Using vertical sidescan sonar as a tool for seagrass cartography. Estuar Coast Shelf S

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5 AUTHORS, INCLUDING:

Noela Sánchez-Carnero
University of Vigo

Juan Freire
Teamlabs / inViable

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Using vertical Sidescan Sonar as a tool for seagrass cartography

N. Sánchez-Carnero[a,*], D. Rodríguez-Pérez[b], E. Couñago[c], S. Aceña[a], J. Freire[a,1]

[a] Grupo de Recursos Marinos y Pesquerías, Universidade da Coruña, Rúa da Fraga 10, A Coruña 15008, Spain
[b] Dept. Física Matemática y de Fluidos, Universidad Nacional de Educación a Distancia, Senda del Rey 9, Madrid 28040, Spain
[c] Kartenn, Tecnologías para la Gestión Ambiental y Territorial, Capitan Juan Varela 35, A Coruña 15007, Spain

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ABSTRACT

An acoustic method, a vertically oriented Sidescan Sonar (SSSv), is used to detect and map *Posidonia oceanica* meadows in the bay of Agua Amarga (SE of the Mediterranean coast of Spain). Sidescan sonar, among other active hydroacoustic techniques, has shown its ability to detect, map and monitor seagrass based on its acoustic backscatter; however, some limitations linked to its power based approach have been reported in the literature. Our method is based on the SSSv measurement of canopy height distribution, making the most use of the SSSv acoustic data and using existing algorithms as statistical mapping methods. The results show a spatially coherent and statistically consistent classification. The comparison with groundtruthing is difficult due to the steep variations in the seafloor cover found in the area of interest, nevertheless the validation is successful (proving low-order discrimination) in a zone with a large range of depth variations (0–25 m).

1. Introduction

The biological relevance of seagrass meadows worldwide has been widely studied and showed they are highly productive ecosystems of ecological and economical importance (see Pollard, 1984; Heck and Valentine, 2006). In the Mediterranean Sea, *Posidonia oceanica* is the most frequent seagrass (Den Hartog, 1970; Lipkin et al., 2003; Belzunce et al., 2005; Diaz-Almela et al., 2007), developing extensive underwater meadows, distributed up to 30–40 m deep (Den Hartog, 1970; Boudouresque et al., 2006), although they can be found at 40–50 m in very clear waters (Duarte, 1991; Olesen et al., 2002). These meadows play a fundamental and varied role in the metabolism of the neritic system, not only regarding the production of living substances, shelter and reproductive grounds for species of economic interest, but also for the maintenance of abiotic equilibria such as sedimentation, concentration of dissolved gases and nutrients (Colantoni et al., 1982).

In recent decades *Posidonia oceanica* has experienced a widespread decline throughout the Mediterranean Sea (Benedito et al., 1990; Sánchez-Lizaso et al., 1990; Marbà et al., 1996; Ardizzone et al., 2006; Boudouresque et al., 2006). The increase of the coast contamination and deterioration, boat anchoring, bottom trawling or climate change, among others, are causing *P. oceanica* meadows regression (Peirano et al., 2005; Diaz-Almela et al., 2007). This decline might result in a significant problem for ecosystem preservation.

Because of the important role of underwater meadows in the marine environment and their value as bioindicator (Colantoni et al., 1982; Komatsu et al., 2003; Descamp et al., 2005), it is important to assess their spatial distribution and biomass and to identify their species composition. In this respect, several direct and indirect methods have been developed to evaluate the ecological status of the *Posidonia oceanica* and other species meadows (e.g. Giraud, 1977; Ott and Maurer, 1977; Fresi and Saggiomo, 1981; Meinesz et al., 1981; Belsher et al., 1988; Buia et al., 1992; Marbà et al., 1996; Boudouresque et al., 2000; Marcos Diego et al., 2000; Pasqualini et al., 2001; Di Maida et al., 2011).

Various techniques have been used in the past to map and monitor seagrass. Direct sampling techniques provide accurate localised data, but are time and labour intensive and provide little insight into the spatial distribution. Optical remote sensing has been often the preferred method for seagrass mapping of intertidal areas, although in submerged areas, it is limited by water clarity, cloud coverage and sea surface roughness (Vis et al., 2003) and frequently results in systematic underestimation of the extent of seagrass (McCarthy and Sabol, 2000).

Active hydroacoustic techniques have shown the ability to detect seagrass. The acoustic impedance difference between water

* Corresponding author.
E-mail addresses: noela.sanchezc@udc.es (N. Sánchez-Carnero), daniel@dfmf.uned.es (D. Rodríguez-Pérez), elena.counago@kartenn.es (E. Couñago), s.acenam@udc.es (S. Aceña), jfreire@udc.es, juan.freire@gmail.com (J. Freire).
[1] Present address: Barrabés Next, Serrano 16, Madrid 28001, Spain.

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and aquatic vegetation, due to the tissue density, which is different from its surrounding medium, and the voids within the tissue and gas bubbles surrounding it (Wilson and Dunton, 2009), produces a stronger backscatter response well above the water column signal. Hydroacoustic monitoring techniques are sufficiently low-cost, neither time-consuming nor labour-intensive, and permit the synoptic coverage of a large area. For these reasons, they have been found useful for detecting and characterising submerged aquatic vegetation in fresh water (Maceina and Shireman, 1980; Maceina et al., 1984; Duarte, 1987; Thomas et al., 1990) and in sea water (Spratt, 1989; Miner, 1993; Carbo and Molero, 1997; Bozzano et al., 1998; Sabol and Burczinski, 1998; Sabol et al., 2002; Tegowski et al., 2003; Di Maida et al., 2011; Paul et al., 2011).

Acoustic single-beam systems have been used for the discrimination of different bottom types (Brouwer, 2008; Orlowski, 2009; Serpetti et al., 2011; among others), including specific works for seaweed (Komatsu, 2007; Minami et al., 2010) and seagrass (Sabol et al., 2002; Tegowski et al., 2003; Valley et al., 2005) cartography. These acoustic methods usually use cheap and readily available equipment (Satyanarayana et al., 2007). Most of those works report good mapping results but with quantitatively varying accuracies, depending on the diversity of bottom types in the study area, its topography, the types of subaquatic vegetation, etc. However, being based on the acoustic response of the shoots, their detection capabilities depend on the day photosynthetic activity (Wilson and Dunton, 2009), the depth range, and the shoot density integrated within the acoustic footprint of the single-beam echosounder (Tseng, 2009). Also, being transect based, spatial interpolation is required.

