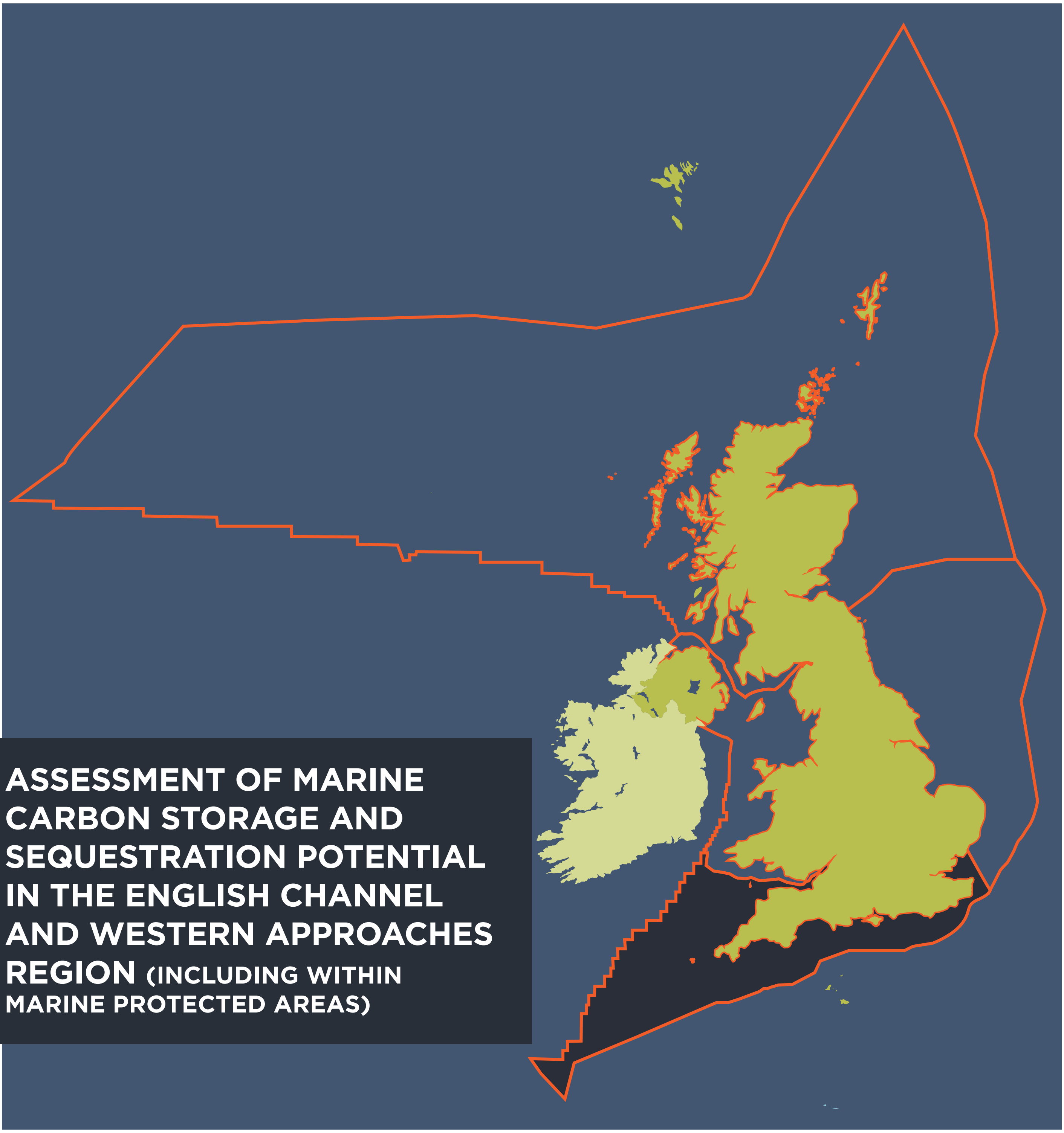
THE UNITED KINGDOM'S BLUE CARBON INVENTORY:



ASSESSMENT OF MARINE CARBON STORAGE AND SEQUESTRATION POTENTIAL IN THE ENGLISH CHANNEL AND WESTERN APPROACHES REGION (INCLUDING WITHIN MARINE PROTECTED AREAS)

The United Kingdom's Blue Carbon Inventory:

Assessment of Marine Carbon Storage and Sequestration Potential in the English Channel and Western Approaches Region (Including Within Marine Protected Areas)

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Year of publication: 2024.

