Operationalizing blue carbon principles in France: Methodological developments for Posidonia oceanica seagrass meadows and institutionalization

Adrien Comte, Jeanne Barreyre, Briac Monnier, Roman de Rafael, Charles-François Boudouresque, Gérard Pergent, Sandrine Ruitton

Version of Record: https://www.sciencedirect.com/science/article/pii/S0025326X23012572
Manuscript_f8dcd687edf33254d73d58eb2e100a12

Operationalizing blue carbon principles in France: methodological developments for *Posidonia oceanica* seagrass meadows and institutionalization

Adrien Comte[1], Jeanne Barreyre[2], Briac Monnier[3], Roman de Rafael[2], Charles-François Boudouresque[4], Gérard Pergent[3], and Sandrine Ruitton[4]

[1] IRD, Univ Brest, CNRS, Ifremer, LEMAR, 29280, Plouzané, France
[2] EcoAct, France
[3] Université de Corse, UMR CNRS SPE 6134, Campus Grimaldi BP 52, Corte, France
[4] Aix Marseille Université - Université de Toulon, CNRS, IRD, Mediterranean Institute of Oceanography (MIO), UM 110, Marseille, France

Corresponding author: Adrien Comte, adrien.comte@ird.fr, Laboratoire LEMAR, Institut Universitaire Européen de la Mer, Technopôle Brest-Iroise, Rue Dumont D'Urville, 29280 Plouzané, France

Operationalizing blue carbon principles in France: methodological developments for *Posidonia oceanica* seagrass meadows and institutionalization

Highlights

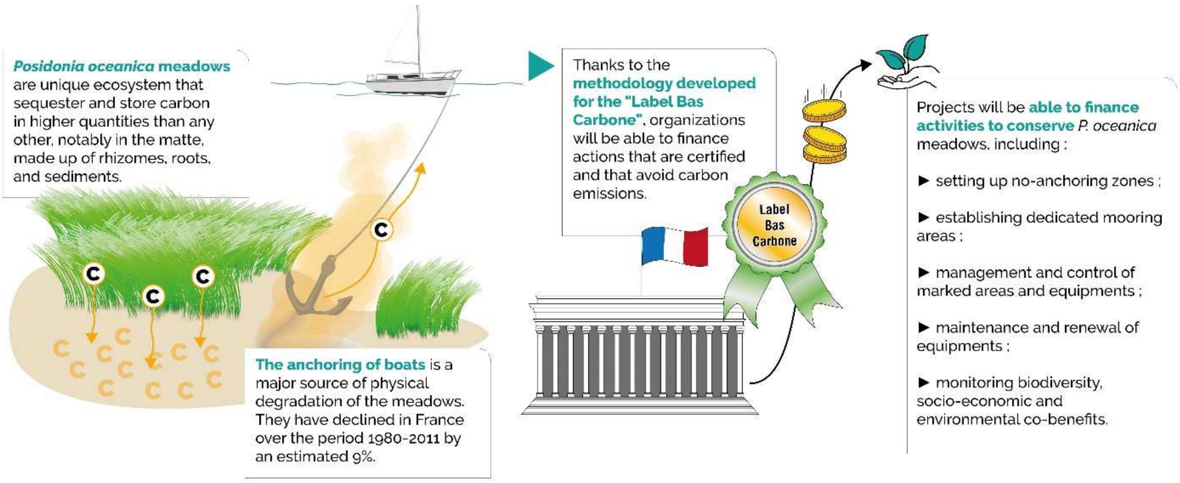
- Blue carbon methodologies are interesting tools to finance conservation
- The first institutional blue carbon methodology in Europe is described
- France has high potential to develop blue carbon projects
- Expansion of methodologies should rest on precautionary principles

Abstract

Conservation of ecosystems is an important tool for climate change mitigation. Seagrasses, mangroves, saltmarshes and other marine ecosystems have particularly high capacities to sequester and store organic carbon (blue carbon), and are being impacted by human activities. Calls have been made to mainstream blue carbon into policies, including carbon markets. Building on the scientific literature and the French voluntary carbon standard, the '*Label Bas-Carbone*', we develop the first method for the conservation of *Posidonia oceanica* seagrasses using carbon finance. This methodology assesses the emission reduction potential of projects that reduce physical impacts from boating and anchoring. We show how this methodology was institutionalized thanks to a tiered approach on key parameters including carbon stocks, degradation rates, and decomposition rates. We discuss future needs regarding (i) how to strengthen the robustness of the method, and (ii) the expansion of the method to restoration of seagrasses and to other blue carbon ecosystems.

Keywords: Blue carbon, *Label Bas-Carbone*, *Posidonia oceanica*, Marine conservation, ecosystem services, Carbon markets

Graphical Abstract



1. Introduction

Atmospheric concentration of greenhouse gases (GHG) continues to rise. Urgent action is needed to mitigate climate change and stay within the objectives defined in the 2015 Paris Agreement of the United Nations Convention on Climate Change, to limit global warming to less than 2°C by the end of the century and as close as possible to 1.5°C (Dimitrov, 2016; UNFCCC, 2016). The loss of biodiversity is another global challenge, which is linked to the issues of biological invasions, coastal development, overexploitation, and climate change (Boudouresque & Verlaque, 2005; Maxwell *et al*., 2016; Boudouresque *et al*., 2023; Pörtner *et al*., 2023). Both issues are driven by human activities, and solutions need to address both threats at the same time.

Nature-based solutions are an important set of options to respond to both global challenges. Nature-based solutions are defined by the International Union for the Conservation of Nature as a set of measures to manage, conserve, and restore ecosystems in order to deal with societal challenges. Measures associated with management and conservation of ecosystems could provide around one third of the necessary reduction in atmospheric GHG by 2030 (Roe *et al*., 2021). Coastal and marine ecosystems represent an important source of solution to address climate change (Gattuso *et al*., 2018, Macreadie et al. 2021) while carbon fixation and sequestration by European and Mediteranean forest decrease due to climate evolution, fire forest and human use (Chuine *et al*., 2023; Vallet *et al*., 2023).

Coastal ecosystems (mangrove, salt meadows, seagrass beds, kelp forests) and terrestrial ecosystems (marshes, peat bogs) represent an important lever. These so-called blue carbon ecosystems store carbon in biomass and sediments under anaerobic conditions over millennia. Thus, their degradation - in addition to destroying unique ecosystems - causes a significant loss of carbon stock. Among other things, it has been estimated that GHG emissions from the degradation of these coastal ecosystems represent between 0.1 and 1.46 $GtCO_2$ per year, or up to 12% of the CO_2 emissions from annual global deforestation (Howard *et al*., 2017). They are particularly productive ecosystems since coastal vegetation represent a sequestration equivalent to half of the carbon stock in ocean sediments despite a small surface area (0.5% of the ocean surface area) (Nellemann *et al*., 2009; Fourqurean *et al*., 2012). Marine magnoliophytes, *i.e*.

seagrasses, play a major role since they are responsible for 40% (50 106 tC yr^{-1}) of the carbon stored each year by coastal vegetation (Nellemann *et al*., 2009). Finally, they are particularly productive ecosystems from the carbon point of view, under anaerobic conditions that strongly slow down the degradation of biomass into carbon dioxide (Pendleton *et al*., 2012).

The conservation (passive restoration through decreased human impacts) and active restoration of blue carbon ecosystems are recognized as one of the tools to mitigate climate change by policy-makers and managers (Macreadie *et al*., 2021), providing important value for society (Bertram *et al*., 2021). Several states include blue carbon ecosystems in their Nationally-Determined Contributions (Gallo *et al*., 2017; Arkema *et al*., 2023; Herr & Landis, 2016). The Intergovernmental Panel on Climate Change (IPCC) has also produced guidelines for countries to account for their blue carbon (Hiraishi *et al*., 2014).

Market-based mechanisms, and particularly carbon markets, are promising tools for financing the conservation and restoration of blue carbon ecosystems (Pergent *et al*., 2019; Vanderklift *et al*., 2019; Friess *et al*., 2022; Macreadie *et al*., 2022; *et alet*). While nature climate solutions could cover around a third of mitigation needs by 2030 (Griscom *et al*., 2017; Roe *et al*., 2021), it receives only 3% of global finance. Common rules on cooperation to achieve climate action, including through carbon markets, have recently been determined within the Article 6 of the Paris Agreement. Outside of climate policies and requirements, voluntary carbon markets are flourishing, with almost 2 billion US$ of value in 2021 (Forest Trends' Ecosystem Marketplace, 2022) and a growing demand for blue carbon (Friess *et al*., 2022).

There are very few existing methodologies on blue carbon for the voluntary carbon markets. At the international scale, several standards have developed methodologies to account for blue carbon. The Clean Development Mechanism (CDM) has developed one on mangroves (AR-AM 00014) with projects in Senegal and Indonesia, Verra organization (Verified Carbon Standard) has produced two methods, the 'VM007' on reducing emissions from deforestation and forest degradation, including wetlands (Verified Carbon Standard, 2020), and the 'VM0033' on tidal wetland and seagrass restoration (Verified Carbon Standard, 2021), with certified mangrove restoration projects in Pakistan. Others exist like microscale project Mikoko Pamoja in Kenya certified by Plan vivo. At the national level, to the best of our knowledge, only Japan and the United States of America (USA) have produced blue carbon methodologies. The methodologies focus on the protection and restoration of seagrasses and macroalgae at the local and national scales in Japan (Kuwae *et al*., 2022). In the USA, the methodologies focus on restoration of wetlands under the American Carbon Registry (Sapkota & White, 2020).

