Distribution of *Posidonia oceanica* (L.) Delile meadows around Lampedusa Island (Strait of Sicily, Italy)

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**ABSTRACT**

We present a seabed map around Lampedusa, the largest island of the Pelagie Islands Marine Protected Area (Italy, western Mediterranean). The seafloor was mapped using bathymetry and backscatter multibeam systems along with an underwater camera for direct observations and ground truthing, from the coastal area to about 50 m depth. The map was produced to monitor the present-day distribution of the *Posidonia oceanica* meadows around the Island. *P. oceanica* is the most important endemic seagrass species of the Mediterranean Sea and it can form meadows or beds extending from the surface to 40–45 m depth. These meadows provide habitat for a large marine community, thus increasing biodiversity of the coastal zone, stabilizing sediments and reducing coastline erosion. The seagrass meadows are susceptible to regression in response to specific impacts, thus their presence and abundance is an indicator of the overall environmental quality of the coastal zone. Recently, within the Marine Strategy Framework Directive (2008/56/EC), *P. oceanica* has been selected as an indicator of the Good Environmental Status for marine areas. Consequently, the Pelagie Islands Marine Protected Area launched a project to assess the conservation status and map the distribution of *P. oceanica* meadows. The resulting 1:15,000 scale map includes information about the Mediterranean seagrass and the distribution of five acoustic facies reflecting hard lithologies and soft substrates. The Lampedusa seabed map provides new information, which contributes to the development of a detailed benthic habitat map and a more comprehensive maritime spatial planning of this Marine Protected Area.

1. Introduction

Given the significant increase in accuracy and resolution of seabed imaging techniques, recent developments in sonar technologies provide new tools for seafloor exploration and data acquisition. Through a qualitative and quantitative analysis of acoustic backscatter, multibeam echo sounder (MBES) systems have been used to infer physical, geological and biological properties of the seafloor, such as surface roughness (e.g. Fonseca, Brown, Calder, Mayer, & Rzhonov, 2009; Fonseca & Mayer, 2007; Stewart, Chu, Malik, Lerner, & Singh, 1994), sediment grain size (e.g. Bentrem, Avera, & Sample, 2006; Brown & Blondel, 2009; Collier & Brown, 2005; Lo Iacono et al., 2008), substrate type (e.g. Dartnell & Gardner, 2004; Karoui, Fablet, Boucher, & Augustin, 2009), and distribution of seagrass meadows and other biota (e.g. De Falco et al., 2010; Innangi, Barra et al., 2015). Seafloor backscatter intensity corresponds to the amount of acoustic energy scattered back from the seafloor toward the echosounder receivers after the interaction with the seabed. The backscatter signal received by MBES systems can be influenced by various variables, which can be categorized into system settings (e.g. power, gain, pulse length), acoustic propagation conditions (e.g. absorption and spreading loss), beam geometry (e.g. range, incident angle, footprint size) and seafloor properties. Accordingly, in order to derive useful information about the substrate and geomorphology of the seafloor, it is important that the received backscatter signal is fully corrected so that it is invariant to system settings, propagation conditions and beam geometry, thus all backscatter changes can be related only to seafloor properties (Parnum, Gavrilov, Siwabessy, & Duncan, 2005). It has been shown that the variation of backscatter intensity is related to sediment properties (e.g. Ferrini & Flood, 2006; Goff et al., 2004; Sutherland, Galloway, Loschiavo, Levings, & Hare, 2007); fine sediments generally exhibit low backscatter intensity due to low sediment bulk density and low acoustic impedance contrast at the water–sediment interface, whereas coarse sediments generally result in higher backscatter intensity given their higher bulk density, high acoustic impedance contrast and greater roughness of the sediment–water interface (e.g. Briggs, Tang, & Williams, 2002; Simmons et al., 2010). Furthermore, it has been
shown that, for sandy sediments, backscatter intensity decreases with mean grain size (Ferrini & Flood, 2006). Accordingly, multibeam bathymetry and the related backscatter signal have been used to map benthic habitats, with the support of seafloor samples or seafloor photographs (e.g. Innangi, Barra et al., 2015; Innangi, Passaro et al., 2015; Kloster, Penrose, & Butler, 2010; Kostylev et al., 2001), and are useful in determining the presence of Mediterranean seagrass Posidonia oceanica (L.) Delile (De Falco et al., 2010; Innangi, Barra et al., 2015; Micallef et al., 2012). P. oceanica is the most important endemic seagrass species of the Mediterranean Sea and it can form meadows or beds extending from the surface down to 40–45 m depth. These meadows provide habitat for a large community, thus increasing biodiversity of the coastal zone (Gobert et al., 2006; Hemminga & Duarte, 2000), stabilizing sediments and reducing coastline erosion (Gacia & Duarte, 2001). The seagrass meadows are susceptible to regression as response to specific impact (e.g. Delgado, Ruiz, Pérez, Romero, & Ballesteros, 1999; Romero, Martínez-Crego, Alcoverro, & Pérez, 2007; Ruiz & Romero, 2003), thus their presence and abundance can be considered as an indicator of the overall environmental quality of the coastal zone. The European Union’s Habitat Directive (92/43/CEE) included P. oceanica beds among priority habitats and, according to the Water Framework Directive (2000/60/EC), each EU Member State defined the method to evaluate the health status of the seagrass. More recently, within the Marine Strategy Framework Directive (MFSFD) (2008/56/EC), P. oceanica has been selected as an indicator of Good Environmental Status for marine areas. Consequently, the Pelagie Islands Marine Protected Area launched a project to assess the conservation status and map the distribution of P. oceanica meadows. The aim of this paper is to present a high-resolution seabed map (1:15,000 scale) around Lampedusa Island, from the coast to about 50 m depth, produced through the use of an MBES system as indirect inspection along with the use of an underwater camera to validate the MBES signal through direct observations. The seabed map has been produced mainly to monitor the present-day distribution of the P. oceanica meadows in comparison to the outcomes of an analogous survey in 2006 (Coastal Consulting Exploration, 2006; Giardina & De Robeis, 2012), in order to check the state of preservation of the marine seagrass.