Report Title	The United Kingdom's Blue Carbon Inventory: Assessment of Marine Carbon Storage and Sequestration Potential in the English Channel and Western Approaches Region (Including Within Marine Protected Areas)
Funder	WWF, The Wildlife Trusts and the RSPB

Recommended citation

Burrows, M.T., Tillin, H., Grundy, S., Smeaton, C., Austin, W.E.N., O'Dell, A. 2024. *The United Kingdom's Blue Carbon Inventory: Assessment of Marine Carbon Storage and Sequestration Potential in the English Channel and Western Approaches Region (Including Within Marine Protected Areas).* A Report to The Wildlife Trusts, WWF and the RSPB. Scottish Association for Marine Science, Oban.

Acknowledgements

We acknowledge the contributions of members of the Advisory Group to the development of this report, including Laura Pettit (Joint Nature Conservation Committee), Roger Proudfoot (Environment Agency), Colin Moffat (individual), Simon Brockington (individual), Paul Gilliland (Marine Management Organisation), Karen Robinson, Kirsten Ramsay (Welsh Government), Helen Elphink, Jack Price, Caroline Price, Marco Meloni (Crown Estate), Adele Shaw, Annie Breaden (Crown Estate Scotland), Colin Armstrong (Department of Agriculture, Environment and Rural Affairs), Jacqui Keenan, Rowan Henthorn (Isle of Man Government), Maija Marsh (Natural England) and Corallie Hunt (NatureScot).

Professor Dan Laffoley and Professor John M Baxter acted as project advisers for the production of this report.

Jo Hargreaves copy edited and proofread this report.

Assessment of Marine Carbon Storage and Sequestration Potential in the English Channel and Western Approaches Region (Including Within Marine Protected Areas): Executive Summary for Policymakers

This report was commissioned by WWF, The Wildlife Trusts and the RSPB to assess the extent, scale, distribution and potential of the current blue carbon sinks in the English Channel and Western Approaches (ECWA) Region of the UK (including parts of the Celtic Sea). The main objective was to identify the present extent and distribution of habitats, with emphasis on those that are identified as blue carbon habitats. Drawing on a previous project in the English North Sea Region (Burrows *et al.,* 2021), further aims were to evaluate the blue carbon potential of the Region by (1) estimating the quantity of carbon currently stored within these various habitats, (2) establishing the average net sequestration rate (in g C m^2/yr) and (3) estimating the potential net total sequestration (in g C/yr) for each blue carbon habitat. The focus of this series of reports has been on stores and accumulations of organic carbon (OC) as particulate material rather than inorganic carbon (IC), given the likely net production of CO_2 through the production of IC as shell material.

Carbon store densities and rates of production and storage have been combined with measures of habitat area to give estimates of total carbon stored in blue carbon habitats and their associated sediment stores. The results are intended to inform management decisions and identify opportunities to protect blue carbon ecosystems, the habitats they provide and their carbon sequestration potential. Evidence of this nature will contribute to exploration of the potential of the UK's marine protected area (MPA) network to help mitigate against the effects of climate change.

The extents of blue carbon habitats for the ECWA Region were derived from available open sources, including the EUNIS level 3 combined map from the Joint Nature Conservation Committee (JNCC), Natural England Marine Habitats and Species Open Data, and recently published estimates of OC and IC stores in surface sediments (Smeaton *et al.,* 2021).

Main Findings

- The English Channel and Western Approaches (ECWA) Region covers an area of **111,469 km^2**.

