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Estimating the size of the carbon sink represented by *Posidonia oceanica* meadows along the coasts of the Balearic Islands

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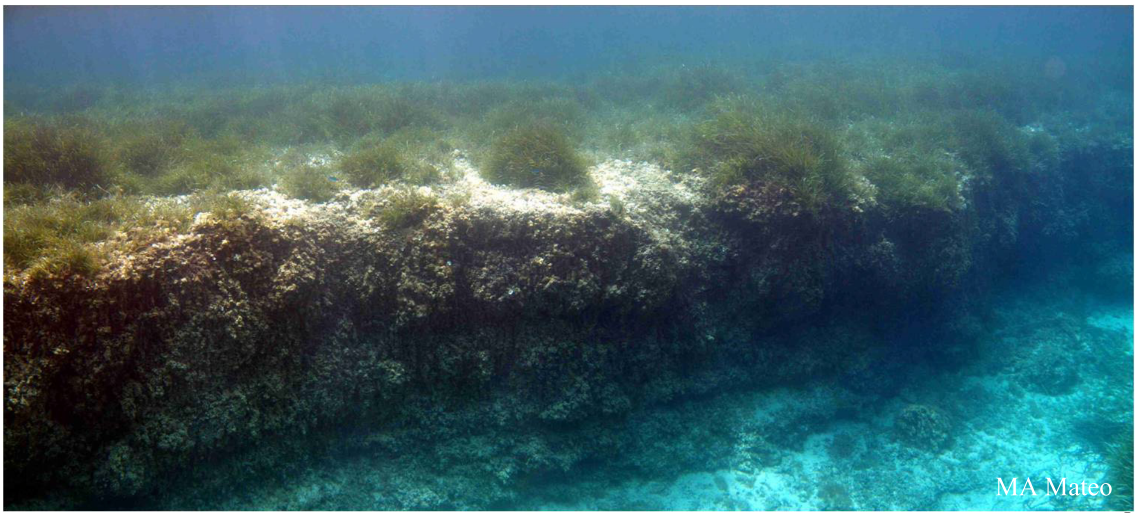

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Fabiana Mac Cord Rodrigues da Silva

Abstract

P. oceanica seagrass meadows can absorb and bury a significant portion of atmospheric CO_2, helping with the lowering of the greenhouse gases and regulation of the planet's climate. In spite of this, very few efforts have been made so far to estimate this burial in the Mediterranean. In this study we attempt a preliminary estimation of the balance between anthropogenic CO_2 emissions and net CO_2 uptake by *P. oceanica* meadows in the Balearic Islands. Here, we suggest that the about 67,000 ha occupied by *P. oceanica* meadows along the Balearic coasts sequester around 8.66% of CO_2 annually and accumulate 105.13 years of CO_2 at 2006 emissions levels. The specific stock under the meadows is of 0.42 tCm^{-2} and we could infer that each km of coast line in the Balearic Islands accumulates ca. 5 times more carbon under *P. oceanica* meadows than the average for the Mediterranean. These estimates support the outstanding role of *P. oceanica* in the Balearic Islands as a carbon sink and their uniqueness in a Mediterranean context.

Keywords: Mediterranean Sea; *Posidonia oceanica* matte; net CO_2 burial, CO_2 emissions; carbon stock; distribution area.

1. INTRODUCTION

Seagrass meadows are made up of angiosperms, plants with flowers and fruits that can only complete their life cycle in the sea. Four species occur on the Spanish coast, being *Posidonia oceanica* (L.) Delile an endemic species to the Mediterranean. In the Mediterranean Sea, *P. oceanica* meadows occupy an area of ca. 35,000 km^2 (Pasqualini *et al*., 1998) being some 2,800 km^2 along the Spanish Mediterranean coast at depths between 0 – 45 m, and account for more than 90% of the total area of seagrass meadows along the Spanish coast (Marbá, 2009).

P. oceanica seagrass meadows tend to produce an excess of organic carbon over community requirements and are believed to store in the sediments an important fraction of that excess. Due to the slow decomposition of lignified rhizomes and roots, the reef structure or "matte" acts as a long-term carbon sink (Mateo *et al*., 2006). The organic fraction of the matte is preserved over thousands of years forming structures several meters thick (Mateo *et al*., 1997; Lo Iacono *et al*., 2008). This preservation results from the highly anoxic conditions in the matte and from the refractory nature of the detritus (Mateo *et al*., 1997, 2006). Mateo *et al*. (1997) took an important step forward in providing the study methods and the first estimates of the size of the carbon sink represented by *P. oceanica* meadows along the Mediterranean coasts significantly contributing to the biosphere carbon cycle. In the current context of climatic change, there is a great importance to identify the main natural carbon sinks in the different ecosystems and quantify their stock and accumulation rates. There are, therefore, two major relevant questions to address concerning the matte of *P. oceanica*: 1) its annual CO_2 sequestration capacity and 2) the carbon/CO_2 equivalents stored in the sediments underlying the meadows. This last question is particularly critical in a global warming scenario as the balance sink/source of the matte may be altered (Østergaard *et al*., submitted).

A large part (42 – 62%) of the net carbon fixed in *P. oceanica* meadows is retained and buried there (Mateo *et al*., 2006). Estimates of the amount of carbon sequestered in the Mediterranean coastal and oceanic habitats is very scarce, so it is hard to make accurate comparisons of the relative importance of seagrass meadows as carbon sinks on a basin-wide scale. However, considering that half the carbon sequestered globally in the oceans is buried in coastal plant habitats, and that seagrass species together account for 15% of the total carbon buried in the oceans (Duarte *et al*., 2005), it must be substantial. Hence, *P. oceanica* meadows absorb and bury a portion of atmospheric CO_2, helping with the lowering of the greenhouse gases (GHG) and regulation of the planet's climate (Marbá, 2009).

In spite of the importance of all this questions, there is a considerable scarcity of works addressing the balance between anthropogenic CO_2 emissions and the fraction of net CO_2 uptake by different sinks. This is particularly obvious for the case of *P. oceanica* meadows in the Mediterranean Sea and the Balearic Islands.

The Balearic Islands contribution to total national emissions of the greenhouse gases (GHG) is 2.44%. However, emissions per capita in the Balearic Islands are slightly higher than the national average and, since 1990, the population of the Islands has increased by 45.3% and has been accompanied by an increase in emissions per capita. By another side, *P. oceanica* meadows of the Balearic Islands are particularly abundant and are in a great conservation state (Diaz & Marbá, 2009).

The area studied was the Balearic Islands, a Spanish archipelago in the western Mediterranean Sea, near the eastern coast of the Iberian Peninsula, composed by four largest islands: Mallorca, Menorca, Ibiza and Formentera – the last two also known as Pitiusas. In this study we perform an exercise to provide the main elements needed to fill in the gap identified above. It is a preliminary attempt to approximate to a value of the carbon sequestered by *P. oceanica* meadows of the Balearic Islands, but we have to emphasise that only two meadows on this study come from the Balearic Islands, being most of the data used for the estimates from meadows studied in different areas of the Mediterranean (see Material and Methods). Moreover, the results have to be considered didactic estimates due to the total limited knowledge of some aspects of the distribution of *P. oceanica* in the Islands, and of the variability of some key variables of the matte composition. In summary in this study we provide:

(1) an estimate of the area covered by *P. oceanica* meadows around the Balearic Islands to the best possible detail based on the available information in the literature; (2) an estimate of the net CO_2 sequestration rates and carbon stocked by *P. oceanica* and (3) a comparison of these rates with the annual anthropogenic CO_2 emissions in the Islands.

