Journal of Ocean and Coastal Economics

Volume 8
Issue 2 *Papers from the 5th International Symposium on Oceans and National Income Accounts*

Article 4

December 2021

Developing ecosystem accounts for the marine and coastal environment: Limitations, opportunities and lessons learned from the United Kingdom experience.

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Recommended Citation

Grilli, Gaetano; Luisetti, Tiziana; Thornton, Ann; and Donovan, Deanna (2021) "Developing ecosystem accounts for the marine and coastal environment: Limitations, opportunities and lessons learned from the United Kingdom experience.," *Journal of Ocean and Coastal Economics*: Vol. 8: Iss. 2, Article 4.
DOI: https://doi.org/10.15351/2373-8456.1145

1 INTRODUCTION

Coastal and marine ecosystems are increasingly recognized as crucial in sustaining human activities and wellbeing (Duarte, 2020). They provide many ecosystem services such as food, materials, storm and flood protection, pollution control, climate regulation and recreational opportunities (Barbier, 2017). Marine and coastal industries and activities have rapidly developed in the recent decades (OECD, 2021), and their contribution to the global GDP is projected to be US$ 3 trillion by 2030 doubling in size from 2010 (OECD, 2016). A 'Blue Economy', as the sustainable activities of these industries and activities are called, is now considered a key element in the strategy to address future growth and development for many countries owning a marine space (Lee at al., 2020; Choudhary et al., 2021). Yet, marine and coastal environments are experiencing unprecedented pressures such as climate change and plastic pollution (Neumann et al., 2015; Jambeck et al., 2015). It is therefore paramount to advance measurement frameworks to track the contribution of marine and coastal ecosystems to national wealth and economic systems and assess the sustainability of their use to support human welfare (OECD, 2021; Kildow and McIlgrom, 2010).

Recording relevant environmental and economic data in interrelated tables within a single comprehensive framework can help visualising the contribution of nature to economic activities and the impact of these activities on the environment. This is how the System of Environmental Economic Accounting (SEEA, UN et al.,2014a, 2014b; UN, 2021) is structured and what it aims to. The SEEA can have a fundamental role in improving the quantification and recording of marine and coastal ecosystems' contribution to society due to its coherency and integration with national economic accounts. A decisive step in this direction is reflected in the recently adopted SEEA Ecosystem Accounting (SEEA EA) framework (UN, 2021) recognising the need to develop a thematic Ocean Accounts Framework comprising a set of ocean ecosystem accounts, accounts for natural resources and pressures from the SEEA Central Framework (SEEA CF) (UN et al., 2014a) and additional accounts on ocean economy, governance, and management. The inclusion of marine and coastal ecosystems in the SEEA framework provides a foundation for the development of an integrated and standardised set of accounts that would support decision making towards the sustainable development and use of the seas (Fenichel et al., 2020; Mulazzani and Malorgio, 2017).

The incorporation of accounts specific to the marine and coastal environment in the SEEA is the result of global initiatives and experimental pilot studies that have intensified in the last decade. At the global level, the High Level Panel for a Sustainable Ocean Economy[1] developed an action plan for the sustainable use of the ocean encompassing the development of a set of accounts. The UN Economic and Social Commission for Asia and the Pacific (UN-ESCAP) and the Global Ocean Accounts Partnership (GOAP) are producing a technical guidance[2] that provides approaches to develop spatially disaggregated marine and coastal accounts and to expand the accounts with governance, ocean economy and socio-economic considerations. National examples of experimental implementation of the SEEA to marine and costal zones include the United Kingdom (ONS, 2021a; Thornton et al., 2019), the Netherlands (Graveland et al., 2017), Australia (IDEEA, 2020), Mauritius (Sultan, 2017), and the pilots supported by UN-ESCAP in Canada, China, Malaysia, Samoa, Thailand and Vietnam[3]. In addition, a number of countries produce statistics on the ocean economy, including the United States (Nicolls et al., 2020; Colgan, 2013), Portugal (Statistics Portugal, 2016), and China (Zhang and Sun, 2018).

However, measuring marine and coastal ecosystems contribution to society for accounting purposes has challenges and encounters limitations strictly related to the complexity of those systems (Fenichel et al., 2020; Townsend et al., 2018). The paucity of suitable spatial data, the connectivity and integration of habitats and ecosystem services delivery, the context-specific socio-economic dynamics involving the use of marine assets are just some of the challenges that practitioners face in adapting accounting frameworks such as the SEEA to marine systems.

In this paper, we address the opportunities, challenges and limitations in developing coastal and marine accounts based on the experience of compiling an

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[1] https://oceanpanel.org/.

[2] https://www.oceanaccounts.org/.

[3] https://communities.unescap.org/environment-statistics/tools/ocean-accounts-national-pilots-3.

DOI: 10.15351/2373-8456.1145

initial experimental set of accounts for the United Kingdom (Thornton et al., 2019) within the SEEA Experimental Ecosystem Accounting (SEEA EEA) (UN et al., 2014b). The aim of these initial accounts was to draw on existing data sources to record information following SEEA guidance and advance the development of the accounts in areas under-researched or overlooked in previous scoping studies or in terrestrial accounts. The Thornton et al. accounts were developed to directly inform the recent United Kingdom marine natural capital accounts published by the Office for National Statistics (ONS, 2021a)[4], and provided input to the ongoing Technical Guidance on Ocean Accounting coordinated by the GOAP, which in turn informed the new SEEA EA Framework. Recently, the Natural Capital Accounting for the North-East Atlantic Area report, which supports the Commission of the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Operational Objective 7.03 of the new North-East Atlantic Environmental Strategy (Alarcon Blazquez, 2021), was also, among others, informed by the Thornton et al. accounts. The accounts compiled by Thornton et al. and discussed in this paper are, indeed, one of the first examples of experimental application of the SEEA approach to nation-wide coastal and marine ecosystems. As such, they provide some relevant empirical and methodological insights, such as the complexities in mapping coastal and marine ecosystems' extent, the inclusion of shelf sea sediments in the quantification and valuation of carbon sequestration and storage, and the potential solution to account for regulating services such as coastal protection and waste remediation.

