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THE *POSIDONIA OCEANICA* MATTE: A UNIQUE COASTAL CARBON SINK FOR CLIMATE CHANGE MITIGATION AND IMPLICATIONS FOR MANAGEMENT

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POSIDONIA OCEANICA MEADOW
CARBON SINK
MAPPING
SEISMIC REFLECTION
CARBON SEQUESTRATION
CARBON STOCK
CLIMATE CHANGE MITIGATION

ABSTRACT. – Seagrass meadows have long been recognized for their high ecological and economic value (ecosystem services). More recently, a potential role in climate regulation, due to their ability to fix and sequester carbon, has been the focus of intensive study. In the Mediterranean Sea, the matte, a specific structure built by the seagrass *Posidonia oceanica,* is of particular interest because it keeps buried for thousands of years massive amounts of carbon. Recent studies carried out along the Corsican coasts show a mean fixation of 1.62 Mg C ha^{-1} yr^{-1}, with a sequestration rate of between 27 and 30 %, a mean matte thickness of 210 cm and 711 Mg C ha^{-1} of organic carbon trapped in the matte. That is to say, a stock corresponding to 1,580 years of *P. oceanica* carbon sequestration, confirmed by radiocarbon analysis. An extrapolation to the Mediterranean basin (1.0 to 1.5 million hectares covered by *P. oceanica* meadow; mean matte thickness: 210 cm) shows that the total stock of organic carbon sequestered in the *P. oceanica* matte might be as much as 711 to 1,067 million Mg C. The conservation of the *P. oceanica* meadows thus constitutes an issue of major importance since any degradation of the matte, which has been built up over the past millennia, would very likely result in the release of considerable quantities of carbon. Rather than playing a major role in the attenuation of the impact of climate change (blue carbon sequestration), the *P. oceanica* meadow would then become a source of carbon that would be likely to amplify the greenhouse gas emissions. Management of *P. oceanica* meadows should take into account not only their role in carbon sequestration, but also the whole the full range of their ecosystem services, in relation with the functioning of the ecosystem.

INTRODUCTION

Seagrass meadows have long been recognized for their high ecological and economic value and associated ecosystem services (Costanza *et al.* 1997, Boudouresque *et al.* 2012, Vassallo *et al.* 2013, Picone *et al.* 2017). More recently, a potential role in climate regulation, due to their ability to fix and sequester carbon, has been the focus of intensive study (Nellemann *et al.* 2009, Fourqurean *et al.* 2012, Pergent *et al.* 2014). Carbon sequestration by seagrass is estimated at 15 % of total blue carbon, although seagrass cover represents only 17.7 to 61.0 million hectares at biosphere scale (Spalding *et al.* 2003, Kennedy & Björk 2009, UNEP-WCMC 2013).

Among the sixty-four species of seagrass (Guiry & Guiry 2020), *Posidonia oceanica* (Linnaeus) Delile, a Mediterranean endemic species, appears to be the most efficient in carbon storage; the *P. oceanica* meadow is the only ecosystem able to match peatlands and mangroves because it builds a unique structure: the matte. Made up of rhizomes and roots, with sediment that fills the interstices this highly resistant structure can reach several meters in height, and the organic matter it contains can persist for millennia (Mateo *et al.* 1997, 2006, Serrano *et al.* 2012, Boudouresque *et al.* 2016, Monnier *et al.* 2019a). In the light of the Paris Agreement, where major carbon sinks such as coastal vegetation are taken into account for the first time, and due to the exceptional extension of the *P. oceanica* meadows in Corsica (Valette-Sansevin *et al.* 2019), an extensive survey of these blue carbon sinks was performed to (i) inventory the main Blue Carbon Ecosystems (surface area and 3D extension – matte thickness), (ii) estimate the fixation and carbon sequestration rates, and (iii) assess the standing carbon stocks within the matte.

MATERIAL AND METHODS

The study was conducted in the Natura 2000 area "*Grand Herbier de la Côte Orientale*", a 100 km sandy coastline area along the eastern coast of Corsica (Fig. 1).