In France, the government has set-up its own standard to certify voluntary carbon projects, called *Label Bas-Carbone* (LBC - low carbon label). This standard was introduced in 2018 by the French government. It is administered by the Ministry of Ecological Transition, and has approved thirteen methods so far, mostly dedicated to agricultural lands and forests. Since 2018, the LBC has certified 628 projects, which amount to 2.2 million potential tCO_{2e}.

Within the LBC, two methods are focused on blue carbon ecosystems. The first one, on the protection of *Posidonia oceanica* meadows, has been approved officially in April 2023. The second method, on the restoration of mangroves and wet forests, is under development and is scheduled for publication before the end of 2023. The remaining of this article will focus on the description of the former.

There are many types of seagrass meadows in the world and in France (86 species at this day in Guiry & Guiry, 2023). The present method is dedicated to *P. oceanica* meadows only, located on the French Mediterranean coast. These seagrass beds play an important role in mitigating climate change, thanks to their high capacity to capture, sequester and store carbon over millennia. *P. oceanica* meadows are unique in this respect: they are the type of seagrass that sequesters the most carbon in the long term, notably in the *matte* (Pergent *et al.*, 2012; Boudouresque *et al.*, 2016; Pergent-Martini *et al.*, 2021; Monnier *et al.*, 2022). This below-ground formation, reaching several meters in thickness, is made up of rhizomes, roots and various organic debris clogged with sediment (Serrano *et al.*, 2012; Monnier *et al.*, 2021).

Posidonia oceanica is protected in France under the French Nature Protection Act of July 10, 1976, by the decree of July 19, 1988 on the list of protected marine plant species; it is mentioned in the Bern Convention, and since 1999 in Annex II of the Barcelona Convention's Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean, and finally in the Council of Europe's 1992 "Habitats-Fauna-Flora" Directive (Directive 92/43/EEC of May 21, 1992, amended by Directive 97/62/EEC) (Boudouresque & Bianchi, 2013).

Despite their protection status, *P. oceanica* meadows are subject to multiple pressures, including in marine protected areas (MPAs) where numerous past or authorized human activities have led to the loss of around 10% of their surface area in the Mediterranean basin over the last 100 years (Boudouresque *et al.*, 2009; Dunic *et al.*, 2021). These seagrass meadows are subject to physical impacts from a variety of sources as coastal development, trawling, anchoring, turbidity, erosion, beach nourishment (Boudouresque *et al.*, 2009; Deter *et al.*, 2013; Holon *et al.*, 2015). The anchoring of pleasure boats, via moorings, is a major source of physical degradation of the meadows (Ganteaume *et al.*, 2004; Cossu *et al.*, 2006; Deter *et al.*, 2017; Pergent-Martini *et al.*, 2022a). Thus, *P. oceanica* showed a decline in France over the period 1980-2011: 9% according to Telesca *et al.* (2015), a value that may be overestimated (Boudouresque *et al.*, 2021).

The aim of this article is to present the process of operationalizing and institutionalizing blue carbon principles within a methodology applicable for the LBC standard in France. The development of this method should result in the enhancement and preservation of a stock of carbon sequestered within seagrass beds and in the process of being degraded, thanks to additional projects improving the abiotic and ecosystem conditions of *P. oceanica* seagrass beds in the Mediterranean. The method describes all the criteria for eligibility, additionality, the consideration of risks associated with general and climatic uncertainties, and the procedures for estimating net reductions in greenhouse gas emissions from projects aimed at protecting Posidonia meadows. The method will enable project promoters to obtain funding by implementing and monitoring actions that result in the preservation of carbon stocks threatened by the degradation of the storage environment.

2. Material and methods

2.1 Literature review

In order to produce a robust and operational carbon accounting methodology for *P. oceanica* seagrass meadows protection, a literature review of published and grey literature was conducted. This literature review fed into an iterative process of methodological development, with a team writing the methodology and a tool for the accounting of projects, feedbacks from discussions with the *Parc National des Calanques* (Calanques National Park, western Provence, France) on their operational needs and constraints, and with the scientific committee that gave expert opinion on the items developed in the methodology and provided additional literature.

To produce a methodology that meets scientific robustness while aiming for cost-effectiveness, a tiered approach is used for the different parameters that make up the accounting guidelines. The tiered approach follows in its principle the guidelines developed by the IPCC (Hiraishi *et al.*, 2014) but tailors it to the specificities of the LBC and of the protection of *P. oceanica* seagrasses.

2.2 Case study in *Calanques National Park*

Marine protected areas are important solutions to address climate change mitigation and adaptation (Roberts *et al.*, 2017; Jacquemont *et al.*, 2022). In order to test and inform the development of the methodology, a partnership was developed with the Calanques National Park (CNP) (Figure 1). The CNP was established in 2012. It covers 8 500 ha on land and 43 500 ha on sea. The high frequentation of its sites leads to impacts on seagrasses, so that the development of methods for the protection of *Posidonia* seagrass meadows could directly bring resources to contribute to decreasing anthropogenic pressures and protection of seagrass carbon stocks. The CNP is in the process of designing no-go zones for boats and dedicated mooring areas, in several of its locations.

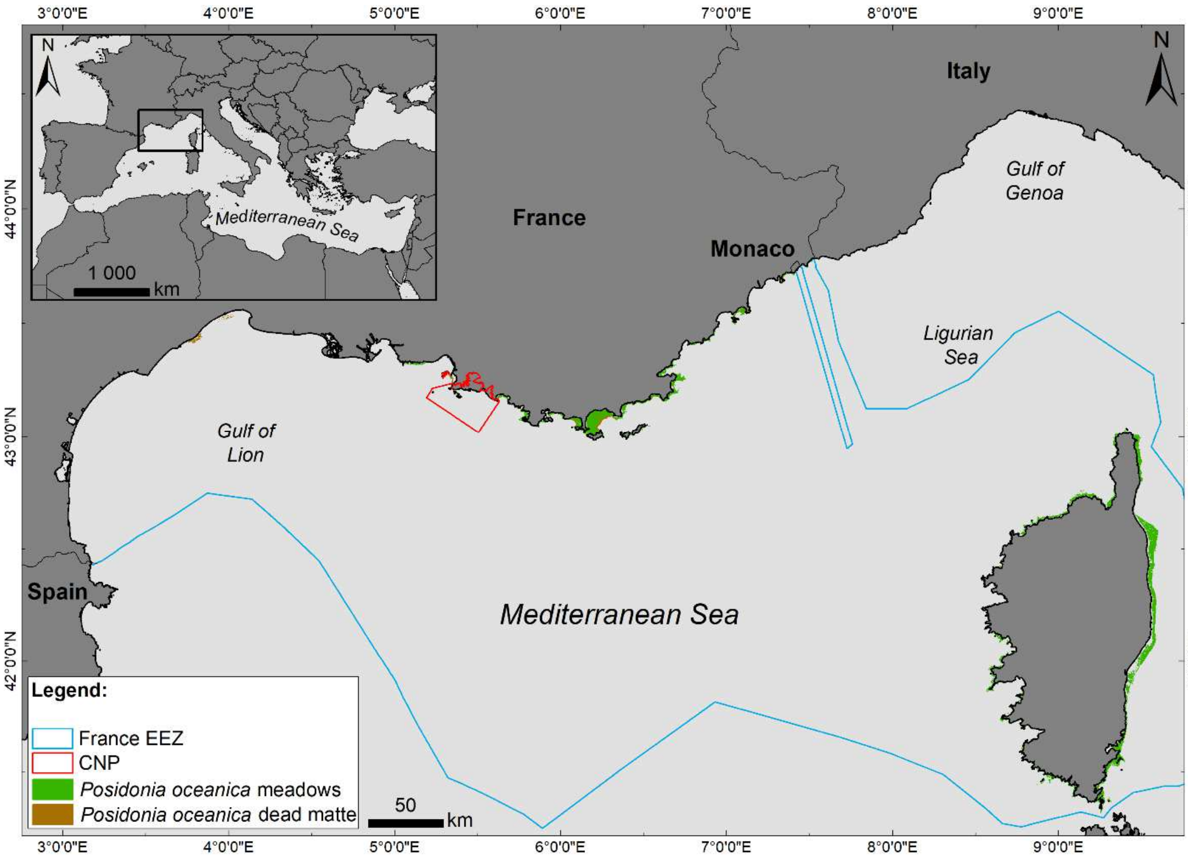


Figure 1: Distribution of *Posidonia oceanica* seagrass meadows and dead *matte* located in the Mediterranean region of the French Exclusive Economic Zone (EEZ), and location of the Calanques National Park (CNP) within it. Data of *P. oceanica* seagrass meadows and dead *matte* are retrieved from Office Français de la Biodiversité (2023).