2. Study area

The Pelagie archipelago (Sicily, Italy) is located in the southern Mediterranean, at halfway between Sicily and Libya (35°30′13″N–12°36′25″E), arising from the northern edge of the African continental plate (Rossi, Gandolfi, Baraldi, Bellavere, & Menozzi, 2007). Lampedusa (surface area 20 km²; maximum elevation 133 m above sea level), the largest of the Pelagie islands (Figure 1), is located inside the Sicily Channel, at the southern shoulder of a Plio-Quaternary foreland rift zone that exhibits deep, NW–SE trending, fault-controlled structural depressions (e.g. the grabens of Pantelleria, Linosa and Malta). The island represents a small horst structure formed by Neogene–Quaternary carbonate sequences (Grasso & Pendley, 1985), characterized by the four main lithological units: carbonate bioclastic breccias (late Pleistocene–Holocene age); eolian dunes formed of bioclastic grainstones (late Pleistocene); wave-cut platform and sand raised beaches (late Pleistocene, Tyrrenhian); bioclastic grainstones (early Pleistocene) and limestones of the Lampedusa Formation (Tortonian–Early Messinian) (Lombardo et al., 2014). The island exhibits a subplanar surface inclined toward the southwest and is carved by deep valleys that connect with the narrow inlets along the coast. It displays rocky cliffs up to 120 m high, which outline a rugged coastline, with tens of rocky highs at a short distance from the coast, mostly occurring along the northwestern sector (Giraudi, 2004). The absolute age of Tyrrenhian marine deposits pertaining to the OIS 5e (Martinson et al., 1987) above the sea level shows that vertical movements are negligible and do not exceed the 0.0–0.19 mm/y range (Ferranti et al., 2006). Lampedusa island can be considered almost stable. The Lampedusa’s shoreline can be divided into two main sectors: in the north (from Capo Ponente to Capo Grecale) they are indented, with dominant coastal features varying from steep to sub-vertical cliffs, along with small promontories and bays; in the south, the coast gradually slopes down and includes pocket beaches in the coves. Among the beaches, the ‘Isola dei Conigli’ is the largest and most famous, mainly due to its environmental relevance as an area where the Caretta caretta L. sea turtles deposit their eggs.