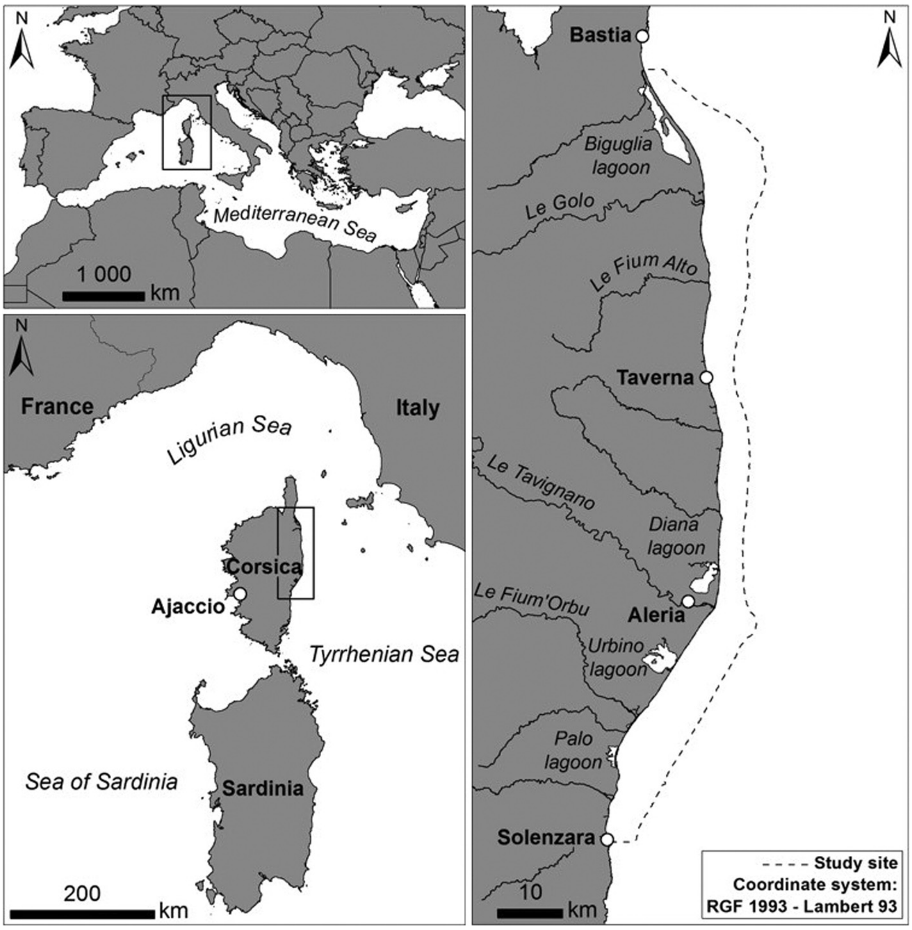

Fig. 1. – Location of the study site (Eastern continental shelf of Corsica Island, NW Mediterranean Sea).

The inventory of surface area covered by seagrass beds was performed, (i) for the shallow area (surface to –15 m), by remote sensing based on aerial images (BD ORTHO® of the IGN – French National Geographic Institute) with a 0.5 m resolution, (ii) for the deep area (–10 to –50 m), through several oceanographic surveys using exhaustive acoustic coverage (coupling a multibeam echosounder and a side-scan sonar), and (iii) for the other sectors, by a survey of existing data (Valette-Sansevin *et al*. 2019). Ground truthing data were acquired using a bathyscope for the shallow area (0 to –10 m) and for deeper areas, a Remotely Operated Vehicle (ROV), scuba diving inspections, underwater video camera recording (Pergent *et al*. 2017) and by collecting samples (Van Veen grab). After remote sensing following the method of Bonacorsi *et al*. (2013), data were integrated into a Geographic Information System (ArcGIS® 10.2.2., ESRI).

