CARBON STOCKS AND FLUXES ASSOCIATED TO ANDALUSIAN SEAGRASS MEADOWS

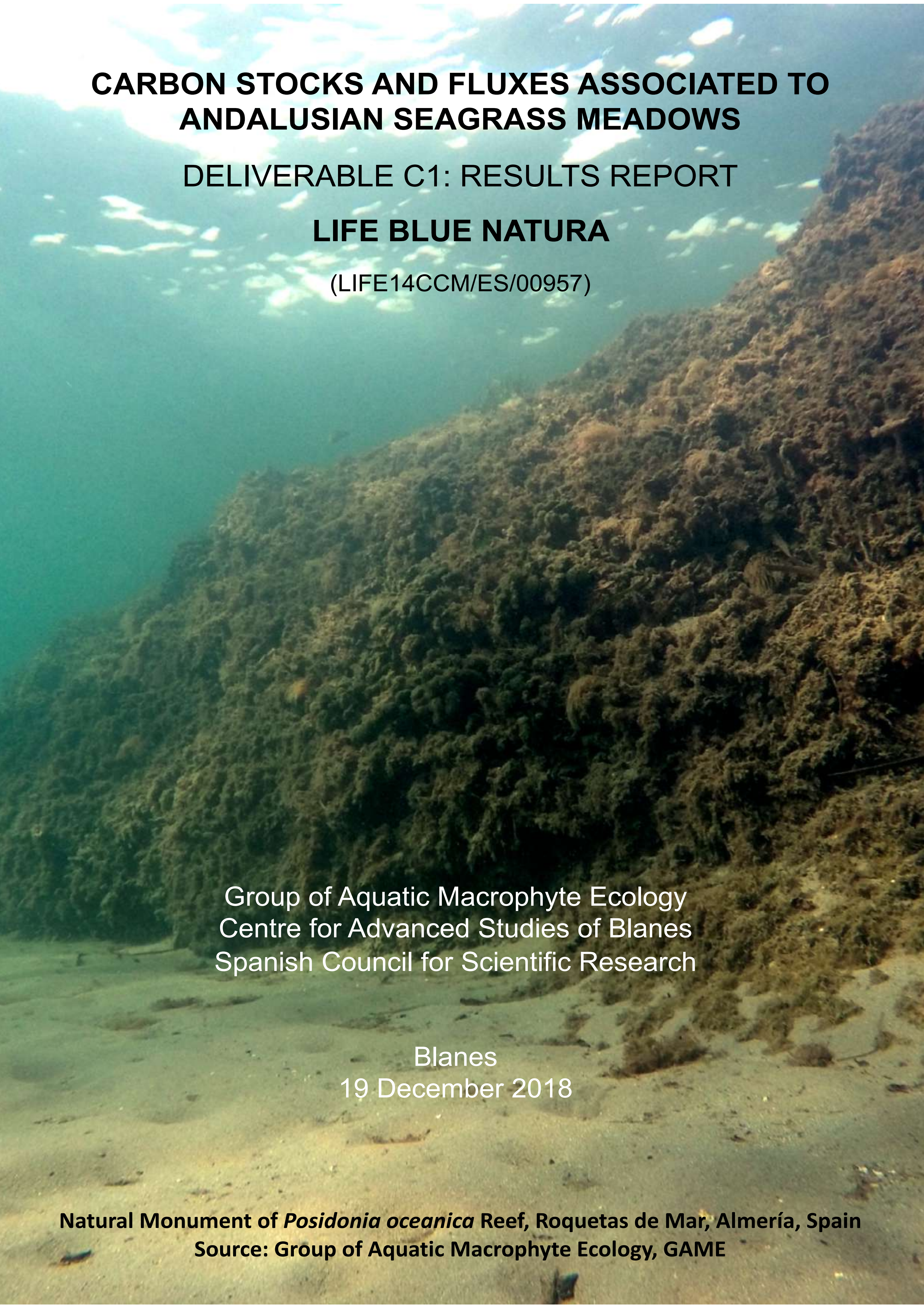
DELIVERABLE C1: RESULTS REPORT

LIFE BLUE NATURA

(LIFE14CCM/ES/00957)

Group of Aquatic Macrophyte Ecology
Centre for Advanced Studies of Blanes
Spanish Council for Scientific Research

Blanes
19 December 2018



Natural Monument of *Posidonia oceanica* Reef, Roquetas de Mar, Almería, Spain
Source: Group of Aquatic Macrophyte Ecology, GAME

CARBON STOCKS AND FLUXES ASSOCIATED TO ANDALUSIAN SEAGRASS MEADOWS

DELIVERABLE C1: RESULTS REPORT

STOCKS Y FLUJOS DE CARBONO ASOCIADOS AL SUMIDERO DE FANERÓGAMAS MARINAS EN ANDALUCÍA

ENTREGABLE C1: INFORME DE RESULTADOS

LIFE BLUE NATURA

LIFE14CCM/ES/000957

Authors:

Miguel Ángel Mateo Mínguez
Elena Díaz-Almela
Nerea Piñeiro-Juncal
Carmen Leiva Dueñas
Santiago Giralt Romeu
Candela Marco Méndez

Collaborators:

Agustín Barrajón Domenech
Diego Moreno Lampreave
María Teresa Carreto Díaz

Blanes 19 December 2018

Group of Aquatic Macrophyte Ecology
CEAB-CSIC

Socios beneficiarios:

Cofinanciador:

Table of Contents

Abbreviations

LIFE BN	Life Blue Natura
AMAYA	Agencia de Medio Ambiente y Agua de Andalucía
CMAOT	Consejería de Medio Ambiente y Ordenación del territorio
GAME	Group of Aquatic Macrophyte Ecology (CEAB-CSIC)
CEAB-CSIC	Centro de Estudios Avanzados de Blanes - Consejo Superior de Investigaciones Científicas
IUCN	International Union for the Conservation of Nature
HyT	Hombre y Territorio
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel for Climate Change
COP	Conference of the Parties
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
ITMOs	Internationally Transferable Mitigation Outcomes
SMEs	Small and Medium Enterprises
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
VCS	Verified Carbon Standard
BC	Blue Carbon
BCE	Blue Carbon Ecosystem
POM	Particulate Organic Matter
POC	Particulate Organic Carbon
TOM	Total Organic Matter
TOC	Total Organic Carbon
SOM	Sediment Organic Matter
PIC	Particulate Inorganic Carbon
TIC	Total Inorganic Carbon
GHG	Greenhouse Gasses
tCO_2	Ton of Carbon Dioxide
tCO_{2-e}	Ton of Carbon Dioxide equivalents
R/V	Research Vessel
ROV	Remotely Opperated Vehicle

Units

kt	Kiloton, 1000 tons, 10^9 grams.
Mt	Megaton, 1 million tons, 10^{12} grams.
Pg = Gt	Petagram = Gigaton, 10^{15}. Common unit for the global carbon cycle.
C to CO_2	1 g of Carbon equals 3.67 grams of CO_2.
Yr	Years
Km, ha, m^2	Square kilometers, hectares and square meters. Common units to express carbon stocks per unit surface.

Glossary of terms and definitions

LIFE Programme: "LIFE is the EU's financial instrument supporting environmental, nature conservation and climate action projects throughout the EU. Since 1992, LIFE has co-financed more than 4500 projects. For the 2014-2020 funding period, LIFE will contribute approximately €3.4 billion to the protection of the environment and climate." (LIFE)

LIFE Blue Natura: Project funded within the EU LIFE Programme entitled "Andalusian Blue Carbon for Climate Change Mitigation Quantification and Valorisation Mechanisms" (LIFE14CCM/ES/000957). It aims at providing the scientific knowledge on the distribution and size of the blue carbon carbon sinks associated to seagrass meadows and saltmarshes in the region of Andalusia, as well as providing the instruments to make possible its inclusion in the inventories of the national emission compensation systems as well and its monetization in the voluntary carbon markets.

Seagrass: flowering marine vascular plants (angiosperms) that grow in marine waters along the coasts of the world with the exception of subpolar and polar areas. There are around 60 species that belong to four families coming from several ancestors: *Posidoniaceae*, *Zosteraceae*, *Hydrocharitaceae*, and *Cymodoceae*.

Blue Carbon: Term coined in 2009 by Nellemann et al., (2009) that typically refers to the organic carbon captured by coastal vegetated ecosystems, mainly mangrove forests, tidal saltmarshes, and seagrass meadows. Both the organic carbon in the living tissues and buried in the sediments are considered BC. Whether the carbon contained in the form of carbonates is to be considered Blue Carbon, is still a matter of debate within the scientific community. The organic carbon accumulated in other areas of the ocean, in a chemical form or in the sediments, would also be a part of the BC but not typically included in the global inventories.

Biospheric carbon sink: A carbon sink is any compartment of the biosphere that captures a net amount of carbon and locks it for a long period of time, relevant to global change. Oceans, forest and soils are the main biospheric carbon sinks. When a sink stops adding net carbon, it no longer is a sink but turns into a in steady state stock, in stationary stock, or in a slow source .

Carbon stock: Mass of organic or inorganic carbon accumulated by seagrass ecosystems. The organic forms can be living or dead debris of the seagrass, both from above or belowground. The inorganic fraction is basically represented by carbonates, largely calcium carbonate.

Carbon sequestration rate = carbon flux = carbon long-term burial rate: is the pace at which the fraction of organic or inorganic carbon is buried in the sediments of seagrass meadows to stay for long periods of time. Not to be confused with photosynthetic carbon fixation by primary producers. Only a small fraction of the photosynthetically fixed carbon will be derived by some types of macrophytes to the long-term compartment in the sediments (namely, saltmarshes, mangrove forests, and seagrass meadows).

Mat: complex combination of belowground parts of seagrasses (mainly roots and rhizomes) that intermingle in a matrix of sediment of various sizes (from mud to coarse sand and rock). In the larger species such as *Posidonia oceanica* in the Mediterranean, mats can achieve several meters in thickness representing massive carbon deposits. Their aspect and dynamics are very analogous to those of terrestrial peat.

***Posidonia oceanica* 'reef'**: In some special cases, the massive accumulation and preservation of organic carbon in *P. oceanica* meadows, results in the formation of a peat-like deposit that can be directly observed and reach several meters in height. In Roquetas de Mar, Almería, Spain, there is an outstanding example of this formations that has been declared 'Natural Monument of the Posidonia Reef'. The area protected as natural monument occupies 108 ha.

Saltmarsh, tidal (or salt marsh): is a coastal ecosystem in the upper coastal intertidal zone between land and open saltwater or brackish water that is regularly flooded by tides. It is dominated by dense stands of salt-tolerant plants such as herbs, grasses, or low shrubs. These plants are terrestrial in origin and are essential to the stability of the saltmarsh in trapping and binding sediments. Saltmarshes play a large role in the aquatic food web and the delivery of nutrients to coastal waters. They also support terrestrial animals and provide coastal protection.

Cap and trade system: consists in measurably reducing national GHG emissions below certain levels (cap) in strategic economic activities. Flexibility mechanisms allow entities to compensate their GHG emissions excess from these caps, by purchasing carbon credits, which consist in certified carbon emission reductions (carbon offsets), or un-used carbon emission permissions from other countries.

Carbon credit: a carbon credit is a generic term for any tradable certificate or permit representing the right to emit one tone of carbon dioxide or the mass of another greenhouse gas with a greenhouse effect equivalent to that of one ton of carbon dioxide.

Carbon market: Markets where carbon credits/carbon offsets are traded, directly or indirectly between entities seeking to compensate for their carbon emissions and enterprises that have reduced their carbon emissions below a certain quantity assigned (under the Kyoto protocol) and have the permission to sell their carbon offsets (cap and trade scheme), or entities implementing projects to produce a net reduction in global GHG emissions. The carbon markets can be regular, where clients are enterprises obliged to maintain their GHG emissions under certain thresholds, and where the carbon credits/offsets that can be traded are regulated, both things under the Kyoto Protocol. There are also voluntary carbon markets, for enterprises and projects producing carbon credits are not regulated by the Kyoto Protocol.

Carbon offset: a carbon offset is a reduction in emissions of carbon dioxide or greenhouse gases made in order to compensate for or to offset an emission made elsewhere. Carbon offsets are produced by projects that carry out on-the-ground emissions reduction activities, and are typically measured in metric tonnes of carbon dioxide equivalents, or tCO_{2e}.

Verified Carbon Standard (VCS): Standard for Certifying Carbon Emissions Reductions. "The VCS Program is the world's most widely used voluntary GHG program. More than 1300 certified VCS projects have collectively reduced or removed more than 200 million tonnes of carbon and other GHG emissions from the atmosphere". (Verra)

Conference of the Parties: Is the supreme decision-making body of the UNFCCC. Its main task is to review the implementation progress made in reducing GHG emissions by the nations having joined the Conference (Parties).

Paris Agreement: was an initiative of the UNFCCC that aimed at bringing for the first time "all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so". (UNFCCC).

^{14}C age = radiocarbon age: time since and organic material stopped being biomass and started to be necromass, estimated through its remaining content in the radioactive ^{14}C isotope. This method is is used for determining the age of an object containing organic material by using the properties of radiocarbon, a radioactive isotope of carbon, that decays regularly with time. Given that the half life of ^{14}C is 5730 years (± 40), this technique allows us to date organic materials usually between 100 and 50.000 years of age.

^{210}Pb age: age of a sediment layer estimated from its excess content in the radioactive isotope ^{210}Pb. its half-life of 22.3 years, allows to date sediments from present to 150 years ago.

Chronological model: is a statistical model to interpolate several ages assigned with one or different dating methods to several sediment layers, in order to assign a date to any sediment layer along a core.

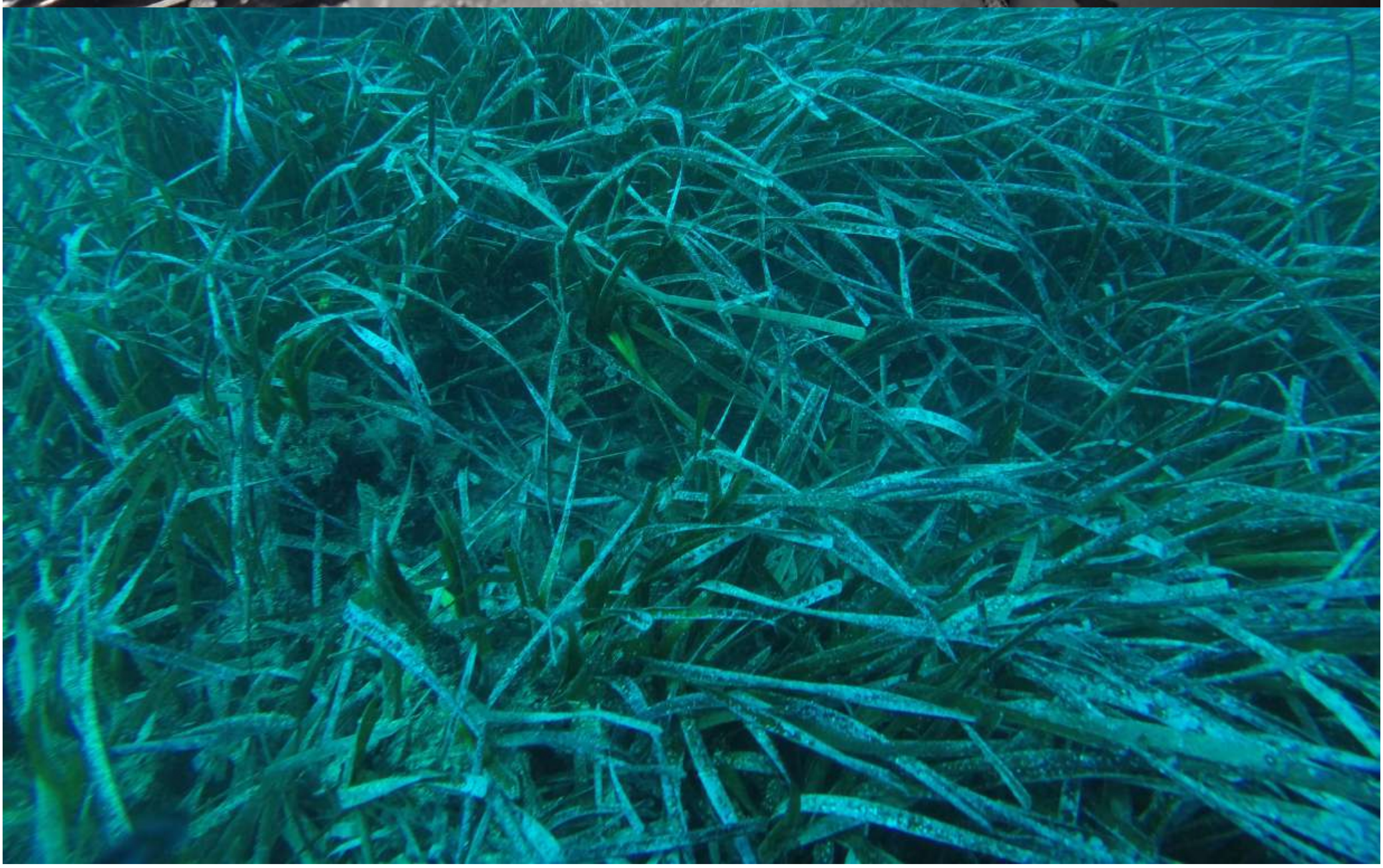
Corer, core, coring: A corer is a cylinder that can be made of various materials, have different diameters and be driven into de soils or sediments manually or using different percussion and rotation devices. The core is the soil/sediment sample within the corer which, a priori, conserves its chronological sequence of sedimentation. Coring is the action of sampling cores using corers.

Vibrocoring: Coring method that uses a metal barrel lodging a PVC or polycarbonate pipe inside and uses gravity and vibration to penetrate in the sediments. On its top end, the barrel is fitted with an electrical vibrating 1ton-head. Because of its length and weight, it is usually operated from a research vessel or platform and hence cannot be used in waters shallower than 10 m. Continuous cores of up to 6 m can be obtained using this technique.

Manual coring: Were mechanical coring techniques cannot be used, typically in shallow waters, manual coring is the choice. It consists on slowly hammering PVC corers down in the sediments while rotating them to minimize core compression. Depending on the grain size of the sediments being cored, the pipe will require to be fitted with a core catcher to retain lose sediments. Core lengths of up to 3 m can be obtained using this technique. Both the penetration and removal of the manual cores can be a very arduous work, especially when it has to be performed underwater in SCUBA. Retrieval usually requires the participation of several divers and a lift air balloon.

Grain size analysis: measurement of the abundance of different sediment grain-size classes. It is performed by successive sieving through decreasing size-mesh, or analyzing laser diffraction patterns.

1. Introduction



1. Introduction

A relentless CO_2 rise in the atmosphere is also increasing the interest in the conservation and promotion of biosphere carbon sinks to attenuate that trend (Howard et al. 2017). Coastal ecosystems such as mangroves, tidal saltmarshes, and seagrass meadows can remove and lock significant amounts of carbon for relevant periods of time resulting in very large carbon stocks (Mateo et al., 1997; Duarte et al., 2004; Lo Iacono et al., 2008). These "Blue Carbon Ecosystems" (BCE) are considered an asset to reduce the CO_2 concentration in the atmosphere and therefore mitigating climate change (Fourqurean et al., 2012; Lavery et al., 2013, Hiraishi et al., 2014). While the global impact of this ability is a current matter of controversy, the potential for monetization of this carbon is a fact (Crooks et al., 2012).

In the same way as each additional ton of CO_2 captured or not emitted by terrestrial forests can be traded within the regular or voluntary carbon markets (cap and trade approach), the CO_2 sequestered by BCE could be turned into tradable carbon credits via offsetting projects (Crooks et al., 2012, Hamrick and Galland, 2018). The path to monetization is not easy. First, a detailed quantification of sinks size and dynamics is imperative. These are important challenges, both conceptual and technical, given the high complexity of the processes involved, the extension and diversity of the BCE, and the overall scarcity of information available. Then, the tons of carbon captured or emissions avoided have to be certified through labyrinthine numerical approximations and, finally, integrated in the current environmental legislations (Herr et al., 2017).

The Paris Agreement acknowledges the importance of the gas sinks and encourages the Parties to take measures to conserve and enhance them and to provide a national inventory report of their magnitude and distribution (UNFCCC, 2016). Furthermore, the interest in CO_2 trading, the inclusion in 2013 of a Supplement for wetlands to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, (Hiraishi et al, 2013) and the momentum of the research in BC, sets a favorable scenario to stimulate inventorying and quantifying these BC sinks, and to design mechanisms to include them in climate change mitigation strategies, because it can play a role in this challenge, as well as in local economic development (Barbier et al., 2011; Costanza et al; Nelleman et al, 2009).

As mentioned above, the first key step in order to bring the BC to climate change mitigation strategies is to assess, with the best possible detail, the abundance, distribution, and dynamics of the carbon stocks and fluxes associated to these ecosystems. It is time to do so.

The structure of the Project LIFE Blue Natura is a faithful reflection of the reality exposed above. Very briefly, its preparatory actions have provided the cartographic information on the distribution of blue carbon sinks of the Andalusia Autonomous Community (Action A1: Cartography and Characterization of habitats); performed and extensive coring survey of blue carbon habitats growing under various environmental settings (geographic, depth, substrate, and degradation gradients; Action A2: Design and sampling needed to assess the stocks and fluxes associated to Andalusia seagrass meadows, and the corresponding action A3 for saltmarshes), and has determined the stocks and fluxes of organic carbon associated to those different settings (Action C1: Estimate of stocks and fluxes associated to Andalusia seagrass meadows, of which this report is the action deliverable. The corresponding results for saltmarshes will be addressed in deliverable C3).

In this report we present the results for this last Action (C1). They include all the variables planned in the proposal for the action (see Material and Methods section), most of them leading to obtain the variables to answer three key questions:

1. How much organic and inorganic carbon (or CO_2 equivalents for other GHG) is stored/stocked in the biomass and sediments of the four Andalusian seagrass species? (stock).

2. How much does this stock differs among the various environmental settings along the Andalusian coasts? (Distribution).

3. At what rate does this stock accumulate? (Sequestration rates) and how it is affected by habitat degradation/recovery?

The answers to these questions are crucial to determine the potential of this carbon as a monetizable asset through conservation or reforestation projects, in a first stage, in the voluntary markets.

This report also contains a description of the methodology used in the field, in the laboratory, as well as the numerical procedures applied.

In the Results and Discussion section, the results are presented and commented. The uncertainties and limitations associated to these results are discussed in the annex IV. Inventorying the stocks and fluxes of the organic carbon accumulated by the seagrass meadows growing along 945 km of coastline, from 0 to 20 m depth, is not a minor endeavor. The immensity of the area under study was therefore one of the main challenges to be tackled. To guarantee adequate representativeness of the variability of the sink stocks and fluxes in Andalusian coasts, 88 cores from 1 to 5 m in length were taken at 32 stations (10 locations) using, when necessary, diving operations both from the shore and from a research vessel (R/V). The R/V proved to be indispensable for the coordination of the dives in the deep stations (around 20 m depth), and to operate the heavy coring devices (vibrocore and multicorer). These long cores allowed estimating a potential total size of the sink (maximum stock until steady state; what will be addressed in forthcoming deliverables) to a very high level of accuracy, impossible to achieve with just manual cores. Modeling observed (standing) stocks along a 5 m-core takes us closer to understanding what happens with the carbon that a meadow accumulates over all its life as a net sink until it turns into a steady state stock.

Finally, this report provides some background information and recommendations of interest to the elaboration of compensation projects and suggests future lines of action to improve our knowledge of the phenomenon of organic carbon refractory accumulation under seagrass meadows. A sound knowledge is, after all, the foundation that (1) policy makers need to take safe steps on the path to the inclusion of the coastal carbon in the national emissions and sink inventories, and in order to evaluate blue carbon economic value, and (2) what the SMEs and NGOs need to assess to decide whether Blue Carbon offset projects are or not financially viable (O' Sullivan et al, 2011 ; Solaun et al, 2011 ; Herr et al, 2011).

The results presented in this report provide key elements for the actions to follow in the project LIFE Blue Natura, specially implementation Actions C3 to C7, as well as dissemination actions, mainly for E3 and E4. These actions are aimed at facilitating the the issuance and retirement of carbon offset projects based on restoration of vegetated coastal ecosystems, by elaborating a seagrass and saltmarsh-derived carbon credits certification standard for Andalusia (C4), a handbook to guide the certification for offset projects based on seagrass meadows and saltmarshes (C5), among others, as well as to reach different sectors of the society, like SME and NGO technicians, and public officials (E3), and public and private decision-makers (E4), as well as journalists (E5) and the general public (E1 and E6). These results will also contribute to the growing international effort to bridge key knowledge gaps for inclusion of blue carbon in climate change mitigation strategies, mainly through actions E2 and E7.

Overall, LIFE Blue Natura aims are contributing to broader international climate policy discussions and sharing knowledge with other countries with a wealth of BC resources, willing to conserve or restore vegetated coastal ecosystems, while promoting local economic development.

Summarizing: This report aims at providing an inventory of the blue carbon stocks and fluxes in Andalusia, to characterize its spatial variability and to identify some of the main factors influencing carbon sequestration, preservation, and past/future dynamics which may be relevant for carbon offsetting projects. The basis for the monetization of the resource, is set.

2. Materials and Methods

2. Materials and methods

2.1. Field sampling strategy

The vast geographic extension of the Andalusian coast, as well as the large variability of environmental conditions makes a full factorial sampling design totally out of reach and of scope of this project. We therefore sought to capture as much as possible of the variability in seagrass carbon stocks and fluxes associated to species (*Posidonia oceanica, Cymodocea nodosa*, *Zostera noltei* and *Zostera marina)*, geography (Atlantic, Mediterranean and Alboran seas), environmental factors (depth, sea bottom) and plant health status. In a post-hoc discussion, it was decided to consider 'Stable meadows' all those that were not notoriously degraded (see later).

In total we sampled seagrass habitats at 10 sites and 32 stations, from Almería to Cadiz. We collected 88 cores, of which 14 were vibrocores, and the rest were manually collected. We also collected 75 biomass samples and 78 *P. oceanica* vertical shoots, as well as samples of the various dominant plant species growing in each area, in order to measure the primary producers isotopic signal (to try establishing the main total organic carbon – TOC – contributors to the sink). The results for the isotopic signals and lepidochronological analyses are not part of this deliverable. They will be used in future elaborations of the data in the form of scientific manuscripts.

Below we provide a summary of the sampling strategy, and the field and laboratory methods used. The full details on the sites and stations sampled, are available in the LIFE BN Deliverable A2 (Anejo A2 Deliverable Resultados muestreos en praderas andaluzas.pdf, 2017).

Table 2.1. Location sampled: coordinates, species present and codes.

Region /Province	Natura 2000 SAC	Location	Coordinates		Depth (m)	Species	Categories	Code
Mediterranean, Almería	ES6110010	Terreros	37º21´0.12´´N	1º40´36.37´´W	5.5	*Posidonia oceanica*	Shallow, type	TE.S
Mediterranean, Almería	ES6110010	Terreros	37º20´58.02´´N	1º39´32.10´´W	12.5	*P. oceanica*	Intermediate, type	TE.I
Mediterranean, Almería	ES6110010	Terreros	37º20´59.70´´N	1º39´32.40´´W	12.5	*P. oceanica*	Intermediate, unvegetated	TE.I-C
Mediterranean, Almería	ES6110010	Terreros	37º20´37.00´´N	1º39´10.60´´W	18.5	*P. oceanica*	Deep, type, living matte	TE.D
Mediterranean, Almería	ES6110010	Villaricos	37º15´18.93´´N	1º45´29.53´´W	15.9	*P. oceanica*	Intermediate, chemically degraded, dead matte	DE.I
Mediterranean, Almería	ES6110010	Palomares	37º12´27.13´´N	1º47´30.20´´W	10.2	*Cymodocea nodosa*	Intermediate, type	PA.I
Mediterranean, Almería	ES0000046	Aguamarga	36º56´15.66´´N	1º56´0.42´´W	4.8	*P. oceanica*	Shallow, type	AG.S
Mediterranean, Almería	ES0000046	Aguamarga	36º56´10.20´´N	1º55´55.32´´W	10.8	*P. oceanica*	Intermediate, healthy	AG.I
Mediterranean, Almería	ES0000046	Aguamarga	36º55´59.40´´N	1º55´55.32´´W	18	*P. oceanica*	Deep, type	AG.D
Mediterranean, Almería	ES0000046	El Alquian	36º49´39.10´´N	1º23´14.00´´W	6.8	*C. nodosa*	Shallow, vegetated	BA.S
Alboran, Almeria	ES0000046	El Alquian	36º49´38.54´´N	2º23´13.36´´W	7.1	*C. nodosa*	Shallow, unvegetated	BA.S-C
Alboran, Almeria	ES6110019	Roquetas	36º47´15.50´´N	2º35´20.10´´W	1.5	*P. oceanica*	Shallow, type, living matte	RO.S
Alboran, Almeria	ES6110019	Roquetas	36º47´11.35´´N	2º35´24.10´´W	0.7	*P. oceanica*	Shallow, chemically degraded, dead matte	RO.S-C
Alboran, Almeria	ES6110019	Roquetas	36º47´12.2´´N	2º35´24.20´´W	1	*C. nodosa*	Shallow, type	RO.S-Cn
Alboran, Almeria	ESZZ16003	Roquetas	36º47´16.08´´N	2º34´39.06´´W	14.8	*P. oceanica*	Intermediate, type	RO.I
Alboran, Almeria	ESZZ16003	Roquetas	36º47´9.24´´N	2º34´47.64´´W	14.7	*P. oceanica*	Intermediate, mechanically degraded (trawled)	RO.I-E

Region /Province	Natura 2000 SAC	Location	Coordinates		Depth (m)	Species	Categories	Code
Alboran, Almeria	ESZZ16003	Roquetas	36º47´9.24´´N	2º34´47.64´´W	14.8	*P. oceanica*	Intermediate, recolonizing patch	RO.I-R
Alboran, Almeria	ESZZ16003	Roquetas	36º47´9.24´´N	2º34´47.64´´W	14.5	*P. oceanica*	Intermediate, chemically degraded (border trawling mark, silted)	RO.I-B
Alboran, Almeria	ESZZ16003	Almerimar	36º41´51.72´´N	2º49´32.46´´W	4.5	*P. oceanica*	Shallow, live matte on rock + sand (patchy)	AL.S
Alboran, Granada	-	Melicena	36º44´53.99´´N	3º14´3.78´´W	4.2	*P. oceanica*	Shallow, in decline (70% dead matte)	ME.S
Alboran, Granada	-	Melicena	36º44´51.10´´N	3º14´12.10´´W	11.8	*P. oceanica*	Intermediate, unvegetated	ME.I-C
Alboran, Granada	ES6170030	Calaburras	36º29´22.88´´N	4º41´37.02´´W	0.5	*P. oceanica*	Shallow, rock	CA.S
Alboran, Málaga	ES6170030	Calaburras	36º29´26.60´´N	4º41´36.40´´W	0.5	*P. oceanica*	Shallow, dead matte on rock	CA.S-C
Alboran, Málaga	ES6170030	Calaburras	36º29´25.9´´N	4º41´37.25´´W	0.5	*C. nodosa / P. oceanica*	Shallow, dead matte colonized with *C. nodosa*	CA.S-Cn
Atlantic, Cadiz	ES0000140	Santibañez	36º28´5.96´´N	6º15´5.99´´W	0	*Zostera noltei*	High intertidal, lagoon	SA.Zn-S
Atlantic, Cadiz	ES0000140	Santibañez	36º28´7.99´´N	6º15´4.59´´W	0.3	*Z. noltei*	Low intertidal, lagoon	SA.Zn-D
Atlantic, Cadiz	ES0000140	Santibañez	36º27´59.16´´N	6º14´40.75´´W	0	*Z. noltei*	Intertidal, in recovery, lagoon	SA.Zn-C
Atlantic, Cadiz	ES0000140	Santibañez	36º28´9.41´´N	6º15´2.81´´W	0.5	*C. nodosa*	Subtidal, lagoon	SA.Cn
Atlantic, Cadiz	ES0000140	Santibañez	36º28´10.45´´N	6º15´1.40´´W	1.5	*C. prolifera*	Subtidal, lagoon (algae)	SA.Cp

2.1.1. ***Sampling on Posidonia oceanica meadows: description and discussion***

We sampled in 7 *P. oceanica* sites and 21 stations (see Fig. 2.1 and Table 2.1). Following the design of action A2, we studied *P. oceanica* stocks and fluxes variability depending on the following factors:

a. Geography

Posidonia oceanica meadows and dead mats were sampled in the Mediterranean (Terreros = TE, Villaricos = DE and Aguamarga = AG sites) and Alboran seas (Roquetas = RO, Almerimar = AL, Melicena = ME, Calaburras = CA). Five sites were in the coasts of Almería (TE, DE, AG, RO, AL), 1 in Granada (ME) and 1 in Málaga (CA). In all the sites but Almerimar (which substituted Punta Entinas due to bad weather), there’s background information from the Andalusian monitoring network POSIMED-Andalucia (AMAyA-CMAOT, 2017).