3. Methods

Before the beginning of the survey, the sidescan sonar data from 2006, acquired within the framework of former ‘Mappatura morfo-batimetrica di Lampedusa’ project (Coastal Consulting Exploration, 2006), were processed using the software Triton Perspective (Figure 2(a)). On the basis of these data, a draft map marking P. oceanica boundaries was produced (Figure 2(b)) and used to plan the new data acquisition. The sectors marked with the question mark in the legend on Figure 2 were areas of uncertain interpretation.

In April 2015, a bathymetric survey was carried out aboard the M/B ‘Risal’, in order to map the whole margin of Lampedusa Island, in the 2–50 m depth range. The survey was done using a pole-mounted Reson
SeaBat 7125, a multi-frequency MBES (200–400 kHz) that provides sub-centimetric depth resolution data (Table 1). The vessel was equipped with a Trimble BX982 HP-XP Oministar Differential Global Position System and an Ixsea Octans Subsea 3000 that provide positioning data (with sub-meter accuracy) and attitude data (0.01° accuracy) to the navigation software. A Valeport Mini SVS Sound Velocity Sensor was installed near the transducers, thus providing real-time sound speed for beam steering, a process that allows examination of the sounds coming from different angles simultaneously (L-3 Communications Sea-Beam Instruments, 2000). A sound velocity profiler, Reson SVP15, was lowered through the water column every 6–8 h to get the velocity profile required for the depth computation. Reson PDS2000 software was used for positioning and logging MBES data (see Di Martino, Innangi, Felsani, Giardina, & Tonielli, 2015). Data were acquired using the 400 kHz frequency, in the equi-distant mode to ensure the highest resolution. The survey navigation lines were run parallel to the coast with an overlap of 20% between adjacent swaths (Figure 3). Furthermore, corrections for tide were applied in order to relate all data to the averaged sea level.

Table 1. Technical characteristics of the multibeam Reson SeaBat 7125.

| Parameter                      | Details                                      |
|-------------------------------|----------------------------------------------|
| Frequency range               | 200–400 kHz                                  |
| Max ping rate                 | 50 Hz ±1 Hz                                  |
| Along-track beam width        | 2° at 200 kHz & 1° at 400 kHz                |
| Across-track beam width       | 1° at 200 kHz & 0.5° at 400 kHz              |
| Pulse length                  | 30–300 μs Continuous Wave 300–20 ms FM (X-Range) |
| Number of beams               | 512 EA/ED at 400 kHz 256 EA/ED at 200 kHz   |
| Max swath angle               | 140° in ED Mode 165° in EA Mode              |
| Typical depth                 | 0.5–150 m at 400 kHz 0.5–400 m at 200 kHz    |
| Max depth                     | >175 m at 400 kHz >450 m at 200 kHz          |
| Depth resolution              | 6 mm                                         |

