Ecological Economics 227 (2025) 108420

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Marine ecosystem services of seagrass in physical and monetary terms: The Mediterranean Sea case study

Anna Maria Addamo [a,b,c,*,1], Alessandra La Notte [d,1,2], Silvia Ferrini [e,f], Gaetano Grilli [f]

[a] European Commission, Joint Research Centre (JRC), Ispra, Italy
[b] Faculty of Biosciences and Aquaculture, Nord University, Bodø, Norway
[c] Climate Change Research Centre (CCRC), University of Insubria, Varese, Italy
[d] International Consultant on Natural Capital Accounting, Gorgonzola (MI), Italy
[e] University of Siena, Department of Political Science and International, Siena, Italy
[f] University of East Anglia, Norwich, United Kingdom

ARTICLE INFO

Keywords:
Ecosystem services
Accounting
Marine
Coastal
Seagrass
Mediterranean sea

ABSTRACT

Seagrass habitats are essential and vulnerable ecosystems with several key roles, from biodiversity hotspots to climate change mitigation. Their characteristics, current condition and potential benefits, are the main core of this study which presents one of the first applications of marine accounts for the European Mediterranean Sea. The assessment focuses on four marine and coastal ecosystem services (i.e. fish and raw biomass provision, blue carbon, and nature-based recreation) and relies on habitat modelling for the biophysical assessment and a diversity of economic valuation tools (e.g. resource rent, avoided costs, benefit transfer) for the monetization of benefits. The findings highlight the essential benefits provided by seagrass meadows for Mediterranean European countries. Accounting tables display the role of seagrass to enhance environmental and economic well-being and the support that accounting evidence can provide for conservation, restoration and marine spatial planning.

1. Introduction

Marine ecosystems, and their importance as sources of services, are the basis of the sustainable blue economy. The current global and European policy context includes several technical and legislative tools that highlight the relevant link between the economy and the environment. Some of the most relevant tools available include Regulation on European environmental economic accounts (Regulation (EU) No 691/2011, http://data.europa.eu/eli/reg/2011/691/oj), the recently adopted Nature Restoration Law (Regulation (EU) 2024/1991, http://data.europa.eu/eli/reg/2024/1991/oj), the Taxonomy Regulation for Sustainable Activities (Regulation (EU) 2019/2088, https://eur-lex.europa.eu/eli/reg/2020/852/oj), the Maritime Spatial Planning Directive (Directive 2014/89/EU, http://data.europa.eu/eli/dir/2014/89/oj), the Sustainable Blue Economy (COM/2021/240 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A240%3AFIN), the Common Fisheries Policy Regulation (Regulation (EU) No 1380/2013, https://eur-lex.europa.eu/eli/reg/2013/1380/oj), the Marine Strategy Framework Directive (Directive 2008/56/EC, https://eur-lex.europa.eu/eli/dir/2008/56/oj), the Biodiversity Strategy (COM/2020/380 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380), and the Ecosystem-based Approach & Nature based Solutions (i.e. green infrastructures) (COM/2013/0249 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0249). In particular, the United Nations System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) was adopted as standard to guide and measure the contribution of the environment to the economy targeting specific accounts that reflect the role of ecosystems and their services in a consistent and comprehensive way (United Nations, 2021).

Compared to terrestrial accounts, the marine or ocean ecosystem accounts are in their infancy. The ongoing development of the SEEA Ocean, in collaboration with the Global Ocean Accounts Partnership (GOAP), is addressing the lack of guidance on technical details for the marine or ocean ecosystem account and responding to countries' demands for common methodologies and assessment processes. The status

* Corresponding author at: Faculty of Biosciences and Aquaculture, Nord University, Universitetsalléen 11, PB 1490, 8049 Bodø, Norway.
E-mail address: am.addamo@gmail.com (A.M. Addamo).

[1] These authors contributed equally.

[2] While undertaking this research Alessandra La Notte was Contractual Agent at the Joint Research Centre of the European Commission.

https://doi.org/10.1016/j.ecolecon.2024.108420
Received 17 July 2023; Received in revised form 27 September 2024; Accepted 6 October 2024
Available online 28 October 2024

of ocean accounts for ecosystem extent assessments is advancing quite rapidly with evidence piling up from different initiatives (IDEEA Group, 2021; Carnell et al., 2022; Addamo et al., 2024). The "National Ocean Account, Experimental Estimates" by the Australian Bureau of Statistics, the "Ocean and coastal ecosystem extent account" by Statistics Canada, the pilot ecosystem accounts in China, Malaysia, Indonesia and Liberia, and the national ocean accounts compiled by Finland (Finnish Environment Institute), Ireland (Central Statistics Office), and the Netherlands (Statistics Netherlands) represent initial attempts to provide such assessments. A few promising studies have proposed comprehensive marine ecosystem accounts that also include monetary valuation (Cavalletti et al., 2020; Chen et al., 2020; Grilli et al., 2021; Gacutan et al., 2022; Mengo et al., 2022; La Notte et al., 2024; Vallecillo et al., 2019). However, these studies focus on a specific ecosystem service (Vallecillo et al., 2019), consider a delimited area of interest such as a coastal lake or marine protected areas (Gacutan et al., 2022; Cavalletti et al., 2020), or do not assess full biophysical-economic integrations and ecosystem conditions (Chen et al., 2020; Grilli et al., 2021; Mengo et al., 2022). Moreover, Cavalletti et al. (2020) is a unique case study in the Mediterranean Sea.

Expanding on this literature, our paper represents a methodological and empirical advancement as it presents one of the first European Mediterranean case studies that fully integrates biophysical and economic assessments, including the ecological features of marine functional connectivity (MFC). MFC includes structural connectivity (i.e., physical characteristics of the seascape, measuring its heterogeneity and structuring) and functional connectivity (i.e., all the movements of organisms that result in the exchange of genes, biomass or energy between heterogeneous habitat patches)) that help to streamline biophysical measures for economic valuation and accounting (see Darnaude et al., 2022. Unlike terrestrial ecosystems, MFC is more difficult to define and characterise. As a result, no specific indicators have been developed yet to map and assess the condition of marine ecosystems or manage marine resources (Vallecillo et al., 2022; Darnaude et al., 2022; Addamo and La Notte, 2023). Consequently, this study aims to identify, assess, value and account for marine and coastal ecosystem services (MCES) provided by seagrass meadows. As the paper will demonstrate, seagrass meadows contribute directly and indirectly to the generation of MCES, and their absence may jeopardise these services, leading to significant ecological and socio-economic consequences.

2. Material and methods

2.1. Case study area context description

The Mediterranean Sea is the geographical area of interest for this study. It is the largest of the semi-enclosed European seas with 4600 km of coastline shared by 22 countries, across African, Asian and European continents, and it supplies services to approximately 480 million people living around this eclectic marine region (see EEA, 2015). The regulatory framework for this region encompasses various legislations at both the global (e.g. Food and Agriculture Organization (FAO)'s Agreement on Port States Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (PSMA, 2009, https://openknowledge.fao.org/)) and the European levels (see European legislation mentioned in the Introduction). This particular policy contest has led to the recognition of the need for strong cooperation and coordination among all the countries bordering the Mediterranean Sea to address the main problems and threats that continue to affect this region. For instance, the Mediterranean Sea is a major climate change hotspot (i.e. one of the areas most responsive to climate change) due to water scarcity, concentration of economic activities in coastal areas, and reliance on climate-sensitive agriculture (EEA, 2015). The Mediterranean Sea is also a biodiversity hotspot, harbouring approximately 11 % of all marine species in less than 1 % of the global marine area. Furthermore, approximately 20 % of those species are endemic (Rodríguez-Rodríguez, 2022), of which *Posidonia oceanica* is the most important and well-studied endemic seagrass species of the Mediterranean Sea and it can form meadows or beds extending from the surface to 40–45 m depth. The seagrass meadows rank among the most valuable coastal ecosystems on Earth in terms of goods and services they can provide (Telesca et al., 2015 and references therein). For these reasons, the Mediterranean Sea and seagrass meadows were selected as the marine region and target habitat, respectively, for this study.

2.2. Workflow and components

The conceptual workflow adopted in this study follows the SEEA EA by applying the procedure illustrated in Fig. 1. The first step concerns the identification and assessment of a few selected ecosystem services that the marine ecosystems can provide in the Mediterranean Sea (see Figure SM1 in the supplementary material for details). We aimed to select at least one ES from each division of the Common International Classification of Ecosystem Services (CICES) - provisioning, regulation & maintenance, cultural services. Additionally, we considered services utilised not only by the national economic sectors (i.e., primary and tertiary), but also by households and the global society. After identifying the seagrass ecosystems based on their trophic web ecological features, we can evaluate the selected ES in biophysical terms. Subsequently, this assessment can be translated into monetary values and organised into accounting tables (Fig. 1).

The habitat mapping and extent of the seagrass meadows are based on the European Marine Observation and Data Network (EMODnet), while the information on the Mediterranean trophic web and biomass is based on Piroddi et al. (2017, 2022) and other evidence from the literature (Kletou et al., 2020; Vieira et al., 2018). The targeted species are: Fish – *Engraulis encrasicolus* (European anchovy, ANE), *Lithognathus mormyrus* (Striped seabream, SSB), *Mullus barbatus* (Red mullet, MUT), *Pagellus bogaraveo* (Blackspot Seabream, SBR), *Pagellus erythrinus* (Common Pandora, PAC), *Sardina pilchardus* (European pilchard, PIL), and *Thunnus thynnus* (Atlantic Bluefin Tuna, BFT); Seagrass – *Cymodocea nodosa, Posidonia oceanica, Nanozostera noltei, Zostera Z. marina*; Marine Mammals – *Delphinus delphis, Stenella coeruleoalba, Tursiops runcates, Balaenoptera physalus, Globicephala melas, Grampus griseus, Physeter macrocephalus, Ziphius cavirostris, Monachus monachus*; and Turtles – *Caretta caretta*; *Chelonia mydas*. The main MCES under study are fish provision and raw biomass provision (provisioning services provided to the primary and tertiary sectors), blue carbon (a regulating service provided to global society), and nature-based recreation (a cultural service provided to households).