The assessment of *P. oceanica* matte thickness was carried out using the high-resolution seismic reflection method. Three devices with distinct emission frequencies were deployed for data collection: a Sparker (1 kHz) and two sediment profilers; the Manta EDO (2.5 kHz) and the Pesk Avel (3.5 kHz). In total, 510 seismic profiles were acquired corresponding to 3,095 km of data (Monnier *et al*. 2017, 2019b). Mapping of matte thicknesses is done after integrating the data into the ArcGIS® 10.2.2. software and using the ordinary kriging method. The map covered a range from –10 m (upper limit of data acquisition) to –40 m depth (lower limit of the *P. oceanica* meadow generally observed at this site).

Organic carbon fixation and sequestration were estimated at six sites (between –5 and –30 m) along three transects at the Natura 2000 site (Biguglia, Taverna and Urbino). Carbon fixation was measured through an assessment of primary production by the lepidochronology method (Pergent & Pergent-Martini 1991), and (ii) carbon sequestration was estimated on carbon fluxes (consumption by herbivores and detritivores, leaf litter exportation and seagrass tissues (sheaths, rhizomes and roots) buried in the *P. oceanica* matte; Pergent *et al*. 1997). Elemental analysis contributed to measurement of the total carbon content (%C) in the different tissues of *P. oceanica* after removal of epiphytes.

Estimation and characterization of organic carbon stocks was performed by collecting vertical cores in the matte with a Kullenberg gravity corer during the CARBONSINK oceanographic survey (2018). The matte samples were collected at three stations (–10 m, –20 m and –30 m) close to the same transects (Biguglia, Taverna and Urbino). Analysis of samples were undertaken after drying, sieving (< 2 mm) and separating sediment slices in different fractions (calcium carbonates, mineral and organic material). The total organic matter content (%TOM) and the elemental analysis (%C) were carried out on the fine