The bathymetric data were processed using the PDS2000 software. Data de-spiking was carried out without the application of automatic filters, in order to preserve data accuracy and resolution. Finally, a Digital Terrain Model (DTM) with a 2.5-m grid cell size was produced. The northern sector of the island (Figure 3; 2.5 km wide), where no P. oceanica meadows had ever been reported previously (see also Figure 2), was not surveyed in 2015. Instead, as agreed with the MPA, it was decided to acquire the whole sector outside the boundary of the MPA (Figure 3). Thus, the new DTM was compiled by integrating the bathymetric data acquired in 2006 with Reson SeaBat 8125 data. In addition to bathymetric information, the sidescan-like option of the Reson 7125 was used to log the backscatter intensity of the seabed: bathymetric beams on the port and starboard sides (respectively 0–119 and 120–239 for the sonar used here) are combined to produce the sidescan-like images (see Innangi, Barra et al., 2015). The sidescan-like data processing was carried out using the software SonarWiz 6.1, which is able to visualize and analyze backscatter data from both multibeam and sidescan sonars. The processing workflow included the following steps: smoothing the navigation data; adjusting the TVG (Time Variable Gain), and applying geometric and radiometric corrections (see Beaudoin, Hughes Clarke, Van Den Ameele, & Gardner, 2002). A 2.5-m resolution DTM with a 5-m linespacing contour (Figure 4) and a 20-cm resolution acoustic backscatter mosaic (Figure 5) were obtained from the processed MBES data. Ground truth of the seafloor acoustics facies and mapping of the lower limit of the P. oceanica meadows were carried out in selected sites through video-camera inspections. For this purpose, a GoPro Hero 3 White camera with 1080p30 resolution, 5 MP photos with 3 fps burst mode with integrated flat lens housing, remotely
Figure 2. Panel A shows a sidescan sonar acoustic mosaic of data acquired in 2006 and re-processed in 2015 (20 cm x pixel resolution). Panel B shows the draft map produced with the interpretation of the sidescan sonar mosaic.

Figure 3. The map shows: navigation lines of multibeam data; positions of the collected underwater video inspections with frames reported in Figure 6; Marine Protected Area boundary. In addition, two sectors are shown in the figure: in the north, the area not surveyed in 2015, in the south, the new acquisition area surveyed in 2015, outside the MPA boundary.
controlled, was used. Figure 3 and Table 2 show the locations and the coordinate points of the video records. All collected information (bathymetry, side-scan-like mosaic and video investigations) were analyzed in a geographical information system (GIS), manually digitizing a seafloor map on the basis of the recognized acoustic facies (e.g. De Falco et al., 2010; Innangi, Barra et al., 2015; Kiparissis et al., 2011; Truffarelli, Belluscio, Criscioli, & Ardizzone, 2012).

In order to map the very shallow water areas, unsurveyed in the 0–2 m bathymetric range, the swath mapping was integrated with satellite images of the Italian National Data Portal (http://www.pcn.minambiente.it/GN/) (Figure 4(a)).

4. Results and discussion

4.1. Bathymetric data

The DTM shows a very rugged seafloor all around the island in the first 20 m depth, due to extensive rocky outcrops, localized talus deposits, relict morphologies and ‘matte’ of the *P. oceanica* meadows (Figure 7).

**Table 2.** Geographical data of the underwater video inspections.

| Video | Latitude  | Longitude |
|-------|-----------|-----------|
| Video 1 | 35°31.19’N | 12°31.01’E |
| Video 2 | 35°30.75’N | 12°31.23’E |
| Video 3 | 35°30.40’N | 12°31.48’E |
| Video 4 | 35°30.37’N | 12°33.28’E |
| Video 5 | 35°30.58’N | 12°37.95’E |
| Video 6 | 35°30.79’N | 12°37.90’E |

The matte is a monumental biological construction that the seagrass is able to build, resulting from horizontal and vertical growth of rhizomes with entangled roots and entrapped sediment (Francour, Magréau, Mannoni, Cottalorda, & Gratiot, 2006). In the north, off Punta Muro Vecchio and Punta Ruperta, the seabed slopes steeply at an angle of about 5° in the depth range between 10 and 50 m. In the south, off Isola dei Conigli, an extensive terraced platform develops over about 7 km² at a low gradient (about 1.10°) between 10 and 46 m depth. A small number of terraced surfaces occur around the island, namely T1, T2, T3, T4 and T5 in Figure 4, with angles ranging between 0.7° and 2.6°. These features are sedimentary bodies outcropping on the sea floor at shallow depths (generally within –150 m), with a wedge-shaped geometry, and can be interpreted as relic submerged depositional terraces formed in the coastal environment, below the lower limit of wave-storm action (Hernández-Molina et al., 2000; Pepe et al., 2013). Their absolute age, in stable areas, is meaningful as a palaeo-environmental proxy of past stages of standing sea level (Chiocci, D’Angelo, & Romagnoli, 2004). The depositional terraces have always been found on rather steep and narrow continental shelves, typical of insular, volcanic or tectonic-controlled coasts (Chiocci et al., 2004).