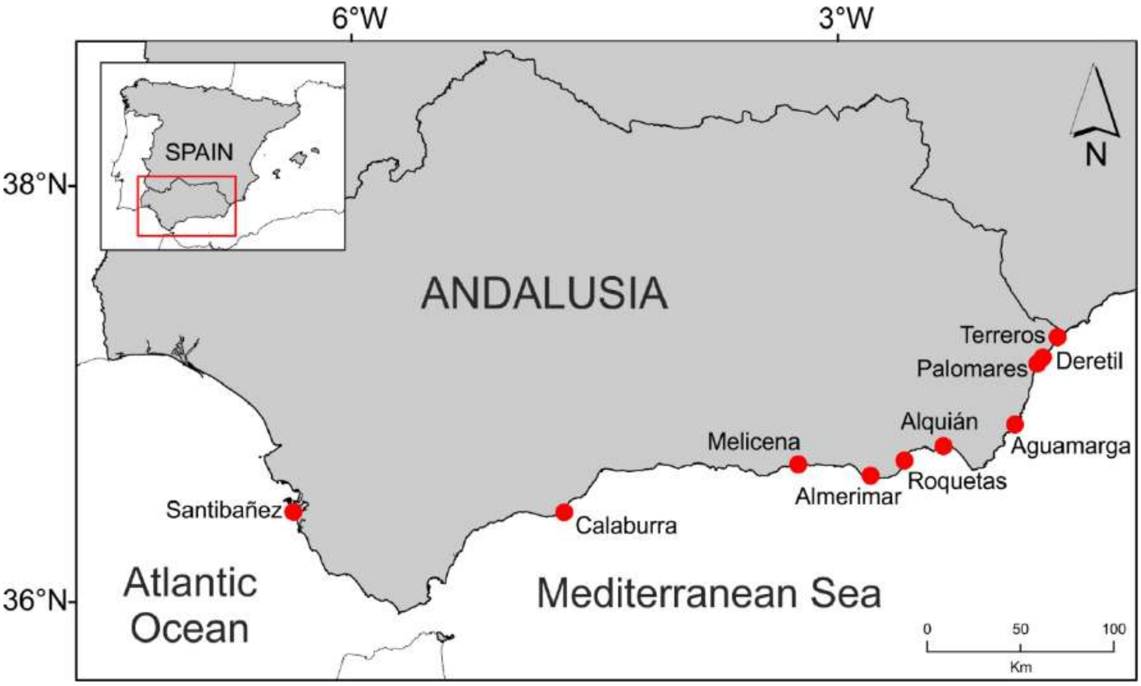


Figure 2.1. Locations sampled for this work

Terreros: the Posimed station at 10.1m shows a 60% to 70% *P. oceanica* coverage (mesoscale and landscape cover, respectively), on a mixed bottom of sands and rocks. Less than 10% dead mat is detected, which indicates a good Conservation Index. Between 2012 and 2017, coverage has slightly increased, shoot density shows contradictory results (fixed plots indicate a slight net increase of 20 shoots/m^2 in 5 years, while transect plots show a shoot density reduction of 100 shoots/m^2 in the same period). On average, vertical rhizomes are not too unburied, and their burial has slightly increased, from 4.5cm to 3.5cm. All this suggest that no erosion is occurring.

Villaricos: This meadow, also installed on mixed sand and rocky bottoms, is very degraded by the chemical effluents of the Deretil factory, established in 1961, which has affected the *P.*

oceanica meadow in 2 km coastline until 10-12m depth (Moreno et al, 1999, 2001). Waste spills have been reduced since 2000, but the Posimed station, at 12 m depth shows that meadow regression is still taking place. Between 2012 and 2014, shoot density has decreased from 75 to 50 shoots m^2, while landscape cover remained low but stable around 25%. Dead mat cover was very high in 2012 (50%), but disappeared from subsequent transects, probably due to burial, as shoot burial increased, from 2.6 to 2 cm above the sediment. The area sampled in this study was 3 m deeper, but presented similar characteristics, although it showed dead mat reefs, 1-2 m in height.

Aguamarga: the Posimed station is in a meadow border at 12 m depth, growing on a soft sediment bottom (fine sand and even mud), and fringed by a *C. nodosa* meadow, which is better adapted to this type of sediment. Therefore, the conditions are not easily extensible to the stations cored in this study. In the Posimed station, between 2012 and 2017, shoot cover has been relatively stable, although dead mat is increasingly appearing (from 5% to 15%). In this period, shoot density has slightly decreased (in 8.5 shoots/m^2). Shoot burial also has slightly decreased, from 6 cm above the sediment, to 8 cm.

Roquetas: the Posimed station is at 11 meters depth, in the deep limit of the Roquetas barrier reef SEC, so that relatively protected from illegal trawling and dredging activities which have severely degraded the deeper meadow area. Plants are settled on sediment rich in shells, sand and also mud, similar to the one observed in the stations cored in this study. In the POSIMED station the plant cover has remained stable between 2012 and 2017 (around 40% and 70%, mesoscale and landscape covers, respectively), while global shoot density measured in transect quadrats, has decreased from 300 to 220 shoots/m^2 (but in the fixed quadrats net decrease of only 8 shoots/m^2). Shoot burial at this station seemed adequate and stable (3 to 3.5 cm, on average, between 2012 and 2017).

Punta Entinas: despite we could not sample in this station, it is an area characterized mainly as *P. oceanica* meadow growing on rocks in the cartography. So it is worth to present some information about it, which will be useful in the discussion of the scaling up of carbon stock estimates. These meadows are characterized by AMAyA-CMAOT (2017) as “extensive and growing on sediments of different granulometries (sands and gravels), or on rock plateaus”. The landscape pictures show mats of around 30-50 cm leaning out of the substrate. The area has very low human pressure and the Posimed station show high and stable cover values, as well as shoot burial near equilibrium and stable (around +4cm).

Melicena: the area monitored by Posimed, at 6 m depth, has greater cover and density values (75% landscape cover, 50% mesoscale cover, around 10% dead mat) than those observed in the station cored at this study, which was shallower, at 4.2 m depth, and showed a great extensions of dead mat (visually around ⅔ of the area). Nevertheless, the sediment characteristics seemed similar (sands). At the Posimed station, shoot burial seemed in equilibrium and stable between 2010 and 2017 (from 3.7cm to 3.2 cm).

Calaburras: the Posimed station is at 3-4m depth patchy meadow on rocky bottom, near the station CA.s sampled in this study. Shoot density and landscape cover seem to have slightly increased between 2004 and 2017, despite there seems to be net erosion in the area (shoot height over the substrate has increased from 2 to 5 cm between 2010 and 2017).

b. Depth

Natural depth variability of *P. oceanica* carbon stocks and fluxes were studied in two relatively healthy meadows in Almería: Aguamarga, in Cabo de Gata (South-Eastern Almeria), and San

Juan de los Terreros (North-Eastern Almeria). Three stations were selected at each site: shallow (TE.S, and AG.S) at 5-6 m depth, intermediate at 10-13 m depth (TE.I and AG.I), and deep, at 18-20 m depth (AG.D, TE.D). Few meadows in Andalusia grow beyond 20 meters-depth, and they are in the Eastern of Almeria. None of the Andalusian meadows in Alboran surpass the 20 m depth, and most of them do not surpass 10 m depth, either.

c. Presence-Absence of vegetation

Determining the places historically lacking *P. oceanica* was not possible in the same environmental conditions than the healthy (stable) meadows. Therefore, we focused in unvegetated areas in the present and the recent past, neighbouring the present vegetated areas. We added a -C to their sample code ("control") as they may represent the difference in carbon stocks and fluxes between currently vegetated and unvegetated areas. In Terreros, we selected 2 sandy areas adjacent to the healthy intermediate meadow of Terreros (TE.I-C, at the same depth), and one unvegetated, sandy area at 10 meters depth (ME.I-C), near the shallow Melicena meadow (ME.S, at 4.2 m, Granada, Table 2.1.).

d. Bottom type

All cores were collected on *P. oceanica* meadows growing on soft bottoms. Additionally, we sampled 3 biomass samples in shallow (3 m depth, CA.S station, Málaga) *P. oceanica* large patches growing on rocks, which had not developed a mat yet or will never develop it at all (Table 2.1.). The dead mat stations CA.S-C and CA.S-CN consisted in shallow, not very thick mats settled on rocky bottom.

The different meadows sampled on soft bottoms showed a range of fractions of silt, clay and sand, as well as of mat development. Such variation was revealed *a posteriori* through granulometric analyses of sediment core subsamples in the laboratory (see Materials & Methods section "2.2. Laboratory analyses".

e. Mat development and living- vs dead mat

There may be differences in carbon stocks between a *P. oceanica* meadow with a well-developed mat (i.e. organic 'peat-like' reef) and one without such structure underneath (and among an infinite number of meadows with infinite different degrees of mat development, as *P. oceanica* meadows tend slowly to develop a mat). During the LIFE BN surveys we sampled a well developed shallow mat in the Natural Monument of the Roquetas Posidonia barrier-reef (Almería). The development dynamics, size of the sink, and carbon sequestration rates could be compared with those measured in TE.S and AG.S, taking into account that there may be also differences due to geography (RO.S in the Alboran sea, TE.S and AG.S in the Mediterranean sea).

Moreover, the mat was sampled in 2 conditions: mat with and without a living overlying *P. oceanica* canopy (RO.S and RO.S-C, respectively). The dead mat area seemed to be recent, and could have originated by the recurrent freshwater discharges occurring in the area since 2005 (D. Moreno, pers. comm.). The mat sampled was a peat-like formation leaning out of the sediment, and covered by diverse algae and encrusting animals. A core was also inserted in a sandy patch at the bottom of that mat reef (core RO.S-C-bottom), in order to see if there was also mat underneath. Also the sandy patch of Terreros (TE.I-C) incidentally showed to have a mat buried under 50 cm of sand, but this will be developed in "3. Results and Discussion".

We also sampled very shallow (0.5-1 m depth) dead mat in Calaburras (Málaga), several decades old: CA.S-C (covered with algae) and CA.S-CN (covered with algae and the smaller seagrass *Cymodocea nodosa*). This dead mat looked thin, and settled on rocks and boulders. The shallow meadow of Melicena (ME.S) also showed large extensions of dead mat.

Finally, the deep Terreros (TE.D, 18.5 m depth) *P. oceanica* meadow had also a well-developed mat. The degraded-intermediate depth meadow sampled in Villaricos (DE.I, 15 m depth) also showed a thick dead mat.

f. Degraded meadows

We sampled 2 severely degraded meadows, due to different disturbance types, which could affect the sediment carbon stock in different ways.

- *Mechanically degraded meadows* (by illegal trawling and/or dredging)**:** we expected that, in addition to a reduction in C fluxes, they could have lost not only its living plant carbon stock, but also a portion of the top part of its sediment C stock. One of those areas was sampled at 14.8 m depth in Roquetas, in the center of a trawling-mark (RO.I-E) as well as in its edge (RO.I-B, 14.5 m). RO.I-E was mainly devoid of *P. oceanica* plants and consisted of bare sediment with few algae, while RO.I-B was partially covered with the small seagrass *C. nodosa* and the invasive algae *Caulerpa cylindracea* (Fig. 2.2).

Figure 2.2. Landscape view of the mechanically degraded *Posidonia oceanica* meadow of Roquetas. The plateau corresponds to the meadow degraded by siltation (corresponding to station RO.I-B), the well area corresponds to the trawling trace (station RO.I-E), and the P. oceanica plant patches corresponds to the station in recovery RO.I-R. (Source: Agustín Barrajón, Programa de Gestión Sostenible del Medio Marino,

- ***Chemically degraded meadows:*** two stations matched this category. The meadow of Villaricos (station DE.I), very close to the chemical factory of Deretil (settled in 1961), has disappeared over 2 km alongside the coast, to a depth of 10-12 m (Moreno et al.,1999, 2001; Hayes et al., 2001). This loss of meadow extension occurred mainly between the 70's and 90'. Despite improvements in effluent management, no evidences of recovery have been observed so far, and the Posimed station indicates that degradation is still in progress. We sampled a dead mat with some surviving shoots in a severely degraded area, at 15 m depth (Fig. 2.3). On the other hand, the death of the shallow dead mat of Roquetas reef (already described in the previous subsection), is likely related to nutrient-rich freshwater effluents.

Figure 2.3. Example of the coring process over a chemically degraded *Posidonia oceanica* meadow Villaricos (Source: Diego Moreno, Programa de Gestión Sostenible del Medio Marino, Junta de Andalucía)

2.1.2. *Meadows in decline*

Two of the meadows sampled fit in this category: a barrier reef in Almerimar bay, which seems to be undergoing erosion or at least it is currently very patchy (AL.S), and the meadow of Melicena (ME.S), which is representative of the few meadows occuring in the coast of Granada. They are shallow, patchy and in decline, with around 60-70% of dead mat, although the causes of the decline are uncertain. Effluents from the numerous adjacent legal and illegal agriculture greenhouses, as well as recent land movements made for their construction in the hillsides may have impacted meadow's health through a reduction in water transparency or nutrient excess. Siltation is not detected, following stable shoot burial rates detected by Posimed. There is also evidence that illegal trawling also has destroyed the deeper areas of the Granada meadows. In the Alboran sea, the meadow depth limits are also naturally shallower (Table 2.1).

2.1.3. *Meadows in recovery*

Two stations were established which seemed to be recolonizing, both at intermediate depths in Roquetas. One was the intermediate station RO.I, neighboring several trawling marks (around 150 m away from disturbed stations RO.I-E and RO.I-B). We assumed a recovery dynamics for this meadow from its low cover and density, together with its great proportion of horizontal (colonizing) shoots. The vertical shoots found were very young and short. In contrast, the other recolonizing station (RO.I-R) consisted on *P. oceanica* patches interspersed in the bare sediment of the RO.I-E station (i.e. the trawling mark), and extremely long vertical shoots revealed that these patches probably consisted in plants having survived trawling and subsequent siltation, and have re-emerged to the surface (Table 2.1).

2.1.4. *Sampling small seagrass meadows*

In the action A2 design, it was planned to characterize Blue Carbon stocks and fluxes of the small seagrass meadows occurring in 3 natural parks (El Estrecho, Cadiz Bay and Odiel Bay), and to study uniquely their variation with depth and among species (*Cymodocea nodosa*, *Zostera marina* and *Z. noltei*). Once in the field, it was found that *Z. marina* presented an extremely low spatial cover in these natural parks, so its presence is to be considered negligible and relict. The meadows of El Estrecho and Odiel Natural Parks could not be sampled due to the severe weather conditions that occurred during the field surveys. To compensate for this, a *C. nodosa* meadow was studied in the province of Almería. Due to the small depth range of distribution of *C. nodosa* meadows, the study of the stocks and fluxes in this species along a depth gradient was not feasible at any site (Table 2.1).

Cymodocea nodosa meadows were studied in 5 sites presenting an interesting diversity of environmental settings:

Palomares, in the the North-Eastern Almerian coast (Mediterranean sea), at 9 and 12 m depth (PA.I station)

El Alquian, in Almeria Bay (Eastern Alboran sea), 7 m depth (BA.S station and the unvegetated adjacent station of BA.S-C)

The Roquetas barrier reef lagoon, in Almeria bay (Eastern Alboran sea), at 1 m depth (station RO.S-CN)

The shallow dead mat colonized by *C. nodosa* at Calaburras (Málaga, Western Alboran sea, station CA.S-CN)

The shallow subtidal area of the Santibáñez lagoon (Cádiz, Atlantic sea, 0.5-1 m depth, station SA.CN).

The carbon associated to *Zostera noltei* sink was studied in Santibáñez bay, in the high (SA.ZN-S station) and low (SA.ZN-D) intertidal areas, as well as in a low intertidal area which has experienced intensive clam harvesting and cultivation activities until 2 decades ago. These activities are still present but to a much lesser extent (SA.ZN-C station, Table 2.1).

2.1.5. *Additional sampling: Caulerpa prolifera meadow*

At the Santibañez lagoon (Cádiz), a *C. prolifera* meadow was studied in order to compare its carbon stocks and fluxes with those of adjacent *C. nodosa* meadow. As *C. prolifera* and *C. nodosa* often compete for space and come one after the other in a typical ecological succession, it was considered relevant to compare their carbon stocks and fluxes, in case they could be discriminated.

2.1.6. *Other carbon compartments*

The vast majority of the Blue Carbon in seagrass meadows accumulates in their sediments (>98%; Mateo et al., 1997; Mateo and Serrano 2012; Duarte et al., 2005; Lo Iacono et al., 2008). Nevertheless, the IPCC protocols for carbon sinks and emissions always recommend including the evaluation of the carbon pool sequestered in the plant living standing stocks (both above and belowground). To keep up with this standard, at each selected station we sampled a minimum of 3 replicate cores (18 to 590 cm long) and 3 replicate biomass samples (within 20 x 20 cm quadrats, up to 2 cm thick down the sediment). As for *P. oceanica* meadows, we also collected 6-9 longest possible vertical shoots, in order to reconstruct their vertical growth and production over the last decade (results not included in this report).

2.2. Laboratory analyses

2.2.1. *Sub-sampling, parameters and analyses on sediment cores*

Two out of three cores per station were subsampled in the field, at 6 to 8 levels, through 3-cm holes pre-made along the cores, at 5-10 cm intervals for the top samples and 25 for the bottom ones. The third core was brought to the laboratory, where it was cut open longitudinally. One hemicore was subsampled in 1 to 2 cm-thick slices, which were dried at 50ºC and subsequently weighted (for full details on subsampling procedures see LIFE BN, 2017 Deliverable A2). The other hemicore was kept as a back up and to perform other determinations in the future.

Each dry-weighted subsample was disaggregated and sieved through a 2 mm-mesh sieve. Coarse Organic matter (COM), coarse shells and stones and gravel were separated and weighted. Part of the COM was used for radiocarbon dating (see below). The sediment fraction below 2 mm plus the COM were the ones included in chemical analyses.

In one core per station, the accretion rates of the sediment for recent times (<100 years) were estimated in the top 30 cm, using the ^{210}Pb technique. The rest of the core was dated at one or two levels selected between the top 50 cm and the bottom.

Total Organic Matter (TOM) was measured in all the sediment subsamples, from 0 to 30 cm core depth, and in every other sample thereafter. Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC) were measured on at most 12 subsamples, evenly selected along the core (See Fig. 2.4).

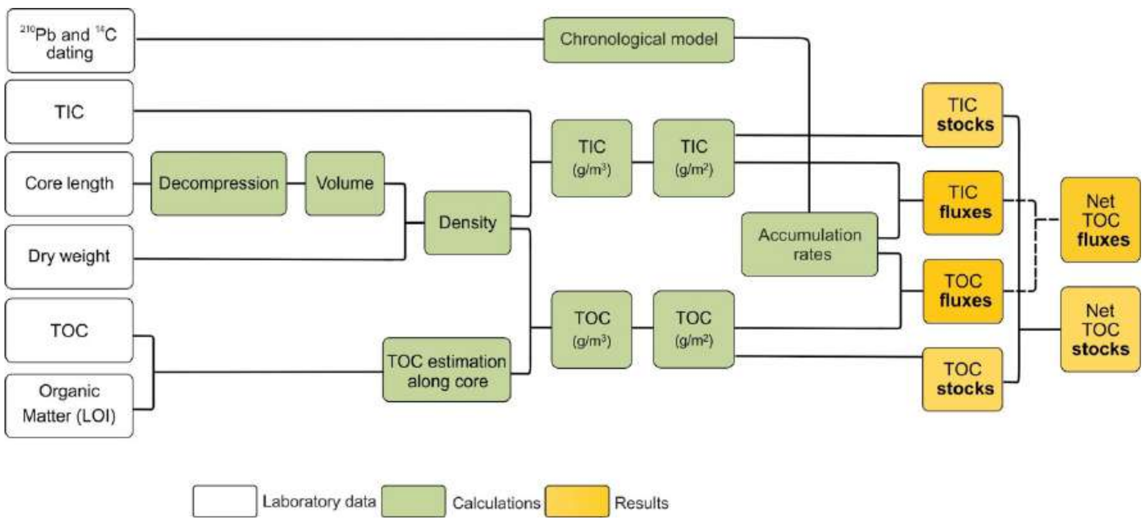


Fig. 2.4. Flow chart of the of GAME laboratory works leading to estimate net organic carbon accumulation in blue carbon ecosystems.

a. *Geochemical and biomass analysis*

A 3-4 g fine (< 2mm) sediment aliquot was digested with 35 % H_2O_2 in order to remove Sediment Organic Matter (SOM), then dried and sieved through a 1 mm, and analyzed in a laser difraction particle analyzer (Mastersizer 2000) to obtain the grain size distribution for small fractions: <0,063 mm (silt and clay), 0,063-0,25 (fine sand), 0,25-0,5 (medium sand), 0,5-1 (coarse sand). TOM was determined as the weight lost in another aliquot of ca. 3g sediment sample, combusted at 450ºC during 5 hours (see Annex C1-C2_ analysis protocols.docx for more details). In 10 to 12 subsamples per core, around 1 g of sediment (< 2mm) was digested by adding HCl 1M until cessation of bubbling. The digestate was centrifuged and rinsed with MQ-water until pH 7 before drying at 50ºC. Weight difference before and after the digestion plus the weight of the shells > 2mm was assumed to be the carbonate content. From this, TIC was calculated. Accuracy and precision were monitored using a certified carbonate standard (SETOC 776 from WEPAL). The digested sediment aliquot was used to measure Total Organic Carbon (TOC) at the IATC-CSIC center in Granada, using a mass-spectrometer and a IRMS (Isotopes Ratio Mass Spectrometer) for subsequent isotopic analysis.

The 3 biomass replicates for each station were washed and sorted into necromass (largely leaf litter) and biomass (leaves, rhizomes and roots). Those fractions were dried and weighed.

b. *Lead (^{210}Pb) and radiocarbon (^{14}C) dating*

From the 30 first cm from each replicates A core (cores subsampled in full at each station), aliquots of 5 g of ground sediment samples were sent to the Unit of Physics of Radiations from the Autonomous University of Barcelona (UAB) to estimate recent sediment accretion rates from ^{210}Pb in excess, through measurement of its daughter element 210Pb. In the same core, we selected 2-3 ancient plant debris (preferably leaf rests) for carbon dating. Carbon datings were performed by accelerator mass spectrometry (DirectAMS - Accium BioSciences), using a NEC Pelletron 500 kV AMS. See Annex C1-C2_ analysis protocols.docx for more details.

2.3. Numerical procedures

2.3.1. *Corrections for core compression*

A decompression factor was applied to all cores presenting less than 30 % compression. The factor was obtained using a simple exponential function ($y=ab^x$) under the assumption that compression is maximum in the top and minimum in the bottom of the core. The function is fitted between two points, (y1, x1) and (y2, x2), being y1 the length of the core minus the penetration depth of the corer, x1=y1; y2 is set to 0.1 and x2 is again the penetration depth of the corer. The resulting equation is then used to calculate a correction factor where 'x' is the observed depth. Then: the corrected (or decompressed) sample depth is the observed depth minus the correction factor. Cores with compressions between 30-40 % were decompressed as the above but using 1 for y2 instead of 0.1. Those cores with a compression exceeding 40 % were decompressed following a linear model ($y=mx+b$), that is, considering a constant compression across the core.

It is relevant to mention that the volume of the subsamples (slices) taken from the cores was calculated after the mathematical core decompression. For the cores subsampled in the field through pre-made holes, the volume taken in the field was corrected applying the % volume increase that would have experienced the slice aligned at the level were each hole was located.

2.3.2. *Estimating TOC from TOM*

Because it is well established that TOM and TOC in seagrass sediments are highly correlated (r^2 = 0.96; p<0.001; Fourqurean et al., 2012), OC analysis were only performed on some of the samples allowing us to fit a linear regression and infer the remaining samples using the equation obtained (R^2 = 0.7 to 0.97; p < 0.001; Table 2.2.).

Table 2.2. TOM and TOC% on each station.[1]TOC estimated with equations from Fourqurean et al. (2012), [2]Organic matter content below methodological measuring limit

Station	Total amount of samples	Samples analyzed for TOC	Equation	R^2
TE.S	43	22	y = 0.5457x - 0.2926	0.76
TE.I	52	23	y = 0.925x - 0.4112	0.84
TE.I-C	85	15	y = 0.8911x - 0.218	0.54
TE.D	19	15	y = 9.0694x + 0.8984	0.84
DE.I	174	36	y = 0.5558x - 0.3616	0.77
PA.I	64	12	y = 0.3844x - 0.1662	0.65
AG.S	138	14	y = 0.7914x - 0.1639	0.95
AG.I	65	14	y = 0.7194x - 0.7841	0.77
AG.D	29	16	y = 0.9653x - 1.6649	0.72
BA.S	51	39	y = 0.1888x + 0.0006	0.55
RO.S	56	28	y = 0.5418x + 0.3866	0.94
RO.S-C	174	35	y = 0.6406x + 0.3795	0.75
RO.S-CN	30	8	y = 0.0774x + 0.1678	0.60
RO.I	23	11	y = 0.3372x + 0.9933	0.97
RO.I-B	53	26	y = 0.7846x - 0.7021	0.7
RO.I-E	25	10	y = 0.4237x + 0.0991	0.78
RO.I-R[1]	35	12	y = 0.4313x + 0.8599	0.64
RO.I-Shall[1]				
AL.S	11	33	y = 0.3933x + 0.0526	0.87
ME.S	30	19	y = 0.5173x - 0.1535	0.88
ME.I-C[2]				
CA.S-CN	27	12	y = 0.9308x - 1.5383	0.95
CA.S-C	33	16	y = 0.6462x - 0.6339	0.95
SA.ZN-S	29	12	y = 0.3219x - 0.3164	0.72
SA.ZN-D	56	23	y = 0.2606x - 0.0121	0.91
SA.ZN-C	64	21	y = 0.3193x - 0.1661	0.82
SA.CN	56	17	y = 0.0947x + 0.2487	0.69
SA.CP	30	13	y = 0.389x - 0.3682	0.70

Organic carbon stocks per unit area - The TOC density in each subsample was calculated from the sample bulk density (D) and TOC content: *TOC density (g/m³) =D*(TOC%/100)*. This value was then multiplied by the area of the subsample (½ of the corer cross section) to express the stock per square area (cm^2, m^2, ha, etc.). The total stock per core was computed by adding the value of all subsamples and normalizing 1 m core thickness (this is the most common thickness used by the Blue Carbon community for inter-study comparative purposes). For those cores subsampled in the field (i.e, those for which only a few subsamples were taken along the core through the premade holes), the TOC of each subsample was used as representative of a proportional length of core around it.

2.3.3. *Chronological models, accretion, stocks and fluxes*

c. Chronological models

Replicates A for each station were used to calculate the TOC flux to the sediment (i.e., the rates of organic carbon sequestration). Radiocarbon ages were used primarily for the models and were combined with the ^{210}Pb technique to fine tune the chronology of the sediments for the last 100 years. The models were elaborated using the "rbacon" package for R software (Blaauw and Christen, 2011). The age of the top most subsample of the core (the year of sampling: 2016 or 2017), was also considered in the model. Radiocarbon dates are expressed as calibrated years before present (marine curve 13; Reimer et al., 2013). Dates were corrected for isotopic fractionation ($^{13}C/^{14}C$), for the reservoir effect and for the local anomaly ($\Delta R=2 \pm 26$ years, Siani et al. 2000).

d. Accretion rates

The rhythm at which the sediment is accreted in the meadow was calculated as the length of core accreted per year.

Stocks were calculated as the average carbon content of the 3 replicates normalized to 1 m core thickness. The long-term carbon fluxes into the sink were estimated by multiplying the carbon content of each sample by its accretion rate. The fluxes have been estimated for the whole core and for the last 100 years. The sequestration rates for any specific period of time (in a context of e.g., the elaboration of compensation projects) can be easily calculated by multiplying the average of the accretion rates for the desired period of years.

2.3.4. *Upscaling: from areal to global estimates*

During the course of Action A1 (Cartography and characterization of habitats), a very complete cartography has been compiled integrating a number of sources and observations taken during the multiple surveys conducted in this project (AMAyA; see further). GIS software allowed us to obtain the total areas covered by the various seagrass typologies for which the areal carbon stocks and fluxes have been calculated in this study (Table 2.2).

Global estimates were therefore calculated by multiplying the representative organic carbon stocks and fluxes of each typology by the area occupied by that typology. A detailed description and discussion of the distribution of these global estimates is out of the scope of this deliverable.

First discussions on board the R/V García del Cid during a LIFE BN mission. October 2017 Source: GAME

3. Results and Discussion

Discussing LIFE Blue Natura results on a global context at the EU Parliament, Brussels. November 2018 Source: IUCN

3. Results and Discussion

The assessment of the organic carbon stocks and sequestration rates made for coastal soils in this study represents the most detailed study performed on seagrass Blue Carbon in the European Union and probably in any other region of the world.