Multibeam echosounders acquire acoustic data from the entire bottom, thus avoiding the need of interportation and notably improving the single-beam spatial resolution. However, being based on the backscattered energy, they again suffer from the depth range and shoot density limitations of the single-beam. Furthermore, the use of a multibeam echosounder greatly increases the survey costs, has a steep learning curve, and requires complex calibration and backscattering processing, and water column backscattering data are not always available (Heyman et al., 2007; Anderson et al., 2008; Di Maida et al., 2011).

Cuvelier (1976) proposed the use of the Sidescan Sonar (SSS) as a rapid and reliable means of mapping *Posidonia oceanica* beds and monitoring their evolution; in fact, SSS offers both the desirable overall view and the necessary detail, accompanied by a great versatility and relatively low operational costs (Colantoni et al., 1982). Despite the fact that some authors have recently questioned SSS efficiency for the discrimination of seabed cover (Van Rein et al., 2011), others find it advantageous as a technique for rapidly mapping and determining the degree of deterioration or recuperation of seagrass meadows of *Posidonia* sp. or *Cymodocea* sp. (Siljestrom et al., 1996; Pasqualini et al., 1998). However, SSS data are usually analyzed by image interpretation techniques (often, visual interpretation), so results can be subjective (Anderson et al., 2008).

A different approach to subaquatic vegetation mapping is based on canopy geometry discrimination. Sabol et al. (2002) used a single-beam echosounder (with depth resolution of 7 cm) to discriminate between three seagrass species, with moderate success. Recently, high resolution (between 1.5 and 4.7 cm) height measurements using a sediment imaging sonar have been used to perform species classification using a Sediment Imaging Sonar (Paul et al., 2011) obtaining good results but within a very limited spatial coverture and in zones where only one species is known to exist (the work focuses on seagrass coverage mapping).

The objective of this paper is to present and validate an acoustic method to map *Posidonia oceanica* meadows from their height distribution, using a variation of Sidescan Sonar adapted to improve vegetation detection and shoot height measurement, and assess its potential for coexisting species discrimination and mapping.

2. Material and methods

2.1. Study area

The study area was the bay of Agua Amarga, in the Natural Park of Cabo de Gata, located in the SE of the Mediterranean coast of Spain (Fig. 1). This area is an open bay, oriented to SE, with an area of 15 km^2 covered by a thin layer of calcareous conglomerate/sand beach deposits (up to 5 m thick) on top of calcareous rock (Martín et al., 1996).

Posidonia oceanica is widely distributed in this area located from 5 to approximately 25 m deep, and with a high annual net shoot recruitment rate and also one of the highest in the Spanish Mediterranean (Marbà et al., 1996). *Posidonia oceanica* has leaf bundles consisting of 5–10 broad leaves. The leaves are about 1 cm wide and have lengths usually from 20 to 40 cm but may be up to 1 m (Borum and Greve, 2004). Another seagrass species usually associated with *P. oceanica* meadows is *Cymodocea nodosa*, that distributes along the boundaries of *P. oceanica* meadows. *Cymodocea nodosa* has leaf bundles consisting of 2–5 leaves. The leaves are 2–4 mm wide and from 10 to 45 cm long. Other seagrass species such as *Zostera noltii*, and macroalgae species, are also present (IUCN, 2010).

2.2. Sidescan Sonar operation

Sidescan Sonar refers to a single beam transducer with a broad transversal angle and a very narrow longitudinal angle. This type of transducers usually work at high frequencies, between 100 and 1000 kHz, and are mounted in a towfish to avoid any sort of perturbations from the vessel. SSS operates as an acoustic imaging device that provides wide-area, high-resolution pictures of the seabed and, because of its low slant angle orientation and high frequencies, allows users to study the textural characteristics of the seafloor thus being ideal for object detection. However SSS images are not usually endowed with a bathymetric information (Kenny et al., 2003) without resorting to interferometric SSS (Stewart and Marra, 1994). Also, SSS image postprocessing software largely relies on subjective visual interpretations of textures, as opposed to the objective image processing and classification of single-beam or multi-beam techniques (Anderson et al., 2008).

In this work, an EA400P Sidescan Sonar echosounder (Simrad, Norway) was placed onto the hull ride of the boat (the way portable single-beam and multi-beam echosounders are often deployed). The frequency used was 200 kHz. This allowed pings of 256 μs of duration still bearing a good signal to noise ratio (shorter pulses would theoretically have better depth resolution, but noise would make boundary detection impractical). The ping rate was set to maximum (about 1.4 ping/s in the surveyed area). The beam angle had a swath amplitude of 49° and 0.5° was in the along track direction (see Fig. 2). Its orientation, usually horizontal, was changed to a quasi-vertical orientation (Fig. 2), thus allowing us to take advantage of the beam angle configuration, to measure depths and heights above the sea bottom. In this way, SSS with vertical orientation (SSSv), works like a vertical single-beam echosounder, but with some advantages regarding its capability to detect any emergent structure above the seafloor, conferred by its beam angular configuration.

Since *Posidonia oceanica* is frequently distributed in meadows or in patches on sandy bottoms, the use of SSSv increases the probability of seagrass insonification before the wavefront reaches the sandy sea bottom. Given that our method aimed statistically to

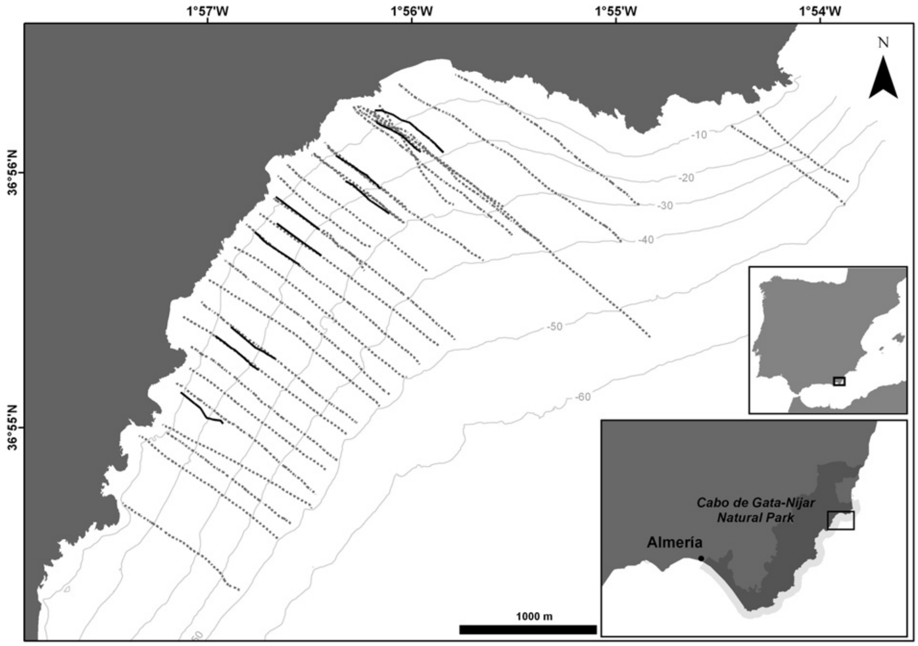

Fig. 1. Survey area with acoustic (dotted lines) and diving (solid lines) transects in Cabo de Gata (SE Spain).

characterize the vegetation heights, the avoidance of pings with missing plants will be paramount. Thus, the alongship narrow and athwartship wide insonification area, provides a more statistically meaningful seagrass height detection, compared with a narrow single beam echosounder (such as Sediment Imaging Sonar). Moreover, the high working frequency and ping length allows us to obtain a high vertical resolution (4.8 cm), while minimizing the diffraction processes, improving seagrass detection and height measurement.