4.2. Backscatter data

The acoustic mosaic is presented using a gray color scale, with high backscatter corresponding to darker...
grays and low backscatter shown in lighter grays (Figure 5). The soft seabed was classified mainly on the basis of its acoustic facies response (i.e. fine sediments exhibit low backscatter) and consistent video inspections, thus a qualitative description of bottom sediments was adopted rather than a quantitative evaluation of the grain size. Figure 5 includes some details: sector A off Cala Creta and Cala Pisana (Figure 1) reveals an alternating coarse and medium-fine sand; along area B, north of Capo Ponente, coarse sand facies are overprinted by ripples or by an irregular distribution of *P. oceanica*. In the same area, a short distance from the coast, high reflective acoustic facies, typical of boulders and pebbles-sized sediments are recognizable. In area C, west of Isola dei Conigli, high acoustic variability can be detected, due to alternating coarse (dark area) and fine (light area) sand patches and dense *P. oceanica* meadows. In the same area, the ‘matte’ structures from *P. oceanica* can be recognized. Finally, area D, the new area acquired in 2015 (Figure 3), revealed extensive and well-developed *P. oceanica* meadows.

### 4.3. Video inspections

Direct inspections (Table 2 and Figure 3) were located in selected sites to calibrate the acoustic facies. Additional sites were also investigated to identify the lower limit of the *P. oceanica* meadows and complete the scientific aims of this study. In Figure 6 sampled frames of the video records are reported with the corresponding seabed topography and acoustic facies. Video number 1 was useful to identify the nature of the rugged seabed and the spotty acoustic facies along the coast in the N–NW area, off Capo Ponente and Muro Vecchio, between 5 and 10 m depth. The images document the occurrence at the seafloor of very coarse heterogeneous materials (well-rounded pebbles and boulders) in poorly sorted calcareous gravels, forming a terraced surface at the foot of the submerged cliffs. This formation was interpreted as a foot-cliff deposit generated by the wave-related winnowing of talus, likely derived by progressive cliff failures (Robinson, 1977). Video number 2 was recorded off Punta dell’Acqua, in the southwestern sector of
the island, to characterize some distinctive acoustic facies, consisting of medium-low backscatter, reflected by an irregular seafloor made of shortly spaced v-shaped furrows: the video revealed the presence of *Cymodocea nodosa* (Ucria) Aschers on a hummock sandy seabed, at a depth range between 10 and 38 m. Video number 3 was recorded off Punta dell’Acqua as well, at about 40 m depth, and showed a dune field with crests NE–SW oriented, on an undulating soft seabed (medium-fine sands). Dune crests are asymmetric toward the SW, have a wavelength of between 25 and 50 m and a maximum height of about 2 m (Figure 7). Video number 4 was located 450 m south of Isola dei Conigli, in order to identify the extent of the *P. oceanica* meadows. In this area, meadows gradually thin out, both in density of leaves and height, down to 38 m depth, where the lower limit can be traced. Video number 5, recorded at 30 m depth off Cala Creta and Cala Pisana, documented the absence of any seagrass, instead Video number 6, located at a 25 m depth off Cala Creta, revealed well-developed and dense *P. oceanica* meadows over a coarse-grained bottom, also identified on the acoustic mosaic (see Figure 5(a)).
4.4. Seabed map

A GIS has been implemented with morphobathymetric, ground truth information and aerial photos to support the drafting of a high-resolution seabed map of Lampedusa Island, at a scale of 1:15,000 (Figure 8 and Main Map). A description of the map and legend is given.