From Almería to Cádiz, over 120 linear meters of coastal soils (88 cores), from 10 sites and 32 stations ranging from 1 to 20 m depth, bearing or not a vegetation cover, have been scrutinized visually, physically and chemically.

As grand summary, the average stock accumulated in the top meter of seagrass soils in Andalusia amounts to 139.6 tCO_2/ha, ranging from 18.6 to 4051 tCO_2/ha (*Z. noltei,* Cádiz Bay to *P. oceanica* in healthy conditions below 15m of depth, respectively; table 3.1, Fig. 3.1). This stock has been accumulating at an average rate of 1.3 tCO_2/ha yr, ranging from 0.1 to 3.1 tCO_2/ha yr (for small seagrasses to *P. oceanica* in healthy conditions, respectively). Scaling up this numbers by assigning the corresponding stocks and fluxes obtained in the field to the total area occupied by each bottom type (table 3.3), the weighted total stocks and fluxes for Andalusian seagrasses are of 13,085.4 $ktCO_2$ and 14,384.1 tCO_2/yr, respectively.

Therefore, the suspected (hypothesized) gradients associated to species specificities, geographic setting, depth, sea bottom type, and state of degradation of the meadows, used as criteria for the sampling design, have proved to be correct and were ranked in their degree of importance as "substrate" (hard vs soft bottom) = "species" *(Zostera noltei* < *Cymodocea nodosa* < *Posidonia oceanica*) > "degradation" (healthy vs degraded) > "depth" (1 m vs 20 m). The effect of geographical location could not be assessed overall as not all of the species were present in each one of the regions of Andalusia. Nevertheless, *P. oceanica*, meadows to the west of Roquetas de Mar (Almeria bay), seemed to have half the carbon stocks than those to the east. As for *C. nodosa*, we found the greatest carbon stock in the lagoon of Santibañez (Atlantic), double the ones measured in open sea meadows, both in the Mediterranean and in Alboran Sea.

A gigantic number of uncertainties and difficulties still prevail, most notably i) the need of knowing the thickness of both the living and dead mats, ii) the always limited mapping effort, ii) the need to delimit the possible role of carbonates as a source of CO_2, iii) the corrections that should be made for meadow cover, iv) the dynamic condition of the sink (growing vs steady-state), v) the complexity of determining the loss of service following meadow death or

Table 3.1. Bathymetric distribution of the rocky bottoms bearing *Posidonia oceanica* (ha)

Type of bottom	Surface covered in rock at each bathymetric range (ha)						
	0-5	5-10	10-15	15-20	20-25	25-30	Total
Dead matt	3.21	2.66	0.50		0.70	0.05	
Posidonia oceanica	79.37	543.35	718.41	494.9	294.77	28.29	
P. oceanica mixed bottom		0	6.21	35	1.67		
P.oceanica in regression		0.23	7.66	6.48	19.93	8.41	
P. oceanica and *Cymodocea nodosa*	5.83	15.51	9.6	15.79	0.59		
Totals	88.41	561.75	742.38	552.17	317.66	36.75	**2299.12**

habitat destruction or vi) the very high cost of monitoring changes in the sink, to mention some. Nevertheless, the various typologies assessed here, constitute an important step forward in providing the grounds for establishing sound criteria for meadow management and for deciding the best settings to guarantee the success of eventual compensation projects, both in restoration and in emissions avoidance initiatives.

These and other matters are discussed in more detail below.

3.1. Main geochemical variables estimated

For each station bulk density, sediment accretion rate, total organic matter, total organic carbon, total organic carbon flux, total inorganic carbon, total inorganic carbon flux and granulometric distribution, were characterized and plotted against depth and age (see Annex III). Examples representative of the main typologies and sampling techniques are shown and briefly discussed below, as differences among stations would be further discussed on following sections. Full results for the rest of stations are given as an annex at the end of this report.

On a well develop meadow it was expected to find a decrease on TOM and TOC along the core that could be adjusted to an exponential curve, according to a fast degradation on the topmost part of the core and slower below it. However, from the 88 cores we only found this pattern in 6 of them (BA.S_A, DE.I_C, SA.ZN.S_A, RO.S-C19, RO.I-R_A, and TE.I), all from different typologies and health status. On TE.S, well preserved shallow *P. oceanica* meadow (Fig 3.1), we can see a curve-fitting trend until 200 cal. yr BP, below where, TOM and TOC content is irregular. This is due to the intrinsic variability of the meadows, as an exponential decay curve would require high stability on the organic matter input (i.e, plant production). Fluxes reach its maximum on the top most layers, as fresh, non degraded matter is present. TIC distribution seems to reflect the fine fractions content (Fig. 3.1). The increase in fine

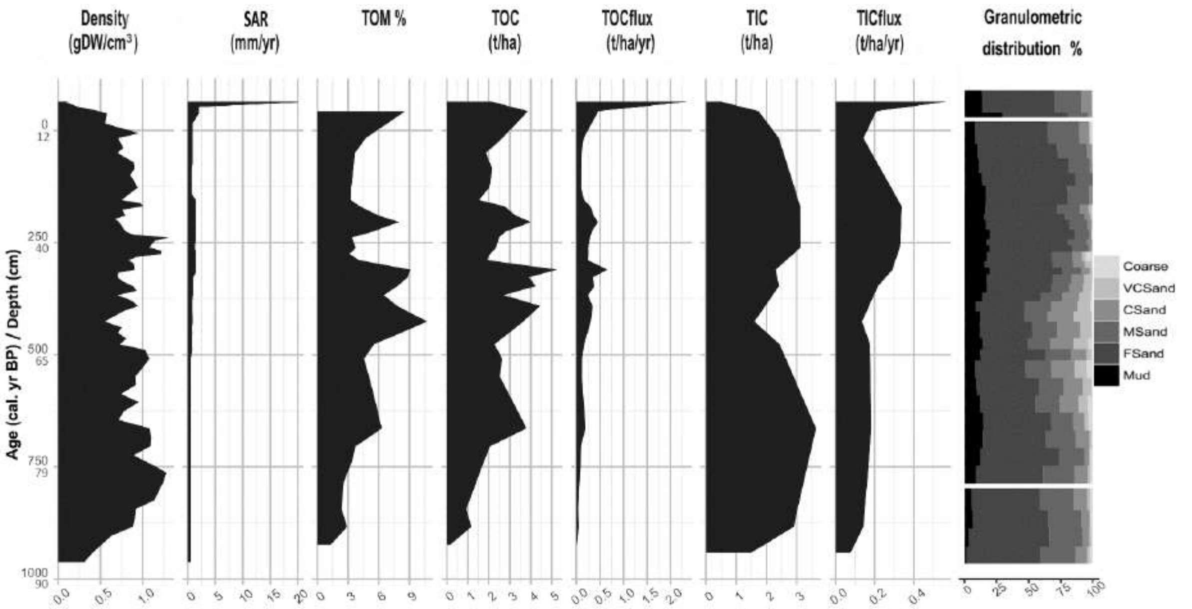


Fig 3.1. Age and depth distribution on TE.S_A core (manual core from a healthy, shallow, *P. oceanica* meadow) of soil density, sediment accretion rate, total organic matter, total organic carbon, total organic carbon flux, total inorganic carbon, total inorganic carbon flux and grain size distribution (coarse, >2mm; very coarse sands, 1-2 mm; coarse sands, 1-0.5 mm; medium sands, 0.5-0.25; fine sands, 0.25-0.063; and mud, <0.063mm).

fractions grain size on the last 500 yr could also alter the degradation pattern of TOM on the meadow, as more fine sediments decrease the porosity and hinder the penetration of oxygen. The sediment accretion rate (SAR) is very high compared to those of deeper meadows (Fig. 3.2, TE.D, well preserved deep *P. oceanica* meadow), as proximity to the continent would imply a higher inorganic input that would stimulate the accretion of the mat.

On the deep meadow (Fig. 3.2) a lower TOM content on the topmost 50 cm (≈ 500 yr), seems to coincide with a higher percentage of fine fractions that would point to more turbidity of the water column, low light penetration and, as a result of this, a lower plant productivity and carbon burial. Light penetration becomes more important as a production factor with depth, as it determines the depth limit for seagrass settlement (Duarte 1991). Density and SAR are very stable, while TIC decreased with depth.

An example of chemically degraded *P. oceanica* meadow is station DE.I (Fig 3.3). Density and SAR followed similar trends than the two examples above. The main change in carbon stocks occurs below the top meter (>1000 cal. yr BP), 950 yr before the start of the chemical disturbance in 1961. It would be expected that a chemical degradation would not affect only the soil being formed at the moment of the perturbation but also to the extant soil. A more specific study would be needed to clarify the causes and consequences of this degradation but comparison between this and healthy stations is discussed on following sections.

Soil density reached its minimum on the topmost layers of the dead mat (Fig. 3.4). The average carbon flux values calculated for the last 100 yr correspond to the performance of the meadow before dying, as core analysis does not allow calculating instantaneous fluxes, but an average over a period, depending on the resolution on sediment accretion rates and sub-sampling frequency. This provides valuable information, as we can follow the degradation pattern that ended up with a loss of the sequestration capacity of 56% in the period after 1961, as compared to the previous period, with a steady decline of 3.4 kg TOC/ha yr. Granulometric distribution seemed to follow cyclical changes that may reflect ecosystem variability.

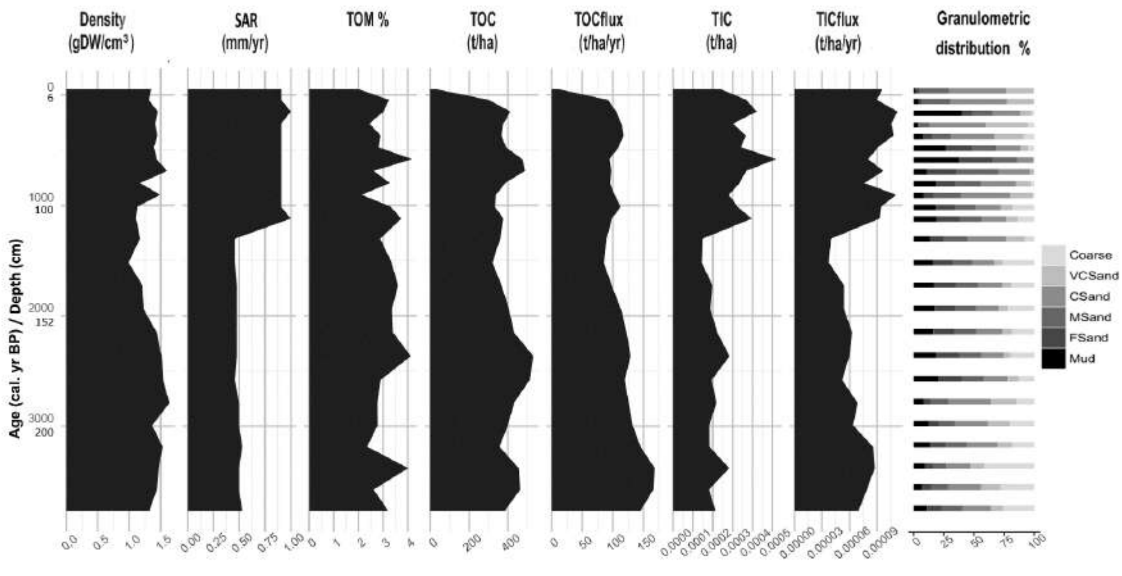


Fig 3.2. Age and depth distribution on TE.D_C core (vibrocore from a healthy, deep, *P. oceanica* meadow). Acronymes as Fig 3.1.

Cymodocea nodosa does show the expected decay curve (Fig. 3.5), suggesting (as also supported by other variables), a considerable stability over the years.

Zostera noltei (Fig 3.6), also showed maximum values of TOM and TOC on the upper layers, very likely influenced by the presence of the living plant, as *Z. nolteii* tissues are much more labile than *P. oceanica* and are not well preserved in the soil.

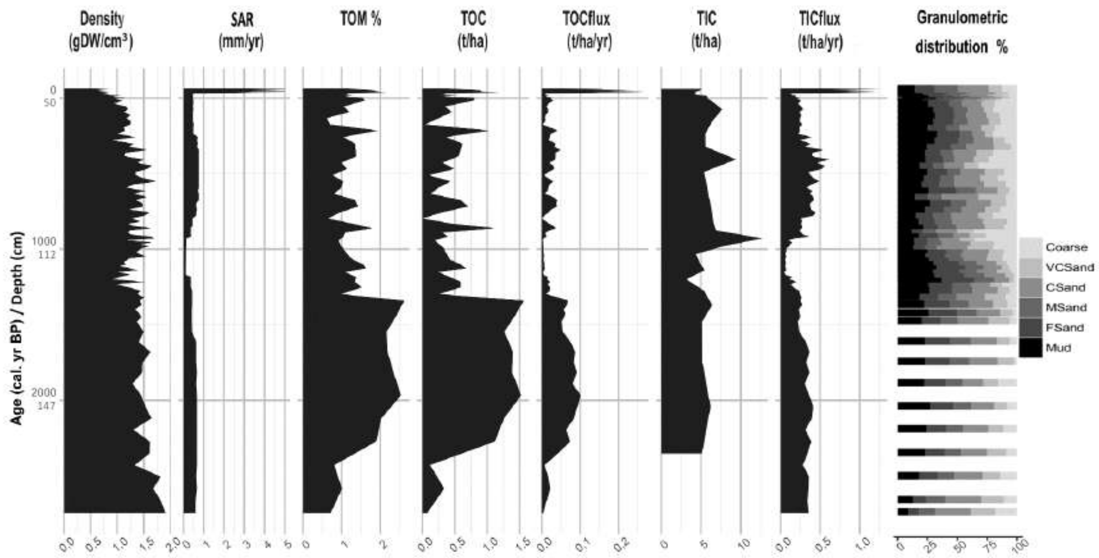


Figure 3.3. Age and depth distribution on DE.I_A core (manual core from a degraded, intermediate, *P. oceanica* meadow) Acronymes as Fig 3.1.

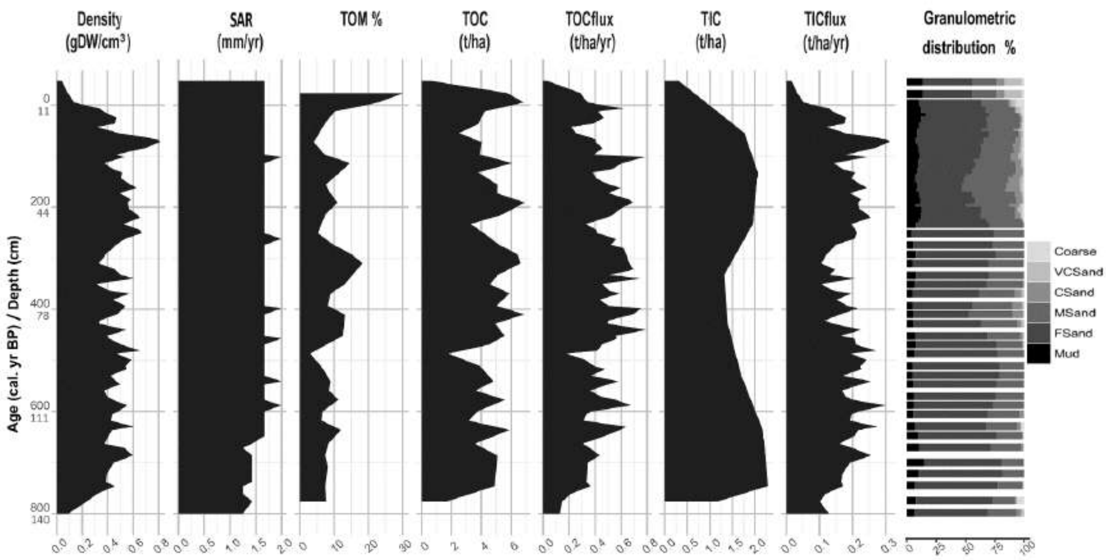


Figure 3.4. Age and depth distribution on RO.S-C19 core (manual core from a dead, shallow, *P. oceanica* meadow). Acronymes as Fig 3.1.

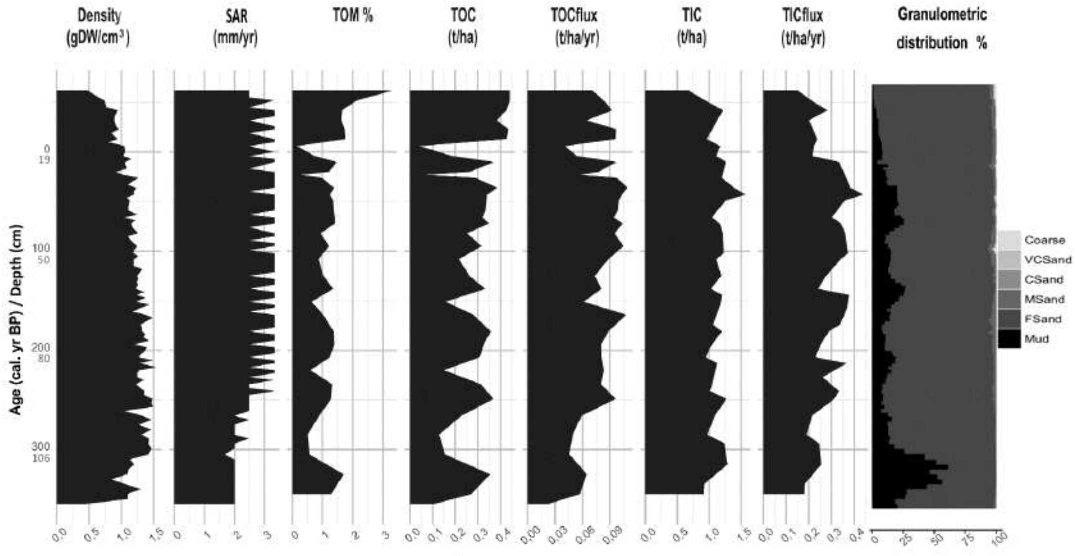


Figure 3.5.: age and depth distribution on BA.S_A core (manual core from a healthy, intermediate, *C. nodosa* meadow). Acronymes as Fig 3.1.

It is relevant to remind here that carbon stocks were estimated in full for the longest cores of each station and in a smaller number of sub-samples for the other 2 replicates. Estimates were also normalized to 1 m of sediment thickness. The latter estimate was provided in order to allow for comparisons among meadows (within this study and to other studies).

For carbon fluxes, we estimated the average flux for all core sections (long-term flux) as well as for the sections corresponding to the last 100 years of sediment accretion (medium-term average). This latter estimation fulfils two objectives: 1) make comparisons among meadows, and 2) this carbon flux includes the total carbon being deposited in the meadow sediment, without taking into account the medium-term degradation (i.e. less than 100 years). Once organic matter is buried, aerobic and anaerobic degradation continues to transform it into CO_2. In the “fresh” organic matter there is a fraction of labile organic matter which is readily mineralized. There is also (or it is formed during the diagenetic process) a fraction of more recalcitrant organic matter that will last much longer within the sediment. As aerobic degradation is usually many times faster than anaerobic degradation (Fenchel et al., 1998), the oxidation of the organic matter will depend on the sediment accretion rate and the depth reach of the oxygen within the sediment (which depends on hydrodynamism, water oxygen concentration and sediment porosity, among other factors).

Carbon fluxes estimated for the last century were higher than averages calculated with the whole sediment core (see Annex II), because the average carbon flux for the last 100 years is much more influenced by the carbon-rich top sediment sections. Even though part of this carbon flux estimation will not nurture millenary carbon stocks, it still may be relevant for certain carbon offset projects, as it will be discussed in section 3.6.

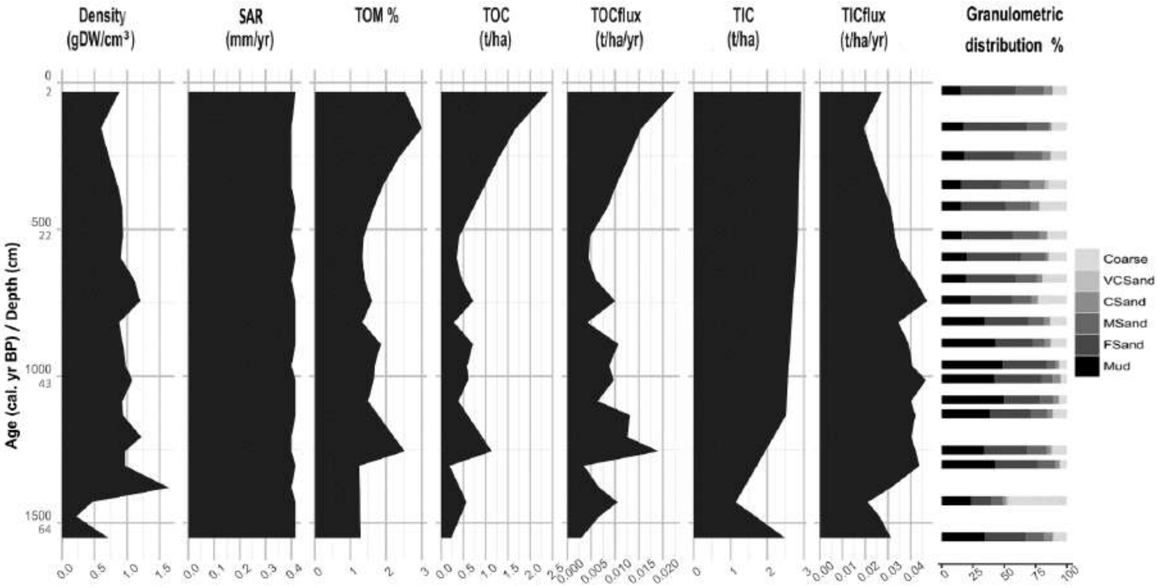


Figure 3.6: age and depth distribution on SA.ZN-S_A core (manual core from a healthy, intertidal, Z. noltii meadow). Acronymes as Fig 3.1.

3.1.1. ***Overall comparisons –***

The overall variation of the carbon stocks in the top sediment meter of Andalusian seagrasses was very large, as much as two orders of magnitude (Fig. 3.7). The station showing the highest carbon stocks at 1 m was the *P. oceanica* deep meadow of Terreros (18-20 m, Almeria, TE.D), with more than 1,838 tTOC/ha, although with a very high standard deviation, of 1,681 tTOC/ha). The lowest sediment carbon stock was found in RO.S-CN station, a sand-sediment

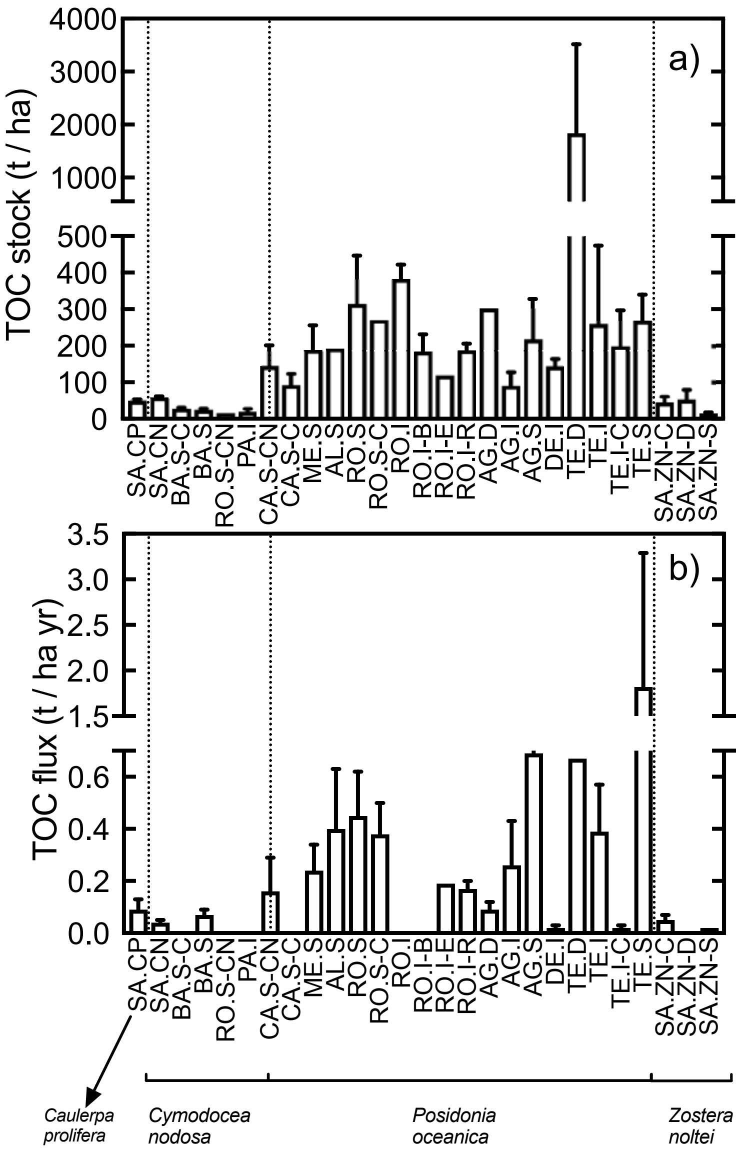


Fig. 3.7. a) carbon stocks (tTOC/ha) accumulated in the first sediment meter in all the seagrass stations; b) Average carbon flux (tTOC/ha yr) in the last century.

colonized by *C. nodosa*, inside the Roquetas barrier-reef lagoon, with a carbon stock (based on just 1 core) of 16.1 tTOC/ha.

The average carbon stock in healthy *P. oceanica* meadows was of 497 ± 296 tTOC/ha (standard error) in the Mediterranean sea (eastern Andalusia), while in the Alborán sea (western Andalusia), the average carbon stocks in *P. oceanica* meadows was of 277 ± 55 tTOC/ha. As for *C. nodosa*, carbon stocks in Alborán and Mediterranean seas were similar (23 ± 5 tTOC/ha and 20 ± 6 tTOC/ha, respectively), while at the Santibáñez lagoon (Cadiz), the carbon stock under *C. nodosa* meadow was twice as high (59 ± 2 tTOC/ha) as in the Alboran and Mediterranean open sea.

Carbon fluxes in Andalusian seagrasses in the last century also varied two orders of magnitude (Fig. 3.7). The station with the highest C fluxes in the last century was the shallow areas of the Terreros meadow, at 5.5 m depth (1.82 ± 1.47 tTOC/ha yr), while the station showing the lowest C flux was the degraded meadow of Villaricos-Deretil at 16 m depth (0.02 ± 0.01 tPOC/ha).

3.1.2. ***Variability among species –***

Three different species were sampled on this project, as representative of the diversity of Andalusian meadows: *Posidonia oceanica*, *Cymodocea nodosa* and *Zostera noltei* (additionally, a *Caulerpa taxifolia* core was taken in Santibañez Bay for comparison purposes). *Posidonia oceanica* is a big slow growing seagrass, the two others being small, fast growing species. *Zostera noltei* was only sampled in de Santibáñez bay and *P. oceanica* along the Andalusian coast but not on the Santibáñez bay, where is was not present (Fig. 3.8), while *C. nodosa* was present on both systems. Consequently, *C. nodosa* and *Z. noltei* were compared on the Santibañez bay system. The best stations to discuss differences in accumulation between *P. oceanica* and *C. nodosa* were those from Almeria bay, where we found both species in very developed and differentiated meadows. Direct comparison between *P. oceanica* and *Z. noltei* were not possible, but the data from both species will be discussed using *C. nodosa* as a standard for the comparison.

Posidonia oceanica TOC in the top meter of sediment holds an average of 309 tTOC/ha, one order of magnitude more than the small seagrass *C. nodosa* (22 to 59 tTOC/ha) and the even smaller *Z. noltei* (38 tTOC/ha). The stock under the sediments of the seaweed *C. prolifera* was comparable to that of the smallest seagrass (50 tTOC/ha, Fig. 3.7). The only *C. nodosa* meadow growing on a *P. oceanica* dead mat showed carbon stocks comparable to those of *P. oceanica* meadows (Calaburras), but similar to those of the dead mat just colonized with algae, which indicates that the presence of *C. nodosa* would not add a differential effect in the stocks as compared with algae. However, in a context where the recolonizabion by *P. oceanica* is so slow, it does not invalidate the possible convenience of restoring the damaged habitat with smaller, faster growing seagrass species that could act as a 'lid' for the extant stock, by reducing erosion. Once the substrate was stabilized and the adequate conditions for the larger seagrass re-established, then a natural succession of recolonization might begin.

Over the last century, *P. oceanica* meadows accumulated organic carbon in their sediments 6 times faster than *C. nodosa*, and 13, 15 and 6 times faster than *C. nodosa*, *Z. noltei* and *C. prolifera* growing in Santibáñez lagoon, respectively (Fig. 3.7). The small seagrass species and *C. prolifera* had comparable carbon stocks and fluxes among them.

Posidonia oceanica TOC stocks and fluxes measured in Andalusia were within the range measured in other Mediterranean *P. oceanica* meadows (i.e. 47 to 755 tTOC/ha in Ibiza and Formentera islands, and 0.2 to 1.9 tTOC/ha yr in Portlligat and Formentera islands, respectively; Mateo et al., 1997; Serrano et al., 2012, 2014).

Carbon stocks and fluxes recorded for *P. oceanica* meadows did not show a marked pattern with depth. In Terreros and Aguamarga meadows, carbon stocks did not seem to change substantially between shallow and intermediate meadows (5 and 10-12 m depth) but seemed to increase in the deep meadows. Carbon flux in shallow meadows are greater than in deep meadows at both sites, while intermediate-depth meadows show intermediate carbon fluxes (Aguamarga) or similar to those observed in the deep meadow (Fig. 3.8).