3. Results

3.1 Projects characteristics

The duration of a *P. oceanica* meadow protection project is 10 years, renewable twice, *i.e.* 30 years. The calculation of Emission Reductions (ER) generated by the project will be carried out over 10 years. All the project owner's commitments are based on a 10-year period, renewable twice, in line with the duration of the temporary use agreement for the maritime public domain in France (*Autorisation d'occupation temporaire*).

Eligible actions under this methodology concern any project to protect *P. oceanica* meadows, located in mainland France, and involving the elimination or reduction of impacts linked to anchoring in *Posidonia* meadows.

The anchoring of boats in *P. oceanica* meadows is a major physical pressure, causing bundle tearing, *matte* degradation, and preventing recolonization over long periods (Ganteaume *et al.*, 2005; Lloret *et al.*, 2008; Boudouresque *et al.*, 2012; La Manna *et al.*, 2015; Abadie *et al.*, 2016; Deter *et al.*, 2017). Eligible *Posidonia* meadow protection activities are thus associated with the reduction of impacts linked to anchoring and mooring by:

- setting up no-anchoring zones,
- the establishment of dedicated mooring areas, including the necessary preparatory technical studies,
- relative management and control of marked areas and equipment,
- maintenance and renewal of the equipment installed,
- management of payment systems for use of the mooring areas.

Whatever activities are put in place, they must reduce the impact on the meadows by managing and maintaining them over time, at least for the duration of the project.

3.2 Additionality

To be eligible, projects must show their additionality in terms of regulatory, financial, and common practice dimensions, to be able to claim that they would not have been able to come to fruition without carbon finance. Projects need to go beyond regulatory obligations. Regulations protecting seagrass beds do exist but lack the means to be effective. Projects to protect seagrass beds by implementing management and protection measures that go beyond regulations, by preventing recreational boaters from damaging this ecosystem, by financing the establishment of mooring areas and no-go zones, as well as monitoring, surveillance and knowledge enhancement programs, could be considered additional.

Projects must not be financially viable. The protection of *P. oceanica* meadows is not a direct revenue-generating activity, even though the ecosystem services they provide to society are estimated at several tens of thousands of Euros per hectare (Rigo *et al.*, 2021). The proposed management plans therefore rely solely on public funds or royalties linked to the commercial and/or recreational use of these areas. In particular, the project developer must demonstrate that the project is economically unfavorable, by studying the possibilities of user fees and public financing, as well as the costs of implementing and maintaining the anchorage areas, to ensure that the project is additional and therefore eligible for carbon finance. Only few anchoring management and mooring zones projects have been implemented so far, thanks to several factors including small size of the system, funding possibilities via MPAs status, proximity to a port facilitating collection of fees, proximity to the beach facilitating collection of fees. An economic model is required to be eligible. The project owner can rely on the demonstration of financial additionality with a Net Present Value analysis to prove that the project is not financially viable without additional carbon financing.

3.3 Environmental integrity

Projects to protect seagrass meadows can generate co-benefits on biodiversity, socio-economic, and water dimensions (Table 1). These can be integrated in the Monitoring, Reporting, and Verification (MRV) of the project to generate premiums and add value to the project for potential voluntary buyers.

Table 1. Description of co-benefits that can be integrated in the project. Note that the "*Posidonia oceanica* rapid easy index" and the "Biotic index using the seagrass *Posidonia oceanica" are water quality indices, not biodiversity indices*

Type	Description	Indicator
Biodiversity	Protected species	Number of protected species inventoried
Biodiversity	Habitats rich in biodiversity	Ecosystem-based quality index (Personnic *et al.*, 2014; Boudouresque *et al.*, 2015, 2020)
		Posidonia oceanica rapid easy index (Gobert *et al.*, 2009)
		Biotic index using the seagrass *Posidonia oceanica* (Lopez y Royo *et al.*, 2010)
Biodiversity	Active restoration	Number of *Posidonia* cuttings or surface area restored
Biodiversity	*Banquette* of dead leaves on beaches	Volume of *banquette*
Socio-economic	Low-impact mooring systems	Number of ecological moorings put in place
Socio-economic	Fish nurseries function	Fish abundance and richness monitoring
Socio-economic	Public communication on conservation	Number of hours dedicated to communication
Socio-economic	Jobs and trainings	Number of jobs and trainings created
Socio-economic	Offshore beaconing and signage system	Number of systems installed
Socio-economic	Landscape	Reduced visual impact of moorings on landscape (Verlaque *et al.*, 2023)
Water	Removal and recycling of waste	Percentage of waste removed and recycled from site
Water	Water quality	Monitoring of water quality

3.4 Treatment of risks and uncertainties

Projects will need to incorporate the risk of general and climatic uncertainties, *i.e.* the risk of unforeseen carbon emissions due to sources of environmental disturbance such as storms, sea-level rise or other man-made pressures (*e.g.* macro-waste, dumping at sea, lost fishing gear). The degradation of seagrass beds is multifactorial, stemming from other sources of disturbance in addition to the impacts of anchoring. In particular, there are many anthropogenic pressures to consider, such as the risks associated with macro-waste discharged by boats, or fishing gear, which are major sources of seagrass degradation (Ruitton *et al.*, 2021). Unfortunately, these are difficult to quantify, predict or control.

The effects of rising sea levels linked to climate change are manifold, and can lead to potential changes in the distribution of ecosystems (*e.g.* the submersion of the midlittoral algal rim (*trottoir* of *Lithophyllum byssoides*; Blanfuné *et al.*, 2016), and flooding or high-water levels in major rivers. Global change is also responsible for the acidification of the marine environment. Acidification can lead to changes in the functioning of *P.* meadows (Scartazza *et al.*, 2017) and associated communities (Cox *et al.*, 2015, 2016). The long-term consequences of this phenomenon have yet to be determined. However, these effects are currently considered negligible (Boudouresque *et al.*, 2009) in terms of impact on seagrass beds, and no discount will be considered. In addition, sea-level rise could potentially modify the spatial extent of the meadows, in which case the project perimeter will have to be adapted. In fact, deep seagrass beds are directly affected by the reduction in available light due to rising sea levels (Pergent *et al.*, 2015).

The risk associated with general and climatic uncertainties will not be incorporated into the biomass growth models, for reasons of complexity for the project developer. However, the risk linked to general and climatic uncertainties will be considered in the form of a discount for all identified risks of 10% on the emissions reductions generated. Indeed, the LBC standard views this discount as a buffer to pool risk of failure across all projects using this method.

3.5 Quantification of Emission Reductions

3.5.1 General considerations for the calculation of emission reductions

Seagrass meadows can be divided into several carbon pools: (i) above-ground living biomass (bundles of living leaves); (ii) below-ground living biomass (surface *matte*: rhizomes and roots); (iii) dead biomass (underlying dead *matte*); (iv) accumulation of dead leaves washed up on the shore (Boudouresque *et al.*, 2017; IUCN, 2021). The various carbon compartments included in the methodology and evaluated include only the dead and living *matte* biomass.

Above-ground biomass is made up of leaf bundles and the epiphytes that attach to them. The carbon captured (photosynthetic fixation) in this compartment is negligible compared with the carbon stored and sequestered in the *matte* and is therefore not considered in this method. Below-ground biomass is separated into two categories: the superficial *matte* (about 30 cm layer) and the underlying dead *matte*. Apparent dead *matte* (visible on the bottom) results from the disappearance of leaf bundles (canopy), for natural or anthropogenic causes, but it is of course also be present under a living seagrass bed. In these areas of dead *matte*, the carbon fixation and sequestration process are interrupted, but existing carbon stocks are considered stable on the time scale of projects eligible for this method.

The natural washing up and deposition of *P. oceanica* leaves on the coast created structure called *banquettes*. Among other things, this process naturally protects the coastline, stores carbon in the short term (a few months to a few years), and supports biodiversity (a specific food web) (Boudouresque *et al.*, 2016, 2017; Boudouresque & Perret-Boudouresque, 2023). As these *banquettes* are protected, regulations prohibit their removal unless a specific exemption is granted. Despite these benefits and regulatory protection, they are often considered a source of nuisance tour operators local authorities, who often decide to remove them (Boudouresque *et al.*, 2017). Local authorities claim they do it at the request of users, which is totally contradicted by all users' surveys (Boudouresque *et al.*, 2022). In the present methodology, it was decided to not consider the allochthonous carbon sequestered in these *banquettes*, due to the different temporality of the carbon present compared to other compartments. Indeed, the degradation of fallen leaves is variable. However, the co-benefits associated with activities on these *banquettes* are considered in the method.

