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Fast and easy method for seagrass monitoring: Application of acoustic telemetry to precision mapping of *Posidonia oceanica* beds

Descamp Pierre [a,1], Holon Florian [a,1], Ballesta Laurent [a], Guilbert Antonin [a], Guillot Marie [b], Boissery Pierre [c], Raimondino Valérie [d], Deter Julie [b,*]

[a] *Andromède Océanologie, 21 Chemin des Oliviers, 34400 Saturargues, France*
[b] *L'OEil d'Andromède, Institut de botanique, 163, rue Auguste Broussonnet, 34090 Montpellier, France*
[c] *Agence de l'Eau Rhône-Méditerranée-Corse, Délégation de Marseille, Immeuble le Noailles, 62, La Canebière, 13001 Marseille, France*
[d] *Région Provence-Alpes-Côte d'Azur, Service Mer, 27 place Jules Guesde, 13481 Marseille Cedex 20, France*

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ABSTRACT

Posidonia oceanica is an endemic seagrass from the Mediterranean Sea. It is an indicator of water quality and of the ecological state of coastal ecosystems. The aim of this paper is to test acoustic telemetry for monitoring the position of *P. oceanica* meadow limits with varied types. After evaluating the accuracy of the system, we present results from a spatiotemporal survey of *P. oceanica* meadows on nine sites located on the French coast. The method has been demonstrated to be highly efficient for high precision underwater mapping regardless of meadow type, with 1 cm accuracy for a distance of 40 m between the base and the pointer. A temporal survey led at Cerbere–Banyuls shows a weak global progression of 4 m^2 (progression of 26 m^2 - regression of 22 m^2) between 2006 and 2010. Finally, we discuss the cost and efficiency of this method, and wether it should be generalized for further studies.

1. Introduction

The Mediterranean Sea is an attractive region with 70 million inhabitants concentrated in its coastal cities with an additional 175 million tourists visiting every year as a holiday destination. This crowd generates important financial gains (Benoit and Comeau, 2005), but it also places drastic pressure on marine ecosystems. Human activities, such as trawling, mining and agricultural wastes, urban and industrial sewage, coastal constructions, beach replenishment, and aquaculture loads are associated with water quality decline and cause serious damages to the marine environment, especially along the coasts. The European Union has established the bases of policies for the monitoring, protection and enhancement of the status of aquatic systems (http://ec.europa.eu/environment/water/index_en.htm) by engaging the Water Framework directive (WFD 2000/60/CE) for water protection and management. WFD aims to conserve and recover a "good water status" for all European waters by 2015. Among the indicators defined by WFD for the evaluation of the ecological state and condition of coastal ecosystems in European countries are seagrasses, especially *Posidonia oceanica*. *P. oceanica* (L.) Delile, an endemic species to the Mediterranean Sea that is distributed between the surface and a depth of 44 m depending on water clearness (Ruiz et al., 2009; Boudouresque et al., 2009). It forms monospecific meadows, constituting an engineering ecosystem that plays a major role in coastal zones (Francour et al., 2001). Human activities might be the cause of seagrass meadow regression; the impact can be direct, through physical (e.g., burial, uprooting) and chemical damages (e.g., noxious substances), or indirect, through the alteration of the environment (e.g., increase in turbidity, sedimentary deficit), ecosystem organization (e.g., leaf epibiota development) and processes (e.g., overgrazing) (Boudouresque et al., 2009). *P. oceanica* is regularly used as a bioindicator, or biological sentinel, because of its sensitivity to disturbance; any change in seagrass distribution, such as reduction in the lower limit, signals changes in the environment (Orth et al., 2006; Boudouresque et al., 2009; Ruiz et al., 2009). However, the survey of lower limit depths and the quantification of the extent of losses require precision mapping and an effective monitoring approach. The choice of a *Posidonia* mapping method or device is always a function of costs, study area width, and the collected data acquisition scale. Generally, changes in seagrass meadow limits at scales of centimeters are obtained by two methods. The first method (Réseau de Surveillance Posidonie, the so-called RSP method) consists of measuring the distance between permanent cement markers placed along meadow limits and the current position of the limit at time intervals (Meinesz, 1977; Meinesz and Laurent, 1978; Boudouresque et al., 2000; Charbonnel et al., 2000). Unfortunately, the set phase is long and fastidious and must

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[*] Corresponding author. Tel.: +33 4 67 66 32 48; fax: +33 4 67 41 93 34.
E-mail address: julie.deter@andromede-ocean.com (J. Deter).

[1] These authors equally contributed to this study.

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sometimes be done again when the distance between the meadow and the markers becomes too important (i.e., after an important regression or progression). In these conditions, only twelve markers are usually placed per meadow. This restricted number of points decreases the precision of the technique; mapping is crude and the survey of patchy meadows or sparse limits is impossible (Boudouresque et al., 2006; Descamp et al., 2009). The second method, called acoustic telemetry, uses an underwater acoustic positioning system composed of a hand pointer held by a SCUBA diver that allows for precise signaling of the meadow limits to a measuring base, which detects ultrasonic pulses emitted by the pointer (Descamp et al., 2005). The capabilities of this technique were presented by Descamp et al. (2005) and Boudouresque et al. (2006). The advantages of this accurate, fast and ''non-invasive'' (i.e., without markings that potentially prevent seagrass growth) method should permit high precision mapping of all *P. oceanica* meadows, particularly in cases where meadows are patchy and when limits are not straight. The aim of this paper is to test acoustic telemetry for precision mapping of *P. oceanica* meadows with varied types and lower limits on the French Mediterranean coast. In this way, we will evaluate the accuracy of the system, present results concerning a spatiotemporal survey of *P. oceanica* meadows and discuss the cost and efficiency of the method.