Our paper contributes to the literature on ecosystems accounts by providing a critical assessment on the empirical application of the SEEA framework to the context of coastal and marine environments in the UK. The paper also highlights some of the novel approaches used, and the main issues encountered, in the development of the marine and coastal accounts in Thornton et al. (2019), discussing potential solutions. We critically review if and how the encountered issues have been solved in the process or have been addressed in the SEEA EA (UN, 2021) and in the Office for National Statistics marine accounts (ONS, 2021a). Section 2 briefly summarises the process of marine and coastal accounts

4 https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/marineaccountsnaturalcapitaluk/2021

development in the United Kingdom; Section 3 reports on the experience and challenges of compiling the initial set of experimental accounts; Section 4 offers some lessons learned, and Section 5 provides concluding remarks.

2 DEVELOPING COASTAL AND MARINE ECOSYSTEM ACCOUNTS IN THE UK

In 2011 the UK Government, with the aim of better recognising the benefits of nature, committed to incorporating natural capital and ecosystem services in the UK Environmental Accounts by 2020. The following year the Office for National Statistics (ONS) together with the Department of Environment, Food and Rural Affairs (Defra) published a 'roadmap' detailing priorities for developing environmental accounts, with commitments reinforced in 2018 with the publication of the 25 Year Environment Plan (HM Government, 2018) and the Revised 2020 Roadmap (ONS and Defra, 2018). The ONS and Defra set the ambitious aim of developing a complete suite of accounts for all UK broad habitats by 2020, which would include an initial account for marine and coastal ecosystems.

Ideally, coastal and marine ecosystem accounts compiled following the UN SEEA guidelines (UN et al., 2014a, 2014b; UN, 2021) should include the full set of integrated accounting tables, complete of all their elements (Figure 1). In particular, based on the SEEA EA guidelines coastal and marine ecosystem accounts should include *i)* ecosystem extent accounts in physical terms, recording and organising data on the area (and changes) of different coastal and marine ecosystem types within an accounting area; *ii)* ecosystem condition accounts in physical terms, recording and organising biophysical indicators (and changes) which describe the condition of the different coastal and marine ecosystem types (such as pollution, physical state, composition, etc.) and their capacity to provide ecosystem services; *iii)* ecosystem services flow accounts, recording and organising the supply of final ecosystem services provided by coastal and marine ecosystems and their use by society, quantified in physical and valued in monetary terms; iv) ecosystem asset accounts in monetary terms, recording information on values of ecosystem stocks (and changes).

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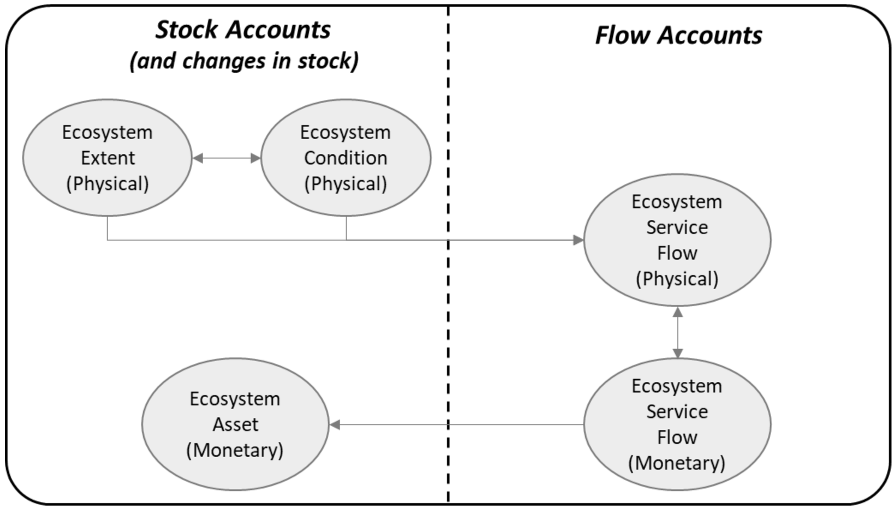
DOI: 10.15351/2373-8456.1145

Figure 1: Links in between SEEA EA ecosystem accounts. Adapted from SEAA EA (UN, 2021).



The ONS/Defra work on marine and coastal accounts dates from the publication of the report Developing UK Natural Capital Accounts: Marine Scoping Study (Eftec, 2015). The study included a review of the available data and provided initial accounting tables for food provision, carbon sequestration and recreational services. The following year, the ONS published the report Scoping UK Coastal Margin Ecosystem Accounts report (ONS and Defra, 2016) with the objective of further scoping the development of marine accounts, discussing the methodological challenges involved, and providing guidance on approaches for future applications.

The initial experimental set of marine and coastal ecosystem accounts discussed in this paper explicitly aimed at testing and developing further the methodologies detailed in the ONS 2016 report. The Thornton et al. (2019) study was built using only existing available data and provided estimates of the value of a wider set of services flowing from broad-scale marine and coastal habitats within UK waters. The initial accounts by Thornton et al. (2019) included both coastal and marine habitats and both biotic and abiotic services (Table 1). The SEEA EA clearly highlights the link between environmental asset accounts, which are part of the SEEA CF, and the ecosystem accounts, part of the SEEA EA. The Thornton et al. (2019) report did not make that explicit distinction, but biotic and abiotic services were combined in a single set of physical and monetary accounts.