While the data sources used per biophysical assessment of each MCES are documented in detail throughout the individual sections of the manuscript, Table SM1.1 reports a brief summary.

2.3. Biophysical assessment of MCES

To identify the flow of MCES from seagrass meadows, we integrated the seagrass trophic web and capacity as illustrated in Fig. 1. This allowed us to quantify the biomass and density of fish, seagrass biomass, and the abundance of turtles and marine mammals in physical terms. Additionally, dead seagrass leaves, currently considered as waste, have the potential to be repurposed as a valuable resource. This is accounted for as "prospective" MCES, which will require further investigation. The geographical boundaries of our assessment are the Geographical Sub Areas (GSAs) identified by the Food and Agriculture Organization (FAO) in the General Fisheries Commission for the Mediterranean area (GFCM). The correspondence of GSAs to specific countries and how they are aggregated to the national level are based on the reporting documents of FAO and available in Table SM2.1. Results are displayed in a raster grid 100×100 m^2 with QGIS (further details are in supplementary material SM1).

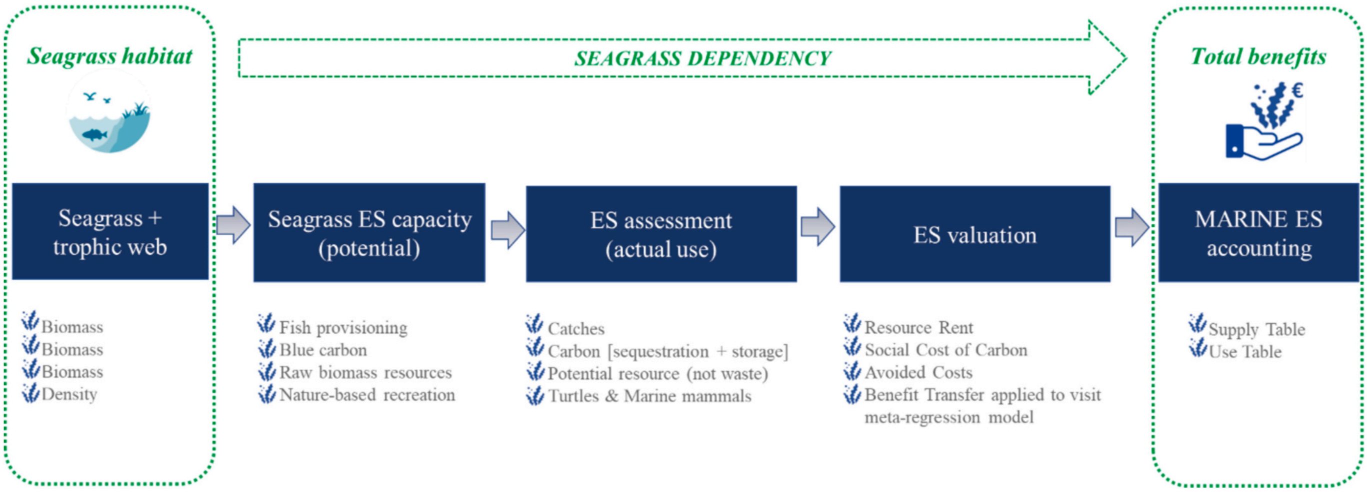

Fig. 1. Workflow on Ecosystem Services (ES) accounting adopted in this study. Seagrass dependency is the direct and indirect contribution of seagrass habitats to the marine and coastal ES and benefits.

2.3.1. *Fish provision*

Although the fishery sector is already accounted for in the standard economic system, the contribution to the sector from natural habitats such as seagrass is overlooked. In this paper, we estimate the seagrass contribution through the food-web network for each selected fish species. Fish provision refers to the provision of fish biomass for human consumption and the condition to grow it (see Liquete et al., 2013). Therefore, considering total landings or catch per unit effort while excluding aquaculture activities and the human interventions, we can identify the ecosystem's contribution to the fisheries sector. The total catch data (in tonne, t) for each target species is related to year 2018 and retrieved from the FishStatJ software v.2021 of FAO Regional capture fisheries statistics. This information is cross-checked with data reported in International Commission for the Conservation of Atlantic Tunas (ICCAT) statistical databases (https://www.iccat.int/en/accesingdb.html) for tuna, and Scientific, Technical and Economic Committee for Fisheries (STECF) reports (when available) for all the other species.

We define here *seagrass dependency (SGd)* as the direct and indirect contribution of seagrass habitats to the services and benefits that marine ecosystems provide to humans. In particular, the trophic-based seagrass dependency (TB-SGd) is the contribution to the total mass of living organisms in each trophic level (i.e. trophic biomass). It is computed considering the food-web network and the different functional groups (FGs) included in each trophic level (TL) linked to seagrass (see Fig. 2). Following Piroddi et al. (2022), both biomass and diet composition matrix for the Mediterranean marine ecosystem have been used to derive the proportion of prey-predator biomass for the whole trophic web from seagrass to each fish target species included in this study. The total TB-SGd represents the whole contribution of seagrass as primary producer (TL1) to the final trophic biomass that includes species from

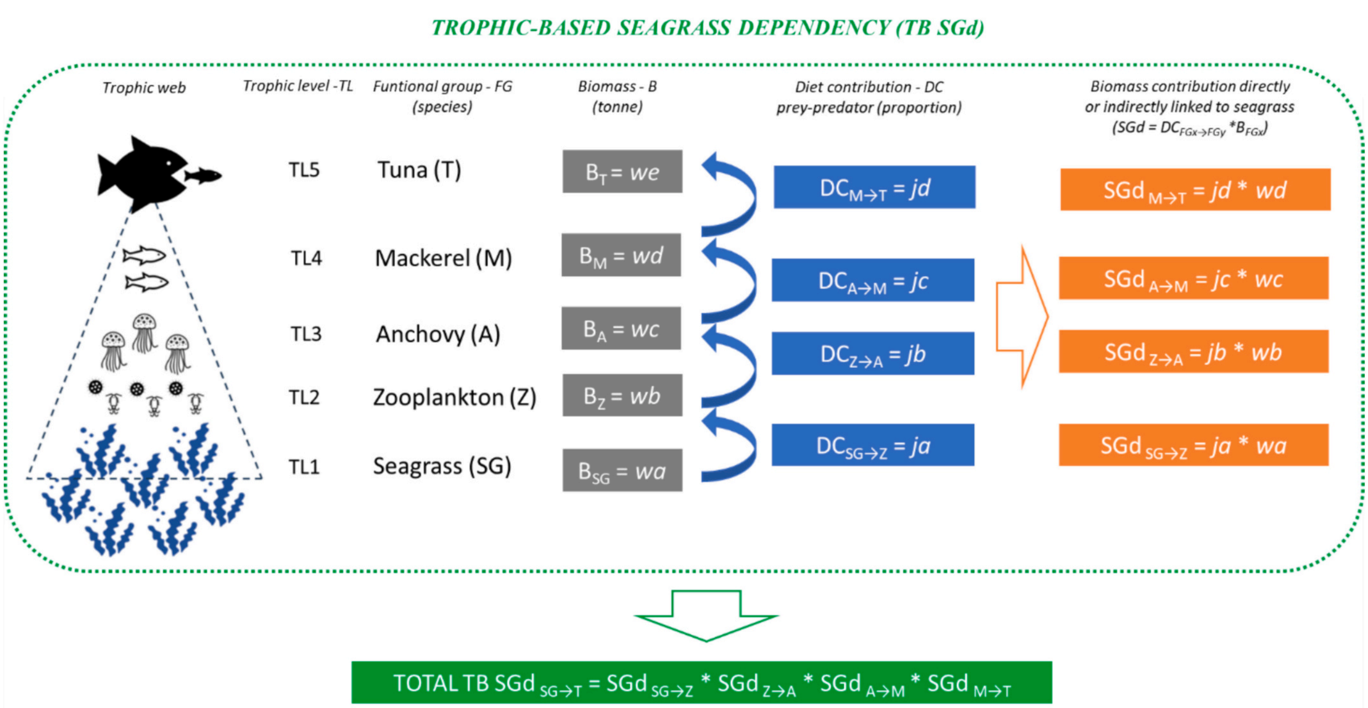

Fig. 2. Diagrammatic representation of the trophic-based seagrass dependency (TB-SGd) computation. Trophic level (TL), functional groups (FGs) are mere examples. *wa-we* represent the potential biomass values (in tonne) of each FG, while *ja-jd* represent diet contribution (in proportion) per each prey-predator pair.

low trophic (e.g. prey TL2) to high trophic (i.e. top predator, TL5) level. TB-SGd is calculated as the multiplication of the diet contribution of each prey-predator pair involved in all TLs and FGs of the trophic web linked to seagrass (see Fig. 2), as follow:

$$\mathrm{TB-SGd} = \prod \mathrm{DC}_{\mathrm{FGx}\rightarrow\mathrm{FGy}}{}^{*}\mathrm{B}_{\mathrm{FGx}} \quad (1)$$

where, DC_{FGx} is the diet contribution (in terms of proportion, %) of prey *FGx* to predator *FGy*, and B_{FGx} is the biomass (in tonne, t) of prey *FGx*. See Table SM1.2 and SM1.4 for further details on the values for the seagrass dependency computed for each target species.