2. Materials and methods

2.1. Acoustic telemetry

Mapping was performed using the underwater positioning system AQUA-METRE D100 (PLSM, Paris, France) and its new graphical pointer (developed in 2005) (PLSM, France). This method, based on an acoustical interferometric scheme mainly known as Ultra Short Base Line, or USBL, was described in detail by Descamp et al. (2005). Briefly, the system was composed on one hand of a measurement base consisting of an interferometric framework in communication with a computer at the surface, and on the other hand of two portable graphic pointers allowing two divers to point the objects to be positioned. We chose to point the boundary of the meadow with one point every 40 cm on average. This distance was adjusted depending on the complexity of the limit to be pointed; the distance was reduced for complex shapes and increased for straight limits. The maximum range between the pointer and the base could reach 200 m (nominally 100 m). Up to 1500 points could be recorded and then transferred by an infrared interface onto a computer (Pentium PC). The results were first analyzed in a basic graphic view with the pointer. During the study, points were recorded using the smart average function. With this mode, the system waited for at least n (here $n = 3$) consistent points before measurement completion, which consisted of a 3D average and result storage. Points were considered to be consistent when located within a sphere with a radius smaller than the expected absolute accuracy vs. range. The use of acoustic telemetry required the referencing and recording of two noticeable points, i.e., handset markers or natural points, located less than 100 m from the measurement base. The georeferencing of these points with an underwater GPS (USBL tracking system Tritech Micron Nav, Tritech International Limited, United Kingdom) allowed the integration (dxf format, WGS84 projection) of the points in a Geographical Information System (ArcGIS 9.3, ESRI France). Points were then linked to draw the patch outline or the seagrass bed lower limit and areas were calculated.

2.2. Testing the measurement accuracy of the method

We recorded one point located at a fixed place three times. This was done at several distances from the base (10, 20, 30, 40, 50, 60, 80 and 100 m) in the following three ways: (i) with the smart function inactivated or with the smart function activated on (ii) two or (iii) three consistent points. Variations in measurements obtained at each distance and depending on the function activated were compared using Statistica 6.1 (Statsoft, Inc.).

2.3. Diving equipment

For practical and safety reasons, every dive was performed using INSPIRATION VISION rebreathers (Ambiant Pressure Diving Ltd., United Kingdom). Air recycling reduces the volume of breathing gas used, enabling longer dives with a lighter and more compact system relative to an open-circuit breathing set for the same duration. Gas saturation of CCUBA (Closed Circuit Underwater Breathing Apparatus) divers being minimal, diving periods are virtually unlimited (no stage) until a depth of 15 m. Moreover, except on ascent, no bubbles, and thus no noise, are produced that could slow down acoustic telemetry.

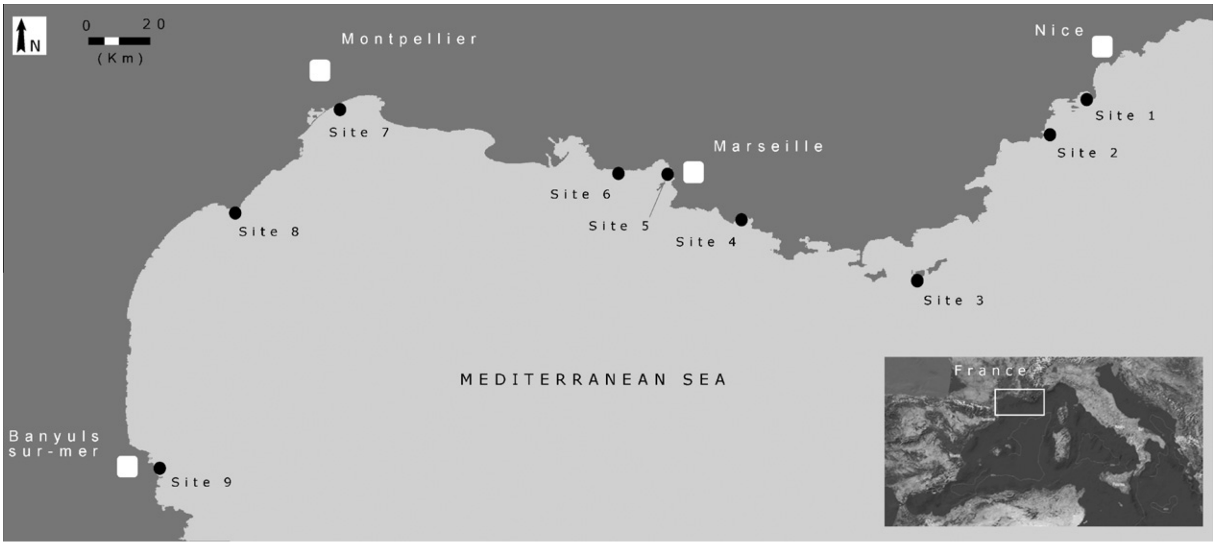

Fig. 1. Map of the French Mediterranean Sea showing the locations of the study sites. See Table 1 for geographic coordinates and details concerning the study sites.