- **Carbon in long-term stores** is carbon that is locked away from atmospheric circulation for significant time periods (generally over 100 years). In total, an estimated **36.4 million tonnes (Mt) of OC in long-term stores** are found in the Region, with 98% of that total stored in the top 10 cm of seabed sediments, mostly as sublittoral mud and sand/mud seabed sediments. The remaining 2% (**0.7 Mt**) of OC is found within **coastal vegetated blue carbon habitats**, predominantly stored in the soils of coastal saltmarshes (96%) and in sediment in seagrass beds (4%). Seabed sediments are thus by far the most important habitat for carbon storage in the ECWA Region. However, it is important to note that this analysis considers only surficial sediments, which make up the top 10 cm of the seabed, and it therefore represents a fraction of the overall carbon stored in the full thickness of the seabed sediments. Coastal vegetated habitats with long-term stores (saltmarshes, maerl and seagrass beds) form only 1.0% of the total area of the Region, but contain 2% of the long-term OC stores, and account for 4% of annual accumulated OC in those stores.

- **Carbon *in short term stores*** is considered as carbon that is temporarily fixed or removed from atmospheric circulation for less significant time periods. Most of this is as living biomass: with living kelp (102,600 tC), saltmarsh vegetation (35,000 tC) and intertidal macroalgae (5,500 tC) forming the remainder.

- In this Region the marine protected areas (MPAs) – that is, Marine Conservation Zones (MCZs), Special Areas of Conservation (SACs), Special Protection Areas (SPAs) and marine areas of Sites of Special Scientific Interest (SSSIs) – cover a total area of **35,671 km^2** (the sum of designated areas inside protected areas and including overlapping designations where areas have been designated more than once), representing 32% of the ECWA Region. Long-term stores of carbon within the MPAs are estimated to hold **11.4 Mt of OC**, accounting for 32% of the total OC stores in the Region, and **33.8 Mt of IC** (see Section 2.6), accounting for 37% of the total IC stored across the Region. These values do reflect the multiple designations of some areas as MPAs and will be lower if that double counting is considered. Combining the areas covered and counting the overlapping areas only once (Burrows *et al.*, 2024c) gives a total area of 30,621 km2 covered by the MPAs in the English Channel and Western Approaches Region, such that the total area covered by any kind of protected area is 27% of the area of the Region.
- Offshore MCZs, SACs and SPAs contain the largest proportion of OC and IC in long-term stores, but inshore littoral MPAs, and notably the smaller marine portions of SSSIs, have the highest densities and rates of OC accumulation per unit area in their coastal muds, saltmarshes and seagrass beds. MPAs with predominantly rocky habitats have less OC in long-term stores and reduced OC accumulation rates relative to sediment habitats, but do support extensive kelp beds that contribute carbon to neighbouring areas of sediment.
- Annually, an estimated **1.80 Mt OC/yr** is added to **sediment stores** across the Region, predominantly within mud and sand/mud seabed sediments. **Saltmarshes and seagrass beds** store a considerably smaller fraction of this (**0.067 Mt OC/yr**, i.e., 4% of the total annual value, albeit at a higher rate per unit area), with saltmarsh soils representing 96% of the accumulation among blue carbon habitat stores.
- Growth and reproduction of algae and plants (primary producers), with subsequent losses and transport to stores in the seabed, are the primary mechanism for removal of CO_2 by the marine ecosystem in the Region. Unlike rates of plant growth, the proportion of plant and algal detritus that reaches storage over climatically relevant time periods has been little studied. Reflecting values typically adopted in ecosystem models, we used a value of 10% of plant material produced per year in the Region (see Section 3.3, Table 19: 9.5 Mt OC/yr) to predict the fraction of OC transported from living biomass and stored within seabed sediments. Based on this assumption, **0.95 Mt C/yr** (see Table 19) is thought to be added to the particulate organic carbon (POC) pool for transport and incorporation into stores.
- Production of particulate OC that may be added to sediment stores by algae and plants in the Region is dominated by **phytoplankton** (**0.91 Mt C/yr**), with much smaller fractions contributed by **kelp** (**37,900 t C/yr**), **saltmarsh plants** (**1,700 t C/yr**), **seagrasses** (**300 t C/yr**) and **intertidal macroalgae** (**1,700 t C/yr**).
- Although the analysis here is based on the best information available at the time of writing, it must be understood that values presented for sizes of carbon stores and rates of accumulation are built on critical assumptions and caveats. Carbon in seabed sediments has been considered here for only the top 10 cm of marine deposits. This has been driven by the sampling of such sediments using surface grabs and very shallow sediment cores. The full depth of coastal sediments has not been assessed, and represents a much larger store of carbon. However, carbon in surface sediments is the most recently deposited and most vulnerable to the effects of physical disturbance. Information on rates of seabed sediment accumulation is much more limited, especially compared with much higher rates in coastal vegetated habitats, which have been the focus of much recent research.
- Integrating the understanding of carbon storage provided by marine habitats into decisions relating to marine management could improve the protection provided for these habitats and enhance their capacity to act as carbon sinks. In some cases, where blue carbon habitat is covered by an existing MPA designation, management measures that have the specific objective of protecting or restoring habitats which contain such long- and short-term carbon

