

DELIVERABLE C2.2 (a C2.1 update):

RESULTS REPORT

STOCKS Y FLUJOS DE CARBONO ASOCIADOS AL SUMIDERO DE MARSIMAS EN ANDALUCÍA

y estima del impacto en los stocks y flujos ante diversos cambios del uso del suelo

ENTREGABLE C2.2 (actualización del C2.1).

INFORME DE RESULTADOS

LIFE BLUE NATURA

LIFE14CCM/ES/000957

Blanes, 30 April 2019 (Updated September 2019)

## CARBON STOCKS AND FLUXES ASSOCIATED TO ANDALUSIAN SALTMARSHES

# and estimates of impact in stocks and fluxes by diverse land-use changes

DELIVERABLE C2.2 (a C2.1 update):

#### RESULTS REPORT

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Group of Aquatic Macrophyte Ecology CEAB-CSIC





Socios beneficiarios:











#### **Table of Contents**

Unit	s		4				
Glos	ssary of	terms and definitions	4				
1.	Introdu	ction	7				
2.	Materia	als and methods	.10				
2.1.	Field	sampling strategy	.10				
	2.1.1.	Sampling the sediment carbon stocks	.14				
	2.1.2.	Other carbon compartments	.14				
2.2.	Labo	oratory analyses	.14				
	2.2.1.	Sub-sampling, parameters and analyses on sediment cores	.14				
2.3.	Num	erical procedures	.16				
	2.3.1.	Corrections for core compression	.16				
	2.3.2.	Estimating TOC from TOM	.16				
	2.3.3.	Chronological models, accretion, stocks and fluxes	.18				
	2.3.4.	Upscaling: from areal to global estimates	.18				
3.	Results and Discussion1						
3.1.	Main	geochemical variables estimated	.22				
	3.1.1.	The interplay between marsh horizontal and vertical variability and gradients	.23				
	3.1.2. potenti	Short-term vs long-term TOC fluxes in natural saltmarsh (cores) sediments and i al use for conservation status diagnoses					
	3.1.3.	Effects of some land-use changes in saltmarsh carbon stocks and fluxes	.29				
3.2.	Impli	cations of these results for carbon offsetting projects and other project actions	.39				
	3.2.1.	Quality estimates: basis for an efficient implementation of BC initiatives	.40				
	3.2.2.	A 'big push' by the Andalusian Government	.40				
	3.2.3.	News from the European Parliament	.41				
4.	Conclu	sions, recommendations and future work	.42				
5.	Literatu	ure cited	.45				
6.	Acknow	vledgments	.47				
		ensity, SAR, TOM, TOC, TOC fluxes, TIC and Granulometry distribution per	.49				
		verage carbon stocks and fluxes estimates used for up-scaling and mapping bl					
Ann	ex III: Is	ssues affecting the reliability of the estimates	.74				
Ann	ex III: T	he Tier Concept	.77				

#### LIFE Blue Natura

**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 Soil Organic Matter (<2mm particle size)
COM Coarse Organic Matter (>2mm particle size)

PIC Particulate Inorganic Carbon

TIC Total Inorganic Carbon
GHG Greenhouse Gasses
tCO<sub>2</sub> 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<sup>9</sup> grams.

Mt Megaton, 1 million tons, 10<sup>12</sup> grams.

Pg = Gt Petagram = Gigaton, 10<sup>15</sup>. Common unit for the global carbon cycle.

C to CO<sub>2</sub> 1 g of Carbon equals 3.67 grams of CO<sub>2</sub>.

Yr Years

Km, ha, m<sup>2</sup> 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." (<u>LIFE</u>)

**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.

**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).

#### LIFE Blue Natura

**Saltflat or salina:** a flat expanse covered with salt or very salty waters and other minerals. In the area of study, they are originated by human action for salt production purposes, as artisanal or industrial salinas.

**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<sub>2e</sub>.

**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).

<sup>14</sup>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 <sup>14</sup>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.

<sup>210</sup>**Pb** age: age of a sediment layer estimated from its excess content in the radioactive isotope <sup>210</sup>Pb trapped with sedimentation. 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.

**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<sub>2</sub> 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, salt tidal saltmarshes, and seagrass meadows can remove and lock significant amounts of carbon for relevant periods of time resulting in very large carbon stocks (Duarte et al., 2005; Lo lacono et al., 2008; Mateo et al., 1997). These "Blue Carbon Ecosystems" (BCE) are considered an asset to reduce the CO2 concentration in the atmosphere and therefore mitigating climate change (Fourqurean et al., 2012; Hiraishi et al., 2013; Lavery et al., 2013). 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., 2015).

In the same way as each additional ton of CO<sub>2</sub> captured or not emitted by terrestrial forests can be traded within the regular or voluntary carbon markets (cap and trade approach), the CO<sub>2</sub> sequestered by BCE could be turned into tradable carbon credits via offsetting projects (Crooks et al., 2015; Hamrick and Gallant, 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<sub>2</sub> 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., 1998; Nellemann 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. And the corresponding results for saltmarshes, action C2, of which this report is the action deliverable).

In this report we present the results for this last Action (C2). 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<sub>2</sub> equivalents for other GHG) is stored/stocked in the biomass and sediments of the four Andalusian salt marshes? (stocks).
- 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. To guarantee adequate representativeness of the variability of the sink stocks and fluxes in Andalusian coasts, 49 cores from 1 to 2 m in length plus 3 soil profiles were taken at 24 stations (2 locations). This report also 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 (Herr et al., 2011; O'Sullivan et al., 2011).

The results here presented 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.

Addition with respect to C2.1: This report provides an updated inventory of the blue carbon stocks and fluxes in Andalusia, improving the characterization of its spatial variability (with new natural and transformed marsh typologies sampled during the complementary mission of

#### LIFE Blue Natura

autumn 2018) and the identification of the main factors influencing carbon sequestration, preservation, and past/future dynamics which may be relevant for carbon offsetting projects.

In addition, this report analizes the effects of saltmarsh degradation and recovery by several land-use changes on habitat carbon stocks and fluxes: desiccation, re-wetting, vegetation, revegetation, exploitation as salinas, and recovery after salina abandonment. In this way we aim at improving the knowledge basis for the monetization of saltmarsh conservation and restoration projects under climate mitigation policies.





# 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 the 2 tidal saltmarshes contemplated in the project, which are those of Cadiz Bay and Odiel Natural Parks:

**Odiel saltmarsh** is a bar built estuary in the confluence of the Odiel and Tinto rivers mouths, which is growing eastwards, parallel to the coastline, by the combined effects of the sediments transported by these rivers and the main coastal current sediment transport in this area (J. Borrego, 1997). Most of its surface is a non transformed saltmarsh (Thematic cartography of Odiel saltmarsh, A1.1 deliverable).

Cadiz Bay saltmarsh is mainly formed by the landward net sediment transport in that area, which coastline is perpendicular to the main eastward current, although there are also inputs from some small rivers (Gracia et al., 2017). More than half of the Cadiz Bay saltmarsh surface has been traditionnally exploited as artisanal salinas. Today, only one third of that surface is still being exploited for salt. Roughly another third has been transformed for aquaculture, and the rest have been abandoned, with varying degrees of restoration of the tidal influence (Thematic cartography of Cadiz Bay saltmarsh, A1.2 deliverable). Only 26% of the Cadiz Bay space consists in un-transformed tidal saltmarsh. Half of it is located towards the north, in the area called Los Toruños.

Following the design of action A3, we studied saltmarsh stocks and fluxes variability depending on the tidal immersion gradient (dependent on saltmarsh and tide height), identified by changes in vegetation and flora. Odiel (OD) and Toruños (TOR), were sampled at vegetated mid saltmarshes (stations ODE.M, in El Manto islet, and TOR.M, respectively) and high saltmarshes (stations ODE.H, in El Saltés islet, and TOR.H). At the low marsh we sampled in vegetated (ODM.L, in El Manto islet, and TOR.L) and un-vegetated (ODM.L-C, TOR.L-C) sediments. In addition to the natural gradient, we also explored at Odiel changes in carbon stocks and fluxes in a station of continentalized saltmarsh in the northern part of the site, with low influence of tidal regime. Within this area, we distinguished one part conserving typical high saltmarsh vegetation (ODN.D-V), and another of bare sediment (ODN.D-C), which would represent a degraded saltmarsh area, which is typically called "sterile saltmarsh" (Borrego, 1997). We also sampled an area called Llanos de Bacuta (ODB.Z), which had been dry before 1956, and which has been re-wetted by reconnection to the tidal regime since 2005. Finally, we sampled in an area close to the delta tip, which was planted with vegetation typical of mid marsh in 2012, after sediment movements to install a pipe (Sealine, ODL.R; Fig. 2.1).

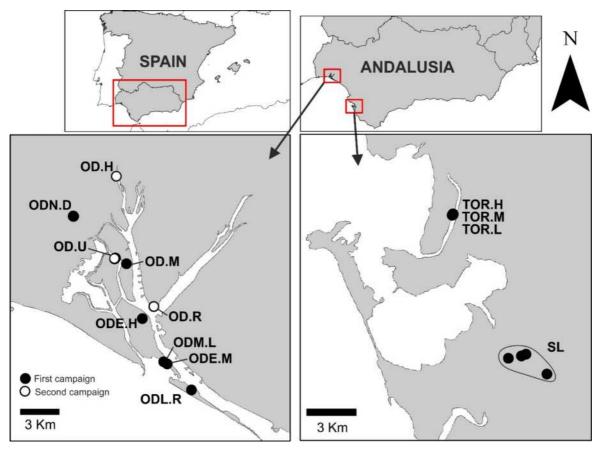


Fig. 2.1. Location of the salt-marsh and salt-flat stations sampled in 2016 and 2018 field missions

An aditional sampling field trip was performed on november 2018 to allow us to better understand the spatial variability of saltmarsh stocks and fluxes, and to identify the posibility of salina areas restoration. Four new stations were sampled on the Odiel saltmarsh: one in healthy high saltmarsh, dominated by *Arthrocnemum macrostachyum*, in the continentalized saltmarsh area of Manzorrales (OD.H, Table 2.1), two stations in the Enmedio island, at the intermediate saltmarsh section: one covered by midmarsh vegetation (OD.M) and one covered by the alien high marsh species *Spartina densiflora* (OD.UH), one un-vegetated subtidal channel station (Mojarrera channel, OD.U, Table 2.1), and 1 restored area replanted with the autochthonous low-marsh species *Spartina maritima* (OD.R, Punta del Sebo, Table 2.1). The restoration experiment of this area has been extensively studied by the group of Fernando Castillo, at the University of Huelva (e.g. Castillo and Figueroa, 2009).

In Cadiz bay, we sampled sediment carbon stocks and fluxes in:

- An active artisanal salina (El Águila, SL, Table 2.1), in 2 stations (1 core per station): the "estero" (core SL1), which is the first basin of the salina, the one with the lowest salinity, similar to that of the saltmarsh. The difference with the natural marsh is that the water is only allowed to come in when needed. Another important difference is that the basin is not allowed to fill-up, and that the sediments are periodically dredged. The second core was taken in the last evaporation basin, with higher salinities, attaining

the precipitation point (SL3). No tidal dynamics takes place, and it is also periodically dredged to collect the salt. Nevertheless, this basin had not been dredged for salt collection since 2010.

- An abandoned salina with low tidal influence: abandoned since at least 1956-57 (San Joaquin y Santa Ana, SL-C, Table 2.1): we sampled 2 cores in an ancient evaporation basin (SL-C1 and SL-C2)
- An abandoned salina since 1984-1985 with regular daily tidal influence (Santa Teresa, SL-CW, Table 2.1): we sampled 1 core in an evaporation basin (core SL-CW1), and 1 profile in the adjacent abandoned salina wall (SL-CWP1).

#### Low marsh ecological restoration in Punta del Sebo (ODR station):

The salt marsh restoration project was carried out from November 2006 to January 2007 in Odiel Marshes (S.W. Iberian Peninsula; lat 37°089–37°209N, long 6°459–7°029W; Castillo and Figueroa, 2009). The restored area, known locally as "Punta del Sebo," borders the main channel of the estuary. Before the installation of an industrial site in the 1960s, these marshes were used by Huelva citizens as a recreational area, originally occupied by multiple *Spartina maritima* tussocks. Previous to restoration of the marshes, the sediments were polluted with heavy metals (van Geen et al., 1997), and several oil deposits were found 1.5 m below the sediment surface due to historic oil spills from neighboring industries. Further- more, the South American neophyte *Spartina densiflora* Brongn., which colonizes a wide range of habitats and competitively displaces native species (Nieva et al., 2001), was actively invading these marshes and had already occupied 2.01 ha. Also, one location was suffering high erosion rates, evidenced by detachment of substrate blocks from an erosive bank (Castillo et al., 2002). The result was a degraded landscape dominated by unvegetated mudflats (Castillo and Figueroa, 2009).

Table 2.1 Saltmarsh stations, coordinates and typologies studied in these report.

Region /Province	Natura 2000 SAC	Location	Coordinates		Categories	Code	
El Odiel	ES0000025	El Manto Isle	37° 10,460` N 6°55,865'W		Low marsh, vegetated, healthy	ODM.L	
					Marine part		
El Odiel	ES0000025	El Manto Isle	37° 10,460`	6°55,865'W	Low marsh, un-vegetated, healthy	ODM.L-C	
			N		Marine part		
El Odiel	ES0000025	El Saltés	37° 12,228′	6° 57,081'	High marsh, vegetated, healthy	ODE.H	
					Mid part		
El Odiel	ES0000025	El Manto Isle	37° 10,373'N	6° 55,690'W	Intermediate marsh, vegetated, healthy	ODE.M	
					Marine part		
El Odiel	ES0000025	Llanos de Bacuta	37.24160°N	6.96730°W	Intermediate marsh, vegetated, rewetted	ODB.Z	
					Mid part		

#### LIFE Blue Natura

Region /Province	Natura 2000 SAC	Location	Coordinates	Categories	Code	Region /Province
El Odiel	ES0000025	Northen Odiel	37.27347°N	7.01543°W	High continentalized marsh, vegetated High part	ODN.D
El Odiel	ES0000025	Northen Odiel	37.27347°N	7.01543°W	High continentalized marsh, unvegetated, degraded (sterile marsh)	ODN.D-C
					High part	
El Odiel	ES0000025	El Manto Isle	37° 09,310'N	6° 54,357'W	Low marsh, vegetated, planted (living shoreline)	ODL.R
					Marine part	
El Odiel	ES0000025	Manzorrales, Odiel	37°18'08.2"N	6°58'45.6"W	Continentalized high marsh	OD.H
El Odiel	ES0000025	Canal Mojarrera, Odiel	37°14'43.0"N	6°58'37.4"W	Saltmarsh chanel	OD.U
El Odiel	ES0000025	Isla de en medio, Odiel	37°14'41.0"N	6°58'39.4"W	Low marsh	OD.UH
El Odiel	ES0000025	Isla de en medio, Odiel	37°14'41.4"N	6°58'39.4"W	Medium marsh	OD.M
El Odiel	ES0000025	Fe descubridora, Odiel	37°12'45.4"N	6°56'30.6"W	Restored low marsh	OD.R
Los Toruños	ES0000140	San Pedro River	36° 32,923'N	6° 12,597'W	Low marsh, vegetated, healthy  Marine Part	TOR.L
Los Toruños	ES0000140	San Pedro River	36° 32,923'N	6° 12,597'W	Low marsh, unvegetated, healthy	TOR.L-C
Los Toruños	ES0000140	San Pedro River	36° 32,923'N	6° 12,600'W	Marine part Intermediate marsh, vegetated, healthy Marine part	TOR.M
Los Toruños	ES0000140	San Pedro River	36° 32,919'N	6° 12,613′W	High marsh, vegetated, healthy, Marine part	TOR.H
Los Toruños	ES0000140	S. Joaquin y Sta. Ana, Cádiz	36°27'48.6"N	6°08'34.5"W	Abandoned dry salina	SL-C
Los Toruños	ES0000140	Salina del Águila,	36°28'22.5"N	6°09'38.0"W	Salina	SL
		Cádiz	36°28'26.3"N	6°09'27.0"W		
Los Toruños	ES0000140	Santa Teresa, Cádiz	36°28'17.0"N	6°10'09.5"W	Abandoned salina. High marsh vegetation	SL-CW

#### 2.1.1. Sampling the sediment carbon stocks

During the 2016 sampling field trip, in each selected station we obtained 3 replicate sediment samples, which consisted in manual gravity cores (21 to 159 cm long), with the exception of ODN.D-C, were only 2 sediment cores were taken. Additionally, in stations ODE.H and ODN.DV, one gravity core was substituted by a vertical profile.