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Table 1
Geographic coordinates and characteristics of *Posidonia oceanica* beds mapped during the study. Meadow and limit types were classified according to Meinesz and Laurent (1978) and Pergent et al. (2008) but revised typologies of the lower limits were also added following Montefalcone (2009).

Site	Date	Coordinates	Meadow type	Limit type	Revised typology	Lower limit
1. Antibes Cape’s Natura 2000 site	June 2008	43°32′44.7”N 07°06′21.8”E	continuous	regressive	regressive shaded limit	28.7 m
2. Esterel’s Natura 2000 site	June 2008	43°26′53.6”N 06°55′42.4”E	continuous	regressive	regressive limit with patches	27.5 m
3. Port Cros’ National park	June 2008	43°00′496”N 06°21′426”E	continuous	straight with low recovery	natural sharp limit	31.2 m
4. La Ciotat’s Natura 2000 site	June 2008	43°10′254”N 05°39′470”E	continuous	sparse	regressive limit with patches	32.1 m
5. Marseille	April 2008	43°18′43”N 05°21′17”E	patchy	straight with high recovery	natural sharp limit	20.3 m
6. Marine Park « côte bleue »	May 2008	43°19′11”N 05°09′37”E	continuous	regressive and sparse	regressive shaded limit	30.2 m
7. Palavas-les-flots’ Natura 2000 site	August 2006	43°32’11”N 04°01′48”E	patchy	regressive	regressive shaded limit	10 m
8. Agde cape’s Natura 2000 site	July 2008	43°16′22”N 03°28′04”E	patchy	straight with high recovery	regressive sharp limit	7 m
9. Marine reserve «Cerbère/Banyuls sur mer »	August 2006 July 2008 June 2010	42°27′45”N 03°09′43”E	patchy	regressive	regressive sharp limit	19.6 m

2.4. Study sites

Lower limits of *P. oceanica* meadows were surveyed on nine sites distributed along the Mediterranean French coast (Fig. 1) and presenting varied morphotypes. Meadow and limit types were classified according to Meinesz and Laurent (1978), Pergent et al. (2008) and Montefalcone (2009).

Five sites corresponded to continuous meadows and four to patchy ones; six sites had regressive and/or sparse limits, whereas three had straight ones. The detailed placement and characteristics of the sites are described in Table 1. These sites were located in different water bodies and chosen in cooperation with the French Water Agency (Agence de l’Eau). They were all located in water bodies with good chemical quality (Agence de l’Eau and Bassin Rhône-Méditerranée, 2009) and all but two (sites eight and nine in medium quality waters) of these sites had good ecological quality (SDAGE (2009)). Because of the influence of the Rhone, coastal water turbidity is known to increase from site one (<0.5 Formazin Nephelometric Units in summer 2008 at −1 m) to site seven (around 10 FNU at −1 m) and to decrease from site seven to site nine (around five FNU at −1 m) (IFREMER (2010a, 2010b)). Meadows were mapped between April and August 2008 except at Palavas-les-Flots where the field work was conducted in August 2006. Several of these sites were previously monitored via the RSP method. When still visible, we also pointed these RSP marker positions.

2.5. Analysis of temporal variation in meadow limits

A four-year temporal survey with a two-year time interval was conducted at the Cerbère–Banyuls marine reserve with mappings in August 2006, July 2008 and June 2010 (Table 1). Comparisons between the maps obtained at different dates were performed using ArcGIS 9.3 (ESRI, France) and interpreted in terms of meadow stability, progression or regression.

3. Results

Whatever their morphology or lower limit types, all of the nine meadows were mapped easily and quickly. One work day, consisting of a 5 h dive, was spent per site with a team of two divers and one boat driver on an inflatable dinghy. If divers had not been independent workers, French regulation would have imposed a third safety diver.

3.1. Accuracy of the method

Under a distance of 60 m, the mean distance between measurements at a fixed point varied from 1.02 to 12.04 cm. Globally, no significant differences were observed between mean variations recorded at distances less than 50 m (10–50 m, Kruskal Wallis test: $\chi^2 = 6.964$, $P = 0.138$) and using different functions (Kruskal Wallis test: $\chi^2 = 3.750$, $P = 0.153$). All distances confounded, the weakest variation (4.22 cm) was observed when the smart average function was activated with three consistent points. Beyond 50 m, the efficiency of the system decreased greatly; the variation reached more than 360 cm except with the activation of the smart average function with two consistent points, in which case the accuracy remained less than 30 cm (8.88 cm at 60 m, 27.52 cm at 80 m). At a distance of 100 m from the base, it was impossible to record points. The results are presented in Table 2.