stores can be considered alongside primary biodiversity considerations as potential nature-based solutions (NBS) to mitigate the impacts of climate change.

• For policy considerations, a distinction may be made between “actionable” blue carbon ecosystems, for which management interventions can be applied and for which carbon markets may be developed (such as the UK Saltmarsh Code (see UK Centre for Ecology and Hydrology, 2024)), and “emerging” blue carbon ecosystems (kelp, intertidal macroalgae and the significant amounts of carbon in long-term stores within marine sediments) where a precautionary approach to management is needed while uncertainties around carbon fixation and management issues may require addressing.

• The most widespread threat to OC in long-term stores is physical disturbance of the seabed (surface abrasion, and subsurface penetration and disturbance), which arises from a range of human activities. The predominant anthropogenic source of physical disturbance is demersal fishing, which occurs throughout the Region, but deployment of moorings and installation of offshore energy platforms and associated cables and pipelines also disturb the seabed. However, for subtidal sediments that are also subject to natural background disturbance the net effects are highly uncertain.

• The impacts of increased atmospheric CO_2 concentrations, such as ocean acidification, are likely to have mixed effects on blue carbon capture and storage, with a negative impact on calcareous organisms (i.e., those that build carbonate skeletons) and carbonate sediments, but potential benefit for photosynthetic species (e.g., kelp, intertidal algae and other macrophytes).

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Acronyms and Abbreviations

ASSI	Area of Special Scientific Interest
BAP	Biodiversity Action Plan
BGS	British Geological Survey
CCW	Countryside Council for Wales
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CSI	Community Seagrass Initiative
Defra	Department of Environment, Food and Rural Affairs
DOM	Dissolved organic matter
EA	Environment Agency
ECWA	English Channel and Western Approaches
EECMHM	Eastern English Channel Marine Habitat Map
EEZ	Exclusive Economic Zone
EMS	European Marine Site
EUNIS	European Nature Information System
GIS	Geographic information system
HCRP	Habitat Compensation and Restoration Programmes(s)
HPMA	Highly Protected Marine Area
HRA	Habitats Regulations Assessment
IC	Inorganic carbon
IFCA	Inshore Fisheries and Conservation Authority
JNCC	Joint Nature Conservation Committee
MCZ	Marine Conservation Zone
MDS	Multidimensional scaling
MMO	Marine Management Organisation
MNR	Marine Nature Reserve
MPA	Marine Protected Area (general term for an area designated for protection)
MR	Managed realignment