In March 2021, expanding on the initial accounts of Thornton et al. (2019), the ONS published the first full set of experimental accounting tables for UK marine areas[5].

Table 1: Biotic and abiotic ecosystem services selected for the accounts in Thornton et al. (2019). Adapted from Thornton et al. (2019).

Ecosystem services	**Goods and benefits**
Provisioning	
Finfish & shellfish	Food provision
Regulating	
Waste (nutrient) remediation	Clean waters
Natural hazard mitigation	Coastal erosion and flood prevention
Climate regulation (carbon sequestration and storage)	Healthy climate
Cultural	
Recreational places and seascapes	Nature watching and enjoyment (tourism)
Abiotic (provisioning services from the abiotic component of the environment)	
Renewable energy	Electricity from renewable source - Offshore Wind Farms
Aggregates extraction	Construction material

5 www.ons.gov.uk/economy/environmentalaccounts/bulletins/marineaccountsnaturalcapitaluk/2021.

DOI: 10.15351/2373-8456.1145

3 ACCOUNTING CHALLENGES HILIGHTED BY THE UK COASTAL AND MARINE INITIAL ACCOUNTS

The Thornton et al. report (2019) was developed in an experimental form within the SEEA EEA and related technical recommendations (UN, 2019). It developed extent and condition accounts for a number of ecosystems including littoral, infralittoral, and sublittoral habitats, saltmarshes, dunes and shingle, and deep-sea habitats. Some habitats are missing from these accounts due to lack of data, for example seagrass meadows, although they represent a relevant blue carbon sequestration and storage habitat. The supply tables (physical and monetary accounts) were prepared with reference to the ecosystem services in Table 1.

3.1 Ecosystem extent account

Based on the UK National Ecosystem Assessment (UK NEA, 2011), broad habitat definitions based on the European Nature Information System (EUNIS) habitat codes (EEA, 2019) were used to compile the extent accounts. The working definition of marine ecosystems adopted in Thornton et al. (2019) was "*habitats directly connected to the oceans, i.e. part of the continuous body of water which covers the greater part of the earth's surface and which surrounds its land masses*" and for coastal ecosystems "*habitats that are above spring high-tide limit (or above mean water level in non-tidal waters) occupying coastal features.*" (EEA, 2019). EUNIS sub-component at levels 2 and 3 for categories A (marine habitats) and B (coastal habitats) were employed. These sub-component levels incorporate some distinctive, defining biological features important to the delivery of specific ecosystem services of interest. The habitats included in the accounts and their extent[6] are summarised in Table 2.

[6] Extent of the habitats was calculated based on data from the Joint Nature Conservation Committee (UKSeaMap, JNCC, 2017, 2019), Scotland's Environment (HABMoS, Scotland's Environment, 2017), Natural Resources Wales (Lle Geo Portal, 2019), and the Department for Environment, Food & Rural Affairs (Data Service Platform, Defra, 2019).

Table 2: Extent of marine and coastal habitats in the United Kingdom. Adapted from Thornton et al. (2019).

EUNIS L2/L3	Habitat name	Area (ha)
A1	Littoral rock and other hard substrata	21,656
A2.1	Littoral coarse sediment	7,248
A2.2	Littoral sand and muddy sand	187,831
A2.3	Littoral mud	100,303
A2.4, A2.6, A2.7	Littoral mixed sediments, sediments dominated by aquatic angiosperms, biogenic reefs	15,807
A2.5	Coastal saltmarshes and saline reedbeds	52,832
A3	Infralittoral rock and other hard substrata	292,127
A4	Circalittoral rock and other hard substrata	491,616
A5.1	Sublittoral coarse sediment	16,497,908
A5.2	Sublittoral sand	26,484,814
A5.3	Sublittoral mud	6,149,456
A5.4	Sublittoral mixed sediments	1,241,882
A6.1	Deep-sea rock and artificial hard substrata	633,871
A6.2-A6.5	Deep-sea mixed, sand, muddy sand, mud	2,887,260
B1	Coastal dunes and sandy shores	96,518
B2	Coastal shingle	10,494
B3	Rock cliffs, ledges and shores, including the supralittoral	25,542
Seabed	Mainly infralittoral. (No substrate data available therefore predictive modelling not possible.)	347,937
Known unknown	'Known unknown' habitat. (No survey data for some coastal and littoral habitats. Shallow sublittoral habitats	33,068,352

https://cbe.miis.edu/joce/vol8/iss2/4
DOI: 10.15351/2373-8456.1145

	that cannot be assessed using bathymetric surveys or physical surveys.)	
Total		**88,613,454**

The first challenge in measuring the extent of marine and coastal habitats lies in the definition used and the spatial boundaries considered. Distinguishing marine from coastal ecosystems using the spring high-tide mark does not solve the issue of overlapping services provision with subsequent risk of double counting. Moreover, some habitats might need further disaggregation for the specificities in delivering ecosystem services. The SEEA EA acknowledges that the scale at which the ecosystems are considered is smaller than the national scale; this could be either the local scale or even at a specific ecosystem scale within an area of interest.