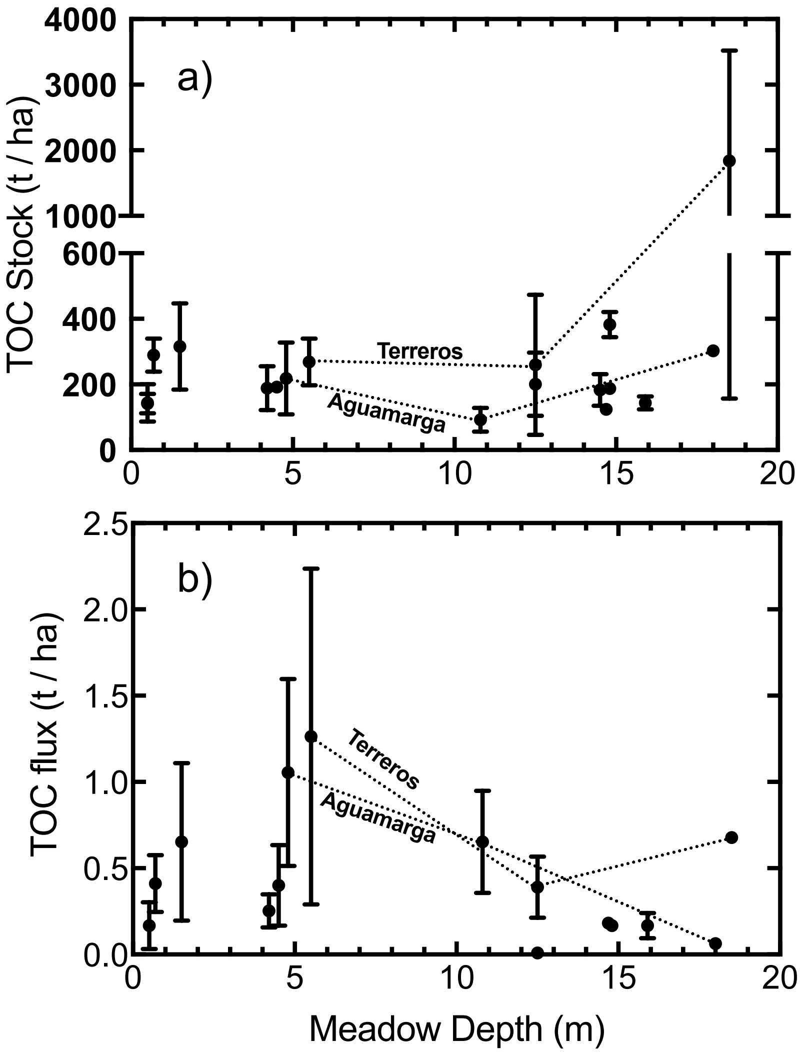
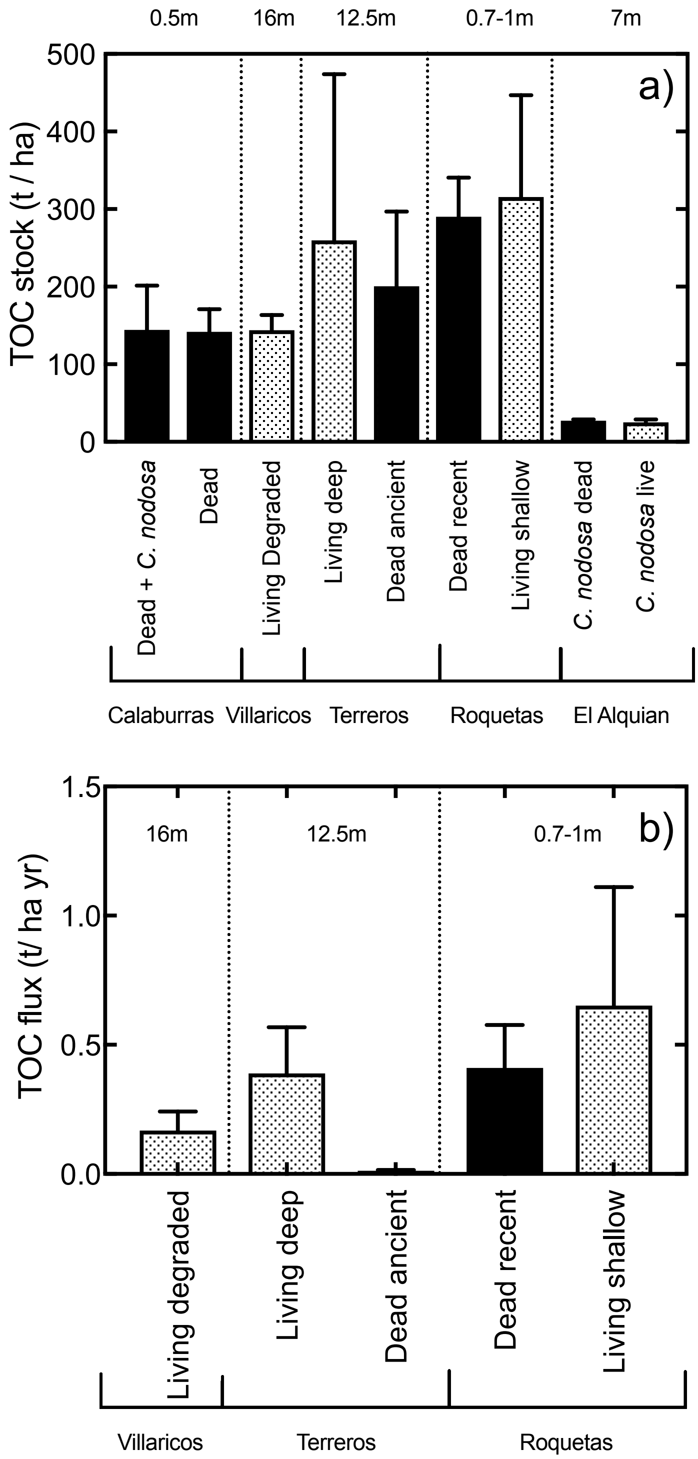


Figure 3.8. Carbon a) stocks and b) fluxes variability along a depth gradient in Andalusian meadows.



F

Figure 3.9. a) Differences in stocks between dead and living mat in different sites. b) Differences in carbon flux between living mat and dead mat.

Differences observed in carbon stocks and fluxes with depth are most probably and mainly related to differences in sedimentation and productivity, and therefore, in overall accretion rates. Factors explaining higher sedimentation and accretion rates on shallow meadows are: (1) higher input of terrestrial material due to the proximity to the continent, and (2) higher

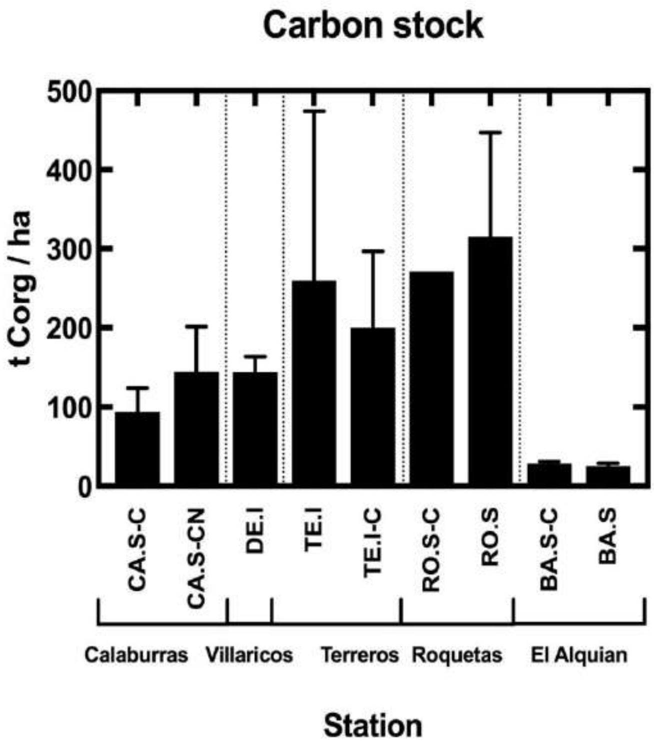


Figure 3.10. Variability of the carbon stock in the first meter sediment at the different stations of intermediate depth meadow of Roquetas, in an area affected by trawling.

production (due to higher light availability) and higher and denser canopies, which would act as more efficient sediment traps (van Katwijk et al., 2010). The higher sediment inputs would dilute the percentage of carbon accumulated, resulting in a lower carbon concentration and thus, lower TOC stock at shallow areas than at deep ones. In contrast, in deep meadows, TOC is denser (i.e. implying higher carbon stocks at equal sediment thickness), therefore, carbon stocks at both depths would result from slow inorganic sedimentation, combined with long-term burial, rather than from higher sink capacity.

Several authors have found evidences supporting that deep meadows are older than shallow ones (Boudouresque et al., 2016). Therefore, we may expect deep meadows to have accumulated greater C stocks (especially if we consider more than 1-m of sediment thickness), despite being less intensive carbon sinks at present.

e. Variability with substrate type and granulometry –

Carbon sequestration is not a direct effect of grain size, although both can be influenced by seagrass production. Grain size has been shown to influence carbon accumulation through preventing or facilitating organic matter remineralization (Keil & Hedges 1993, Burdige 2007), and also of seagrass canopy density being linked to grain size sorting (van Katwijk et al., 2010).

The regression models of the 6 granulometric fractions defined with TOM along cores (Table 3.2) were not cosntant among sites and stations. Santibáñez bay showed the highest covariance between grain size and TOM. Among the three species found, *C. prolifera* is the most dependent on grain size, as it positively covariates with mud content (R^2 = 0.84) and negatively with coarser fractions (R^2 between 0.76 and 0.25). *Cymodocea nodosa* shows a similar pattern, but co-varying positively with mud and fine sands (R^2 = 0.71 and 0.55, respectively) and negatively with coarse sand and gravel (R^2 = 0.44 and 0.32). Both sediment cores below *Z. noltei* plants varied positively with fine sand (R^2 = 0.26 and 0.33, for the high and low intertidal meadow, respectively). The high intertidal meadow (SA.ZN-S) also varied positively with sediment mud content (R^2 = 0.39). Grain size seem to be the main driver of *C. prolifera* organic matter accumulation. This could be explained by its physiology, as an algae, *C. prolifera* lacks roots or any other buried organ that could directly modify or interact with soil. In contrast, both *C. nodosa* and *Z. noltei*, have roots and rhizomes that can stay buried as organic matter when the plant dies, interacting with soil bacteria, and pump O_2 into the soil while alive, what prevents sulfide formation (Borum et al., 2006), thus influencing sediment organic matter mineralization.

Among *P. oceanica* stations, just in AG.S (R^2 = 0.31), RO.I (R^2 = 0.33) and TE.D (R^2 = 0.27) TOM covaried positively with mud content (Table 3.2). The lack of a consistent pattern across stations suggests that grain size becomes more important when other factors that influence carbon accumulation are absent. This is consistent with previous results found by Serrano et al. (2016), where grain size was correlated with carbon preservation on small seagrass meadows and unvegetated sediments, but not in large meadows.

Table 3.2. Correlation coefficients of TOM-particle sorting linear regression. Positive correlation is in green while negative in red. R^2 < 0.25, letter colored; 0.25-0.5 light color; > 0.5 dark color.

	R^2 linear regresion (TOM-particle sorting)					
	Mud	Fine sand	Medium sand	Coarse sand	Coarse	Gravel
AG.S	0.31	0.21	0	0.2	0.13	0.06
AG.I	0.12	0.18	0.09	0.01	0.01	0
AG.D	0.15	0.02	0	0.01	0.04	0.06
AL.S	0.13	0.03	0.03	0.01	0.25	0.33
SA.ZN.S	0.11	0.26	0.09	0	0	0
SA.ZN.D	0.39	0.33	0	0.15	0.05	0.2
SA.ZN.C	0.02	0.02	0.17	0	0.04	0
SA.CN	0.71	0.55	0.01	0.44	0.16	0.32
SA.CP	0.84	0.53	0.76	0.76	0.25	0.55
BA.S	0.04	0.03	0.06	0	0	0.01
CA.S	0	0	0	0	0.01	0.01
DE.I	0.2	0.11	0.08	0.01	0.2	0.16
ME.S	0	0.02	0.09	0.01	0.02	0.1
ME.I-C	0.23	0.13	0.01	0.14	0.2	0.02
PA.I	0.05	0.04	0.01	0.01	0	0
PA	0.68	0.68	0.25	0.09	0	0
RO.S	0.12	0	0.03	0	0.01	0
RO.CN	0.07	0.28	0.13	0.18	0.23	0.29
RO.S-C	0.04	0.04	0	0	0.25	0
RO.I	0.33	0.09	0.18	0.28	0.31	0.01
TE.S	0.18	0.09	0.13	0.08	0.19	0.02
TE.I	0.18	0.05	0	0	0	0
TE.D	0.27	0.24	0.02	0.46	0.34	0.14

Our results show that determining a cause-effect relation is not straightforward. Granulometric information helps understanding geochemical processes, which play a key role in carbon accumulation, and hence in better informed management measures (when choosing or trying to improve a BC ‘friendly’ habitat).

3.1.3. *Conservation status and meadow dynamics, presence/absence of the habitat*

Comparisons of carbon stocks (for 1 m sediment) between *P. oceanica* meadows and their adjacent areas where the living plant has disappeared show very slight but consistent reductions in carbon stocks (Fig. 3.7.). This pattern was observed at both, intermediate (Terreros) and shallow depths (Roquetas barrier reef). The carbon stock of the Villaricos dead mat (DE.I, at 16 m depth) was only slightly lower than in the neighbor dead mat of Terreros (TE.I-C)

In contrast, no differences in carbon stocks were detected between El Alquián *C. nodosa* meadow (TE.S) and its adjacent sand patch (‘Control core’; TE.S-C). TE.S_C cores revealed that the sand patch had been occupied by a *C. nodosa* meadow in the recent past (Fig. 3.7.).

The very shallow, ancient dead mat of Calaburras (Málaga) showed lower carbon stocks in 1-m sediment thickness when compared with its Almerian counterpart, the Roquetas dead mat (RO.S-C, Fig. 3.7.). The dead mat colonized with *C. nodosa* (CA.S-CN) showed slightly higher carbon stocks than the dead mat colonized only by algae (CA.S-C, Fig. 3.3).

In turn, in the intermediate meadow of Roquetas, an area affected by sea-bottom illegal trawling, the carbon stock at the trawl mark was 69 % lower than in the intermediate meadow, 100 - 150 meter apart (Fig. 3.8.). In the border of the trawling mark, the carbon stock was 52 % lower, the same as in *P. oceanica* recolonization patches inside the trawling mark (51 % less carbon per unit surface, Fig. 3.8.).

These results suggest that carbon stock is slightly affected when the seagrass meadow is degraded by factors other than erosion. However, when meadow disappears due to mechanical erosion of the sea-bottom, the sediment carbon stocks is significantly more intensively reduced.

Regenerating or increasing carbon fluxes and stocks:

The areas where highest carbon burial rates take place, are shallow *P. oceanica* meadows. Projects sustainably increasing sediment carbon fluxes and stocks, through replanting or reducing coastal erosion, for example, would generate more carbon credits in shallow meadows.

3.1.4. *Advancing the upscaling of the estimates: from areal to regional*

The upscaling of the areal results to global estimates is not a primary goal for this report but given that a substantial amount of the results from A1 are becoming available at this very moment, it was considered useful to make a first attempt at providing global numbers of carbon stocks and fluxes for the main gradients established at the regional level. Refinements will follow in forthcoming deliverables during 2019.

Table 3.3. Area and global CO_2 stocks and fluxes. SE: Standard error of the mean.

Type of bottom	Depth (m)	Area (ha)	tCO_2/ha	se	tCO_2/ ha yr	se	$ktCO_2$/ Andal.	$tTCO_2$/ Andal. yr
P. oceanica stable	<5	183.2	866.5	126.3	2.7	0.3	158.8	495.1
	5-10	706.2	814.4	94.6	3.1	0.4	575.2	2188.6
	10-15	841.1	906.7	259.7	2.2	0.4	762.6	1813.0
	15-20	658.2	4051.0	2396.2	1.4	1.6	2666.2	896.7
	>20	665.3	4051.0	2396.2	1.4	1.6	2694.9	906.3
C. nodosa stable (open sea)	<5	48.4	79.6	9.5	0.1	0.2	3.9	7.1
	5-10	897.6	79.6	9.5	0.1	0.2	71.5	131.8
	10-15	1560.4	79.6	9.5	0.1	0.2	124.3	229.1
	15-20	989.6	79.6	9.5	0.1	0.2	78.8	145.3
	>20	356.2	79.6	9.5	0.1	0.2	28.4	52.3
C. nodosa semi-enclosed	0.1	249.6	104.2	14.8	0.1	0.0	26.0	33.2
C. nodosa and *Z. noltei*	<5	0.3	91.9	12.2	0.1	0.1	0.0	0.0
P. oceanica regression	<5	2.2	632.6	308.6	1.7	0.5	1.4	3.6
	5-10	48.1	594.5	272.4	1.9	0.5	28.6	91.8
	10-15	170.0	661.9	416.1	0.7	0.4	112.5	113.6
	15-20	61.0	2957.2	2761.0	0.4	0.6	180.5	25.8
	>20	287.7	2957.2	2761.0	0.4	0.6	850.7	121.5
P. oceanica and *C. nodosa*	<5	70.7	866.5	126.3	2.7	0.3	61.3	191.1
	5-10	94.2	814.4	94.6	3.1	0.4	76.7	292.0
	10-15	410.7	906.7	259.7	2.2	0.4	372.4	885.4
	15-20	280.4	4051.0	2396.2	1.4	1.6	1136.0	382.1
	>20	36.3	4051.0	2396.2	1.4	1.6	147.2	49.5
P. oceanica, C. nodosa and *Zostera spp.*	<5	1.7	866.5	126.3	2.7	0.3	1.5	4.6
	5-10	35.2	814.4	94.6	3.1	0.4	28.7	109.1
	10-15	19.5	906.7	259.7	2.2	0.4	17.7	42.0
P. oceanica and *Caulerpa cylindracea*	10-15	1.4	4051.0	2396.2	1.4	1.6	5.7	1.9
	15-20	40.8	4051.0	2396.2	1.4	1.6	165.3	55.6
P. oceanica mixed bottom	5-10	7.9	814.4	94.6	3.1	0.4	6.5	24.6
	10-15	21.1	906.7	259.7	2.2	0.4	19.1	45.4
	15-20	26.8	4051.0	2396.2	1.4	1.6	108.6	36.5
	>20	1.0	4051.0	2396.2	1.4	1.6	3.9	1.3
P. oceanica dead mat	<5	3.8	1064.4	107.4	1.1	2.6	4.1	4.1
	5-10	15.6	900.0	230.4	0.6	1.3	14.0	8.6
	10-15	51.2	735.6	353.4	0.0	0.0	37.6	1.9
	15-20	24.6	900.0	230.4	0.6	1.3	22.1	13.5
	>20	29.0	900.0	230.4	0.6	1.3	26.1	15.9
P. oceanica on rock	<5 to >20	2299.2	1069.0	1054.6	2.1	0.9	2457.7	4911.8
C. nodosa on dead mat	<5	0.1	1224.0	394.2	1.2	2.6	0.1	0.1
Z. noltei stable (semi-enclosed)	<5	473.7	18.6	8.4	0.1	0.1	8.8	52.2
Zostera marina stable	<5	0.1	18.6	8.4	0.1	0.1	0.0	0.0
	10-15	1.2	18.6	8.4	0.1	0.1	0.0	0.1
Total / Mean		11671.2	**1393.6**	736.2	**1.3**	0.7	**13085.4**	**14384.1**

Once the tCO_2 stocks and sequestration rates per unit surface have been calculated for the various meadow typologies, the next step is assigning to each one of those typologies the area they represent in the Andalusian coasts. These kind of estimates are key as they set reference values for the natural resource/ecological service under study, that are the basis for establishing management plans or for assigning them an instrumental value. In this case, the value of a ton of CO_2 is well defined in the regular carbon markets (EU Emissions Trading System - EU ETS) or in the voluntary markets (Ullman et al., 2013).

As an example, if a rate of meadow loss has been determined, then the global economic loss in terms of CO_2 not captured or emitted can also be estimated. Reciprocally, if a compensation project reduces that rate or stops it, the stocks and sequestration capacity that have been saved could be certified as carbon credits and the potential global benefit of conservation actions could be estimated.

The task of upscaling discrete field observations to a large area of ecosystem is hampered by a number of challenges. On the one hand, delimiting the total area the values from a core (or 3 replicates) is representative of, is particularly complicated. The simple fact that seagrass meadows are largely subtidal, makes it impractical the use of aerial imagery techniques. So if even determining the presence of the seagrass is already complicated, characterizing limits or transitions between typologies is almost impossible. Only direct expert observations (in SCUBA or ROV technology) can provide reliable information. Owing to the slow and costly nature of such observations, they are always very limited.

Fortunately, the large experience and knowledge accumulated by the AMAyA team through the various projects they have led on Andalusian seagrasses, and the monitoring programs funded by the Andalusian Autonomous Government, helped to significantly overcome this limitation. This expertise has led to the elaboration of a series of GIS layers compiling and integrating all the cartographic information on sea bottoms available for the Andalusian coasts (see Action A1 deliverables). This integration of the mapping efforts yields a total area occupied by seagrass meadows of 11,539.9 ha (not including dead mat areas) and distinguishes all 4 seagrass species growing on different sea bottoms and in the 3 status of conservation: normal (= stable, healthy), in regression, and dead mat (Table 3.3.).

3.1.5. *Distribution, areal stocks and fluxes*

Cymodocea nodosa and *P. oceanica* in stable status occupy similar areas as monospecific meadows, but they can also be found sharing a meadow together, with algae, or with *Zostera spp.* The area occupied by *P. oceanica* in regression or dead (dead mat), adds up 742.9 ha, representing about 15% of the monospecific stable *P. oceanica* meadows. To be noted are the 939.8 ha occupied by mixed meadows of *P. oceanica* and *C. nodosa.*

The small species *Z. noltei* is fundamentally found in semi-confined environments (bays and saltmarsh channels) adding up 473.7 ha.

It is already known that *Z. marina* is actually a relict species in the Mediterranean (Pergent et al., 2014), clearly reflected by the low area occupied (1.3 ha). The impact of this species in the global stocks and fluxes is therefore negligible.

Stocks - As hypothesized, the largests stocks of carbon were those associated to *P. oceanica*, with an average maximum of 4,051 tCO_2/ha recorded for meadows growing below 15 m of depth. This value has been assigned to all those types of bottom at that depth bearing *P. oceanica* (as it is hypothesized that the main stock is that stored by *P. oceanica* irrespectively of the other kind of vegetation or feature on the shared area). The stock held by *P. oceanica* dead mats was 2.5 times (42%) lower than in stable living *P. oceanica* meadows, revealing an important feature with key implications for emissions compensation projects (see later). This decrease in the stocks is to be attributed to erosion of the sink. Whether the 42% eroded is emitted back to the atmosphere as CO_2 in full or partially, is a matter of current intense research (using molecular tracers; Duarte and Krause-Jensen, 2017).

Deciding on a value for the stocks accumulated under meadows growing on a rocky substrate, is controversial. The identification of this type of bottom is only possible when rocks are directly visible under the vegetation. Whether there is rock or not under the sediments (and at which depth is it) can only be assessed by probing the bottom manually or using high resolution surface seismics (Lo Iacono et al., 2008; Monnier et al. 2016). This is a gigantic endeavor that was absolutey out of the scope of this project. As an approximation, following expert observations, in this report the meadows on rocky bottoms have been assigned ½ of the stock of the meadows growing in soft bottom (i.e., 50 cm; let us keep in mind the stock values in this report are given for the top meter of sediment).

In summary, the sea bottom presenting *P. oceanica* adds up 6,969 ha, most of it (5,353 ha) belonging to monospecific stable *P. oceanica* meadows, and 33% growing on rocky substrate. This result is an important one to take into account when it comes to decide where to plan restoration interventions or to quantify extant stocks susceptible of protection.

As expected, the small seagrasses *C. nodosa* and *Z. nolteii* accumulated 30 times less than *P. oceanica* (i.e., 3% of that by *P. oceanica*). The reason is well known: *P. oceanica* belowground organs represent a massive entry of organic matter ‘by default’ that becomes rapidly buried in anoxic conditions. Moreover, its molecular composition includes highly recalcitrant carbon fractions (Kaal et al., 2016l). This combination of factors leads to an unusually massive burial of carbon. In the small seagrasses most of their belowground material decomposes within the year. It, therefore, becomes obvious that when planning restoration or protection plans with seagrass meadows, the choice should *P. oceanica* (see later).

Fluxes - Again, the large *P. oceanica* presented much higher average carbon sequestration rates than the smaller ones (2.2 vs 0.1 tCO_2/ha yr; 17 times higher; 5.8 % of the large seagrass).

Table 3.4. Areal stocks and fluxes determined for some special types of *P. oceanica* meadow. n/a, not available. SE, Standard Error. *Chemical disturbance from Deretil effluents, before and after 1961.

Special types	Depth (m)	Area (ha)	tCO_2/ ha	SE	tCO_2/ha yr	SE	$ktCO_2$/ Andal.	tCO_2/ Andal.yr
P. oceanica recolonization	14.5	n/a	187.4	18.4	0.17	0.03	-	-
P. oceanica siltation trawling	14.0	n/a	183.5	47.8	0.02	0.01	-	-
P. oceanica eroded trawling	14.5	n/a	118.6	n/a	0.18	0.02	-	-
P. oceanica degraded chemically Pre-disturbance*	15.0	0	-	-	0.69	n/a	-	-
P. oceanica degraded chemically Present *	15.0	40	143.9	13.9	0.51	n/a	5756	20.4

In *P. oceanica* maximum fluxes were recorded at intermediate depths (5-10m), what is consistent with a preference by the species of well illuminated areas but with a moderate hydrodynamism (Infantes et al., 2009).

Posidonia oceanica dead mat 'historical' sequestration rates were 4 times lower than stable *P. oceanica* meadows. Strictly, a dead mat does not accumulate carbon, it simply represents a stock. The fact that the calculated rates are clearly lower, may be indicating that the faster sequestration rates of the overlying layers of mat are not computing in the calculation because they have been eroded, hence resulting in lower overall rates. A lower illumination in deeper areas of the meadow would explain the decline in the sequestration rates of *P. oceanica* from shallow to deeper areas (3.0 to 1.4 tCO_2/ha yr; 2 times higher in shallow areas).

3.1.6. *Global stocks and sequestration rates for Andalusia*

The upscaling for the entire Andalusia reveals valuable and unedited information. Combining abundance, stocks and fluxes, the largest stocks of *P. oceanica* occur at intermediate to deep areas of the meadow (15-20 m), adding up 13,1 $MtCO_2$. A faster plant growth in shallower areas results in a 'dilution effect' of the carbon stock in a thicker portion of mat, resulting in an overall lower carbon density. The smaller seagrasses contribution to that total stock is only 0.34 $MtCO_2$, representing 2.5 % of the total. In other words, *C. nodosa* and *Zostera* spp. represent an almost negligible contribution to the Andalusian Blue Carbon.

Global entries to the long-term sink in Andalusian seagrass meadows were higher at shallower areas in both of the dominant species. In *P. oceanica* the global carbon sequestration rates were found to be around 2 times higher at shallow-intermediate than at the deeper areas of the meadow (2000.8 vs 901.5 tCO_2/yr), as a consequence of the also higher overall productivity and sedimentation rates of the system in that areas. The value for *P. oceanica* growing on rock stands out (Table 3.4.). As explained somewhere else, a 50 cm-thick mat has been assigned to this type of bottom. It has been considered that this assumption is conservative because it may account for many patches of *P. oceanica* growing in rocky areas that do present a well developed mat underneath and for the small mat of variable thickness observed for patches growing directly on rock.

The same depth gradient was observed for the small seagrass *C. nodosa.* Maxima of sequestration rates were observed at intermediate to shallow areas of the meadows being about 1.8 faster in capturing organic carbon than deeper areas. Once again, the contribution of the small Andalusian seagrasses to the total flux of organic carbon the long-term sink was very small, of about 4.5 % of the total.

3.2. Implications of these results for carbon offsetting projects and other project actions

LIFE Blue Natura is an Andalusian Blue Carbon 'accounting effort' pursuing the implementation of BC initiatives in the carbon markets in the form of conservation (emissions avoided) and restoration (reforestation) projects. In the recent agreements reached in Paris, the Parties committed to 'conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gasses'. The article refers to another specific article (4.1, d) of the UNFCCC referring to the natural carbon sinks 'biomass, forests, and oceans, as well as other terrestrial, coastal and marine ecosystems'.

The reason why seagrass meadows, saltmarshes and mangroves exhibit a notorious incomplete status at the national inventories is fundamentally the lack of i) sufficiently accurate and extensive quantifications of the carbon stocks and fluxes and ii) the lack of a clear path to monetization and accounting rules.

3.2.1. *Quality estimates: basis for an efficient implementation of Blue Carbon initiatives*

It is therefore pertinent to remind here that the main goal of this study is to provide numbers of stocks and fluxes of organic carbon associated to the sink of Andalusian seagrass meadows to serve as the basis for the elaboration of i) an economical valorization of the Blue Carbon in Andalusia (Deliverable C3 - IUCN), ii) elaboration of the Certification Andalusian Standard for conservation projects of seagrass meadows (Deliverable C4 - CMAOT), iii) elaboration of a manual for the certification of Blue Carbon projects derived from conservation and restoration actions on seagrass meadows (Deliverable C5 - IUCN), iv) dialog and elaboration of carbon compensation projects for the conservation and restoration of seagrass meadows (Deliverable C6 - IUCN), and v) elaboration of a catalogue of conservation projects for *Posidonia oceanica* (Deliverable C7 - CMAOT).

3.2.2. *A 'big push' by the Andalusian Government*

In October 8th this year, the Andalusian Parliament approved the Law for Climate Change with unprecedented additions. In its Title V (Emissions mitigation), Chapter 1 (Objectives and measures for the mitigation of emissions), the Article 37, Item 2 says: 'It will be considered as carbon emissions offset projects, all those dealing with afforestation, reforestation, restoration, and conservation of the extant forests and wooded lands, littoral ecosystems, those dealing with the conservation or restoration of wetlands, seagrass meadows and analogous areas'. This parliamentary initiative opens the door for seagrass meadows to be object for conservation and restoration projects in that autonomous community.

3.2.3. *News from the European Parliament*

The 27th November this year, the European Parliament Intergroup on 'Climate Change, Biodiversity, and Sustainable Development, organized the session 'Blue Carbon in EU Policy'. During this session, the results of LIFE Blue Natura were shown demonstrating that the conservation and restoration of EU Blue Carbon ecosystems could be economically sustainable, given the large stocks they accumulate (7.7 GtCO_2/EU BC; Blue Carbon in EU Climate Policy, 27 November 2018). The Members of the Parliament hosting the event acknowledged that, "The role of Blue Carbon is a key in reducing emissions and supporting climate action, as we are now discussing about implementing the Paris Agreement and the Paris rulebook. According to the MEP, legislation is a driving force and we have the responsibility to move from reflection to action, including Blue carbon in the EU climate agenda. Destroying ecosystems contributes to the release of CO_2 they absorbed for years or centuries. Although the role of blue carbon ecosystems is well recognized by scientists, a gap analysis is needed to identify research and financial needs, as well as to identify priorities and the way to transfer knowledge across sectors. With reference to the latter, the Life Blue Natura project serves as an example to examine the missing knowledge, moreover as a pilot to transfer the experience to the wider region. There is a need to improving the dialogue within the EU, to jointly find solutions and share good practices. At the European level, the Mediterranean region offers plenty of best practices". Maria Spyrakis (MEP).

The conclusions made direct references to the project LIFE Blue Natura, as aN example to follow at the EU level, on how to clear the path for implementation of BC initiatives.

3.2.4. *Stock vs sequestration rate*

The results of this project confirm the widely recognized higher importance of seagrass stocks with respect to the sequestration rates. Andalusian seagrass ecosystems have been burying organic carbon since at least 4,400 years (maximum carbon age recorded within the cores obtained in Life Blue Natura).

