C. R. Biologies 338 (2015) 484–493

Contents lists available at ScienceDirect

Comptes Rendus Biologies

www.sciencedirect.com

Ecology/Écologie

Dynamic of *Posidonia oceanica* seagrass meadows in the northwestern Mediterranean: Could climate change be to blame?

Dynamique des herbiers à Posidonia oceanica *en Méditerranée nord-occidentale : le changement climatique est-il à pointer du doigt ?*

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ARTICLE INFO

Article history:
Received 21 February 2015
Accepted after revision 14 April 2015

Keywords:
Seagrass
Posidonia oceanica
Mediterranean Sea
Monitoring
Vitality
Climate change

Mots clés :
Magnoliophytes marines
Posidonia oceanica
Méditerranée
Surveillance
Vitalité
Changement climatique

ABSTRACT

The distribution and the vitality of the *P. oceanica* meadow were monitored in the western Mediterranean at 15 sites along the coasts of Corsica (1000 km of coastline) using two monitoring systems, the Posidonia Monitoring Network and SeagrassNet, between 2004 and 2013. While the vitality of the meadow is satisfactory overall, due to the low impact of human pressure along these coasts, patterns of change over time show a slight degradation of the main descriptors of the meadow. The meadow's vitality index had declined on average by 8.6%, the BiPo index by 9.8%, and there was a regression of the lower limit at six sites. While this pattern of change may reflect local alterations in the environment (increase or decline in human pressure), the regressive dynamic of the meadow observed at the lower limit at several reference sites (e.g., Marine Protected Areas, sites distant from sources of human impact) is more worrying. Two hypotheses might explain the regression observed: (i) the rise in mean sea level during the study period, which may have resulted in a significant regression in sectors where the slope is relatively slight, and (ii) the North Atlantic Oscillation (NAO), which declined from 2002 to reach very low values in 2010.

RÉSUMÉ

La distribution et la vitalité de l'herbier à *P. oceanica* étaient suivies, en Méditerranée occidentale, sur 15 sites répartis le long du littoral de la Corse (1000 km de côte) par deux méthodes de surveillance, le réseau de surveillance Posidonie et le *SeagrassNet*, entre 2004 et 2013. Si la vitalité de l'herbier est globalement satisfaisante, du fait des faibles pressions anthropiques exercées sur ce littoral, l'évolution temporelle montre une dégradation des principaux descripteurs de l'herbier. Ainsi, l'indice de vitalité de l'herbier

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http://dx.doi.org/10.1016/j.crvi.2015.04.011

diminue en moyenne de 8,6 %, l'indice BiPo de 9,8 % et la position de la limite inférieure régresse pour six sites. Si cette évolution peut traduire des modifications locales de l'environnement (augmentation ou diminution des pressions anthropiques), la dynamique régressive de l'herbier observée en limite inférieure dans des sites de référence (par exemple, aires marines protégées, sites éloignés de sources anthropiques) est plus préoccupante. Deux hypothèses pourraient expliquer la régression observée: (i) l'augmentation du niveau moyen de la mer pendant la période d'étude, qui pourrait entraîner un recul significatif dans des secteurs où la pente est relativement faible et (ii) l'oscillation Nord Atlantique (NAO), qui a diminué depuis 2002 pour atteindre des valeurs très faibles en 2010.

1. Introduction

The development of powerful bioindicators has provided a basis for setting up various monitoring systems throughout the world, starting in 1975 with Mussel Watch [1], focused on monitoring the concentration of pollutants in marine waters by means of this bio-accumulator organism. More recently, the European Water Framework Directive (WFD), adopted in 2002 [2], makes use of a panel of bioindicators to assess the ecological status of a body of water [4,4]. Among the Biological Quality Elements adopted, the seagrass *P. oceanica* (L.) Delile was used for the Mediterranean; several integrative indicators have been developed along these lines: BiPo [5], POMI [6] and PREI [7], applied in different eco-regions.

Because of their ecological roles, their sensitivity to disturbances and their very extensive geographical range, seagrasses often constitute excellent biological indicators [3,8]. Several networks based on these species have thus been developed over the past decades in order to investigate the general state of the ecosystem [9,10]. The first network was the Posidonia Monitoring Network for the Provence-Alpes-Côte d'Azur region (PMN), founded in 1984 [11]; this initiative was extended in 1988 in the Euro-Mediterranean region with Cost 647 (Spain, France, Italy and Greece; [12]). In 2001, the first worldwide network, SeagrassNet, was set up in the United States [13]; it now includes 122 sites in 33 countries (two in the Mediterranean, one at Calvi in Corsica; http://www.seagrassnet.org/).

The development of monitoring networks in the Mediterranean has been strengthened by the adoption by the contracting parties of the Barcelona Convention, the Action Plan for the Conservation of Marine Vegetation in the Mediterranean Sea [14] and the guidelines for the Standardization of Mapping and Monitoring Methods for Mediterranean Seagrasses [15]. For this purpose, many Mediterranean countries have set up monitoring networks for seagrasses [10,16–18]. These networks have generally a two-fold purpose: (i) to monitor the state of conservation of the *P. oceanica* meadows, and (ii) to use the *Posidonia oceanica* meadows as an indicator of the quality of the environment.

The regression of seagrass meadows is a worldwide phenomenon observed over several decades, though the amplitude of this regression varies depending on the species and geographical zones under consideration [19]. In the Mediterranean Sea, *P. oceanica* is subject to natural and anthropogenic pressures and even if the decline of meadows seems in general to be relatively limited (between 0% and 10% throughout the 20th century; [20–22]), more significant rates of decline (up to 5%–8% per year) have been observed locally in sectors subject to strong anthropogenic pressures [23–25].