2.3.2. Blue carbon

Carbon sequestration is the process of removing carbon from the atmosphere and seawater (e.g., short-term storage in leaves as biomass carbon pool), and eventually storing it in a form that cannot immediately be released (e.g., long-term storage in sediment as sedimentary carbon pool). Blue carbon refers to sequestration of organic carbon, which is captured (hereafter considered as carbon sequestration, C_{seq}) and locked/stored in the marine sediment (hereafter considered as carbon storage C_{stor}) by marine living organisms (see Nellemann et al., 2009). Hendriks et al. (2020) stress the key role of marine ecosystems in cycling and storing carbon over short, medium, and long timescales, and thus in mitigating climate change effects. This function of carbon storage ultimately contributes to human well-being and is accounted as a flow of ES rather than a stock, therefore translating into societal benefits (see cascade model in Liquete et al., 2013). The estimation of C_{seq} and C_{stor} is calculated considering the above-ground and below-ground biomass of seagrass in tonnes of carbon per hectare (C/ha). Monnier et al. (2020), Bañolas et al. (2020), Sousa et al. (2019) and Röhr et al. (2018) provide evidence of this service and their estimates inform our analysis. The selected species of seagrass are *C. nodosa*, *P. oceanica*, *Z. Z. marina*, *N. noltei* which are the predominant in the area. The distribution of each seagrass species (up to 40 m of depth) used in this study is based on observational data retrieved from EMODnet (O'Keefe and Lillis, 2019), the model in Piroddi et al. (2022), and the relevant scientific literature.

To assess estimate the seagrass above-ground biomass (ABG) and below-ground biomass (BGB) are estimated as kilogram per hectare (kg/ha) following Cebrian et al. (1997) and Collier et al. (2021), respectively:

$$\mathrm{AGB} = (48.8^{*}\ \mathrm{total\ BGB})/100 \quad (1)$$

$$\mathrm{BGB} = (67.6^{*}\ \mathrm{total\ AGB})/100 \quad (2)$$

The total blue carbon (C_{stock}) is calculated based on the total biomass (available biomass layers, tonne per hectare (t/ha) estimates by Collier et al., 2021) as follows:

$$\mathrm{C_{seq}} = (33.4^{*}\ \mathrm{total\ AGB})/100 \quad (3)$$

$$\mathrm{C_{stor}} = (33.9^{*}\ \mathrm{total\ BGB})/100 \quad (4)$$

$$\mathrm{C_{stock}} = (39.6^{*}\ \mathrm{total\ biomass})/100 \quad (5)$$

see Table SM1.3 for further details.

2.3.3. Nature-based daily recreation

The nature-based recreation service is characterised by nature-based tourism and daily recreation activities (Zulian and La Notte, 2022). Specifically, we assumed that marine natural "attractors" motivate the daily visits and the presence of marine species, supported by the seagrass density, will determine the value of the visit. The seagrass density (SD) is computed as:

$$\mathrm{SD} = \Sigma\ \mathrm{average}\ (\mathrm{number\ of\ shoots/ha})\ \mathrm{of\ each\ species\ in\ the\ area} \quad (6)$$

see Table SM1.3 for further details.

The estimation of turtles and mammals' density (TMD) measured as number of individuals per hectare (inds/ha) is calculated considering their abundance based on the data reported in ACCOBAMS (2021) and Camiñas et al. (2020). In particular:

$$\mathrm{TMD} = \Sigma\ \mathrm{number\ of\ individuals/ha\ of\ each\ species\ in\ the\ area} \quad (7)$$

see Table SM1.4 for further details.

Once the two indicators are calculated, they are ranked defining three classes (high, medium, low) as reported in Table SM1.5.

2.3.4. Raw biomass provision

Another ecosystem service that stems from seagrass meadows is the raw biomass provision from dead seagrass leaves. This represents a prospective MCES since it is not currently commercially (or artisanal) exploited but it represents a promising contribution of nature to economic activities. It refers to the provision of biomass or biotic elements for non-food purposes (see Liquete et al., 2013). More specifically, it is the amount of seagrass leaf loss reaching the coastline that can be exploited as biofuel and used for other commercial or industrial purposes (e.g., plant fertilisers). Estimates of biofuel production and reusable process-waste for alternative applications are based on information retrieved in Masri et al. (2017). We used this estimate to calculate the share of dead seagrass leaves biomass (SLB) that can be turned into an ecological input for economic uses. For each seagrass species the total turnover of leaf loss is estimated as follows:

$$\mathrm{Biofuel} = (0.21^{*}\ \mathrm{total\ SLB})/100 \quad (8)$$

$$\mathrm{Other\ biomass\ uses} = (0.37^{*}\ \mathrm{total\ SLB})/100 \quad (9)$$

and then reported the average of raw biomass (kg/ha) for each GSA. See Table SM1.3 for further details. To assess the source of raw biomass, the seagrass AGB, indicating the leaves biomass, is estimated as kg/ha following Cebrian et al. (1997) (see Eq. (1)).

2.4. Monetary valuation of ES

Following Fig. 1, once ES are assessed in biophysical terms they can be translated in monetary terms. The "translation" implies that (i) there cannot be a monetary valuation without a biophysical assessment first, and (ii) the valuation technique is chosen and applied in a way that is consistent with the meaning of the biophysical outcomes. Valuation techniques for each of the four ES are explained in the following subsections. In the valuation stage we exclusively refer to European data sources.

2.4.1. Fish provision

The monetary value of provisioning services should only estimate the value related to the physical flows that are harvested for non-recreational, consumptive use, commonly as inputs to wider supply chains (United Nations, 2021). In the context of harvested biomass, the monetary valuation should focus on isolating the contribution of seagrass to the market product values. For some extractive ecosystem services, this contribution is directly observable in the form of exchange values, e.g., rental prices in agriculture, stumpage values in timber extraction, or, in the case of marine ecosystems, levies and royalties for marine aggregates extraction. However, in the case of fish provision, these types of values are not directly observable or are difficult to isolate.

When looking at the literature, the resource rent approach is commonly used to value fish provision (see SM2 for further details on the RR approach). The resource rent (RR) is the profit from environmental assets that is above the cost of producing the product, taking into account operational costs, fixed capital depreciation, and returns on other assets.

In this application, ex-vessel landings value, human capital, produced capital and operating costs are retrieved and processed to identify the contribution of seagrass to fisheries' profit. The RR is then estimated at the single fishery or species level. The calculation might diverge between studies considering the inclusion or exclusion of certain economic parameters (e.g., subsidies), the availability of coherent information (e.g., taxes), and the methodological approaches (e.g., treatment of returns from fixed capital). Here the fish provision resource rent at the time t (RR_t) is calculated as:

$$\text{Fish\_provision\_RR}_t = \text{GOS}_t - (\text{CFC}_t + \text{RA}_t) \quad (10)$$

$$\text{GOS}_t = \text{OUT}_t - (\text{OCt} + \text{IC}_t + \text{EC}_t + \text{NetTAX}_t) \quad (11)$$

where, GOS_t is the gross operating surplus calculated as the total output sales, CFC_t is the consumption of fixed capital, RA_t is return on produced assets, OUT_t is the total value of landings,

OC_t are operating costs, IC_t are intermediate consumption costs, EC_t are employment costs, and $NetTAX_t$ is the net taxation.

For the fish species targeted in this paper we retrieved and recorded the value of landings and live weight landed for each country of the Mediterranean Sea (i.e., GSA1 to GSA27) in nominal terms for the year 2018. Values for Eqs. (10) and (11) are extracted from two European datasets. The first dataset is the STECF Fisheries Dependent Information (FDI) catch data reporting the catch information – landings (value and weight) plus discards – for the European fishing fleet by country for the year 2018. This dataset is used to extract the total value of landings. The second dataset is the STECF economic fleet performance reporting information regarding operating costs, intermediate costs, employment costs, subsidies to production, consumption of fixed capital, per country and per fleet segment for the year 2018.

Given the nature and quality of the datasets used, some methodological points need to be specified. For the seven selected fish species in the Mediterranean area, the STECF FDI dataset contains 19.6 % of observations that are considered confidential, and therefore not reported in landings data. These observations were also excluded from our analysis. Data related to subsidies and taxes on production, subsidies and taxes on extraction, and on return to produced assets are not available, so are not considered in the RR estimation. In principle, the fleet segment-level economic data can be linked with landings per species to allow a disaggregated calculation of the RR which would provide a more refined estimate of the fish provision value. In practice, however, this is not a trivial task. The format of the economic data is not readily usable for the calculation of the RR and would require a time-intensive data management to check for consistency and potential missing monetary values.

As a consequence, the methodological steps involved for the current application involve (i) isolating the value and weight of landings for the area and species targeted, (ii) estimating a RR at the country level considering the whole fleet and fishing methods, and (iii) apportioning the RR for each country and year to the species targeted based on their relative weight on the total value of landings for all the species.

It is worth noting that while the RR approach provides a robust economic perspective to account for the contribution of seagrass meadows to commercial fisheries, it might partially overlook the ecological nexus between seagrass ecosystems and fish populations. In this application, we address this challenge considering the food-web network as discussed in Section 2.3.1.

2.4.2. Blue carbon

Seagrass meadows provide two blue carbon ecosystem services, namely sequestration and storage. The sequestration is provided by both above- (i.e., photosynthesis by the entire plant is functioning to sequester carbon) and below-ground biomass of seagrass. However, the storage is provided by the belowground biomass of seagrass which seals the carbon in the roots. Table SM2.4 summarises the main valuation studies concerning blue carbon in the Mediterranean Sea. As shown, there is no single convergent valuation approach.