2. MATERIAL AND METHODS

2.1. *Posidonia oceanica* distribution in the Balearic Islands

A set of the latest cartographic information of the studied area were selected within the archives of the Council of the Environment of the Balearic Islands Government (the original name: Consejería de Medio Ambiente del Govern de les Illes Balears) to generate a habitat map distribution and calculate the covered area by *P. oceanica*. The current detailed cartography of *P. oceanica* used was from the project LIFE Posidonia (LIFE 00/NAT/E/7303; 2001 to present) and covers large areas along the Balearic Islands coast classified as Sites of Community Interest (the original name: Lugares de Importancia Comunitária – LIC's) (Appendix 1). As it does not cover the entire Balearic Islands, another source of cartographic information from the Habitats Directive (the original name: Directiva Hábitats) (Dir 92/43/CEE) was used to complete some missing sites, irrespectively of their lower degree of detailed and missing categories.

From the GIS information, polygons were created for each segment and loaded into the ArcMap 9.3 software (ESRI® ArcGIS™ 9.3, 2008). In order to standardize all the information from the LIC's cartography, a scheme was conceptualized at 2 simple levels: 1) areas with continuous coverage of *P. oceanica* beds and 2) areas with patchy coverage of *P. oceanica*. The former, includes the areas classified as *P. oceanica* continuous beds and areas with more than 70% of *P. oceanica* coverage, according to the original classification. The latter, comprises the areas in which *P. oceanica* beds were less than 70% coverage, combined with coral or algae communities or sparse in sandy or rocky sediments. Otherwise, information from the Habitats Directive source was originally classified in a single level indicating presence of *P. oceanica* meadows, with no vegetation coverage information. It was created a distribution map for all the Balearic Islands (figure 1) and zoomed in each Island: Mallorca, Menorca and Pitiusas (figures 2, 3 and 4, respectively).

An accuracy assessment of the calculated areas of the polygons loaded in the ArcGIS software was made using the implement X-tools Pro. The LIC's areas and length (table 1) were calculated distinguishing the following categories: 1) length of the coastline (L; km), 2) *P. oceanica* continuous covered area (A pc; ha), 3) *P. oceanica* patchy covered area (A pp; ha), 4) total *P. oceanica* coverage (sum of *P. oceanica* continuous and patchy covered (A ptotal; ha) and, 5) total *P. oceanica* area normalized per kilometres of coastline (LIC's coastline and islands coastline) (A ptotal / L; ha/km). The same categories were calculated for each island and for the sum of all islands. As the polygons layers had some overlapped areas and the sum of all them generated an overestimated value, we created a single polygon layer with all the information and calculated a corrected total area excluding overlapping surfaces. The same was calculated for the Habitats Directive polygons (table 2) for each islands and the archipelago, but without distinguishing between *P. oceanica* continuous and patchy beds. While both sources bring complementary information from different sectors of the island that should be considered together for a more realistic total area, they also bring a lot of information from the same sectors (overlapping surface). Therefore, we integrated all the polygons into the ArcGIS program to a single polygon to have a unique layer of the *P. oceanica* distribution and calculated this final combined area.

The meadows of this species can extend from less than 1 meter to over 40 meters depth (Hemminga & Duarte, 2000). To compare the current known distribution (mapped) with a potential distribution of the seagrass, some estimates have been attempted based on the species depth limit of growth. To this end, the bathymetric information from 0 to 40 m around the Balearic Islands was loaded into the ArcGIS software and with the X-ToolsPro extension the surface area extended to these depth limits was calculated. It is important to emphasize that the distribution of *P. oceanica* is constrained by other factors not being considered here, such as sediment suitability and stability, nutrient concentrations in the water column (Hemminga & Duarte, 2000) and, in the vertical direction, the hydrodynamics and the irradiance and underwater light attenuation (Ruiz & Romero, 2001). The area obtained here, therefore, is very likely to be an overestimate of the real potential distribution area.

2.2. Carbon Sequestration Estimates

In this section, part of the variables used in the calculations come from *P. oceanica* mattes from other areas of the Mediterranean, and part come from only two mattes studied in Ibiza and Formentera (SUMAR project, 2006-2010; Østergaard *et al*., submitted).

Most of the information regarding how to estimate carbon burial rates and the size of the sink under *P. oceanica* meadows is given in detail in Mateo *et al*. (1997, 2001, 2006) and Lo Iacono *et al*. (2008). Accretion rates (vertical growth) of the mattes in Talamanca (Ibiza) and Es Pujols (Formentera) coves were calculated by assuming that the rate of loss of mass is directly proportional to the amount of observed material remaining along the matte profile (as for soils in Jenny *et al.* 1949):

$$dM / dt = p - \alpha M \quad \text{(eq. 1)}$$

where M and t are known variables of mass and time, and p and α the searched constants of biomass accretion and decomposition rates, respectively.

After dividing all terms by α and doing a change of variables we get,

$$dM / (p/\alpha - M) = \alpha \, dt$$

integrating, according to the chain rule,

$$\int dM / (p/\alpha - M) = \int \alpha \, dt$$

$$\mathrm{Ln}\,(p/\alpha - M) = -\alpha\, t + ctt$$

For an initial condition of no biomass; M=0 at t=0 the ctt can be determined

$$ctt = \mathrm{Ln}\,(p/\alpha)$$

Then, substituting on equation,

$$\text{Ln}(p/\alpha - M) = -\alpha t + \text{Ln}(p/\alpha)$$

$$\text{Ln}[(p/\alpha - M) / (p/\alpha)] = -\alpha t$$

The antilog of which is,

$$(p/\alpha - M) / (p/\alpha = e^{-\alpha t})$$

And solving for M, taking common factors we finally obtain,

$$M = (p/\alpha) \times (1 - e^{-\alpha t}) \qquad \text{(eq. 2)}$$

Since it was first proposed, this exponential function has been extensively used to model a wide scope of biological processes and in particular to hold for litter production and decomposition in soils (Greenland and Nye, 1959; Olson, 1963) and peat-forming systems (Maltby *et al.*, 1976; Clymo, 1984), including *P. oceanica* mattes (Mateo *et al.*, 1997).

The cumulative mass (or carbon) of *P. oceanica* (M) is obtained by weighting the total organic matter at different levels along the core. The age of the material (t) correspond to *P. oceanica* AMS-dated sheath detritus. The parameters p and α are estimated by the model (fitting was conducted till convergence for the estimation of *p* and α using STATISTICA software). Concretely, *p* is the carbon accretion rate (AR) in gDW or C $m^{-2}y^{-1}$. Primary data of AR for Talamanca and Es Pujols coves were used (2.43 and 4.16 mm y^{-1}, average 3.30 mm y^{-1}; source: SUMAR).