During the 2018 sampling field trip, we obtained three replicate cores in OD.H and OD.R; two cores in the rest of stations, with the exception of ODU.H, where we only took 1 core. In SL-CW, the two cores were not pure replicates, as we obtained one core in the abandoned salina channel bottom, and 1 vertical profile in the adjacent abandoned wall. The same occurred in SL, where we obtained one core in the first (lowest salinity) basin, and another one in the last (highest salinity basin).

#### 2.1.2. Other carbon compartments

Most of the blue carbon in saltmarshes is accumulated in their sediments. Nevertheless, the IPCC protocols for carbon sinks and emissions always include the evaluation of the carbon pool sequestered in the plant living standing stocks (above and belowground plant biomass). Therefore, at each vegetated station we obtained 3 replicate plant biomass samples (within quadrats of 20x20cm, up to 2 cm thick belowground).

In total, during 2016, we sampled 12 stations in the 2 saltmarshes: 4 in Cadiz bay (area of Los Toruños), and 8 stations in Odiel saltmarsh (Huelva province). We collected 36 manual and 3 vertical profiles. As well as 30 biomass samples, and 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).

Additionally, 15 cores and 1 vertical profile were taken during the 2018 field mision. In 2018, we only took biomass samples in 1 vegetated station (OD.H). In total, we collected 51 cores and 4 vertical profiles (55 vertical soil samples), and 34 biomass samples, on emerged saltmarshes, a subtidal saltmarsh channel as well as active and abandoned saltflats.

Full details and pictures of those sites and stations, as well as pictures and main core characteristics and subsamplings, are available in the updated LIFE BN Deliverable A3 (Anejo A3 Deliverable Resultados muestreos en marismas andaluzas.pdf, 2017-2019).

#### 2.2. Laboratory analyses

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

For the cores taken in 2016, 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 50°C and subsequently weighted (for full details on subsampling procedures see LIFE BN, 2017 Deliverable A3). The other hemicore was kept as a back up, stored in darckness at 4° C.

Each dry-weighted subsample was disaggregated and coarse shells and stones (>2 mm) and gravel were separated and weighted. 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 <sup>210</sup>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).

As for the cores taken in 2018, at stations OD.H, OD.R and OD.M, there was also 1 main core, subsampled with more detail, and 1 or 2 replicate cores subsampled at 9 to 10 levels. For the rest of stations, all cores were considered main cores. Vertical subsampling of the main cores was also modified with respect to 2016 cores: the first 30 cm were subsampled each cm, and 3 additional 2 cm subsamples were taken along the rest of the core length. Coarse shells and stones were removed by hand, and the rest of material (< 2mm) was directly ground for chemical and radionucleid analyses, which were all performed in external laboratories.

The external standard sediment SETOC 776 served to detect and quantify any systematic difference in TOM or TOC quantificantions between our laboratory and the external laboratory contracted (HILO University, Hawaii).

#### a. Geochemical and biomass analysis

A 3-4 g fine (< 2mm) sediment aliquot was digested with 35 % H<sub>2</sub>O<sub>2</sub> 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 450°C 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 50°C. 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 marine sediment 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 (separating aereal and subterranean plant parts). Those fractions were dried and weighed.

#### b. Lead (210Pb) and radiocarbon (14C) 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 <sup>210</sup>Pb in excess, through measurement of its daughter element <sup>210</sup>Pb. In the same core, we selected 2-3 bulk samples 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.

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

TOM and TOC in saltmarsh soils present an excellent correlation, what allows to fit a linear regression and infer TOC content in all samples after their organic matter content ( $R^2 = 0.99$  to 0.46; p < 0.002; Table 2.2.). Hence TOC analyses was estimated in all levels sampled by direct analyses of by applying the given equation.

**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  $(g/m^3) = D^*(TOC\%/100)$ . This value was then multiplied by the area of the subsample (½ of the corer cross section) to express the stock per square area (cm², m², ha, etc.). The total stock per core was computed by adding the TOC content per unit area of all subsample slices and to 1 m core thickness (for inter-stations and inter-studies comparation 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 average TOC between succesive subsamples was integrated along the core length between both subsamples. The TOC content per unit area was added along the

#### LIFE Blue Natura

whole core and also to 1m sediment thickness, for the abovementioned comparative purposes.

Table 2.2. Regressions and correlation coefficients between Carbon and organic matter contents in each station.

Station	Total amount of samples	Samples analyzed for TOC	Equation	R2
ODM.L	68	23	y = 0.1852x + 0.4135	0.61
ODM.L-C	51	10	y = 0.1103x + 0.9136	0.55
ODN.D-C	93	29	y = 0.3558x - 0.4803	0.84
ODN.V	32	7	y = 0.3014x - 0.034	0.87
ODE.H	56	21	y = 0.1912x + 0.0098	0.83
ODE.M	48	9	y = 0.4511x - 1.4023	0.92
ODB.Z	59	12	y = 0.1727x + 0.6219	0.61
ODL.R	75	13	y = 0.3546x - 0.2192	0.95
OD.H	40	19	y = 0.5023x - 2.9306	0.99
OD.U	62	22	y = 0.1387x + 0.5689	0.46
OD.UH	32	11	y= 0.3734x - 1.9109	0.95
OD.M	42	22	y = 0.2827x - 1.0593	0.9
OD.R	33	12	y = 0.1281x + 0.705	0.72
TOR.L	77	17	y = 0.2891x - 0.5065	0.74
TOR.L-C	48	8	y = 0.2643x - 0.31	0.63
TOR.M	49	13	y = 0.5534x - 1.6236	0.7
TOR.H	39	7	y = 0.2983x + 0.2043	78
SL-C	12	33	y = 0.0193x + 0.1753	0.69
SL	17	8	y = 0.0988x - 0.7476	0.88
SL-CW	35	14	y = 0.4178x - 3.7198	0.96
TOTAL	986	310		

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

#### c. Chronological models

Replicate cores A for each station were dated with radiocarbon (<sup>14</sup>C) and lead (<sup>210</sup>Pb), in order to estimate the TOC flux to the soil (i.e., the rates of organic carbon sequestration) on them. Radiocarbon ages were used primarily for the models and were combined with the <sup>210</sup>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 Christeny, 2011; R Core Team, 2013). The age of the top most subsample of the core (the year of sampling: 2016 or 2017), was also considered in the model.

#### Accretion rates

The Soil Accretion Rate (SAR) was calculated as the length of core accreted per year.

Average carbon stock and dispersion for each station were estimated by constructing a "consensus core" from the three replicates. For that, average and standard deviation of TOC density was calculated from replicated subsamples. We considered as such, the sediment subsamples from the three replicate cores that had been taken at similar sediment depth levels. In the levels whithout replicated values, the TOC density value of the principal core (replicate A), was adopted. Standard deviation of the averaged sediment levels was also calculated. These standard deviations were combined though their coefficient of variation to estimate standard deviation of the carbon stock per unit area, at each replicated level. The average of these standard deviations of C stocks, conceptually equivalent to the standard deviation among groups in an ANOVA, was used as estimate of carbon stock horizontal variability within the station.

The long-term carbon fluxes into the sink were estimated by multiplying the carbon content of each sample by its accretion rate. The carbon fluxes have been estimated from the dated core of each station, along its whole length and for the last 100 years (as a worldwide standard core length). 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 by AMAyA for Odiel, and by the contracted enterprise Biogeos, for Cadiz Bay), a thematic cartography was compiled, integrating a number of sources and new observations undertaken in this project. GIS software allowed us to obtain the total areas covered by the various saltmarsh typologies for which the areal carbon stocks and fluxes have been estimated 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.





# 3. Results and Discussion

#### 3. Results and Discussion

The assessment of the organic carbon stocks and sequestration rates presented in this report is amongst the most detailed studies performed worldwide to date.

In Odiel and Cádiz saltmarshes, over 522 linear meters of soil (53 cores), from 2 sites and 19 stations, bearing or not a vegetation cover, have been scrutinized visually, physically and chemically.

As grand summary, the average organic carbon stocks accumulated in the top meter of non degraded saltmarsh soils in Andalusia range from to  $498.8 \pm 42.96(SE)$  tCO<sub>2</sub>/ha, in the medium marsh to  $177.5 \pm 86.1$  tCO<sub>2</sub>/ha in low marsh vegetated with *Sarcocornia spp.* (table 3.1, Fig. 3.1). This stock has been accumulating at the healthy saltmarsh in the last century at an average rate of  $0.9 \pm 0.2$  tCO<sub>2</sub>/ha yr<sup>-1</sup>, ranging from negative values in the eroding low unvegetated marsh of Los Toruños (Cadiz Bay) to 2.1 tCO<sub>2</sub>/ha yr<sup>-1</sup> in the neighbouring vegetated mid marsh, respectively (Fig. 3.1).

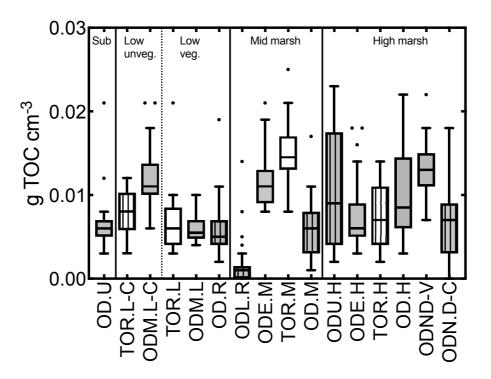


Fig. 3.1. Tukey boxes of carbon densities along the consensus cores of each saltmarsh station. White boxes correspond to marsh stations in Cadiz bay (Los Toruños), and grey boxes correspond to saltmarshes in Odiel. Plain boxes represent stations considered to be "healthy", and used to estimate the average and scale-up carbon stocks and fluxes of the different categories of wild marshes considered (subtidal, low marsh un-vegetated, low marsh vegetated, mid-marsh, and high marsh). Lined boxes represent stations that have suffered some kind of degradation or treatment: erosion (TOR.L-C, OD.M), mixing with arids (TOR.H), invasion by S. densiflora (ODU.H), planting (ODL.R), replanting (OD.R), or dessication-salination (ODN.D-C).

In the active salina, the average organic carbon stock  $142.8 \pm 116.5$  (SE) tCO<sub>2</sub>/ha was lower than in any healthy saltmarsh station. Nevertheless, the core taken in the first evaporation pond (the less salty) had very low carbon stock for the top meter of sediment (60.4 tCO<sub>2</sub>/ha) in comparison with the cristallizer pond (225.18 tCO<sub>2</sub>/ha), which had a carbon stock in its top meter similar to that in the low saltmarsh vegetated with *S. maritima* (Table 3.1, Fig. 3.1).

Scaling up these numbers by assigning the corresponding stocks and fluxes obtained in the field to the total area occupied by each bottom type in both saltmarshes (table 3.2), the weighted total stocks in the first meter sediment and average annual fluxes in the last century for both sites are of 2.14 MtCO<sub>2</sub> and 5.5 ktCO<sub>2</sub> yr<sup>-1</sup>, respectively.

Extending such aereal stocks and fluxes to the rest of tidal saltmarshes present in Andalusia (around 50.341 ha more, Vasquez-Loarte, 2017), we estimate a global stock of 18.4 Mt CO<sub>2</sub> in the top 1m sediment layer, and an average C flux to the sediment of 47 Kt CO<sub>2</sub> yr<sup>-1</sup> in the last century. The estimates for the stocks are probably underestimates, as the sediment organic carbon seem to continue far beyond the 1 meter sediment thickness; the actual total stock could easily duplicate the given estimate.

Comparing aerial pictures from 1956 to 2013, Vasquez-Loarte (2017) estimated that 41% of Andalusian coastal saltmarshes have been lost (2% per year on average between 1956 and 1998, and 1% per year on average from 1998 to 2013). This would suppose a concomitant loss of the carbon stocks and sink capacity of these areas, depending on the nature of the land use change. The main causes of saltmarsh loss have been agriculture (75%), salt industry (10%) and urban sprawl (5%).

A gigantic number of uncertainties and difficulties still prevail, most notably i) the types of saltmarsh explored are limited with respect to the large natural variability, especially with respect to different typologies of degraded saltmarshes, ii) the limited spatial information on the extent of different saltmarsh typologies in other andalusian coastal marshes, iii) the need to delimit the possible role of carbonate precipitation as a source of CO<sub>2</sub> to the atmosphere, iv) the need to explore the magnitude and sign of CH<sub>4</sub> and N<sub>2</sub>O fluxes, depending on salinity regime and organic and nutrient inputs in soils and watersheds (although there is some recent background information for Cadiz Bay (Burgos et al., 2017) and Doñana (Huertas et al., 2019) saltmarshes, or v) the complexity of determining the loss of service following different types of habitat destruction, to mention some. Nevertheless, the various typologies assessed here, constitute an important step forward in providing sound criteria for saltmarsh management and for deciding the best settings to guarantee the success of eventual compensation projects, both in restoration and in emissions avoidance initiatives. These results also provide a baseline for future estimations of changes in carbon stocks and fluxes, through stock difference and/or gain-loss methods, as specified by IPCC (2006 and 2013).

Table 3.1. Averages and standard deviations of Carbon stocks (in the canopy biomass as well as in the top 1 meter soil, in t CO<sub>2</sub> ha<sup>-1</sup>), of Sediment Accretion Rates (SAR, in cm yr<sup>-1</sup>) and carbon fluxes in the last century (t CO<sub>2</sub> ha-1 yr-1) in the different wild saltmarsh stations studied, saltmarsh types following their elevation and vegetation, as well as their horizontal position in the estuary, are presented.

Type of bottom	Vegetation Type	Saltmarsh part	Predominant species	Code	Aerial biomass TOC Stock tCO <sub>2</sub> /ha	SD	TOC Stock1m tCO <sub>2</sub> /ha	SD	SAR100yr cm/yr	SD	TOC flux100yr tCO <sub>2</sub> / ha yr	SD
Odiel wild	High continentalized	Continentalized	Several + S. densiflora	ODND-V	37.2	14.5	492.8	127.9	0.20	0.05	0.89	0.53
	High continentalized	Continentalized	A. macrostachyum	OD.H	21.5	10.3	209.1	32.8	0.10	0.05	0.72	0.13
	High Vegetated	Intermediate	Several, eveness	ODE.H	19.0	7.6	264.4	141.7	0.29	0.14	0.66	0.33
	High vegetated	Intermediate	Spartina densiflora	ODU.H	44.8	22.3	243.9					
	Medium Vegetated	Intermediate	Sarcocornia sp.	OD.M			177.5	86.2				
	Medium Vegetated	marine	Sarcocornia sp.	ODE.M	13.1	7.6	424.4	181.4	0.96	0.70	4.58	3.36
	Low unvegetated	marine	-	ODM.L-C	0		450.8	103.0	0.32	0.11	1.10	0.24
	Low vegetated	marine	Spartina maritima	ODM.L	24.7	8.4	217.6	118.7	0.27	0.06	0.38	0.20
	Subtidal cannel	medium	-	OD.U	0		256.6	59.2				
Cadiz bay wild	High vegetated	marine	Several, eveness	TOR.H	9.9	6.7	286.8	155.3	Erosion or	arids ad	dition	
,	Medium vegetated	marine	Sarchocornia spp.	TOR.M	18.8	4.7	573.2	192.6	0.42	0.13	1.98	1.03
	Low unvegetated	marine	-	TOR.L-C	0		297.5	134.6	Erosion			
	Low vegetated	marine	Spartina maritima	TOR.L	6.0	2.2	232.3	112.1	0.21	0.08	0.49	0.38

#### 3.1. Main geochemical variables estimated

Data on bulk density, sediment accretion rate, total organic matter, total organic carbon, total organic carbon flux, total inorganic carbon, and granulometric distribution are characterized and plotted against sediment depth and age (see Annex III, cores sampled on 2016). Grainsize distribution is similar at all stations, with predominant fractions of mud and fine sands along the cores. The only exception is the planted station of Odiel (ODL.R), which is sandy almost in all its profile, with the exception of the top 10 cm (the roots horizon). The low sediment porosity of these fines-dominated soils would contribute to the conservation of organic matter, by reducing oxygen penetration (Sawstrom et al, 2016). Bulk density increased with depth, as expected by soil consolidation and compresion, except in some cores from stations ODB.Z, ODU, SL and ODN.D-V ODN.D-C (Annex C2.2-I), that is, the stations which are or have been disconnected from the tidal regime, the subtidal station, and the salina, with other patterns to be exposed in the two following sections. In the active salina, bulk density increased from the top to 30 – 40 cm, and decreased below.