A possible, generally accepted alternative is the social cost of carbon (SCC). SCC considers the total global damages caused by an incremental unit of carbon emitted today, summed over its entire time in the atmosphere, and discounted to present value terms (Price et al., 2007; Wang et al., 2019; Pindyck, 2019). Multiple factors influence its assessment including the high uncertainty around extreme events (also known as 'fat tails', Pycroft et al., 2011), environmental tipping points (Lenton et al., 2008; Weitzman, 2009), and the biosphere's response to climate change (IPCC, 2007). As a consequence, the establishment of global total damages varies widely. Moreover, given the timescales involved, estimates of SCC are particularly sensitive to the discount rate used, as well as to a multitude of other assumptions regarding consumption growth rates, projected CO_2 emissions, carbon cycle, and environmental sensitivity to CO_2 concentrations and temperature change (see SM2 for further details on the SCC approach). Thornton et al. (2019) propose the valuation of CO_2 at €33.54/tCO_2 in 2018. An additional option would rely on the EU ETS price although the price is high volatile Following previous marine accounting studies (e.g., Visintin et al., 2022; IDEEA Group, 2021, Eigenraam et al., 2016), the suggested average price is equal to €32.43/tCO_2 (or equivalently, €119.02 t/C).

2.4.3. Nature-based daily recreation

Recreation opportunities depend on natural attractions as well as infrastructures and facilities. Generally, tourists require a number of facilities (accommodations, tours, etc.) to enjoy nature, whereas households living nearby marine environments enjoy nature with minimal facilities thus benefiting from nature-based recreation opportunities.

When looking at the literature, several papers look at marine recreation opportunities studying different attractions and using a variety of monetary quantification approaches (e.g., prices vs willingness to pay, see SM2 for further details). Few papers have addressed the accounting of coastal and marine tourism providing evidence on the number of annual visits and/or costs (Fitch et al., 2022; Stebbings et al., 2021; OSPAR, 2021; IDEEA Group, 2021; Thornton et al., 2019). Fitch et al. (2022) propose a categorization of tourism and leisure opportunities and a subsequent spatial distribution of values based on UK tourists' expenditures. This study focuses on nature-based visit expenditures and overlooks the number of visits. Similarly, Stebbings et al. (2021) propose another categorization system alternative to Fitch et al. (2022) but report an average number of 49.83 million days of participation in marine wildlife watching and water sports. The study reports what they call the "RR" of recreational activities but a more correct terminology would be the "net benefit value" per person per visit since we are not dealing with extractive uses. While Stebbings et al. (2021) and Fitch et al. (2022) single out nature's contribution for tourism accounts, Thornton et al. (2019) consider daily recreation opportunities cost as travel expenses.

For this application, we expanded on previous studies combining an ad-hoc calculation of daily recreation opportunities with the average net benefit value provided by Stebbings et al. (2021). To estimate the number of daily recreation trips to marine habitats in the Mediterranean area, we relied on individual visit patterns gathered through a survey conducted by La Notte et al. (2024). The survey was administered in four European countries including Italy. Respondents were asked, among other things, to report the monthly number of nature-based visits to different locations including trips to the marine areas. Therefore, this survey provides both the probability to visit marine spaces among the total number of nature-based visits and the average number of visits to the sea. The number of people in the Italian sample is equal to 399. Based on partial postcodes reported by respondents, we can geolocate responses in 90 Italian councils (NUTS3[3]). Each NUTS3 is described by its relevant biophysical and socio-demographic characteristics including population density and Gross Domestic Product (GDP) which are used to model the probability to visits the marine space (*prob_(visits_j)* and the average number of visits to the marine space in each NUTS3 (*Average_visitsj*). Both models are developed including the following variables: the share of urban, cropland, grassland, heathland, sparsely vegetated, woodland, wetland, and marine habitats land cover on the total extent of the NUTS3; a dummy variable which takes value 1 if there are marine protected area included in the EU network of protected area "Natura 2000" in the NUTS3; the number of diving centre per NUTS3; the population and GDP of NUTS3 regions. The share of land cover is extracted from Coordination of Information on the Environment (CORINE) Land Cover (CLC) data, the map of diving centres located in each NUTS3 has been retrieved from secondary sources, and the information on the population and the per capita GDP are extracted from Eurostat data.

The dependent variable used in the probability of visit model is a dummy that takes value 1 if the respondent visits predominantly the marine space and zero otherwise. The logit model allows one to determine the probability to sea visits as a function of the NUTS3 features. The average probability of visiting is roughly 30 % with a spatial differentiation among NUTS3 regions. The dependent variable for the number of visits model is also derived from La Notte et al. (2024). The implicit assumption is that the visits were motivated by the presence of marine species and also dependent on the NUTS3 features. A weighted Poisson regression models the number of visits.

The accounting value of nature-based marine recreation (NBMR) can be obtained at the country level following equation:

$$\mathrm{NBMR} = \mathrm{prob\_}(\mathrm{visits\_j})^{*}\left(0.8^{*}\mathrm{Pop\_j}\right)^{*}\mathrm{Average\_visitsj}^{*}2^{*}15.02€ \tag{12}$$

where *Pop_j* represents the population in the 137 Mediterranean NUTS3. The value of €15.02 is derived from Stebbings et al. (2021) and represents the lower end of the values summarized in Table SM2.5 for the Mediterranean area.

Population is multiplied by 0.8 to exclude the youngest segment from the computation since they were not included in the sample. Considering that in the Mediterranean regions there are at least two months where users can enjoy the marine space, the average number of visits is multiplied by 2.[4] On the one hand, €15.02 is the average value that is applied to the areas where the combination of seagrass presence (as proxy for diving) and mammals' density (as proxy for whale watching) scores "medium". On the other hand, from the 75 percentile (€37.28) and the 25 percentile (€6.94) of the studies in SM2.5, we can apply a range of values to capture where the recreation opportunities score "high" or "low", respectively.

2.4.4. Raw biomass provision

The annual accumulation of dead leaves and fibres on the shore from seagrass meadows provides conflicting management effects. These piles of biomass and sand called banquettes are annually stranded on the shore and help the beach and dune system to reduce wave energy and prevent erosion. At the same time, this biomass slowly degrades producing unpleasant odours which reduces the amenity value of the beach, especially in touristic areas. In the Mediterranean Sea, banquettes are primarily formed in the autumn but can persist on beaches for months. Banquettes can be sent to landfill or burned, and these costs are normally paid via local taxes since, like in the Italian legislation, they are considered residential urban waste and not resources. However, the legislation is changing and differences among Mediterranean countries exist to anticipate a possible commercial uses of the biomass, from biofuel to animal fodder (e.g., Scaffaro et al., 2018; Balata and Tola, 2016; Cornara et al., 2018). In the supplementary material, Table SM2.3 summarises the primary studies that consider the different uses of biomass as a production resource.

The opportunity cost of replacing, for instance, fossil fuel with seagrass biofuel in producing plastic or electricity is a possible method to assess the monetary value of this prospective raw material. However, the lack of well-developed sectors for seagrass raw materials prevents the production of reliable economic estimates and we therefore opt for a conservative approach. So, rather than focusing on the future contribution of nature to emerging economic sectors, the valuation focuses on avoided costs of dumping/burning stranded seagrass. According to IUCN (2018), many coastal Italian towns remove and dispose of seagrass annually but details on costs are scarce. Di Gennaro (2018) reports the cost of generic seagrass biomass removal in the municipality of Orbetello (Italy) which has a collection cost of €155 per tonne and loading, shipping, and disposal cost of €126/t. Balata and Tola (2016) consider the cost of seagrass removal from a coastal town in Sardinia and the reported cost is €30.47/t. We selected the latter estimate.

2.5. Accounting

Based on official standards and guidelines (United Nations, 2021; GOAP, 2021), the accounting for MCES is structured according to Supply and Use tables (Fig. 3). For this specific application, we focus on Supply tables, which report the flow of services provided by ecosystem types. Marine Ecosystem Types are coastal waters (hosting seagrass habitat), shelves and open oceans (that for the Mediterranean Sea are renamed "open waters"). Marine Ecosystem Services, as reported in the SEEA EA, are provisioning services (fish provision and raw biomass provision), regulation and maintenance services (carbon storage and sequestration), and cultural services (nature-based daily recreation).

Ecosystem service flow is accounted for in physical terms first, and then translated in monetary terms. For each ecosystem service, it is possible to single out the role of seagrass and therefore provide a total monetary estimate without double counting, as visually simplified in Fig. 3.

Practitioners should be aware that supply tables provide a yearly flow, therefore the total of services gives the sum of what seagrass can provide per year and not the value of seagrass as an asset, a "stock". Current guidelines (United Nations, 2021) and proposals (La Notte et al., 2024) suggest calculating the capacity as virtual stock, by applying the Net Present Value for each single flow. The capacity is not computed as part of this application.

3. Results

Once the biophysical and monetary information are retrieved, the accounting tables can be populated. Firstly, we map the extent of our MCES across the GSA as quantity of fish (t/ha), raw biomass provision (kg/ha), blue carbon (tC/ha), and nature-based recreation (number of shoots/ha for seagrass species or number of individuals/ha for turtle and marine mammals). Fig. 4 for the Mediterranean Sea reports the distribution, ecosystem condition and other abiotic variables that affect the status of conservation of the seagrass.

The information in Fig. 4 is then tabulated in the ES supply table (Table 1).

In Table 1 we can observe the flows of services that are directly and uniquely provided by seagrass, such as raw biomass and blue carbon in the coastal areas. For other services (i.e., fish provision and nature-based recreation), seagrass contribute indirectly, and this distinction should be

[3] NUTS3 level refers to small regions for specific diagnoses.