The carbon content in the organic matter used in the estimates is the average carbon percentage (%C) derived from a *P. oceanica* coarse organic matter fraction (>1 mm) sorted along the matte cores from Talamanca and Es Pujols coves (n = 26) (44.80 and 46.36% C; average 45.58% C). The carbon percentage in the fine organic fraction (SOM) is not available yet so that of the coarse organic matter has been used instead.

The percentage of carbonates carbon content used in the estimates is the average (83.95% $CaCO_3$) derived from calcimetries performed in bulk matte samples along the matte cores from Talamanca and Es Pujols Coves (n = 26).

Annual carbon dioxide sequestration estimates in terms of organic matter are derived by combining the average matte accretion estimated by the model and the mass of carbon contained in the accreted material (AR × total C). It is assumed that the $CaCO_3$-derived carbon along the matte profile does not undergo any substantial diagenetic alteration. The carbon accretion rate is then multiplied by the calculated area of *P. oceanica* of the Balearic Islands (A ptotal) to have the Balearic C accretion rate (kt C y^{-1}). Carbon is translated into CO_2 equivalents (kt CO2 y^{-1}) by multiplying by the ratios of the molecular weights, 44/12, or 3.67.

2.3. Carbon Stocks Estimates

The spatial / bathymetric variability of matte thickness under *P. oceanica* is very poorly known representing one of the main obstacles to achieve accurate estimates of the size of the carbon sink under the meadows. The available literature (Mateo *et al*., 1997) and abundant personal observations of matte cores (MA Mateo), suggests that, at shallow and intermediate depths (5 to15 meters), *P. oceanica* mattes can easily exceed 4 meters of thickness. Therefore, the carbon stock under the meadows has been estimated here assuming an average 4m-thick matte under Balearic meadows.

2.4. Emissions vs. Net Annual CO_2 Sequestration and Total Stock

The Balearic emissions of the greenhouse gases were obtained at the Council of the Environment of the Balearic Islands Government. Data were previously grouped in ten different energetic and economic sectors (Appendix 2) and by the different gases. In order to estimate the annual net balance (%) between the amounts emitted by the Islands and absorbed by the *P. oceanica* meadows, the total CO_2 emissions in 2006 was used (9,742.52 kt CO_2 y^{-1}). The same value was used to estimate the 'emissions-years' stocked in the matte.

3. RESULTS

3.1. *P. oceanica* Covered Area and its Potential Distribution

The two sources of information used showed different spatial distributions of the *P. oceanica* meadows (Figures 1-4), but with 21,974.84 ha of common areas mapping the same sectors of the islands (24.70% of overlapping areas). The areas calculated for Mallorca were highest after both sources, but, comparing them, we can observe that the Habitats Directive gives greater weight to the areas of Pitiusas and Menorca, meanwhile the LIC's source gives higher weight to Mallorca. This can be easily observed by the areas mapped by each source, where the Habitats Directive presented a more detailed mapping of the Pitiusas, and the LIC's presented lots of gaps (see Figure 4).

The largest areas calculated, in absolute values, for the LIC's categories of *P. oceanica* were found for Mallorca (36,475.6 ha; 77.93% of the total area) followed by Pitiusas (6,800.4 ha; 14.53% of the total area) and by Menorca (3,529.5 ha; 7.54% of the total area) (Table 1). The same pattern was found for the Habitats Directive with the largest absolute area for Mallorca (20,080.2 ha; 46% of the total area) followed by Pitiusas (15,936.9 ha; 36.51% of the total area) and by Menorca (7,631.5 ha; 17.48% of the total area) (Table 2). However, when normalizing for the length of coastline after the Habitats Directive, Mallorca still presented the highest values, but Menorca presented higher values of *P. oceanica* area per kilometre than Pitiusas (97.5, 77.5 and 66.8 ha/km, respectively; Table 2). Also, when normalizing these areas by the coastline of each island, Pitiusas presented a notable greater value followed by Mallorca and then Menorca (57.1, 36.2 and 26.7 ha/km; Table 2). Further, this will be important to identify which are the areas with more specific capacity to absorb carbon.

The final *P. oceanica* area calculated using the information of both sources, excluding overlapping, was 66,997.8 ha and the normalized area occupied by *P. oceanica* per km of coastline of the Balearic Islands was 54.1 ha/km. The potential area based on the depth (0 to 40 meters) was 149,377 ha, more than the double found by our results.

3.2. Carbon Sequestration Rates and Carbon Stocks

Using the inorganic ($CaCO_3$) and organic carbon fractions of the matte cores obtained in the SUMAR project (see section 2.3 of Material and Methods), the total carbon content found was 104.1 gC m^{-2} per mm of accreted material. Also, using the accretion rates for Talamanca and Es Pujols coves, we obtained a total carbon accretion rate of 343.1 gC m^{-2} y^{-1}. From this and from the total area calculated for the Balearic Islands (66,997.8 ha) we obtained a total accretion rate of 229.9 kt C y^{-1} and, converting this value to carbon dioxide, we have a final CO_2 accretion for the Balearic Islands of 843.71 kt CO_2 y^{-1}.

Also, assuming a matte thickness of 1 – 4 meters and 0.82 gDW cm^{-3} of bulk density (estimation for Talamanca cove; unpublished data) we obtained a carbon stock of 2.8×10^5 kt C (10.24×10^5 kt CO_2) under *P. oceanica* meadows.

3.3. Net Annual CO_2 Sequestration Rates and Buried Stocks

The CO_2 emission by the Balearic Islands for the year 2006 is 9742.52 kt CO_2 y^{-1}, here including all the different sectors (Appendix 2). A net annual CO_2 sequestration of 8.66% of the emissions was obtained for the *P. oceanica* meadows of the Balearic Islands considering the emission levels of 2006. Assuming 4 m-thick mattes, this would represent a stock of CO_2 equivalent to 105.13 years of CO_2 emissions (at 2006 emission levels).

4. DISCUSSION

The preliminary estimates made here suggest that the about 67,000 ha occupied by *P. oceanica* meadows along the Balearic coasts, sequester a discrete but significant amount of carbon annually, and accumulate more than 1 century of CO_2 at 2006 emissions levels. The specific stock estimated is of 0.42 tC m^{-2}, what is 2.3 times higher that the recent estimates by Lo Iacono *et al*. (2008) in a semi-enclosed bay of the western Mediterranean and 4.2 times higher than the average estimated for the Mediterranean (unpublished data, MA Mateo). It could also be inferred that each km of coast line in the Balearic Islands accumulates ca. 5 times more carbon under *P. oceanica* meadows than the average for the Mediterranean. These estimates support the outstanding role of *P. oceanica* in the Balearic Islands as a carbon sink and their uniqueness in a Mediterranean context.