However, new pressures, indirectly or directly linked to global change, could be the cause of significant regressions, notably the introduction of exotic species, the rise of Sea-Surface Temperature (SST) and of the sea level [26–32]. However, in the absence of sufficiently long and precise series (baseline) regarding the distribution and vitality of the meadow, it is often difficult to confirm these hypotheses and/or to assess with precision the extent of the regression observed.

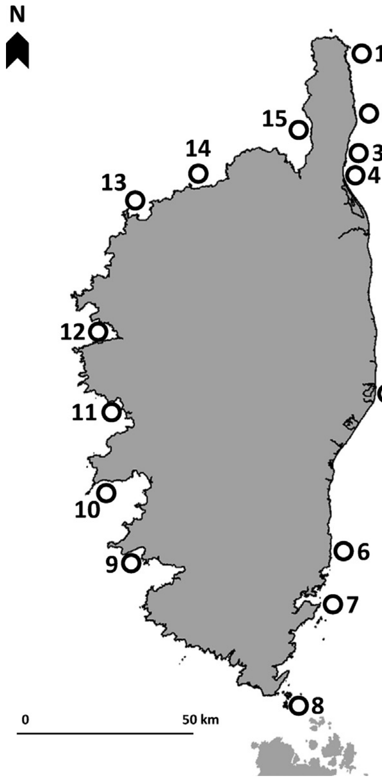
The aim of the present work is to monitor the distribution and the vitality of the *P. oceanica* meadow at 15 sites along 1000 km of coastline (Corsica Island, north western Mediterranean basin) in order to assess the dynamic of the meadow and to determine the possible causes of the changes observed (direct human impact, global change). Developed between 2004 and 2007, this monitoring network is based on the PMN method but one site is also monitored using the SeagrassNet protocol in order to inter-calibrate the two monitoring methods.

2. Material and methods

The 15 sites taken into account correspond to sites with no or with low identified human pressure (significant distance to city/harbor, low exploitation of living resources without trawling, no urban or industrial discharge, Marine Protected Areas) and sites exposed to significant human pressure; the Stareso site is also monitored on the basis of the SeagrassNet network (Fig. 1).

For two depths, specific measurements were taken at each site for the PMN (an intermediate depth between 14 and 16 m depth and the lower limit) and for three depths for the SeagrassNet, the upper limit (8 m), an intermediate depth (25 m) and the lower limit (37 m).

The PMN sites were set up between 2004 and 2007 (measurements recorded between May and July) and there were follow-up visits to each site in 2013 during the same period (between May and July, and $\pm$ 8 days in relation to the original measurement dates); the SeagrassNet system was initiated in October 2006 with follow-ups in October 2009 and October 2012.



	Site	Date	Specifications
1	Macinaggio	2004	Reference meadow
2	Cap Sagro	2004	Reference meadow
3	Toga	2004	City and marina
4	Arinella	2004	Urban effluent
5	Bravone	2004	Trawling
6	Favone	2005	Reference meadow
7	La Chiappa	2005	Urban effluent
8	Lavezzi	2005	Reference meadow
9	Porto Pollo	2005	Reference meadow
10	La Parata	2005	Aquaculture farm
11	Sagone	2007	Reference meadow
12	Porto	2007	Reference meadow
13	Stareso*	2006	Reference meadow
14	Ile Rousse	2007	Urban effluent
15	Canari	2007	Mine spoil

Fig. 1. Location, environmental specifications and dates of setting up of the 15 sites of Posidonia Monitoring Network (PMN) along the coast of Corsica. *: SeagrassNet and PMN site (common site).

The PMN procedure consisted in setting up eleven fixed markers every five meters, along the edge of the lower limit of the meadow; the precise position of each marker was then recorded with a compass [11]. A detailed map of the position of the meadow along the limit was established on the basis of these compass bearings and of vertical photographs taken and then assembled; horizontal photographs of the meadow above its limit were also taken at the level of each marker to compare the changes in the location of the limit over time ([33]; Fig. 1).

Several descriptors were also measured, at the intermediate depth and the lower limit, in order to assess the vitality of the meadow (Table 1) and the quality of the water body in which it was growing (BiPo index [5]; Table 2). The interpretation of the measurements is based on the standardized scales validated by the Barcelona Convention [15] and the Ecological Quality Ratio calculated in the BiPo index [5].

The SeagrassNet protocol requires three permanent transects of 50 m length parallel to the coastline, at the three depths defined by the protocol [33]. The in situ measurements (cover, density) and the sampling (*P. oceanica* shoots) are carried out at predefined distances along each transect (12 measurements and samples per transect). Density is measured in 25 cm × 25 cm quadrats and cover is estimated in 40 cm × 40 cm quadrats by

Table 1
Assessment of the vitality of the meadow, based on several relevant descriptors, according to [14] adapted.

Location	Descriptors (Metric)	High (5)	Good (4)	Normal (3)	Poor (2)	Bad (1)
Lower limit	Lower limit type	Progressive (P)	Sharp high cover (S^+)	Sharp low cover (S^-)	Sparse (Sp)	Regressive (R)
Lower limit	Lower limit depth (m)	> 34.2	34.2–30.4	30.4–26.6	26.6–22.8	< 22.8
Lower limit	Cover (%)	> 35	35–25	25–15	15–5	< 5
Lower limit	Plagiotropic rhizomes (%)	> 70	70–30	< 30	–	–
Lower limit	Leaf production (leaf number·a^{-1})	≥ 8.0	7.9–7.0	6.9–6.0	5.9–5.0	< 4.9
Lower limit	Rhizome elongation (mm·a^{-1})	≥ 8.0	7.9–6.0	5.9–4.0	3.9–2.0	< 1.9
15 m	Leaf surface (cm^2·$shoot^{-1}$)	> 362	361–292	291–221	220–150	< 150
15 m	Density (shoot·m^{-2})	> 339	339–239	238–172	< 172	Na

Na = not applicable. The vitality index corresponds to the average of metrics corresponding to the eight descriptors (max = 5, min = 1).

means of video images. The shoots collected are divided into three parts: leaf, rhizome (maximum length of 10 cm) and sheaths. The length of the longest leaf determines the canopy height. Each shoot part is then dried and weighed in order to measure the biomass.