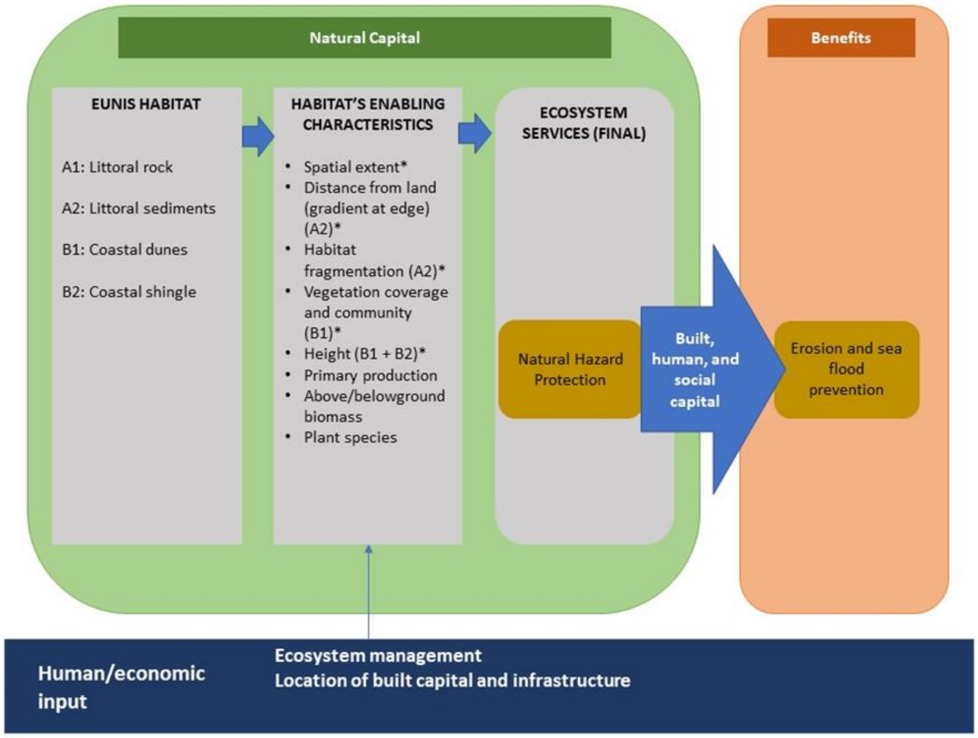
The second challenge was related to establishing a basic set of data for the compilation of an accurate extent account. Habitat extent data are often taken from a single survey carried out over several years. It is financially prohibitive and technically challenging to map marine and coastal habitats through field surveys; field surveys are currently impossible for shelf-sea and deep-sea habitats. This translates into a scarcity of data from, temporally or spatially, routinely replicated surveys and the need to draw on predictive modelling. However, even using predictive models presents challenges. Around 30% of the area of UK marine waters was classified as “known unknown” in the initial accounts. In other words, the area could not be assigned to specific habitats. Therefore, it is extremely challenging to define a yearly opening and closing extent for marine and coastal ecosystems and precisely compile an extent account table as proposed in the SEEA framework. Moreover, this uncertainty and unavailability of information cascades its effect on the other elements of the accounts, such as the ecosystem services supply tables.

3.2 Ecosystem condition account

The capacity of an ecosystem to deliver goods and services depends on its condition, that is the overall quality of an ecosystem in terms of its defining characteristics, which can be different depending on the ecosystem services considered (see for example Figure 1). Ecosystems condition cumulatively reflects past and present human interventions and exogenous environmental changes. Ecosystem condition accounts are, therefore, an important component of the SEEA framework because they provide the link between ecosystem assets, services provision, and the economic valuation methods that is possible to apply. While the measurement of condition indicators has made progress in the last years, Maes et al. (2020) note how a lack of clarity generally remains around the most relevant condition characteristics to monitor, the key indicators to measure, the possibility to define a reference condition level, and the aggregation (and disaggregation) of indicators across ecosystem types or accounting units.

The approach taken to identify the condition indicators in Thornton et al. (2019) was based on the development of a logic chain for each of the ecosystem services considered. These logic chains allowed us to link each service to the ecosystems providing it and to identify a list of enabling ecosystem characteristics. Measurable aspects of those characteristics that could be practically used as condition indicators were then identified. As an example, Figure 1 reports the logic chain for the natural hazard mitigation service.

Figure 2: Logic chain for natural hazard mitigation. Source: Thornton et al. (2019).



Several challenges have been encountered in defining condition indicators for the marine and coastal environment. These result from limited data availability and the need to use proxy indicators that might not specifically reflect the delivery of particular ecosystem goods and services. Several key indicators can be potentially used for each habitat type. A better scientific understanding of the complex ecological processes associated with the delivery of key ecosystem services is needed to identify more appropriate indicators. Another challenge relates to keeping the number of indicators to a physically and financially manageable level, and to those ensuring policy relevance and consistency with, for example, the Water Framework Directive, the OSPAR framework, the Sustainable Development Goals. Table 3 details the indicators shortlisted in the initial marine and coastal accounts. These indicators were identified based on existing availability of data sources and referred widely to the broad scale marine and coastal habitats.

Table 3: Condition indicators and corresponding data source shortlisted in Thornton et al. (2019).