[4] Based on the data extrapolated from the EU Tourism Dashboard (and specifically on the monthly data view), the two months that record in Mediterranean countries almost 2/3 more than usual arrivals are July and August. This is used as a proxy to estimate the number of months to be considered for this valuation (https://tourism-dashboard.ec.europa.eu/?lng=en&ctx=tourism)

SUPPLY TABLE

	Ecosystem types			
	Coastal (C)	Shelves (S)	Open waters (OW)	Total
Fish provision (F)	x	x	x	TF(x)
(associated with seagrass)				*(y)*
Raw biomass provision (RB)	x	x	x	TRB(x)
(associated with seagrass)				*(y)*
Blue carbon (BC)	x	x	x	TBC(x)
(associated with seagrass)				*(y)*
Nature-based recreation (NB)	x	x	x	TNB(x)
(associated with seagrass)				*(y)*
Total	TC(x)	TS(x)	TOW(x)	**TOT(x)**

USE TABLE

	Economic units					
	Primary sector	Secondary sector	Tertiary sector	Households	Global Society	Total
Fish provision (F)	TF(x)					TF(x)
Raw biomass provision (RB)			TRB(x)			TRB(x)
Blue carbon (BC)					TBC(x)	TBC(x)
Nature-based recreation (NB)				TNB(x)		TNB(x)
Total	TF(x)		TRB(x)	TNB(x)	TBC(x)	**TOT(x)**

Fig. 3. Accounting structure of Supply and Use tables for marine and coastal ecosystem services associated with seagrass habitats (i.e. seagrass dependency). x = value associated to each ecosystem type or economic unit; y = share value associated with seagrass habitats that are not counted in the final total TOT(x). TF(x) = total value associated with fish provision; TRB(x) = total value associated with raw biomass provision; TBC(x) = total value associated with blue carbon; TNB(x) = total value associated with nature-based recreation; TC(x) = total value associated with coastal zones; TS(x) = total value associated with shelf zones; TOW(x) = total value associated with open water zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

made clear to avoid double counting. However, the accounting framework we adopted eliminate this risk. The services reported as "*associated with seagrass*" in the table represent a share of the overall services. For example, the average contribution of seagrass to the biomass of the selected fish species for fish provision is approximately 0.01 (refer to Tables SM1.7). This is considered an indirect value of seagrass in relation to the total fish catch. The quantity *associated with seagrass* for the selected species is only 1892 t, while the flow at risk reaches 209,379 t. Although this share seems to be very low, the absence of seagrass meadows exposes the entire trophic chain at risk.

The same applies to nature-based recreation, where the major underlying hypothesis is that the number of visits depends on the presence of turtles and mammals for diving and whale watching activities. For example, turtle presence is allocated across the three ecosystem types, with the highest proportion (0.5) allocatedto coastal areas, as turtles are often associated to seagrass habitats, which serve as their primary foraging grounds. The remaining 0.25 + 0.25 is evenly distributed between shelves and open waters. Turtles' reliance on seagrass accounts for 23.33 % (see Tables SM1.6–7). The presence of cetaceans is equally distributed (0.5 + 0.5) between shelves and open waters and their dependency from seagrass is estimated to be approxiamtely 0.51 %.This dependency is computed as an average of about 12 % with respect to the total of visits and can be considered as an indirect value of seagrass. However, the remaining 88 % may be at risk, based on the assumption that the number of visits depends on the presence of turtles and mammals.

The biophysical information can now be converted in monetary terms using the different pricing results for the MCES. For the provisioning service of fish, we derive the RR for the targeted species. Table SM2.6 summarises for each country the total and per tonne landed value in 2018. Values are reported in nominal terms.

Table SM2.6 shows that the RR is positive for all countries but Croatia. Local features of production costs or/and government support, as well as the lack of precision in reporting information to the central EU dataset, might influence this negative value.

Fig. 5 reports the average RR for species in the Mediterranean Sea expressed as €/kg. On average, our estimates are in line with the results in Stebbings et al. (2021) although for a subset of species. Atlantic bluefin tuna and the sea bream species have a higher RR value relative to other targeted species, on average between €3.64/kg and €4.20/kg. In contrast, European anchovy and pilchard species have the lowest RR value among the species considered equal to an average of €0.40/kg.

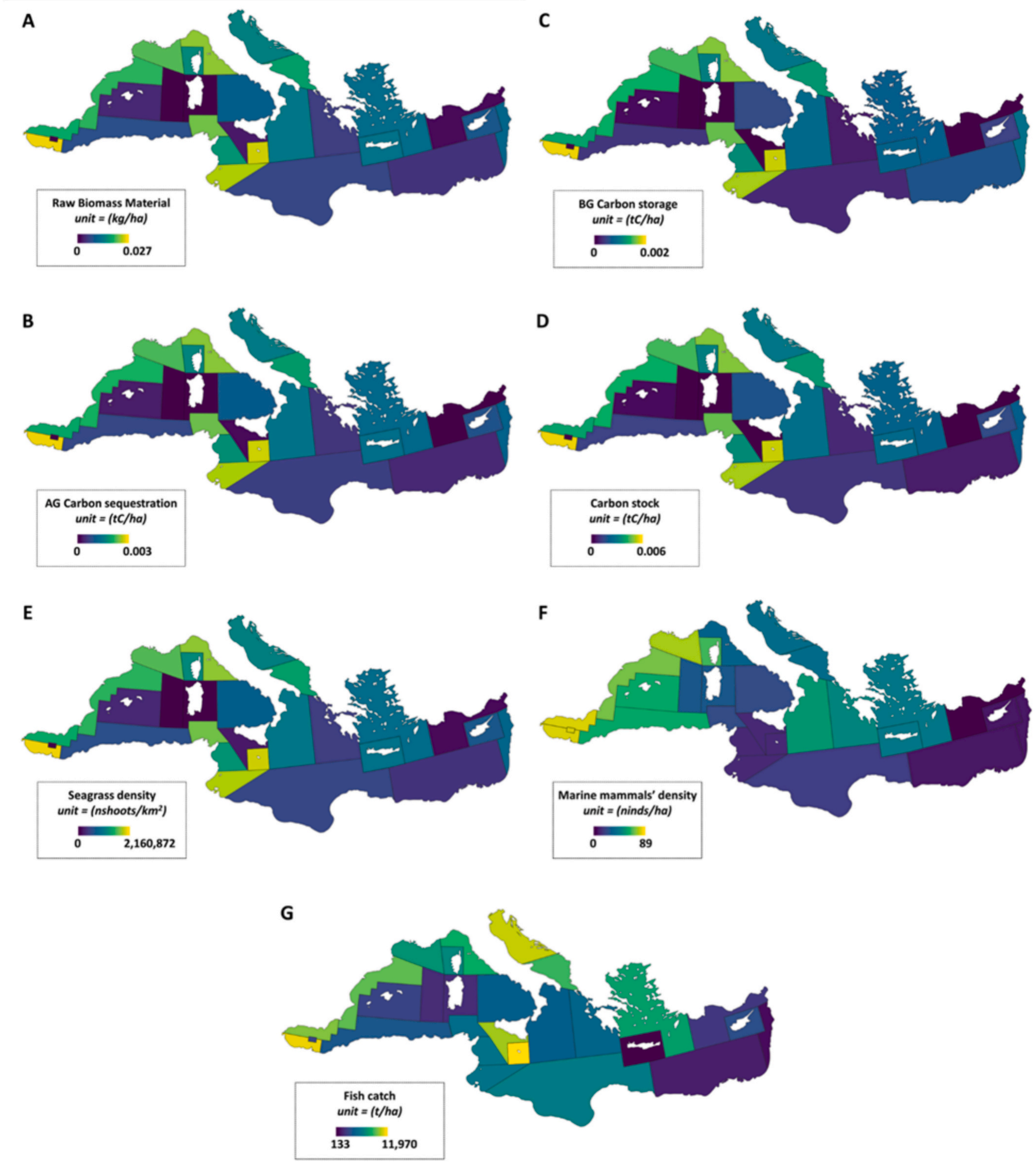

Fig. 4. Map of marine and coastal ecosystem services (MCES) provided by seagrass in physical terms per geographical subarea (GSA: (A) raw biomass provision and (B, C, D) blue carbon, (E, F) nature-based recreation and (G) fish provision. AG = above ground, BG = below ground, ha = hectare, ninds = number of individuals, nshoots = number of shoots, tC = tonne of carbon, TOT = total. Please, note the different scale units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the accounting tables, hen applying the RR estimates to fish catch data from the STECF, we use the lowest euro value for Croatia, instead of a negative value. We need to consistently translate the biophysical outcomes into monetary terms. Marine ecosystems provide an ecological input (fish biomass) which represents a positive flow. However, the market system is affected by external mechanisms (such as subsidies) that fall outside the ecosystems' role. As result, the estimate should remain positive. For this reason, we chose to apply the lowest (positive) RR per species for Croatia.

The other prospective provisioning ecosystem service is raw material

Table 1
Supply Table in physical terms (tonne and number of visits), year 2018, associated to seagrass habitats (i.e. seagrass dependency).

Supply Table (physical terms)	Ecosystem Types			
	Coastal	Shelves	Open waters	TOTAL
PROVISIONING SERVICES (in tonne)				
Fish provision	3823	12,131	193,425	**209,379**
associated with seagrass				***1892***
*Raw biomass provision	4353			**4353**
associated with seagrass				***4353***
REGULATION & MAINTETNANCE SERVICES (in tonne)				
Carbon sequestration	3,167,593	6,156,394	16,593,350	**25,917,337**
associated with seagrass	*534*			***3,167,593***
Carbon storage				
associated with seagrass				
CULTURAL SERVICES (in number of visits)				
Nature-based daily recreation				**21,260,860**
associated with seagrass				***2,534,295***

* Perspective ecosystem service.

a significant positive role, as expected. The presence of diving centres shows weak statistical significant, making it difficult to determine their role that in explaining the average number of sea visits. This result does not hamper the role that marine turtles and mammals can play in attracting nature-based daily visits.

Based on the estimated models' parameters and a benefit function transfer approach, we can predict the probability to sea visits and the average number of trips taken monthly by individuals in all 137 Mediterranean coastal NUTS3 areas located in the eight European Mediterranean countries (Cyprus, Greece, Spain, Malta, France, Italy, Slovenia and Croatia). Results are summarized in Table SM2.8, while the accounting table in monetary terms is reported in Table 2.