3. Results

Of the 165 PMN markers, placed along the lower limit, only three were not recovered in 2013, or less than 2%; these were replaced on the basis of the compass bearings taken when they were initially installed.

The meadow had regressed above 73 markers, it had remained stable for 63 and it had progressed for 29; while the regressive dynamic is high (44%), the meadow had progressed or remained stable in the case of more than half of the markers (Table 3). With regard to the sites, at six sites the meadow had regressed, eight had remained stable and one had progressed. The highest regressions observed also concerned both the sites with the highest human pressure impact (Arinella and La Parata) and the reference sites (Cap Sagro and Porto Pollo). The only progression was recorded at the Canari site.

The typology of the lower limit remained the same for 8 sites out of 15; in contrast, for the 7 other sites, the differences observed always reflect a degradation of the limits, in particular for the sites of Cap Sagro, Arinella and Porto Pollo, where the lower limit declined from ‘sharp high cover limit’ to ‘regressive limit’ (Table 4).

A similarly regressive dynamic was found for the density recorded above the markers (Table 4). During the study period, 11 sites out of 15 showed a significant change in this descriptor: nine sites presented a decline in the mean density whereas two presented an increase. The most significant decline concerned the site of Arinella, which dropped from 130 ± 21 to 41 ± 7 shoots per square meter (confidence level 95%). Over the whole set of sites, the mean density declined from 121 ± 27 to 90 ± 28 shoots per m^2, or a decline of 25%.

Table 2
Assessment of water body quality (EQR) based on the BiPo index according to [4]. The lower limit types have been modified according to [14] (See Table 1 for abbreviations). X corresponds to the value measured for each descriptor; for instance a lower limit observed at a depth of 30 m corresponds to an EQR of 0.7375 $(((30-25)/6) \times 0.225) + 0.55)$.

Location	Descriptors (Metric)		High (1.000–0.775)	Good (0.774–0.550)	Normal (0.549–0.325)	Poor (0.324–0.100)	Bad (< 0.100)
Lower limit	Lower limit depth (m)	Values	> 31	25–31	19–25	< 19	Na
		EQR	$(((X-31)/7 \times 0.225) + 0.775)$	$((((X-25)/6) \times 0.225) + 0.55)$	$((((X-19)/6) \times 0.225) + 0.325)$	$(((X/19) \times 0.225) + 0.1)$	0.05
Lower limit	Lower limit type	Values	P	S^+	S^-	Sp	R
		EQR	1.00	0.89	0.66	0.44	0.21
15 m	Density (shoot·m^{-2})	Values	> 339	239–339	172–238	< 172	Na
		EQR	$(((X-339)/260 \times 0.225) + 0.775)$	$(((X-239)/100 \times 0.225) + 0.55)$	$(((X-172)/67 \times 0.225) + 0.325)$	$(((X/172) \times 0.225) + 0.1)$	0.05
15 m	Leaf length (mm)	Values	> 812	651–812	481–651	< 481	Na
		EQR	$((((X-812)/143) \times 0.225) + 0.775)$	$((((X-651)/161) \times 0.225) + 0.55)$	$((((X-481)/170) \times 0.225) + 0.325)$	$(((X/481) \times 0.225) + 0.1)$	0.05

Table 3
Patterns of change in the location of *P. oceanica* lower limit above the marker (PMN). For each site, synthesis is based on the mean evolution of the 11 markers (position of the median).

Site	Progression	Stability	Regression	Synthesis
Macinaggio (ref)	0	8	3	Stability
Cap Sagro (ref)	0	1	10	Regression
Toga	2	4	5	Stability
Arinella	0	0	11	Regression
Bravone	1	8	2	Stability
Favone (ref)	0	11	0	Stability
La Chiappa	0	7	4	Stability
Lavezzi (ref)	3	2	6	Regression
Porto Pollo (ref)	0	0	11	Regression
La Parata	0	0	11	Regression
Sagone (ref)	3	5	3	Stability
Porto (ref)	5	6	0	Stability
Stareso (ref)	1	4	6	Regression
Île Rousse	4	6	1	Stability
Canari	10	1	0	Progression
Total	29	63	73	Stability

Ref: reference site.

Table 4
Patterns of change in the lower limit type and meadow density between the setting up (2004–2007) and the monitoring phase (2013). Mean ± standard deviation (95%).