Stocks - The values for the stocks reported correspond to the top meter of soil. Considering that the thickness of the mat under seagrass canopies in the region, i.e., that containing organic carbon, can extend for several meters, the figures above could be several fold higher, so the ones presented can be taken as conservative estimates. As mentioned somewhere else, emission compensation projects can be based on emissions avoidance or on additional carbon capture. In the first instance, a major and hot issue is determining how much of that stock can be lost following habitat degradation or destruction, as this stock would be the one susceptible to be monetized in the markets (see below). Experimenting or modeling this rate of loss is a complex endeavor and completely out of the scope of this project, where implementation actions are the focus. However, the sampling was designed with the idea of providing some indicative numbers. On the one hand, the highly degraded *P. oceanica* meadows (chemical degradation) accumulated 27% ± 16 % less organic carbon than the reference ones (1,021.6 ± 84.2 vs 753.2 ± 165.9 tCO_2/ha, Villaricos vs Terreros and shallow Roquetas). On the other hand, *P. oceanica* dead mat soils present a 40% lower areal stock than living, non-degraded meadows (900 vs 2,076 tCO_2/ha; Table 3.4). Finally, from the area impacted by trawling that was sampled in Roquetas in this study (mechanical degradation), it was directly observed that the erosion of an average of 50 cm of mat resulted in a direct loss of around 734 tCO_2/ha. Moreover, the top meter of the bottom of the eroded meadow, presented a 3.5 times lower stock than the adjacent unimpacted meadow, confirming that the organic-richer top portion of the mat had been removed.

Flux - The annual amount of CO_2 captured and derived to the long-term carbon sink in seagrasses is not of a high quantitative and, therefore, economical relevance. As shown above, the carbon sequestration annual rate is only of 0.1-3.1 tCO_2/ha yr. As a reference, an ongoing restoration and conservation project involving 117 ha of mangroves in Kenya is yielding around 26 tCO_2/ha annually with a total price in the voluntary markets of 12,500 USD (after factoring in a 30% risk buffer). This project does not account for the carbon stored in the sediments, only that stocked annually in the wood. A simple comparison clearly evidences that the economic potential of restoring seagrass meadows shall rely more on its effect in protecting the carbon stock than in the annual rate of CO_2 sequestration.

3.2.5. *Regular and voluntary carbon markets*

In 1992, the Declaration of Rio set out as a prime objective to stabilize GHG atmospheric concentrations under levels dangerous for climate. In its article 4.2., the 190 signing countries committed to limit their anthropogenic GHG emissions and to protect and enhance their GHG sinks and reservoirs. In 1997, the UNFCCC adopted the Kyoto Protocol, which established an international cap and trade system and regular offset markets, where legally bound entities could compensate their (temporarily irreducible) excess GHG emissions by purchasing other country's unused emission permissions, or certified carbon emission reductions contemplated by the protocol. In 2005, the first voluntary carbon markets appeared where people, companies, organizations, and governments not legally obliged by the Kyoto protocol could compensate their carbon footprint by purchasing carbon offsets generated by emission reductions not included in the Kyoto Protocol.

Voluntary markets have developed rules and procedures, including official project registries and standard methodologies to estimate measure and verify net carbon emissions reductions generated by projects, and to translate them to carbon offsets. Project developers can then issue and transact these offsets directly to end buyers, who can claim the emissions reductions as their own if they retire and remove the offsets from circulation. Intermediary retailers or brokers can also resell or charge a fee for finding end buyers.

All voluntary standards require that offsets be real, measurable and verifiable by an independent third-party, and prove that those emissions reductions would not occur without those project activities (additionality). Many projects also have additional positive impacts on sustainable economy, known as “co-benefits”, (local job training and creation, safeguarding environmental services and biodiversity). In many cases, co-benefits are one of the main reasons that suppliers and many buyers are engaged in voluntary carbon markets, increasing the monetary value of the carbon offsets. In contrast to compliance markets, where offsets typically sell at a relatively consistent price, offset prices on voluntary carbon markets can range widely, from US$ 0.1/tCO_{2e} to just over $ 70/tCO_{2e} ($ 3-$ 6/tCO_{2e}; EMP, 2018, Fig. 3.11.).

Since trading of voluntary carbon offsets first took off in 2008, voluntary carbon projects have helped to reduce, sequester, or avoid over 437.1 MtCO_{2e}. But this is still far away from the total action needed on a global scale. Even with countries’ new pledges under the Paris Agreement, at least an 11,000 MtCO_{2e} emissions reduction gap remains to keep the world from warming above two degrees Celsius (EMP. 2018).

It would be easy to dismiss the climate impact of the voluntary carbon markets as insignificant, in comparison with compliance carbon markets like the EU-ETS, which are still un-accessible

Figure 3.11. Historical Voluntary Carbon Offset Issuances and Retirements (from Hamrick and Gallant 2018).

to most blue carbon projects. But voluntary markets are growing fast. In the last decade, demand for voluntary carbon offsets has grown by over 140-fold, from just 0.3 $MtCO_{2e}$ in 2008 to 42.8 $MtCO_{2e}$ in 2018 (Fig. 3.11). In 2017, issuances (62.7 $MtCO_{2e}$) and retirements (42.8 $MtCO_{2e}$) reached record-highs. Moreover, offsetting projects based on forestry and land use are a growing source of offset issuance and retirement (59% and 49%, respectively, came from these project types in the first trimester of this year; EMP, 2018).

This uptick in 2017 coincides with the Paris Agreement. The signing countries are implementing more and more domestic carbon pricing schemes (like the Spanish Footprint registry and the Andalusian SACE, including voluntary and compliance schemes). Moreover, the Paris Agreement articles 6.2 and 6.4 establish a unit of emissions reductions (called Internationally Transferable Mitigation Outcomes, ITMOs) that could be traded between countries and propose the creation of a centralized, global mechanism to trade ITMOs, to be supervised by an international governing organization. The mechanism may increase the market actors, including companies from new sectors or individuals to purchase and retire offsets on a voluntary and/or compliance basis, in order to enhance demand and supply of emissions reductions ensure that they occur above what countries have promised.

Also in Paris, countries agreed to collaborate in reduction of emissions occurring across borders (and thus not easily accountable to any country), namely from international aviation and shipping, through two United Nations (UN) sector-specific agencies: International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO). ICAO is opening of the international aviation CORSIA market, the first-ever sector-wide cap-and-trade program, which will start in 2021 on a voluntary basis. CORSIA could increase the carbon offset demand in 1.6-3.7 billion tonnes for emissions reductions from 2021-2035. This would dwarf any other operational or planned market, including the European Union's Emissions Trading Scheme and China's cap-and-trade program. Which standards will be eligible in this market is still to be decided. All EU countries will participate in the CORSIA program.

There are still few blue carbon offset projects (mostly on mangroves), and just one on seagrasses. The Ocean Foundation has developed the carbon offset program Seagrass Grow!, which will soon adopt the wetlands blue carbon offset methodology developed by Restore America's Estuaries (RAE), which is undergoing its final revisions under the Verified Carbon Standard (VCS). SeaGrass Grow! has developed a Blue Carbon Offset Calculator which allows to calculate annual individual, family, company or organization carbon dioxide emissions, and then calculates the amount of Blue Carbon habitat restoration required to fully offset those emissions (https://www.oceanfdn.org/calculator). They are also undergoing a number of seagrass restoration programs in USA saltmarshes, mangroves and seagrasses. (http://www.gefblueforests.org/tof-blue-carbon-initiatives/)

About compensation projects - There are several factors hampering the development of seagrass offset projects :

Until recently, there were no standard methodologies available for calculating and verifying the carbon credits generated by seagrass restoration (since 2015, there is an VCS methodology approved), and there is still no standard available just for conservation activities

The techniques for seagrass restoration, specially for seagrass planting, are still not well developed, and their success rate still needs to be improved for the slow growing species *P. oceanica*.

The low seagrass carbon fluxes into the sediments make that the potential carbon emission reductions that can be obtained through increasing seagrass carbon fluxes are limited, and the project scale needed for financial feasibility may be too large and not viable. The greatest potential for carbon offset generation would come therefore from avoiding the erosion of their large sedimentary carbon stocks.

In order to increase their financial feasibility, seagrass restoration carbon offset projects should then ensure that the restoration will help avoiding the destruction of the large carbon stocks. Restoring declining meadows with large mats, and large *P. oceanica* dead mats risking erosion should be a priority. Many of these mats are deep and remain uncharted.

Beyond planting - There has been a good number of low-scale transplantation experiences in *P. oceanica* and *C. nodosa* (see OCEANA, 2010 and references there in). These experiences have allowed defining some good practices, and the effectiveness of reforestation of these species, which is relatively low and expensive in comparison with terrestrial ecosystems. Nevertheless, there are other possible restoration measures that could increase the scale of the restoration project, and thus its cost-effectiveness.

An example would be improving water quality through increasing the efficiency, size or number of water treatment plants, as seagrass health and dynamics is strongly correlated to water quality (e.g., Montefalcone, 2009). This well-established relationship would probably allow developing tier 2 estimates of the carbon credits generated (see Annex V for a description of the Tier concept).

Another effective action in many Mediterranean meadows could be restoring the coastal sedimentation regime, for example through restoring river sediment fluxes using industrial aerial cables to transport the sediments retained in dams. Substituting or improving coastal promenades and other coastal infrastructures in order not to disrupt land-sea sediment inputs and coastal flow, or sustainably managing of beach seagrass litter. Improving sedimentation regime would reduce both meadow and sediment erosion, thus producing direct and indirect positive effects on sediment carbon stocks and sequestration. This well-established relationship would probably allow developing at least tier 2 estimates of the carbon credits generated.

Restoring meadows eroded by illegal trawling and intensive anchoring, should include using passive and active surveillance systems, as well as ecological moorings. These may be cost-effective measures with high impact in ensuring reforestation success and avoidance of sediment stock losses.

Beyond carbon - Given the many important environmental services provided by seagrasses (coastal protection, water transparency, biodiversity, fisheries), it is clear that seagrass carbon offset projects should exploit all these co-benefits in order to obtain higher prices for their carbon offsets in the voluntary markets, in order to improve their financial viability (Herr et al., 2017).

Potential areas for restoration - In Andalusia, following the cartography generated by the A1 action, there are 124.1 ha of dead mat identified, although the undetected area is probably larger, as many dead mats at intermediate and deeper depths remain buried. The cartography also defines 569 ha of *P. oceanica* meadow in regression.

There are also 892.5 ha of *C. nodosa* and *P. oceanica* mixed meadows. Such typologies are most often indicators of *P. oceanica* meadow regression, and thus potential candidates for restoration. There are also 42.2 ha of *P. oceanica* with *Caulerpa cylindracea*, although the presence of this alga only indicates meadow regression when it is intermingled with meadow shoots (not when it is only on the meadow sand patches), and the cartography does not distinguish between both types. Therefore, there are at least 1,627.8 ha candidate for carbon offset projects based on *P. oceanica* meadow restoration, that is, 12% of Andalusian *P. oceanica* meadows.

Nevertheless, given the high carbon stocks and vulnerability detected in the degraded meadows and dead mats of Roquetas and Villaricos, we think that these two areas would be ideal candidates for carbon offset projects. Such projects should consist first in improving water discharge management in the case of Villaricos and the Roquetas shallow barrier-reef. Then, seagrass recolonization could be accelerated through reforestation activities.

In the case of the intermediate meadows of Roquetas, which have been mechanically degraded by trawling, the restoration project should include sediment remediation in the silted borders of the grooves, and enhancing effective protection against illegal trawling in order to completely stop this pressure. Accelerating plant recolonization through reforestation activities could also be convenient, given the slow growth-rate of the species *P. oceanica*.

Coring a *Cymodocea nodosa* meadow in El Alquián, Almería, Spain. Source: GAME

4. Conclusions

4. Conclusions, recommendations and future work

Posidonia oceanica should undisputably be the target seagrass species for any conservation or restoration carbon offset project in Andalusia. It holds 97.4 % of all the CO_2 stored in the sediments of Andalusian segrasses.

The annual input of CO_2 to the sink is 14,384 tCO_2 for all Andalusian segrasses, of which 95.5 % is attributed to *P. oceanica*. In a context of carbon offset projects, this amount is little relevance.

From the above, an overall conclusion is that carbon offset projects in Andalusian seagrasses should focus on the conservation of the millenary stocks of *P. oceanica*, that is to say, on efforts leading to avoid the loss of healthy meadows and on the recovery of meadows in regression.

A sound methodology to determining the CO_2 emissions resulting from the degradation or destruction of seagrass habitat is still lacking. Assuming that a 2 % of annual loss of Andalusian meadows led in the erosion and complete remineralization of the top meter of sediment, the resulting CO_2 emissions would be 261,995 tCO_2 (including the loss of sequestration capacity).

The potential revenues from avoiding that emissions in the regular carbon markets, assuming a price around 20 € /tCO_2, would be about 5,250,000 € / year.

Carbon offset projects based on seagrass meadows should focus on two primary actions: 1. promoting measures to prevent the mechanical destruction of the habitat (anchoring, trawling, siltation) and 2. improving the quality of the waters hosting seagrass meadows (chemical and organic pollution).

The main obstacles to bring the carbon locked by seagrass meadows to the carbon markets are: 1. lack of quality scientific information (mapping, stocks and fluxes quantification, quantification of the real impact of habitat loss in the stock), 2. lack of a sound certification standard and verification method for carbon offset projects, and 3. from the two first, lack of clear policies for the implementation of the Blue Carbon in the national inventories.

Future efforts in action C1 will be in the direction of:

- Developing models of carbon stock and flux change with degradation of the seagrass meadow and with time, in the cases of chemical and/or mechanical degradation. These models will help to estimate carbon credits potential by conservation and restoration projects in a 30 years time horizon.

- Integration of A1 mapping efforts and the present stocks and fluxes estimates, in collaboration with the partner AMAyA. We have made a crude integration of the average stocks and fluxes obtained in the seagrass cartography delivered by A1 action (Figs. 4.1 and 4.2). This integration will be fine-tuned with the assignment of site-specific values and more detailed intra-polated gradient output for the graphics.

In general, future BC research should be directed to remove the barriers cited above: 1. ensuring a good knowledge of the extension of the seagrass meadows habitat and its different characteristics, 2. quantifying the stocks and fluxes of the different types identified. Using aerial imagery where practicable, side scan sonar, high resolution surface seismics, and ground truthing surveys (SCUBA and ROV) would be the necessary fields methods to combine, 3. performing *in situ* or mesocosms experiments to determine the impact of mechanical and chemical degradation of the habitat in the loss of stock, 4. put all the knowledge and methods above to establish effective monitoring programmes and verification methods, 5. with sound knowledge and methods, implementing BC in the national policies will be smoother, 6. advertise the BC resource as an attractive marketable asset among carbon trading companies and emitters, with emphasis in those looking for an added value (voluntary markets).

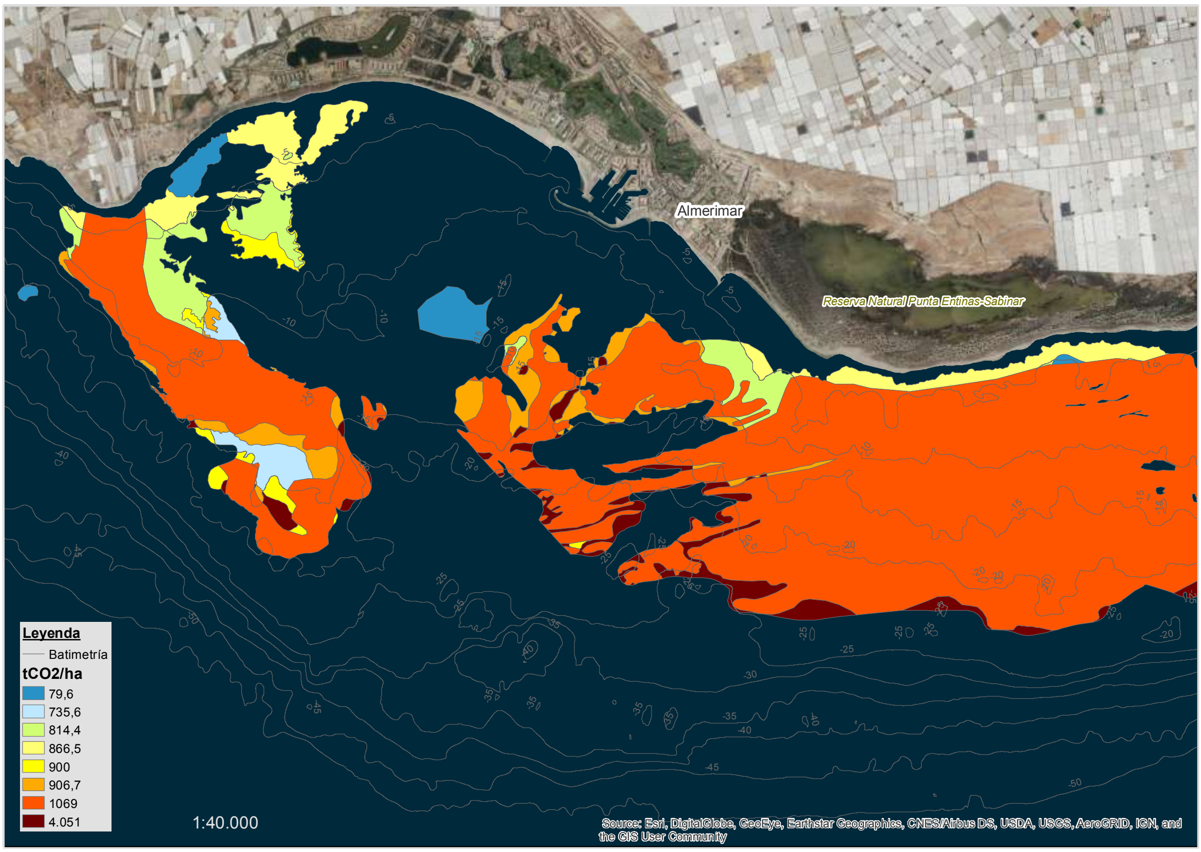


Figure 4.1. Graphic example of the 1.0 combination of the Andalusian seagrass cartography delivered by project action A1 with average carbon stocks (tCO_2/ha) calculated for different depths, bottom types, species, and meadow conditions.

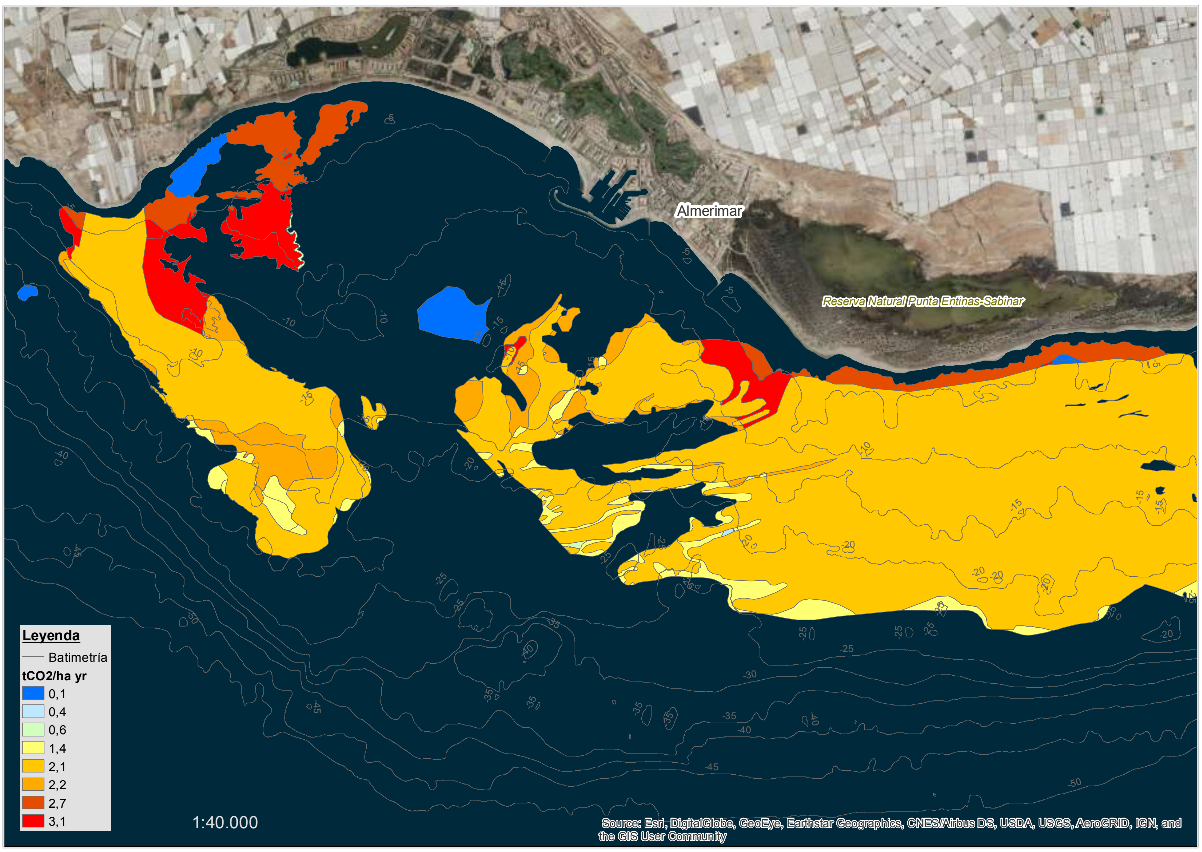


Figure 4.2. Graphic example of the 1.0 combination of the Andalusian seagrass cartography delivered by project action A1 with average carbon fluxes (tCO_2/ha yr) calculated for different depths, substrates, species and meadow conditions.

5. Literature cited

For the sake of simplicity, the literature cited in this report only considers the main works that are key to the various aspects dealt with. The list below is therefore far from being exhaustive.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193. https://doi.org/10.1890/10-1510.1

Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Anal. 6, 457–474.

Borum, J., Pedersen, O., Greve, T. M., Frankovich, T., A. Zieman, J. C., Fourqurean, J.W., Madden, C.J., 2005. The potential role of plant oxygen and sulphide dynamics in die-off events of the tropical seagrass, *Thalassia testudinum*. J. Ecol. 93, 148–158.

Burdige, D.J., 2007. Preservation of organic matter in marine sediments: controls, mechanisms, and an imbalance in sediment organic carbon budgets? Chem. Rev. 107, 467–85. https://doi.org/10.1021/cr050347q

Crooks, S., Orr, M., Emmer, I., von Unger Silvestrum Ben Brown, M., Murdiyarso, D., Jerker Tamelander, C., Luis Valdes, J., Isensee, K., Briggs, C., Bonells, M., Herr, D., Nakamura, T., Grimsditch, G., n.d. Guiding principles for delivering coastal wetland carbon projects Lead authors Advisory body.

Duarte, C., 1991. Seagrass depth limits. Aquat. Bot. 363-377.

Duarte, C.M., Middelburg, J.J., Caraco, N., 2004. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences Discuss. 12, 1–8. https://doi.org/10.5194/bgd-1-659-2004

Duarte, C. M., & Krause-Jensen, D. (2017). Export from seagrass meadows contributes to marine carbon sequestration. Frontiers in Marine Science, 4, 13.

European Parliament Intergroup on “Climate Change, Biodiversity & Sustainable Development” Blue Carbon in EU Climate Policy, 27 November 2018. http://ebcd.org/event/blue-carbon-in-eu-climate-policy/

Fenchel T, King GM, Blackburn H (1998) Bacterial biogeochemistry: The Ecophysiology of Mineral Cycling., 3rd edn. Elsevier Ltd, San Diego

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 5, 505–509. https://doi.org/10.1038/ngeo1477

Hayes, M.A., Jesse, A., Hawke, B., Baldock, J., Tabet, B., Lockington, D., Lovelock, C.E., 2017. Dynamics of sediment carbon stocks across intertidal wetland habitats of Moreton Bay, Australia. Glob. Chang. Biol. 23, 4222–4234. https://doi.org/10.1111/gcb.13722

Herr, D., von Unger, M., Laffoley, D., & McGivern, A. 2017. Pathways for implementation of blue carbon initiatives. Aquatic Conservation: Marine and Freshwater Ecosystems, 27, 116-129.

IPCC 2014, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/wetlands/

Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M., 2014. Coastal Blue Carbon. Conserv. Int. 36, 180.

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., Pidgeon, E., Simpson, S., 2017. Clarifying the role of coastal and marine systems in climate mitigation. Front. Ecol. Environ. 15, 42–50. https://doi.org/10.1002/fee.1451

Infantes, E., Terrados, J., Orfila, A., Cañellas, B., & Álvarez-Ellacuria, A. (2009). Wave energy and the upper depth limit distribution of Posidonia oceanica. Botanica Marina, 52(5), 419-427.

Jiang, Z., Huang, X., Zhang, J., 2013. Effect of nitrate enrichment and salinity reduction on the seagrass Thalassia hemprichii previously grown in low light. J. Exp. Mar. Bio. Ecol. 443, 114–122. https://doi.org/10.1016/j.jembe.2013.02.034

Keil, R.G., Hedges, J.I., 1993. Sorption of organic matter to mineral surfaces and the preservation of organic matter in coastal marine sediments. Chem. Geol. 107, 385–388. https://doi.org/10.1016/0009-2541(93)90215-5

Lavery, P.S., Mateo, M.Á., Serrano, O., Rozaimi, M., 2013. Variability in the Carbon Storage of Seagrass Habitats and Its Implications for Global Estimates of Blue Carbon Ecosystem Service. PLoS One 8. https://doi.org/10.1371/journal.pone.0073748

Lo Iocano, C., Mateo, M.A., Gràcia, E., Guasch, L., Carbonell, R., Serrano, L., Serrano, O., Dañobeitia, J., 2008. Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): Implications for carbon sink estimates. Geophys. Res. Lett. 35, 1–5. https://doi.org/10.1029/2008GL034773

Mason, C.F., Plantinga, A.J., 2013. The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. J. Environ. Econ. Manage. 66, 1–14. https://doi.org/10.1016/J.JEEM.2013.02.003

Mateo, M.A., Romero, J., Pérez, M., Littler, M.M., Littler, D., 1997. Dynamics of Millenary Organic Deposits Resulting from the Growth of the Mediterranean Seagrass *Posidonia oceanica*. *Est. Coast. Shelf. Sci.* 44, 103-110.

Montefalcone, M., 2009. Ecosystem health assessment using the Mediterranean seagrass *Posidonia oceanica*: A review. Ecol. Indic. https://doi.org/10.1016/j.ecolind.2008.09.013

Montefalcone, M., Albertelli, G., Morri, C., Parravicini, V., & Bianchi, C. N. (2009). Legal protection is not enough: Posidonia oceanica meadows in marine protected areas are not healthier than those in unprotected areas of the northwest Mediterranean Sea. Marine Pollution Bulletin, 58(4), 515-519.

Moreno D, Aguilera PA, Castro H. 2001. Assessment of the conservation status of seagrass (*Posidonia oceanica*) meadows: implications for monitoring strategy and the decision-making process. Biological Conservation 102: 325–332.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G., 2009. Blue carbon. A rapid response assessment. United Nations Environment Programme, Grid-Arendal, www.grida.no

OCEANA, 2010.Sustainable Development Manuals: Restoration of seagrass meadows. 24pp. https://oceana.org/reports/restoration-seagrass-meadows

Pergent, G., Bazairi, H., Bianchi, C.N., Boudouresque, C.F., Buia, M.C., Calvo, S., Clabaut, P., Harmelin-Vivien, M., Angel Mateo, M., Montefalcone, M., Morri, C., Orfanidis, S., Pergent-Martini, C., Semroud, R., Serrano, O., Thibaut, T., Tomasello, A., Verlaque, M., 2014. Climate change and Mediterranean seagrass meadows: A synopsis for environmental managers. Mediterr. Mar. Sci. 15, 462–473. https://doi.org/10.12681/mms.621

Serrano, O., Lavery, P.S., Duarte, C.M., Kendrick, G.A., Calafat, A., York, P.H., Steven, A., Macreadie, P.I., 2016. Can mud (silt and clay) concentration be used to predict soil organic carbon content within seagrass ecosystems ? Biogeosciences 13, 4915–4926. https://doi.org/10.5194/bg-2015-598

Siani, G, Paterne, M, Arnold, M, Bard E, Métivier, B, Tisnerat, N, and Bassinot, F, 2000. Radiocarbon reservoir ages in the Mediterranean Sea and Black Sea. Radiocarbon 42:271-280.

Van Katwijk, M. M., Bos, A. R., Hermus, D. C. R., & Suykerbuyk, W. (2010). Sediment modification by seagrass beds: Muddification and sandification induced by plant cover and environmental conditions. Estuarine, Coastal and Shelf Science, 89(2), 175-181.

6. Acknowledgments

This work would not have been possible without the joint effort and collaboration of the LIFE Blue Natura family. In particular:

Anna Sans, Elisabeth Fay Belshe, Manel Bolivar, Oscar Serrano, Karina Inostroza, Paul Lavery and Briac Monnier were absolutely decisive in coordinating, preparing and performing the field campaigns and field subsampling works. Their experience and skills in the water and as scientists were, simply, invaluable.

The García del Cid Captain and crew deserve a very special mention. They are the best professionals a best colleagues one can desire to have side by side in the sea. Their assistance on board and in the water was crucial.

Vibrocoring was a very important part of the LIFE BN research cruise. This task was performed magnificently by staff of Igeotest (GeoScience Group).

The Cádiz Bay seagrass monitoring network FAMAR, from the University of Cadiz gave us useful recommendations and information, as well as field assistance, in order to select the small seagrass stations to be sampled at the Santibáñez lagoon. We would like to thank especially Ignacio González, Rocío Jimenez Ramos and Gonzalo Egea. Also big thanks to the Director of the Natural Park Bahía de Cádiz, Antonio Gómez, for his constant support and help.

While field works were tough and exhausting at times, laboratory works implied endless months of work, sometimes from morning to evening. Montserrat Soler and Daniel Benjumea, highly specialized technicians of CEAB-CSIC, assisted the GAME group and worked beyond duty, and with high professionality, in processing and analysing the gigantic amount of samples obtained (over 6,000).

Several enthusiastic students participated in the extensive laboratory work, making their PhD or MsC thesis, Degree projects, and even University or High School practicums, within the GAME team: Gloria Misson (PhD), Alessio Vásquez Loarte (MSc), Irene Saez Devis and Océane Ménart (MSc), Ona Deulofeu (Degree), Mariona Tolosa, Alex Uréndez, Sergi Matas, Julia García and Samuel Crespo (University Practicums), as well as Laia Rodriguez, María Torres and Inés Riera (High School Practicums). Very special thanks to all of them.

Several external and CSIC laboratories have collaborated in different analyses: Core scanning, XRF and magnetic susceptibility of hemicores have been performed at the CORELAB (University of Barcelona), under the generous guidance of Jaime Frigola Ferrer. The recent (<150 yr) accretion rates have been estimated through 210Pb measurements by Jordi García Orellana and Joan Manel Bruach Menchén, from the Department of Physics at the Autonomous University of Barcelona (UAB); radiocarbon carbon dating has been performed by Direct-AMS (Seattle); while TOC and TON content, as well as isotopic analyses were performed at the IATC-CSIC institute in Granada, by the world reputed experts Antonio Delgado and Arsenio Granados.