3.2. Fast and easy mapping of diverse seagrass limits

P. oceanica beds located on site 1 (Antibes’ cape) were globally continuous but scrappy with typical regressive dynamics at its present lower limit (28.7 m); dead rhizomes were buried and numerous tufts emerged in places from rocks, sand and coralligenous. Acoustic telemetry allowed mapping of not only the straight lower limit (139 points recorded on 59.18 m) but also the different tufts (204 points delimited a perimeter of 45.63 m) (Fig. 2a). Two markers were set on rocks and a total of 343 points around 30 cm apart were recorded. Site Two was deeply located (lower limit 27.5 m) in a fishing reserve and thus exempt from direct anthropogenic disturbance. The meadow was highly scrappy with a regressive limit (Fig. 2b) and a stretched dead rhizome area colonized by the invasive algae *Caulerpa taxifolia*. It represented a

Table 2
Mean distance (cm) separating a fixed point measured three times at different distances from the base (10 to 100 m) with different functions activated (smart average function inactivated = 1, smart average function activated with two = 2 and three = 3 consistent points).

Function	10 m	20 m	30 m	40 m	50 m	60 m	80 m	100 m
1	5.19	3.13	3.00	7.03	3.77	368.47	541.52	no data
2	7.67	4.54	6.00	11.34	4.88	8.88	27.52	no data
3	12.00	2.18	4.00	1.02	2.34	388.75	549.76	no data

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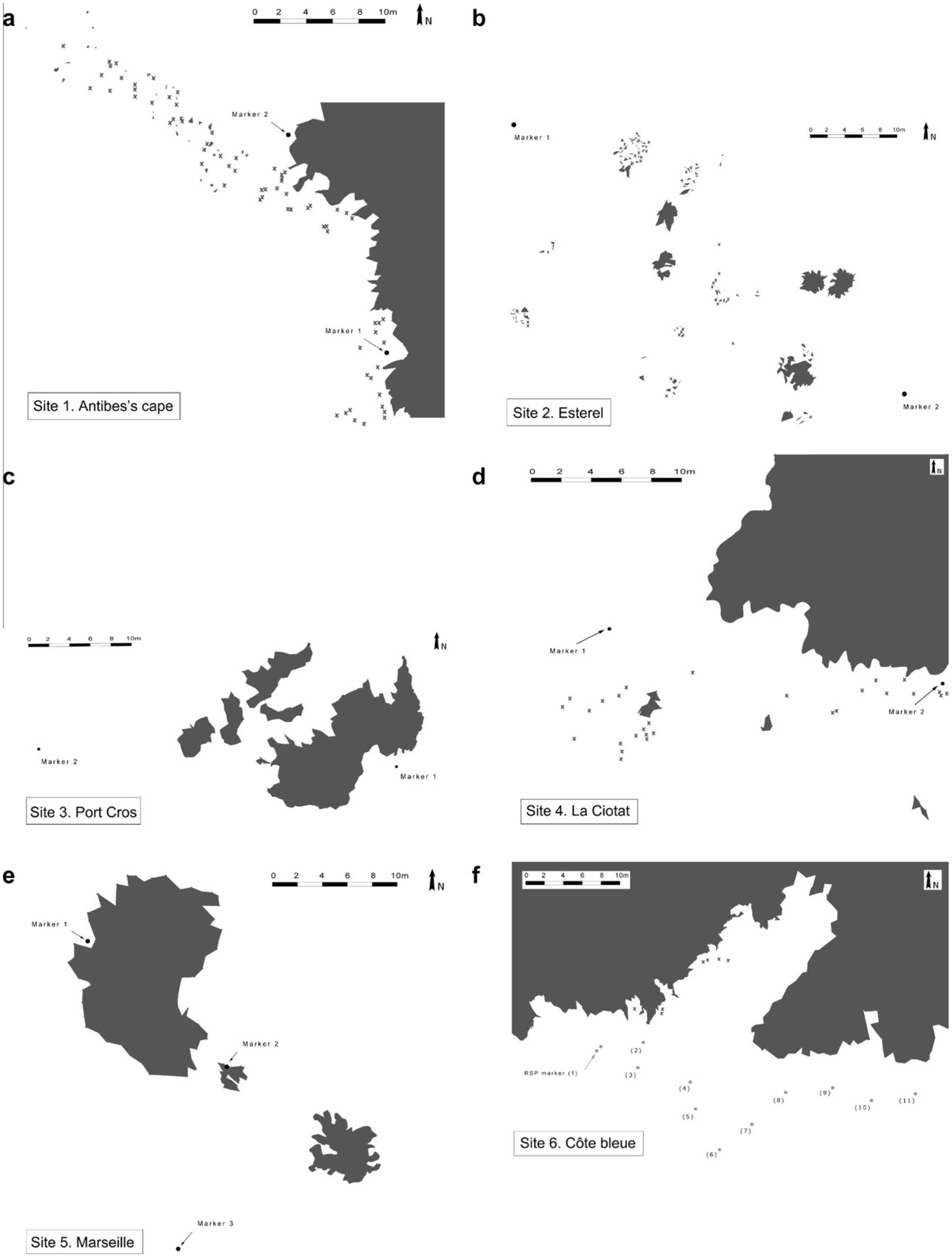

Fig. 2. *Posidonia oceanica* bed precision-maps resulting from acoustic telemetry at (a) Antibes cape's Natura 2000 site (site one), (b) Esterel's Natura 2000 site (site two), (c) Port Cros'National park (site three), (d) La Ciotat's Natura 2000 site (site four), (e) Marseille (site five), (f) Marine Park "côte bleue" (site six), (g) Palavas-les-flots' Natura 2000 site (site seven) and (h) Agde cape's Natura 2000 site (site eight). Meadows are presented in grey and isolated tufts are indentified by "X" symbols. Markers set during the study and RSP markers (when present) are reported on the maps. See Table 1 for geographic coordinates and details concerning the study sites.