2.3. Field work

2.3.1. Acoustic survey

The acoustic survey was carried out on November 3rd and 4th, 2007. Although *Posidonia oceanica* usually decreases in height around this month (Sánchez Lizaso, 1993), previous observations in the study area, by the authors or area users (fishermen), among others, reported lush meadows in this month and small variations along the years. A small oceanographic vessel (12 m long) was used and the survey was carried out under good weather conditions (i.e. with negligible pitch and roll movements of the boat). The boat speed was kept ca. 4 knots. The transducer was located approximately 0.5 m below the water surface.

Fig. 1 summarizes the survey. It consisted of 30 transects, almost perpendicular to the coastline, from 5 to 50 m in depth, covering a total length of 48 km in an area of 9.5 km^2. Distance between contiguous transects was kept between 150 and 200 m. Positions were recorded into the echosounder files using a Simrad GN33 GPS signal input.

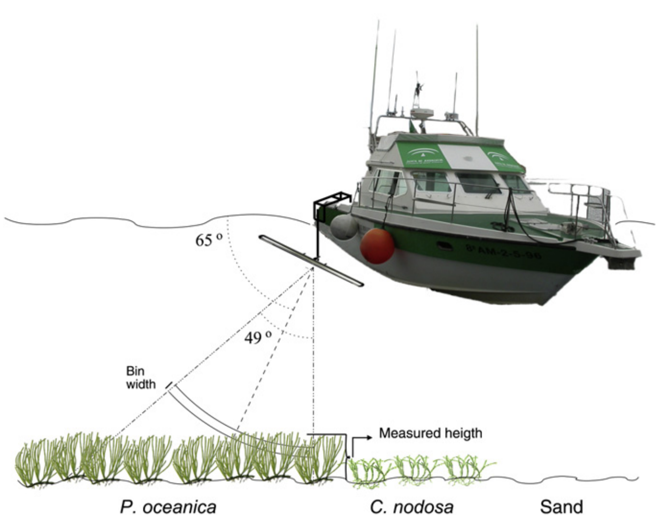

Fig. 2. Height measurement of sand and seagrass bottoms with a Sidescan Sonar with vertical orientation (SSSv).

2.3.2. Ground-truthing

In order to obtain data to validate the acoustic records, scuba diving transects were carried out in the study area. Two were performed on November 2007, short after the acoustic survey and other 8 transects were run on February and April 2009, for completion. A previous exploratory analysis of the echograms was carried out, with the aim of concentrating the maximum of seabed variability in the ground-truthing data. This led to the selection of those transects with the highest variability in bottom type (attending to the vertical structures observed over the bottom). The diving transects were planned approximately parallel to the acoustic transects, at a distance coincident with the center of the acoustic beam.

Ten scuba diving transects covering 400 m each, were carried out (Fig. 1). The average distance from these diving transects to the acoustic ones was about 21 m (comparable to the 6 m employed by Paul et al. (2011) in shallow waters, 8 m deep). Starting at the head of each transect, the boat released a weighted rope, with marks every 5 m, until reaching the ending point of the transect. Divers noted every change observed in the seabed regarding presence, distribution and relative status (visually assessed) and height (measured with a ruler) of the *Posidonia oceanica* (see Table 1) and recorded where in the transect the changes took place.

As the boat and water motions could modify the rope trajectory, to correct any deviation, divers pulled their security buoy to signal

Table 1
Definition of rating used to describe the variables calculated from the video and divers data.

Parameter	Options
Bottom type	Sand
	Gravel
Species	*P. oceanica*
	C. nodosa
	Macroalgae
Distribution	Absence
	Meadows
	Patches
Seagrass status	Leafy
	Disperse
Canopy height	(in cm)

the measurement points. Then the boat approached and recorded the GPS data (similar to Pasqualini et al. (2000)).

All the transects were also recorded with an underwater high resolution video camera (HDR-HC1E, Sony), bearing an illumination system consisting of two flexible bead arms each with a 50 W light. The videocamera was held by the divers approximately 40 cm above the sea floor, keeping within the video field the weighted rope and a representative area of the seafloor and vegetation around the rope (see photograms in Fig. 4).

2.4. Data processing

2.4.1. Acoustic data

Submerged vegetation usually produces a strong backscatter just above the bottom to a height that depends on canopy height (Sabol et al., 2002). Because of this, an analysis of the first tens of centimetres over the sea bottom in the echograms, allows to study the presence and characteristics, coverture and height, of the seagrass (Thomas et al., 1990; Lefebvre et al., 2009; Paul et al., 2011).

The acoustic data acquired with the echosounder was saved to RAW files (one per transect) containing the reflected intensity in the form of digitized pings. The RAW files also stored the information from the accompanying Simrad GN33 GPS in NMEA format. For each ping, the values of the digital samples (bins) were read from the RAW files. The bins within the first 2 m below the transducer were discarded, as their information only contains near field acoustic reverberation. Then the bin with the highest intensity in the ping is found (corresponding to the maximum reflected power from the seabed) and the beginning of that bottom signal is determined as that another bin, closer to the sea surface, where the acoustic bounce intensity is 30 dB smaller than that maximum. This threshold and the vertical alignment of the transducer beam, ensure that the acoustically harder part of the sea bottom (the sand or rock bottom) is correctly identified.

Once the bottom was detected, water column noise level was evaluated for every ping. The average value of the bin intensity in the ping's 20 nearest neighbour pings at heights from 1 to 3 m above the bottom were taken as the water background noise level. Based on the literature (Borum and Greve, 2004), we may consider that only the first metre above the bottom may contain the aquatic plants of interest. Then, the water background energy value was used to differentiate bottom vegetation from the inherent water column scattering noise. In that ping, any signal within 1 m from the sea bottom, and with an appreciable intensity higher than the threshold given by the ping's water column scattering noise plus 10 dB was considered to be vegetation. This 10 dB threshold was determined from visual inspection of the aligned echograms. Since water column noise level presents significant differences, a single absolute threshold cannot be applied for canopy height detection (Paul et al., 2011). Fig. 3 illustrates the steps of this algorithm.