4.1. *P. oceanica* Distribution and Area

The total distribution area of 66,997.80 ha estimated here for *P. oceanica* meadows in the Balearic Islands is almost double the value proposed on in the last technical report published by the Ministry of the Environment, Rural and Marine Affairs of Spain (37,800 km^2; Diaz & Marbá, 2009). However, the authors themselves admit that the real extension for the *P. oceanica* habitats is probably much higher than what they suggest, once they defined their habitat into the limit of 1 nautical mile and many meadows at the inventory exceeded this outer limit. When we analyzed the potential area of distribution into the 0 − 40 m depth (149,377 ha), it is easy to sense that these numbers can be much higher. Lack of accuracy and important gaps are observed in the cartography available of the seagrass around the Islands. Also, when we observe the maps (Figure 1-4) it is easy to identify overlapping areas between different sources of information, with no accuracy at their limits and completely different schemes of meadow characterization that lead us to simplify them and lose some important information about the seafloor type and potential coverage area. One essential concern to conduct a marine habitat map is the use of an appropriate classification scheme. General consensus of the seagrass habitat mapping community is that the simpler the system, the greater the chance of consistency and improved accuracy in the mapping results and the greater the opportunity for replications of the mapping over several time periods (Davison & Hughes, 1998). To better conduct a study that involves the distribution of the *P. oceanica* and its parameters it is urgently necessary to improve the cartographic work and to unify efforts among the different Departments and Administrations.

Even though both sources of information, LIC's and the Habitats Directive, have mapped many different zones, they presented a similar final area (45,324.64 and 43,648 hectares, respectively). A common goal of both sources is to prioritize zones suitable for environmental conservation and biodiversity protection. However, multiple pressures in the touristic sector of these islands make it difficult to enlarge these conservation zones and consequently inhibit future efforts to better map *P. oceanica* habitats and potential distribution beyond the limits found.

As the LIC's provide us more detailed information of the different sectors of each island, it was possible to observe that there is a great difference in *P. oceanica* areas between the islands, but basically proportional to the area analyzed of each site. As expected, Mallorca showed the greatest values. As we do not distinguished the density of the shoots of each area and we used average accretion rates, %C, and same bulk density for all analyses, the carbon sequestration and stocks were all proportional to the area of *P. oceanica* in each island. The only attempt to distinguish the density of each area was separating *P. oceanic*a continuous from patchy beds, but with the only aim of providing an idea of the state of the seagrass meadows. In a scenario of declining *P. oceanica* meadows along all the Spanish Mediterranean (Marbá, 2009), the high values of *P. oceanic*a continuous beds (39,077.52 ha), compared to the patchy ones (6,247.47 ha; table 1), suggests a particularly good state of conservation of the meadows of the Balearic Islands (also mentioned by Diaz & Marbá, 2009).

4.2. Carbon Stock and Balance

The primary values of matte accretion assumed from Talamanca and Es Pujols coves for this study (2.43 and 4.16 mm y^{-1}) fall well within the average estimated along the Mediterranean (2.5 mm y^{-1} on average for the Mediterranean; Mateo *et al*., 1997, and unpublished data).

The high accretion rates, organic matter and carbonates content of Balearic mattes (it must be reminded here that only two mattes where studied, Talamanca and Es Pujols), provided an also high sequestration rate (343.1 gC m^{-2} y^{-1}) compared to the average Mediterranean values. The normalization for the total *P. oceanica* area in the archipelago results in an also greater overall rate of sequestration for all meadows of 229.9 kt C y^{-1} (= 843.71 kt CO_2 y^{-1}), being the maximum value ever recorded for *P. oceanica*. If we consider the potential areas suitable for the species growth, these values would double (based only on the 0 to 40 meters depth and the total area of 149,377 ha). But this potential area is certainly an overestimation only intended to support and highlight here any initiative to protecting the extant meadows and/or to increase the current area occupied. Other limiting factors such as light, temperature, nutrients, and water quality should be taken into account in order to obtain a more realistic 'potential area' of distribution.

Considering previous estimations for the Mediterranean organic carbon stock (not taking into account the carbonates) below *P. oceanica* meadows, 2.0 – 8.1 × 10^{15} gC (Mateo *et al*., 1997) or 1.4 – 5.6 × 10^{15} gC (Laffoley & Grimsditch, 2009; Appendix 3), the carbon stock we estimated for the Balearic Islands (0.056 × 10^{15} gC) is relatively modest and represents a contribution of 0.7 – 2.8% to the global Mediterranean stock. In global terms, these are comparable with the global organic carbon stocks of seagrass meadows worldwide (2.1 × 10^{15} gC) and mangroves (1.2 × 10^{15} gC) (Duarte *et al*., 2005; Kennedy & Bjork, 2009; Appendix 3). The comparison is particularly remarkable when considering the carbon accumulated in the sediments (soil) of *P. oceanica* vs. that accumulated in seagrass sediments world wide (Appendix 3). However, these stocks are much lower than for wetlands (225 × 10^{15} gC;

Laffoley & Grimsditch, 2009; Appendix 3), peat (450 × 10^{15} gC; Warner *et al.*, 1993) or coral reefs (100 – 400 × 10^{15} gC, for the upper 1-4m of reefs; data combined by Mateo *et al*. (1997), from Stoddart (1969), Smith (1978) and Kinsey (1983).

Although seagrass meadows cover a relatively small portion of the ocean (~ 1%), they play an important role in the coastal zone and provide ecosystem goods and services that have been estimated to be of high ecological and economical value compared with other marine and terrestrial habitats. For example, the tropical forests occupy a great global surface and have a moderate standing carbon stock in the soil (12,273 gC m^{-2}; Janzen *et al*., 2004, *appud* Laffoley & Grimsditch, 2009; Appendix 3), meanwhile the Balearic meadows of *P. oceanica*, which occupy a much lower global surface, was found to have a much higher specific carbon stock (420,000 gC m^{-2}; based on Talamanca and Es Pujols coves).

To access the high economical value of these stocks, we can transform 1 tC of each ecosystem stock into real values. Several studies have analysed the costs of the carbon sequestration and stocks in the global carbon market, mainly for terrestrial ecosystems (forests), and the cost estimations have a wide range, from 1$ to over 100$ per tC. Despite this range, most studies estimates costs around 10$ / tC (Deveny *et al*., 2009). As *P. oceanica* meadows of the Balearic Islands (and overall the Mediterranean Sea) stock more carbon than tropical forests and other terrestrial ecosystems (Laffoley & Grimsditch, 2009; Appendix 3), this means that preserving 1 m^{-2} of *P. oceanica* of the Balearic Islands (0.42 tC m^{-2} × 10$/tC = 4.2$) is equivalent of preserving ca. 35 times 1 m^{-2} of tropical forest (0.012 tC m^{-2} × 10$/tC = 0.12$) from the CO_2 sink perspective. Apart from the direct value of the carbon that seagrass stocks underwater, increased marine carbon storage is now seen as an “environmental service function” that slow the increase of greenhouse accumulation and its associated climate change.

The net annual CO_2 sequestration of 8.66% of the emissions found to the *P. oceanica* meadows of the Balearic Islands is a significant balance in a local scale. Comparing with terrestrial ecosystems (forests), and assuming that the forested area of the archipelago consumes

1% of the total annual CO_2eq emissions of the country and stores an equivalent of ca. 2,046,061 tCO_2eq (ASEMFO, 2004) in biomass standing stock (not considering soils), the Balearic Islands forested area would consume ca. 21.01% of the total CO_2eq emissions of the archipelago. From this, we can highlight that the sequestered carbon by the *P. oceanica* meadows of the Balearic Islands is a significant value and comparable with other terrestrial ecosystems.