TOM% and TOC density distributions along the cores showed large variablility among stations and sites, reflecting the high temporal and spatial dinamism of the ecosystem and of sediment carbon degradation. Organic matter and organic carbon decreased exponentially with sediment depth in SL-CW, TOR.L, OD.H, ODE.H, ODU.H, OD.M, ODE.M and ODL.R (see profiles in Annex C2.2.-I). This decrease model could allow us to estimate the total carbon sink by extrapolation, if the depth of the bedrock was known, and supposing that the measured rate of carbon content decline with sediment depth is maintained beyond the sediment thickness explored. The use of high resolution sub-surface seismic profilers (Lolacono et al 2008) could provide that information. In some stations TOM% and TOC density only decreased in the deeper soil sections (SL1, SL3, SL-C, ODB.Z, Annex C2.2-I), which also may allow us to extrapolate the carbon stock to the bedrock level, although with less confidence. In the rest of stations TOM% and TOC% did not decrease with sediment depth (ODU, ODM.L, ODM.L-C, ODN.D-C, ODN.D, OD.R, TOR.L-C, TOR,M and TOR.H, Annex C2.2-I). In these cases, the lack of a monotonous decline in sediment carbon content, precludes extrapolation of data to estimate the total carbon stock.

The <sup>210</sup>Pb profiles were essential in order to estimate recent accretion rates, and to diagnose erosive or vertical mixing patterns in the top 50 cm of sediment, which in some cases could be related to land-use. In some stations near the Rio Tinto (ODE.M, OD.U and OD.R) the atmospheric <sup>210</sup>Pb decline profile was masked by large Pb river loadings from Fertiberia phosphogypsum deposits leaking into the river since 1968 (Illera et al., 2004). But in ODE.M and OD.R, a sharp reduction in <sup>210</sup>Pb loading was detected (although still well above the natural background), and we associated it to year 1997, when a Law-enforced improvement in residual management presumably reduced Pb inputs to the river (CMAOT, 2009). Therefore, this milestone date allowed us to obtain 1 recent layer dating, to add to the <sup>14</sup>C core age model.

In natural saltmarshes from Odiel and Cadiz, the core age models based on <sup>210</sup>Pb and <sup>14</sup>C yielded high accretion rate estimates in the top sediment layers, that were reduced and estabilized below, something that could also be expected from soil consolidation and compaction. The vertical limit between high and low accretion rates seems to be deeper and broader in the low and mid marsh (123 cm in ODM.L, 35 cm in ODM.L-C and TOR.M), and shallower and sharper in the high marsh (16 cm in ODE.H), and as a result, the average core

sediment accretion rates were higher in low and mid marshes, as compared to high marshes. That transition in accretion rates is probably reflecting the transition in sedimentary and diagenetic processes, including the influence of vegetation.

As a consequence of the higher accretion rates and higher carbon densities in the sediment top, the average recent organic carbon flux was significantly higher than the average ancient, estabilized organic carbon flux (both *t*-test and Wilcoxon test:  $p < 10^{-4}$ ; median TOC flux<sub>100yr</sub> was 214% higher than the median TOC flux<sub>>100yr</sub>; CI 95%: 119% to 257%).

## 3.1.1. The complex interplay between marsh horizontal and vertical variability and gradients

The expected (hypothesized) variability in carbon stocks and fluxes associated to saltmarsh tidal regime and its associated vegetation has been confirmed, and the within site horizontal variability seems to be more important than horizontal differences between sites. Nevertheless, within Odiel saltmarsh there is also an important horizontal variability, which probably has to do with the antiquity of the saltmarsh and/or its depositional dynamics:

#### Low marsh:

Low intertidal un-vegetated sediment banks in Odiel (El manto, ODM.L-C) had low bulk densities, which reached 1 g cm<sup>-3</sup> between 62 and 70 cm depth in the three replicate cores (annex C2.2-I). Nevertheless, they had high soil organic matter concentration (Annex C2.2-I), and organic carbon densities (Fig. 3.1) and consequently high 1m organic carbon stocks (TOC stock<sub>1m</sub> =  $451 \pm 103(SD)$ ), similar to carbon densities and stocks in the mid-marsh ODE.M and TOR.M (Fig. 3.2, Table 3.1). ODM.L-C also had high accretion rates (SAR<sub>100yr</sub>=  $3.2 \pm 1.1(SD)$  mm yr<sup>-1</sup>) and organic carbon fluxes (TOC flux<sub>100yr</sub> =  $1.10 \pm 0.24$  tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>; Fig. 3.2, Table 3.1). The bulk organic matter at the sediment layer at 82 cm depth yielded a <sup>14</sup>C age of 937  $\pm$  30 yr BP, which is relatively recent (see further).

The adjacent low marsh patches of *Spartina maritima* (ODM.L) had similarly low bulk densities, which reached 1 g cm<sup>-3</sup> between 48 and 152 cm depth (annex C2.2-I). The main core from this station reached 259 cm, the longest taken in this study in saltmarshes. However, they had lower organic carbon concentration (annex C.2.2-I), lower carbon densities (Fig. 3.1), and consequently lower carbon stocks (TOC stock<sub>1m</sub> = 218  $\pm$  119(SD)). It also had similar recent accretion rates (SAR<sub>100yr</sub>= 2.7  $\pm$  5.8(SD) mm yr<sup>-1</sup>) and lower recent carbon fluxes (TOC flux<sub>100yr</sub> = 0.38  $\pm$  0.20 tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>; Fig. 3.2, Table 3.1) than ODM.L-C.

This was unexpected, because it has been demonstrated experimentally that *S. maritima* increases sediment accretion (Castillo and Figueroa, 2009). In fact, the core age model of ODM.L core, based on  $^{210}$ Pb and  $^{14}$ C dating, showed younger sediments at higher depth (at 119 cm:  $590 \pm 29$  yr BP; annex C2.2-I) than in ODM.L-C, and accretion rates in the whole core ODM.L-C (SAR =  $1.7 \pm 0.9$ (SD) mm yr<sup>-1</sup>) were smaller than in ODM.L, at equivalent core length (123 cm; SAR =  $3.7 \pm 1.0$ (SD) mm yr<sup>-1</sup>), showing that in the long-term, *S. maritima* patches

enhance sedimentation. On both cores, carbon density increased with sediment depth ( $R^2$ = 0.47 to 0.51, p< 10<sup>-4</sup>), but in ODM.L-C, it increased 7 times faster. As a result, the long-term carbon fluxes were not significantly different (TOC flux<sub>ODM.L-C</sub> = 0.85  $\pm$  0.35(SD) tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>; TOC flux<sub>ODM.L</sub> = 0.72  $\pm$  0.21(SD) tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>). The lower sediment carbon densities, stocks and fluxes in ODM.L could be produced by *S. maritima* enhancement of organic matter mineralization through its aerobic rhizosphere, which is maintained by the plant roots pumping oxygen (Duarte et al., 2009).

In Los Toruños (Cádiz Bay), sediment bulk densities were even lower: in the low intertidal unvegetated sand banks (TOR.L-C) reached 1 g cm<sup>-3</sup> between 67 and 110 cm, while in the the low *S. maritima* patches (TOR.L), 1 g cm<sup>-3</sup> was reached between 66 cm and beyond 186 cm. In contrast with Odiel low marsh, TOC density and TOC stock<sub>1m</sub> of TOR.L-C were similar to those of TOR.L (Fig. 3.2), and TOC density of TOR.L-C was significantly lower than TOC density at TOR.M (Fig. 3.1). The <sup>210</sup>Pb profile, combined with the XRF data of the top 50 cm of TOR.L-C sediment, indicated that the low un-vegetated marsh in Los Toruños (Cadiz bay) is under erosion, something that has been reported in the literature for the river San Pedro estuary (Benavente et al., 2006; Gútierrez-Mas and García-López, 2015). So that, the carbon flux could not be estimated for the un-vegetated low marsh station TOR.L-C with our reconstructive method. However, the erosion is probably producing a net carbon stock loss and net emissions of CO<sub>2</sub> to the atmosphere, as suggested by it having lower TOC stock<sub>1m</sub> than ODM.L-C and TOR.M, and similar to those of TOR.L.

In the adjacent vegetated station (TOR.L), the  $^{210}$ Pb profile indicated that sediment accumulation was still taking place (Annex C2.2-I), yielding positive accretion rates for the last century, similar to those in ODM.L (SAR<sub>100yr</sub> =  $2.1 \pm 0.1$ (SD) mm yr<sup>-1</sup>; Fig. 3.2, Table 3.1). This indicates that the remaining *S. maritima* patches are locally preventing loss of the sediment carbon stock, and even increasing it, but that they are unable to prevent the loss of the adjacent sediment banks, probably due to the very low extension of the *S. maritima* patches.

Erosion in the low sediment banks could have increased since the decimation of *Z. noltei* and *S. maritima* meadows in the low intertidal, following water pollution (Brun et al., 2003; Gútierrez-Mas and García-López, 2015), as both species retain sediments (Castillo et al., 1999).

Therefore, from results in Odiel and Cadiz Bay, we may conclude that the low intertidal sediment banks may have larger carbon stocks<sub>1m</sub> and fluxes<sub>100yr</sub> than adjacent *S. maritima* patches, but these stocks and fluxes rely partially or totally -depending on the local hydrodynamic conditions- on the abundance of low intertidal vegetation around it, due to their sediment-retention ecosystem function.

#### Mid marsh:

In both sites, Los Toruños (Cádiz Bay) and in Odiel, the highest sediment organic carbon densities and TOC stocks<sub>1m</sub> among natural saltmarshes were observed in the mid-marsh areas vegetated with *Sarcocornia spp.* (TOR.M and ODE,M) 498.8  $\pm$  105.2(SD) tCO<sub>2</sub> ha<sup>-1</sup> (Annex C2.2-II). The highest accretion rates and organic carbon fluxes for natural marshes

was also measured in mid-marshes (TOC flux<sub>100yr</sub> =  $3.28 \pm 1.84$  tCO<sub>2</sub> ha<sup>-1</sup>yr<sup>-1</sup>, Annex C2.2-II, see station estimates at Fig 3.1 and table 3.1).

In ODE.M, the sediment layer at 75 cm was buried only  $80 \pm 23 (SD)$  yr BP, and only 35 cm deeper (105 cm),  $730 \pm 32 (SD)$  yr BP. The sediment bulk density profile was consistent with a recent burial and this sharp age transition: it remained low (between 0.4 and 0.6 g cm- $^3$ ) until the 92 cm layer, and sharply increased thereafter, to reach 1.3g cm- $^3$ , at 106 cm (Annex C2.2-I). Our core age model situated the cm 92 sediment layer in year 1704 AD (246 years BP). In TOR.M, the sediment bulk density showed a more steady increase with sediment depth, but it also followed changes in the core-age slope with core depth (Annex C2.2-I).

In addition to the ODE.M station, sampled in the marine part of the estuary (El Manto), which is also the youngest (Borrego, 1997) we sampled another mid-marsh station in 2018, at the intermediate Estuary (Isla de Enmedio. OD.M). In OD.M, the narrow mid marsh band vegetated with *Sarcocornia spp.* carbon stocks were significantly lower than in ODE.M, and were more similar to those of EL Manto low marsh, vegetated with *S. maritima* (ODM.L, Table 3.1, Fig. 3.1). Moreover, the OD.M sediment layer at 81 cm was much older than in ODE.M and TOR.M ( $3653 \pm 28(SD)$  yr BP), and the  $^{210}$ Pb profile of the top layers indicated that erosion has taken place in the last decades, although a slight increase in  $^{210}$ Pb in the top 10 cm suggests that sediment accretion may be resuming (Annex C2.2-I). The sediment density was also higher in OD.M: at 10cm it had already reached 1.2 g cm<sup>-3</sup>, only reached at 106 cm and 163 cm depth at ODE.M and TOR.M, respectively.

The organic carbon richness of OD.M was similar to that in ODE.M only in the top 10cm, and decreased sharply below that depth (TOC%, Annex C2.2-I). This is compatible with a greater sediment age below 10 cm and the presence of necromass and belowground organs biomass in the soil top. At the landscape scale, in Isla de Enmedio, *Sarcocornia spp.* mid-marsh formed a narrow band (1 to 10 meters) of *Sarcocornia spp.* vegetation, bordering the Isla de Enmedio, and fringed by steep sediment banks, with little presence of *S. maritima*, while the mid marsh in ODE.M formed a much wider and flat band of one to several hundred meters, indicative of a depositional dynamic (see landscape pictures in updated A3 deliverable).

Aerial pictures show that in this part of the Enmedio island, the coastline receded 12.8 m between 1956 and 2016. Such erosive dynamics has been combatted and documented by the Odiel natural park. This makes us hypothesize that the smaller TOC stock found at OD.M could be the consequence of an erosive process in the past decades. Knowing that the causes of this erosion were mostly anthropogenic (one would be the increased wave energy on marsh borders, due to boat traffic in the channel; E. Martinez-Montes, *pers. comm.*), we chose not to use this station to estimate the average carbon stock for mid-marshes in natural conditions.

TOC flux<sub>100yr</sub> was not estimated for OD.M for this station, because of the lack of reliable estimates of recent accretion rates.

#### High marsh:

In high marshes, soil bulk density generally increased faster with soil depth than in low and mid marshes: in the two cores taken in continentalized saltmarshes colonized with *Arthrocnemum macrostachyum* (cores ODN.D-V\_B and OD.H\_1), it reached 1g cm<sup>-3</sup> near the core top (at 5.3 and 11 cm respectively), while in the 2 cores taken in saltmarshes colonized by the invasive *S. densiflora*, (ODN.D-V\_A, and ODU.H at the continentalized and intermediate estuary saltmarsh, respectively), bulk densities above 1 g cm<sup>-3</sup> were observed at 53 and 35 cm, respectively. Only in TOR.H station a mid-high saltmarsh situated in the marine-intermediate estuary of the river San Pedro (Los Toruños, Cadiz Bay), bulk densities

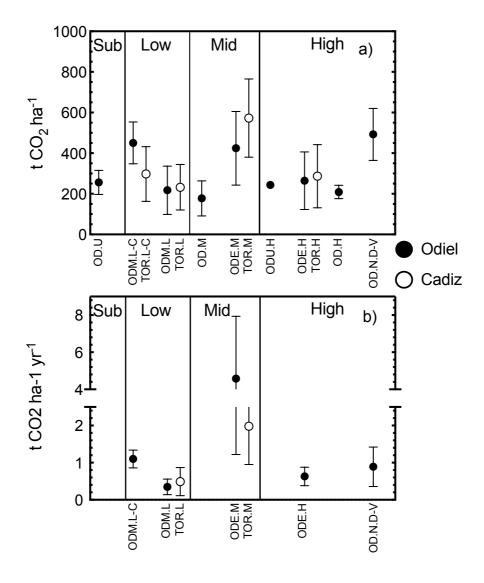


Fig. 3.2. Variability in a) organic carbon stocks in the first meter sediment and b) organic carbon fluxes in the last century, expressed in tonnes of CO<sub>2</sub> per hectare, and tonnes of CO<sub>2</sub> buried per hectare and year. Dots represent average stock values per station or average flux per 100 years in the main core, and bars represent standard deviation. Black dots represent estimates in Odiel saltmarsh stations, and white dots in Cadiz Bay (Los Toruños) saltmarsh stations.

surpassed 1 g cm<sup>-3</sup> below 76 to 100 cm. Organic carbon stocks in the soil top meter were similar to estimates in the low intertidal marshes, but the carbon was much more ancient, with ages at 1m meter depth between 980 and 2553 yr BP (OD.H1 and ODN.D-V\_B, respectively).

High saltmarshes were the ones showing less horizontal variability in carbon stocks (Fig. 3.2a, Table 3.1), maybe reflecting their greater sedimentary stability. In Odiel, the carbon stocks in the top meter of high saltmarsh from the marine-intermediate estuary (ODE.H in El Saltés Island) and the continentalized estuary (OD.H in Manzorrales and ODN.D in Aljaraque) sections were similar. Both continentalized stations showed the same kind of vegetation, as well as sterile saltmarsh areas. OD.H cores were taken on *A. macrostachyum* vegetation, situated between the sterile marsh and a band colonized by the alien saltmarsh species *S. densiflora*. Aerial pictures between 1956 and 2016 show that the area where the cores were taken was continually covered by this kind of vegetation, and that the emerged land has locally gained 51 meters to the channel, although they have been colonized by *S. densiflora*.

The sediment carbon stocks measured in Los Toruños mid-high saltmarsh (TOR.H) were also similar to those measured in Odiel high saltmarshes. Therefore, we pooled the 5 stations estimates to yield an average estimate for carbon stock in the top soil meter of Andalusian high saltmarshes of  $275.5 \pm 62.1 \text{ tCO}_2 \text{ ha}^{-1}$  (Annex C2.2-II)). The carbon stock in the aerial biomass parts was 10 times lower than in the sediment (22.0 tCO<sub>2</sub> ha<sup>-1</sup>  $\pm$  4.3m, Annex C2.2-II).