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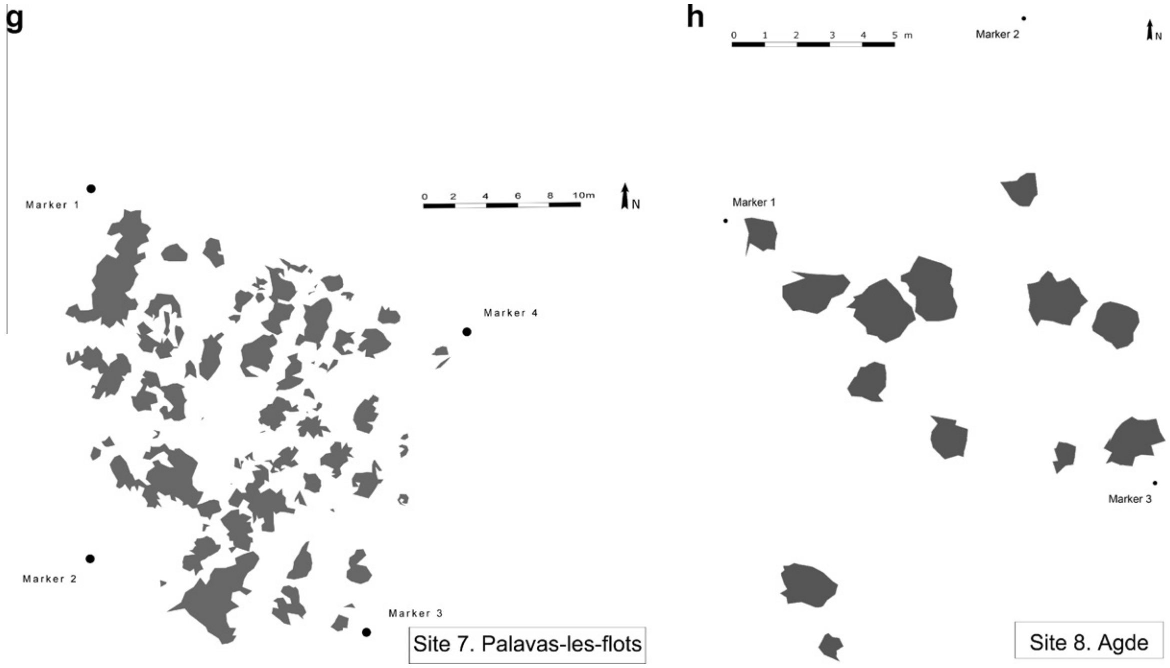

Fig. 2 (*continued*)

32.91 m^2 area mapped using 725 recorded points every 54 cm and two markers, one set on a rock and the other an incongruous marker on a motor. Site three was located along the protected island Port Cros and contained a continuous and well developed *P. oceanica* meadow. The lower limit was deep (−31.2 m) and straight but regressive. Dead rhizomes were colonized by *C. taxifolia*. We used two markers, one set on rock and the other on a coffer, and recorded 360 points 40 cm apart in mean to map 140.35 m^2 of seagrass beds (Fig. 2c). Site four, La Ciotat, was georeferenced by two markers set on rock and an ancient RSP marker of unknown origin. The meadow was continuous and the lower limit was deep (32.1 m) and weakly sparse (Fig. 2d, RSP marker not visible on the figure because it was more than 10 m away from the current meadow limit). One hundred and thirty seven points separated by 48 cm in mean were recorded for the map (77 for the straight limit, 31 for the patches and 27 for the isolated tufts) and drowned a perimeter of 51.8 m. Site five contained a residual and patchy meadow located along the large harbor wall of Marseille at a depth of 20.3 m. Three markers were placed on rocky outcrops. The limit was straight and was easily mapped using 266 points, one every 44 cm, for an area of 137.87 m^2 (Fig. 2e). In site six (the marine park "côte bleue"), the meadow was continuous with a regressive and sparse lower limit at a depth of 30.2 m. We used twelve 1985 RSP markers as references for the map and recorded 338 points located 50 cm apart in mean. All of these markers were located between 2 and 10 m from the present seagrass limit. The *P. oceanica* meadow was scrappy and the limit was irregular in shape (Fig. 2f). Site seven (Palavas-les-Flots) contained a highly scrappy meadow in which most of the patches were <1 m^2 and growing between rocky banks, dead rhizomes and coarse sand. The lower limit was -10 m. Two markers were set in rock and two others in dead rhizomes. The map was based on a total of 1285 points shaping a total area of 88.60 m^2 (Fig 2g). *P. oceanica* beds from site eight, located next to Agde's cape, were composed on well-delimited patches (227 points separated by 27 cm in mean, 17.52 m^2 in area). They developed around 10 m from the beach at a depth of 7 m on sand and dead rhizomes. Two markers were set in rock and a third was set in dead rhizomes (Fig 2h).