The forested area in the Balearic Islands is of about 223,600 ha (National Spanish Forests Inventory – IFN-2; 1990 is considered as the average year; Plan Forestal Español, 2002). The carbon long-term stock in this area is estimated in 8.9 tC ha^{-1} far below the stocks under *P. oceanica* beds (4.2 x 10^3 tC ha^{-1}), although this value does not consider the carbon contained in the soils. The total C stocked in Balearic forested areas is around 1,962 ktC, which represents only the 0.7% of the stock under *P. oceanica* meadows (279,083 ktC). Adding a rough estimate of the carbon content of the soils under the forested areas of the Islands (assuming an average carbon content of the soils of the world of 120 tC ha^{-1}; Eswaran *et al.* 1993), the previous percentage would increase to 9.6% of the stock under *P. oceanica* meadows. This finding strongly supports a long standing claim of marine ecologists urging the administrations to prioritize or, at least, concede the same importance to marine low turnover plants than to terrestrial vegetation as carbon sinks.

The large difference between the coastal marine vegetated habitats (seagrass and mangroves) and terrestrial vegetated habitats is a result of the small areal extent of the former (<2% of the ocean surface). However, vegetated coastal habitats transfer large amounts of carbon to the sediments, contributing about half of the total carbon sequestration in ocean sediments (Duarte *et al.*, 2005). Moreover, these high burial rates can be sustained over millennia (Mateo *et al.*, 1997, 2006).

Another significant result for the *P. oceanica* meadows of the Balearic Islands is the belowground deposit of 105.13 “emissions-years”. This centenary stock is comparable with a limited number of ecosystems with *in situ* accumulations of large quantities of biogenic material over centuries or millennia, such as peat or coral reefs (Mateo *et al*., 1997). Although this stock has been shown to be stable for millennia, global warming threatens such stability if carbon losses due to accelerated microbial decomposition exceeded carbon accretion into the mattes. Recent efforts to assess the behaviour of the matte at different water temperatures have been made showing that organic C decomposition rates increased with a factor 4.5 up to 25^{o}C, indicating that CO_2 emission would be enhanced with the predicted temperature increase, reducing the C sink capacity of the matte (Østergaard et al. submitted).

Managers and planners worldwide are paying too little attention to the importance of this carbon stocks in the world carbon cycle and the consequences that their release could have in the global carbon balance. In future scenarios of increasing temperatures, ocean acidification, coastal degradation and other causes leading to the loss of seagrass meadows, the vulnerability of *P. oceanica* carbon stocks is also increasing compromising the benefits of this outstanding marine costal carbon sink.

5. CONCLUSIONS

(1) Although there are many studies of *P. oceanica* beds in the Mediterranean Sea, there is still a long way to go in the objective of having a proper knowledge of the actual area occupied by this species. This lack of accurate information has been also observed in the Balearic Islands. Inaccurate maps may result in poor criteria where to base management decisions.

(2) The *P. oceanica* meadows along the Balearic coasts sequester a discrete but significant amount of carbon annually, and accumulate more than 1 century of CO_2 at 2006 emissions levels. *P. oceanica* beds of the Balearic Islands are acting locally as a substantial carbon sink and the local Government should implement conservation measures to preserve this carbon trap and the accumulated stocks under the meadows to avoid future losses of this

valuable sink.

(3) Future goals would include the acquisition of a) a better cartographic information of the species distribution exploring the bathymetric variability of the habitat, b) a more accurate information of different seafloor types to assess the regions suitable for *P. oceanica* growth, c) a better characterization of the meadows in the islands, d) a detailed estimate of the size of the *P. oceanica* mattes, and e) most importantly, increased efforts in getting the different Departments of the Balearic Government together in the achievement of the goals mention above. All this should lead to the implementation of the adequate management measures to minimize the deterioration of *P. oceanica* habitats and to preserve this millenary-old carbon stock of the Mediterranean Sea.

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7. TABLES

Table 1: Area categories calculated for the *P. oceanica* meadow (after the classification of LIC's).

Island	LIC	L (km)	A pc (ha)	A pp (ha)	A ptotal (ha)	A ptotal / L (ha/km)
Mallorca	*BPA*	*95.9*	*14,124.9*	*1,036.6*	*15,161.5*	*158.1*
	MA	*27.3*	*4,307.9*	*1,925.3*	*6,233.2*	*228.3*
	CLM	*44.4*	*2,005.6*	*90.3*	*2,095.9*	*47.2*
	AC	*45.7*	*5,113.3*	*482.5*	*5,595.8*	*122.4*
	CEB	*24.7*	*2,307.4*	*3.7*	*2,311.0*	*93.6*
	SD	*10.5*	*187.4*	*44.8*	*232.2*	*22.1*
	AMCL	*49.3*	*3,618.8*	*1,227.1*	*4,846.0*	*98.4*
		297.8 (554.7[a])	**31,665.3**	**4,810.3**	**36,475.6**	**122.5 (65.8[b])**
Menorca	*AMN*	*64.1*	*661.9*	*283.9*	*945.8*	*14.8*
	MAS	*21.3*	*856.5*	*0.0*	*856.5*	*40.2*
	DAA	*16.4*	*661.9*	*360.0*	*1,021.9*	*62.3*
	SAG	*14.9*	*705.2*	*0.0*	*705.2*	*47.3*
		116.70 (285.7[a])	**2,885.6**	**643.9**	**3,529.5**	**30.2 (12.3[b])**
Pitiusas	*EVV*	*7.1*	*144.2*	*15.2*	*159.3*	*22.4*
	IP	*12.1*	*176.8*	*23.5*	*200.4*	*16.6*
	SEF	*62.5*	*3,719.0*	*1,157.4*	*4,876.4*	*78.0*
	CB	*11.0*	*604.9*	*302.2*	*907.0*	*82.5*
	LM	*7.1*	*386.4*	*99.9*	*486.4*	*68.5*
	TAG	*4.8*	*107.2*	*0.0*	*107.2*	*22.3*
	IERC	*4.9*	*62.4*	*1.2*	*63.7*	*13.0*
		109.5 (279.0[a])	**5,201.0**	**1,599.4**	**6,800.4**	**62.1 (24.4[b])**
	Total	**524.0 (1,238.9[a])**	**39,751.9**	**7,053.6**	**46,805.5**	**89.33 (37.8[b])**
	Total $_{corrected}$	**—**	**39,077.2**	**6,247.4**	**45,324.6**	**86.5 (36.6[b])**

L – Lenght of the coastline of the LIC's (km)

A pc – area of *P. oceanica* continuous beds (ha)

A pp – area of *P. oceanica* patchy covered beds (ha)

A ptotal – total area of *P. oceanica* beds (Apc + A pp) (ha)

(a) – Coastline length of each island

(b) – area normalized calculated with the coastline length of each island

* see LIC's abbreviations on Appendix 1

Table 2: Area categories calculated for the *P. oceanica* meadow (after the classification of Habitats Directive).