Indicator	**Indicator detail**	**Indicator data source**	**Responsible agency**
1	Primary production (littoral habitats) measured as biomass and extent of macroalgae	WFD	EA, SEPA, NIEA, NRW
2	Extent of habitat measured at appropriate habitat scale	UKSeaMap and Combined Map (JNCC 2017; 2019)	JNCC
3	Habitat surveys (coastal and littoral habitats)	Defined by reporting tool (e.g. CSM, CS)	JNCC, NE, NRW, SNH, NIEA, EA, CEH
4	Distance from land, length of habitat, habitat fragmentation, measured using existing maps with additional earth observation supported by ground-truthing.	UKSeaMap and Combined Map (JNCC 2017; 2019)	JNCC
5	Sediment type	WFD (littoral habitats) MSFD GES descriptor 6 (JNCC 2010) BGS	EA, SEPA, NIEA, NRW JNCC BGS
6	Aspect / wind direction	Data collected by UKHO, MMO	UKHO, MMO
7	Primary production (marine habitats excl. littoral sediment)	MSFD GES descriptors 4, 5. (JNCC 2010)	JNCC
8	Functioning marine food web	MSFD GES descriptor 4 (JNCC 2010)	JNCC

DOI: 10.15351/2373-8456.1145

3.3 Ecosystem services: physical and monetary quantification

In this section, the main methodological and conceptual challenges related to the physical and monetary quantification of the ecosystem services and the corresponding benefits included in the initial accounts will be reviewed for each service typology (provisioning, regulating, cultural and abiotic). Some of the services considered (e.g., finfish and shellfish, recreation, renewable energy and aggregates extraction) have been included in previous UK national scoping studies for the marine environment and are implicit in the established UK environmental accounts (ONS and Defra, 2016; ONS, 2021b). Regulating services, in contrast, have not been explicitly addressed in previous UK national scoping studies for the marine environment and therefore required a specific focus in the development of the initial accounts, also considering their key relevance as the impacts of climate change intensify. Valuation of ecosystem services is consistent throughout with the exchange values approach required by the System of National Accounts (SNA).

3.4 Provisioning services

The physical supply of finfish and shellfish was quantified using nominal catch data in tonnes live weight recorded by the International Council for the Exploration of the Sea (ICES, 2019a). Data include commercial, artisanal, subsistence fisheries, and recreational catch where available, but do not include non-recorded catch and discards. We considered catch of the UK fleet within the UK EEZ overlapping the relevant ICES statistical rectangles (ICES 2019b). Monetary value of finfish and shellfish was estimated using a resource-rent-to-output ratio approach. Landings of marine finfish and shellfish from the UK commercial fleet in UK and foreign ports as collated by the Marine Management Organisation (MMO, 2013-2017) were used to quantify the total output of the sector. The resource-rent-to-output ratio was obtained for the whole “fisheries and aquaculture” sector in the SNA.

The valuation approach could be refined in several areas. The first issue was related to data limitations concerning costs of the fishing industry. The use of operating costs, employment costs, tax and other costs that are directly derived from the national fleet through nation-wide surveys would be advisable as the catch of different species has different costs for fishers. If such data were available, the costs of catching a particular species would have been directly linked with the ex-vessel price landings, and a more reliable resource rent value could be calculated. The second issue was related to the assessment of discards, which are usually not accounted for in official statistics. The third issue was related to recreational fisheries with its role on the stock of finfish biomass, which should be further investigated, for example, using bio-economic modelling and sectoral surveys.

3.4.1 Regulating services

Waste remediation (through breakdown, detoxification, burial, removal, or neutralisation) is an important service for the health of the marine environment and all who use it. Different coastal and marine ecosystems work together to provide this service and remediation capacity varies depending on the particular ecosystem and the pollutant or nutrient being processed. As a working assumption, we considered all the coastal and marine ecosystems involved in waste remediation processes to be completely capable of meeting the demand for remediation. In other words, we assumed that all the pollutants and nutrients reaching coastal and marine habitats are remediated through natural processes. In practice, not all the service demand is met, resulting in a deterioration of the ecosystem, which would be ideally recorded in the condition accounts and could eventually result in the ecosystem's reduced capacity for providing this service.

The information used to assess the service in physical and monetary terms relates to the quantity of pollutants and nutrients discharged into UK marine and coastal waters by urban wastewater treatment plants, and to the value of industrial treatment of a unit of the same pollutant or nutrient. The estimated quantity of pollutants and nutrients discharged was based on data collected for the EU Urban Wastewater Treatment Directive. A replacement cost approach of treating a unit of pollutant was then used to estimate a monetary value for the service based on values reported in Hernández-Sancho et al. (2010). Only nitrogen, phosphorus and organic compounds were considered in the analysis. This method is likely to underestimate the actual value of the waste and nutrient remediation service provided by UK coastal and marine environments, as only some of the elements discharged and only some of the pollution sources are accounted for.

The ecosystem service of natural hazard mitigation relates to the moderating effect that coastal habitats have on natural hazards, such as storm surges and coastal flooding, thus diminishing the risk to human life and economic resources. Several marine and coastal habitats can contribute differently to natural hazard mitigation. The initial difficulty when assessing and valuing natural hazard mitigation was whether to disaggregate the single services, e.g., flood protection, wave and tidal dissipation, storm protection, or to consider them as a whole. This challenge is intertwined with the development of appropriate condition accounts allowing for such disaggregation. A further difficulty occurred in assessing the degree of protection provided by different coastal habitats and, therefore, identifying the most suitable service provision indicators to use.

We based our monetary valuation on a simplified version of the replacement cost method. Only saltmarshes were considered in assessing the protection from both recurrent (e.g., waves, tides) and infrequent (e.g., storms, floods) natural disturbances. It was assumed that if the natural defence provided by saltmarshes did not exist, the capital cost of building a seawall would be incurred, an approach already suggested in the ONS and Defra scoping study (2016). This working assumption was required to obtain an exchange-type value coherent with accounting principles. However, seawall capital costs were only available for linear measurements. Therefore, we further assumed that all saltmarshes in the UK have, at minimum, the width necessary to deliver excellent ecosystem service provision (i.e., 200m). This assumption was needed to calculate a linear measurement of the total coastline protected by saltmarshes. This method is likely to overestimate the value of the ecosystem service, being implicitly assumed that all the saltmarshes provide the same excellent level of protection. At the same time, other important habitats are not considered. Finally, the value of the economic activities that are protected by coastal ecosystems is a relevant component of the value of the service that is not accounted for in our approach.