The sediment carbon stock measured in 1 core of Enmedio Island, in an area vegetated with the high saltmarsh invasive species *Spartina densiflora* (ODU.H), near to OD.M, was similar to that measured in the rest of the high saltmarsh stations. The <sup>210</sup>Pb profile showed an accretion curve. But to date, there are some subsamples to be analysed, and the profile was incomplete to estimate accretion rates from it.

#### Subtidal channel:

The shallow subtidal sediment banks in the Mojarrera channel (intermediate estuary section, in front of Enmedio island), had low bulk densities: in one core, (ODU.1), it varied between 0.24 and 0.48 g cm<sup>-3</sup>, and it did not increase with sediment depth in the whole core length (85 cm). In the other core, bulk density increased slowly until 80 cm and faster then after, attaining 0.82 g cm<sup>-3</sup> at the bottom core, of 100 cm (annex C2.2.-I). Organic carbon densities (Fig. 3.1) and stocks (256.6  $\pm$  59.2 tCO<sub>2</sub> ha<sup>-1</sup>; Fig. 3.2a, Table 3.1) were low and similar to those found in the low intertidal vegetated saltmarshes (ODM.L, TOR.L). As the subtidal sediment banks were un-vegetated, the canopy biomass carbon stock compartment was 0.

## 3.1.2. Short-term vs long-term TOC fluxes in natural saltmarsh (cores) sediments and its potential use for conservation status diagnoses

In almost all cores from undisturbed marsh areas for which we could estimate recent accretion rates with <sup>210</sup>Pb dating, we observed higher accretion rates in the core top, with the exception of ODM.L. The greatest organic carbon densities were also found in the core top for most of the cores. As a result, TOC fluxes reconstructed from sediment accretion rates and TOC densities, are greater in the shallower and more recent sediment layers, with the exception of ODM.L. This vertical pattern is common in blue carbon deposits: we can differentiate an horizon of less compacted material, containing fresh organic matter and belowground plant organs, and another horizon of older, more recalcitrant organic matter (Belshe et al, submitted).

The two horizons often coincide approximately with the 100 years sediment age threshold, which is also an important time threshold for climate change mitigation policies. This is why we estimated average centennial organic carbon fluxes (TOC flux $_{100yr}$ ), from accretion rates and organic carbon densities in all the sediment layers accumulated in the last century, as well as the millenary organic carbon fluxes (TOC flux $_{100yr}$ , Table 3.2). In the natural saltmarshes examined in this study, we found that the centennial carbon flux was significantly higher than the millenary carbon flux (Mann-Whitney and Kolmogorov-Smirnoff tests:  $p < 10^{-4}$ ). The average TOC flux $_{100yr}$  was 338% of the average TOC flux $_{100yr}$ . The median TOC flux $_{100yr}$  was 161% of the median TOC flux $_{100yr}$  (95% C.I: 213% to 481%).

Some kind of ratio between centennial and millenary carbon fluxes in healthy saltmarshes could be used as a yardstick to compare temporary patterns in degraded or recovered saltmarsh soil sinks, although it cannot be used alone or as a definitive diagnostic means, as we have seen that healthy saltmarshes like ODM.L may fall outside that 95% confidence interval, while degraded saltmarshes like ODN.D-C may fall within, as we will see below. Nevertheless, used in conjunction with other core patterns, like vertical profiles of bulk density and <sup>210</sup>Pb, or, ideally, comparison with control stations, or before/after samplings, it may provide useful clues about how much the present carbon sink has been affected by a landuse change.

Centennial TOC fluxes do not have to be dismissed from carbon sinks evaluation, even though it includes carbon that will be mineralized within the century: we have to consider that, if the blue carbon habitat maintains its carbon sink function, it will always have this short-term (centennial) carbon sink added to the long-term (millenary) one. On the contrary, when a blue carbon habitat is altered, both carbon sinks will be affected.

Table 3.2. Comparison of medium-term (last century) and long term (more ancient than 100 years) TOC fluxes (t  $CO_2$  ha<sup>-1</sup> yr<sup>-1</sup>) reconstructed along cores with age models based in medium ( $^{210}$ Pb) and long-term ( $^{14}$ C) dating techniques. The ratio of both carbon fluxes are also shown. In bold when they are greater than the whole core coefficient of variation of carbon flux. Finally, the average ( $\pm$  Standard Deviation) carbon flux is also shown.

	TOC flux <100yr	SD	TOC flux > 100yr	SD	Flux % (<100/>100yr)	Average core TOC flux	SD	CV% complete core
ODE.M	4.6	3.4	0.7	1.4	615%	2.0	3.5	116%
_						3.0		
TOR.M	2.0	1.0	0.8	0.3	252%	0.9	0.6	67%
ODM.L ODM.L-	0.4	0.2	0.7	0.2	52%	1.7	2.1	124%
C	1.1	0.2	0.8	0.3	141%	0.8	0.3	41%
TOR.L ODE.H ODN.D- V	0.5 0.7 0.9	0.4 0.3	0.4 0.2 0.1	0.2 0.1 0.1	138% 430% 757%	0.4 0.3	0.3 0.3 0.5	71% 101% 223%
ODN.D- C	0.6	0.5	0.2	0.1	321%	0.2	0.3	109%
ODB.Z	1.0	0.2	0.9	0.3	115%	0.7	0.4	53%
SL-CW	0.9	0.1	0.3	0.4	311%	0.4	0.4	103%

### 3.1.3. Effects of some land-use changes in saltmarsh carbon stocks and fluxes

#### Disconnection from the tidal regime (desiccation): sterile saltmarsh

The area of the continentalized high saltmarsh near Aljaraque, despite is now barely influenced by the tidal regime, and is partially un-vegetated ("sterile marsh"), due to salination process, had the highest carbon stocks among high marshes, comparable to those measured in the marine estuary natural marsh (ODE.M), at least where it retained its high-marsh vegetation cover (ODN.D-V, Fig. 3.2, Table 3.1). Nevertheless, its disconnection from the regular tides seems to have been stronger in the past: Aerial pictures (REDIAM) show larger extension of the sterile marsh in 1956 and 1983, and the initiation of a recovery of the marsh vegetation in the 1997 picture.

In the area where vegetation was lost since at least 1956 (ODN.D-C), and has remained unvegetated until nowadays, the sediment carbon density was significantly lower than in the vegetated station ODN.D-V (t-test, p< 0.001, Fig. 3.1), although the carbon stock (TOC stock<sub>1m</sub>

= 216.8  $\pm$  107.4(SD) t CO<sub>2</sub> ha<sup>-1</sup>) and reconstructed flux (TOC flux<sub>100yr</sub> = 0.59  $\pm$  0.46(SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>; Table 3.2) at ODN.D-C were still high.

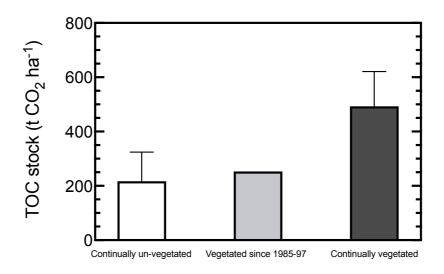


Fig. 3.3. TOC stocks in the top soil meter of different cores and profile taken in the area permanently un-vegetated since at least 1956, in the area permanently vegetated, since at least 1956, and in the area spontaneously re-colonized with A. macrostachyum since 1985-1997.

The aerial pictures show that one of the cores of the vegetated station (ODN.DVmid, taken in an area covered with *Arthrocnemum macrostachyum*), was devoid of vegetation until a moment between 1983 and 1997. The carbon stock in such core was much more similar to that of the un-vegetated main core ODN.D-CA than to the other cores 2 cores of the vegetated station, taken in points which have been permanently (at least since 1956) vegetated (Fig. 3.3). Therefore ODN.DVmid core was excluded from the global estimates of wild high marsh TOC stocks, used for up scaling carbon stocks to Andalusian saltmarshes.

At both sub-stations, but especially at the un-vegetated one, sediment bulk density increased downwards to a certain layer, and then decreased (annex C2.2-I): in the recently vegetated soil core ODN.D-Vmid, the maximum bulk density (1.61g cm<sup>-3</sup>) was at 23-27 cm soil depth, while in the un-vegetated core ODN.D-CA, the maximum bulk density (2.12 g cm<sup>-3</sup>) was observed at 45 cm soil depth, while in the permanently vegetated cores, bulk density increased until at least cm 92, and reached a maximum bulk density of 1.20 g cm<sup>-3</sup>. This suggests that desiccation may favor some compaction in the shallower soil horizons.

TOC flux in the last century was not significantly different between ODN.D-Vmid (TOC flux< $_{100y}$  =  $0.89 \pm 0.53$ (SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>) and ODN.D-CA (TOC flux< $_{100y}$  =  $0.59 \pm 0.46$ (SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>; Mann-Whitney test: p= 0.7). However, if we focus in the top 7 cm of both cores (2 to 3 slices, insufficient to perform a test), the reconstructed TOC fluxes yield that in the recently vegetated ODN.D-Vmid core, sediment has accumulated faster (since 1985), with carbon fluxes between 22 and 89 g TOC m<sup>-2</sup> yr<sup>-1</sup>, while in the un-vegetated ODN.D-CA core, they

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have accumulated slower (since 1965), with reconstructed carbon fluxes ranging between 3 and 7.5 g TOC m<sup>-2</sup> yr<sup>-1</sup>. If we look at the SAR and TOC fluxes since 1997, the year when ODN.D-Vmid starts to appear vegetated in aerial pictures, this latter core showed SAR 1.75 times greater and TOC fluxes 19 times greater than in the permanently un-vegetated core ODN.D-CA (SAR: 0.25 vs 0.14 cm yr<sup>-1</sup> and TOC flux: 55.2 vs 2.9 g TOC m<sup>-2</sup> yr<sup>-1</sup>, for ODN.D-Vmid and ODN.D-CA, respectively).

Increased salinities in dried marsh areas usually preclude vegetation to colonize the soil. Therefore, this natural recolonization by *A. macrostachyum* usually requires a previous removal of salt in the soil, through re-establishment of the tidal regime, or increased freshwater runoff. In that case, we do not know the cause of plant re-colonization process. Anyway, it seems that saltmarsh re-wetting and plant re-colonization are enhancing carbon flux to the sediment.

Table 3.3. Carbon stocks (in the canopy biomass as well as in the top 1 meter soil, in t CO<sub>2</sub> ha<sup>-1</sup>) and average Sediment Accretion Rates (SAR, in cm <sup>yr-1</sup>) and carbon fluxes in the last century (t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>) in saltmarshes transformed by some land-use change. Saltmarsh types following their elevation and vegetation, as well as their horizontal position in the estuary, are presented. SAR value in italics comes from Curado et al (2013). "Estero" means the water stock basin of the salina, the first in the circuit; "Cristalizador" is the last evaporation basin of the salina, the one from which the salt is collected. "Caño" means a salina water channel in the evaporation circuit. "Muro" means "wall", made of soil from the basin and other materials, stacked in the borders.

Type of bottom	Vegetation Type	Saltmarsh /salina part	Predominant species	Code	Aerial biomass TOC Stock tCO <sub>2</sub> /ha	SD	TOC Stock1m tCO₂/ha	SD	SAR100yr cm/yr	SE	TOC flux after tCO <sub>2</sub> / ha yr	SD
Odiel dry	Sterile	High	-	ODND-C	0		216.8	107.4	0.12	0.04	0.59	0.46
Odiel reweted	Medium vegetated	Intermediate	Sarcocornia spp.	ODB.Z	4.2	1.4	609.5	240.4	0.13	0.03	1.04	0.19
Cadiz Salina	-	All		SL	0		142.8	116.5			0	0
	-	Estero		SL1	0		60.4				0	0
	-	Cristalizador		SL3	0		225.18				0	0
Cadiz Wet abandoned salina		All		SL-CW			199.2	116.7			0.92	0.11
		Caño		SL-CW1			281.7				0.81	0.11
		Muro		SL-CWP1			116.7				-	-
Cadiz Dry abandoned salina		All		SL-C + SL-CWP1			148.8	45.4			-	-
		caño		SL-C			182.1	101.7			<0.1	
Odiel planted	Medium living shoreline	Marine	Sarcocornia sp.	ODL.R	21.2	12.8	56.1	34.0	1.8	0.2	6.64	2

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Odiel planted	Low revegetated	Marine-	Spartina	OD.R	242.5 117.4	2.3	3.61 2.04
	saltmarsh	Intermediate	maritima	02	242.5 117.4		3.01 2.01

#### Re-wetting and natural re-colonization:

The TOC stocks in the top sediment meter, measured in the recently re-wetted area of the Llanos de Bacuta Island (ODB.Z, intermediate estuary;  $609.5 \pm 240.4$  t CO<sub>2</sub> ha<sup>-1</sup>, Table 3.3) were surprisingly high -and higher than in the wild mid-marsh colonized with *Sarcocornia spp.*, in El Manto (marine section of the Estuary, ODE.M, Table 3.1)- for an area which has been dry and un-vegetated between at least 1956 (the year when the first aerial picture of the area was taken) and 2004. This area has been naturally colonized by typical mid-marsh vegetation, after spontaneous re-wetting (following an accidental break of walls in 2004).

We explored if the high carbon stock in the top sediment meter of ODB.Z was an artifact, such as a consequence of soil compaction during the decades it has been desiccated and deprived of vegetation. ODB.Z bulk density (0.92  $\pm$  0.14(SD) g cm<sup>-3</sup>) duplicated that of the marine estuary mid-marsh ODE.M (0.53  $\pm$  0.20(SD) g cm<sup>-3</sup>), as well as in the mid-high marsh invaded by S. densiflora ODU.H (intermediate estuary;  $0.55 \pm 0.22$  g cm<sup>-3</sup>; Kruskall-Wallis, pairwise comparisons: p< 0.0001 in both cases, annex C2.2-I); but it was not significantly different from soil bulk density in OD.M mid-marsh (probably eroded, see above; 1.09 ± 0.29(SD) g cm<sup>-3</sup>), and in ODE.H high marsh (1.09  $\pm$  0.41 (SD) g cm<sup>-3</sup>), both also located in the intermediate estuary. Nevertheless, the soil bulk density profile at the re-wetted station ODB.Z was different from that of the wild saltmarshes (see Annex C2.2-I graphs), as bulk density slightly decreased with soil depth (Fig. 3.4a;  $R^2$ = 0.30, p< 10<sup>-4</sup>) instead of increasing or remaining constant throughout the profile, as it was the case of the wild marsh cores. Soil bulk density has been demonstrated to be higher in saltmarshes dried for agriculture, and to decrease along decades since re-wetting (Burden et al, 2019). Desiccation may have compacted the top-soil of ODB.Z, but this would not be enough to explain the high TOC stock<sub>1m</sub> measured there. Given that desiccation reduces soil carbon stocks (Burden et al, 2019), such high sediment carbon stocks in an area that has been dry and un-vegetated for several decades until 2004, suggest than Llanos de Bacuta could have had even larger carbon stocks before desiccation.

Reconstructed TOC flux<sub>100yr</sub> was of  $1.04 \pm 0.19(SD)$  t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Table 3.3), lower than in wild mid-marsh ODE.M ( $4.58 \pm 3.36(SD)$  t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, Table 3.1). Burden et al (2019) showed that re-wetting initially generate high carbon fluxes of around 3.9 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> during the first 20 years, which slow thereafter to around 2.4 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, and that it takes approximately 100 years for a restored saltmarsh to obtain the same carbon stock as natural sites in the top 30 cm of soil. This makes us expect sediment carbon stock in ODB.Z to further increase in the next decades, if re-wetting is maintained.

A possible effect of drying could be the significant reduction detected in the reconstructed accretion rate (Kruskal-Wallis test:  $p < 10^{-4}$ ) and concomitantly in TOC flux (Brown-Forsythe and Welsch corrected ANOVA test test:  $p < 10^{-4}$ ; Fig. 3.4b) between core centimeters 15 and 54, as compared to the sediment accretion rates estimated above and below this depth. These cm correspond to years 1896 and 1166 A.D. However, we know that re-wetting started in 2004, while drying occurred in an unknown year before 1956, but likely not in the scale of centuries. This indicates that drying and re-wetting may have affected carbon stocks accumulated before both land use changes. Carbon flux did not differ between the top and bottom core sections (p = 0.74 and p = 0.18 for accretion rate and TOC flux, respectively), which is not the pattern observed in wild marshes, where deep reconstructed carbon fluxes

(low-carbon high bulk density) are usually lower, reflect long-term, millenary fluxes, than top soil (high carbon, low bulk densities) carbon fluxes. In fact, the TOC flux<sub>above15cm</sub>/ TOC flux<sub>below54cm</sub> was 115% (Table 3.2), which falls below the 95% CI of centennial to millennial scale TOC fluxes. This result indicates that this relationship could be of diagnostic value.