The measured canopy height for each ping was georeferenced and saved in ASCII format to be imported into a GIS. Given that all the data processing is described in terms of bin intensity level comparison, no power corrections (time-variable gain) were needed. Also, as the transducer was vertically oriented, and the first return echo was almost that of a vertical path, no geometric height or position correction were needed. The previous algorithm was run using the Octave based open source software *ecosons seagrass* available in http://www.recursosmarinos.net/download/SSSv.

2.4.2. Ground-truthing processing

Scuba diving transect trajectories were corrected for departures from the straight line joining the transect head and end points using the GPS marks recorded at the security buoys during the transects. The video recorders were replayed slowly to allow adequate time to make observations. Every observed seabed change was recorded and referenced to the transect length using the 5 m marks visible in the rope. The seabed characteristics were defined as shown in Table 1, in order to compare it with the on-site observations noted by the divers. The scuba diver notes and the video classification were downloaded into a GIS database and associated to the transect trajectories exported by the *ecosons seagrass* software. Scuba diver records were used for acoustic data validation after testing their good match with the continuous video

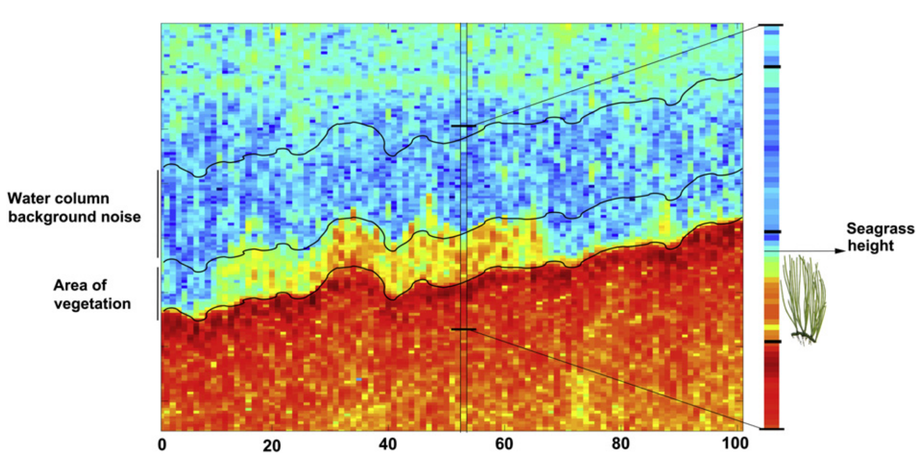

Fig. 3. Scheme of the computation of vegetation heights on an echogram. The water column background noise is apparent in the 1–2 m area above the detected bottom. Also a detail of a sample ping is shown (right) illustrating the determination of the canopy top within the 0–1 m band above the bottom.

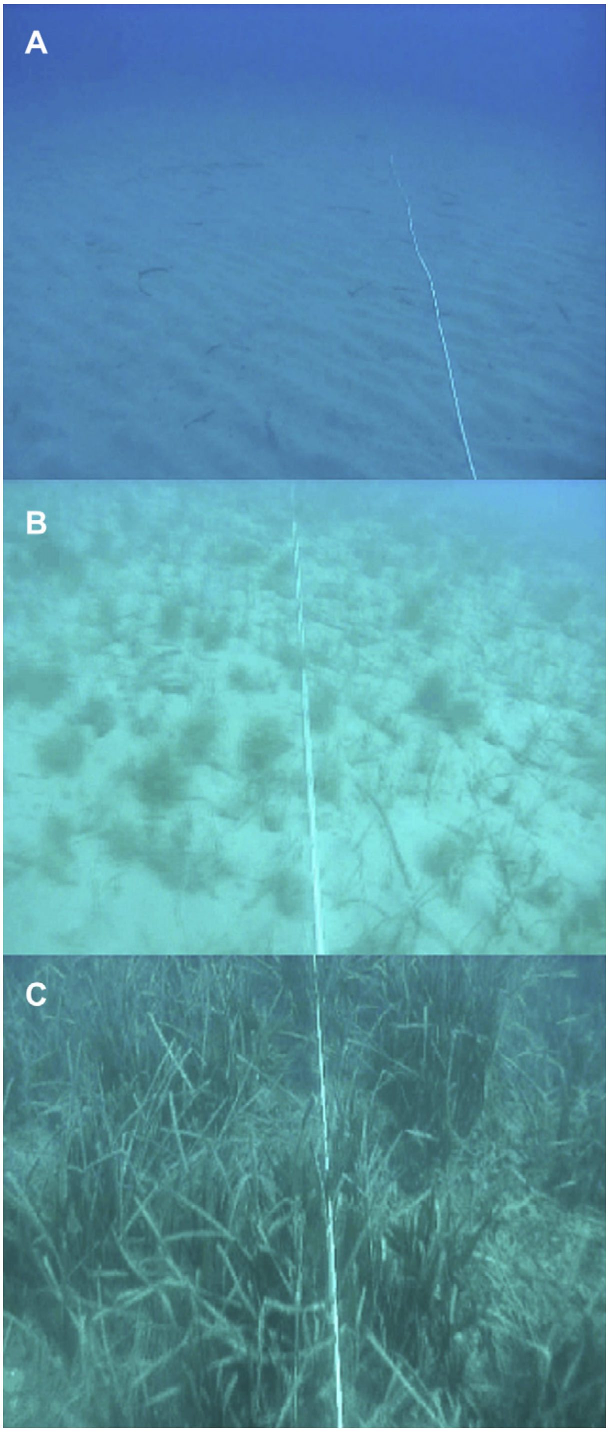

Fig. 4. Types of seabed classified according to the presence and structure of *P. oceanica* beds. (A) Sandy bottom, (B) *C. nodosa*, and (C) dense *P. oceanica* beds.

recordings (i.e. that both data sources correspond to the same bottom class and qualitative features, ensuring that no transcription errors occurred). The different seabed combinations (Table 1) were reduced to five main seabed types: three homogeneous types (Fig. 4), one mixed type (bottoms classified as *Posidonia oceanica* with interspersed *Cymodocea nodosa* patches and vice versa) and another type called "others", to simplify the acoustic classification of the study area. For instance, sandy bottom with isolated groups of dense *P. oceanica* was considered as *P. oceanica* as the large observed heights fit better within this class.