The emission reductions considered correspond to the difference between the reference scenario (in which the seagrass beds continue to be degraded by anchoring) and a project scenario (in which the seagrass beds are preserved by the necessary developments, and their proper management over time). Emissions reductions will therefore be calculated using the following formula:

$$EER_{i-j} = (1 - Discount_1 - Discount_2 - Discount_3) * \Delta CO_{2_{i-j}}$$

Where:

EER_{i-j}	Effective Emission Reductions between year i and year j, in tCO_{2e}
$Discount_1$	Discount due to general risks on permanence of carbon stocks
$Discount_2$	Discount due to uncertainties on the Tier 1 generic value of carbon stored in the *matte*
$Discount_3$	Discount due to the uncertainties on the duration of projects beyond 30 years
$\Delta CO_{2_{i-j}}$	Difference in carbon stocks in the *matte* between year i and year j, in tCO_{2e}

The formula for calculating the difference in carbon stock in the *matte* between year i and year j of the project is:

$$\Delta CO_{2_{i-j}} = (CO_{2_{project}}(j) - CO_{2_{reference}}(j)) - (CO_{2_{project}}(i) - CO_{2_{reference}}(i))$$

Where:

$CO_{2_{project}}(n)$	Carbon stock in the *matte* in the project scenario in year n, in tCO_{2e}
$CO_{2_{reference}}(n)$	Carbon stock in the *matte* in the project scenario in year n, in tCO_{2e}
j	Final year of the monitoring period
i	Initial year of the monitoring period (year 0 for the first verification period)

3.5.2 Reference scenario

The reference scenario is the continuation of practices observed in the project area prior to its implementation, *i.e.* the perpetuation of seagrass degradation by anchoring. In this scenario, the carbon stored in the *matte* will be released into marine water bodies and/or the atmosphere through the detachment and remineralization of organic matter immobilized on the seabed as a result of repeated anchoring in the same area. To achieve this, three parameters need to be assessed by the project developer including the surface area of seagrass in the project zone, the quantity of carbon stored in the *matte*, and the rate of degradation, which combines regression of the seagrass beds (the surface area affected by abrasion from anchoring) in the project area and decomposition of the *matte* (the depth of carbon localized in the *matte* affected).

These three parameters are found in the following equation:

$$CO_{2_{reference}}(n+1) = CO_{2_{reference}}(n) * (1 - T_{regression\ ref} * T_{decomposition})$$

Where:

$T_{regression\ ref}$	Annual rate of regression of seagrass meadows in the project zone, in %
$T_{decomposition}$	Decomposition rate of the carbon stock in the seagrass meadow, in %

And at the beginning of the project (year = 0):

$$CO_{2_{reference}}(0) = A_{seagrass} * C_{matte} * \frac{44}{12}$$

Where:

$A_{seagrass}$	Surface area of seagrass meadows in the project zone at the beginning of the project, in hectares (ha)
C_{matte}	Carbon stock in the seagrass meadows *matte* in the project zone, in tC ha^{-1}

To determine the carbon stock in the *matte*, a tier logic is available to project developers. They can either use simple but conservative default data (Tier 1, Tier 2) or carry out more detailed analyses, which will require more effort but may provide better results (Tier 3). The data to be used for this method are as follows.

Tier 1: Use of a default value of 327 tC ha^{-1} (Monnier *et al*., 2022), considering a *matte* thickness of 1 m (Mateo *et al*., 2019). Although carbon density (g C cm^{-3}) is lower in the first 5 cm of dead *matte* than in living *matte* (Piñeiro-Juncal *et al*., 2021), the values observed between these two types of *matte* follow the same trend within the first meter of sediment. The same values will therefore be taken into consideration for both categories. Given the uncertainties associated with these default values and to incentivize project owners to use Tier 2 and 3 values, a discount rate of 10% applies if the project developer chooses to use Tier 1 to assess the carbon stock in the *matte*.

Tier 2: Use of a default value of 1 m *matte* thickness likely to be degraded by anchoring, coupled with the use of local values of estimated C density in *matte* to determine carbon stock in tC ha^{-1} (Romero *et al*., 1994; Mateo *et al*., 1997; Mateo *et al*., 2010; Serrano, 2011; Serrano *et al*., 2011; Serrano *et al*., 2012; Monnier, 2020). *Matte* density can be derived from *in situ* data using a standard protocol such as Howard *et al*. (2014) or IUCN (2021) (see SPM1).

Tier 3: Use of carbon stock data for each category (living and dead *matte*) from a local peer-reviewed study or *in situ* data using a standard protocol among Howard *et al.* (2014) or IUCN (2021) (see SPM1). If carbon stock data cannot be obtained in dead *matte* at the local scale, values obtained in live *matte* will be applied. *Matte* thickness can be measured according to the protocol established by Monnier *et al.* (2021).

The regression of the seagrass corresponds to the surface area of the seagrass that decreases due to the abrasion of the anchor chains. To determine the regression rate, $T_{regression\,ref}$, a tier logic is also proposed to the project developer, given the disparities in regression values observed (Boudouresque *et al.*, 2009). No discount is associated with this parameter. The data to be used for this method are as follows.

Tier 1: Use of a default regression rate of 0.29%. Value taken from the publication by Telesca *et al.* (2015), which provides a summary for the Mediterranean region and assigns a 9% regression rate for France between 1980 and 2011, *i.e.* an average annual regression rate of 0.29%.

Tier 2: Use of data from the anchoring surface on seagrass beds and the abrasion surface caused by anchoring.

$$T_{regression\,ref} = \frac{(x * 0{,}016)}{A_{seagrass}} * 100$$

Where:

$A_{seagrass}$	Surface area of seagrass meadows in the project zone at the beginning of the project, in hectares (ha)
x	Number of boats anchoring in the project zone per annum

The abrasion surface depends on both anchoring depth and boat size. In this methodology, the average value of 160 m^2 (0.016 ha) will be considered for estimating the abrasion surface of the chain used by anchored pleasure craft. This result is derived from catenary curve calculations and considering a 45° oscillation circle, for seven depth ranges (Griffiths *et al.*, 2017).

Tier 3: Use of data from a local peer-reviewed study or standardized methods to assess seagrass regression due to anchoring, taking into account the type of boat, the type of anchor, the type of chain and their locations on the seagrass beds.

The decomposition rate of seagrass beds represents the carbon in the *matte* that is decomposed due to the repeated action of anchors. To calculate this rate, two tiers are proposed. There is no discount associated with this parameter.

Tier 1: Using the results of the linear model developed as part of the LIFE Blue Natura project (Mateo *et al.*, 2019) estimating carbon loss in the first meter of *matte* as a result of mechanical degradation due to the repeated action of dredging chains. Additional mechanical erosion also occurs.

$$T_{decomposition} = \frac{\left(100 - (-1{,}42\ (n) + 103{,}5)\right)}{100}$$

With n the number of years of the project duration.

Tier 2: Use of data from a local peer-reviewed study or standardized methods to assess the decomposition of carbon stock in seagrass beds due to anchoring.

3.5.3 Project scenario

The project scenario is the scenario in which the protection actions are implemented as part of the project. In order to guarantee monitoring of the carbon stock and the state of the seagrass beds over the duration of the project, it is necessary to monitor and verify certain parameters in the ER calculations. These parameters can be found in the following two equations:

$$CO_{2_{projet}}(n) = A_{seagrass} * C_{matte} * \frac{44}{12}$$

And

$$CO_{2_{project}}(n+1) = CO_{2_{project}}(n) * (1 - T_{regression\ project} * T_{decomposition})$$

With regard to the regression rate, this method proposes monitoring using a tiered approach identical to that described in the previous section. This rate is called $T_{regression\ project}$, as opposed to the $T_{regression\ ref}$ of the reference scenario. Note that the choice of Tier for the project scenario must be the same as for the reference scenario. The Tier 1 of the regression rate calculation is a default value equal to zero.

For Tier 2 of the regression rate: Monitoring of the seagrass surface ($A_{seagrass}$) and the number of boats anchoring in the project area will be carried out using data from recognized scientific data online platforms. It will be necessary to justify the robustness of the source mobilized (by explaining the methodology considered, the level of uncertainty, etc.).

For Tier 3: monitoring of seagrass regression must be based on data from a local peer-reviewed study or the use of standardized methods. These methods should use the sensors and field data presented in SPM1. The measurement tools to consider include optical sensors for surface data (*e.g.* aerial imagery from satellite and/or drone) combined with acoustic sensors for deeper data (*e.g.* multibeam echo-sounders - MBES, side-scan sonar - SSS), and/or permanent systems positioned on the seabed (*e.g.* concrete markers, permanent squares, geo-localized photos, cameras). For Tier 3, regardless of the option used, field data must be collected to validate sensor data (*e.g.* underwater dives). Finally, the decomposition rate is the same for the project and for the reference scenarios.

3.6 Monitoring, reporting and verification

The monitoring of project activities and its impacts on seagrass carbon stocks is conducted by the project developer throughout the project. In order to generate ERs, third-party audits are carried out at least every five years. The purpose of verification is to show that the promised actions have been implemented and that the level of follow-up has been respected. The verifications will be based on the documents provided by the project developers and by on-the-ground field work. These dispositions should allow transparent and accurate accounting of the carbon stocks protected by the project, to minimize the overestimation of ERs produced by the project.

4. Discussion

4.1 Operationalization

The method developed here for the French voluntary carbon market answers one of the main hindrances to investments in blue carbon, which is the lack of robust methods to estimate blue carbon stocks and co-benefits (Vanderklift *et al.*, 2019). There is an inherent tension between ensuring integrity of carbon projects and the costs of monitoring, reporting, and verification. In order to ensure the development of projects on the ground, the choice has been made here to produce methods with low costs of MRV. The integrity is ensured via conservative estimates of carbon stocks, and omission of harder to measure carbon fluxes in *Posidonia* seagrass meadows. Other possible options include the use of more precise MRV methods, which then risks increasing costs beyond the price range found in voluntary carbon markets, thus preventing on the ground development of projects. This was the case with the outcome of the Blue Natura project in Spain (Mateo *et al.*, 2019), which developed a solid methodology that required a market price of 900 € per tCO_2, way above any market price found in the world (and above the value of the social cost of carbon).