Last but not least at all, very big thanks go to our project partners AMAyA, CMAOT and HyT, for their great assistance before, during and after field missions. The marine technicians from

AMAyA Agustín Barrajón, Diego Moreno, half human, half cetaceans, Chemi Remón, Julio de la Rosa, Manuel Fernández and María del Carmen Arroyo, all coordinated by Maria Soledad Vivas Navarro, provided us with key help and information for sites and stations selection, and continued to provide us with expert and local knowledge information and data at every request during data analysis, even beyond the action A1 objectives. Marine technicians accompanied us underwater to the meadows, to help us to fine tune stations selection in the field, and also assisted us in sample collection.

Patricio Peñalver and David León from HyT, have been always there, ‘getting soaked and muddy’ with us when needed, and faithfully recording and disseminating our activities.

Our partner CMAOT put at our disposal the Isla de Tarifa vessel during the first field mission. Many thanks to the crew for their professional and pleasant help.

Finally, thanks to Rosa Mendoza Castellon, Life Blue Natura project Director, for steering this complex project with her wise ‘savoir faire’. We know, not an easy task.

Annexes

Annex I: Carbon stocks

Annex I (Carbon stocks)

C stocks		TE.S[1]		TE.I		TE.I-C[3]		TE.D		PA.I[7]		AG.S		AG.I[2]		AG.D[4]		BA.S[7]		BA.S-C[7]	
		Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation
1 m	kg/m^2	**26.85**	0.71	**25.96**	21.44	**20.04**	9.63	**183.85**	168.12	**1.99**	0.83	**21.85**	10.95	**9.21**	3.63	**30.23**		**2.53**	0.38	2.85	0.27
	t/ha	268.48	7.12	259.64	214.38	200.43	96.30	1838.47	1681.24	19.92	8.35	218.51	109.46	92.09	36.34	302.33	0.00	25.27	3.83	28.50	2.67
Observed	kg/m^2	16.41	1.80	34.24	21.13	10.35	5.81	405.53	492.48	1.77	0.72	25.79	9.56	2.53	0.58	5.49	0.83	2.85	0.27	2.85	0.27
	t/ha	164.08	18.02	342.36	211.29	103.50	58.09	4055.30	4924.85	17.71	7.22	257.93	95.59	25.25	5.83	54.93	8.26	28.50	2.67	28.50	2.67
	Length (cm)	64.91		131.22		150.95		240.00		93.46		105.90		37.51		21.37		109.52		109.52	

C stocks		RO.S[1]		RO.S-C[4]		RO.S-CN[5]		RO.I		RO.I-B		RO.I-E		RO.I-R[3]		RO.I-Shall[5,7]		AL.S[5]		ME.S	
		Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation
1 m	kg/m^2	**31.58**	13.10	**27.14**		**1.61**		**38.32**	3.89	**18.35**	4.79	**11.86**		**18.74**	1.84	**0.09**		**19.21**		18.87	6.68
	t/ha	315.80	130.99	271.44		16.07		383.19	38.92	183.53	47.87	118.63		187.36	18.40	0.89		192.09		188.69	66.83
Observed	kg/m^2	29.16	11.34	16.26	7.00	3.79		11.92	9.12	23.45	6.40	14.25		16.68	1.90	0.15		19.77		5.72	2.79
	t/ha	291.61	113.41	162.63	70.02	37.92		119.25	91.22	234.47	63.97	142.46		166.85	19.04	1.54		197.74		57.20	27.90
	Length (cm)	93.23		57.90		173.53		48.16		137.99		119.02		91.16		492.00		106.88		41.48	

C stocks		CA.S-CN[1,2]		CA.S-C[8]		SA.ZN-S[6]		SA.ZN-D		SA.ZN-C		SA.CN[2]		SA.CP[6]		DE.I	
		Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation	Average	Standar Deviation
1 m	kg/m^2	**14.42**	5.73	**9.40**	2.98			**5.28**	2.70	**4.56**	1.64	**5.88**	0.29			**14.39**	1.97
	t/ha	144.17	57.26	93.97	29.78			52.81	26.99	45.60	16.38	58.77	2.94			143.86	19.69
Observed	kg/m^2	4.83	0.99	9.40	2.98	1.34	0.38	5.09	2.52	4.90	1.96	3.28	0.47	5.01	0.38	14.01	2.07
	t/ha	48.33	9.94	93.97	29.78	13.37	3.85	50.89	25.24	49.04	19.58	32.85	4.66	50.05	3.77	140.07	20.72
	Length (cm)	59.00		59.76		67.80		90.25		104.86		56.07		38.00		97.70	

1 Asuming all cores reached 1m
2 Only cores A and B were used for the estimation
3 Only cores B and C were used for the estimation
4 Only one core was used for the estimation as was the only one to reach 80 cm
5 Only one core available
6 None reach 80 cm
7 %POC estimated acording to Fourqurean 2012
8 Bottom of the deposit reached

Annex II: Carbon fluxes

Annex II (Carbon fluxes)

These fluxes are calculated using only radiocarbon dating unless laballed otherwise. Due to that, fluxes for the last 100 years are preliminar and must be recalculated once 210Pb dates are available

C Fluxes		TE.S [1]		TE.I		TE.I-C		TE.D [4]		PA.I [3]		AG.S [1]		AG.I [1]		AG.D		BA.S	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Whole core	Length (cm)	89		528		151		390				173		162		137		117	
	Age (cal. y BP)	962		9422		4052		6816				1256		725		3725		355	
	Kg TOC/m^2/y	0.035	0.060	0.024	0.012	0.007	0.004	0.041	0.014			0.062	0.040	0.034	0.048	0.013	0.006	0.008	0.002
	t TOC/ha/y	0.350	0.600	0.240	0.120	0.070	0.040	0.410	0.140			0.620	0.404	0.338	0.477	0.130	0.060	0.080	0.020
Last 100 years	Length (cm)	22		10		4		10				30		16		13		23	
	Kg TOC/m^2/y	0.182	0.147	0.039	0.018	0.002	0.001	0.067				0.105	0.054	0.065	0.030	0.009	0.003	0.007	0.002
	t TOC/ha/y	1.820	1.470	0.390	0.180	0.020	0.010	0.670	0.000			1.055	0.542	0.653	0.296	0.090	0.030	0.070	0.020

C Fluxes		RO.S [1]		RO.S-C		RO.S-CN [5]		RO.I-B		RO.I-E		RO.I-R		AL.S		ME.S		CA.S-CN	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Whole core	Length (cm)	138		142				137		120		106		106		78		102	
	Age (cal. y BP)	1084		792				3768		1429		2213		1213		372		283	
	Kg TOC/m^2/y	0.027	0.014	0.045	0.013			0.004	0.002	0.019	0.008	0.039	0.096	0.015	0.013	0.031	0.014	0.068	0.037
	t TOC/ha/y	0.270	0.140	0.450	0.130			0.040	0.020	0.190	0.080	0.390	0.960	0.150	0.130	0.310	0.140	0.680	0.370
Last 100 years	Length (cm)	16		35				4		12		28		8		22		31	
	Kg TOC/m^2/y	0.045	0.017	0.038	0.012			0.002	0.001	0.019	0.000	0.017	0.003	0.040	0.023	0.024	0.010	0.016	0.013
	t TOC/ha/y	0.450	0.170	0.380	0.120			0.020	0.005	0.190	0.001	0.170	0.030	0.400	0.230	0.240	0.100	0.160	0.130

C Fluxes		SA.ZN-S [4]		SA.ZN-D [2]		SA.ZN-C		SA.CN		SA.CP		DE.I [1]	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Whole core	Length (cm)	66				113		96		38		157	
	Age (cal. y BP)	1551				2124		1991		838		3594	
	Kg TOC/m^2/y	0.001	0.001			0.003	0.003	0.003	0.002	0.008	0.004	0.004	0.006
	t TOC/ha/y	0.009	0.005			0.030	0.030	0.030	0.020	0.080	0.040	0.042	0.056
Last 100 years	Length (cm)	4				10		8		6		27	
	Kg TOC/m^2/y	0.002				0.005	0.002	0.004	0.001	0.009	0.004	0.017	0.007
	t TOC/ha/y	0.020	0.000			0.050	0.020	0.040	0.010	0.090	0.040	0.168	0.074

1 14C + 210Pb
2 Material too modern to 14C dating
3 No plant material available
4 Only one measurment for the last 100 years
5 Not posible to date with 14C neither with 210Pb

Annex III: Density, SAR, TOM, TOC, TOC fluxes, TIC and Granulometry distribution per station

This annex compiles all age and depth profiles for all stations, showing bulk density (gDW/cm^3), sediment accretion rate (SAR, mm/yr), total organic matter (TOM, %), total organic carbon (TOC, t/ha), total organic carbon flux (TOCflux, t/ha yr), total inorganic carbon (TIC, t/ha), total inorganic carbon flux (TICflux, t/ha ry) and granulometric distribution, from the longest core of each station.

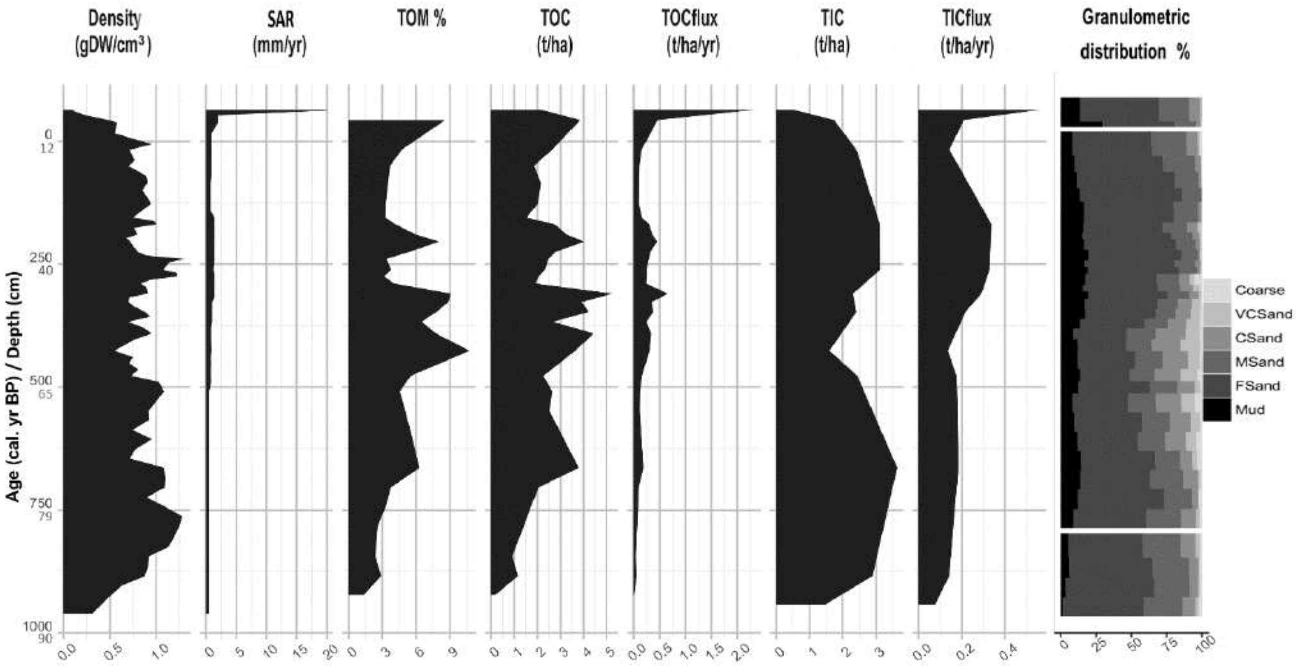


Figure III.1. Age and depth distribution on TE.S_A core (manual core from a healthy, shallow, *P. oceanica* meadow) of soil density, sediment accretion rate, total organic matter, total organic carbon, total organic carbon flux, total inorganic carbon, total inorganic carbon flux and grain size distribution (coarse, >2mm; very coarse sands, 1-2 mm; coarse sands, 1-0.5 mm; medium sands, 0.5-0.25; fine sands, 0.25-0.063; and mud, <0.063mm).

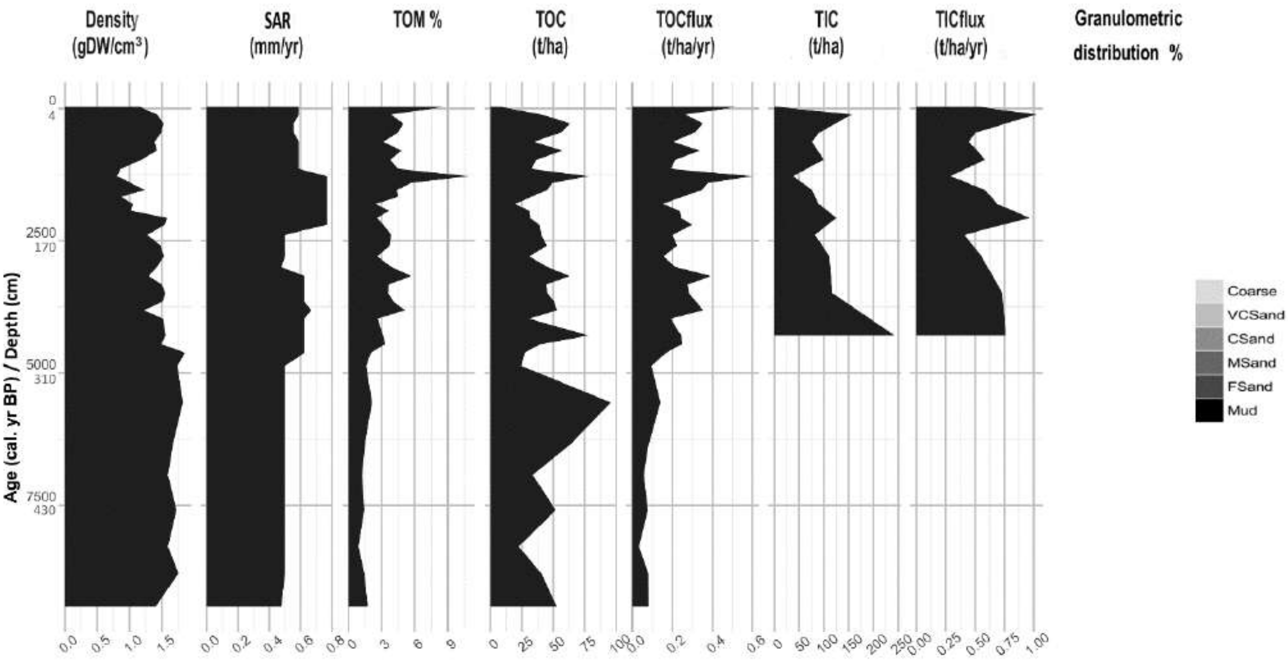


Figure 3.2. Age and depth distribution on TE.I_A core (virbocore from a healthy, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

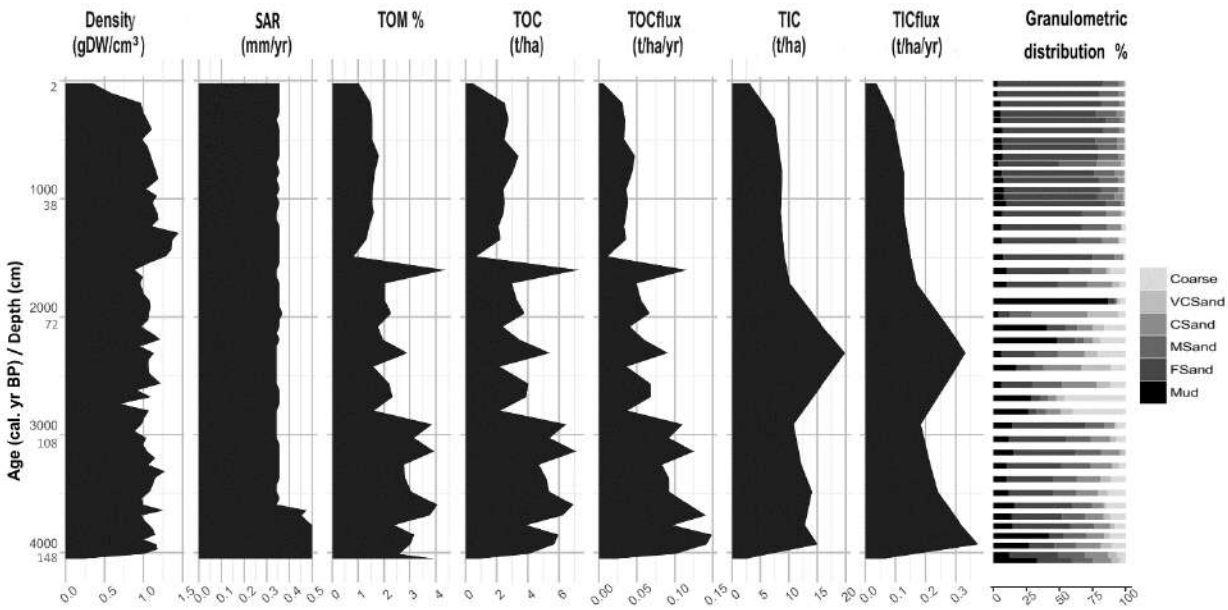


Figure III.3. Age and depth distribution on TE.I_C core (manual core from a control area, death mat below, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

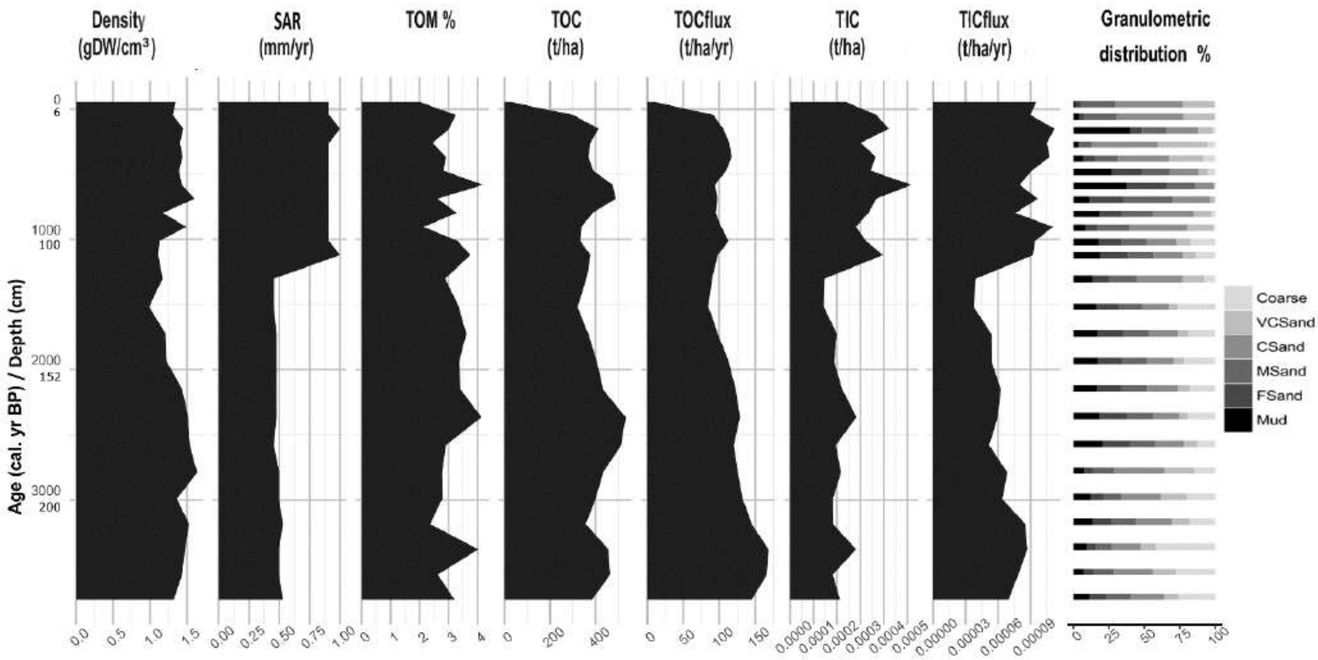


Figure III.4. Age and depth distribution on TE.D_A core (vibrocore from a healthy, deep, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

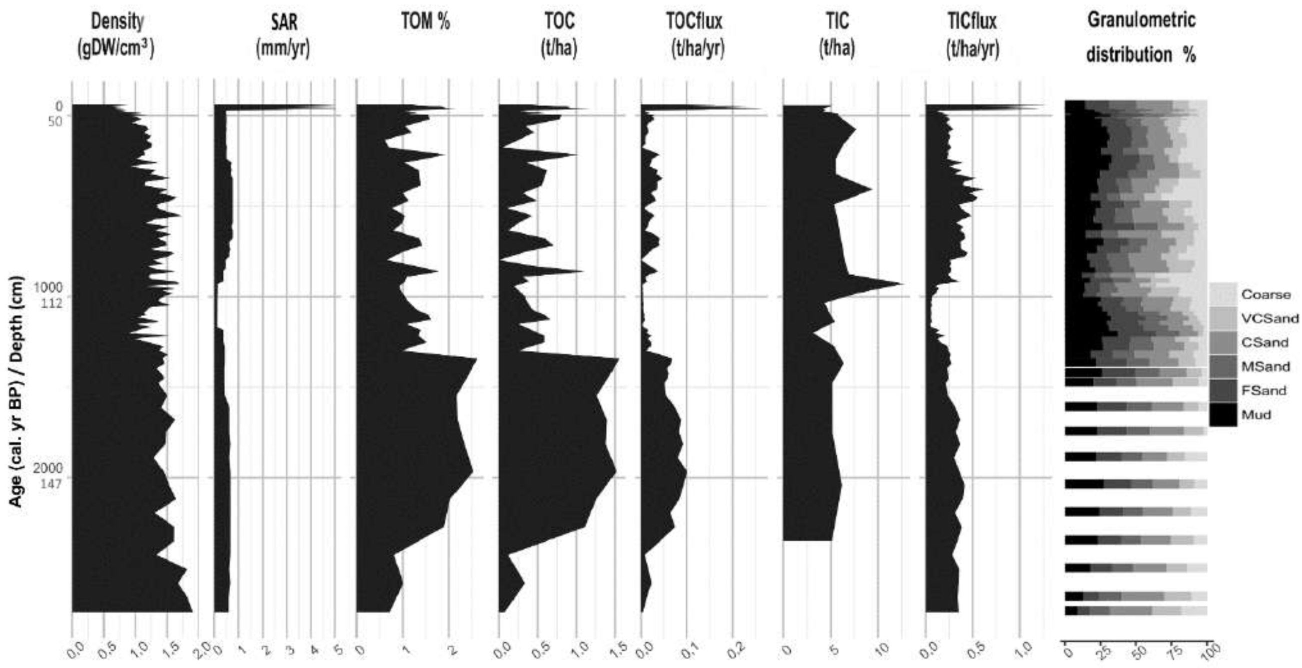


Figure III.5. Age and depth distribution on DE.I_A core (manual core from a degraded, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

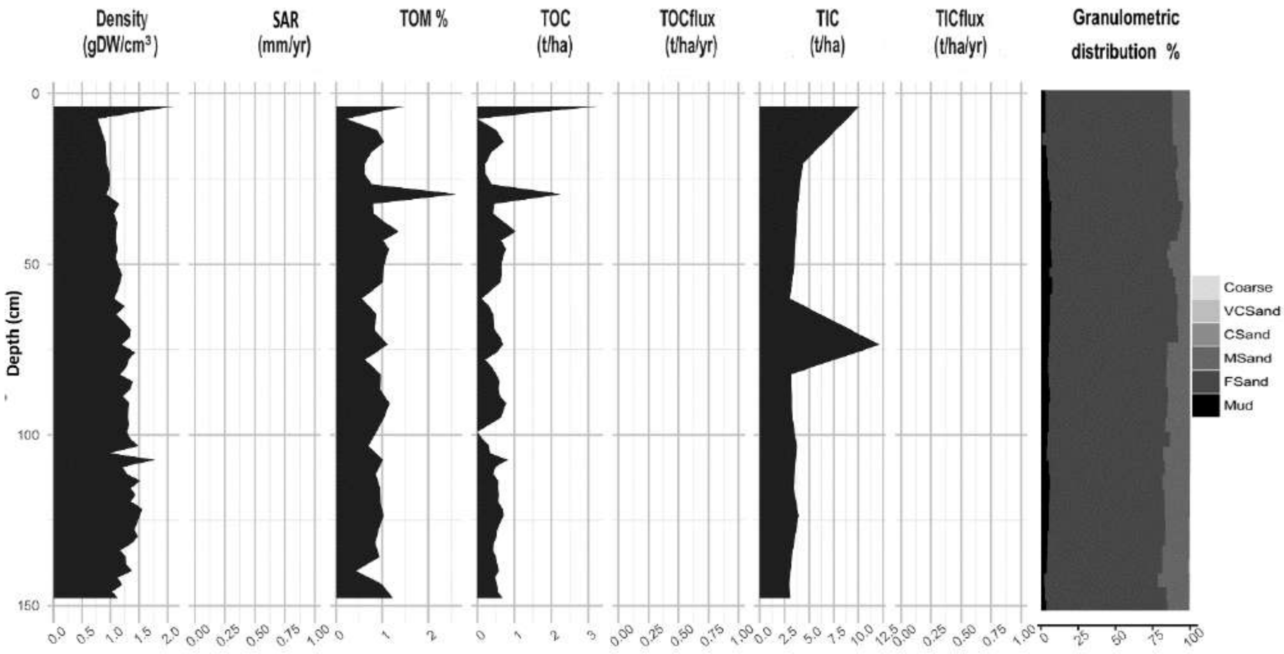


Figure III.6. Age and depth distribution on PA.I_A core (manual core from a healthy, intermediate, *C. nodosa* meadow). See acronyms definitions in Fig. III.1.

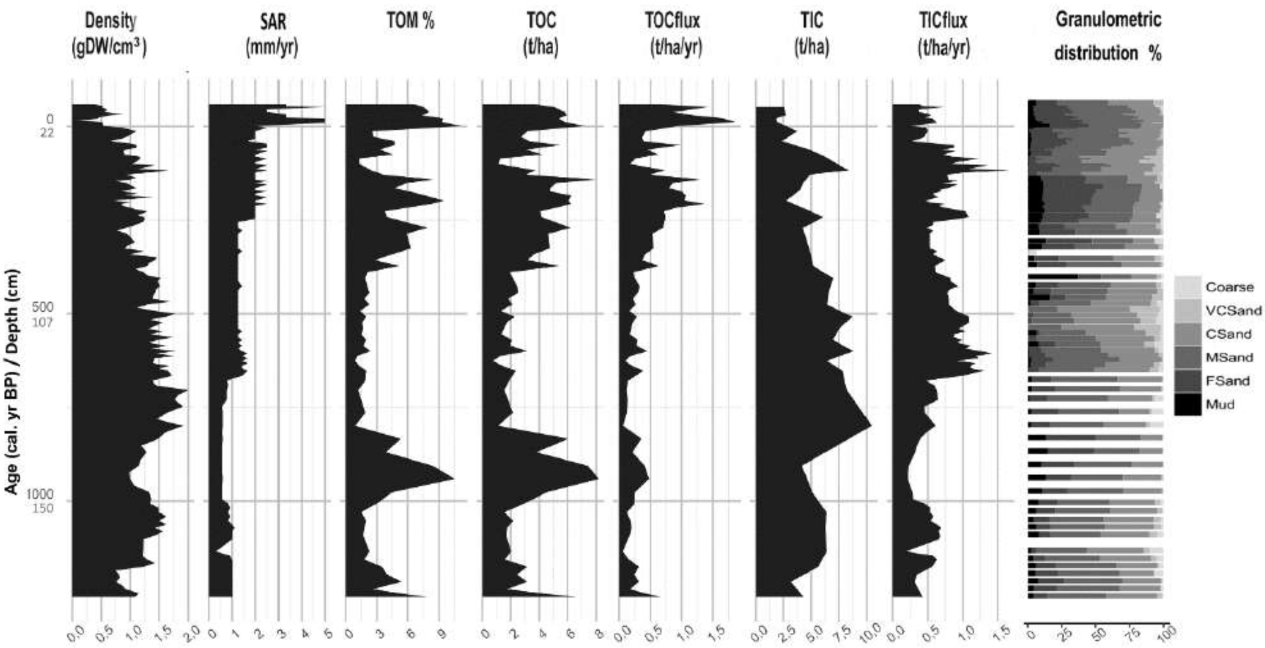


Figure III.7. Age and depth distribution on AG.S_A core (manual core from a healthy, shallow, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

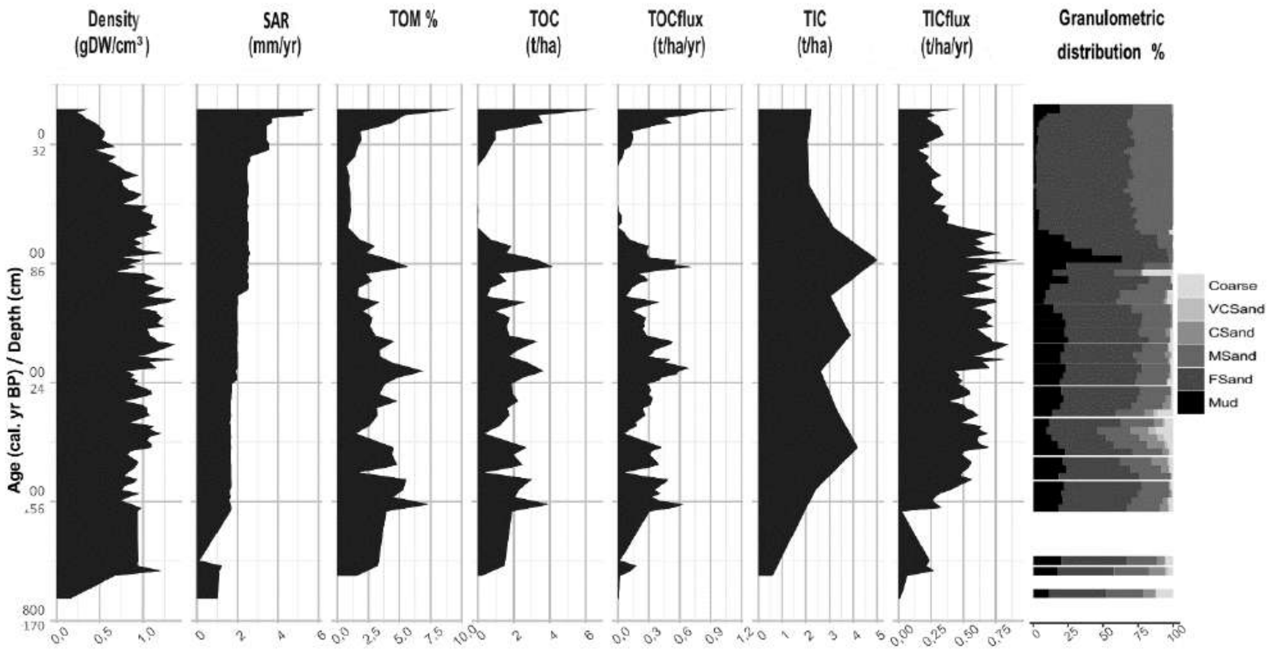


Figure III.8. Age and depth distribution on AG.I_A core (manual core from a healthy, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