Table 2 reports the value of the MCESs as well as their dependency on seagrass. These values, reported as *associated with seagrass*, represent the ecosystem services that seagrass meadows provide to various economic sectors. These sectors could face increased risks if seagrass species, which play a key role in the trophic chain, were to disappear (Fig. 6). As explained for the flow in physical terms, the same logic applies to the flow in monetary terms: the flow at risk is computed based on the components of fish provision and nature-based recreation that depend

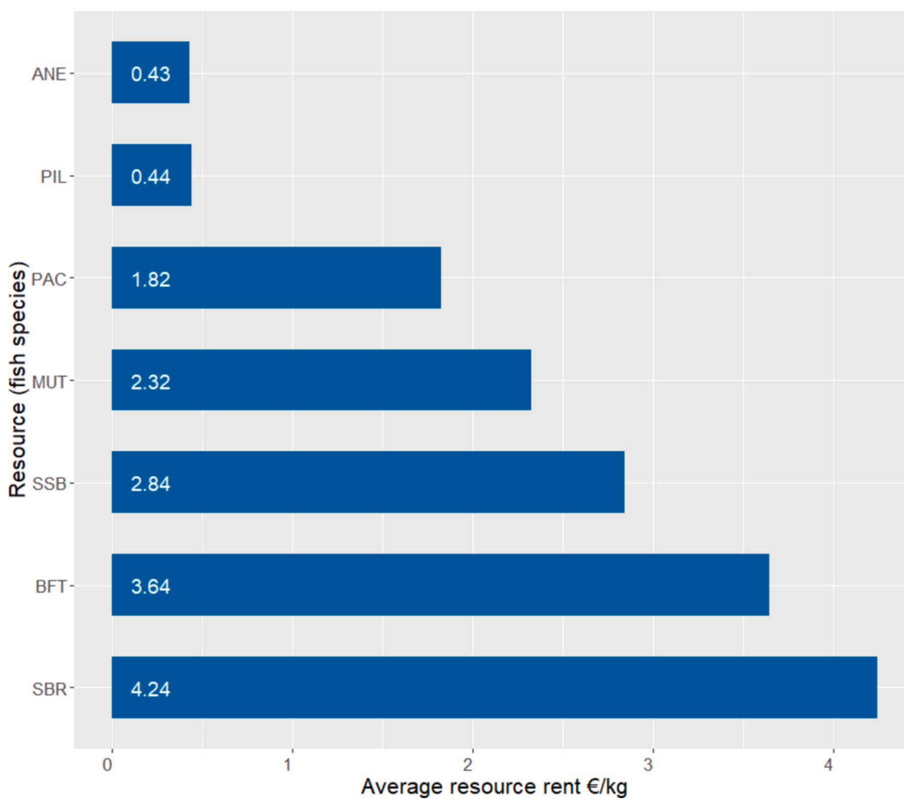

Fig. 5. Average resource rent for the selected species in the Mediterranean Sea (€/kg). ANE = European anchovy, BFT = Atlantic bluefin tuna, MUT = Red mullet, PIL = the European pilchard, PAC = Common pandora, SBR = Blackspot seabream, and SSB = Striped seabream. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which can support a variety of innovative industries. However, to adopt the precautionary principle, the service is cost as the avoided cost of removing banquette estimated in the literature at €35/t.

Table SM2.7 summarises the results of the modelling exercises to determine the probability of visiting the marine space and the average number of visits.

The probability to sea visits increases as the share of urban areas, cropland, heathland and woodland increases in comparison to the baseline of rivers. The probability is not directly influenced by the share of marine land and protected area. Contrarily, the number of visits model reveals that both the share of marine land and protected area play on seagrass. Seagrass meadows prevents the loss of crucial services and/or benefits that stem from this habitat (as part of fish provision[5] and part of nature-based daily recreation[6]) and may be at risk if this ecosystem is damaged. Fig. 6 reports for the European Mediterranean countries in 2018 the direct use of seagrass which is worth €239,120 per year in

[5] This is the actual fish provision flow (without seagrass contribution) computed for anchovy, pilchard and mullet.

[6] This is the actual nature-based recreation flow (without seagrass contribution) computed for whale watching component.

Table 2
Supply table in monetary terms (Euro, €), year 2018, associated with seagrass habitats (i.e. seagrass dependency).

Supply Table (in monetary terms)	Ecosystem Types			
	Coastal	Shelves	Open waters	TOTAL
PROVISIONING SERVICES (in Euro €)				
Fish provision	179,625,433	29,145,205	134,435,878	**343,206,515**
associated with seagrass				***1,129,568***
*Raw biomass provision	133,681			**133,681**
associated with seagrass				***133,681***
REGULATION & MAINTETNANCE SERVICES (in Euro €)				
Carbon sequestration	377,006,958	732,733,980	1,974,940,560	**3,084,681,498**
associated with seagrass				***63,504***
Carbon storage	41,935			**41,935**
associated with seagrass				***41,935***
CULTURAL SERVICES (in Euro €)				
Nature-based daily recreation	241,276,577	361,914,866	361,914,866	**965,106,310**
associated with seagrass				***115,040,672***
TOTAL	**798,084,585**	**1,123,794,051**	**2,471,291,304**	**4,393,169,940**
associated with seagrass				***116,409,361***
TOTAL per km^2	**1735**	**977**	**2776.73**	**1757**
associated with seagrass				***253***

* Perspective ecosystem service.

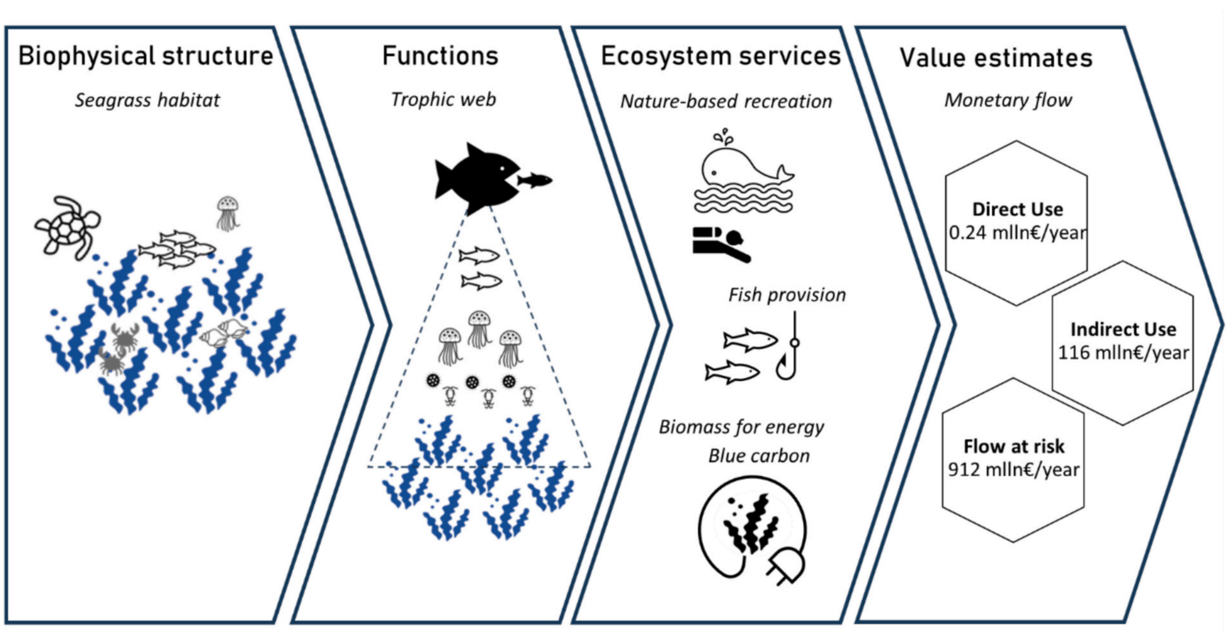

Fig. 6. Diagrammatic representation of the monetary flows (in million Euro [mlln€]) that depend on seagrass habitats for the four marine and coastal ecosystem services (i.e. nature-based recreation, fish provision, biomass for energy, and blue carbon). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

terms of carbon storage and sequestration and (as a prospective service) raw biomass provision. Although the amount might appear negligible, the indirect value equates to €116 million. This value takes into consideration the role of seagrass in the trophic chain for supporting the species selected for fish provision and nature-based recreation. In addition, the flow of fish provision and nature-based tourism may be at risk entirely if seagrass were absent. The flow at risk (counted neither as direct nor as indirect flow) would be about €912 million per year. Therefore, it is possible to account for the importance of seagrass far beyond its direct use and eventually provide policymakers and planners with important information to drive strategic decisions.

4. Discussion and conclusions

In this paper we addressed the assessment, valuation and accounting of marine and coastal ecosystem services by focusing on their dependency on seagrass habitat. The study is pioneering for several reasons. First, it stands out as one of the few examples of marine ecosystem accounts, especially when considering the high number of terrestrial ecosystem accounts. However, thanks to the SEEA EA standards and to initiatives like GOAP, interest in marine ecosystems increasing, which is expected to lead more case studies in the near future. Second, the inclusion of seagrass as one of the ecological features of marine functional connectivity, raises the importance of intrinsic, fundamental, and often neglected, components of marine ecosystems and their capacity to provide services (see Addamo and La Notte, 2023). The seagrass constitutes a unique habitat that raises different accounting challenges described in the previous sections. Its presence and abundance significantly affect numerous ecosystem services, and the purpose of accounting is to track the effect on economy and society. Third, we consistently presented our measurements in both physical and monetary terms. Although we often adopt techniques based on value transfer, the selection of value is fundamentally grounded in biophysical units, their meaning and implications. This allows for a reliable translation of any changes in physical terms –such as shifts from tonne to abundance) into monetary terms. Finally, we leverage a well structured accounting framework to accurately and consistently report the contributions of seagrass, ensuring that the value of ecosystem services flows is not double-counted.