Mt	Million tonnes
NBS	Nature-based solutions
NE	Natural England
OC	Organic carbon
OM	Organic matter
PAH	Polycyclic aromatic hydrocarbon
PIC	Particulate inorganic carbon
POC	Particulate organic carbon
POM	Particulate organic matter
PPMLC	Port of Plymouth Marine Liaison Committee
RSPB	Royal Society for the Protection of Birds
RTE	Regulated tidal exchange
SAC	Special Area of Conservation
SMP	Shoreline Management Plan
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
TCE	The Crown Estate
TECF	Tamar Estuaries Consultative Forum
TWTs	The Wildlife Trusts
UK	United Kingdom
USA	United States of America
VNAZ	Voluntary No Anchor Zone
WAG	Wembury Marine Conservation Area Advisory Group
WFD	Water Framework Directive (European Union)
WWF	World Wildlife Fund

1 Introduction to the UK Blue Carbon Assessment

1.1 Background and rationale

This series of reports, commissioned by WWF, The Wildlife Trusts and the RSPB, takes a habitat-orientated approach to assess marine carbon in long-term stores in UK seas, including such stores within marine protected areas (MPAs). 'Blue carbon' ecosystems are broadly considered here to be all those ecosystems that make significant contributions to the fixation and storage of carbon (beyond the narrow definition of coastal vegetated habitats, i.e., saltmarshes, seagrasses and kelp forests, and mangroves in tropical regions). Such habitats present in the area are identified and reviewed with regard to their potential to fix and store (i.e., sequester) carbon, focusing on the ecology of the key carbon-fixing and habitat-forming species, the dynamics of physical habitats, and quantitative estimates of carbon in short-term (less than 100 years) and long-term (over 100 years) stores, and of rates of carbon fluxes. The report considers exports from and imports to these habitats, and threats to stores and fluxes, as well as the potential for restoring lost habitats to improve carbon storage and sequestration. Habitat reviews have identified sources of information on known and predicted habitat extents and combined these into maps and associated GIS data files. This collected information is used to synthesise an ecosystem-scale carbon inventory of the key rates and ultimate sequestration capacity of each habitat.

This project has been carried out in distinct phases divided into regional seas, including the English Channel and Western Approaches Region (this report), the Irish Sea and Welsh Coast Region (Burrows *et al.*, 2024a) and the Scotland Region (Burrows *et al.*, 2024b). These reports are combined with the earlier assessment of carbon capture and storage in the English North Sea Region (Burrows *et al.*, 2021) and synthesised into a UK-scale assessment (Burrows *et al.*, 2024c). The resulting synthesis and assessment of carbon sequestration capacity aims to establish a baseline that will help to guide conservation and restoration efforts.

Assessment of carbon sequestration and storage follows the sequence of combining estimates of area with habitat-specific rates of production, loss, import and export of carbon, and thence area-specific rates of sequestration, to give area-integrated estimates of the total amount of carbon locked away by biological activity in the coastal zone. The approach follows that of successful and widely used audits of carbon storage and sequestration processes, primarily the review of Scotland's blue carbon stores (Burrows *et al.,* 2014) and more recently the assessment of carbon capture and storage in the English North Sea Region, which preceded this report (Burrows *et al.,* 2021). Within both projects, further partitioning of blue carbon in short- and long-term stores and processes among MPAs informed the role of designated areas in protecting the capacity of coastal and offshore habitats to sequester carbon (Burrows *et al.,* 2017).

Primary information on the area and location of blue carbon habitats and associated long-term stores in sediment has been compiled from existing habitat maps, building on the data sources used in recent reviews of blue carbon by Natural England (Gregg *et al.,* 2021) and Defra/Cefas (Parker *et al.,* 2021) for England and Wales, incorporating the addition of primary data from archived sediment samples to improve the spatial resolution of sediment types, and the contribution of MPAs to the protection of carbon in long-term stores (Flavell *et al.,* 2020). Where observed data do not give the extent of habitats or patterns of carbon stored directly, estimates of carbon density and total amounts stored have been made from the predictions of statistical models of habitat suitability (Burrows *et al.,* 2018; Kettle *et al.,* 2020; Wheater *et al.,* 2020) and carbon types stored (Diesing *et al.,* 2017; Smeaton *et al.,* 2021) based on relationships between known records and data layers for physical and biological drivers of species distributions and carbon stored by sediments. Such estimates have been reported for the whole region and for focal areas, including MPAs. Although they have lower confidence levels than direct observations, such models highlight where natural processes result in hotspots for carbon storage, and where these hotspots may be especially susceptible to remobilisation and oxidation through anthropogenic activity such as trawling and renewable energy developments, as well as to natural processes such as wave-driven sediment resuspension and river-derived plumes.