Island	**L (km)**	**A ptotal (ha)**	**A ptotal / L (ha/km)**
Mallorca	206.0 (554.7[a])	20,080.2	97.5 (36.2[b])
Menorca	98.5 (285.7[a])	7,631.5	77.5 (26.7[b])
Pitiusas	238.7 (279.0[a])	15,936.9	66.8 (57.1[b])
Total	**543.2 (1,238.9[a])**	**43,648.6**	**80.4 (35.2[b])**

L – Lenght of the coastline of Habitats Directive sector (km)

A ptotal – total area of *P. oceanica* beds (ha)

(a) Coastline length of each island

(b) Area normalized calculated with the coastline length of each island

8. FIGURES

Figure 1: Balearic Islands: distribution of *P. oceanica* meadows. Information from two sources: the LIC's (from the Project LIFE Posidonia) divided in *P. oceanica* continuous beds and *P. oceanica* patchy beds; and the Habitats Directive classified only as "*P. oceanica* beds". The map also delimitates the bathymetry from 0 to 40 metres depth.

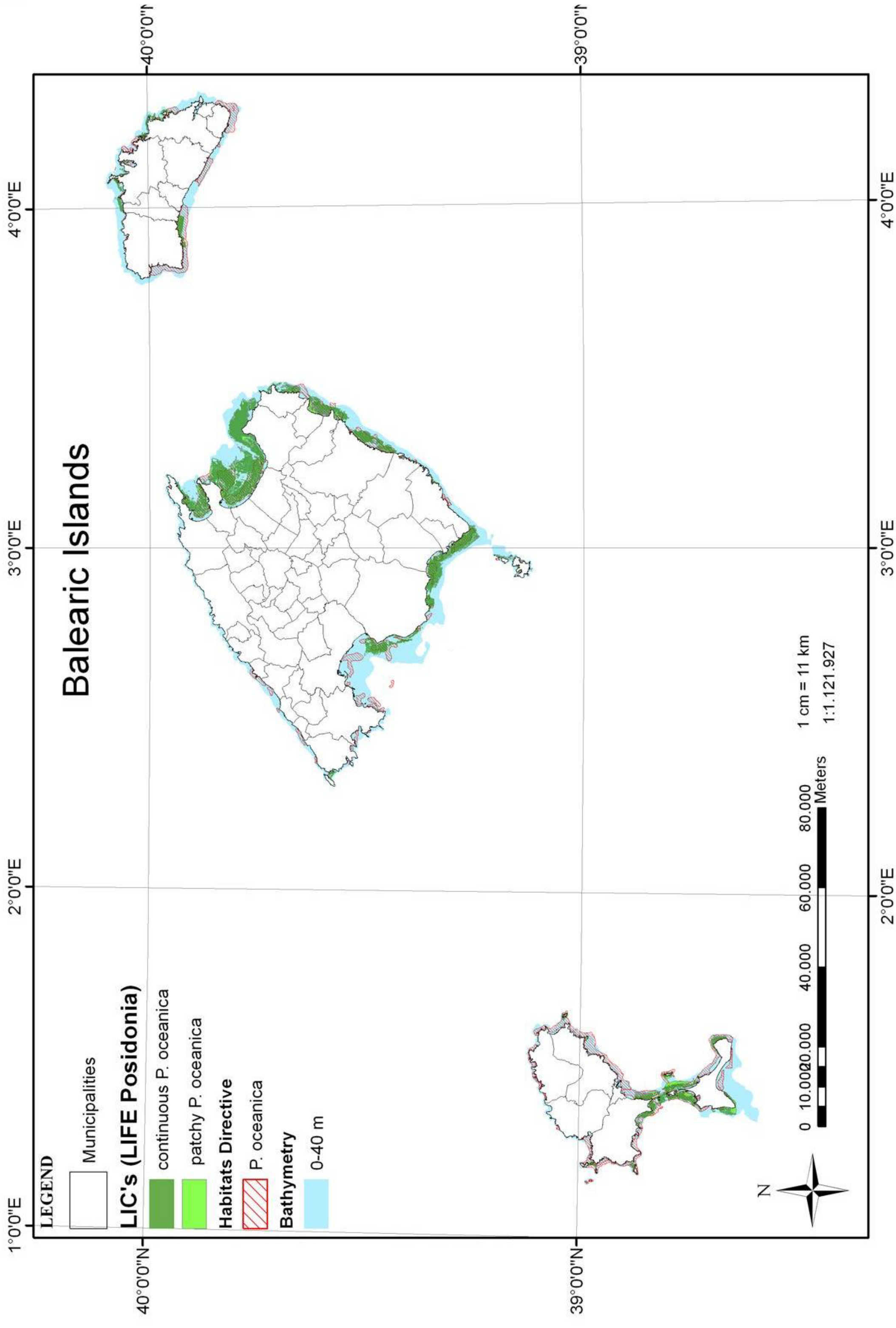


Figure 2: Mallorca: distribution of *P. oceanica* meadows. Information from two sources: the LIC's (from the Project LIFE Posidonia) divided in *P. oceanica* continuous beds and *P. oceanica* patchy beds; and the Habitats Directive classified only as "*P. oceanica* beds". The map also delimitates the bathymetry from 0 to 40 metres depth.