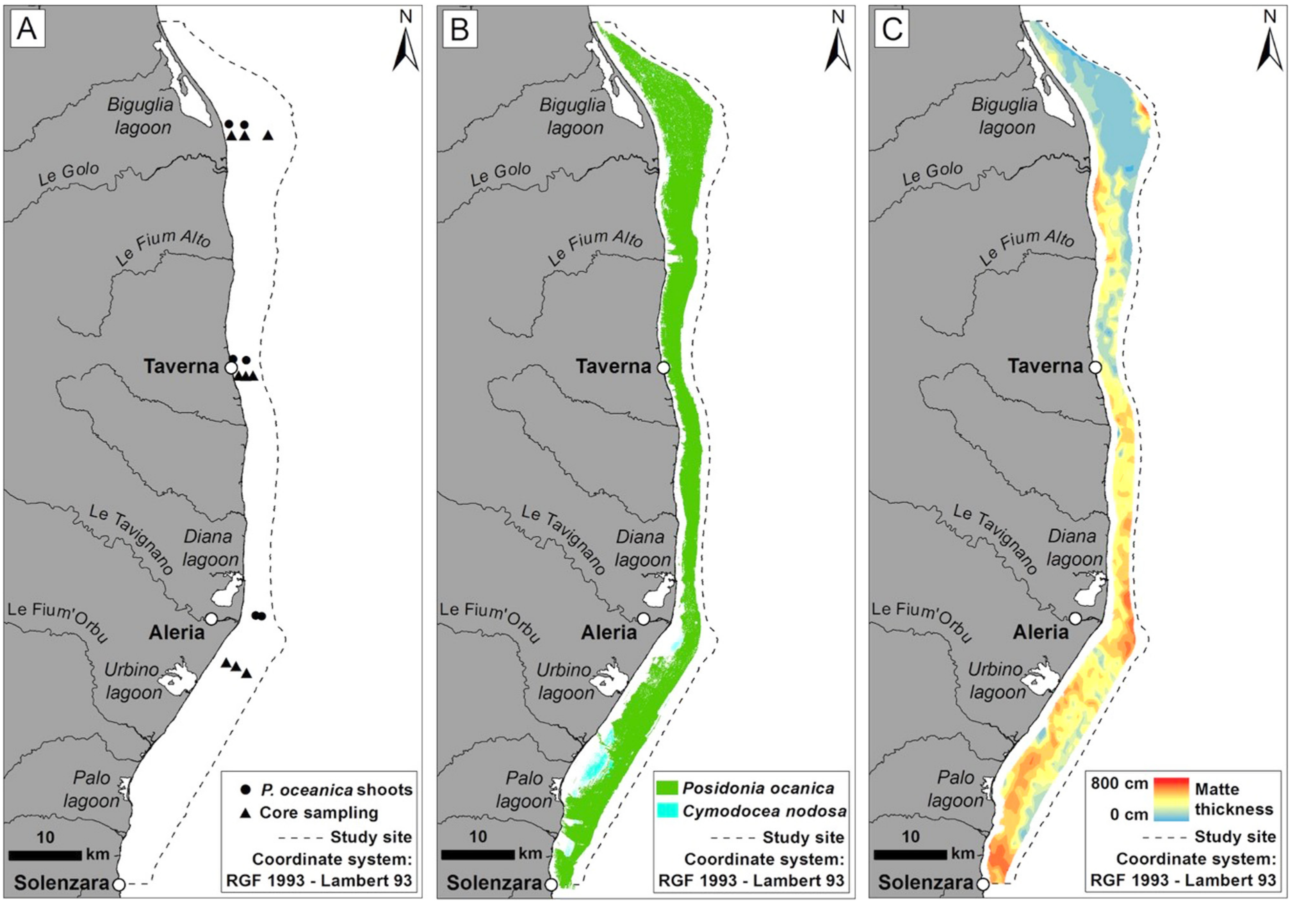

Fig. 2. – **A**: Location of *P. oceanica* transects and shoots and matte core sampling; **B**: Distribution of seagrass meadows (from Valette-Sansevin *et al*. 2019); **C**: Map of *P. oceanica* matte thickness estimated within the study site (from Monnier *et al*. 2017).

fraction and the coarse organic fraction following Monnier *et al*. (2019b). The standing organic matter and carbon stocks per unit area (cumulative stocks; kg C m^{-2} or Mg C ha^{-1}) were calculated according to Howard *et al*. (2014).

RESULTS

At the Natura 2000 site, seagrass meadows represent the most extensive habitat with a surface area of 20,425 ha for biocoenosis of *P. oceanica* meadows and 798 ha for association with *Cymodocea nodosa* (Ucria) Ascherson; respectively, more than 38 % and 47 % of the seagrass beds along the Corsican coastline (Fig. 2). The mean upper and lower limits of *P. oceanica* meadows range from –5 m to –40 m respectively. The distribution of *C. nodosa* beds is mainly located near the mouth of coastal rivers and locally beyond the lower limit of the *P. oceanica* meadows (Fig. 2).

The matte thicknesses of the *P. oceanica* meadow shows a high variability (Fig. 2). The mean thickness of the matte, estimated at 210 cm for the whole site, increases from north (160 cm) to south (270 cm). The thickness of the matte also seems to be greater near the coast with

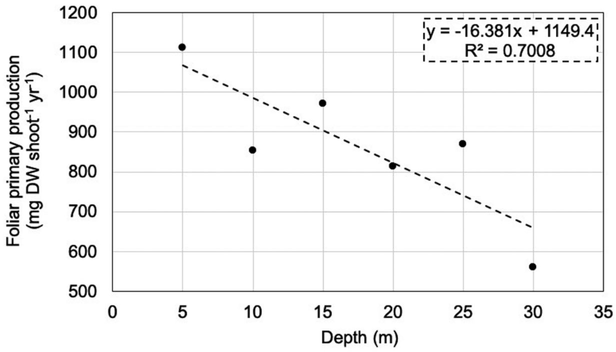

Fig. 3. – Foliar primary production of *P. oceanica* (blades) according to depth at the Natura 2000 site.

gentle slopes (between –10 and –25 m). Maximum thickness (up to 8 m) is recorded at the mouth of the main coastal rivers (Golo, Tavignano, Fium'Orbo and Travo).