2.4.3. GIS

We used a GIS statistical procedure to obtain a map of the study area using ArcGis 10.0 (ESRI) and the R statistical package. The process involved three steps: computation of the height histograms of the different seagrass (end-members of the classification), computation and interpolation of the log-likelihood functions (using the histograms), and selection of the most likely seabed covert. To compute the height histograms, the computed seagrass heights georeferenced were arranged in a database and related to seabed classification (from scuba divers). This correspondence was obtained associating to each SSSv ping the bottom type defined by the nearest point in the nearest groundtruthing transect. Since data recorded with SSSv and groundtruthing were not spatially coincident it was required to establish a maximum distance for this comparison. This radius, r_{op}, of the groundtruthing neighborhood was determined as the one providing the best validation results for the classification process following Scardi et al. (2006), in our case, 50 m. Pings with no groundtruthing point closer than this distance were not considered to compute the histograms. The different histograms used for the classification are shown in Fig. 5. Monte Carlo simulations showed that random samples extracted from these histograms could be classified with less than 5% error using the maximum likelihood (ML) method if more than 100 samples were taken, corresponding (at the speed the transects were sailed) to about 35 m (hence 50 m lays above this lower bound). The height frequency histogram was computed (using the R statistical package) for each seabed type, taking as interval width the bin width (4.8 cm). These (normalized) histograms provide the empirical height probability distributions of their respective seabed types.

Three different classifications, from the main seabed types (*Posidonia oceanica*, *Cymodocea nodosa* and sandy bottom) were performed, in increasing order of complexity: (1) *P. oceanica* meadows and no-*P. oceanica* meadows (that include *C. nodosa* meadows and sandy bottom); (2) *P. oceanica* meadows, *C. nodosa* meadows and sandy bottom; and (3) homogeneous *P. oceanica* meadows, homogeneous *C. nodosa* meadows, mixed bottoms (bottoms classified as *P. oceanica* with interspersed *C. nodosa* patches and vice versa) and sandy bottoms.

Around each ping, the seabed type can be then estimated through an ML approach, where the "parameter" to maximize is the seabed type to which that ping (and its neighborhood local histogram) belongs. For each seabed class, the log-likelihood of the observed heights around each ping, can be computed as the average logarithm of height frequencies (determined from that seabed class histogram) measured within a distance r_{op} of the ping. This differs slightly from the simple sum, usual in statistical inference, but does not affect the result. Then, the ML seabed type (the one providing the highest log-likelihood value for that ping) was assigned to that ping position.

To overcome the limitations of the sampling by transects and of the uneven ping density, we use interpolation. This interpolation algorithm will actually estimate the average log-likelihood function used by the ML procedure just described, not only along the transects, but also in the space between them. The log-likelihood field thus interpolated will assess the most likely convert in every point of the study area. Two interpolation methods were tested: neighborhood statistics (mean) and ordinary kriging. A neighborhood statistics algorithm calculates in each point of the map the arithmetic mean of the log-likelihood values of the pings within a neighborhood of that point (defined by the radius r_{op} on the acoustic transects, but larger of those transects). An ordinary kriging algorithm computes in every point of the map the least variance error estimation of that mean, thus providing a stable (i.e. with the least dependent variance on the point distribution)

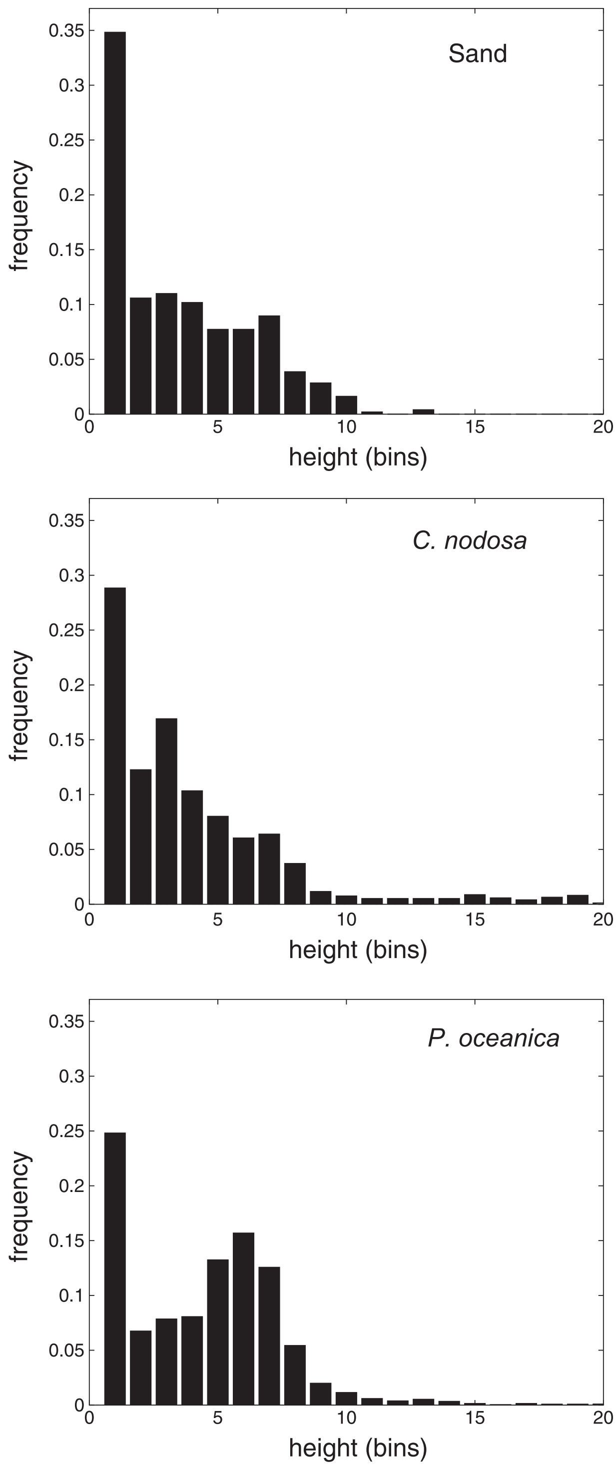

Fig. 5. Normalized height frequency histograms corresponding to acoustic measurement points within 50 m of the diving transects grouped in the three classes sand, *C. nodosa* and *P. oceanica* used for the three-class ML classification.

estimator of the average log-likelihood. These methods have the advantage of also providing an extrapolated classification outside the transects, that is, the thematic map of the area. For both methods a maximum search radius of 150 m was set. For the kriging algorithm the number of maximum used neighbors was 140, roughly equivalent to 50 m along the transects. To validate the obtained thematic maps, confusion matrices were generated using diving transects. Points were established every 1 m of the diving transects, and seabed types recorded were compared with those in the classification surface.