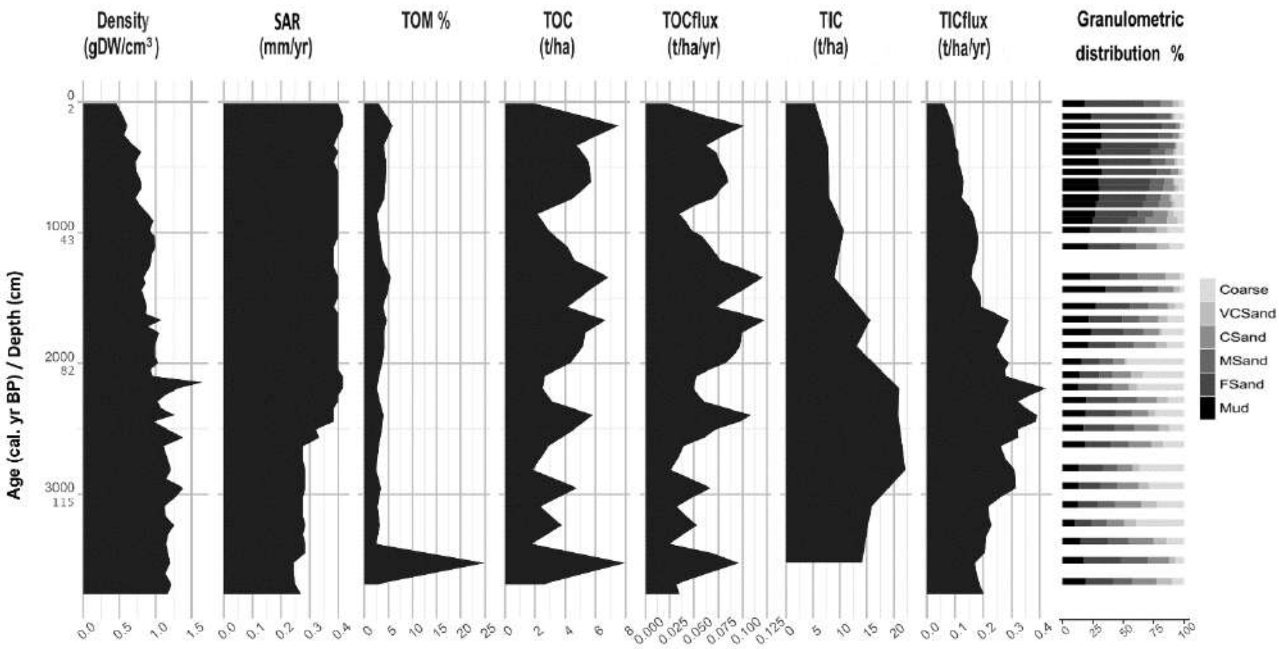


Figure III.9. Age and depth distribution on AG.D_A core (manual core from a healthy, deep, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

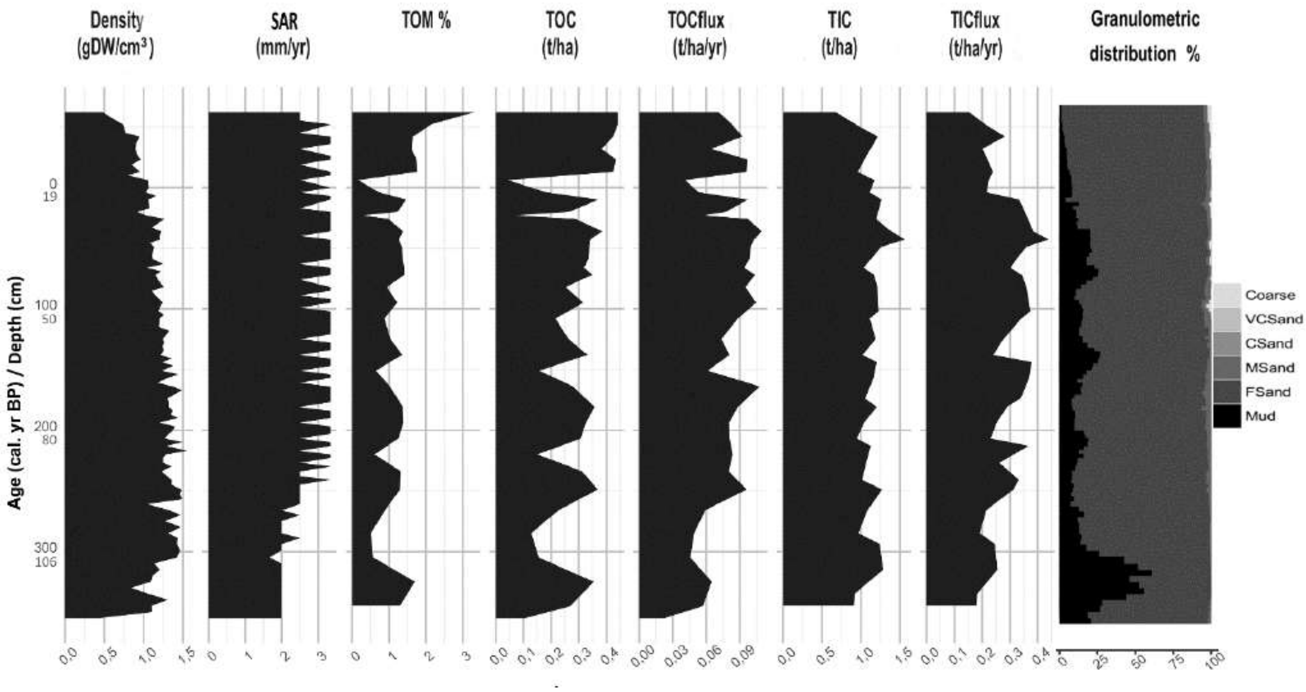


Figure III.10. Age and depth distribution on BA.S_A core (manual core from a healthy, intermediate, *C. nodosa* meadow). See acronyms definitions in Fig. III.1.

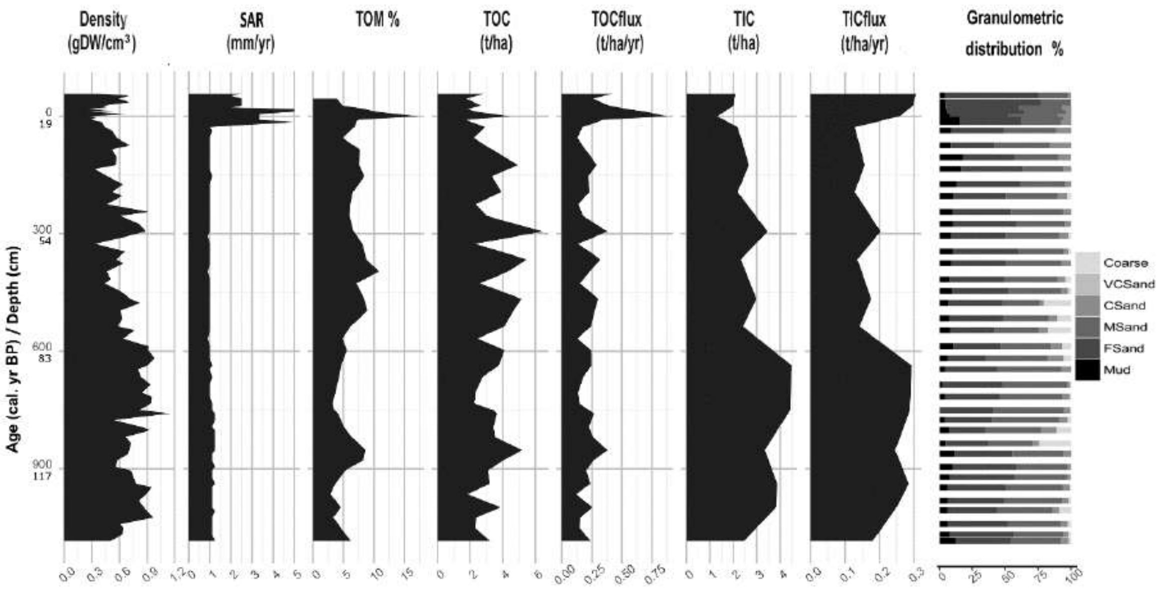


Figure III.11. Age and depth distribution on RO.S_A core (manual core from a healthy, shallow, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

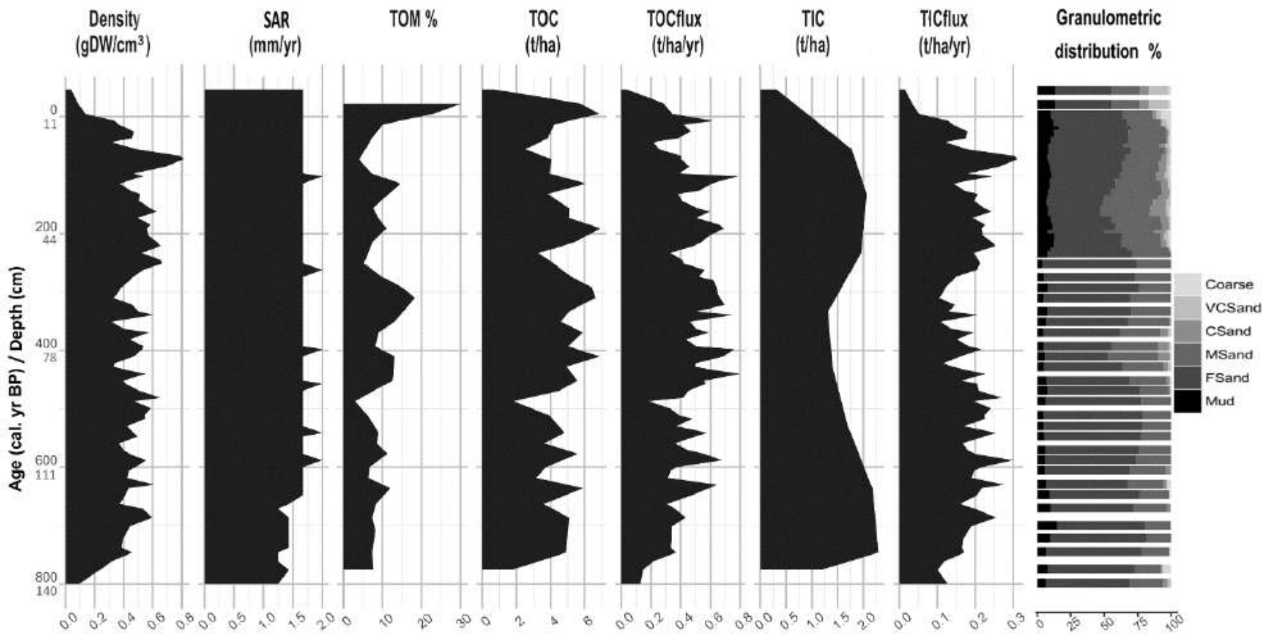


Figure III.12. Age and depth distribution on RO.S_C19 core (manual core from a dead, shallow, P. oceanica meadow). See acronyms definitions in Fig. III.1.

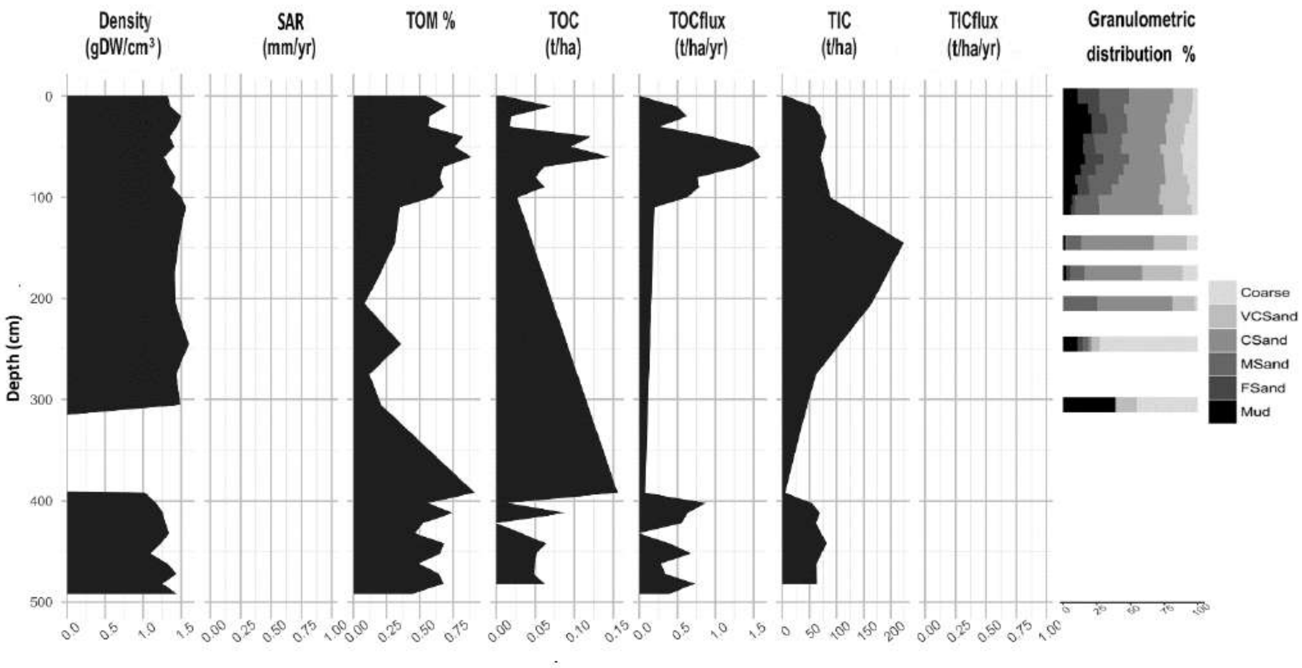


Figure III.13. Age and depth distribution on RO.I_Shall core (manual core from helthy, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

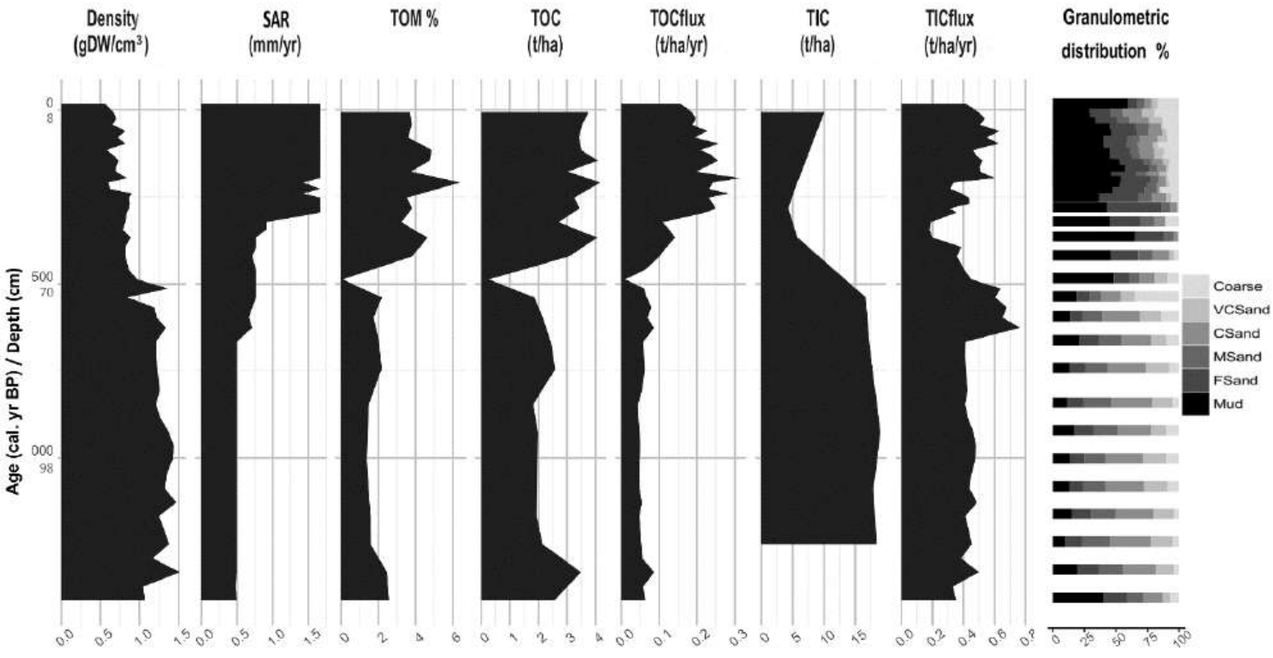


Figure III.14. Age and depth distribution on RO.I-E core (manual core from a eroded, intemediate, *P. oceanica* meadow). See acronymes definitions in Fig. III.1.

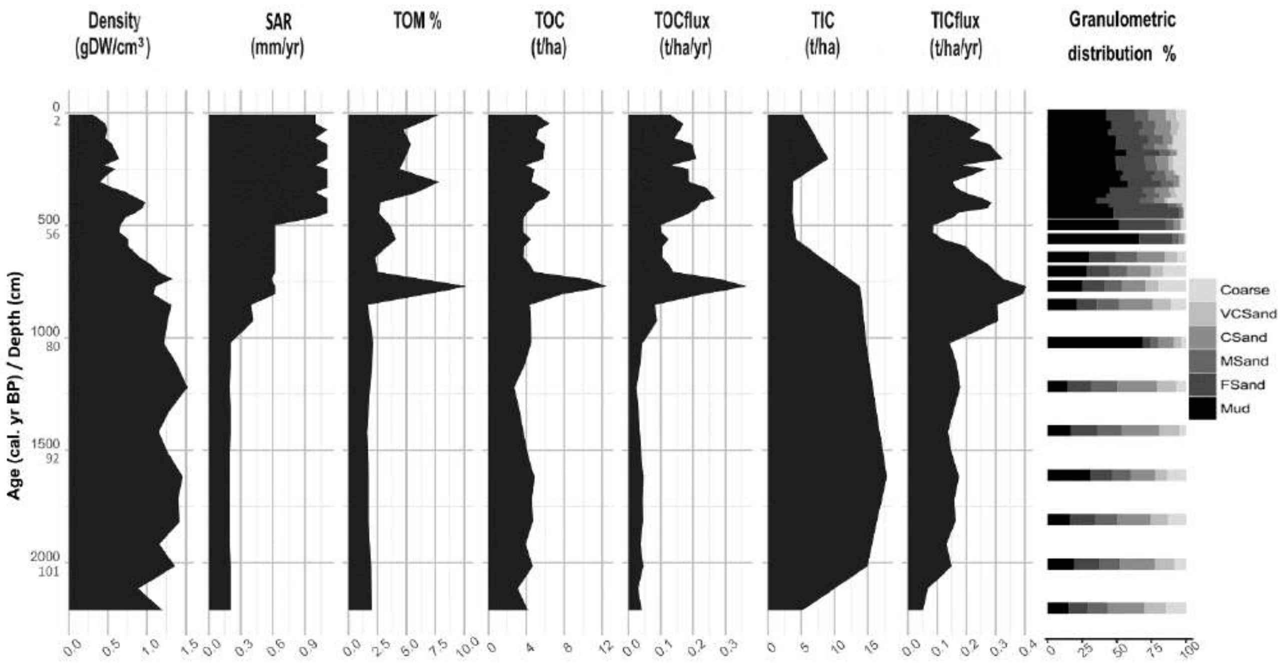


Figure III.15. Age and depth distribution on RO.I-R_A core (manual core from a recolonized, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

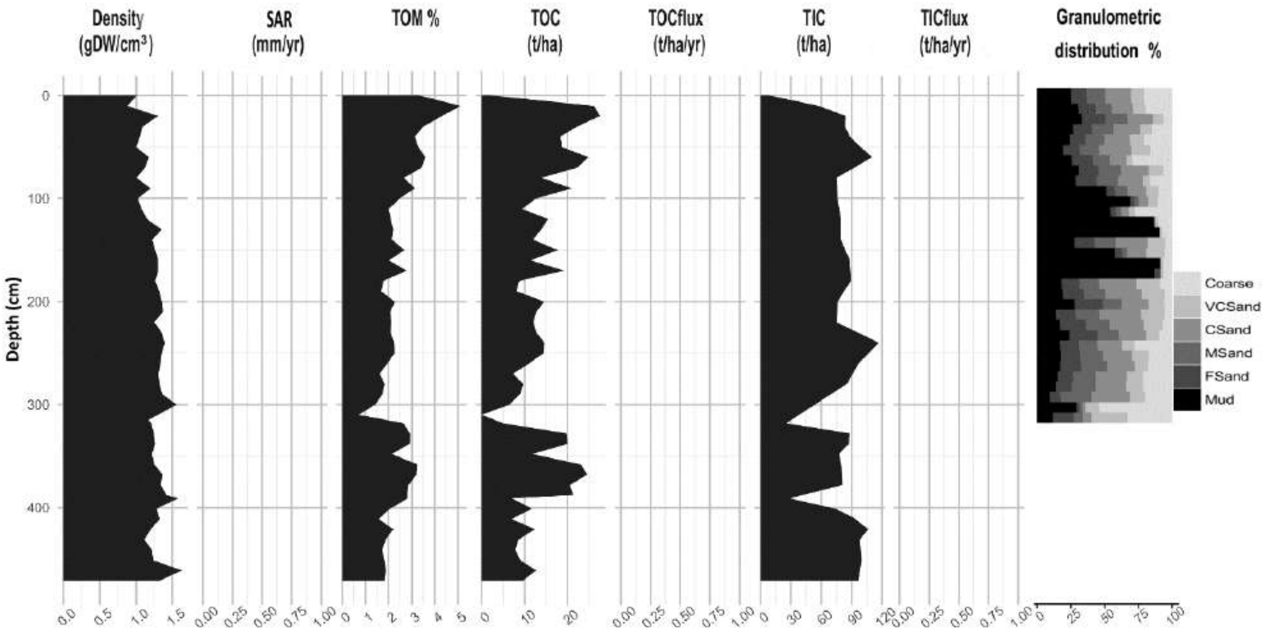


Figure III.16. Age and depth distribution on RO.I-B_A core (manual core from a eroded, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

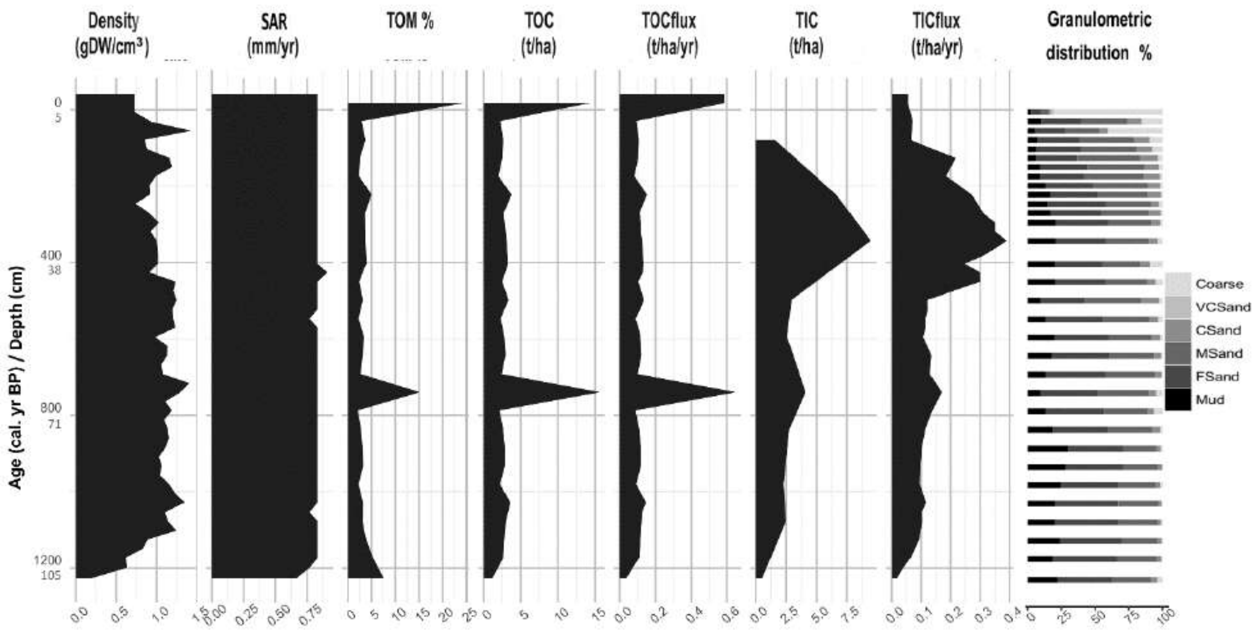


Figure III.17. Age and depth distribution on AL.S_A core (manual core from a healthy, shallow, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

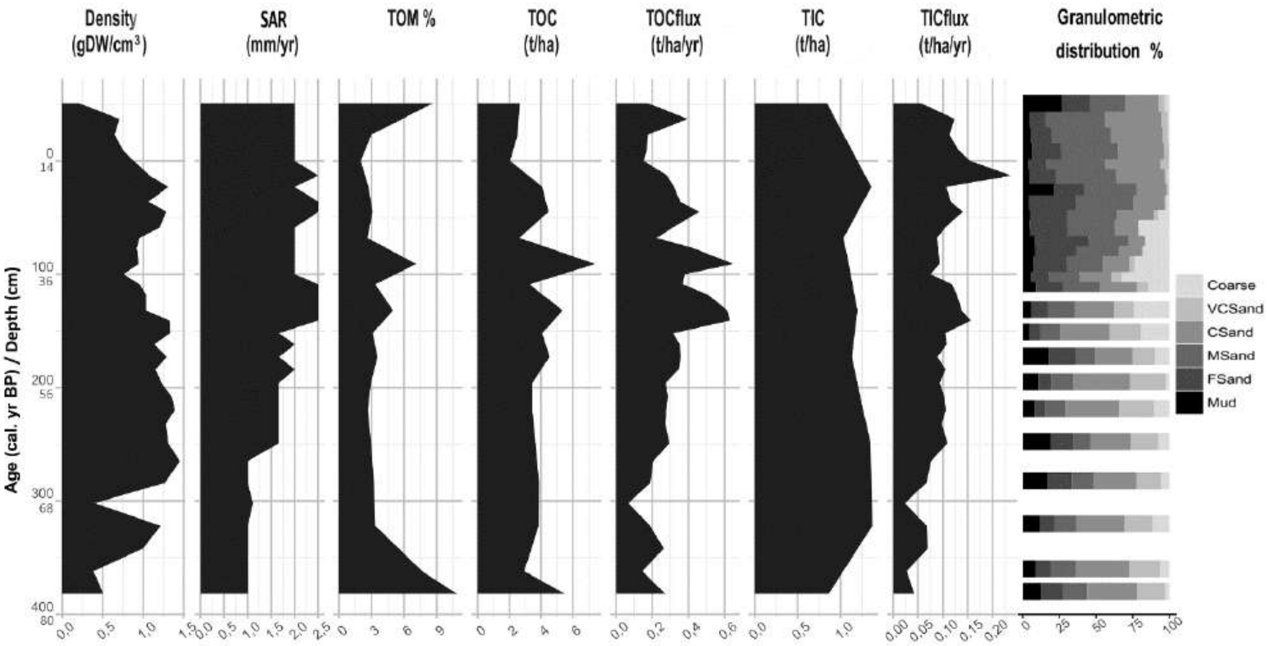


Figure III.18. Age and depth distribution on ME.S_C core (manual core from a healthy, shallow, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

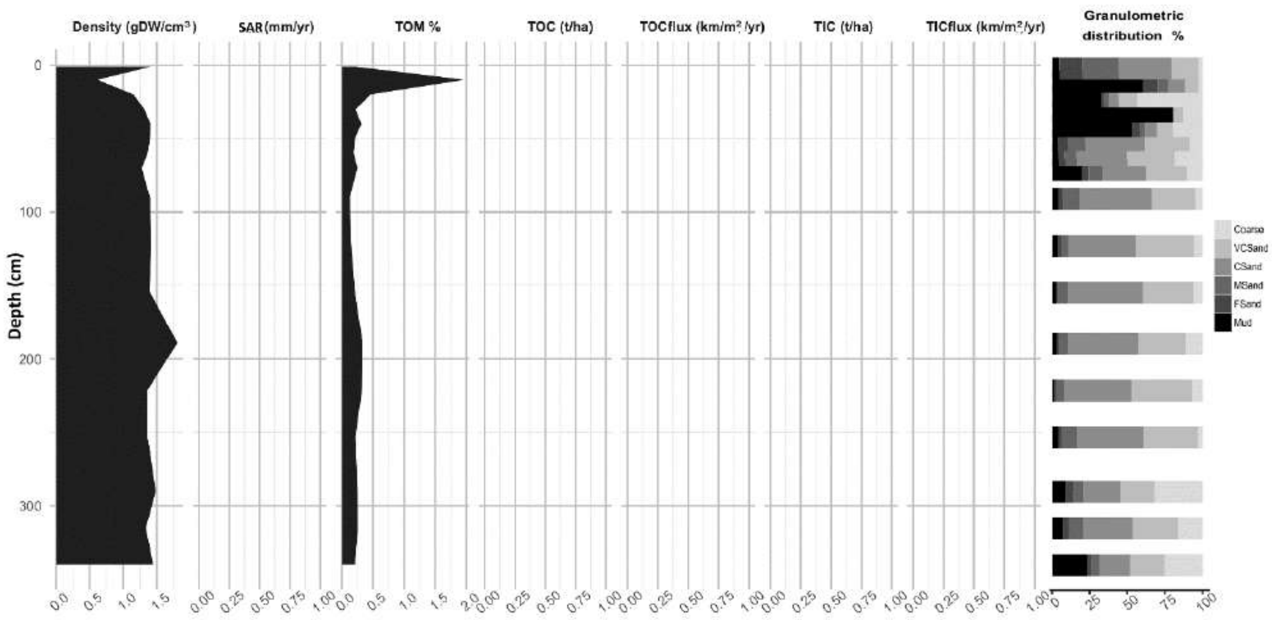


Figure III.19. Age and depth distribution on ME.I core (vibrocore from a control area, intermediate, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

.