The primary production of blades decreases significantly with depth and varies between 1,112.0 mg DW $shoot^{-1}$ yr^{-1} (–5 m) and 560.8 mg DW $shoot^{-1}$ yr^{-1} (–30 m) (Fig. 3). Total carbon fixation by the *P. oceanica* meadow (blades, sheaths and rhizomes) also varies with depth, between 3.51 (–5 m) and 0.34 Mg C ha^{-1} yr^{-1} (–30 m) with an average of 1.62 Mg C ha^{-1} yr^{-1} (Table I). The total fixa-

Table I. – Carbon fixation by *P. oceanica* at the Natura 2000 site.

Sites	Density	Blades		Sheaths		Rhizomes		Total carbon fixation	
	shoot.m^{-2}	g DW.m^{-2}.yr^{-1}	g C.m^{-2}.yr^{-1}	g DW.m^{-2}.yr^{-1}	g C.m^{-2}.yr^{-1}	g DW.m^{-2}.yr^{-1}	g C.m^{-2}.yr^{-1}	kg DW.ha^{-1}.yr^{-1}	kg C.ha^{-1}.yr^{-1}
–5 m	550.5	612.1	249.9	178.9	71.9	69.1	28.9	8601.0	3507.5
–10 m	377.2	332.3	138.7	93.8	38.5	47.3	20.2	4734.3	1973.2
–15 m	300.6	295.5	122.0	65.3	27.7	39.0	16.6	3998.6	1662.8
–20 m	279.4	226.9	93.9	49.3	20.1	28.0	11.9	3041.1	1258.2
–25 m	204.2	177.4	73.0	39.1	15.9	18.6	7.9	2351.5	968.0
–30 m	106.1	59.5	24.0	14.9	6.2	9.1	3.8	834.6	342.9