	Type of limit		Density (nb shoot·m^{-2})	
Site	Setting up	Monitoring phase	Setting up	Monitoring phase
Macinaggio (ref)	Progressive	Progressive	150 ± 31	69 ± 10[a]
Cap Sagro (ref)	Sharp high cover	Regressive	134 ± 23	55 ± 11[a]
Toga	Regressive	Regressive	261 ± 33	142 ± 28[a]
Arinella	Sharp high cover	Regressive	130 ± 21	41 ± 7[a]
Bravone	Regressive	Regressive	121 ± 22	83 ± 11[a]
Favone (ref)	Sparse	Sparse	79 ± 19	53 ± 11[a]
La Chiappa	Sharp low cover	Regressive	112 ± 34	79 ± 13
Lavezzi (ref)	Progressive	Progressive	127 ± 17	134 ± 17
Porto Pollo (ref)	Sharp high cover	Regressive	75 ± 10	48 ± 8[a]
La Parata	Sparse	Regressive	80 ± 14	43 ± 11[a]
Sagone (ref)	Progressive	Sharp low cover	181 ± 42	138 ± 25
Porto (ref)	Sharp low cover	Sharp low cover	122 ± 43	110 ± 21
Stareso (ref)	Sharp high cover	Sharp low cover	67 ± 12	50 ± 10[a]
Île Rousse	Regressive	Regressive	42 ± 8	62 ± 10[a]
Canari	Sharp high cover	Sharp high cover	128 ± 25	242 ± 26[a]

[a] Significant difference (Student *t* test, *p* value > 0.05).

The mean vitality of the meadow, calculated on the basis of all the eight descriptors measured at the lower limit and at intermediate depth, remained 'good', even if a decline in the mean vitality index was recorded over time (setting up: 3.8 ± 0.2; monitoring phase: 3.5 ± 0.2) and the number of sites ranked as 'good' declined over course of the study period (Tables 5 and 6). This decline in vitality was observed both at the reference sites (50%) and at the high human pressure impact sites (53%).

The quality of the water body (BiPo Index) declined over the course of the study period (setting up: 0.74 ± 0.06; monitoring phase: 0.67 ± 0.07) but also remained 'good' at the scale of the Corsican coasts as a whole (Tables 7 and 8). This decline was observed both for the reference sites (75%) and for the high human pressure impact sites (80%).

The three transects of the SeagrassNet system, installed at the Stareso site in 2006, were recovered at each follow-up visit to the site (2009 and 2012). The meadow density declined when the depth increased for the three years studied (Fig. 2). Between 2006 and 2012, the density increased at the upper limit (8 m depth), remained stable at the intermediate depth (25 m) and declined at the lower limit (37 m). At the lower limit, it declined from 24 ± 16 to 12 ± 13 shoots per m^2.

The meadow cover also declined at the lower limit where it dropped respectively from 23.3 ± 10.0% in 2006, to 20.0 ± 9.0% in 2009 and to 19.2 ± 12.6% in 2012

4. Discussion

The introduction of the PMN for Corsica between 2004 and 2007 constituted the first stage towards achieving a reference state for the localization and the vitality of the *P. oceanica* meadows along the coasts of Corsica [33]. The follow-up visit to the site in 2013 made it possible to assess the effectiveness of the protocol used and to monitor changes in the state of conservation of the meadows over time.

The protocol used for the PMN for the Corsican coasts provided a basis for:

Table 5
Vitality of *P. oceanica* meadow at the time of the setting up of the PMN (2004–2007). Mean ± standard deviation (95%).

Setting up	Lower limit type	Lower limit depth (m)	Cover (%)	Plagiotropic rhizomes (%)	Leaf production (number·y^{-1})	Rhizome elongation (mm·y^{-1})	Density (shoot·m^{-2})	Leaf surface[a] (cm^2·shoot^{-1})	Synthesis (Mean metric values)
Macinaggio (ref)	P	38.0 ± 0.1	21.8 ± 4.2	20.6 ± 9.9	7.1 ± 0.2	6.6 ± 1.6	243.8 ± 11.6	371	4.1 (Good)
Cap Sagro (ref)	S+	33.0 ± 0.3	13.2 ± 5.2	12.4 ± 9.0	6.3 ± 0.3	6.5 ± 1.5	270.8 ± 19.0	412	3.6 (Good)
Toga	R	24.2 ± 0.4	19.1 ± 7.1	8.6 ± 2.9	7.0 ± 0.4	5.5 ± 0.9	230.7 ± 16.2	348	2.9 (Normal)
Arinella	S+	26.9 ± 0.3	54.5 ± 11.9	30.9 ± 5.6	8.1 ± 0.1	5.1 ± 0.4	246.4 ± 10.7	314	4.0 (Good)
Bravone	R	36.1 ± 0.1	40.9 ± 7.7	24.1 ± 2.9	7.6 ± 0.4	8.5 ± 1.8	315.1 ± 17.2	302	3.9 (Good)
Favone (ref)	Sp	36.9 ± 0.3	7.7 ± 2.2	80.0 ± 5.3	6.2 ± 0.6	4.4 ± 1.7	325.0 ± 17.4	316	3.5 (Good)
La Chiappa	S–	35.3 ± 0.1	17.7 ± 5.0	9.3 ± 6.2	7.4 ± 0.6	9.0 ± 1.9	304.0 ± 13.6	292	3.9 (Good)
Lavezzi (ref)	P	30.3 ± 0.1	66.3 ± 16.7	17.7 ± 7.0	8.2 ± 0.7	6.6 ± 1.2	169.3 ± 17.2	345	3.9 (Good)
Porto Pollo (ref)	S+	32.2 ± 0.2	32.0 ± 5.6	94.5 ± 3.1	7.2 ± 0.5	4.3 ± 1.4	256.3 ± 14.7	303	4.0 (Good)
La Parata	Sp	35.3 ± 0.2	10.1 ± 4.3	95.5 ± 3.1	8.7 ± 0.8	6.3 ± 1.7	176.1 ± 7.7	300	3.8 (Good)
Sagone (ref)	P	33.2 ± 0.1	26.5 ± 12.8	75.5 ± 14.5	8.2 ± 0.4	6.1 ± 1.2	472.4 ± 21.8	226	4.4 (Good)
Porto (ref)	S–	36.5 ± 0.2	20.1 ± 8.1	96.2 ± 5.4	6.5 ± 0.4	4.2 ± 0.7	338.4 ± 16.8	310	3.8 (Good)
Stareso (ref)	S+	38.6 ± 0.3	27.6 ± 10.2	77.3 ± 15.0	7.3 ± 0.7	4.5 ± 1.2	310.4 ± 27.9	367	4.3 (Good)
Île Rousse	R	35.8 ± 0.2	33.6 ± 15.5	56.6 ± 17.0	6.5 ± 0.3	5.4 ± 1.0	208.3 ± 11.9	181	3.1 (Normal)
Canari	S+	27.4 ± 0.8	87.0 ± 6.7	11.7 ± 7.4	8.2 ± 0.5	7.1 ± 1.4	280.2 ± 14.7	245	3.9 (Good)

[a] Only mean data are available.