Carbon budgets and long- and short-term carbon stores for each blue carbon habitat described in this report use the available information on extent and biomass. Net sequestration capacity (in g C/m^2/yr) of each habitat depends on the balance of processes of net production as reported in the relevant habitat review sections, which has been synthesised for each regional assessment as well as the cumulative analysis.

The occurrence and extent of blue carbon habitats and long-term sediment stores in MPAs, including Nature Conservation Marine Protected Areas (NCMPAs) in Scotland, Marine Conservation Zones (MCZs) in England, Wales and Northern Ireland, Marine Nature Reserves (MNRs) in the Isle of Man, Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) in all devolved administrations, as well as Sites of Special Scientific Interest (SSSIs) with areas below the highest astronomical tide mark in all devolved administrations (see Figure 1), are evaluated and combined with existing work on the contribution of habitats within MCZs (Flavell *et al.,* 2020). This regional report is the second in a series of four, and gives a breakdown of short- and long-term carbon stores and sequestration capacity within 101 MPAs and 221 SSSIs in the English Channel and Western Approaches Region.

Plans to implement Highly Protected Marine Areas (HPMAs) are at the pilot stage in the Region. In England, in response to the Benyon Review (Benyon *et al.,* 2020), the UK Government outlined recommendations for HPMA selection and approaches. This was followed in 2022 by the publication of a policy paper outlining the overview of the process, plans for management and a consultation process which has received over 900 responses (UK Government, 2022). The designation of MPAs is a devolved process, so English and Scottish designations proceed separately. In England, five sites were included in the consultation process, and plans to summarise consultation responses were received in early 2023. At the time of writing this report, several HPMA sites in England have been designated as pilot projects, and in Scotland HPMAs are planned to be designated in 2026. They have therefore not been included in the present report.

1.2 Project objectives

The main purpose of this project is to ascertain and assess the extent, scale, distribution and potential of the current blue carbon sinks in the UK (saltmarsh, kelp forests, seagrass beds, biogenic reefs and seabed sediments). The aims of the project were as follows:

- to review the current extent and distribution of each blue carbon habitat
- to estimate the quantity of carbon currently stored within each blue carbon habitat
- to establish the average net sequestration rate(in g C/m^2/yr of organic carbon) of each blue carbon habitat
- to estimate the potential net sequestration (in g C/yr) of each blue carbon habitat
- to estimate the quantity of carbon stored in and potential carbon sequestration rates of UK and Isle of Man MPAs (NCMPAs, MCZs, MNRs, SACs, SPAs, SSSIs and ASSIs)
- to further develop analytical methodology and approaches that can be refined on an ongoing basis.

The results are intended to help to inform management decisions and identify opportunities to enhance the biodiversity and carbon sequestration potential of the seabed. Evidence of this nature will contribute to exploration of the potential of the UK's MPAs to help to mitigate the effects of climate change by capturing and storing carbon.

The project is split into regional phases. This report covers the English Channel and Western Approaches (ECWA) Region. Maps of major long- and short-term carbon stores and the associated blue carbon habitats are presented throughout this report. They include regional maps of sediment organic carbon (OC) density (see Figure 5) and inorganic carbon (IC) density (see Figure 6), as well as detailed maps of selected habitats, namely seagrass beds and kelp beds (see Figure 20 and Figure 21, respectively), for Plymouth Sound as a case study area.