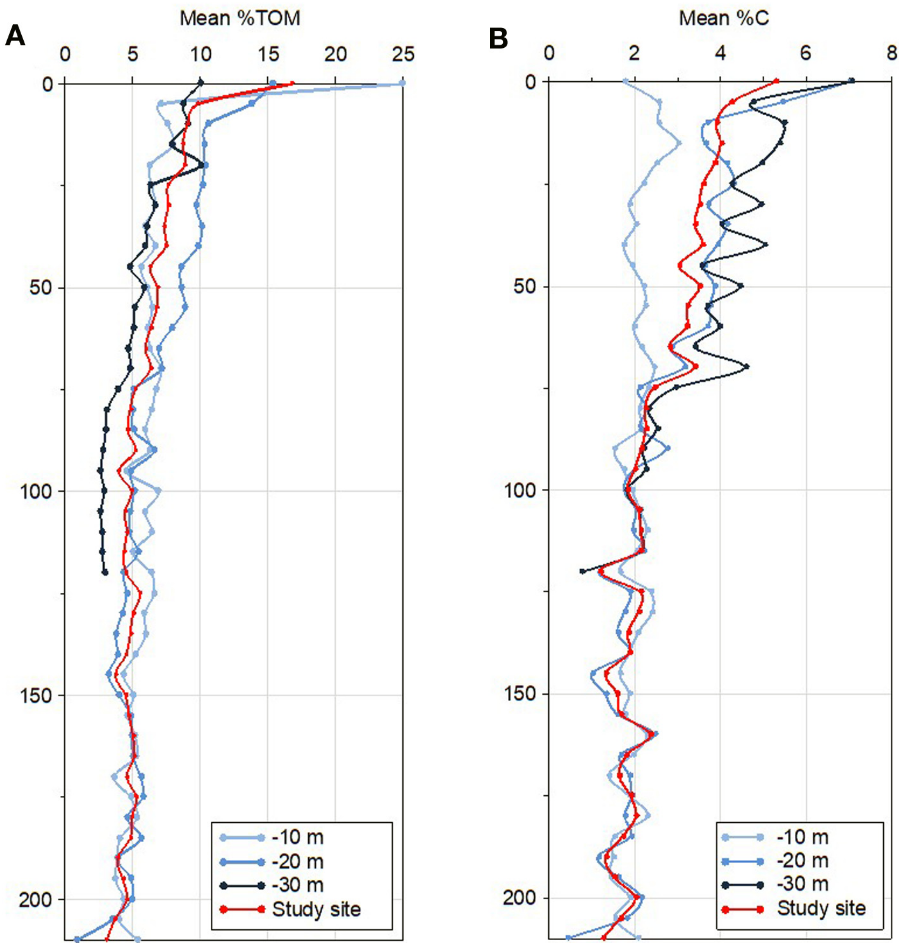

Fig. 4. – Changes in the main parameters (%TOM and %C) in) the *P. oceanica* cores collected at the Natura 2000 site. %TOM and %C are expressed as percentage of the total sample dry weight (%). Study site (red lines) correspond to the mean values for the different stations and depths.

tion at the Natura 2000 site corresponds to 33,063 Mg C yr^{-1}.

Primary production allocated to the sheaths, rhizomes and roots is estimated at between 0.1 (–30 m) and 1.0 (–5 m) Mg C ha^{-1} yr^{-1}, with an average of 0.45 Mg C ha^{-1} yr^{-1}. The total carbon sequestration at the Natura 2000 site represents 9,175 Mg C yr^{-1}, corresponding to a mean of 27.8 % of carbon fixation.

Table II. – Average stock of total organic matter and organic carbon of *P. oceanica* at the Natura 2000 site (SD: Standard Deviation).

Bathymetry	100 cm core		210 cm core	
	kg TOM m^{-2}	kg C m^{-2}	kg TOM m^{-2}	kg C m^{-2}
– 10 m	83.3	38.5	183.3	91.4
– 20 m	69.3	33.2	121.5	76.2
– 30 m	51.0	27.3	92.0	42.6
Study site (Mean ± SD)	68.5 ± 20.3	33.2 ± 9.2	133.8 ± 48.7	71.1 ± 28.9

The matte cores collected at the study site are mainly constituted of seagrass debris (sheaths, rhizomes and roots) integrated in a dark brown sandy-muddy sedimentary matrix. The average length of the cores sampled at the study site is 215 cm, with a maximum value of 365 cm. The base of the matte (reflector) is thus frequently reached, contributing to calibration of the high-resolution seismic reflection data in complement to the matte wall heights measured in the 'intermattes' by scuba diving.

The standing stocks of total organic matter (kg TOM m^{-2}) and organic carbon (kg C m^{-2}) were standardized to 100 cm to allow comparison with literature, and 210 cm corresponding to the mean estimated matte thickness at the study site. Although different locations are compared, soil parameters of the cores change with water depth and seagrass soil depth. The vertical trends feature a slow decrease in %TOM and %C with soil depth and water depth (Fig. 4). The proportion of TOM and C in sediment significantly decreases through the top 100 cm of the soil and remains rather constant down to the core bottom (210 cm; Fig. 4). Thus, the mean TOM and C content decrease (respectively from 16.8 % to 4.0 % and from 5.3 % to 2.0 %) for the 0-100 cm section, and remain relatively constant in the lower section (100-210 cm) with 4.6 ± 0.6 %TOM and 1.8 ± 0.3 %C (mean ± SD). The characterization of samples shows that cores contained on average 68.5 ± 20.3 kg DW TOM m^{-2} and 33.2 ± 9.2 kg C m^{-2} in the first meter of soil (Table II). For the total core sequence (*i.e.*, 210 cm), the average amount of TOM and C stored are 133.8 ± 48.7 kg DW TOM m^{-2} and 71.1 ± 28.9 kg C m^{-2}, respectively (Table II). Whatever the soil depth considered, the TOM and C stock decrease with water depth (Table II).