Table 6
Vitality of *P. oceanica* meadow during the monitoring phase (2013). Mean ± standard deviation (95%).

Control phase	Lower limit type	Lower limit depth (m)	Cover (%)	Plagiotropic rhizomes (%)	Leaf production (number·y^{-1})	Rhizome elongation (mm·y^{-1})	Density (shoot·m^{-2})	Leaf surface (cm^2·shoot^{-1})	Synthesis (Mean metric values)
Macinaggio (ref)	P	38.0 ± 0.1	14.2 ± 9.2	78.5 ± 12.6	7.2 ± 0.7	5.2 ± 1.7	368.8 ± 22.0	307.2 ± 37.7	4.1 (Good)
Cap Sagro (ref)	R	33.0 ± 0.3	5.7 ± 3.7	90.9 ± 12.8	6.9 ± 0.5	4.0 ± 1.0	307.6 ± 32.2	304.4 ± 29.8	3.1 (Normal)
Toga	R	24.3 ± 0.4	41.2 ± 13.2	21.3 ± 13.7	7.0 ± 0.8	6.2 ± 1.7	268.4 ± 29.3	253.7 ± 37.5	3.3 (Normal)
Arinella	R	26.9 ± 0.3	6.8 ± 4.5	52.1 ± 19.0	7.6 ± 0.6	4.3 ± 0.8	260.4 ± 33.0	352.1 ± 27.9	3.1 (Normal)
Bravone	R	36.1 ± 0.1	28.3 ± 12.1	65.1 ± 12.5	7.0 ± 0.6	4.7 ± 1.1	308.4 ± 30.6	171.5 ± 21.6	3.4 (Normal)
Favone (ref)	Sp	36.9 ± 0.2	7.6 ± 2.6	81.4 ± 8.5	7.0 ± 0.8	6.2 ± 1.7	322.8 ± 49.7	188.7 ± 29.6	3.5 (Good)
La Chiappa	R	35.3 ± 0.1	12.5 ± 5.9	83.4 ± 17.2	6.9 ± 0.6	4.2 ± 0.9	318.0 ± 32.0	195.3 ± 37.8	3.1 (Normal)
Lavezzi (ref)	P	30.3 ± 0.1	44.0 ± 18.4	67.2 ± 17.4	8.1 ± 0.7	5.2 ± 1.3	241.6 ± 32.3	312.1 ± 62.4	4.1 (Good)
Porto Pollo (ref)	R	32.2 ± 0.2	4.8 ± 2.2	79.3 ± 13.6	7.6 ± 0.7	4.0 ± 1.1	351.2 ± 46.2	215.6 ± 33.1	3.1 (Normal)
La Parata	R	35.3 ± 0.2	1.0 ± 0.9	92.5 ± 10.2	7.9 ± 0.7	3.5 ± 0.8	211.6 ± 25.0	244.2 ± 36.0	3.0 (Normal)
Sagone (ref)	S–	33.2 ± 0.1	35.2 ± 16.0	67.7 ± 11.6	7.8 ± 0.6	4.9 ± 0.9	448.0 ± 32.3	106.5 ± 21.2	3.6 (Good)
Porto (ref)	S–	36.5 ± 1.3	23.5 ± 9.5	85.8 ± 15.7	7.0 ± 0.6	4.9 ± 1.4	298.4 ± 47.3	288.1 ± 38.7	3.8 (Good)
Stareso (ref)	S–	38.6 ± 0.3	19.2 ± 4.6	94.5 ± 8.0	7.0 ± 0.7	3.7 ± 0.7	240.8 ± 20.5	276.0 ± 28.3	3.6 (Good)
Île Rousse	R	35.8 ± 0.2	22.6 ± 12.7	81.5 ± 14.1	7.1 ± 0.7	3.8 ± 1.1	258.4 ± 25.0	139.5 ± 20.9	3.1 (Normal)
Canari	S +	27.4 ± 0.8	97.5 ± 3.5	28.5 ± 11.3	8.1 ± 0.6	6.3 ± 1.5	376.8 ± 38.1	387.5 ± 78.3	4.3 (Good)

- validating the sustainability of the structures used (99% still found after 5 to 9 years without maintenance);
- comparing with precision the data acquired during the setting up phase (2004–2007) and at the time of the first follow-up visit (2013);
- detecting and quantifying the alterations recorded with regard to the lower limit, the vitality of the meadow and the quality of the water body, and;
- comparing the data collected with those resulting from another monitoring system, the SeagrassNet system, for the Stareso site.

For the PMN system, a considerable effort was made with regard to the data acquisition protocol to limit the degree of observer subjectivity and in order to dispose of reproducible raw data. These raw data could perhaps be optimized in the years to come depending on the new tools that become available and on advances in scientific knowledge. The PMN protocol is consistent with the guidelines validated by the Barcelona Convention [15], which means that it can offer a basis for comparison with other similar networks that have been developed for the Mediterranean [10,11,17].