3. Results and discussion

The methodology applied to the acoustic SSSv data of the study area renders the two thematic maps shown in Fig. 6 for the classification in two classes: *Posidonia oceanica* and non-*P. oceanica*. Maps obtained using two interpolation methods show the same pattern of *P. oceanica* distribution in the study area. However, validation accuracy, that is, the number of *P. oceanica* and non-*P. oceanica* diving transect points falling in areas of the map correctly classified as such, divided by the total number of diving transect points considered, shows slightly better accordance in mean maps than ordinary kriging maps (a larger fraction of the *P. oceanica* and sand get correctly classified as such by the mean based classifier, for instance) (Table 2).

Following the mean map, in the total surveyed area, the estimated coverage of the *Posidonia oceanica* meadows was 152 ha, mostly concentrated in a strip close to the coast in the middle of the Agua Amarga bay. The two halves of the strip are approximately located between 10 and 25 m, in the south, and 5–20 m deep, in the north. In the northern part of the study area, closer to Agua Amarga town (see Fig. 6), no *P. oceanica* was mapped close to the coast and only a small area (12 ha at some 500 m from the main town beach) was located. Also, in the southern part of the surveyed area in the bay, an area of no *P. oceanica* was mapped surrounding a patch of *P. oceanica* (4.8 ha).

There is no *Posidonia oceanica* found below 25 m, thus agreeing with the known distribution in the study area (with presence of *P. oceanica* up to 23–25 m deep), and with the diving information.

The results are similar to those reported in EGMASA (2009) and Méndez et al. (2012). These studies were performed using an airborne-CASI and satellite imaging. The boundaries of the *Posidonia oceanica* meadows reported in that work fit approximately with the boundaries obtained in this work, (within the study area, as satellite images comprehend a larger area). The observable differences fall within distances smaller than the interpolation radius of our method (that limits its spatial resolution). The thematic map obtained by kriging-ML classification (Fig. 6B) provides a map with more irregular boundaries. However, this map reproduces some features of the EGMASA (2009) map that are smoothed out by the mean filter.

When compared with the diving transects, the classification approximately reproduces 8 out of 10 and some misclassified segments of those transects are shown in Fig. 7. In mean maps (A and B), homogeneous *Posidonia oceanica* diving transects were well classified (A), however small sandy patches observed by divers fell within the larger *P. oceanica* meadows (A, B), due to the small size of the formers and generalization effect of the mean filter on the laters. In the case of kriging maps some of the sandy patches were well mapped (D), however nonexistent sandy patches were mapped in continuous *P. oceanica* meadows (C, D). Both effects are explained because this method smoothes less than mean filter.

The validation accuracy of the two-class classification (with respect to the groundtruthing data) was 0.72. Thus its accuracy is above the 60% accuracy limit of a low-order discrimination as accepted by Riegl et al. (2005). For comparison, using the EGMASA (2009), a similar calculation provided a 0.73 accuracy for a two-class classification.

In the three-class classification, the attempt was to differentiate the non-*Posidonia oceanica* class into sand and *Cymodocea nodosa* (mixed bottom included in "others"). The *P. oceanica* strip changes little with respect to the previous two-class classification.

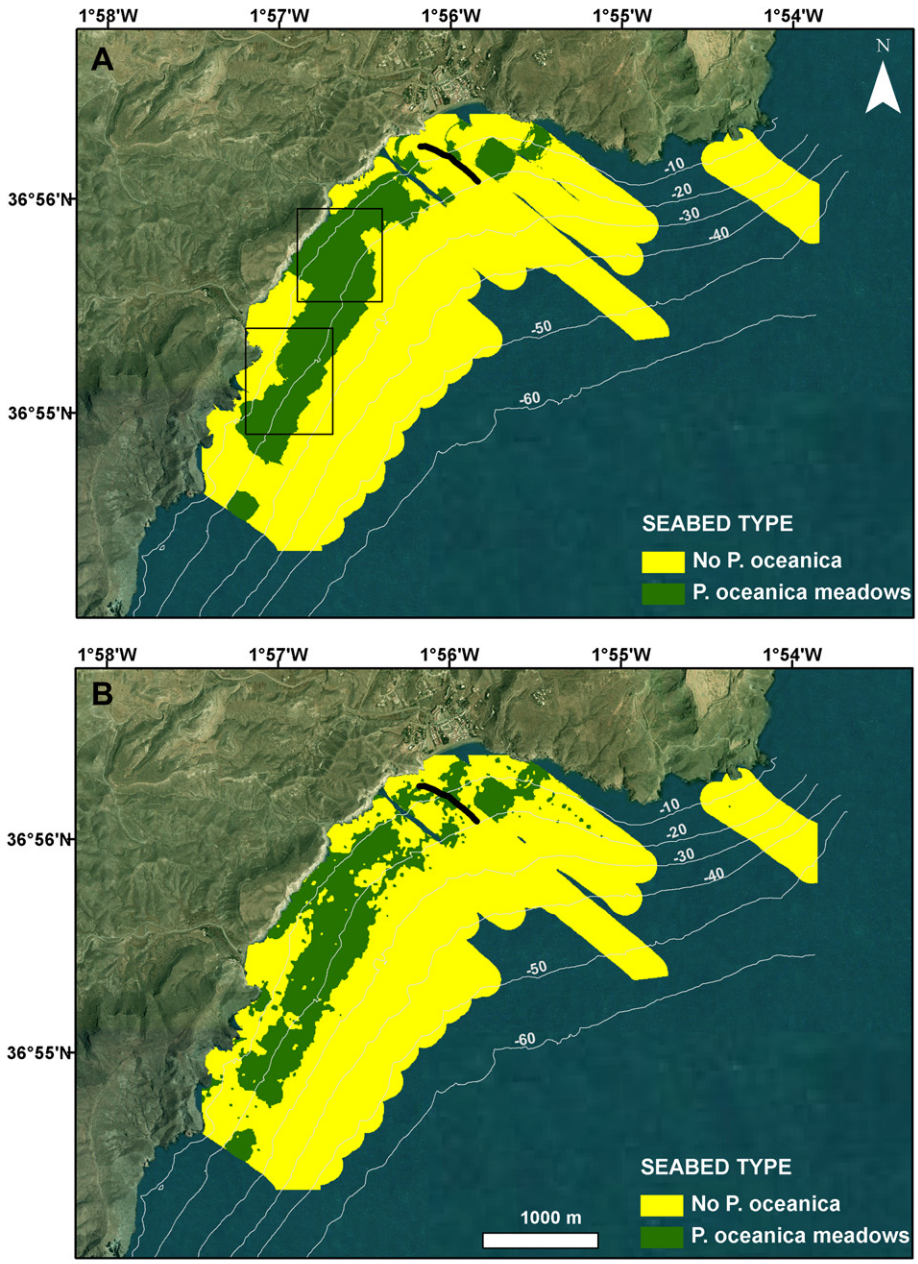

Fig. 6. Classification of the study area showing the results of the two interpolation schemes: (A) mean, (B) ordinary kriging. The areas within the squares are shown in Fig. 7 compared with the diving transect classification. The highlighted diving transect is used in Fig. 8 to illustrate the correspondence between height profile and diver's observations.