4.2 Institutionalization

There is a gap between the funding needed to protect biodiversity and prevent further losses and the actual amount of funding available. Some estimate this gap at 600 to 800 billion US$ per year (Deutz *et al.*, 2020). In the current situation, public funding is not sufficient to bridge this gap, which leads many to discuss “alternative” or “innovative” finance mechanisms. Voluntary carbon markets are therefore an important source of funding for the protection of biodiversity (Macreadie *et al.*, 2021). However, in situations where buying carbon credits prevent organizations from reducing their own emissions, this new market mechanism could divert money away from climate mitigation (Seyller *et al*., 2016). At least, this money goes towards the conservation of ecosystems.

The importance of private sources of funding to fight global environmental challenges is the primary factor that lead France to establish the LBC. The question is why develop its own national standard when other standards exist. This creates the possibility for high transaction costs. However, the way the LBC is designed allows small projects to emerge and provides a transparent ledger where developers and financiers can meet. The possibility to design large programs on blue carbon is limited by the surface area of habitats and by the fragmented management and ownership of these areas, which increases the cost of carbon credits. This method thus can appeal to companies that operate near seagrass meadows in the Mediterranean, for strategic and corporate social responsibility purposes (Vanderklift *et al*., 2019).

4.3 Future research needs

Throughout the course of the development of the methodology to account for carbon stocks and protection offered by carbon projects, research gaps have forced us to consider proxy or conservative ways of quantification. In order to improve this methodology (a process which is in principle continuous and supervised by the Ministry in charge of the environment), several scientific developments have been identified on the different dimensions accounted for here, including carbon stocks, regression rate, and degradation rate.

There is currently no cheap way of measuring the *matte* height over large areas, which requires development in order to improve the accuracy of the values proposed as default, or to decrease the cost of sampling. There are few methods that make the link between boats dimensions and their impacts on seagrass meadows. This impact depends on the type of anchor, the chain, the weight and height of the boat, and the water depth (Abadie *et al*., 2016; Griffith *et al*., 2017). Not all boats are equipped with tracking devices, so that monitoring techniques, via cameras, drones, or else, need to be put in place in order to be able to characterize boats anchoring in project areas and better estimate the surface area of seagrass meadows impacted by them. One issue with the current model is the assumption that boats anchor in different locations, but it is possible for different boat to anchor close to each other and have overlapping effects on the carbon stocks (Pergent-Martini *et al.* 2022b). This should be investigated in the future.

Even less studied is how much carbon is released by this impact. We used an estimation from Mateo *et al*. (2019) that was calculated from one experiment in Spain but needs to be replicated over time and space to reflect more accurately how much carbon is released from repeated anchoring. Furthermore, more complex ecosystem processes, including primary production and pelagic cycles, are left out of the approach taken here but could play a role in the changes in carbon stocks (Mazarrasa *et al.* 2018).

The cost of monitoring, reporting, and verification is a huge determinant hindering the development of blue carbon projects, due to the need for underwater surveys, the difficulty of using remote sensing at large scale, and the complex determinants of carbon stocks and fluxes. Ecosystem accounting is now gaining traction, since the approval as an accounting norm of the System of Environmental Economic Accounting – Ecosystem Accounting (SEEA-EA) in 2021 by the United Nations (Edens *et al.,* 2022). Marine ecosystems are still under studied in the context of ecosystem accounting (Comte *et al.,* 2022), but development is under way in order to better map marine ecosystem extent and condition (Kervinio *et al*., 2023), and fluxes of ecosystems services including carbon (Montero-Hidalgo *et al.,* 2023). Ecosystem accounting thus offer a way to systematically account for marine ecosystems and their carbon stocks and fluxes.

4.4 Future developments of methods on blue carbon

Active seagrass restoration activities (replanting, transplanting) are not eligible under this method. Experiments are currently underway, notably the RENFORC project (Université de Corse-GIS Posidonie), as well as the REPAIR (Stareso-Université de Liège) and REPIC (Andromède océanologie) projects, and will contribute to a better understanding of the effectiveness of these actions and their impact on carbon storage and sequestration. The aim is to produce a best practice guide on active restoration (Boudouresque *et al*., 2021). A specific methodology incorporating these new elements could be developed in the future.

Many blue carbon ecosystems can be found in France, outside of *Posidonia* seagrass meadows. In the Economic Exclusive Zone, other seagrasses, macro-algae, and salt marshes thrive. The French oversea territories, particularly the Caribbean islands of Guadeloupe and Martinique, French Guyana, and Mayotte, are home to mangrove forests and seagrass meadows that provide important ecosystem services, including climate mitigation (Trégarot *et al*., 2021). The need for restoration and protection of these ecosystems, and the current lack of coverage of highly protected MPAs, call for innovative mechanisms. The extension of the *Label Bas Carbone* standard to methods applicable to these ecosystems is thus an interesting possibility to explore, and is indeed underway with the development of a method on mangrove restoration and of a method on Zostera seagrass meadows restoration.

4.5 Precautionary on methods and carbon markets

There are many criticisms around these types of methodologies. On the one hand, the carbon removal using coastal and marine ecosystems has been qualified as uncertain and unreliable (Williamson & Gattuso, 2022). We agree that the underlying processes of fixation and sequestration are still far from being known and accounted for in an exhaustive way (Johanssen and Macdonald, 2016). In this method, we disregard carbon fluxes for this reason, and only account for carbon stocks in the *matte*. On the other hand, avoided emissions (protecting standing stock) are being criticized widely, because the counterfactuals are never easy to produce which undermines the claim that projects are additional (Gillenwater *et al*., 2007). Against this criticism, the method developed here is very conservative on the type of impacts taken into account and on the degradation rate that is used for the counterfactual, which greatly limits the risk of overestimating the carbon gains from projects using this method. Main issue for *Posidonia* seagrasses is indeed protection of the current carbon stocks, as they took hundreds of years to form, and restoration is slow and costly.

Several avenues for modifications exist to improve the efficiency and robustness of the French LBC standard. First, the standard allows for anticipatory generation of emission reduction, that has been used in several methodologies, including on forest restoration. This option is risky as several things can happen to carbon stocks in these projects. A precautionary approach would suggest not being able to claim anticipatory emission reductions, which we use in this methodology. We therefore suggest to the Ministry for an Ecological Transition to modify its LBC standard in order to allow only ex-post accounting of emission reductions. Second, major events that can impact carbon stocks along the project life cycle should be better monitored and accounted for via a stronger buffer of carbon emission reductions. Third, there are high transaction costs in developing specific methodologies for the French territories while such methods already exist in international standards. Stronger connections should be made in order to adapt at low cost existing international methodologies to the LBC.

Lack of control and of satisfactory accounting method could lead to overestimation and undermine the fight against climate change by allowing polluters to offset without actual climate benefits (Johannessen and Macdonald, 2016). Here, this threat is unlikely as the Label Bas Carbone is in dire need of projects as new regulation requires several French economic sectors, including energy and aviation, to buy LBC emission reductions in addition to other stringent policies that aim at reducing emissions from these sectors (EU ETS, ban of short distance flights). In other settings, this risk is however not excluded and should be carefully considered when designing carbon markets (Gillenwater *et al.*, 2007).

5. Conclusions

Thanks to an iterative process including methodology developers, scientific committee, on the ground experts (staff from the Calanques National Park) and support from the Ministry in charge of the environment, the first methodology on the protection of *P. oceanica* seagrass for the French voluntary carbon market has been developed and approved. This methodology uses a tiered approach to balance scientific robustness and cost of monitoring of carbon stocks and project activities. The method takes careful consideration of the problematic issues of carbon offsetting methodologies, including additionality, integrity, and monitoring.

We hope that many project developers and financiers will take up this method to put in place protection measures against the negative impacts of anchoring on *P. oceanica* seagrass beds in the French Exclusive Economic Zone. This method could be expanded to other geographies in the Mediterranean region, and to other activities that promote the conservation and restoration of these important marine ecosystems.

Acknowledgments

This work was supported by Schneider, Digital Realty, and EcoAct. We thank the Calanques National Park for the discussions and information provided that contributed to the development of the methodology. We thank Sébastien Hervé for his work on the graphical abstract.

References

Abadie A., Lejeune P., Pergent G., Gobert S., 2016. From mechanical to chemical impact of anchoring in seagrasses: the premises of anthropogenic patch generation in *Posidonia oceanica* meadows. Marine Pollution Bulletin, 109(1), 61-71.

Arkema, K.K., Delevaux, J.M.S., Silver, J.M. *et al.* Evidence-based target setting informs blue carbon strategies for nationally determined contributions. *Nat Ecol Evol* (2023). https://doi.org/10.1038/s41559-023-02081-1

Bertram C., Quaas M., Reusch T.B., Vafeidis A.T., Wolff C., Rickels W., 2021. The blue carbon wealth of nations. *Nature Climate Change*, *11*(8), 704-709.