The SeagrassNet protocol has from the outset been standardized in a very precise way [34]; its adaptation to take into account the specificities of the Mediterranean seagrass meadows [35] will allow very effective temporal comparisons (http://www.seagrassnet.org/).

The vitality of the *P. oceanica* meadows and the quality of the water body (BiPo index) along the Corsican coasts, respectively "Normal" and "Good", are strongly correlated ($r = 0.86$ in 2013). The "High" values recorded for lower limit depth may be explained in particular by the high degree of limpidity of the waters, because of the small number of permanent coastal rivers and the limited impact of human activities. In general, the sites situated in the highly oligotrophic sectors (e.g., Cyprus [36,37]) often present high values for the BiPo index [38] whereas sites exposed to high turbidity (e.g., Catalonia [6]), even if of natural origin, present lower values ([39]; Table 9).

Concerning the PMN Corsica, no clear patterns of change over time of the *P. oceanica* meadows can be observed (Table 10), even if the vitality index value has slightly declined by 8.6% on average. However, taking into account changes in (i) the position of the lower limit, (ii) the vitality index and (iii) the BiPo index, the median

Table 7
Water body quality (BiPo index) at PMN sites during setting up (2004–2007). Mean ± standard deviation (95%).

Setting up	Lower limit depth (m)	Lower limit type	Density (shoot·m^{-2})	Leaf length (cm)	EQR
Macinaggio (ref)	38.0 ± 0.1	P	243.8±11.6	978.1 ± 28.5	0.89 (High)
Cap Sagro (ref)	33.0 ± 0.3	S +	270.8±19.0	989.7 ± 36.7	0.84 (High)
Toga	24.2 ± 0.4	R	230.7±16.2	853.8 ± 40.7	0.52 (Normal)
Arinella	26.9 ± 0.3	S +	246.4±10.7	913.9 ± 36.5	0.75 (Good)
Bravone	36.1 ± 0.1	R	315.1±17.2	830.8 ± 44.7	0.67 (Good)
Favone (ref)	36.9 ± 0.3	Sp	325.0±17.4	903.0 ± 30.0	0.77 (Good)
La Chiappa	35.3 ± 0.1	S–	304.0±13.6	839.3 ± 28.2	0.77 (Good)
Lavezzi (ref)	30.3 ± 0.1	P	169.3±17.2	914.7 ± 32.2	0.76 (Good)
Porto Pollo (ref)	32.2 ± 0.2	S +	256.3±14.7	730.0 ± 23.4	0.74 (Good)
La Parata	35.3 ± 0.2	Sp	176.1±7.7	732.1 ± 39.1	0.59 (Good)
Sagone (ref)	33.2 ± 0.1	P	472.4±21.8	576.7 ± 31.2	0.80 (High)
Porto (ref)	36.5 ± 0.2	S–	338.4±16.8	785.8 ± 59.4	0.87 (High)
Stareso (ref)	38.6 ± 0.3	S +	310.4±27.9	887.1 ± 18.9	0.87 (High)
Île Rousse	35.8 ± 0.2	R	208.3±11.9	810.7 ± 40.8	0.59 (Good)
Canari	27.4 ± 0.8	S +	280.2±14.7	690.8 ± 46.6	0.69 (Good)

Table 8
Water body quality (BiPo index) at PMN sites during the control phase (2013). Mean ± standard deviation (95%).

Control phase	Lower limit depth (m)	Lower limit type	Density (shoot·m^{-2})	Leaf length (cm)	EQR
Macinaggio (ref)	38.0 ± 0.1	P	368.8 ± 22.0	964.5 ± 97.1	0.95 (High)
Cap Sagro (ref)	33.0 ± 0.3	R	307.6 ± 32.2	962.9 ± 53.4	0.69 (Good)
Toga	24.3 ± 0.4	R	268.4 ± 29.3	714.8 ± 74.7	0.49 (Normal)
Arinella	26.9 ± 0.3	R	260.4 ± 33.0	972.0 ± 53.4	0.61 (Good)
Bravone	36.1 ± 0.1	R	308.4 ± 30.6	612.8 ± 61.0	0.59 (Good)
Favone (ref)	36.9 ± 0.2	Sp	322.8 ± 49.7	592.2 ± 85.5	0.66 (Good)
La Chiappa	35.3 ± 0.1	R	318.0 ± 32.0	675.0 ± 122.7	0.61 (Good)
Lavezzi (ref)	30.3 ± 0.1	P	241.6 ± 32.3	990.5 ± 93.1	0.82 (High)
Porto Pollo (ref)	32.2 ± 0.2	R	351.2 ± 46.2	683.2 ± 69.5	0.60 (Good)
La Parata	35.3 ± 0.2	R	211.6 ± 25.0	715.8 ± 72.9	0.55 (Good)
Sagone (ref)	33.2 ± 0.1	S–	448.0 ± 32.3	410.7 ± 47.0	0.65 (Good)
Porto (ref)	36.5 ± 1.3	S–	298.4 ± 47.3	903.1 ± 103.8	0.80 (High)
Stareso (ref)	38.6 ± 0.3	S–	240.8 ± 20.5	634.1 ± 35.2	0.69 (Good)
Île Rousse	35.8 ± 0.2	R	258.4 ± 25.0	455.6 ± 47.8	0.49 (Normal)
Canari	27.4 ± 0.8	S +	376.8 ± 38.1	982.1 ± 122.6	0.83 (High)

showed a pattern of stability for 9 sites (including 5 reference sites), regression for 5 sites (including 3 reference sites), and progression for 1 site (Table 10).