4.5. Seagrasses

A distinction from the *P. oceanica* meadows and the *P. oceanica* meadows in patches was achieved as overprinted symbols; this distinction is relevant to differentiate the distribution of the seagrass as dense and spread meadows with often the presence of ‘matte’ (see Figure 5(c)), from meadows in patches, where the distribution of the seagrass is more irregular and discontinuous, without ‘matte’ (see Figure 5(b)). Another layer was added, scattered tuft of *P. oceanica*, to indicate the presence of seagrass without meadows or defined boundaries, as reported by the scuba investigations carried out by the former project of the MPA (Giardina & De Robeis, 2012).

One last overprinted symbol was used to map the *Cymodocea nodosa* meadow, identified by the underwater camera, backscatter and bathymetry (see Figure 6, Video 2).

4.6. Lithofacies

Five main categories of loose deposits have been identified, which refer to the most common sediment types occurring in the area.

- **Fine sands to pelitic sands (FS):** facies characterized by the lowest and most homogeneous backscatter values (light area in the mosaic), occurring in the lower infralittoral sectors.
- **Medium sands to medium-fine sands (MS):** facies presenting intermediate backscatter values and a mostly homogeneous signal, corresponding to a smooth and regular seafloor.
- **Medium to coarse sands and gravels (CS):** presenting high backscatter values and corresponding to the darkest area in the mosaic and to a rugged seafloor, usually wrinkled by ripples.
- **Boulders, pebbles, gravel (B), and Bedrock (R):** both facies present the highest backscatter values and shadows; these are commonly colonized by scattered tuft of *P. oceanica*.

4.7. Other information in legend

Other information included in the map are: the location of the video inspections and their frames, the 10 m line-spacing contour and the bed forms of *Ripples* and *Dunes field*, that were also traced as overprinted symbols.

4.8. Distribution of *P. oceanica* meadows 2006–2015

Since the main purpose of this work was monitoring the distribution of the *P. oceanica* meadows after 10 years, a comparison between the *P. oceanica* meadow mapped in 2006 and that mapped in 2015 was carried out (Figure 9). Only the layers of the meadows, either continuous or discontinuous, were considered in the analysis (without tuft). The 2006 layers are those of Figure 2. As can be seen in Figure 9, there are no sharp differences in the distributions after 10 years, and some improvements in our detailed mapping are

![Figure 7](image-url). The dune field, NE–SW oriented. The profile shows a wavelength between 25 and 50 m and the 2 m maximum height. In the right-up it is possible recognize the relict structures of *P. oceanica* ‘matte’. 
Figure 8. Seabed map of Lampedusa Island.

Figure 9. Comparison between the $P.~oceanica$ meadows mapped in 2006 and in 2015. Sector A encloses the area without meadows while sector B encloses the area surveyed in 2015.
due to the improved resolution of the acoustic acquisition and to the contribution of the video ground truth and satellite images.

5. Conclusions

Acoustic backscatter and bathymetric data derived from MBES surveys allowed the production of a high-resolution map of Lampedusa Island inner shelf environments between 0 and 50 m depth. The map provides a necessary baseline of the present-day distribution of *P. oceanica* for upcoming monitoring activities of the seagrass health status. The outcomes highlighted that the marine seagrass grows both on sandy and rocky substrates, forming wide meadows. The greatest development of *P. oceanica* was observed south of the island, where it extends below 40 m depth and ‘matte’ morphologies are present (Figures 5(c) and 7 right-up). To the northwest of the island, even though *P. oceanica* reaches a depth of about 30–38 m, less dense and more discontinuous patches were observed. In conclusion, comparing the data with those acquired in 2006 (Figure 9), the distribution of the *P. oceanica* meadow had not substantially changed over the last 10 years.

**Software**

Bathymetric data were processed with PDS2000, as well as the final DTM. The sidescan-like data were processed using Triton Perspective and with SonarWiz 6.1. The final mosaic was optimized with Global Mapper. The Main Map was produced using with Esri ArcGIS.

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