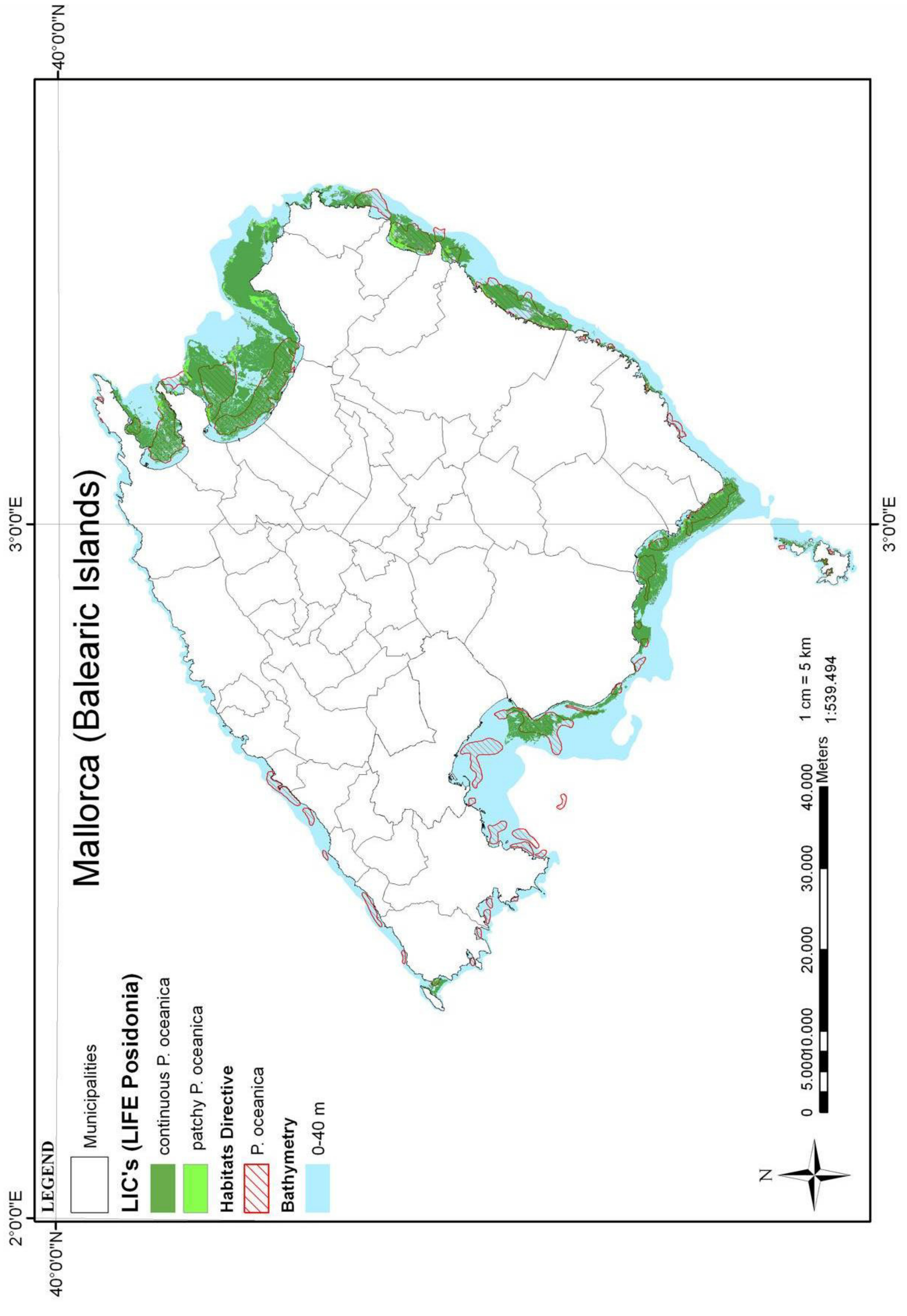


Figure 3: Menorca: distribution of *P. oceanica* meadows. Information from two sources: the LIC's (from the Project LIFE Posidonia) divided in *P. oceanica* continuous beds and *P. oceanica* patchy beds; and the Habitats Directive classified only as "*P. oceanica* beds". The map also delimitates the bathymetry from 0 to 40 metres depth.

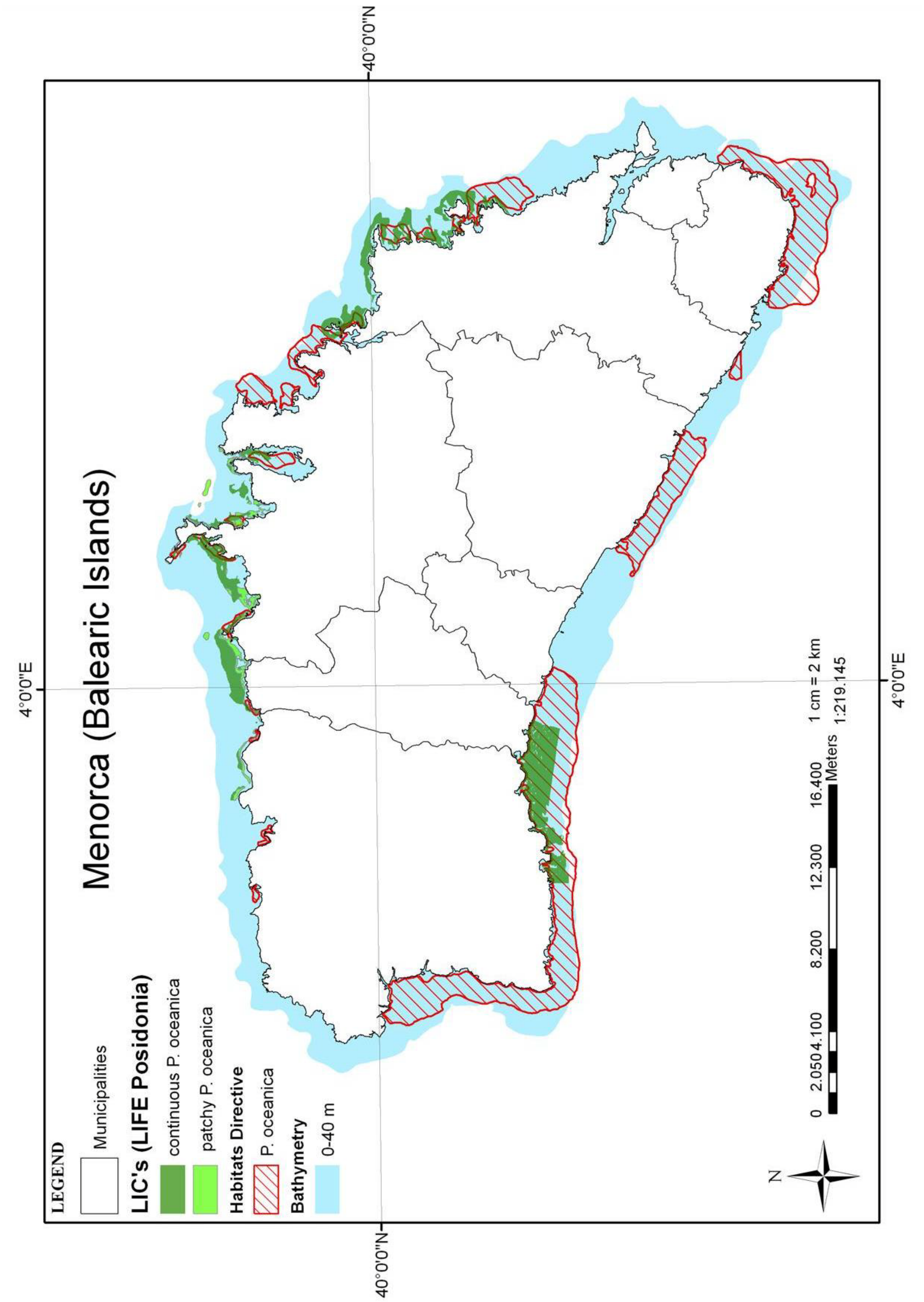
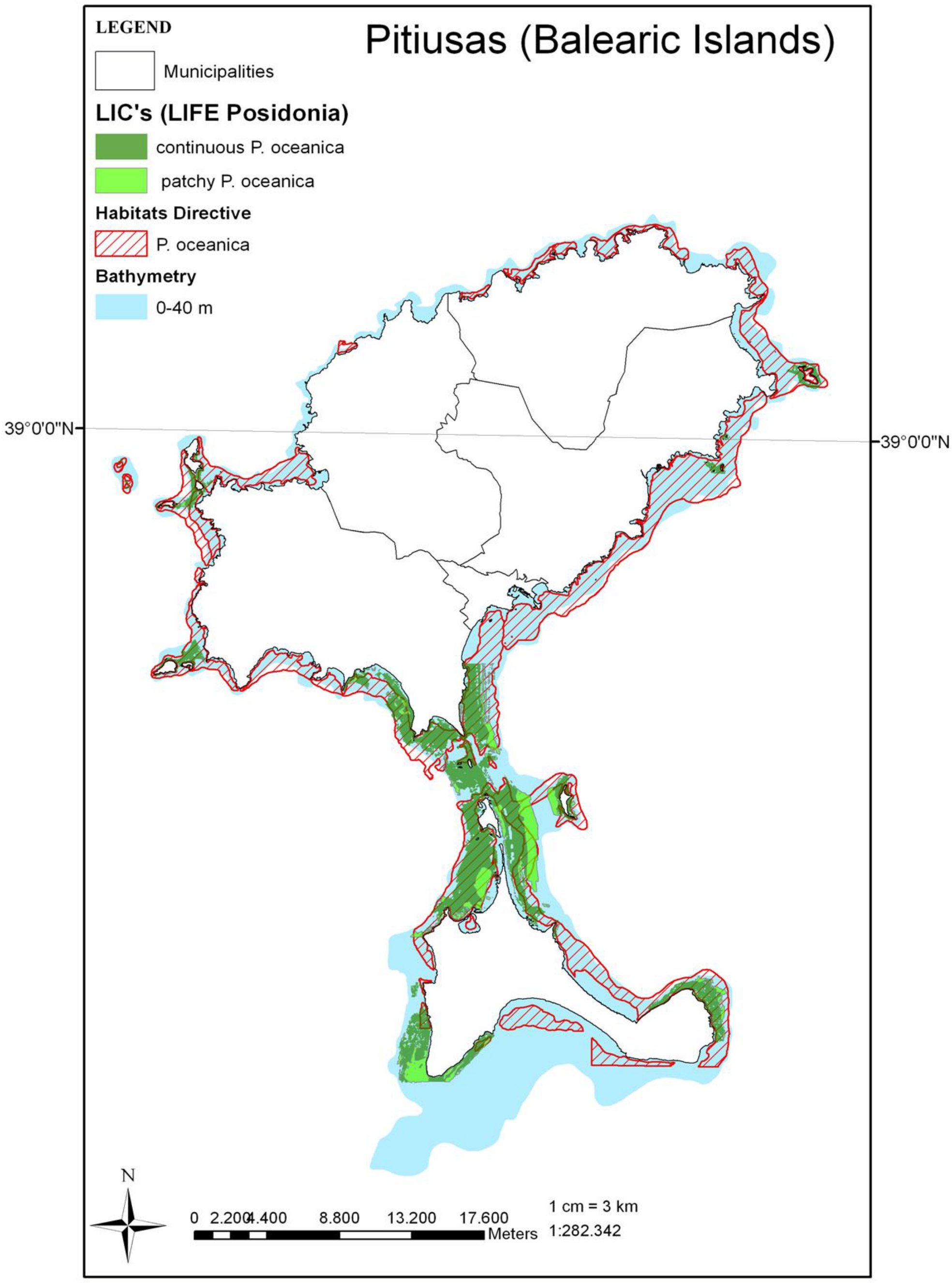