Concerning the reference sites, other disturbing observations underlined their regression. In terms of values, 50% presented a decline of the vitality index value (Tables 5 and 6) and 75% of the BiPo index value (Tables 7 and 8). More specifically, 25% of these sites presented a regressive lower limit type, in 2013. Moreover, the number of reference sites where the pattern of change in the location of the lower limit was "regressive" was the same as that where it was "stable" [4].

The regression recorded at the level of the lower limit of the meadows cannot be imputed to local degradation of the environmental conditions, given that they were distributed along the whole coastline of the island and in view of their distance from potential sources of human pressure. In addition, a similar phenomenon was observed for the Provence-Alpes-Côte d'Azur Region PMN (between 1988 and 1999 in [12]), and more particularly at the level of the lower limit of the Côte Bleue seagrass meadows [41].

Similarly, in the "Parc national de Port-Cros" (reference meadow), [42] observed a very severe decline in the meadow density and cover at the level of the lower limit between 2002 and 2008. A similar pattern was also observed at Kerkennah Islands (Tunisia), in the south-western basin, between 2007 and 2014 (Pergent and Langar, unpublished data). In the Western Pacific region, in sites with other seagrass species and stable human influence, the SeagrassNet also exhibited a clear decline [43].

For the common reference site, Stareso, the two monitoring systems (PMN and SeagrassNet) show the same regressive dynamic with a decline in the meadow vitality, in particular with regard to the density and cover at the lower limit.

If *P. oceanica* regression could be related to the rise in temperature of the seawater at shallow depth [32,44], this

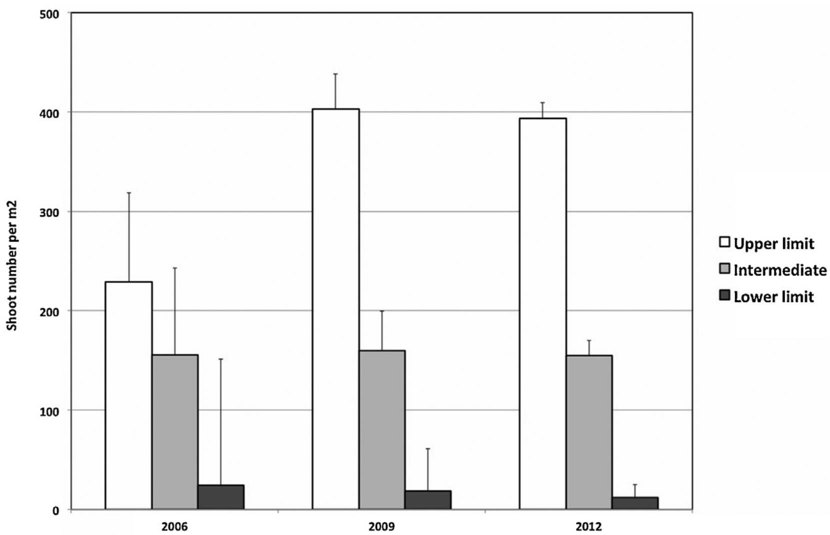


Fig. 2. Changes in meadow density (mean shoot number per square meter ± confidence level 95%) between 2006 and 2012 at different depths, from the upper limit to the lower one.

Table 9
Assessment of the water quality on the basis of the BiPo index at different Mediterranen sites.

Country	Site	BiPo index	Reference
Spain	Catalonia – Montroig	0.36	[40]
	Catalonia – Mataro	0.55	[40]
France	PMN Corsica (2013)	0.49–0.95 mean: 0.67	This study
	Corsica – Punta Bianca	0.84	[39]
	Corsica – Stareso	0.82	[39]
	Corsica – Cages	0.77	[39]
Italy	Ischia – Lacco Ameno	0.59	[40]
	Ischia – Scarrupata	0.78	[40]
Cyprus	Akamas	0.94	[38]
	Cavo Greko	0.90	[38]
	Limassol	0.79	[38]
	Moulia	0.95	[38]
	Nisia	0.87	[38]
	Polis	0.82	[38]
Tunisia	Sidi Ali El Mekki	0.86	[17]
	Kerkennah island	0.65	[17]
Turkey	Gokceada[a]	0.49	[17]
	Mersin[b]	0.34	[17]

[a] Off the Dardanelles Straight.
[b] Southeastern limit of the range of *P. oceanica*.

seems less plausible at depths where the temperature is lower and more stable [42], even if some regression has been locally observed, along the lower limit, during warm water episodes [41]. The lower limit corresponds to the depth of compensation of the species, beyond which the amount of light is insufficient to enable photosynthetic production to compensate for the losses due to respiration [45]; any reduction of this light will inevitably entail a decline in the vitality of the meadow and a regression of the position of the lower limit [46]. Two hypotheses might explain the regression observed:

- *the mean sea level* rose between 1870 and 2000 by 18 cm, including 6 cm over the past 20 years [47]. Measurements taken in Corsica, at the Ajaccio tidal gauge station, show a mean increase of 2 cm over the past 10 years (SONEL network; http://www.sonel.org/-Maregraphes-.html). For the deep lower limits (below 35 m depth), this increase in the height of the water column over the past decade has resulted in a decline in the amount of light at the seabed. This reduction may result, in areas where the slope is relatively slight, in a significant regression of the position of the lower limit [21]. Thus, for a slope of 2%, an increase of 2 cm in the depth of the water column (vertical) corresponds to a linear regression of 1 m of the position of the lower limit (horizontal) of the seagrass meadow (Fig. 3);
- *the North Atlantic Oscillation* (NAO) may play a role in the penetration of the light within the water column. This climatic oscillation (NAO) may entail, when it is slight, an increase in precipitation (increase in inflow from coastal rivers and cloud cover) at Mediterranean scale [48]. On the basis of the high values during the 1990s, the NAO index declined after 2002 to reach very low values in 2010 [49,50].