3.3. Temporal survey

With their patchy conformation, *P. oceanica* beds from site nine (Cerbère/Banyuls, Pin parasol inlet) were totally and easily mapped in 2006, 2008 and 2010. Two markers (climbing pitons) were added to eight pre-existing RSP markers. These latter markers were all located except number seven on sand or dead rhizomes and recognized as belonging to studies performed in 1989 (Pergent-Martini and Pergent, 1989), 1997 (Ballesta et al., 2000)(Ballesta, 1997) and 2006 (Descamp et al., 2007) (see Fig. 3). Between 2006 and 2010, the lowest limit (regressive type) remained stable at a depth of 19.6 m. The seagrass meadow represented a total of 86.24 m^2 in 2006 with a perimeter of 275.38 m (630 points, 43.7 cm apart in mean, Fig. 3 (a), 95.68 m^2 with a perimeter of 269.62 m (943 points, 28.6 cm apart in mean, Fig. 3 (b) in 2008, and 90.94 m^2 with a perimeter of 340.04 m (612 points, 55 cm apart in mean) in 2010 (Fig. 3 (c)). In 2010, all RSP markers except number 1 and 2 had disappeared.

The comparison between the two precision-maps obtained in 2006 and 2008 showed regions in regression and others in progression. Four small patches, one at the south of RSP marker three and three on the Western part of RSP marker seven, had disappeared when two new leaf bundles were noted (Fig. 4 (a)). The progression was more important on the Eastern most and deepest part of the meadow. Between 2008 and 2010, four (almost five next to RSP marker two) small patches had disappeared, one on the Northern part of the meadow and three next to RSP marker seven, when the biggest one was widened (Fig. 4 b). Colonization is clearly visible next to RSP markers one and two.

The comparison of the maps (Table 3 and Fig. 4) showed relatively similar progression between 2006 and 2008 (22.88 m^2) and 2008 and 2010 (18.99 m^2). However, seagrass regression was almost double during the period 2008–2010 (23.71 m^2) as what was observed between 2006 and 2008 (13.44 m^2) leading to a weak global progression (4 m^2) among the four-year period 2006–2010 (Fig. 4 c). This weak global progression is the consequence of a progressive period (9.44 m^2 in 2006–2008) followed by a regressive period (4.72 m^2 in 2008–2010). The evolution