Figure 4: Pitiusas: distribution of *P. oceanica* meadows. Information from two sources: the LIC's (from the Project LIFE Posidonia) divided in *P. oceanica* continuous beds and *P. oceanica* patchy beds; and the Habitats Directive classified only as "*P. oceanica* beds". The map also delimitates the bathymetry from 0 to 40 metres depth.



9. APPENDICES

Appendix 1: General information about the LIC sites from the Project LIFE Posidonia: location, name, acronyms adopted in this study and code.

Island	LIC name	LIC abbreviation	LIC code
Mallorca	Badies de Pollença i Alcúdia	*BPA*	ES5310005
	Muntanyes d'Artà	*MA*	ES0000227
	Costa de Llevant de mallorca	*CLM*	ES5310030
	Arxipèlag de Cabrera	*AC*	ES0000083
	Cap Enderrocat-Cap Blanc	*CEB*	ES0000081
	Sa Dragonera	*SD*	ES0000221
	Area marina Costa del Levant	*AMCL*	ES5310097
Menorca	Àrea Marina del Nord de Menorca	*AMN*	ES5310035
	Àrea Marina del Sud de Menorca	*MAS*	ES5310036
	D'Addaia a s'Albufera	*DAA*	ES0000233
	S'Albufera des Grau	*SAG*	ES0000234
Pitiusas	Es Vedrà-Es Vedranell	*EVV*	ES0000078
	Illots de Ponent	*IP*	ES5310023
	Ses Salines d'Eivissa i Formentera	*SEF*	ES0000084
	Cap de Barbaria	*CB*	ES5310025
	La Mola	*LM*	ES5310024
	Tagomago	*TAG*	ES0000082
	Illots de Santa Eulària, Rodona i Es Canar	*IERC*	ES0000242

Appendix 2: Greenhouse gases emissions in the Balearic Islands for the year 2006.

Sector	**CO_2 (kt CO_2 eq)**	**CH_4 (kt CO_2 eq)**	**N_2O (kt CO_2 eq)**	**Fluorates (kt CO_2 eq)**	**Total (kt CO_2 eq)**
Production and processing energy	4,803.69	2.12	31.53	–	4,837.34
Industry	934.34	1.32	11.91	114.23	1,061.79
Tranport	3,450.50	5.70	75.84	–	3,532.04
Other	554.00	401.62	179.86	–	1,135.47
Total	**9,742.52**	**410.75**	**299.15**	**114.23**	**10,566.65**

Appendix 3: Organic carbon stocks and accumulation rates in terrestrial ecosystems (Jazen *et al*., 2004) and seagrass meadows (Duarte & Cebrian 1996, Duarte & Chiscano 1999, Duarte *et al*., 2005), with global pools determined by using the reported surface areas covered by each ecosystem.

[Adapted from Laffoley & Grimsditch, 2009]

Ecosystem tipe	**Standing carbon stock ($gC\ m^{-2}$)**		**Total global area ($\times 10^{12}\ m^2$)**	**Global carbon stock ($\times 10^{15}$ gC)**		**Longterm rate of carbon accumulation in sediment ($gC\ m^{-2}\ y^{-1}$)**
	Plants	**Soil**		**Plants**	**Soil**	
Tropical forests	12,045	12,273	17.6	212	216	2.3-2.5
Temperate forests	5,673	9,615	10.4	59	100	1.4-12.0
Boreal forests	6,423	34,380	13.7	88	471	0.8-2.2
Tropical savannas grasslands	2,933	11,733	22.5	66	264	
Temperate grass- and shrublands	720	23,600	12.5	9	295	2.2
Deserts and semi-deserts	176	4,198	45.5	8	191	0.8
Tundra	632	12,737	9.5	6	121	0.2-5.7
Croplands	188	8,000	16	3	128	
Wetlands	4,286	72,857	3.5	15	225	20
Tidal salt mashes			Unknown (0.22 reported)			210
Mangroves	7,990		0.152	1.2		139
Seagrass meadows	184	7,000[b]	0.3	0.06	2.1	83
Posidonia oceanica	*124*[a]	*40,000-160,000*[c]	*0.035*	*0.004*	*1.4-5.6*	*9.0-343*[c,d]
Kelp forests	120-720	na	0.02-0.4	0.009-0.02	na	na

(a) Romero *et al*., 1992

(b) Calculated using organic carbon concentration of 0.7 wt%, porosity of 80% and dry solid density 2.5 g cm^{-2}

(c) Mateo *et al*., 1997 and unpublished data

(d) Updated data

Photos: *P. oceanica* matte (2008). Es Pujols cove, Formentera, Balearic Islands
By: MA Mateo