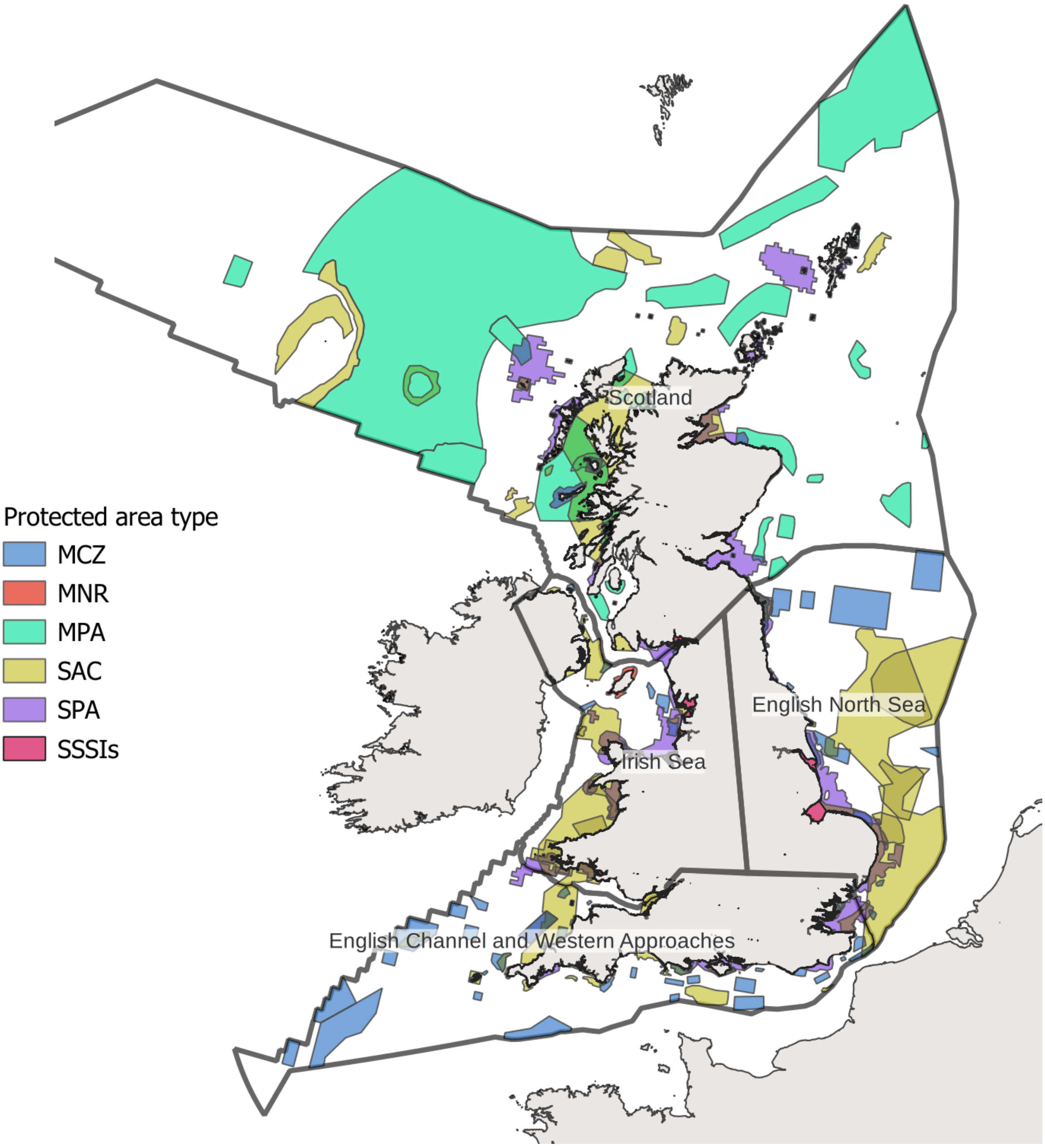


Figure 1. The UK's marine protected areas, showing the four UK Blue Carbon Inventory Regions. Protected area types include Marine Conservation Zones (MCZs) in England and Wales, Marine Protected Areas (MPAs) in Scotland, Marine Nature Reserves (MNRs) in the Isle of Man Territorial Seas, and Special Protection Areas (SPAs) (including offshore areas) and Special Areas of Conservation (SACs) in all devolved administrations. Sites of Special Scientific Interest (SSSIs) and Areas of Special Scientific Interest (ASSIs) are not shown, but are predominantly coastal.