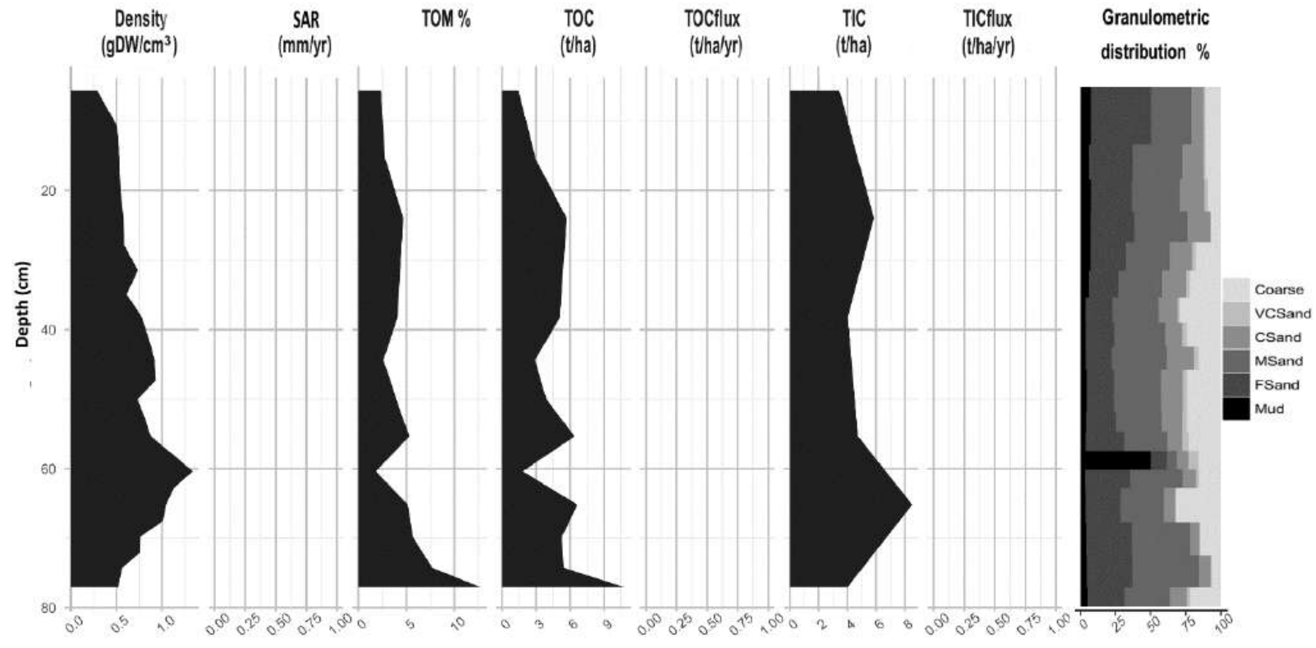


Figure III.20. Age and depth distribution on CA.S-C_A core (manual core from a dead, shallow, *P. oceanica* meadow). See acronyms definitions in Fig. III.1.

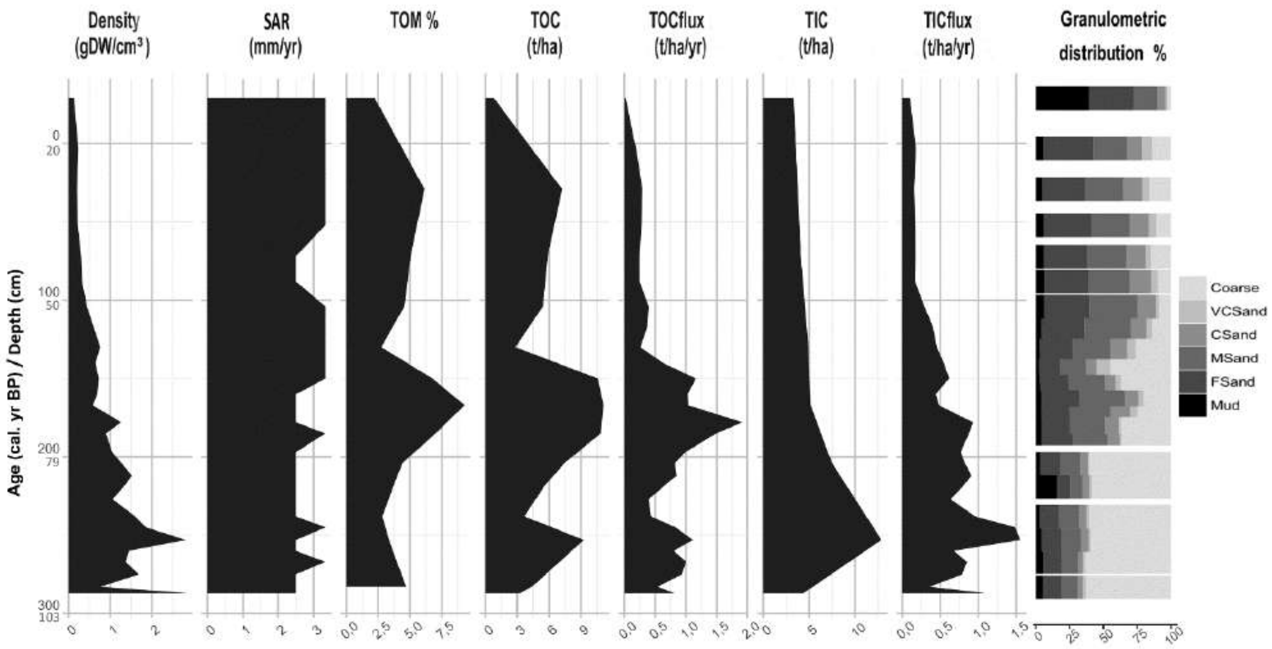


Figure III.21. Age and depth distribution on CA.S-CN_C core (manual core from a dead, shallow, *P. oceanica* meadow with *C. nodosa* on top). See acronyms definitions in Fig. III.1.

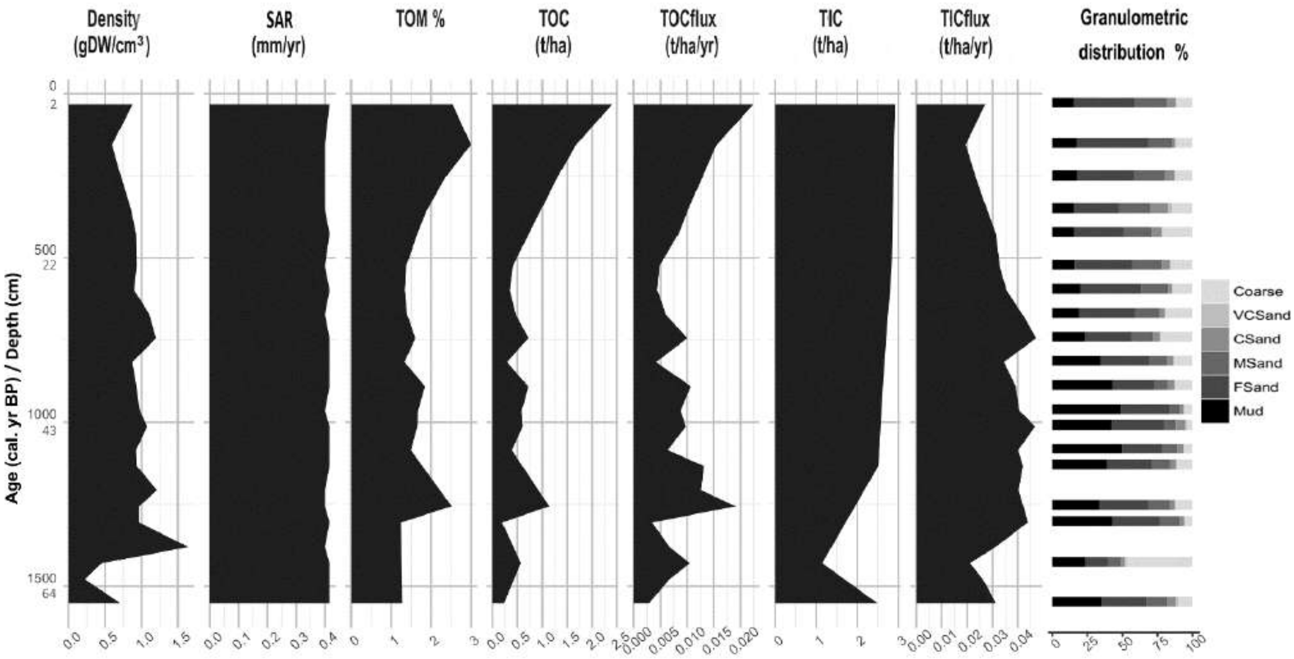


Figure III.22. Age and depth distribution on SA.ZN-S_A core (manual core from a healthy, intertidal, *Z. noltei* meadow). See acronyms definitions in Fig. III.1.

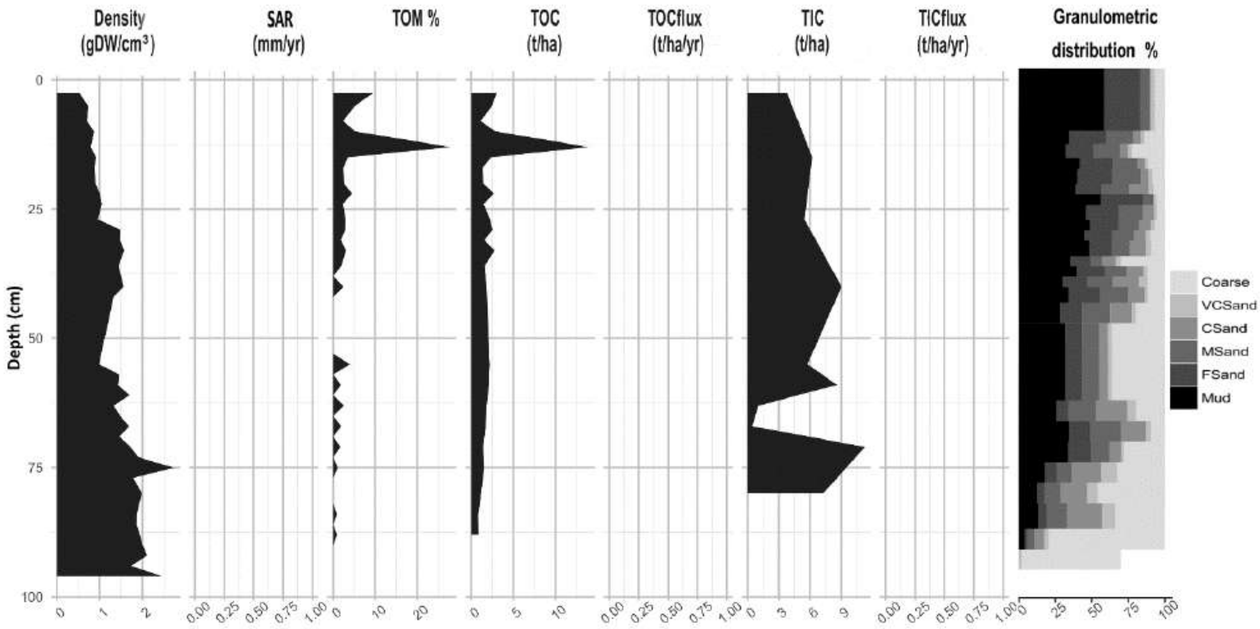


Figure III.23. Age and depth distribution on SA.ZN-D_A core (manual core from a degraded, intertidal, *Z. noltei* meadow). See acronyms definitions in Fig. III.1.

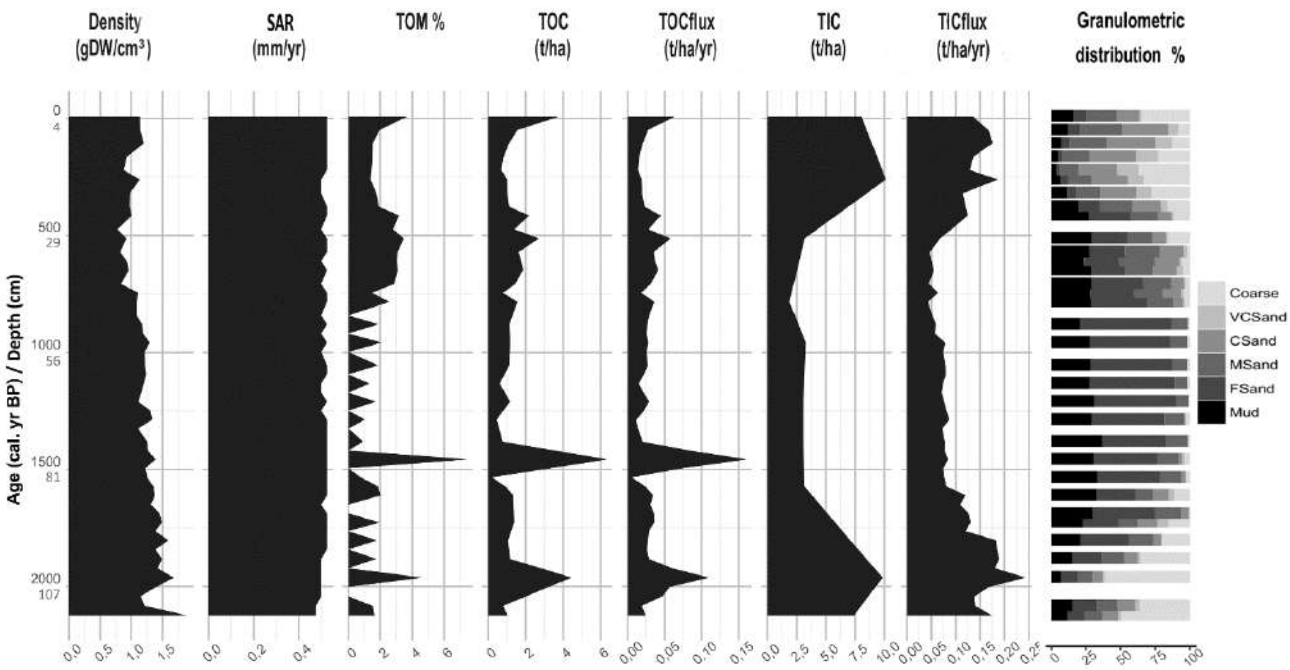


Figure III.24. age and depth distribution on SA.ZN-C_A core (manual core from a control area, shallow, *Z. noltei* meadow). See acronyms definitions in Fig. III.1.

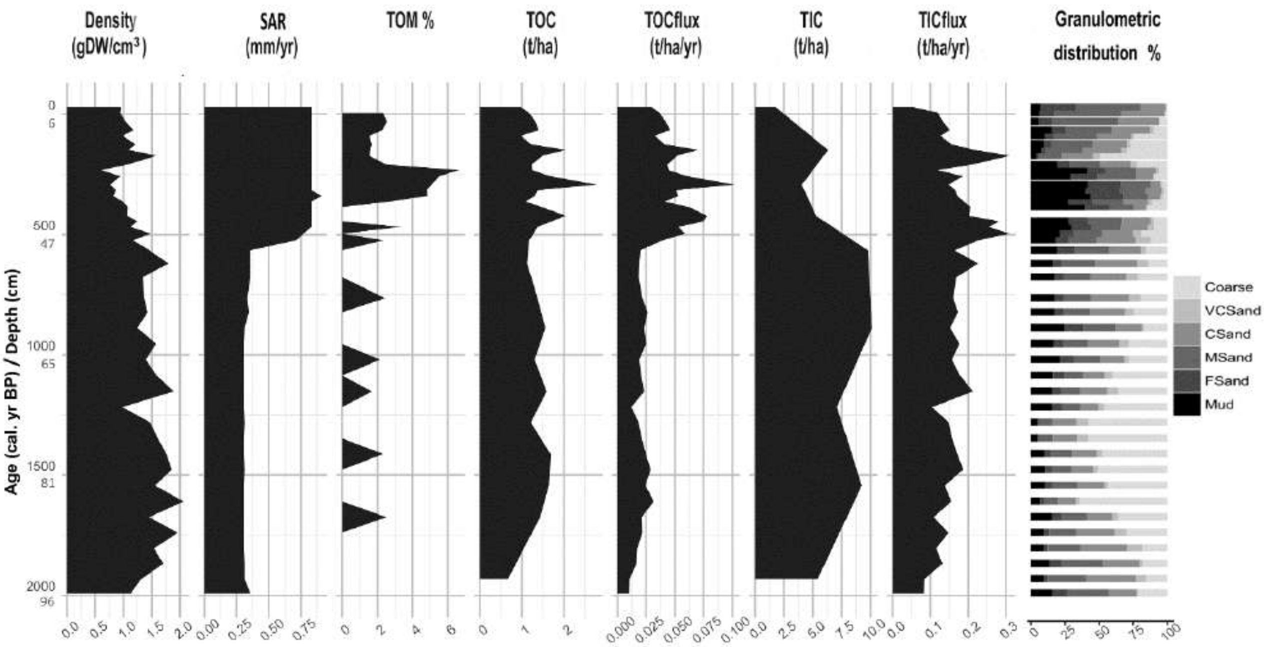


Figure III.25. Age and depth distribution on SA.CN_A core (manual core from a healthy, shallow, *C. nodosa* meadow). See acronyms definitions in Fig. III.1.

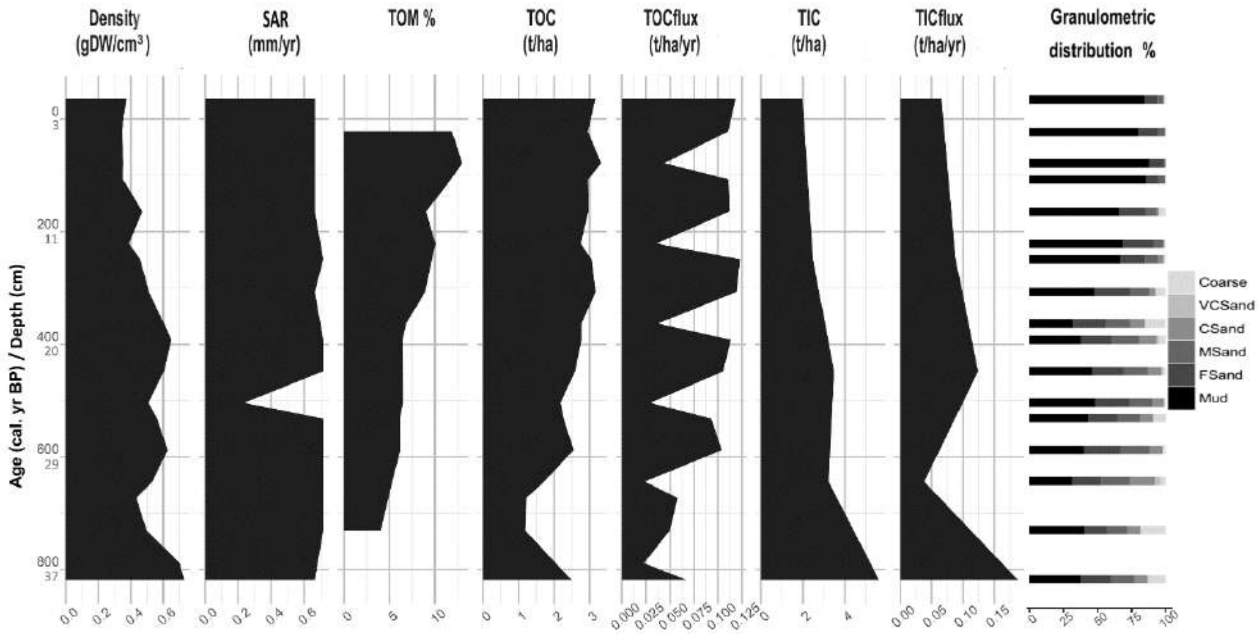


Figure III.26. Age and depth distribution on SA.CP_A core (manual core from a healthy, shallow, *Caulerpa spp.* meadow). See acronyms definitions in Fig. III.1.

Annex IV: Issues affecting the reliability of the estimates

Although the estimates of Blue Carbon stocks and fluxes performed in this study are probably the most detailed ones in the EU and probably beyond, there is a number of important limitations and uncertainties that affect them. They are related to the sample size, to field sampling and laboratory techniques, and even to conceptual aspects. Although some of them have been already introduced above, some of the most critical are listed and commented in this annex.

a. Sampling effort

The huge extension and complexity of seagrass ecosystems implies simplifications to adjust the sampling effort to the material and human resources available. Sample size limitations have to be overcome through (1) a detailed analysis and interpretation of the local conditions and temporal variation across key cores and stations and (2) the knowledge of experts with a large history of personal direct observations in the study sites. Not all environmental conditions or meadow categories were present at every region, site or station. Also, small seagrasses, could not be sampled on all its geographical range. So very often, any attempt to perform a complete factorial analysis is simply not feasible.

b. Dating techniques limitations

Dating the soil samples is key to estimate the long-term carbon sequestration rates of the meadows. The two techniques used in this study were radiocarbon ^{14}C and lead ^{210}Pb.

Radiocarbon dating is used for material that is expected to be older than 200 yr. As the date we need to estimate is that when the soil layer was deposited, we have to assume that organic matter from the layer we are using for the dating, must have been produced at that time. Particularly in the lowest sections of the cores, it is not rare that macro-debris of seagrass cannot be found. In these cases, an alternative is to send an aliquot of bulk sediment to the laboratory for a dating of the total organic carbon contained in the sample.

It is known that the choice of the material to be dated has repercussions on the radiocarbon ages (Belshe et al., 2017).

To check for this, we dated a layer of the core BA.S_A using both plant debris and bulk sediment. The dates obtained differed nothing less than ~2500 yr! So dating bulk samples in this study was discarded and the dating of those deep layers of the sediment not showing enough macro-debris of plant material was abandoned.

The ^{210}Pb dating technique is used for the top most layers of the soil, i.e., for the recent history of the meadow (0-200 yr), and depend on a good chronological sequence that allows to get a consistent ^{210}Pb radioactive decay curve. This technique is finer than the ^{14}C and fails when the top cm of the core under study has suffered a stratigraphic alteration. This alteration can mainly happen as a consequence of i) inadequate sampling techniques, ii) alterations during core transport (in SCUBA, once on board, once on the road, etc.), iii) in situ resuspension of the sediments due to currents or wave action, or iv) to bioturbation. In this study, the ^{210}Pb curves for some of the cores showed incoherencies in the top layers, not allowing for a proper elaboration of the chronological model (see annex II.). For these cores, the chronological model was elaborated based on radiocarbon ages.

c. Core decompression correction

As explained in Materials and Methods, and in the deliverable of action A2, two different coring methods were used: vibrocoring, which does not lead to core compression (but may alter the 50 top cm of core), and manual coring, which does. Although the compression does not affect the estimation of global core carbon stock or flux, knowing the actual amount of material up to the first meter depth or accreted in the last 100 years is essential to standardize carbon stock and fluxes spatially and temporally. The ^{210}Pb was not applied in the vibrocores, but only in the manual cores.

Some mathematical methods have been pondered to better estimate the real depth of the material. The Coastal Blue Carbon Manual (Howard et al., 2014) recommends calculating a “compaction correction factor” that distributes the compression equally through the entire core. Although this is a very straightforward solution, there are at least two ways in which the material would not be equally compressed. First, changes in the material with depth may lead to differential, idiosyncratic resistance to compression. Second, the topmost layers are subjected to the compacting force for a longer time during the coring operation than the deeper ones, so the compaction would often decrease from the surface to the deeper layers.

To detect the first case, it would be necessary to measure core-shortening several times during coring into the sediment, which significantly increases sampling effort when extracting lot of cores, especially scuba diving at deep stations, making it not feasible. So in this study, as in any other BC quantification study, compression was measured based on the final compression parameters (i.e., once the corer has arrived to its maximum depth). As for the second factor, Morton and White (1997) showed that logarithmic core shortening is the most common on wetland sediments. Thus, instead of the linear decompression recommended by Howard et al. (2014), we decided to follow Morton and White (1997) and fit a logarithmic curve to decompress our cores by default. However, we found problems decompressing in this way the highly compressed cores. The issue is that the logarithmic model assumes, unrealistically, that the material can be infinitely compressed, but any material can reach a maximum beyond which it does not compress further. So our method tends to overestimate compression in the shallowest core layers. This is why, after some tests, we decided to use a logarithmic correction with $y_2 = 0.1$ below 30 % of compression, from 30-40 % we also fitted a logarithmic correction, but with $y_2 = 1$ (which moderates the logarithmic curve slope growth towards the core top, reducing decompression in those sections); while for compressions above 40 %, we decided to apply linear decompression.

Compression is a limiting factor on the methodology. Carbon stocks in the top meter without compression correction can be overestimated up to 60% according to our data.

d. Estimates variability

From the three cores taken on each station the longest one was used as standard and the two shortest ones were subsampled in the field. Some of the replicates did not reach 1 m. To calculate the mean and the standard deviation among cores in the station, they must reach the same depth. The first approximation would be to extrapolate the stock at 1 m. Since the carbon on seagrass soils often follow a logarithmic decline function with depth, the sediment carbon content in the deeper centimeters can be estimated fitting this function, assuming the input of carbon and degradation to be stable; but in several cores, no logarithmic decline of carbon content with depth was detected.

If the replicates length was superior to 80 cm, the remaining 20 cm until the meter was assumed to have the same carbon density as the last section sampled. If not, the deviation between the replicates was calculated using the carbon above the maximum depth of the shortest core.

Differences in core length are an unavoidable issue, so the approximation above is the only one possible and certainly the resulting standard deviations reliable. We include this section for practical purposes and to highlight once again the complexity of works involved in inventorying carbon stocks and fluxes.

e. Carbonate precipitation as possible CO_2 source

Calcification process release 0.63 net molecules of CO_2 for each mol deposited at the average sea pH (Smith 2013). The higher carbonate production was found on Santibáñez bay, where there is shellfish exploitation. Although presence of seagrass favor shellfish communities, these higher carbonates production was more related to the closure of the bay than with any characteristic depending on the seagrass. The average CO_2 content from carbonates in the sediments of *P. oceanica* healthy meadows analysed in this study was of 1,371 ± 334 tCO_2/ha, in the top m of sediment, accumulated at a rate of 1.24 tCO_2/ha yr. Following the rule above, this would imply a 'sink offset' of about 822 tCO_2/ha at 0.74 tCO_2/ha yr or 2.5 $MtCO_2$ at 2,269 tCO_2/yr for the entire Andalusia. Because not all the carbonates stored in seagrass soils have actually been precipitated in situ (i.e., an unknown fraction has been imported from adjacent waters or from the land), that potential offset cannot be yet applied until new methods allow to distinguish with certainty the locally precipitated carbonates (Macready et al., 2017).

f. Scaling-up for global estimates

Most of the obstacles to achieve a satisfactory global estimate for the Andalusian carbon stocks and fluxes associated to seagrass meadows, have been discussed in several instances over this report. One limitation to add has to do with the lack of a marked bathymetric gradient in carbon stocks and fluxes observed. It was initially planned to obtain a function describing the changes in stocks and fluxes associated to the depth gradient. But a pattern was not found (what, as a matter of fact, is one very valuable outcome of this study). In the absence of such a gradient, stocks and fluxes found for a core at a certain depth was used as representative of the closest range of depths distinguished in this study.

Seagrass cover – Areas with different seagrass cover are all taken equally as if they were homogeneously and totally occupied by the seagrass. This is probably leading to one of the greatest overestimations of the carbon sink associated to seagrass meadows. The spaces 'inter-patches' can arguably be considered to hold or to have held a well-developed mat in the sediment, but not necessarily. At least, the totality of the sequestration capacity should be subtracted together with a substantial part of the stock. If the average cover of *P. oceanica* in Andalusia has been reported to vary from 25 % to 70 %, the same proportional stock and flux of the total stocks and fluxes determined in this study should be subtracted. This procedure is not currently a standard one in the BC scientific community but should probably begin to be considered in the near future. Because the mapping in A1 has only a very few entries of seagrass cover, an estimate of this potential wane is not attempted.

g. Stocks and fluxes of unvegetated areas

It is established that the carbon susceptible of being certified as a carbon credit from an emission offset project, is only that which represents an addition to what it was naturally already in the system (additionality). In the case of seagrass meadows, is only a recent practice to sample cores in sandy sediments without any vegetation as a reference, to determine the content and the rate of carbon sequestration that occurs without the mediation of the seagrass meadow. In this study, the ‘control cores’ were taken at intermediate depths in a bare sandy bottom adjacent to *P. oceanica* meadows but with no patches of any seagrass in a radius of at least 100 m. The stock for the control cores was measured at 106.8 tCO_2/ha and the flux at 0.11 tCO_2/ha yr. It is to be noted that both values are comparable to those exhibited by the small seagrasses, confirming that the actual contribution of the these seagrasses to the total stocks in their sediments is virtually null. This stock is about 7 % and 8 % of the average areal stock and flux of the vegetated areas, respectively. This should be, therefore, a value to subtract to the carbon accounting of any emission offset project.

Annex V: The Tier Concept

"The IPCC has classified the methodological approaches in three different Tiers, according to the quantity of information required, and the degree of analytical complexity (IPCC, 2003, 2006).

Tier 1 - Employs the gain-loss method described in the IPCC Guidelines and the default emission factors and other parameters provided by the IPCC. There may be simplifying assumptions about some carbon pools. Tier 1 methodologies may be combined with spatially explicit activity data derived from remote sensing. The stock change method is not applicable at Tier 1 because of data requirements (GPG2003).

Tier 2 - Generally uses the same methodological approach as Tier 1 but applies emission factors and other parameters which are specific to the country. Country-specific emission factors and parameters are those more appropriate to the forests, climatic regions and land use systems in that country. More highly stratified activity data may be needed in Tier 2 to correspond with country-specific emission factors and parameters for specific regions and specialised land-use categories. Tiers 2 and 3 can also apply stock change methodologies that use plot data provided by NFIs.

Tier 3 – At Tier 3, higher-order methods include models and can utilize plot data provided by NFIs tailored to address national circumstances. Properly implemented, these methods can provide estimates of greater certainty than lower tiers, and can have a closer link between biomass and soil carbon dynamics. Such systems may be GIS-based combinations of forest age, class/production systems with connections to soil modules, integrating several types of monitoring and data. Areas where a land-use change occurs are tracked over time. These systems may include a climate dependency, and provide estimates with inter-annual variability.

Progressing from Tier 1 to Tier 3 generally represents a reduction in the uncertainty of GHG estimates, though at a cost of an increase in the complexity of measurement processes and analyses. Lower Tier methods may be combined with higher Tiers for pools which are less significant. There is no need to progress through each Tier to reach Tier 3. In many circumstances it may be simpler and more cost-effective to transition from Tier 1 to 3 directly than produce a Tier 2 system that then needs to be replaced. Data collected for developing a Tier 3 system may be used to develop interim Tier 2 estimates."

Source: REDDcompass.org

https://www.reddcompass.org/mgd-content-v1/dita-webhelp/en/Box1.html

The GAME team onboard the R/V García del Cid at the end of one of the missions in the harbour of Málaga. October 2018. Source: GAME

Blanes 19 December 2018

Group of Aquatic Macrophyte Ecology
CEAB-CSIC

JUNTA DE ANDALUCIA
CONSEJERÍA DE MEDIO AMBIENTE Y ORDENACIÓN DEL TERRITORIO

Life

Socios beneficiarios:

JUNTA DE ANDALUCIA
CONSEJERÍA DE MEDIO AMBIENTE
Y ORDENACIÓN DEL TERRITORIO
Agencia de Medio Ambiente y Agua

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

UICN

HyT

Cofinanciador:

CEPSA