Blanfuné A., Boudouresque C.F., Thibaut T., Verlaque M., 2016. The sea level rise and the collapse of a Mediterranean ecosystem, the *Lithophyllum byssoides* algal rim. *In: The Mediterranean region under climate change. A scientific update*. Thiébault S., Moatti J.P. (eds.), AllEnvi, IRD éditions publisher, Marseille: 285-289.

Boudouresque C.F., Bianchi C.N., 2013. Une idée neuve: la protection des espèces marines. *In: GIS Posidonie: plus de 30 ans au service de la protection et de la gestion du milieu marin*. Le Diréach L, Boudouresque C.F. (eds.), GIS Posidonie publ., Marseille: 85-91.

Boudouresque C.F., Perret-Boudouresque M., 2023. Les banquettes de feuilles mortes de posidonies : un enjeu écologique, économique et culturel. *Naturellement*, 143: 32-34

Boudouresque C.F., Verlaque M., 2005. Nature conservation, Marine Protected Areas, sustainable development and the flow of invasive species to the Mediterranean Sea. *Sci. Rep. Port-Cros Natl. Park*, 21: 29-54.

Boudouresque C.F., Bernard G., Pergent G., Shili A., Verlaque M., 2009. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: a critical review. Botanica Marina, 52 : 395-418

Boudouresque C.F., Bernard G., Bonhomme P., Charbonnel E., Diviacco G., Meinesz A., Pergent G., Pergent-Martini C., Ruitton S., Tunesi L., 2012. Protection and conservation of *Posidonia oceanica* meadows. RAMOGE and RAC/SPA publ., Tunis: 1-202.

Boudouresque C.F., Pergent G., Pergent-Martini C., Ruitton S., Thibaut T., Verlaque M., 2016. The necromass of the *Posidonia oceanica* seagrass meadow : fate, role, ecosystem services and vulnerability. *Hydrobiologia*, 781: 25-42.

Boudouresque C.F., Ponel P., Astruch A., Barcelo A., Blanfuné A., Geoffroy D., Thibaut T., 2017. The high heritage value of the Mediterranean sandy beaches, with a particular focus on the *Posidonia oceanica* 'banquettes': a review. *Sci. Rep. Port-Cros Natl. Park*, 31 : 23-70.

Boudouresque C.F., Personnic S., Astruch P., Ballesteros E., Bellan-Santini D., Bonhomme P., Botha D., Feunteun E., Harmelin-Vivien M., Pergent G., Pastor J., Poggiale J.C., Renaud F., Thibaut T., Ruitton S., 2015. Ecosystem-based versus species-based approach for assessment of the human impact on the Mediterranean seagrass *Posidonia oceanica*. *In: Marine productivity: perturbations and resilience of socio-ecosystems*. Ceccaldi H., Hénocque Y., Koike Y., Komatsu T., Stora G., Tusseau-Vuillemin M.H. (eds), Springer International Publishing Switzerland: 235-241.

Boudouresque C.F., Astruch P., Bănaru D., Blanfuné A., Belloni B., Changeux T., Chevaldonné P., Fernandez C., Harmelin J.G., Perez T., Pergent P., Pergent-Martini C., Ruitton S., Thibaut T., 2020. Ecosystem-based quality indices : valuable tools for environment management. *Vie et Milieu - Life and Environment*, 70 (3-4): 3-15.

Boudouresque C.F., Blanfuné A., Pergent G., Thibaut, T., 2021. Restoration of seagrass meadows in the Mediterranean Sea: a critical review of effectiveness and ethical issues. *Water*, 13 (1034): 1-35.

Boudouresque C.F., Marinier M., Cavalier M., Driancourt T., Blanfuné A., Perret-Boudouresque M., Thibaut T., 2022. The perception of *Posidonia oceanica* banquettes by beachgoers in the French Riviera. *7th Mediterranean Symposium on marine vegetation*, Genoa, Italy, 19-20 September 2022, RAC/SPA publ., Tunis: 37-42.

Boudouresque C.F., Blanfuné A., Changeux T., Pergent G., Perret-Boudouresque M., Ruitton S., Thibaut T., 2023. Marine biodiversity in the era of global warming. *La Mer* (in press).

Cossu A., Ragazzola F., Demelas S., 2006. Distribution and ecological conditions of *Posidonia oceanica* (L.) Delile meadows in La Maddalena National Park (Sardinia). *Biol. Mar. Medit.*, 13(4): 194-198.

Chuine I., Ciais P., Cramer W., Laskar J., 2023. Les forêts françaises face au changement climatique. Rapport du Comité des sciences de l'environnement de l'Académie des sciences et points de vue d'Académiciens de l'Académie d'Agriculture de France - juin 2023 : 1-52.

Cox T.E., Schenone S., Delille J., Diaz-Castaneda V., Alliouane S., Gattuso J.P., Gazeau F., 2015. Effects of ocean acidification on *Posidonia oceanica* epiphytic community and shoot productivity. *Journal of Ecology*, 103: 1594-1609.

Cox T.E., Gazeau F., Alliouane S., Hendriks I.E., Mahacek P., Le Fur A., Gattuso J.P., 2016. Effects of in situ CO2 enrichment on structural characteristics, photosynthesis, and growth of the Mediterranean seagrass Posidonia oceanica. Biogeosciences, 13 : 2179-2194.

Deter, J., Guibert, A., Freschet, E., Boissery, P., Holon, F., 2013. Assessment on 90 years of coastal development in France and consequences for *Posidonia oceanica* beds. *Rapp. Comm. Int. Mer Mediterr*. 40, 520.

Deter J., Lozupone X., Inacio A., Boissery P., Holon F., 2017. Boat anchoring pressure on costal seabed: quantification and bias estimation using AIS data. *Marine Pollution Bulletin*, 123(1-2): 175-181.

Deutz, A., Heal, G. M., Niu, R., Swanson, E., Townshend, T., Zhu, L., Delmar, A., Meghji, A., Sethi, S. A., and Tobinde la Puente, J. 2020. Financing Nature: Closing the global biodiversity financing gap. The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability.

Dimitrov R.S., 2016. The Paris Agreement on climate change: behind closed doors. *Global Environmental Politics*, 16 (3): 1-11.

Dunic J.C., Brown C.J., Connolly R.M., Turschwell M.P., Côté I. M., 2021. Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biology*. 27: 4096–4109

Edens, B., Maes, J., Hein, L., Obst, C., Siikamaki, J., Schenau, S., Javorsek, M., Chow, J., Ying Chan J., Steurer, A., & Alfieri, A. (2022). Establishing the SEEA Ecosystem Accounting as a global standard. *Ecosystem Services*, *54*, 101413.

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., ... & Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature geoscience*, *5*(7), 505-509.

Friess, D. A., Howard, J., Huxham, M., Macreadie, P. I., & Ross, F. (2022). Capitalizing on the global financial interest in blue carbon. *PLoS Climate*, *1*(8), e0000061.

Forest Trends' Ecosystem Marketplace. 2022. The Art of Integrity: State of Voluntary Carbon Markets, Q3 Insight Briefing. Washigton DC: Forest Trends Association.

Gallo, N. D., Victor, D. G., & Levin, L. A. (2017). Ocean commitments under the Paris Agreement. *Nature Climate Change*, *7*(11), 833-838.

Ganteaume A., Bonhomme P., Emery E., Hervé G., Boudouresque C.F., 2005. Impact sur la prairie à *Posidonia oceanica* de l'amarrage des bateaux de croisière, au large du port de Porquerolles (Provence, France, Méditerranée). *Sci. Rep. Port-Cros Natl. Park*, 21: 163-173.

Gattuso, J. P., Magnan, A. K., Bopp, L., Cheung, W. W., Duarte, C. M., Hinkel, J., ... & Rau, G. H. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, 337.

Gillenwater, M., Broekhoff, D., Trexler, M. *et al.*, 2007. Policing the voluntary carbon market. *Nature Clim Change*, 1, 85-87.

Gobert G., Lefebvre L., Boissery P., Richir J., 2019. A non-destructive method to assess the status of Posidonia oceanica meadows. *Ecol Indic* 119:106838. doi:10.1016/j.ecolind.2020.106838

Griffiths C.A., Langmead O.A., Readman J.A.J., Tillin H.M., 2017. Anchoring and mooring impacts in English and Welsh Marine Protected Areas: Reviewing sensitivity, activity, risk and management; Defra Impacts Evidence Group, UK.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645-11650.

Guiry, M.D. & Guiry, G.M. 2023. *AlgaeBase*. World-wide electronic publication, National University of Ireland, Galway. https://www.algaebase.org; searched on 26 juin 2023.

Herr D and Landis E. 2016. Coastal blue carbon ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief. Gland, Switzerland: IUCN and Washington, DC, USA: TNC

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (2014). 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. *IPCC, Switzerland*.

Holon F., Boissery P., Guilbert A., Freschet E., Deter J., 2015. The impact of 85 years of coastal development on shallow seagrass beds (*Posidonia oceanica* L.(Delile)) in South Eastern France: a slow but steady loss without recovery. *Estuarine, Coastal and Shelf Science*, 165: 204-212.