Table 2
Error matrices of the two interpolation methods for different numbers of seabed covers (P: *P. oceanica*, NP: non-*P. oceanica*, C: *C. nodosa*, S: sand, M: mixed *P. oceanica* and *C. nodosa*). Error values and accuracies (Acc) are given in percents of the validation points in the diving transects.

		P	NP	P	C	S	P	M	C	S
Mean	*P. oceanica*	75	25	72	0	28	32	15	0	53
	C. nodosa	24	76	22	0	78	3	54	0	43
	Sand	64	36	49	0	51	10	22	0	67
		Acc = 72%		Acc = 62%			Acc = 34%			
Ordinary kriging	*P. oceanica*	68	32	63	0	37	34	15	11	40
	C. nodosa	58	42	48	0	52	17	31	29	23
	Sand	61	39	53	0	47	8	27	20	45
		Acc = 63%		Acc = 54%			Acc = 32%			

Cymodocea nodosa patches appear near the *P. oceanica* in the northern part of the study area. These patches lay outside the area sampled by the divers, but their presence in nearby diving transects makes their presence likely here. This is also in accordance with EGMASA (2009) and Méndez et al. (2012) who observe *C. nodosa* patches in that area. Other *C. nodosa* patches were found below 35 m depth, in areas were groundtruthing are not available. Although unlikely here, *C. nodosa* has been reported (although not in this area) up to 40 m deep by Borum and Greve (2004). It is more likely that the height distribution is caused by bottom gears (pots, traps, etc.) localized in those places.

In the four-class classification, the *Cymodocea nodosa* classification remains. However, area classified previously as *Posidonia oceanica* is now divided into two (*P. oceanica* and mixed bottoms), but their extent does not correspond with the groundtruthing

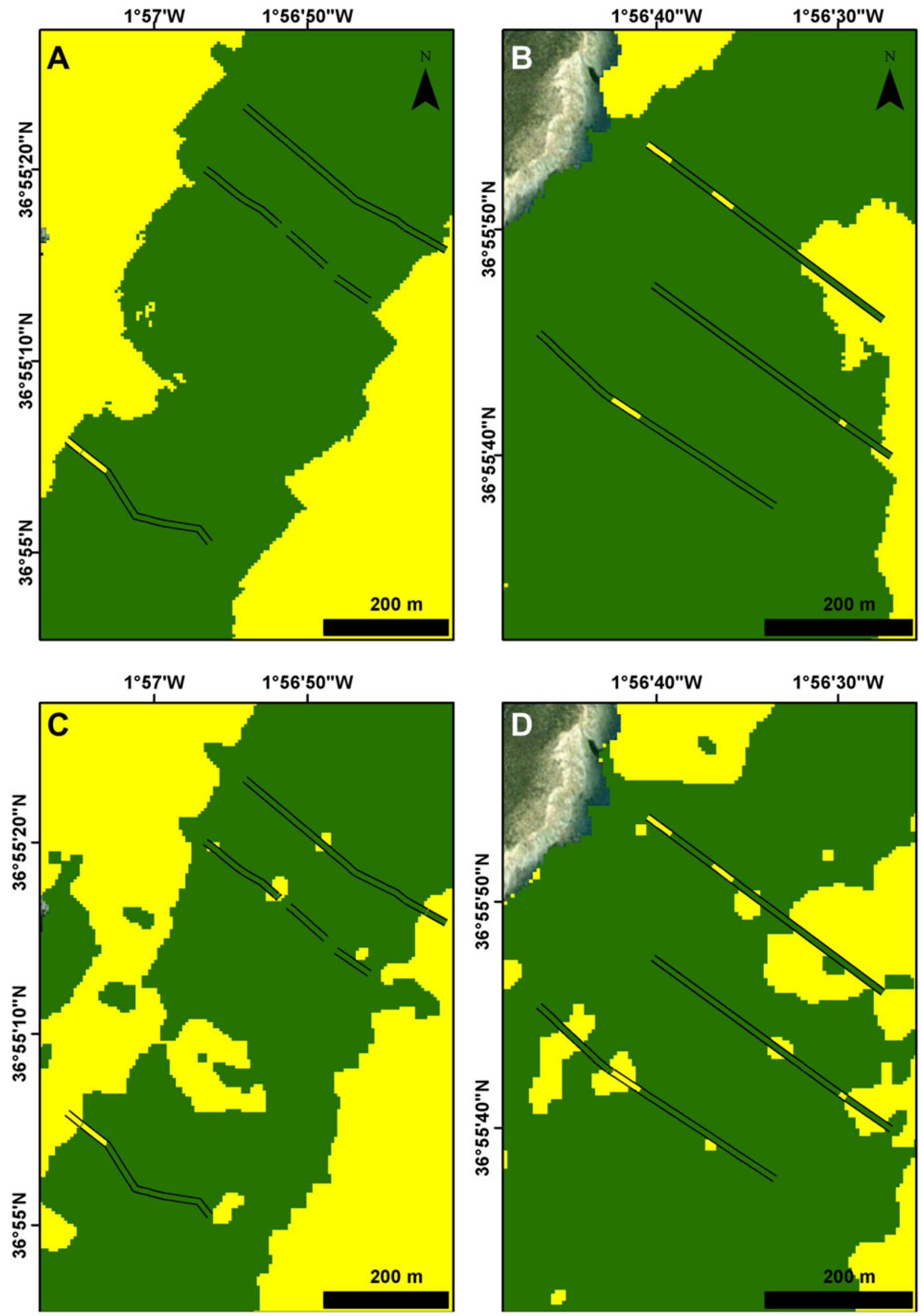

Fig. 7. Two closeups of the two-class classification (two squares in Fig. 6) showing the differences between the results of the mean filter (A and B) and the kriging ML methods (C and D). Superposed are the diving transects following the same color coding scheme, for comparison.

information. However, most mixed bottoms appear in zones where the divers reported high dispersion of the *P. oceanica* plant heights.

In all cases, the classification errors appear small in sand and *Cymodocea nodosa* or *Posidonia oceanica* patches (between 2–51 m and 1–30 m, respectively, along the diving transects) compared with the interpolation/search radius employed in the different steps of the classification method. For instance, the isolated groups of dense *P. oceanica* in sand bottoms are not identified as a different type, since their heights are a mixture of two different types (dense *P. oceanica* and sandy bottom). This can be tested reducing the interpolation radius to 100 m, for instance; then new *C. nodosa* patches and boundaries appear, showing that this is an artefact caused by class mixture. This can be also seen in Fig. 8, where the height profile of a diving profile (estimated from the nearby acoustic transect) is shown, with peaks appearing where isolated groups of dense *P. oceanica* were observed during the scuba transects.