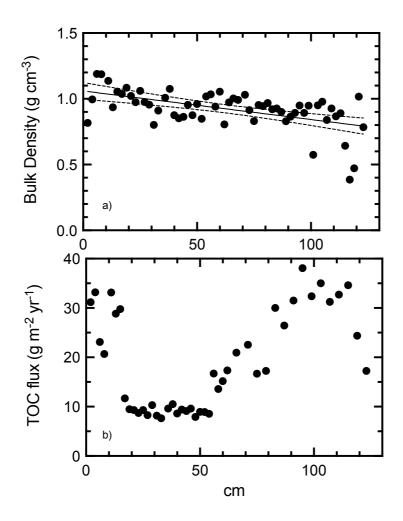


Fig. 3.4. Significant reduction of soil bulk density with soil depth on ODB.Z. b) Reduction of reconstructed TOC flux between cm.

#### Planting an artificial saltmarsh (vegetation): living shorelines

An Odiel area situated in the marine estuary sand bar, which was planted with mid-marsh vegetation on sands in 2012 (ODL.R), after some coastal works (such constructed saltmarsh habitats are called "living shoreline", Davis et al., 2015). Four years later, it has the lowest sediment carbon stocks ( $56.4 \pm 24.4 \text{ t CO}_2 \text{ ha}^{-1}$ ), but the highest carbon flux to the sediment of all stations surveyed ( $6.64 \pm 2.0 \text{ t CO}_2 \text{ ha}^{-1} \text{yr}^{-1}$ ; Table 3.3, Fig. 3.2), owing to a fast initial sediment accretion rate ( $1.8 \pm 0.2 \text{ cm yr}^{-1}$ ), c.a. 45% greater than in ODE.M. The carbon flux

measured in ODL.R station is within the range found for other living shorelines in USA (Davis et al, 2015). These results indicate that the carbon sink ecosystem service of saltmarshes can be rapidly set up, although Davis et al (2015) found that it decreases with time since the saltmarsh onset, and is expected to stabilize, after few decades, into typical carbon flux rates of natural saltmarshes.

#### Restoring a degraded and invaded low saltmarsh (re-vegetation):

Several hectares of degraded low saltmarsh at Punta del Sebo (37°08′–37°20′N ;6°45′–7°02′W), which were degraded since the 1960`s, due to multiple factors (vegetation loss, invasion by the alien grass *Spartina densiflora*, oil and heavy metals pollution at 1.5m sediment depth), and local strong erosion, Castillo et al, 2009), were restored through phytoestabilization (plantation of *S. maritima*) and removal of *S. densiflora* (Castillo et al, 2009), between November 2006 and January 2007. Twenty eight months later, in May-June 2009, Curado et al., (2013) recorded 85 t CO<sub>2</sub> ha<sup>-1</sup> in the top 20 cm of sediment (and 17 t CO<sub>2</sub> ha<sup>-1</sup> in plants biomass), and a net carbon flux to the sediment of 8.4 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (plus a net carbon flux to the biomass compartment, due to vegetation expansion, of 7.5 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>). Curado et al (2013) reported an accretion rate of 2.2 cm per year, which is even greater than that observed in the station ODL.R, 4 years after planting (1.8 cm per year).

Supposing that the accretion rate measured by Curado et al (2013) in 2009 has been stable in the last 9 years, between June 2009 and November 2018, 21cm of sediment would have accumulated. Supposing that the top 21 cm of ODR cores have accumulated in the last 9 years, this would suppose a carbon stock accumulation of 32.5  $\pm$  18.4 (SD) t CO<sub>2</sub> ha<sup>-1</sup>, during 9 years, which would suppose an average carbon flux to the sediment of 3.61  $\pm$  2.04 (SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Table 3.3), nearly half of the carbon flux measured in the ODL.R vegetated station, in the marine part of the estuary, and planted with Sarcocornia spp. and other midmarsh species (Table 3.3). Such difference is consistent with our observation in wild marshes, where mid marshes had greater carbon flux to the sediment than low marshes. <sup>210</sup>Pb sedimentation profile in OD.R was masked by the high lead contamination, coming from the nearby Fertiberia phosphogypsum deposits. Nevertheless, the lead inputs to the Tinto River decreased sharply in 1997, after improvements of residues management by this enterprise. In ODR core, we detect a sharp reduction in <sup>210</sup>Pb at cm 31, which could correspond to this 1997 management change. So we can hypothesize that between 1997 and 2009, the sediment accreted 10 cm (8.33 mm yr<sup>-1</sup>), yielding a net carbon flux of 1.3  $\pm$  0.5 (SE) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> previous to restoration. Therefore, the restoration and re-vegetation with S. maritima would have multiplied both, the sediment accretion rate and the carbon flux to the sediment, by a factor of 2.8.

The sediment accretion rate in Punta del Sebo (OD.R) before the planting, already doubled sediment accretion rate in the un-vegetated wild low marsh of the marine part of the estuary (ODM.L-C: 3.2 mm yr<sup>-1</sup>, Table 3.1), but similar carbon flux to the sediment (ODM.L-C:  $1.1 \pm 0.2$  (SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, Table 3.1). However, two years after the treatment, the carbon flux in OD.R reported by Curado et al (2013) was 10 times greater than in the marine estuary low marsh vegetated with *S. maritima* (ODM.L:  $0.27 \pm 0.06$  (SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>).

The top sediment meter at OD.R contained a carbon stock of  $243 \pm 117$  (SD) t CO<sub>2</sub> ha<sup>-1</sup>, similar to that measured in ODM.L:  $218 \pm 119$  (SD) t CO<sub>2</sub> ha<sup>-1</sup>.

The sediment carbon density reported by Curado et al (2013) in the top 20 cm was of 0.013 g cm<sup>-3</sup>, and a bit lower in the first 2 cm (0.009 g cm<sup>-3</sup>). Such carbon density values triplicate our measurements in the top 20 cm of OD.R cores (0.0042  $\pm$  0.0005 (SE) g cm<sup>-3</sup>). The carbon density values reported by Curado et al (2013) were observed by us much deeper in the cores, at 71 cm depth.

#### Carbon stocks and fluxes in exploited and abandoned Salinas:

On average, carbon stocks in active and abandoned salinas were 56% of the average wild marsh (TOC stock<sub>1m</sub> = 173.2  $\pm$  87.3(SD) tCO<sub>2</sub> ha<sup>-1</sup> vs 308.6  $\pm$  94.5(SD) tCO<sub>2</sub> ha<sup>-1</sup>). Nevertheless, we found differences between active and abandoned salinas

#### **Active salina:**

In the active salina of El Águila (Cadiz Bay) the sediment of the "Estero" (i.e. the water stock basin, see updated Annex A3) was very black and muddy, with little consistency. The core sediment bulk density was low, attaining a maximum of 0.9 g cm<sup>-3</sup> at 18 cm depth, and decreasing below (core SL1, annex C2.2.-I). The sediment also had a very low carbon richness and carbon density, which decreased with depth. Consequently, the organic carbon core stock was very low (TOC stock<sub>1m</sub> = 60.4 tCO<sub>2</sub> ha<sup>-1</sup>). The <sup>210</sup>Pb profile indicated that there was no accretion (core SL1, annex C2.2.-I), which could be expected, as the basins are periodically and superficially dredged, in order to prevent fill-up. The <sup>14</sup>C ages indicated that the bulk sediment organic matter was very ancient: at 39 cm it was already 2045 ± 25(SD) yr BP old. This indicates that the carbon stock was ancient, probably produced before land-use change from saltmarsh to salina. Taking into account the average age of the wild saltmarsh sediments of Los Toruños at 39 cm depth (187 ± 167(SD) yr BP), and its average long-term carbon flux (0.53 ± 0.36(SD) t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>), we estimate that the land-use change to "Estero" has costed the global TOC stock loss of 992 t CO<sub>2</sub> ha<sup>-1</sup> during the whole (unknown) period of exploitation.

The sediment of the last evaporation basin "Cristalizador" was also muddy, but more compacted and sticky. The core collected there (SL3) showed higher bulk densities than in the "Estero" (SL1) attaining 1 g cm<sup>-3</sup> at 8.7cm and a maximum of 1.2 g cm<sup>-3</sup> at 24 cm depth; then decreased to around 0.8 g cm<sup>-3</sup> (annex C2.2-I). The  $^{210}\text{Pb}$  profile also indicated erosion (core SL1, annex C2.2-I). The  $^{14}\text{C}$  dating indicated that the sediment bulk organic matter was even more ancient than in the "Estero" (SL1): at 39 cm it was 3598  $\pm$  30(SD) yr BP old. We estimate that the land-use change to "cristalizador" has costed the global TOC stock loss of 1092 t CO<sub>2</sub> ha<sup>-1</sup> during the whole (unknown) period of exploitation.

The organic carbon richness (SL3:  $0.52 \pm 0.19$ (SD)%) was similar to that of the "Estero" (SL1:  $0.57 \pm 0.44$ (SD)%), although it increased in the two bottom-most subsamples. However, owing

to the higher bulk densities, the organic carbon stock in core SL3 was higher, and comparable to that observed in some natural marshes (TOC stock<sub>1m</sub> =  $225.2 \text{ t CO}_2 \text{ ha}^{-1}$ ).

The average active salina organic carbon stock<sub>1m</sub> was of  $142.8 \pm 116.5$ (SD) t CO<sub>2</sub> ha<sup>-1</sup> (Table 3.3), but given it's old age, it was probably relict carbon stock, accumulated before land-use change from saltmarsh to salina.

#### Abandoned salina with low tidal influence:

The salina SL-C of San Joaquin y Santa Ana is abandoned since 1956-57, but has low tidal influence. In 2018 it still had low vegetation cover as compared to marshes and to the abandoned salina with tidal influence (see landscape pictures in updated Deliverable A3), and many areas seem affected by the salination process, and can be called "sterile marsh". Sediment was muddy, compacted and sticky, with bulk densities ranging from 0.5 to 1.8 g cm $^3$  (0.912  $\pm$  0.35(SD) g cm $^3$ ). Sediment carbon richness (0.49  $\pm$  0.11%(SD)) and density (0.004  $\pm$  0.001 g TOC cm $^3$ ) were low and similar to those of the active salina, and did not show any trend with soil depth. Average carbon stocks in the top 1 m soil was also similar to that of the active salina, 182.1  $\pm$  101.7(SD) t CO<sub>2</sub> ha $^{-1}$ ; Table 3.3), and it also consisted mainly in ancient TOC stock: the  $^{210}\text{Pb}$  profile indicated erosion, and thus no net carbon sequestration was taking place (annex C2.2-I). The  $^{14}\text{C}$  ages also indicated that the bulk sediment carbon was ancient: at 42 cm depth, it had an age of 2090  $\pm$  31(SD) yr BP.

Therefore, we estimate the carbon flux of the abandoned salina to be 0 (although it also could be negative, i.e., erosion so, therefore, CO<sub>2</sub> emissions).

#### Salina abandoned with tidal influence:

The salina of Santa Teresa, inactive since 1985 but receiving the tide inflow on a daily basis was much more covered by typical saltmarsh vegetation: more high saltmarsh vegetation in the walls, and more mid-saltmarsh species in the channels (see updated deliverable A3). The core taken in the channel (SL-CW1) showed low sediment bulk densities of  $0.56 \pm 0.12$  g cm<sup>-3</sup>, lower than in SL-C (annex C2.2-I), while the soil bulk density in the walls was higher (0.82  $\pm$  0.15g cm<sup>-3</sup>), although it did not exceeded 1g cm<sup>-3</sup>. Sediment carbon richness was higher than in SL-C, and increased towards the core top (1.87  $\pm$  0.85(SD)%; Annex C2.2-I). The same occurred with carbon density (0.010  $\pm$  0.004(SD) g TOC cm<sup>-3</sup>).

At the wall (SL-CWP1), organic carbon richness (0.64  $\pm$  0.48(SD)%) and density (0.005  $\pm$  0.003(SD) g TOC cm<sup>-3</sup>, Fig. 3.1) were lower than in the channel, but it also increased towards the profile top.

In SL-CW1, the  $^{210}$ Pb profile indicated that accretion had resumed and added 6 cm sediment since 1985, although sediment organic carbon at 98 cm depth was still very ancient (3448  $\pm$  26(SD) yr BP). TOC fluxes since 1985 were on average  $0.92\pm0.11(SD)$  t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, similar to the average for wild marsh (0.88  $\pm$  0.2 tCO<sub>2</sub> ha<sup>-1</sup>yr<sup>-1</sup>). Although the real flux when the salina was active was virtually 0, the comparison with the reconstructed ancient TOC flux before

1985 indicates that carbon flux after re-establishment of the tidal marsh dynamics is 311% of that before 1985. Being within the natural range of centennial/millenary TOC fluxes measured in natural marshes, we hypothesize that SL-CW has fully recovered its carbon sink capacity in 23 years.

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

The natural areas where highest carbon burial rates take place are marshes covered with *Sarcocornia spp.* and *Salicornia spp.*, which sediments are submerged daily during high tide. This marsh band seems the strongest carbon sequestration reactor of the ecosystem.

The fact that the C stock in the high marsh (which was formerly a midmarsh) is lower than in the mid marsh is probably due to long-term carbon mineralization processes. Mid marsh usually transforms in high marsh at the scale of several centuries (Borrego, 1997), so these mineralization processes probably take place very slowly (i.e. well beyond 100 years) and so do not invalidate the relatively large importance of the mid-marsh band for climate change mitigation, which typically takes into account carbon sequestered for at least 1 century.

Despite that, the finding of great carbon stocks in upper parts of the river, suggests that the highest carbon stocks could be linked to the age and long-term stability of the saltmarsh at the scale of millenia. As tidal marshes are most often associated to sand bar growth in estuaries, the long-term temporal dynamics of sediment accumulation in these areas is probably key to predict were are the highest sediment carbon stocks accumulated, which should be protected, in order to prevent the switch of the saltmarsh ecosystem from net sink to net emmiter of GHG.

Projects sustainably increasing sediment carbon fluxes and stocks, through re-wetting replanting or reducing coastal erosion, for example, would generate more carbon credits in areas were there are large stocks accumulated, under risk of being mineralized. On the other hand, intermittent re-wetting of dry ancient saltmarsh soils has been shown to enhance carbon mineralization (Borken and Matzner, 2009). This means that when considering the conservation of ancient carbon deposits in transformed saltmarsh soils, re-wetting would be an option if we intend to regenerate the natural saltmarsh dynamics. For example, using ancient saltmarsh soils for irrigated agriculture is expected to increase carbon emissions from such soils (Borken and Matzner, 2009).

Protecting saltmarsh from erosion through better coastal management and also through reforestation of the low intertidal with *S. maritima* and *Z. noltei* could also generate carbon credits, which could help to finance such conservation and restoration projects. A potential candidate place to implement it, would be the river San Pedro.

Creating new saltmarsh through afforestation may also produce significant carbon credits, owing to the high carbon fluxes to the sediment produced by the vegetation, in addition to the biomass compartment in itself. On dry un-vegetated saltmarsh soils (known as "sterile saltmarshes", formed by aridity and excess of soil salinity, the restoration of the vegetal cover would require the previous restoration of the tidal regime.

Last, but not least, improving water quality through reducing eutrophication would be an important management measure, which not only would improve local human health, but also would reduce GHG flux of N<sub>2</sub>O and CH<sub>4</sub> in saltmarshes (well managed saltmarsh watersheds

may even be net sinks of N2O, Burgos et al, 2017), so they don not offset saltmarsh net C sequestration.

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. The present results contribute to bridge this knowledge gap, for tidal marshes.

# 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 saltmarshes 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).

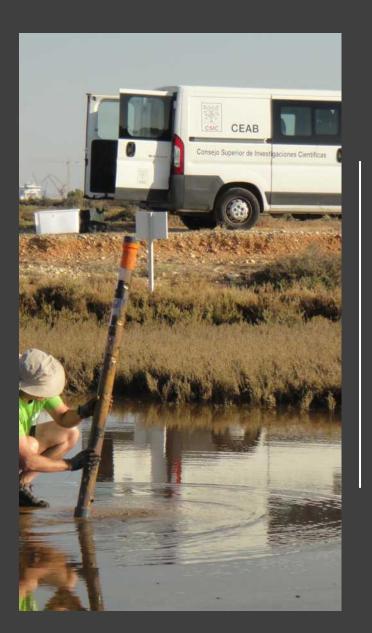
#### 3.2.2. A 'big push' by the Andalusian Government

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<sub>2</sub>/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 CO2 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.