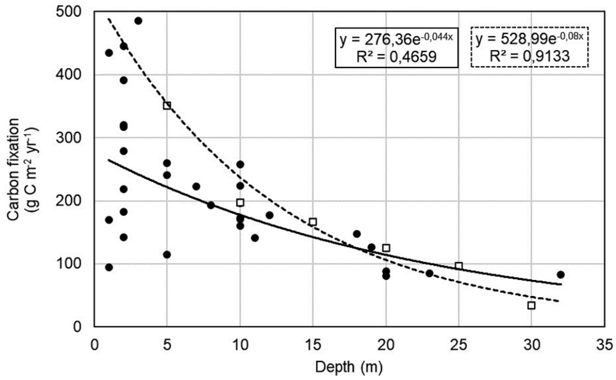

Fig. 5. – Carbon fixation (g C m^{-2} yr^{-1}) by *P. oceanica* meadows (blade, sheaths and rhizomes) in the Mediterranean Sea (circles, solid line) and in the study site (squares, dotted line). Data from Pergent-Martini *et al.* 1994, Pergent *et al.* 1997, Guidetti 2000, Dumay 2002, Vela 2006 and references therein.

DISCUSSION

The surface area covered by *P. oceanica* meadow in the Natura 2000 site is more extensive than anywhere else in the Mediterranean Sea, with more than 64 % of the seabed between 0 and 40 m depth and up to 206 ha km^{-1} of coastline covered, even in comparison with the Corsican coastline as a whole where this biocoenosis covers on average 61 % of the seabed (Valette-Sansevin *et al.* 2019, Table III). This exceptional coverage is linked to the particular topography of the eastern continental shelf of Corsica (very low slope: < 2 %; Pluquet 2006) and to reduced anthropogenic pressures (Cannac-Padovani 2014).

Total carbon fixation recorded at the Natura 2000 site is comparable with other values recorded in the Mediterranean Sea, but is slightly higher, mainly between the sea surface and –20 m (Fig. 5). The fixation and carbon sequestration at this site correspond respectively to 6.5 % and 1.75 % of annual CO_2 release by anthropogenic activities on the island of Corsica (based on mean release rates by inhabitant in France in 2018, approximately 1.9 million Mg CO_2; Global Carbon Atlas 2020). At regional scale, the *P. oceanica* meadows as a whole (53,737 ha; Valette-Sansevin *et al.* 2019) contribute respectively to the fixation and carbon sequestration of 16.6 % and 4.6 % of CO_2 emissions on the island (Global Carbon Atlas 2020).

On the basis of (i) the mean carbon fixation corresponding to the integrative depth of –15 m (138.5 g C m^{-2} yr^{-1}), and (ii) the area covered by *P. oceanica* (1.0 to 1.5 million hectares; Topouzelis *et al.* 2018, Traganos *et al.* 2018, Valette-Sansevin *et al.* 2019), the total carbon fixation for the whole of the Mediterranean Sea should be between 1.39 and 2.08 million Mg C yr^{-1}, that is to say the equivalent of 5.08 to 7.62 million Mg equivalent CO_2 release.

The use of the high-resolution seismic reflection method has contributed to providing an accurate estimate of the

Table III. – Surface covered by the *Posidonia oceanica* meadow at the Natura 2000 site and on the main islands of the Western Mediterranean basin (* Valette-Sansevin *et al.* 2019, ** Ruiz *et al.* 2015, *** Ministero dell'Ambiente e della Tutela del Territorio 2001, **** Calvo *et al.* 2010, # GADM 2020, ## EMODnet, 2020).

	P. oceanica **surface area (ha)**	**Length of coastline (km) #**	***P. oceanica*** **surface area by length of coastline ($ha.km^{-1}$)**	**Seabottom surface area in 0-40 m depth range (ha) ##**	***P. oceanica*** **surface area in 0-40 m depth range (%)**
Study site	20,425	99	206.3	31,769	64.3 %
Corsica*	53,735	1,177	45.7	88,509	60.7 %
Balearics**	63,316	1,435	44.1	112,022	56.5 %
Sardinia***	153,382	2,403	63.8	303,740	50.5 %
Sicily****	76,000	2,007	37.9	318,393	23.9 %

spatial extent of carbon stocks represented by *P. oceanica* matte at the study site. The edification of this structure is mainly due to the vertical growth of orthotropic rhizomes which avoids the burial (sediment inflows) of the aboveground living biomass, resulting in a relatively slow upward rise of the bottom (Boudouresque & Jeudy de Grissac 1983, Boudouresque *et al*. 1984). The thickness of the matte results from the balance between an accretion of material (sediment and debris) and decomposition and erosion processes linked to different factors (Mateo *et al*. 1997, 2006).