In our study, there was a one year delay between the acoustic survey and some of the grountruthing diving transects. This delay could affect the shoot length of the *Posidonia oceanica* and *Cymodocea nodosa* plants. However, in this work only the spatial distribution reported by divers (assumed mostly constant along the year; Marbà et al., 2004) was used to assign seagrass class to each height measurement (determined from acoustic data obtained in the same period), thus the effect of this delay should be negligible.

The method, however, has two limitations: a physical one and a statistical one. The physical limitation is common to all acoustic

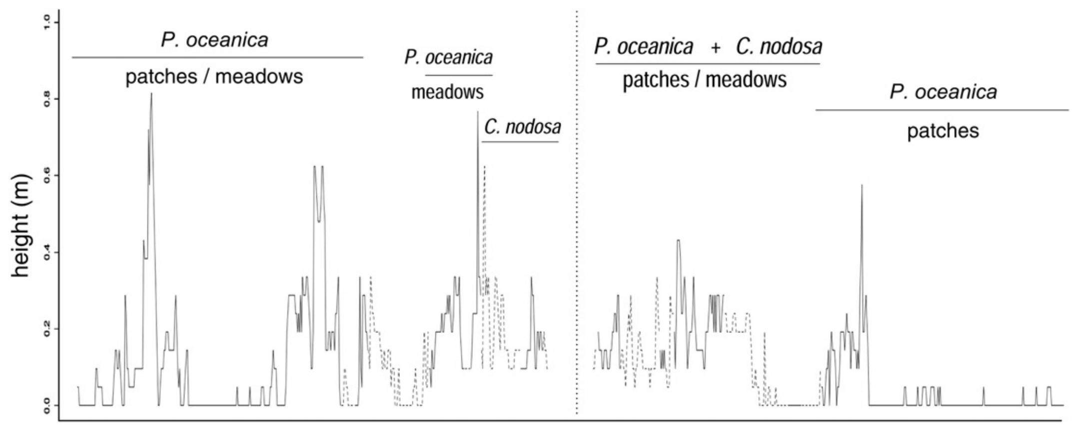

Fig. 8. Illustrative height profile of a diving transect (highlighted in Fig. 6) computed as the nearest vegetation heights in a nearby acoustic transect. Two acoustic transects are shown, that run the transect in both directions (the *X*-axis represents the diver advance along the transect). The line types correspond to the divers and video observations (solid, *P. oceanica*, and dashed, *C. nodosa*). The isolated height peaks correspond to vegetation patches.

methods: leaf height variations may affect the histograms of the classes, making differences provide better classification. For instance, in spring, the leaves will be longer and will have a more clear acoustic signature, due to higher photosynthetic activity; then they will appear clearly different from the sand, and different from one species to another. Poorer classifications may be obtained in other seasons. SSSv resolution (4.8 cm) will not influence the result as the histogram differences are already observable with the binning provided by this pulse length. A smaller pulse length would imply more noise in bottom detection and less samples per bin for the classification, thus 256 μs is a compromise between spatial resolution and statistical significance.

The statistical limitation is related to the study area topography and seagrass distribution. As the seagrass lay close to the shore and extends up to the depth limit reached by the divers, the grountruthing area is mostly populated by *Posidonia oceanica* (i.e. this class concentrates most of the training data) and sand. The *Cymodocea nodosa* patches are very small and this, together with the non-coincidence of the diving and acoustic transects, involves many misassignments in the training data for this class. This limitation could be resolved including in the methodology the use of other sampling devices as ROV (remote observation vehicles) that may provide data, similar to the diver's, from greater depths.

We have presented the two-class classification results obtained with two interpolation methods. The higher accuracy of the mean classification with respect to kriging may have its origin in the location of the diving transect in a zone rich in *Posidonia oceanica*, and the generalization properties of the mean filter. Both algorithms have advantages and limitations, and which of the classifications is best is difficult to assess. The selection must take into account the research objectives. For instance, in Fig. 7, some of the sand patches signalled by the kriging classification are found in nearby diving transects and may correspond to actual sand patches within the meadow (but located in a different position). Thus, global cartography could take advantage of a smooth mean classification, whereas for patch identification the kriging classification could be more adequate.

Seagrass mapping methods, not only acoustic ones but also optical remote sensing methods, have been aimed at assessing the seagrass presence, as our method does. They rely on the detection of groups of plants or meadows, and rarely detect individuals (Paul et al., 2011). Our method, statistical in essence, requires the existence of a homogeneous "population" around each point to get it classified. However, being based on a supervised classification, the density of this population will only determine the number of samples to be taken (to discriminate between that population and the bottom sand) and thus the spatial resolution of the resulting map. The quality of the populations assessed (most important, during the groundtruthing) is, thus, an issue with the method.

The method here combines several good features from other published methods, such as being based on height profile (Lefebvre et al., 2009; Paul et al., 2011) or statistical distribution (Di Maida et al., 2011), or using a readily available SSS transducer (Pasqualini et al., 2000; Piazzi et al., 2000; Sabol et al., 2002). The statistical ML approach using a GIS is also new, and very efficient to produce a thematic map. Resolution may be an issue if the objective of a study is to detect very small-scale regressions of the *Posidonia oceanica* meadows, for their monitoring. In those cases, it might be required to use a multibeam acoustic survey or use hyperspectral imaging classification. However, to obtain a medium resolution map of the *P. oceanica* beds, our method gives sufficiently good results for bio-assessment, and is cheaper and quicker (taking into account the data processing) than a multibeam survey and than flown hyperspectral remote sensing imaging.

4. Conclusions

The proposed method is based on a cost-effective SSS survey carried out with the acoustic beam directed towards the nadir to provide profiles of seafloor vegetation heights. The statistic height profiles classification information is provided by the diving transects carried out in the area of interest, and designed to have samples from all the relevant covers (thus selected following the highest variability of the transects). The classification is performed using an ML method such that it can be carried out with a GIS simultaneously providing an interpolated thematic map of the study area.

The above considerations indicate that the method proposed is adequate for a low-order discrimination of *Posidonia oceanica* meadows in wide areas. The results compare well (within reasonable quality criteria) with the groundtruthing and also with other results reported in the literature, acquired with more expensive (multibeam sonar, airborne optical sensors) and elaborate techniques (optical atmospheric and water column correction). Hence, the method can be used for long-term monitoring of *P. oceanica* meadows. With an appropriate diving groundtruthing, the method could also estimate the position of *Cymodocea nodosa*. However, the results presented from the survey, were not sufficiently good as they located this species outside its natural depth interval.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2012.09.015.

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