il existe une relation entre la tendance évolutive du trait de côte et celle de la limite supérieure de l'herbier à *Posidonia oceanica* (L.) Delile, principal écosystème en place. Les résultats obtenus montrent d'une part que certaines portions côtières, concentrées sur la partie sableuse du littoral, ont subi des variations significatives et qu'il existe d'autre part une corrélation entre l'évolution de la limite supérieure de l'herbier et la position de la côte lui faisant face. Principalement d'origines naturelles, cette tendance évolutive doit également être reliée à l'impact anthropique sur l'herbier de posidonies. Ce dernier exerce une influence capitale sur le littoral, de par son rôle de pourvoyeur de sédiments biogéniques, son contrôle sur la pente de la plage et son action de frein sur les masses d'eaux côtières.