The important learning from this application is the relevant ecological and economic importance of seagrass. On the one hand, there are services that entirely rely on seagrass presence and density, such as carbon storage and sequestration in coastline and raw biomass provision. On the other hand, there are services that jointly depend on seagrass and human-input, such as fish provision and nature-based recreation. When calculating the seagrass' contribution to the total value, the figures appear to be underwhelming. However, several important elements deserve a second thought. While seagrass dependency may account "only" for 0.3 % of total fish provision, the reality is that the entire value of fish catch may be at risk without the presence of seagrass. The same applies for nature-based recreation. This "input dependency" affects the entire value chain involved in the generation of fish provision. In this paper, we conducted a biophysical assessment and a monetary valuation that enabled us four MCES and their reliance on seagrass. However, it Is important to include an additional indicator that can measure the socio-economic loss of the absence of seagrass. Furthermore, considering the relative importance of habitat in comparison to their absolute significance may lead to different conclusions. Coastlines, for instance, occupy a much smaller area than shelves and open water. Therefore, assessing value per km^2 provides a more appropriate perspective than evaluating total value, especially since human activity - and their use of certain services, such as coastal protection- is primarily focused along the coastline.

There are several limitations to consider. The first set of limitations relate to the data used. In physical terms, we relied more on modelled data than on collected data, which introduce a level of uncertainty. This uncertainty is further increased when translating the data into monetary terms through benefit transfer techniques. Original datasets show a remarkable variability. Additionally, there are limitations in the detailed classification of users; a more granular breakdown is necessary for accurately distributing data across economic units.

The second set of limitations concerns the scope of this application. We focus only on a subset of ecosystem services related to a wide range of MCES that still require assessment and consideration. For fish provision, we have only considered a limited number of species, which drastically reduces the overall value of the ecosystem service flow. According to the estimates in Table 6, carbon sequestration and nature-based recreation stand out as the most valuable services, especially in comparison to fish provision. It is important to remember that this pilot study only includes a small selection of species. In fact, the proprotion of the species selected relative to the total catch and landings in each country is averages less than ¼, with a few exceptions. Specifically, we only account from 8 to 17 % in Cyprus, France and Slovenia, to 18–24 % in Italy, Malta and Greece, while Spain has the highest percentage at 32 % and Croatia at 54 %. More details are provided in Table SM3.1. Consequently, we are likely underestimating the fish provision service significantly.

The raw biomass provision is currently limited to seagrass, yet marine ecosystems can supply other valuable economic resources. Nature-based recreation should also account for other recreational activities like bathing, which could be assessed through water quality indicators. Additionally, we need to improve our methodology for both of these services. Regarding raw biomass as a prospective service, we would need to complete the procedure, as we are currently only acknowledging the potential to convert waste into a resource without adequately exploring and tracking its utilisation. For nature-based recreation, we need to improve and expand our methodology with more detailed data to better attribute the species presence to the visits number.

This numerous limitations reinforces the idea that this application is merely a starting point. By concentrating on seagrass, it highlights the importance of considering the interconnections among habitats, species, and services within marine ecosystems. The accounting framework facilitates the accurate recording and clear organization of ecosystem service flows along with their individual components, effectively avoiding the issue of double counting.

A well-strucutred roadmap should therefore outline strategies to increase data availability while also implementing a broader range of applications across multipleMCES, considering their interconnectivity. Utilising the SEEA EA general framework for the cosystem services accounting can provide a cohesive framework to guide the entire process.

Author contributions

This work was realised under the collaboration of all authors. AMA and ALN conceived and designed the analysis; AMA collected the data and performed the analysis on biophysical assessment; SF and GG reviewed literature and performed the analysis on monetary valuation; ALN performed the analysis on accounting. All authors participated in the discussion of the results and in the writing of the manuscript. All authors approved the final version.

The views expressed are purely those of the writers and may not in any circumstance be regarded as stating an official position of the European Commission.

Funding

AMA is supported by Horizon Europe MPA Europe (Grant Agreement 101059988).

CRediT authorship contribution statement

Anna Maria Addamo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandra La Notte:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Silvia Ferrini:** Writing – review & editing, Formal analysis, Data curation. **Gaetano Grilli:** Writing – review & editing, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

All data are available in the paper and supplementary materials

Acknowledgments

The authors would like to thank Chiara Piroddi (European Commission Joint Research Centre) for providing input to preliminary brainstorming and data on food web in the Mediterranean Sea. The authors are grateful to the editor and two anonymous reviewers for their comments and suggestions that improve the quality of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108420.

References

ACCOBAMS, 2021. Estimates of Abundance and Distribution of Cetaceans, Marine Mega-Fauna and Marine Litter in the Mediterranean Sea from 2018–2019 Surveys. Eds. Panigada S., Boisseau O., Cañadas A., Lambert C., Laran S., McLanaghan R., Moscrop A. ACCOBAMS - ACCOBAMS Survey Initiative Project, Monaco, p. 177.

Addamo, A.M., La Notte, A., 2023. Towards an ecosystem-based approach in the marine ecosystem accounting. In: Seagrass ecosystems in the Mediterranean Sea: from Diversity to Restoration. Publications Office of the European Union, Luxembourg https://doi.org/10.2760/612075, JRC130756.

Addamo, A.M., La Notte, A., Guillen, J., 2024. Status of mapping, assessment and valuation of marine ecosystem services in the European seas. Ecosyst. Serv. 67, 101631. https://doi.org/10.1016/j.ecoser.2024.101631.

Balata, G., Tola, A., 2016. Cost-opportunity analysis of the use of *Posidonia oceanica* as a source of bio-energy in tourism-oriented territories, The case of Alghero. J. Clean. Prod. 172, 4085–4098. https://doi.org/10.1016/j.jclepro.2017.02.072.

Bañolas, G., Fernández, S., Espino, F., Haroun, R., 2020. Evaluation of carbon sinks by the seagrass *Cymodocea nodosa* at an oceanic island: spatial variation and economic valuation. Ocean Coast. Manag. 187, 105112. https://doi.org/10.1016/j.ocecoaman.2020.105112.

Camiñas, J.A., Kaska, Y., Hochscheid, S., Casale, P., Panagopoulou, A., Báez, J.C., Otero, M.M., Numa, C., Alcázar, E., 2020. Conservation of Marine Turtles in the Mediterranean Sea. IUCN, Malaga, Spain.

Cavalletti, B., Di Fabio, C., Lagomarsino, E., Ramassa, P., 2020. Ecosystem accounting for marine protected areas: a proposed framework. Ecol. Econ. 173, 106623.

Carnell, P., McLeod, R., Young, M., Gillies, C., Obst, C., Macreadie, P., Ierodiaconou, D., Reeves, S., Eigenraam, M., Janes, H., Kelvin, J., and Nicholson, E. 2022. Prioritising the restoration of marine and coastal ecosystems using ecosystem accounting. PREPRINT (Version 1) available at Research Square. doi: 10.21203/rs.3.rs-1617940/v1.

Cebrian, J., Duarte, C., Marba, Nuria, Enriquez, S., 1997. Magnitude and fate of the production of four cooccurring Western Mediterranean seagrass species. Mar. Ecol. Progr. Series 155, 29–44.

Chen, W., Van Assche, K.A.M., Hynes, S., Bekkby, T., Christie, H.C., Gundersen, H., 2020. Ecosystem accounting's potential to support coastal and marine governance. Mar. Policy 112, 103758.

Cornara, L., Pastorino, G., Borghesi, B., et al., 2018. *Posidonia oceanica* (L.) delile ethanolic extract modulates cell activities with skin health applications. Marine Drugs 16, 21.

Collier, C.J., Langlois, L.M., McMahon, K.M., Udy, J., Rasheed, M., Lawrence, E., Carter, A.B., Fraser, M.W., McKenzie, L.J., 2021. What lies beneath: predicting seagrass below-ground biomass from above-ground biomass, environmental conditions and seagrass community composition. Ecol. Indic. 121, 107156. https://doi.org/10.1016/j.ecolind.2020.107156.

Darnaude, A.M., Arnaud-Haond, S., Hunter, E., Gaggiotti, O., Sturrock, A., Beger, M., Volckaert, F.A.M., Pérez-Ruzafa, A., López-López, L., Tanner, S.E., Turan, C., Ahmet Doğdu, S., Katsanevakis, S., Costantini, F., 2022. Unifying approaches to functional marine connectivity for improved marine resource management: the European SEA-UNICORN COST action. Res. Ideas Outcomes 8, e98874. https://doi.org/10.3897/rio.8.e98874.

Di Gennaro, V., 2018. Valutazione dei servizi ecosistemici e valorizzazione commerciale della biomassa algale: il caso della Laguna di Orbetello. Available at https://comunivirtuosi.org/wp-content/uploads/2018/08/Di-Gennaro.pdf.

EEA, 2015. The European Environment — State and Outlook 2015: Synthesis Report. European Environment Agency, Copenhagen, p. 212.

Eigenraam, M., McCormick, F., Contreras, Z., 2016. Marine and Coastal Ecosystem Accounting: Port Phillip Bay. Report to the Commissioner for Environmental Sustainability. State of Victoria, Department of Environment, Land, Water and Planning (DELWP). https://www.environment.vic.gov.au/_data/assets/pdf_file/0025/49813/Marine-and-Coastal-Ecosystem-Accounting-Port-Phillip-Bay.pdf.

Fitch, A., Kuyer, J., Kharadi, N., Gower, J., Roberts, C., Dewey, N., Jones, L., 2022. Under the influence of nature: the contribution of natural capital to tourism spend. PLoS One 17 (6), e0269790.

Gacutan, J., Lal, K.K., Herath, S., Lantz, C., Taylor, M.D., Milligan, B.M., 2022. Using ocean accounting towards an integrated assessment of ecosystem services and benefits within a coastal lake. One Ecosyst. 7, e81855. https://doi.org/10.3897/oneeco.7.e81855.

GOAP, 2021. Technical Guidance on Ocean Accounting for Sustainable Development, 1.0. March 2021. Available at https://www.oceanaccounts.org/technical-guidance-on-ocean-accounting-2/.