Howard J., Hoyt S., Isensee K., Telszewski M., Pidgeon E. (eds.), 2014. Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., ... & Simpson, S. (2017). Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and the Environment*, *15*(1), 42-50.

IUCN, 2021. Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.

Jacquemont, J., Blasiak, R., Le Cam, C., Le Gouellec, M., & Claudet, J. (2022). Ocean conservation boosts climate change mitigation and adaptation. *One Earth*, *5*(10), 1126-1138.

Johannessen, S. C., & Macdonald, R. W. (2016). Geoengineering with seagrasses: is credit due where credit is given? *Environmental Research Letters*, *11*(11): 113001.

Kervinio Y, Surun C, Comte A, Levrel H (2023) Defining ecological liabilities and structuring ecosystem accounts to support the transition to sustainable societies. *One Ecosystem* 8: e98100.

Kuwae, T., Watanabe, A., Yoshihara, S., Suehiro, F., & Sugimura, Y. (2022). Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. *Marine Policy*, *138*, 104996.

La Manna G., Donno Y., Sarà G., Ceccherelli G., 2015. The detrimental consequences of ineffective marine park management related to boat anchoring. *Marine Pollution Bulletin*, 90: 160-166.

Lloret J., Zaragoza N., Caballero D., Riera V., 2008. Impacts of recreational boating on the marine environment of Cap de Creus (Mediterranean Sea). *Ocean & Coastal Management*, 51 (11): 749-754.

Lopez y Royo C., Pergent G., Alcoverroe T., Buiac M.C., Casazzad G., Martinez-Cregoe B., Pérez M., Silvestre F., Romero J., 2011. The seagrass Posidonia oceanica as indicator of coastal water quality: Experimental intercalibration of classification systems. *Ecological Indicators.* 11: 557-563.

Macreadie, P. I., Costa, M. D., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., ... & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, *2*(12), 826-839.

Macreadie, P. I., Robertson, A. I., Spinks, B., Adams, M. P., Atchison, J. M., Bell-James, J., ... & Rogers, K. (2022). Operationalizing marketable blue carbon. *One Earth*, *5*(5), 485-492.

Mateo M.A., Romero J, Pérez M, Littler M.M., Littler D.S., 1997. Dynamics of millenary organic deposits resulting from the growth of the Mediterranean seagrass *Posidonia oceanica. Estuar Coast Shelf Sci*. 44: 103–110. doi:10.1006/ecss.1996.0116

Mateo M.A., Renom P., Michener R.H., 2010. Long-term stability in the production of a NW Mediterranean *Posidonia oceanica* (L.) Delile meadow. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 291(3-4): 286-296.

Mateo, M.A., Diaz-Almela E., Piñeiro-Juncal N., Leiva Duenas C., Giralt Romeu S., Marco Mendez C., 2019. *Carbon stocks and fluxes associated to Andalusian seagrass meadows.* Deliverable c1: results report Group of Aquatic Macrophyte Ecology Centre for Advanced Studies of Blanes Spanish Council for Scientific Research, (December).

Maxwell S.L., Fuller R.A., Brooks T.M., Watson J.E.M., 2016. The ravages of guns, nets and bulldozers. *Nature*, 536: 143-145.

Mazarrasa, I., Samper-Villarreal, J., Serrano, O., Lavery, P. S., Lovelock, C. E., Marbà, N., ... & Cortés, J. (2018). Habitat characteristics provide insights of carbon storage in seagrass meadows. *Marine pollution bulletin*, *134*, 106-117.

Monnier B, 2020. Quantification et dynamique spatio-temporelle des puits de carbone associés aux herbiers à *Posidonia oceanica*. Thèse Doctorat « Ecologie marine », en co-direction, Université de Corse & Centre d'Etudes Avancées de Blanes: 1-222 + Annexes.

Monnier B., Pergent G., Mateo M.Á., Carbonell R., Clabaut P., Pergent-Martini C., 2021. Sizing the carbon sink associated with *Posidonia oceanica* seagrass meadows using very high-resolution seismic reflection imaging. *Marine Environmental Research*, 170: 105415.

Monnier B., Pergent G., Mateo M.Á., Clabaut P., Pergent-Martini C., 2022. Quantification of blue carbon stocks associated with *Posidonia oceanica* seagrass meadows in Corsica (NW Mediterranean). *Science of the Total Environment*, 838 (155864): 1-14.

Montero-Hidalgo, M., Tuya, F., Otero-Ferrer, F., Haroun, R., & Santos-Martín, F. (2023). Mapping and assessing seagrass meadows changes and blue carbon under past, current, and future scenarios. *Science of The Total Environment*, *872*, 162244.

Nellemann, C., & Corcoran, E. (Eds.). (2009). *Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment*. UNEP/Earthprint.

Office Français de la Biodiversité, 2023. Inventaires des données d'herbiers de posidonie en France métropolitaine (polygone). Access at: https://data.ofb.fr/catalogue/srv/fre/catalog.search#/metadata/83c4eedb-311c-4a90-b394-4a40a69bc60a

Pendleton L, Donato DC, Murray BC, Crooks S, Jenkins WA, *et al.* (2012)3 Estimating Global ''Blue Carbon'' Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. *PLoS ONE* 7(9): e43542. doi:10.1371/journal.pone.0043542

Pergent G., Barralon E., Pergent-Martini C., 2019. Regression of Posidonia oceanica lower limit: a consequence of climate change? 6th Mediterranean Symposium on Marine Vegetation (Antalya, Turkey, 14-15 January 2019): 80-85.

Pergent G., Bazairi H., Bianchi C.N., Boudouresque C.F., Buia M.C., Clabaut P., Harmelin-Vivien M., Mateo M.A., Montefalcone M., Morri C., Orfanidis S., Pergent-Martini C., Semroud R., Serrano O., Verlaque M., 2012. Les herbiers de Magnoliophytes marines de Méditerranée. Résilience et contribution à l'atténuation des changements climatiques. IUCN publ (ISBN 978-2-8317-1458-5), Gland, Málaga: 1-79.

Pergent, G., Pergent-Martini, C., Bein, A., Dedeken, M., Oberti, P., Orsini, A., Santucci, J.F. and Short, F., 2015. Dynamic of *Posidonia oceanica* seagrass meadows in the northwestern Mediterranean: Could climate change be to blame?. *Comptes rendus biologies*, *338*(7), 484-493.

Pergent G., Barralon E., Monnier B., Pergent-Martini C., Valette-Sansevin A., 2019. Strategy to study blue carbon ecosystems in Corsica. *In : Proceedings of the 6th Mediterranean symposium on marine vegetation*, Antalya, Turkey, 14-15 January 2019, Langar H., Ouerghi A. eds., RAC/SPA publ., Tunis: 15-20.

Pergent-Martini C., Pergent G., Monnier B., Boudouresque C.F., Mori C., Valette-Sansevin A., 2021. Contribution of *Posidonia oceanica* meadows in the context of climate change mitigation in the Mediterranean Sea. *Mar. Environ. Res.*, 165 (105236): 1-10.

Pergent-Martini C., Acunto S., André S., Barralon E., Calvo S., Castejón-Silvo I., Culioli J.M., Lehman L., Molenaar H., Monnier B., Oberti P., Pey A., Piazzi L., Santoni M.C., Terrados J., Tomasello A., Pergent G., (2022a). *Posidonia oceanica* restoration, a relevant strategy after boat anchoring degradation? *7th Mediterranean Symposium on marine vegetation*, Genoa, Italy, 19-20 September 2022, RAC/SPA publ., Tunis: 78-83.

Pergent-Martini, C., Monnier, B., Lehmann, L., Barralon, E., & Pergent, G. (2022b). Major regression of Posidonia oceanica meadows in relation with recreational boat anchoring: A case study from Sant'Amanza bay. *Journal of Sea Research*, *188*, 102258.

Personnic, S., Boudouresque, C. F., Astruch, P., Ballesteros, E., Blouet, S., Bellan-Santini, D., ... & Ruitton, S. (2014). An ecosystem-based approach to assess the status of a Mediterranean ecosystem, the Posidonia oceanica seagrass meadow. *PloS one*, *9*(6), e98994.

Piñeiro-Juncal, N., Díaz-Almela, E., Leiva-Dueñas, C., Deulofeu, O., Frigola, J., Soler, M., ... & Mateo, M. Á. (2021). Processes driving seagrass soils composition along the western Mediterranean: The case of the southeast Iberian Peninsula. *Science of The Total Environment*, *768*, 144352.

Pörtner, H. O., Scholes, R. J., Arneth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., ... & Val, A. L. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642), eabl4881.

Rigo I., Paoli C., Dapueto G., Pergent-Martini C., Pergent G., Oprandi A., Montefalcone M., Bianchi C.N., Morri C., Vassallo P., 2021. The Natural Capital Values of the Seagrass Posidonia oceanica in the North-Western Mediterranean. *Diversity*, 13, 499. https://doi.org/10.3390/d13100499

Roberts, C. M., O'Leary, B. C., McCauley, D. J., Cury, P. M., Duarte, C. M., Lubchenco, J., ... & Castilla, J. C. (2017). Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences*, *114*(24), 6167-6175.