The important welfare benefit provided by carbon sequestration and storage is maintaining an equitable climate which facilitates the existence of life on this planet. To calculate the flow of services provided by marine and coastal ecosystems for climate regulation (carbon sequestration and storage), we followed methodologies widely adopted in the literature as detailed for example in Luisetti et al. (2019). The extent of marine ecosystems providing the service was extracted from the extent account. However, the boundaries relevant for carbon processing do not consistently match to EUNIS sediment type boundaries. Therefore, based on data availability, the sub-habitats selected for the calculations were limited to coastal saltmarshes, sublittoral sand, and sublittoral mud.

We relied on carbon burial rates found in the literature to estimate the ecosystem service flow of carbon sequestration and storage in saltmarshes (Luisetti et al., 2019), and seabed sediments (de Haas et al., 1997), taking a conservative approach by selecting the lowest rates available given the high level of uncertainty. For a given region, unless there is a radical impact or change which would affect carbon cycling, the carbon burial rate should stay approximately constant year on year. Accordingly, we assumed that the flow of carbon storage is the same for all the years considered. The estimation of the economic value of carbon relied on the abatement cost of non-traded carbon central value provided by BEIS (2017), which is in line with the exchange values requirement.

3.4.2 Cultural services

Coastal and marine ecosystems provides numerous recreational opportunities that are enhanced by the aesthetic value of the surrounding natural environment and the man-made amenities aimed at improving the experience. Another relevant aspect relates to positive health and psychological effects (White et al., 2016). In general, cultural ecosystem services provided by coastal and marine places and seascapes embrace a much broader class of benefits.

In the initial marine and coastal accounts, a simple travel cost method was used to estimate the value of cultural ecosystem services, considering the expenditures associated with travelling to the coastal and marine environment as a suitable proxy. The value obtained represents a conservative proxy for the recreational value of coastal and marine habitats in that it aggregates all the

DOI: 10.15351/2373-8456.1145

different cultural values previously described. The travel cost calculation relied on data about recreational visits in England collected in the Monitoring the Engagement with Natural Environment survey (MENE) (Natural England, 2019). It does not account for visits with no costs incurred, generally resulting in an underestimation of the total value (see for a discussion Defra and ONS, 2016).

3.4.3 Abiotic services

Energy generated by offshore wind sources is routinely published in the annual Digest of United Kingdom Energy Statistics (BEIS, 2013–2018). A residual value resource rent approach was used to estimate the monetary value of the ecosystem service provided by offshore wind power generation. Economic data, mainly operating costs, were sourced from the annual financial statements of major wind power producers representing the 78% of total production. A unit resource rent was then calculated by dividing the total resource rent by the total units of wind energy generated for a given year. The use of financial documents provided by energy companies enabled the derivation of accurate estimates of the resource rent. However, not all the companies operating in the sector have financial documents readily available and considering only the major producers might be a source of bias. Moreover, the production of wind energy by terrestrial and offshore farms might incur different costs.

The quantity of aggregates provided by the coastal and marine environment was obtained from the Crown Estate[7] with reference to the removal of sand and gravel from the seabed of English and Welsh territorial seas and continental shelf. The monetary valuation of the ecosystem service provided by the extraction of marine aggregates was also obtained through a resource rent-based approach. The total output sales of the sector were calculated based on a market price for aggregates of around £7.00 per tonne including levies and royalties (ABPmer and ICF, 2019). Detailed data on production costs and capital assets of the licensed companies are not publicly available. Therefore, the resource rent was calculated

[7] https://www.thecrownestate.co.uk/

using data recorded in the SNA for the whole "mining and quarrying" sector. The ecosystem services of marine aggregates extraction for the UK is likely to be underestimated as the data used only refer to England and Wales. In addition, the market price is usually not disclosed by extraction companies therefore an average value was taken as benchmark in the initial accounts.

4 LESSONS LEARNED AND FORWARD LOOK

There are a number of conceptual and methodological issues in developing marine and coastal accounts that are still widely debated. Whilst the recently proposed SEEA EA Ocean Accounts Framework (UN, 2021) provides a framework for the compilation of marine and coastal accounts, technical guidance is still under development and the experimental applications undertaken to date, such as the initial accounts in the UK summarised in this paper, offer some key lessons learned and research needs.

The overlap between marine and coastal ecosystems, and the subsequent overlap between information recorded in marine accounts and terrestrial accounts remains at the forefront. In the initial UK accounts both marine and coastal ecosystems were included. The recently published ONS UK marine accounts (ONS, 2021), in contrast, only considers EUNIS category A (marine habitats). However, a more in-depth look at relationships and integrations between marine and coastal ecosystems, and the activities taking place at the intersection, would aid in giving a realistic assessment of the benefits of these ecosystems as well as the sustainability of the services provided.

The suitability of information developed from survey data as opposed to modelling is another issue that needs to be addressed. Much of the data used to map ecosystems and habitats in the initial UK accounts (Thornton et al., 2019) was incomplete or inconsistent. Nearly 36% of UK marine and coastal environment was mapped in the category of just 'Seabed' or 'Known unknown'. New technologies, particularly earth observations and remote sensing (including undersea robots and autonomous monitoring systems), must be applied to this challenge. It is worth noting that whilst technological solutions are increasingly sophisticated (see for example the deployment of soft robots in the deep sea[8]), mapping the marine habitats is extremely complex and more immediate (and realistic) advancements could be reached through encouraging the use of more advanced and accurate models. For example, the development for the ocean of an interactive tool such as the recently launched artificial intelligence SEEA tool ARIES[9], may help to overcome these limitations and improve international comparison. Strictly related is the appropriate level of spatial disaggregation. Accounts developed at the national level may be less useful at the local level. As much of the data is collected by different country or local agencies with diverse responsibilities for environmental conservation and management, better coordination and collaboration may be needed to develop a system that serves the potential beneficiaries better and allows top-down disaggregation (from national to local scale) and bottom-up aggregation (from regional or even local scale to national scale).