The seismic data highlight a high variability of the thickness of bioformations which could be explained by (i) the natural land-based inputs at the mouth of the coastal rivers, but also near the lagoon inlets ('flushing flow'), and (ii) the sediment dynamics related to ocean currents (coastal drift) at the underwater deltas (Monnier *et al*. 2017, 2019a). Although high-resolution seismic reflection data appears to be a reliable tool to determine the thickness of the sedimentary carbon stocks buried under the *P. oceanica* meadows (Lo Iacono *et al*. 2008, Tomasello *et al*. 2009), core sampling and the subsequent geochemical analysis remain essential as a basis for a precise quantification of carbon stocks.

The decrease in total organic matter (%TOM) and carbon (% C) with depth within the matte (Fig. 4) suggests that contrary to what is often claimed – that is to say that within the matte, sheaths, rhizomes and roots are rot-resistant (Molinier & Picard 1952, Boudouresque *et al*. 2012) – degradation does occur within the matte. This hypothesis has already been formulated by Boudouresque *et al*. (2019) in the Bay of Hyères (Provence, France).

Taking into account (i) the average thickness of the matte (210 cm), (ii) the average quantity of carbon measured (711.4 ± 289.4 Mg C ha^{-1}), and (iii) the average annual carbon sequestration rate (0.45 Mg C ha^{-1} yr^{-1}), the carbon stock present at the Natura 2000 site would correspond to the carbon sequestered over a period of approximately 1,580 years.

In the context of climate change, the carbon storage capacity of the *P. oceanica* matte over several thousand years is a major advantage (Boudouresque *et al*. 1980). Within the "*Grand Herbier de la Côte Orientale*" site, the average carbon stock in the first meter of sediment (33.2 ± 9.2 kg C m^{-2}) is generally comparable to values observed in the literature for similar heights of matte (28-237 kg C m^{-2}; Romero *et al*. 1994, Mateo *et al*. 1997, Serrano *et al*. 2012, 2014, 2016). Compared with other seagrass beds, the amount of carbon stored by *P. oceanica* is globally higher (Fourqurean *et al*. 2012, Lavery *et al*. 2013). The carbon stocks for the *P. australis* and *P. sinuosa* seagrasses are estimated as between 10.8-32.0 kg C m^{-2} and 1.8-6.6 kg C m^{-2}, respectively (Lavery *et al*. 2013, Serrano *et al*. 2014, 2016). Moreover, this value is similar or higher than those measured in several terrestrial ecosystems considered to be efficient in carbon storage such as peatlands (120 kg C m^{-2}; Warner *et al*., 1993), wetlands (13-73 kg C m^{-2}; Laffoley & Grimsditch 2009) and the boreal forests (9-34 kg C m^{-2}; Serrano *et al*. 2014).

The carbon stock present at the Natura 2000 site is estimated at 14.5 ± 5.9 million Mg C. For the entire coastline of Corsica, the value is estimated at 38.2 ± 15.6 million Mg C, the equivalent of 79 years of CO_2 emissions (based on mean release rates by inhabitant in France in 2018; Global Carbon Atlas 2020), much more than all of the cumulative emissions since the mid of 20th century.

At the scale of the Mediterranean basin, where the surface area covered by *P. oceanica* is estimated at between 1.0 and 1.5 million hectares (Topouzelis *et al*. 2018, Traganos *et al*. 2018, Valette-Sansevin *et al*. 2019), the total carbon stock present in *P. oceanica* matte is estimated as 711 to 1,067 million Mg C, the equivalent of 1 to 3 years of CO_2 emission by all Mediterranean countries (Global Carbon Atlas 2020). Even partial degradation of these mattes, and the concomitant release of this carbon into the environment, would have negative consequences for the patterns of change in temperature in an already worrying context of climate change.

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