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., ... & Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, *27*(23), 6025-6058.

Romero J., Pérez M., Mateo M.A., Sala E., 1994. The belowground organs of the Mediterranean seagrass *Posidonia oceanica* as a biogeochemical sink. *Aquatic botany*, 47(1) 13-19.

Ruitton S., Belloni B., Boudouresque C.F., Cabral M., Cadville B., Guillemain D., Legendre F., Malengros D., Thibault D., 2021. Suivi de l'effet du retrait d'engins de pêche perdus sur trois sites pilotes de Provence. MIO publ., Marseille, 31 pp.

Sapkota, Y., & White, J. R. (2020). Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review. *Science of The Total Environment*, *701*, 134497.

Scartazza A., Moscatello S., Gavrichkova O., Buia M.C., Lauteri M., Battistelli A., Lorenti M., Garrard S.L., Calfapietra C., Brugnoli E., 2017. Carbon and nitrogen allocation strategy in *Posidonia oceanica* is altered by seawater acidification. *Science of the Total Environment*, 607-608: 954-964.

Serrano, 2011. Insights in the mat of Posidonia oceanica: Biogeochemical sink and paleoecological record. PhD thesis, Universitat de Barcelona, 1-164.

Serrano, O., Mateo, M.A., Dueñas-Bohórquez, A., Renom, P., López-Sáez, J.A. and Cortizas, A.M., 2011. The Posidonia oceanica marine sedimentary record: A Holocene archive of heavy metal pollution. *Science of the Total Environment*, 409(22), 4831-4840.

Serrano O., Mateo M.A., Renom P., Julià R., 2012. Characterization of soils beneath a *Posidonia oceanica* meadow. *Geoderma*, 185: 26-36.

Seyller, C., Desbureaux, S., Ongolo, S., Karsenty, A., Simonet, G., Faure, J., & Brimont, L. (2016). The 'virtual economy' of REDD+ projects: does private certification of REDD+ projects ensure their environmental integrity?. *International Forestry Review*, *18*(2), 231-246.

Telesca L., Belluscio A., Criscoli A., Ardizzone G., Apostolaki E. T., Fraschetti S., Gristina M., Knittweis L., Martin C. S., Pergent G., Alagna A., Badalamenti F., Garofalo G., Gerakaris V., Louise Pace M., Pergent-Martini C., Salomidi M., 2015. Seagrass meadows (*Posidonia oceanica*) distribution and trajectories of change. *Scientific Reports*, 5 (1). https://doi.org/10.1038/srep1 2505

Trégarot, E., Caillaud, A., Cornet, C. C., Taureau, F., Catry, T., Cragg, S. M., & Failler, P. (2021). Mangrove ecological services at the forefront of coastal change in the French overseas territories. *Science of the Total Environment*, *763*, 143004.

UNFCCC, 2016. Report of the Conference of the Parties on its 21st session, held in Paris from 30 Nov.-13 Dec. 2015. Addendum. Part two: Action taken by the Conference of the Parties at its 21st session, FCCC/CP/2015/10/Add.1, UNFCCC Secretariat, Bonn, pp. 1-40.

Vallet, L., Schwartz, M., Ciais, P., van Wees, D., de Truchis, A., and Mouillot, F., 2023. High resolution data reveal a surge of biomass loss from temperate and Atlantic pine forests, seizing the 2022 fire season distinctiveness in France, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-529.

Vanderklift, M. A., Marcos-Martinez, R., Butler, J. R., Coleman, M., Lawrence, A., Prislan, H., ... & Thomas, S. (2019). Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Marine Policy*, *107*, 103429.

Verified Carbon Standard. (2020). VCS VM007. REDD+ Methodology Framework (REDD+ MF) v1.6

Verified Carbon Standard. (2021). VCS VM0033. Methodology for Tidal Wetland and Seagrass Restoration, v2.0

Verlaque M., Ballesteros E., Blanfuné A., Boudouresque C.F., Dominici J.M., Duriez O., Grémillet D., Meinesz A. Pergent G., Pergent-Martini C., Sala E., Thibaut T., 2023. Problèmes liés à l'accueil des super-yachts et des navires de croisière. *Sci. Rep. Port-Cros Natl. Park*, 37 (in press)

Williamson, P., & Gattuso, J. P. (2022). Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Frontiers in Climate*, *4*, 130.

Supplementary material

SPM1. Methods available for the monitoring of Posidonia seagrass protection projects. Adapted from UNEP (2015).

Method used in the literature	Key information	Advantages and limits
Acoustic methods		
Side-Scan Sonar	Depth: over -8 m (Clabaut *et al.*, 2006) Precision: From 0.1 m (Kenny *et al.*, 2003) Area mapped: tens of km^2	Most used method but difficulties to obtain density and heights. Allows complete coverage of seabed contrary to the multibeam echosounder
Multi-beam echosounder	Depth: Tens of meters (Valette-Sansevin *et al.*, 2019) Precision: 0.2 m (Komatsu *et al.*, 2003) Area mapped: from 1 m (Kenny *et al.*, 2003)	3D images of meadows. High amount of data necessitates efficient computer processing and archiving, and complex data processing
Optical methods		
Aerial photos	Depth: from 0 to -20 m but more adapted from 0 to -10 m Precision: from 0.2 m (Frederiksen *et al.*, 2004) Area mapped: Small surface areas (10 km^2; in Diaz *et al.*, 2004) but can also be used for large areas (100 km^2)	Image precision can be adapted depending on objective (Pergent *et al.*, 1995) Manual interpretation possible, direct and easy. Sizeable images library with access to chronological series.
Satellite imagery	Depth: from 0 to -20 m but adapted from 0 to -10 m. Technique in progress with visibilities to deeper areas (Traganos & Reinartz, 2018). Precision: from 0.5 m Area mapped: Few km^2 to large surface areas (more than 100 km^2)	Usable everywhere without authorization high geometric precision. Possibility to find free access low resolution images.

Drone imagery	Depth: 0 to -15 m Precision: very high spatial resolution Area mapped: From 0.1 m	Low cost and high flexibility in terms of deployment and customization. High quality and resolution
Field work		
Dives	Most accurate method to describe and identify benthic communities (Bianchi *et al.*, 2004)	Limited operational time and depth (Parravicini *et al.*, 2010)
Permanent square		
Cameras	Depth: whole bathymetric tranche Precision: from 0.1 m (Kenny *et al.*, 2003) Area mapped: Adequate for small area	Non-destructive method, easy to use. Possible to store the images.
Seismic methods		
Seismic reflection	Allows representation of sedimentary layers. Useful to estimate the thickness of the *matte* and carbon stocks at large scales but does not give information on the health of the seagrass meadows. Non-destructive method.	

References for the supplementary materials

Bianchi C.N., Pronzato R., Cattaneo-Vietti R., Benedetti Cecchi L., Morri C., Pansini M., ... & Bavestrello G., 2003. Hard bottoms. In: Mediterranean marine benthos: a manual of methods for its sampling and study. Biologia Marina Mediterranea, 11: 185-216.

Clabaut P., Augris C., Morvan L., Pasqualini V., Pergent G., Pergent-Martini C., 2006. Les fonds marins de Corse. Cartographie bio-morpho-sédimentaire par sonar à balayage latéral - Atlas de sonogrammes. Rapport Ifremer & Univ. Corse, N°GM 06-01 : 78 p

Diaz R.J., Solan M, Valente R.M., 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. Journal of Environmental Management, 73: 165-181.

Frederiksen M., Krause-Jensen D., Holmer M., Laursen J.S., 2004. Longterm changes in area distribution of eelgrass (*Zostera marina*) in Danish coastal waters. Aquatic Botany, 78: 167-181

Kenny A.J., Cato I., Desprez M., Fader G., Schuttenhelm R.T.E., Side J., 2003. An overview of seabed-mapping technologies in the context of marine habitat classification. Ices Journal of Marine Science, 60(2): 411-418.

Komatsu T., Igarashi C., Tatsukawa K., Sultana S., Matsuoka Y., Harada S., 2003. Use of multi-beam sonar to map seagrass beds in Otsuchi Bay on the Sanriku Coast of Japan. Aquatic Living Resources, 16(3): 223-230.

Parravicini V., Micheli F., Montefalcone M., Villa E., Morri C., Bianchi, C.N., 2010. Rapid assessment of epibenthic communities: A comparison between two visual sampling techniques. Journal of Experimental Marine Biology and Ecology, 395(1-2): 21-29.

Traganos D., Reinartz P., 2018. Mapping Mediterranean seagrasses with Sentinel-2 imagery. Marine Pollution Bulletin, 134: 197-209.

UNEP/MAP-RAC/SPA, 2015. Guidelines for Standardization of Mapping and Monitoring Methods of Marine Magnoliophyta in the Mediterranean. Christine Pergent-Martini, Edits., RAC/SPA publ., Tunis: 48 p. + Annexes.

Valette-Sansevin A., Pergent G., Buron K., Pergent-Martini C., Damier E., 2019. Continuous mapping of benthic habitats along the coast of Corsica: A tool for the inventory and monitoring of blue carbon ecosystems. Mediterranean Marine Science, 20 (3): 585-593. doi:http://dx.doi.org/10.12681/mms.19772