Improvement to the condition analysis to reflect changing ecosystem condition due to extreme weather events, climate change, ecological recovery, restoration or various management regimes, needs further examination. Overall, a better understanding of the various ecological processes associated with the delivery of key ecosystem services, such as immobilizing heavy metals in the marine environment, nutrient remediation in the deep-sea, natural hazard mitigation of complex sea margins, and the importance of different species in influencing both the delivery and effectiveness of various ecosystem services, will enable the identification or development of more appropriate condition indicators. The implementation of reporting under national (e.g., protected areas) and international (e.g., OSPAR) policies and agreements can contribute to the provision of better condition data, for example on water quality for marine waters. The recent ONS marine accounts for the UK go in this direction by using marine protected areas, Water Framework Directive and Bathing Water Directive as condition benchmarks.

Ecosystem services are generally considered individually in accounting frameworks although they are generally provided in ‘bundles’ by a specific environmental asset, for example, saltmarshes provide flood protection, carbon

[8] https://www.nature.com/articles/d41586-021-00605-y.

[9] https://seea.un.org/content/aries-for-seea.

sequestration and storage, and fish nurseries. Moreover, the supply of certain ecosystem services is synergistic while others are antagonistic. For example, marine aggregates extraction could disturb carbon sequestration and storage in sediments. This is particularly true in the highly complex marine realm. Since trade-offs are not captured when considering ecosystem services in isolation, this practice may not give the best estimate of their provision, especially in relation to the long-term sustainability of service deliveries. Nevertheless, even considering ecosystem services provision in isolation presents challenges.

Regarding the quantification and valuation of fish and shellfish provision, achieving a better understanding of the interaction between environmental processes and human management aspects is of utmost importance. The fisheries sector is highly relevant from sustainability and governance (national and supra-national) perspectives. Whilst the quantification of the physical supply of this service in the initial UK accounts relied on robust, internationally recognised information, the valuation approach could be refined moving from a resource-rent approach based on SNA recorded information to a more fleet- and species-targeted one. The latest ONS marine accounts provide such refinement by using information disaggregated by species and fleet segment and summarising the sustainability of the sector in relation to key fish stocks. However, the valuation approach could be further improved including impacts of fishing quotas and international agreements. In this sense, and of particular importance for fish and shellfish provision, is the implementation of a governance account within the marine accounts as proposed by the SEEA Ocean Accounts Framework. Overall, a more valuable approach would be to simultaneously model links between biophysical (e.g., stock assessment, nursery grounds, food web), institutional (e.g., quotas and supra-national governance), and economic (e.g., fishing effort, costs) elements.

The importance of climate regulation services is underscored by the establishment of specific thematic climate change accounts in the SEEA EA. In the context of marine and coastal accounts, however, challenges remain regarding the effectiveness of different habitats, especially such as saltmarshes and seagrass meadows, in sequestering carbon, and the impact of changing environmental parameters. In addition, it is acknowledged, but still under research, that sediments in different regions of the shelf sea and deep sea can store different amounts of carbon (Luisetti et al., 2019). In the initial marine accounts, this was in part addressed by using conservative estimates of the carbon burial rates based on a credible range of estimates. To account for uncertainty, in fact, providing a range of physical and monetary estimates is advisable; this is the approach now taken by the ONS (2021) and accepted by the SEEA EA (2021). However, from an accounting perspective, a fundamental challenge still holds and relates to the boundaries relevant for carbon processing not consistently matching to EUNIS habitat categories.

Other coastal and marine regulating services, such as waste and nutrients remediation and natural hazard mitigation, also suffer a general lack of suitable, account-ready data and integrated approaches to complex provision. Different habitats have different pollutants retention rates and thresholds, as well as different protection capacity from hazards with diverse frequency and intensity. Therefore, these services are provided concurrently by bundles of habitats which interactions need to be physically and spatially specified. With regards to remediation of pollutants, the replacement cost approach taken in the development of the initial UK marine accounts in Thornton et al. (2019) has been also adopted in the recent ONS developed accounts. It is worth noting that a replacement cost approach has been previously used in the literature (see for example La Notte et al., 2017). However, only considering wastewater discharge as in Thornton et al. (2019) is likely to produce a considerable underestimation of the service. A more integrated approach would consider waste and nutrients from different point and diffuse sources, generating activities, costs of man-made alternatives, retention rates of different habitats for different waste and nutrient components, and diffusion models of waste and nutrients across coastal and marine habitats. Similarly, a refined quantification and valuation of natural hazard mitigation services would require to simultaneously assess the extent, position and condition of natural habitats, the economic activities and infrastructures protected, and risk modelling to precisely appraise and calibrate the assessment. The approach taken in the initial UK marine accounts suffered from lack of suitable data and relied on strong working assumptions. This has been improved in the ONS marine accounts, which make use of geographical information to estimate land values protected from flooding by saltmarshes. Nevertheless, future research challenges in accounting for pollutants remediation and natural hazard mitigation provided by the marine and coastal environment revolve around the use of bio-economic models including key characteristics of habitats coupled with social and economic attributes. On this line, improvements in condition indicators and accounts are crucial for the assessment of the actual and potential regulating services flow provision.