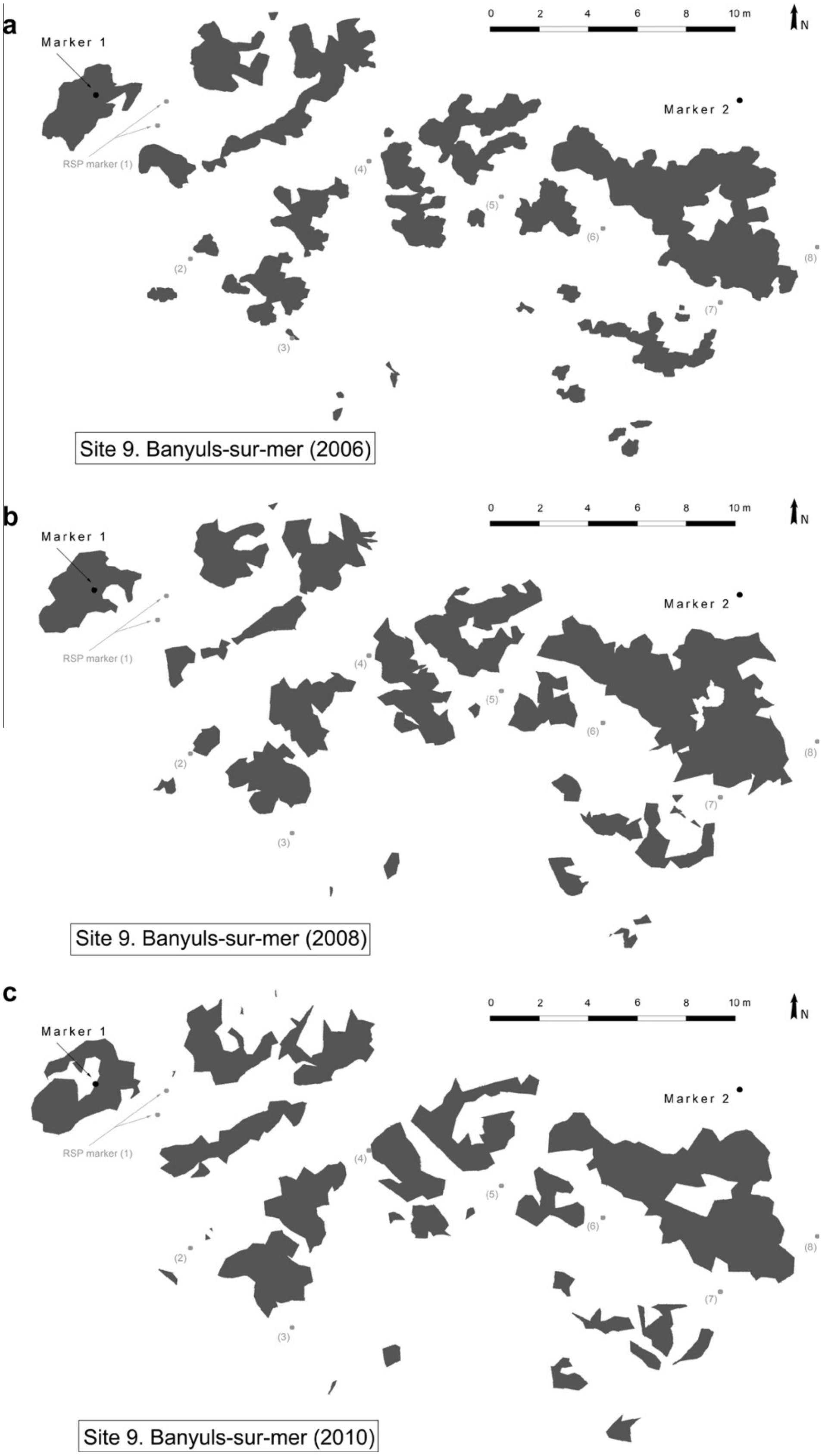

Fig. 3. Limits of *Posidonia oceanica* beds mapped by acoustic telemetry in the marine reserve of Cerbère/Banyuls-sur-mer (site nine) in (a) 2006, (b) 2008, and (c) 2010. Meadows are presented in grey. Markers set during the study and RSP markers are reported on the maps. See Table 1 for geographic coordinates and details concerning the study site.

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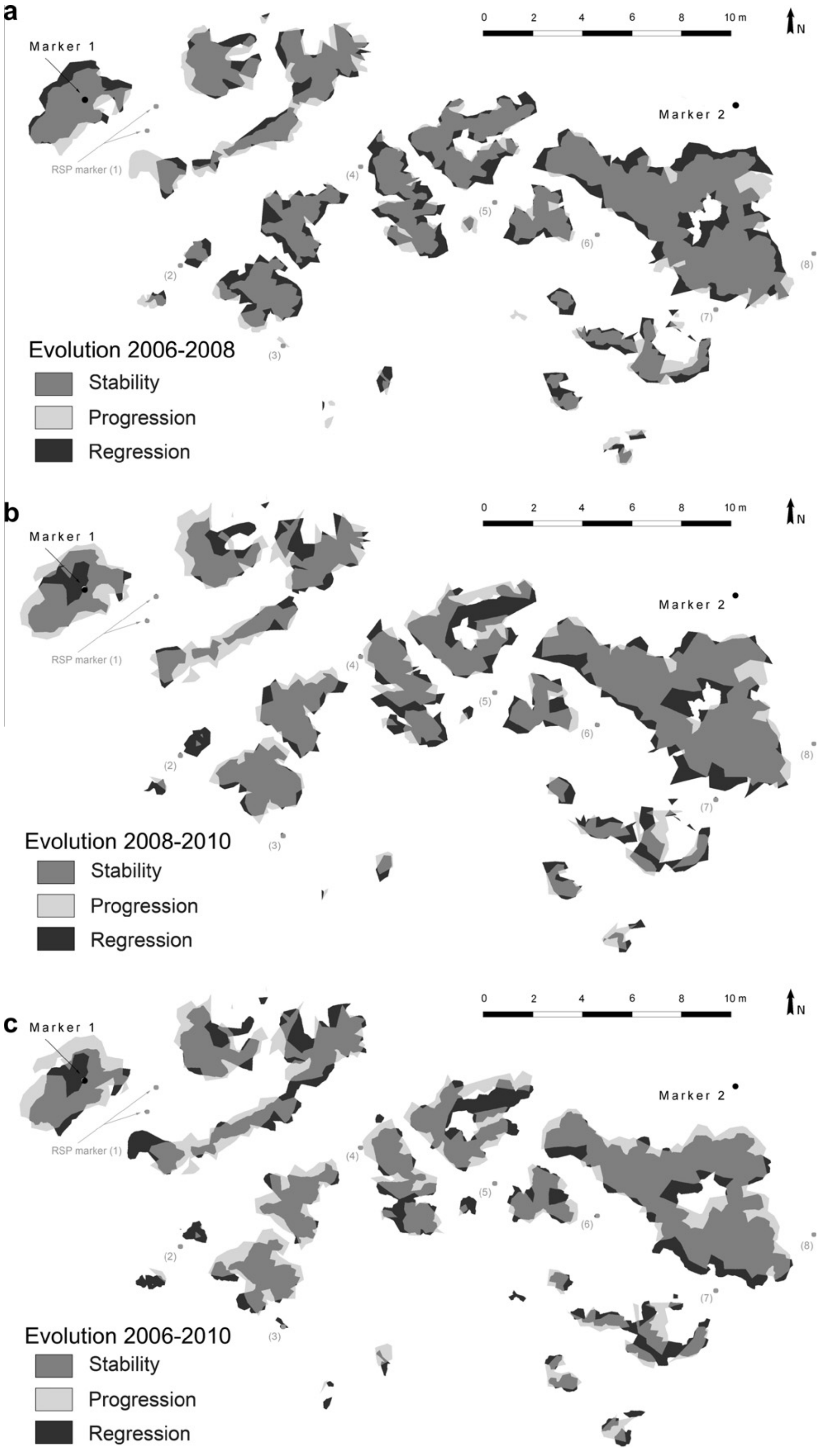

Fig. 4. Evolution of the limits of *Posidonia oceanica* beds mapped by acoustic telemetry in the marine reserve of Cerbère/Banyuls-sur-mer (site nine) between (a) 2006 and 2008, (b) 2008 and 2010, (c) 2006 and 2010. Evolutions (obtained from the comparison of the maps presented in Fig. 3) highlight the progression (light grey), regression (black) and stability (dark grey) of seagrass. Markers set during the study and RSP markers are reported on the maps. See Table 1 for geographic coordinates and details concerning the study site.