Grilli, G., Luisetti, T., Thornton, A., Donovan, D., 2021. Developing ecosystem accounts for the marine and coastal environment: limitations, opportunities and lessons learned from the United Kingdom experience. J. Ocean Coast. Econom. 8 (2), 4. https://doi.org/10.15351/2373-8456.1145.

Hendriks, K., Gubbay, S., Arets, E., Janssen, J., 2020. Carbon Storage in European Ecosystems; A quick scan for Terrestrial and Marine EUNIS Habitat Types. Wageningen Environmental Research, Internal Report, Wageningen, p. 66.

IDEEA Group, 2021. Defining a complete sequence of national ocean accounts. In: Prepared for the Department of Agriculture, Water and the Environment, p. 94. Available at https://www.ideeagroup.com/wp-content/uploads/Defining-a-Complete-Sequence-of-National-Ocean-Accounts.pdf.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

IUCN, 2018. POSBEMED 2 - Governance and management of posidonia beach- dune systems across the Mediterranean. Available at https://www.iucn.org/news/mediterranean/202103/posbemed-2-governance-and-management-posidonia-beach-dune-systems-across-mediterranean.

Kletou, D., Kleitou, P., Savva, I., Attrill, M.J., Charalambous, S., Loucaides, A., Hall-Spencer, J.M., 2020. Seagrass of Vasiliko Bay, eastern Mediterranean: lost cause or priority conservation habitat? J. Mar. Sci. Eng. 8 (9), 717. https://doi.org/10.3390/jmse8090717.

La Notte, A., Addamo, A.M., Ferrini, S., Grilli, G., Polimene, L., Macias, D., 2024. Indicators for ecosystem services and vulnerabilities in the Mediterranean Sea. In: An Initial Application. Ecological Indicators.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. 105, 1786–1793. https://doi.org/10.1073/pnas.0705414105.

Liquete, C., Piroddi, C., Drakou, E.G., Gurney, L., Katsanevakis, S., et al., 2013. Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. PLoS ONE 8 (7), e67737. https://doi.org/10.1371/journal.pone.0067737.

Masri, M.A., Younes, S., Haack, M., Qoura, F., Mehlmer, N., Brück, T., 2017. A seagrass-based biorefinery for generation of single-cell oils for biofuel and Oleochemical production. Energ. Technol. 6 (6), 1026–1038. https://doi.org/10.1002/ente.201700604.

Mengo, E., Grilli, G., Luisetti, T., Conejo Watt, H., Harper Jone, S.C., Posen, P., 2022. Marine and coastal accounts for Small Island developing states: a case study and application in Grenada. One Ecosyst. 7, e84865. https://doi.org/10.3897/oneeco.7.e84865.

Monnier, B., Pergent, G., Valette-Sansevin, A., Boudouresque, C.F., Mateo, M.Á., Pergetn-Martini, C., 2020. The *Posidonia oceanica* matte: a unique coastal carbon sink for climate change mitigation and implications for management. Vie et Milieu / Life & Environ. 70 hal-03342407. https://hal.sorbonne-universite.fr/hal-03342407/document.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdes, L., DeYoung, C., Fonseca, L., Grimsditch, G., 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environmental Programme, GRID-Arendal, Birkeland Trykkeri AS, Birkeland.

O'Keefe, E., Lillis, H., 2019. Generating Essential Ocean Variables. EMODnet Report. Seagrass cover (Essential Ocean Variable) in Europe - points (2021) and polygons (2019). http://gis.ices.dk/geonetwork/srv/eng/catalog.search#/metadata/39746d9c-4220-425c-bc26-7cb3056c36a5.

OSPAR, 2021. Natural Capital Accounting for the North East Atlantic Area.

Pindyck, R.S., 2019. The social cost of carbon revisited. J. Environ. Econ. Manag. 94, 140–160. https://doi.org/10.1016/j.jeem.2019.02.003.

Piroddi, C., Coll, M., Liquete, C., Macias, D., Greer, K., Buszowski, J., Steenbeek, J., Danovaro, R., Christensen, V., 2017. Historical changes of the Mediterranean Sea ecosystem: modelling the role and impact of primary productivity and fisheries changes over time. Sci. Rep. 7, 44491. https://doi.org/10.1038/srep44491.

Piroddi, C., Coll, M., Macias, D., Steenbeek, J., Garcia-Gorriz, E., Mannini, A., Vilas, D., Christensen, V., 2022. Modelling the Mediterranean Sea ecosystem at high spatial resolution to inform the ecosystem-based management in the region. Sci. Rep. 12, 19680. https://doi.org/10.1038/s41598-022-18017-x.

Price, R., Thornton, S., Stephen, N., 2007. The Social Cost of Carbon and the Shadow Price of Carbon: what they are, and how to use them in economic appraisal in the UK. Economics Group, Department for Environment, Food and Rural Affairs (Defra). London, p. 24pp. MPRA Paper No. 74976. Available at:Online at https://mpra.ub.uni-muenchen.de/74976/.

Pycroft, J., Vergano, L., Hope, C., Paci, D., Ciscar, J.C., 2011. A Tale of Tails: Uncertainty and the Social Cost of Carbon Dioxide — Economics E-Journal. Economics: The Open-Access, Open-Assessment E-Journal. https://doi.org/10.5018/economics-ejournal.ja.2011-22.

Rodríguez-Rodríguez, D., 2022. An assessment of marine biodiversity protection in the Mediterranean Sea: a threatened global biodiversity hotspot. In: Interreg Med Biodiversity Protection Project, p. 17.

Röhr, M.E., Holmer, M., Baum, J.K., Björk, Boyer K., et al., 2018. Blue carbon storage capacity of temperate eelgrass (*Zostera marina*) meadows. Glob. Biogeochem. Cycles 32 (10), 1457–1475. https://doi.org/10.1029/2018GB005941.

Scaffaro, R., Lapresti, F., Botta, L., 2018. PLA based biocomposites reinforced with Posidonia oceanica leaves. Composites Part B: Engineering 139, 1–11. https://doi.org/10.1016/j.compositesb.2017.11.048.

Sousa, A., Figueiredo da Silva, J., Azevedo, A., Lillebø, A.I., 2019. Blue Carbon stock in *Zostera noltei* meadows at Ria de Aveiro coastal lagoon (Portugal) over a decade. Sci. Rep. 9, 14387. https://doi.org/10.1038/s41598-019-50425-4.

Stebbings, E., Hooper, T., Austen, M.C., Papathanasopoulou, E., Yan, X., 2021. Accounting for benefits from natural capital: applying a novel composite indicator framework to the marine environment. Ecosyst. Serv. 50, 101308. https://doi.org/10.1016/j.ecoser.2021.101308.

Telesca, L., Belluscio, A., Criscoli, A., et al., 2015. Seagrass meadows (*Posidonia oceanica*) distribution and trajectories of change. Sci. Rep. 5, 12505. https://doi.org/10.1038/srep12505.

Thornton, A., Luisetti, T., Grilli, G., Donovan, D., Phillips, R., Hawker, J., 2019. Initial natural capital accounts for the UK marine and coastal environment. In: Final Report. Report Prepared for the Department for Environment Food and Rural Affair.

United Nations, et al., 2021. System of environmental-economic accounting - ecosystem accounting (SEEA EA). In: White Cover Publication, Pre-Edited Text Subject to Official Editing. Available at https://seea.un.org/ecosystem-accounting.

Vallecillo, S., La Notte, A., Zulian, G., Ferrini, S., Maes, J., 2019. Ecosystem services accounts: valuing the actual flow of nature-based recreation from ecosystems to people. Ecol. Model. 392, 196–211. https://doi.org/10.1016/j.ecolmodel.2018.09.023.

Vallecillo, S., Maes, J., Teller, A., Babí Almenar, J., Barredo, J.I., Trombetti, M., Abdul Malak, D., Paracchini, M.L., Carré, A., Addamo, A.M., Czúcz, B., Zulian, G., Marando, F., Erhard, M., Liquete, C., Romao, C., Polce, C., Pardo Valle, A., Jones, A., Zurbaran-Nucci, M., Nocita, M., Vysna, V., Cardoso, A.C., Gervasini, E., Magliozzi, C., Baritz, R., Barbero, M., Andre, V., Kokkoris, I.P., Dimopoulos, P., Kovacevic, V., Gumbert, A., 2022. EU-Wide Methodology to Map and Assess Ecosystem Condition: Towards a Common Approach Consistent with a Global Statistical Standard. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/13048. JRC130782.

Vieira, J., Matos, P., Mexia, T., et al., 2018. Green Spaces Are Not All the Same for the Provision of Air Purification and Climate Regulation Services: The Case of Urban Parks. Environ. Res. 160, 306–313. https://doi.org/10.1016/j.envres.2017.10.006.

Visintin, F., Tomasinsig, E., Marangon, F., Troiano, S., Chimienti, G., Mastrototaro, F., Montesanto, F., Spoto, M., 2022. Integrated Environmental Accounting for Assessing the Value for Money in Marine Protected Areas: The Case of Tremiti Islands (Italy). 10, 253–267. J. Environ. Account. Manage. https://doi.org/10.5890/JEAM.2022.09.001.

Wang, P., Deng, X., Zhou, H., Yu, S., 2019. Estimates of the social cost of carbon: a review based on meta-analysis. J. Clean. Prod. 209, 1494–1507. https://doi.org/10.1016/j.jclepro.2018.11.058.

Weitzman, M.L., 2009. On modeling and interpreting the economics of catastrophic climate change. Rev. Econ. Stat. 91 (1), 1–19. https://doi.org/10.1162/rest.91.1.1.

Zulian, G., La Notte, A., 2022. How to account for nature-based tourism in Europe. An operational proposal. ONE ECOSYSTEM 7, e89312. https://doi.org/10.3897/oneeco.7.e89312. ISSN 2367-8194.