# 4. Conclusions

# 4. Conclusions, recommendations and future work

#### Main conclusions:

Saltmarshes are to be considered as the most attractive and viable Blue Carbon target for any conservation or restoration offset project in Andalusia. The accessibility of the ecosystems, the cost-effectiveness of restoring/afforesting these environments, and the abandoned areas available for restoration, make of the Andalusian saltmarshes the most interesting member of the Blue Carbon where to intensify the efforts.

In the studied marshes, Odiel and Cádiz, over 522 linear meters of soil (53 cores) from 2 sites and 19 stations bearing or not a vegetation cover, have been scrutinized visually, physically and chemically.

Using all marsh typologies studied in the project, the organic carbon stocks accumulated in the top meter of wild saltmarsh soils in Andalusia ranged from  $498.2 \pm 105.2 (SD)$  tCO<sub>2</sub>/ha, in the medium marsh to  $177.5 \pm 86.1 (SD)$  tCO<sub>2</sub>/ha in mid-low marsh vegetated with Sarcocornia spp., under erosive dynamics. The average carbon stock in the top meter of wild andalusian saltmarshes is  $317.5 2 \pm 124.9 (SD)$  tCO<sub>2</sub>/ha (13 stations). As a quick reference, the average carbon stock of healthy Andalusian P. oceanica meadows is  $1509.2 \pm 1388.3 (SD)$  tCO<sub>2</sub> ha<sub>-1</sub> (N= 9 stations), also for the top meter, that is, nearly 3 times higher than in saltmarshes, although also with greater spatial variability. Despite this comparison, given the complexity of restoring seagrass meadows, the initial statement in this section still holds.

At healthy saltmarshes, this stock has been accumulating during the last century at an average rate of  $1.42 \pm 1.50(D)$  tCO<sub>2</sub>ha<sup>-1</sup> yr-<sup>1</sup>, ranging from negative values (positive if we consider the IPCC convention, to signify GHG inputs to the atmosphere) in the eroding low un-vegetated marsh of Los Toruños (Cadiz Bay) or Isla de Enmedio to  $4.6 \pm 3.4$  tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> in the Odiel vegetated mid marsh of El Manto, respectively (Fig. 3.1). This rates are very similar to those of healthy *P. oceanica* seagrass meadows in Andalusia, that averaged 1.8 tCO2  $\pm$  0.4 ha<sup>-1</sup> yr<sup>-1</sup>.

Scaling up these numbers by assigning the corresponding stocks and fluxes obtained in the field to the total area occupied by each bottom type in the two saltmarshes visited (table 3.2), the weighted total stocks in the first meter sediment and average annual fluxes in the last century for both sites are of 2.14 MtCO<sub>2</sub> and 5.5 ktCO<sub>2</sub> yr<sup>-1</sup>, respectively. The interest of this number alone is simply the fact that they are the extant CO<sub>2</sub> tons in the marshes studied, i.e., the reference value upon which to evaluate progression or regression future trends. In other words, these would be the stocks and fluxes to be protected in Cadiz Bay and Odiel Natural Parks.

Extending such areal stocks and fluxes to the rest of tidal saltmarshes present in Andalusia (around 50.341 ha more, Vasquez-Loarte, 2017), we estimate a global stock of 18.4 Mt  $CO_2$  in the top 1m sediment layer, and an average C flux to the sediment of 47 Kt  $CO_2$  yr<sup>-1</sup> in the last century. These are probably underestimates, as the sediment organic carbon seems to continue far beyond the top meter of sediment; the actual total stock could easily duplicate the given estimate.

Comparing aerial pictures from 1956 to 2013, we estimated that 41% of Andalusian coastal saltmarshes have been lost (2% per year on average between 1956 and 1998, and 1% per year on average from 1998 to 2013; Vasquez-Loarte, 2017, master thesis at GAME). This would suppose a concomitant loss of the carbon stocks and sink capacity of these areas,

depending on the nature of the land use change. The main causes of saltmarsh loss have been agriculture (75%), salt industry (10%) and urban sprawl (5%). This result is key to understanding the trends in sink/service loss and, therefore, the potential of the area for protection and restoration projects in the future.

#### Recommendations and future work:

- 1. The approach made in this study was of a 'pilot' type. Given the large variability encountered across the various typologies studied in Odiel and Cadiz Bay, it had become evident the need of augmenting the mapping and horizontal coring efforts, to the rest of Andalusian saltmarshes.
- 2. Attention has to be focused in capturing the variability mentioned above by aerial photography, floristic analyses and ground truthing trips. Using marsh elevation as a criteria alone, has proved to be inaccurate. Vegetation integrates many environmental conditions, helping to define vertical zonation in a more meaningful way for assessing blue carbon stocks, although, the examination of series of aerial pictures, as well as getting as much local background information as possible, is also important to interpret spatial and temporal (along the core record) variability in physico-chemical parameters. The careful examination of all the available information, has allowed us to elaborate trustable hypotheses about the recent (decadal) evolution of some saltmarshes, some of the causes, and to evaluate quantitatively or qualitatively their effects on carbon stocks and fluxes.
- 3. A sound methodology to determining the CO2 emissions resulting from the degradation or destruction of saltmarsh habitat is still lacking. A dedicated experimental approach would be required to obtain rigorous values of rates of loss following destruction by various causes such as global warming, sea level change, erosion, desiccation or pollution.
- 4. The possible  $CO_2$  emissions from  $CH_4$  and  $N_xO$  emissions off the saltmarshes also need to be urgently assessed. A mesohaline environment (5-8 mg l<sup>-1</sup> of saline content), can emit up to 32 g of CH4 m-2 yr-1 (Poffenbarger et al., 2011) and 13 ug m-2 yr-1 of  $N_2O$  (Hirota et al. 2007). Water eutrophication can dramatically increase  $N_xO$  emissions (Burgos et al, 2017). It has to be reminded that methane and nitrous gases have 10 and 100 times the greenhouse effect of  $co_2$ , respectively. Nowadays, the information is scarce, and thus difficult to upscale, but it is absolutely crucial when it comes to elaborate  $CO_2$  compensation projects, some of which could be based in improving water conditions and estuarine metabolism, in order to reduce  $CH_4$  and  $N_xO$  emissions, rather than in creating new habitats.
- 5. Old, stable marsh zones are the ones to be selected for protection and restoration from desiccation. This are typically those at mid-high marsh, away from the main channels and form the river mouth. This ones accumulate and stabilize the largest continuous stocks of organic carbon over millennia, and take long to recover alone, but carbon fluxes increase dramatically after re-wetting and spontaneous re-colonization. The examples of the Llanos de Bacuta, which 12 years after resuming the tidal dynamics has been completely vegetated and has recovered part of its carbon sink capacity, or the continentalized high saltmarsh of Aljaraque-showing carbon fluxes 19 times greater than the sterile salina, around 20 years after plant re-

colonization- are good examples of desiccated marshes which still conserved important carbon stocks, worth to be protected and enhanced.

- 6. Vegetating and revegetating low or mid salt-marshes in marine estuary areas, can also bring great benefits, because these sites are the ones with the greatest carbon fluxes to the sediments, and the enhanced accretion and protection from erosion, provided by these plants, is also of importance for coastal protection, as we could see in Los Toruños, and in Isla de Enmedio (Odiel). Given the greater dynamism of these areas, restoration projects seem also faster in recovering the carbon sink capacity, as we could see in the Punta del Sebo revegetation with Spartina, which 9 years later seems to have fully recovered the low marsh sink capacity. Other mechanical or hydrologic management measures reducing erosion could also be included in carbon compensation projects.
- 7. Transformation of abandoned salinas into saltmarshes has been shown to be effective in recovering the carbon sink, as long as the tidal dynamics is restored. Thirty three years after abandonment, the salina has developed large saltmarsh vegetation cover and fully recovered the saltmarsh sink capacity. By contrast, if the abandoned salina remains disconnected from the daily tidal dynamics, it tends to suffer salination processes and become a "sterile saltmarsh". The low vegetation cover is unable to restore the carbon sink capacity. Another common land-use change of salinas in Cadiz Bay has been their transformation into aquaculture ponds. We haven't assessed the effect of this LULUCF on the GHG sink capacity. However, other studies indicate that these aquaculture ponds tend to become net emitters of GHG like CH<sub>4</sub>, N<sub>x</sub>O or CO<sub>2</sub>, due to the priming effect of eutrophication on sediments heterotrophic paths (Robb et al, 2017).
- 8. Carbon offset projects based in saltmarshes should focus on the recovery of degraded saltmarshes and reducing erosion of the low marsh, through 1) better management of the coastal sediment movements, 2) re-wetting and replanting desiccated areas that have lost vegetation and 3) improving watershed quality to reduce eutrophication, which, by introducing nutrients and labile organic matter to the system, may enhance GHG emissions from the saltmarsh and/or estuary channels.

The main obstacles to bring the carbon locked by saltmarshes to the carbon markets are: 1. lack of quality scientific information (mapping, stocks and fluxes quantification, quantification of the 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. LIFE Blue Natura represents a gigantic step forward towards overcoming those obstacles and we strongly believe that its strategy should be implemented in all those EU countries with a wealth of Blue Carbon ecosystems.

# 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.

- Annex A1.6\_Deliverable\_Odiel\_Cartography-4.pdf in <a href="http://life-bluenatura.eu/wp-content/uploads/2018/09/Annex">http://life-bluenatura.eu/wp-content/uploads/2018/09/Annex</a> A.1.6 Deliverable Odiel cartography-4.pdf
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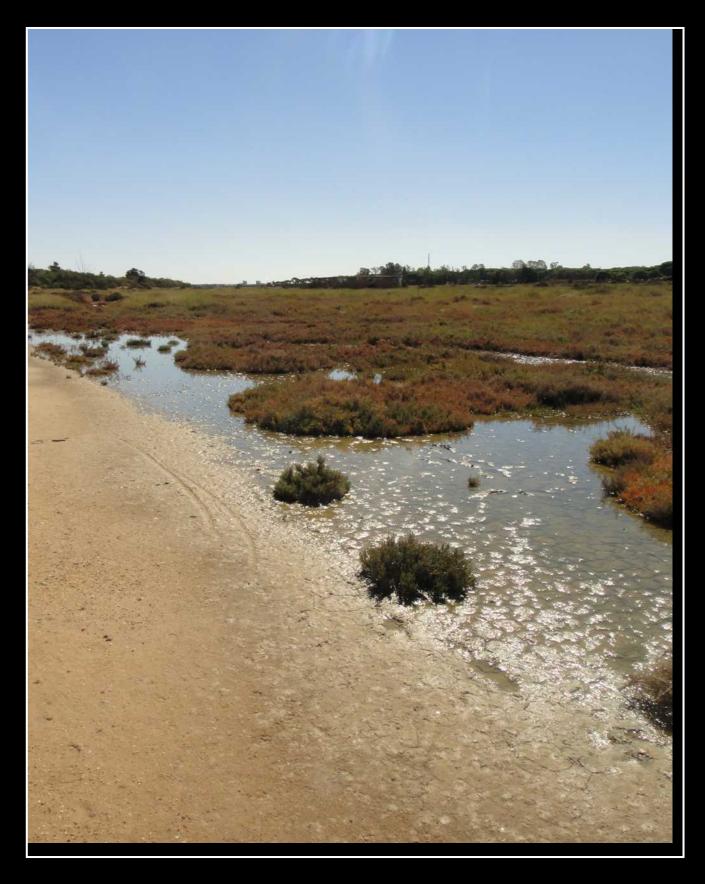
Several external and CSIC laboratories have collaborated in different analyses: Core scanning, XRF and magnetic susceptibility of hemicores have been performed at the CORELAB (University of Barcelona), under the generous guidance of Jaime Frigola Ferrer. The recent (<150 yr) accretion rates have been estimated through <sup>210</sup>Pb 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.

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A note for my team: the pride I feel for having them onbord, is beyond words. They know it.



Annexes

# Annex I: 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/cm³), 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.

#### For each core:

Figure A: Vertical profiles along the core of different soil parameters. From Left to Rigth: bulk density (g (Dry Weight) per cubic centimeter); Sediment Accretion Rate (in mm per year), Percentage of Total Organic Matter; Percentage of Total Organic Carbon; Total Organic Carbon Flux (in tonnes C per hectare and year), abundance of Total Inorganic Carbon (tonnes per hectare), and distribution of grain sizes along the core.

Figure B: Lead 210 (blue) and concentration of fine sediments (diameter >0.063 mm) in each sediment layer (un-compressed core, otherwise, highlighted blow the graph).

## **ODU station:** core ODU.2

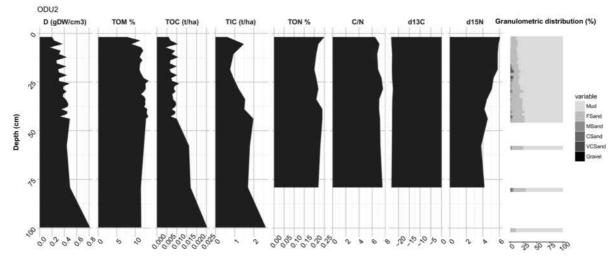


Fig. A.

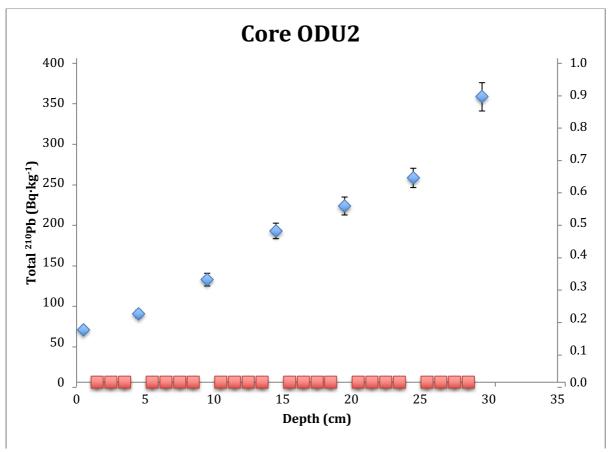


Fig. B.

# **ODML station:** core ODM.L\_A

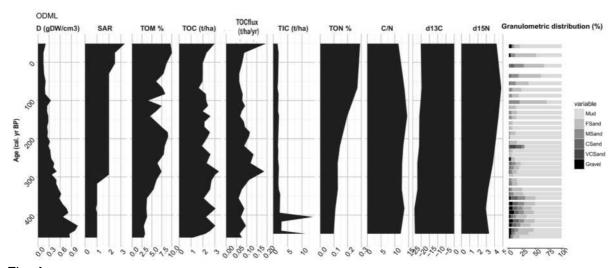


Fig. A

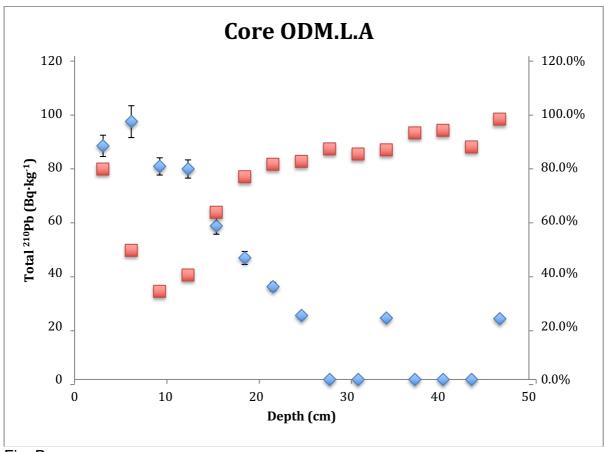


Fig. B.

# ODM.L-C station: core ODM.L-C\_A

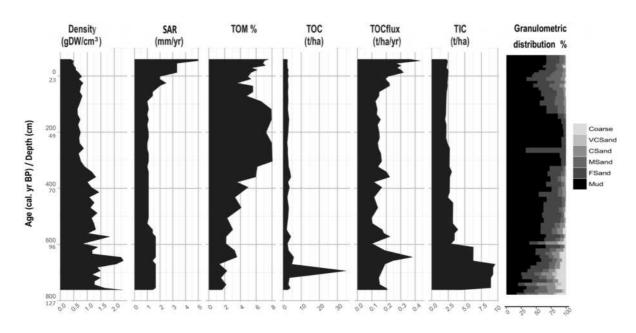
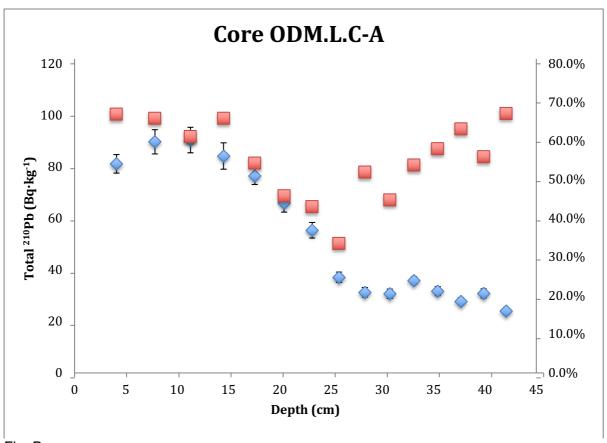


Fig. A.