Table 3
Evolution of *Posidonia oceanica* seagrass monitored at Cerbère–Banyuls (marine reserve) in August 2006, July 2008 and June 2010.

Seagrass area (m^2) in...	2006–2008	2008–2010	2006–2010
Stability	72.80	71.97	64.66
Progression	22.88	18.99	26.28
Regression	13.44	23.71	21.58

map based on 2006–2010 data showed that regression occurred principally on the links of the map (the shallowest part) with seven disappeared patches (two small patches next to marker three, one next to marker four, one on the Northern part of the meadow, three next to marker seven) and two patches next to RSP marker two that almost disappeared. Only two new leaf bundles noted in 2008 were still present in 2010. Globally, seagrass beds tended to be divided into smaller patches.

4. Discussion

4.1. Around 10 cm accuracy for a pointer at less than 60 m from the base

According to the manufacturer, the absolute accuracy of the recordings varied with the distance to the base within a range of up to 150 m from the reference point. At a distance of 10 m from the base, the manufacturer indicated an accuracy of 1.7 cm, 17 cm at 100 m. The best absolute accuracy of the system was expected to be achieved in the area located 2–20 m from the base (P.L.S.M Aqua-meter D100 version 2 user manual). This accuracy is less than what can be expected from the GPS used to import the data in a Geographical Information System. Our study showed a relatively good accuracy (from 1 to 10 cm) of the system when used up to 50 m. In our habitual use conditions (40 m), accuracy can reach either 1.02 cm when the smart average function (three consistent points) is activated or 7.03 cm when the function is inactivated. Differences between our data and the manufacturer's data (see "Materials and Methods" section) may be explained by field conditions such as turbidity and noise disrupting the signal transmission.

4.2. Four-year temporal survey at Cerbère–Banyuls showed globally stable seagrass beds

At this site, *P. oceanica* beds were easily mapped due to their marked outlines. Most of RSP markers that were originally placed in the meadow limit were in sand or dead rhizomes at study time. Based on these markers, a previous study reported a 10% regression in 11 years (1989–2000), the most intensive being between 1989 and 1997 (Descamp et al., 2007). Since then, chronic regression was slowed down and seagrass bed dynamics seemed to be stabilized. The lower limit was deeper in 2008 and 2010 (−19.6 m with acoustic telemetry) than in 1989, 1997 or 2000 (respectively −19.4, −19.2 and −19.1 m measured with a diver depth meter; Descamp et al., 2007); this suggests a weak progressive tendency.

Our results obtained with acoustic telemetry confirmed a weak global progressive tendency (4 m^2) between 2006 and 2010 in spite of an alternation between progressive and regressive periods. After an apparent stability (2000–2006) and weak progression (2006–2008), an important regression occurred between 2008 and 2010. This regression and the disappearance of most RSP markers were certainly caused by two storms that occurred in the sector. The first storm, on December 26th, 2008, broke 50 m of seawall at Cerbere (data from Oservatoire océanologique de Banyuls sur mer http://observation.obs-banyuls.fr/) with 6–9 m waves and a wind speed of more than 33 knots (61 km/h). The second storm, called Klaus, occurred on January 24th, 2009. Klaus was stronger than the first storm, with wind speeds up to 70 knots (130 km/h) (http://observation.obs-banyuls.fr/). Fortunately, these exceptional climatic events were not sufficient to totally destroy colonization efforts; a global progression was still visible for the 2006–2010 period. The next monitoring (planned in 2012) will evaluate how seagrass beds recover after this disturbance. This next map should either confirm the progressive tendency and the exceptional characteristic of the 2008–2010 period or demonstrate the entrance into a new regressive period. Regardless, even if the regression in this case was relatively easy to link to both storms, our results highlight the difficulties encountered by marine ecologists in understanding the explanatory factors behind seagrass bed evolution. The weak colonization capacities of *P. oceanica* would probably require centuries to colonize denuded substrata and/or recover its initial state (Ruiz et al., 2009). This led Boudouresque to qualify *Posidonia* regression as irreversible at human scales (Boudouresque et al., 2009).

4.3. High precision mapping of varied P. oceanica beds. Bases for further temporal surveys

Our work showed that acoustic telemetry is a useful tool for the fine-scale mapping of *P. oceanica* beds. Diverse sites allowed us to test the method on varied lower limits, measuring its accuracy and evaluating its cost. All seagrass meadow types, even the most diffuse ones, were precisely mapped (around 1/50th scale) with 137 to 1243 points separated by a mean of 40 cm (standard error = 9 cm). These micro-maps might constitute an initial state important for further studies. Among these nine sites, some were highly scrappy and could not have been surveyed by a classical method. Even on regressive parts, contrary to the RSP method, patches and tufts were recorded and precisely monitored in a short time. This efficiency makes acoustic telemetry cheaper than the RSP method because it requires less underwater work and less marking material for a telemetric system which costs around 15000 Euros. This would permit us to survey all seagrass species dynamics (colonization, regression, allotments) at a large scale. In parallel, the scientific gain in terms of precision and potential for comparative analyses is enormous and we are convinced that it is time for the method to be routinely used.

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