Overall, the quantification and valuation of regulating services provided by coastal and marine ecosystems suffer from high scientific uncertainty. Considering the utmost importance that regulating services have in mitigating the increasing adverse impacts of climate change, there is a clear need for financing more ecological research to better understand, for example, carbon sequestration and storage processes in different habitats or protection from extreme weather events provided by coastline ecosystems.

The value of cultural ecosystem services provided by coastal and marine environment could be better elicited by considering two main points. The first relates to a more accurate estimation of recreational values considering approaches which include spatial components and control variables. The second important point is how to consider other cultural services (aesthetic values, health and wellbeing, spiritual values, etc.) in the accounts. This broader class of benefits is difficult to quantify within the natural capital accounting boundaries. A suitable approach could be to extend ecosystem accounts with satellite or complementary accounts containing non-monetary indicators and monetary valuations obtained with methods not encompassed in the SEEA framework. Turner et al. (2019), for example, suggest developing a Complementary Accounts Network extending the SEEA-type accounts.

Finally, whilst the quantification and valuation of abiotic materials provision is implicit in the SNA and is usually included in natural capital asset accounts, considerations should be given to the interactions with other ecosystem services. For example, there is some evidence regarding the interaction between wind farms and the provision of finfish and shellfish and carbon storage services. It is also worth noting that some of the aggregates extracted from marine habitats are used for beach replenishment, therefore interacting with the ecosystem services provided by coastal habitats. These stock movements in different assets should be captured by the accounts to avoid double counting.

5 CONCLUSIONS

Ecosystem accounts are becoming widely recognised as a tool to collect and record data and provide information useful for policy and decision making at the national and, when using standardised data, at the international level. In this paper, we have reported the experience of the UK within the SEEA EEA (UN et al., 2014b), which, together with other experimental ecosystem accounts developed worldwide, has contributed to the development of specific Ocean Accounts as presented in the SEEA EA (UN, 2021) thematic accounts chapter. This paper critically review the empirical application of the SEEA EEA framework to the UK coastal and marine environment and contributes to the knowledge base required in the continuing development of a full set of Ocean Accounts. The paper also highlights how the Thornton et al. (2019) study contributes to inform this ongoing process, as demonstrated by the references to it in the recently published Natural Capital Accounting for the North-East Atlantic Area report (Alarcon Blazquez, 2021), and the GOAP guidelines. In addition, novel approaches and insights expanding previous experimental application of the SEEA EEA framework in the coastal and marine environment are also reported, these include the consideration of shelf sea sediments in quantifying and valuing carbon capture and storage, the potential of using replacement cost methods for the valuation of regulating services, and the complexities behind the compilation of full extent and condition accounts.

The feasibility of developing accounts will depend on the benefit provided by the additional information as compared to the cost. Innovative ways should be sought to develop information of benefit to both public and private sector activities. New technologies for remote data collection and automated data analysis, like the SEEA ARIES tool, offer potential for significant advances in ecosystem accounts analysis and information flows. New economic endeavours, such as deep-sea mining, especially in the high seas, should be monitored closely to ensure that the rise of one marine-related industry does not predispose the collapse of another. The SEEA EA now recognise the high seas as an Ecosystem Accounting Area which could be considered in the development of regional or international (even global) accounts. High seas are particularly challenging as they require agreements in place in between countries as the ecosystem services lying in those areas do not belong to anyone, or maybe more precisely belong to all. More attention needs to be given to what are called ‘Inter-services’ (see SEEA CF framework), which addresses inter-sectoral flows with environmental impacts, such as finfish discards as a result of the discards ban, or the release of stored carbon following fishing or aggregates extraction. Social and economic trends need to be monitored with an assessment of their impact on marine and coastal environments. As recognised in the SEEA EA, more research on the valuation methods that could be used within an exchange value framework, including shadow prices, is needed to account for changes in welfare and the sustainable use of the natural resources.

The data gaps faced in developing initial marine and coastal accounts for the United Kingdom in Thornton et al. (2019) were enormous, in nearly every context. Whether map images, or data on length and width of coastline, or on the condition of protective ecosystems, the paucity of useful information for accounting purposes was striking. Whilst on the one hand this implies the need to invest in more ecological research, on the other hand it highlights the inherent difficulty of mapping coastal and marine ecosystems and quantifying ecosystem services due to their dynamic nature and complex interconnections. Here advanced modelling could be helpful. Information on other less tangible services like health benefits of seaside recreation and the cultural importance of maritime heritage are also limited; even if these would not be included directly in the accounts, they could provide policy makers with a more complete understanding of the importance of marine and costal ecosystems.

Climate change will put increasing stress on our environment. Marine habitats will face warming temperatures and marine species will face the increasing threat of ocean acidification. Coastal ecosystems will be under particular stress for the projected increased frequency and intensity of storms and extreme weather events. Rising sea levels threaten to transform significant areas of the coastline worldwide. Understanding, quantifying and systematically recording the ecosystem services associated with marine and coastal habitats will be important for informing policy and management plans to deal with and enhance the resilience to climate change stress. This relatively little understood environment with strong economic links deserves far more attention for both ecological as well as economic reasons.

DOI: 10.15351/2373-8456.1145

Our Thornton et al. (2019) study has been a helpful exercise in uncovering the accounting issues we discussed here, some of which have already been picked up in the SEEA EA (UN, 2021) and in the ONS marine accounts (ONS, 2021). Several other issues still stand, that hopefully will be explored further and captured in the development, and then publication, of specific Ocean Accounting technical guidelines such as those the Global Ocean Accounts Partnership is working on. Although the experimental phase of the SEEA is now over, we might argue that countries will still have to explore how to develop Ecosystem Accounts to improve their practice and their policy uptake.

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