# **ODE.M station:** core ODE.M\_A

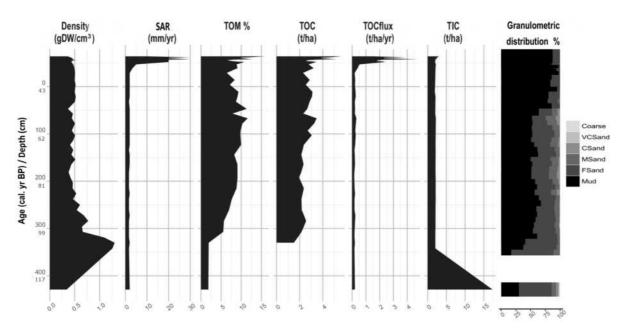


Fig. A.

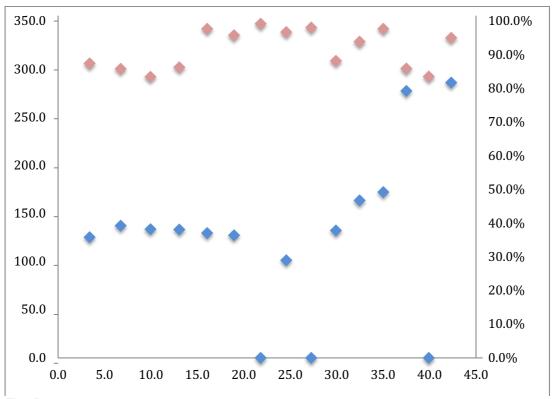


Fig. B.

#### Station OD.M: core OD.M2

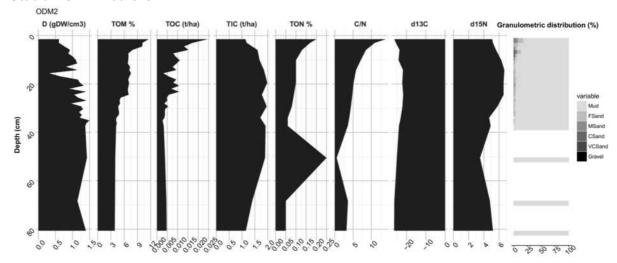


Fig. A.

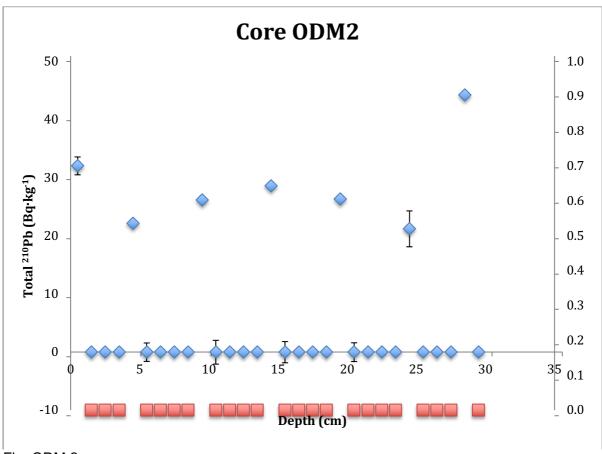


Fig. ODM.2.

## Station ODU.H: core ODU.H

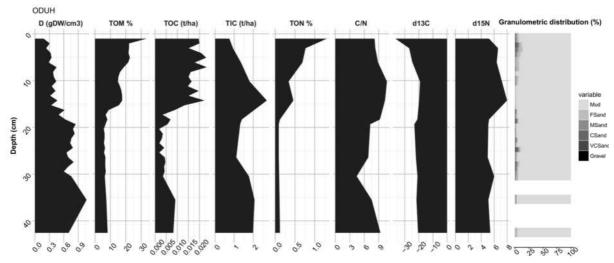


Fig. A.

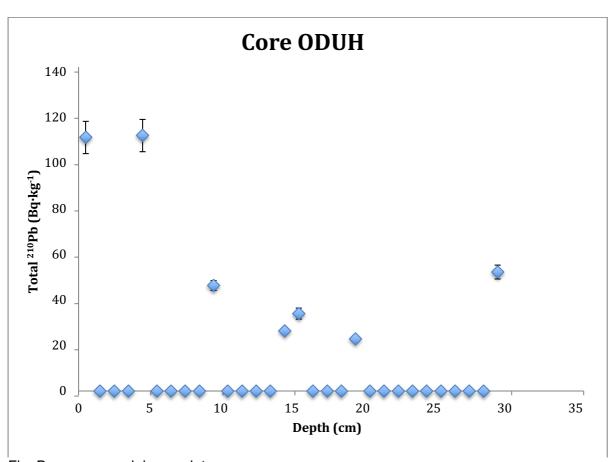


Fig. B. compressed, incomplete.

# **ODE.H station:** Core ODE.H\_A

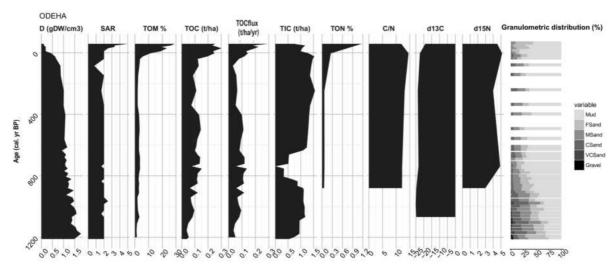


Fig. A.

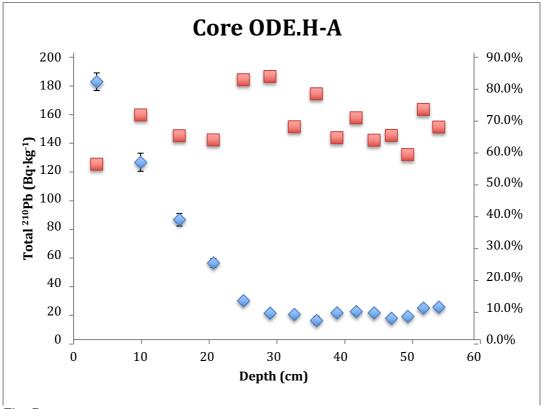


Fig. B.

# ODB.Z station: Core ODB.Z\_A

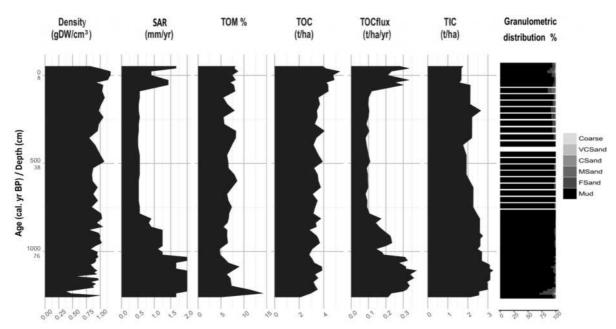


Fig. A.

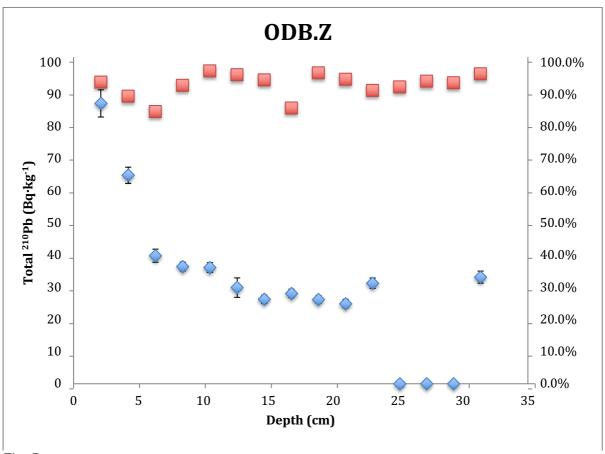


Fig. B.

#### Station OD.H: core OD.H1

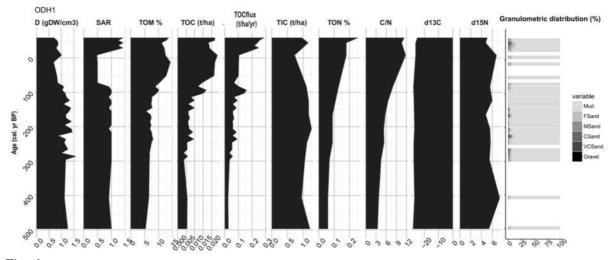


Fig. A.

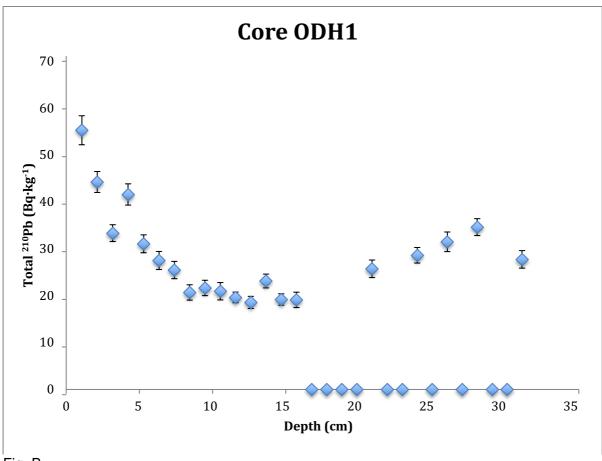


Fig. B.

## ODN.D station: core ODN.D-Vmid

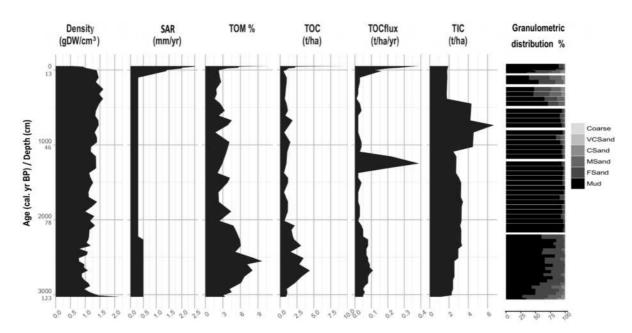


Fig. A.

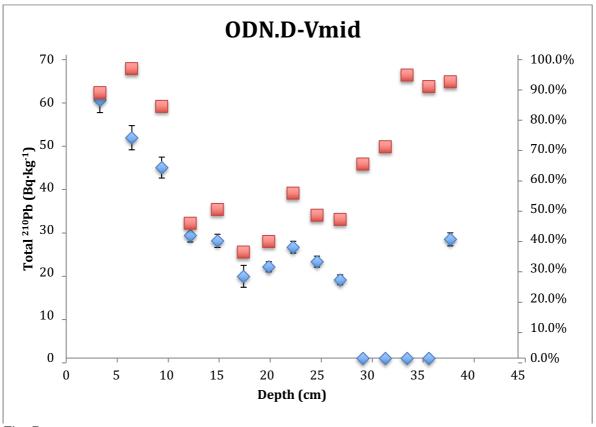


Fig. B.

# ODN.D-C station: core ODN.D-C\_A

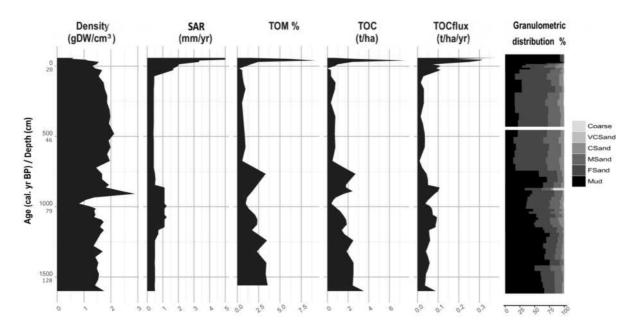


Fig. A.

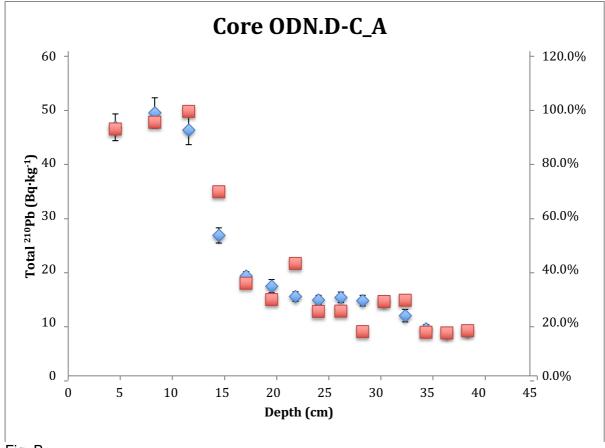


Fig. B.

ODL.R station: Core ODL.R\_A

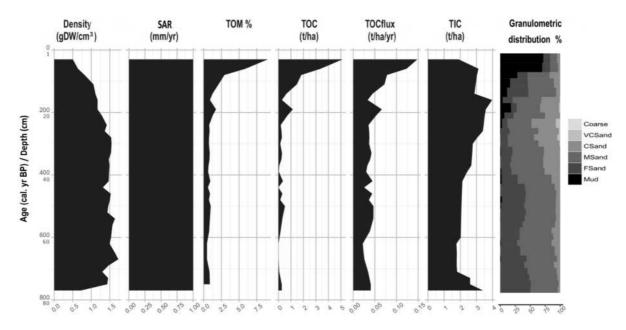
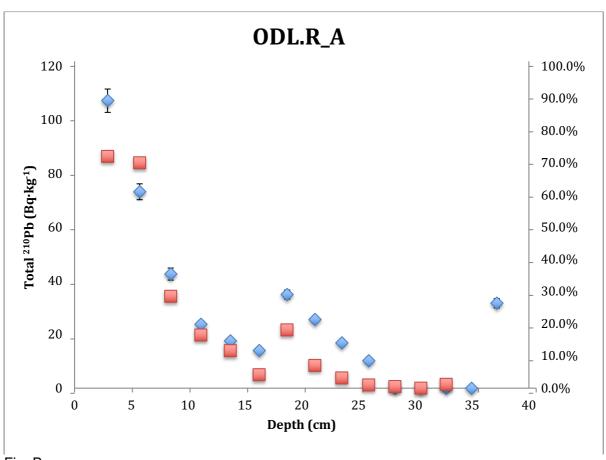


Fig. A.



# OD.R station: Core OD.R\_1

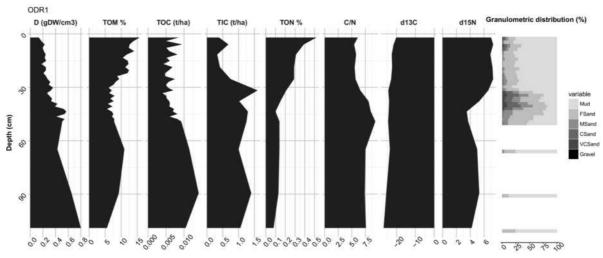


Fig. A.

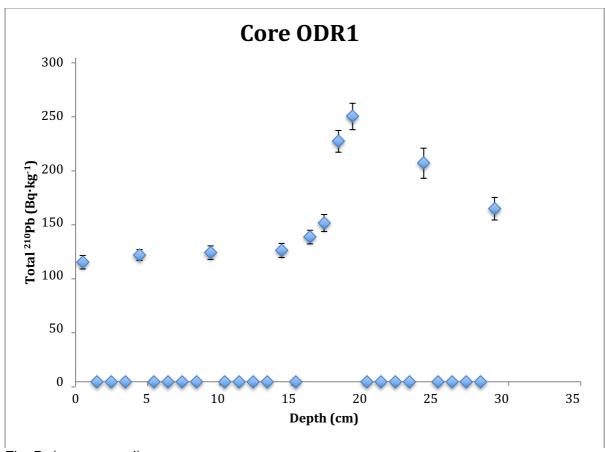


Fig. B. (compressed)

TOR.L station: core TOR.L\_B

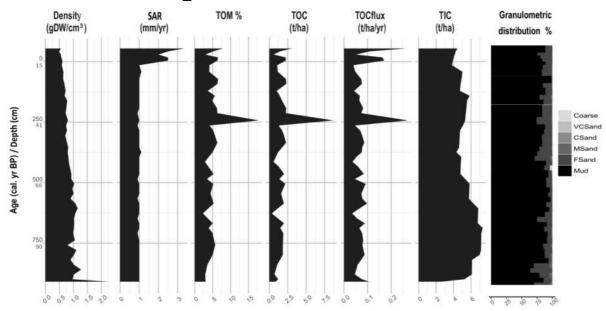


Fig. A.