The sites exposed to human pressure present a more contrasting dynamic. For the sites exposed to the persistence, or even the amplification, of these pressures, the state of conservation of the meadows (vitality index) continues to decline. This is the case for the sites of Arinella (urban sewage outfall) and La Parata (discharges from an aquaculture facility). In contrast, at sites where these pressures are in decline, the state of conservation of the meadow has stabilized (Toga: shutdown of coastal management operations, Île Rousse: establishment of a sewage treatment plant) or progressed (Canari: shutdown of mining discharges at sea).

It is thus clear that the state of conservation of the *P. oceanica* meadow, as a bioindicator, constitutes an effective tool for the assessment of government policy regarding actions undertaken to improve the quality of the environment. The PMN put into application along the coasts of Corsica would appear to be highly sensitive to

Table 10
Indicators dashboard – environmental status and patterns of change in the location of the lower limit, the vitality of the meadow and the water body quality (BiPo) between 2004–2007 and 2013.

Site	Lower limit (Depth) Evolution	Vitality index (Value) Evolution	BiPo index (Value) Evolution	Synthesis
Macinaggio (ref)	(High) ⇔	(Good) ⇔	(High) ⇔	(High) ⇔
Cap Sagro (ref)	(Good) ↘	(Normal) ↘	(Good) ↘	(Good) ↘
Toga	(Normal) ⇔	(Normal) ⇔	(Normal) ⇔	(Normal) ⇔
Arinella	(High) ↘	(Normal) ↘	(Good) ⇔	(Normal) ↘
Bravone	(High) ⇔	(Normal) ↘	(Good) ⇔	(Good) ⇔
Favone (ref)	(High) ⇔	(Good) ⇔	(Good) ⇔	(Good) ⇔
La Chiappa	(High) ⇔	(Normal) ↘	(Good) ⇔	(Good)⇔
Lavezzi (ref)	(Normal) ↘	(Good) ⇔	(High) ↗	(Good) ⇔
Porto Pollo (ref)	(Good) ↘	(Normal) ↘	(Good) ⇔	(Good) ↘
La Parata	(High) ↘	(Normal) ↘	(Good) ⇔	(Good) ↘
Sagone (ref)	(Good) ⇔	(Good) ⇔	(Good) ↘	(Good) ⇔
Porto (ref)	(High) ⇔	(Good) ⇔	(High) ⇔	(High) ⇔
Stareso (ref)	(High) ↘	(Good) ⇔	(Good) ↘	(Good) ↘
Île Rousse	(High) ⇔	(Normal) ⇔	(Normal) ↘	(Good) ⇔
Canari	(Normal) ↗	(Good) ⇔	(High) ↗	(Good) ↗
Synthesis	(High) ⇔	(Normal) ⇔	(Good) ⇔	(Good) ⇔

Ref: reference meadow; ↗: progression; ⇔: stability; ↘: regression. The values into bracket correspond to the situations of 2013. The synthesis is calculated from the median.

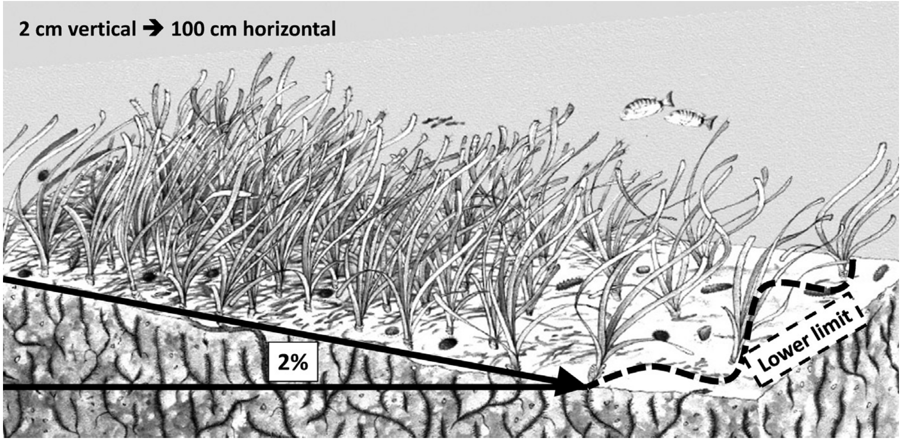


Fig. 3. Regression of the lower limit resulting from increase of water column height and mean slope.

the degradations or improvements in the environmental conditions. In addition, if the regression of the lower limit of the meadow, at several reference sites, in relation with the rise in sea level, is confirmed, this species may also play the role of bioindicator for climate change in the Mediterranean. Climate change might be the cause of a significant regression of the lower limit of the *P. oceanica* meadows, at Mediterranean scale, during the course of the 21th century, given the forecasts for the patterns of change in sea level. [51]. For this reason, an extension of the PMN in Corsica, with the installation of six new reference sites in the "Réserve naturelle des bouches de Bonifacio" (southern coast), was undertaken in 2013. These new sites should provide the means to monitor more precisely the patterns of change in the seagrass meadow where human impact is low and could definitively confirm the impact of climate change.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Acknowledgments

This work was supported by a grant from the "Office de l'Environnement de Corse" (Corsica, France) and received support from the Global Seagrass Monitoring Network. It was carried out within the framework of the programme CHANGE of the FRES 3041, funded by the "Collectivité Territoriale de Corse" (Corsica, France). The authors thank Aurélie Blanfuné-Thibaut for statistics and Michael Paul for checking the English. The authors would also like to express their gratitude to the reviewers for their helpful remarks.

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