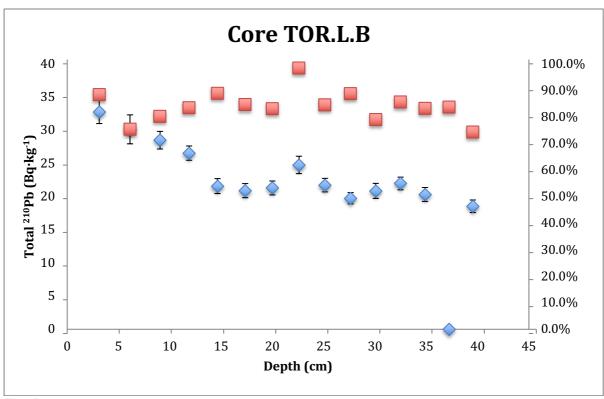


Fig. B.

# TOR.L-C station: core TOR.L-C\_A

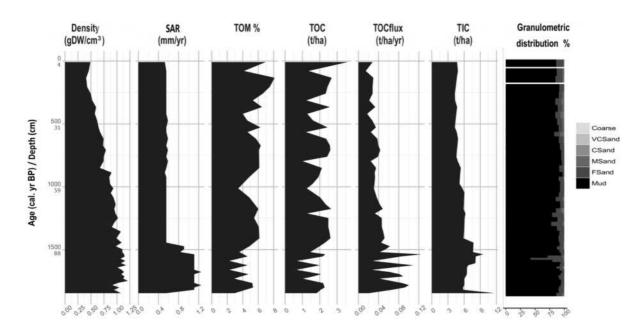


Fig. A

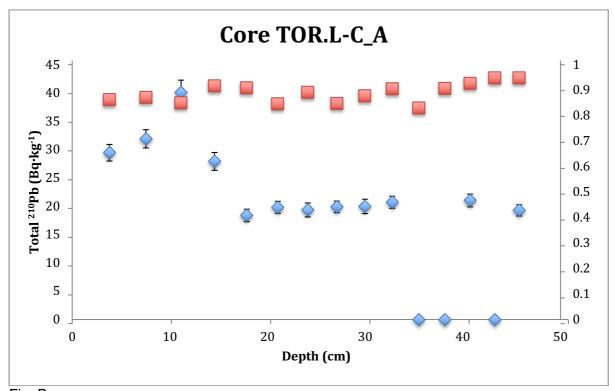


Fig. B.

# TOR.M station: core TOR.M\_A

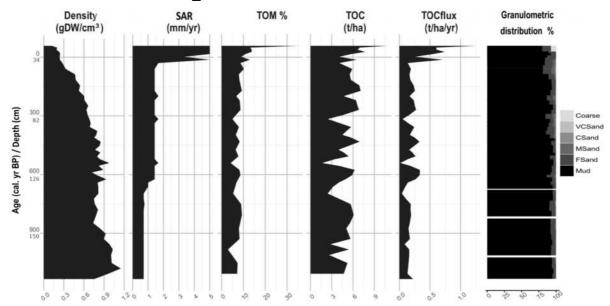


Fig. A.

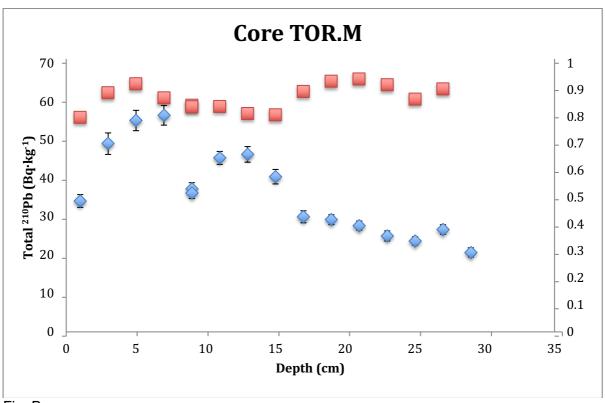


Fig. B.

## TOR.H station: core TOR.H\_A

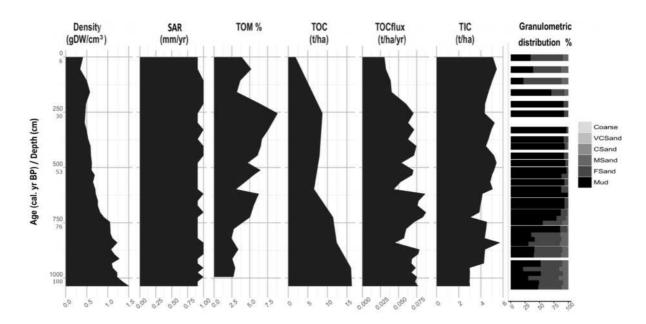
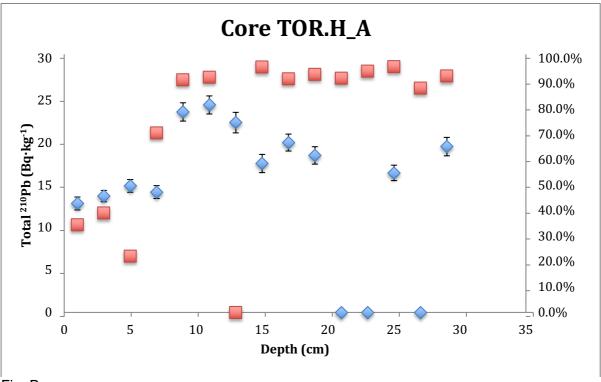


Fig. A.



## SL station: core SL1 ("estero")

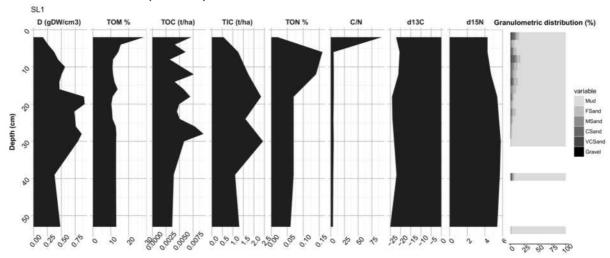


Fig. A.

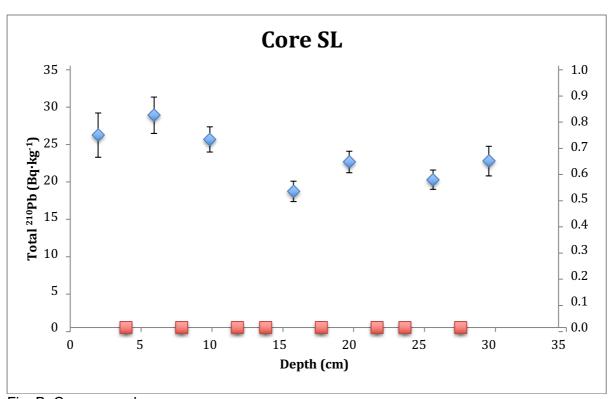


Fig. B. Compressed.

# SL station: core SL3 ("cristalizador")

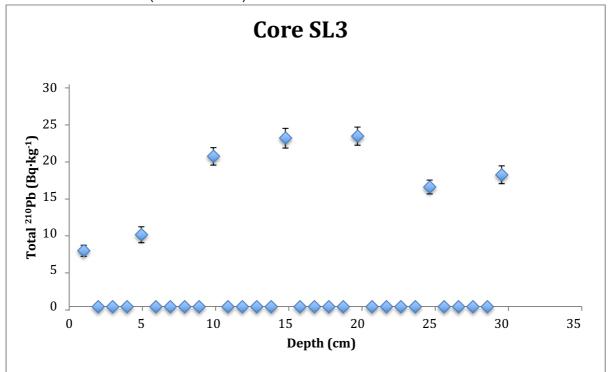


Fig.B. Compressed.

# **SL-C station:** core SL-C\_A

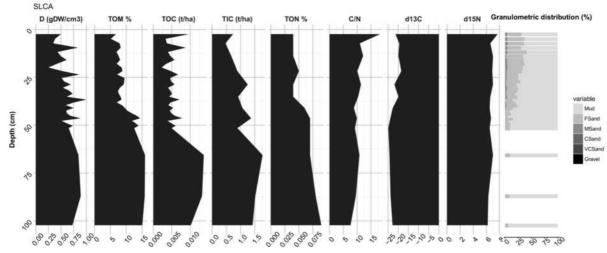


Fig. A.

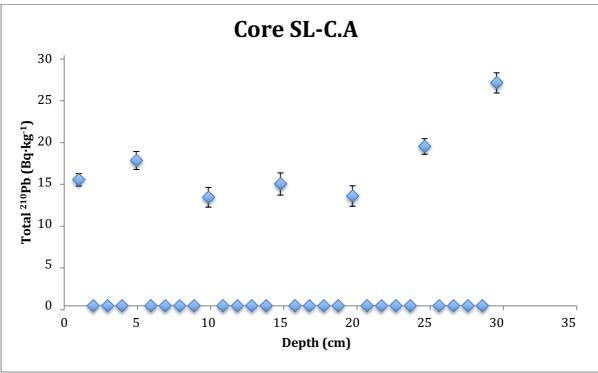


Fig. B. Compressed.

#### SL-CW station: core SL-CW1

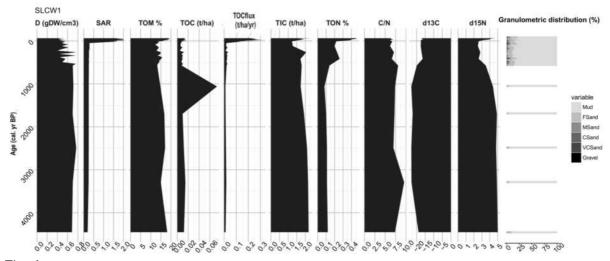


Fig. A.

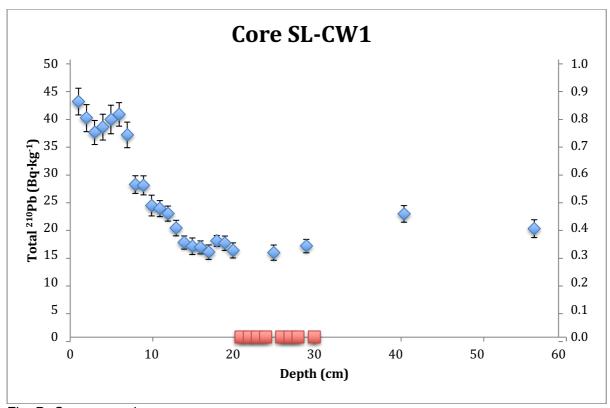


Fig. B. Compressed.

Annex II: Average carbon stocks and fluxes estimates used for up-scaling and mapping blue carbon in Andalusian saltmarshes

Sediment carbon stock in the top 1m soil (includes belowground biomass)						
Saltmarsh category	Map category	tCO <sub>2</sub> /ha	SD	N stations	N quadrats	Based on stations:
High	1	299.4	111.8	5	12	ODE.H, ODND-V, OD.H, ODU.H, TOR.H
Medium	2	498.8	105.2	2	6	ODE.M, TOR.M
Low vegetated	3	207.9	26.9	3	7	ODM.L, TOR.L
Low S. maritima	4	223.1	7.8	2	6	ODM.L, TOR.L
Low Sarcocornia	5	177.5	86.2	1	1	OD.M
Low unvegetated	6	374.1	108.4	2	6	ODM.L-C, TOR.L-C
Subtidal channel	7	256.6	59.2	1	2	OD.U
Subtidal-intertidal channel (Z. noltei patches)	8	280.4	167.7	1	3	SA.ZN.D
High bare (dry-salinized)	9	170.7	63.7	1	2	ODN.D-C respecto a ODN.D-V
Re-wetted	10	615.8	242.8	1	3	ODB.Z
Re-vegetated (S. maritima)	11	242.5	117.4	1	3	OD.R
Planted (mid-marsh vegetation), living shoreline	12	56.1	34.0	1	3	ODL.R
Salina (average "estero" and "cristalizador")	13	142.8	116.5	2	2	SL1, SL3
( estero)	14	60.4		1	1	SL1
(cristalizador)	15	225.2		1	1	SL3
Abandoned salina with daily tidal influence	16	199.2	116.7	1	2	SL-CW (core SL-CW1 and SL-CWP1)
Abandoned salina with low tidal influene	17	148.7	45.4	1	3	SL-C and SL-CWP1
Abandoned salia (wall)	18	116.7			1	SL-CWP1
Abandoned salina daily tidal influence (channel						
"caño")	19	281.7		1	1	core SL-CW1
(Abandoned salina low tidal influene (channel)	20	182.1	101.7	1	2	SL-C

Saltmarsh category	Map category	Secular tCO <sub>2</sub> /ha	SD	Based on stations:
				ODN.DV, ODE.H,
High	1	0.76	0.12	OD.H
Medium	2	3.28	1.84	ODE.M, TOR.M
Low vegetated	3			
Low S. maritima	4	0.44	0.08	ODM.L, TOR.M
Low Sarcocornia	5			
Low unvegetated	6	0.55	0.78	ODM.L
Subtidal channel	7			
Subtidal-intertidal channel ( <i>Z. nolte</i> i patches)	8	1.10	0.24	
High bare (dry-salinized)	9	0.44	0.12	
Re-wetted	10	1.04	0.19	
Re-vegetated (S. maritima)	11	3.61	2.04	
Planted (mid-marsh vegetation), living shoreline	12	6.64	2	
Salina (average "estero" and "cristalizador")	13	0.0		
( estero)	14	0.0		
(cristalizador)	15	0.0		
Abandoned salina with daily tidal influence	16	0.81	0.11	
Abandoned salina with low tidal influene	17	< 0.1		
Abandoned salia (wall)	18			
Abandoned salina daily tidal influence (channel				
"caño")	19	0.92	0.11	
(Abandoned salina low tidal influene (channel)	20	< 0.1		

## LIFE Blue Natura

Aerial biomass carbon stock								
Saltmarsh category	Map category	tCO₂/ha	SD	N stations	N quadrats	Based on stations:		
High	1	22.0	4.3	4	12	ODE.H, ODND-V, OD.H, TOR.H		
Medium	2	16.0	6.2	2	6	ODE.M, TOR.M		
Low vegetated	3	15.4	13.2	2	6	ODM.L, TOR.L		
Low S. maritima	4	15.4	13.2	2	6	ODM.L, TOR.L		
Low Sarcocornia	5	16.0	6.2	2	6	ODE.M, TOR.M		
.ow unvegetated	6	0.0		2	0	ODM.L-C, TOR.L-C		
Subtidal channel	7	0.0		1	0	ODU		
Subtidal-intertidal channel ( <i>Z. nolte</i> i patches)	8	2.7	0.7	2	6	SA.ZN-D, SA.ZN-C		
High bare (dry-salinized)	9	0.0		1	0	ODN.D-C		
Re-wetted	10	4.2	1.4	1	3	ODB.Z		
Re-vegetated (S. maritima)	11	19.6	3.0			Curado et al, 2013		
Planted (mid-marsh vegetation), living shoreline	12	21.2	12.8	1	3	ODL.R		

# Annex III: 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 <sup>14</sup>C and lead <sup>210</sup>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.

It is known that the choice of the material to be dated has repercussions on the radiocarbon ages (Belshe et al., 2017). As plant macro-debries could not be found on the lowest sections of the cores bulk sample was sent for radiocarbon dating. Bulk samples the less preferred material as the carbon on them is a mixture of various sources and their age would be an average of the different ages of the organic matter found in it.

The <sup>210</sup>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 <sup>210</sup>Pb radioactive decay curve. This technique is finer than the <sup>14</sup>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 <sup>210</sup>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.

Those cores where a good <sup>210</sup>Pb decay rate could be found had the best prediction for carbon fluxes while those where only radiocarbon dates where used should be considered with

precaution due to the uncertainties of the bulk sampling and the assumption of the same sedimentation on the last 100 yr than in the timeframe of the carbon dates (>500 yr.)

#### 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 <sup>210</sup>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<sub>2</sub> = 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. CH<sub>4</sub> and N<sub>2</sub>O emmissions

CH4 emissions may be significant in saltmarshes with salinities below 18 ppt (Poffenbarger et al, 2011). Therefore. Some parts of the continentalized high marsh of Odiel may have salinity levels below this threshold. In the next report, we will estimate, using data from the litterature for similar areas, the possible emissions of this part of the Odiel saltmarsh, and will include these figures in the global estimate of carbon sink capacity of this natural park. High inputs of labile organic matter may also enhance emissions of this GHG.

Eutrophication may increase saltmarsh emissions of N<sub>2</sub>O (Burgos 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 saltmarshes have been discussed in several instances over this report.

# Annex III: 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



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Group of Aquatic Macrophyte Ecology CEAB-CSIC





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