1.3 GIS methods

Standardised methods, outlined in this section, were used for each of the regional reports that make up this series, adopting and developing the methods used for the report on blue carbon in the English North Sea Region (Burrows *et al.,* 2021).

1.3.1 Data sources for habitats and marine protected areas (MPAs)

For a first evaluation of the blue carbon habitats of the ECWA Region (see Section 2), biotope map data were downloaded, inspected and assessed. The sources of habitat information that were used are listed in Annex 1. Biotope and EUNIS codes for polygons were assigned to blue carbon habitats (see Table 1 for the key to codes and habitat assignments).

After merging the habitat datasets, the marine protected area shapefiles (MPAs – used for Nature Conservation MPAs in Scotland, MCZs, MNRs, SACs, SPAs and SSSIs clipped to each Region to address any marine protected areas overlapping between Regions) were separated into polygons. Marine protected area shapefiles were used to clip sections of the merged layer of section overlap and then exported for area calculations for habitat categories. Extents (in km^2) were estimated for all marine protected area types by summing the areas of their component polygons in GIS (QGIS, Version 3.2.0, QGIS.org, 2024), and after reading shapefiles in the open-source software ‘R’ (R Core Team, 2022).

1.3.2 Carbon in short- and long-term stores in MPAs

Carbon in short- and long-term stores was estimated from existing spatial data for the entire Region and for individual MPAs. Organic and inorganic carbon densities as gridded (raster) data were interpolated from British Geological Survey (BGS) samples onto 300-m grid maps taken from Smeaton *et al.* (2021) (supplementary material), downloaded from the links specified within the paper. Carbon density maps (see Figures 5 and 6) covered most of the UK’s Exclusive Economic Zone (EEZ), and were cropped to the ECWA Region. For each MPA (NCMPAs, MCZs, MNRs, SACs, SPAs and SSSIs), values were extracted from these gridded datasets by re-projecting MPA shapefiles to the same coordinate system as the carbon density maps (ETRS89) and selecting those grid cells that lay inside the MPA polygons using the 'extract’ function of *raster* library in R (Hijmans, 2022). Total carbon (OC and IC) for each Region and for each MPA was calculated as the product of average carbon density per unit area (in g C/m^2) and the total area of the Region or MPA.

1.3.3 Carbon accumulation from habitat-specific assimilation rates in MPAs

As in previous assessments (Burrows *et al.,* 2014, 2017), area-specific process rates (in g C/m^2/yr) for carbon fixation by algae and plants, the rates of import and export of particulate organic carbon (POC), production of IC as shell material and other rates were derived from literature reviews for each component habitat. To estimate the area-specific rates and total carbon accumulation for each of the MPAs, the Natural England Marine Habitats and Species data layer (see Annex 1) was first cropped to the ECWA Region, and the intersection between this layer and the MPA layer was calculated in GIS (QGIS 3.2.0). That process allowed the area of each habitat type (based on its EUNIS 2012 Level 3 classification code) per MPA to be calculated. The sum of the products of component habitat areas and habitat-specific process rates (for OC accumulation) gave the total accumulation of OC for that MPA, and the average rate of accumulation when divided by the area of the MPA (see Section 3.2.4).

2 Blue Carbon Ecosystems of the English Channel and Western Approaches Region

This section reviews the carbon production, storage and sequestration potential for each blue carbon habitat, based on the existing literature and data. The glossary (see Section 6) provides definitions of the technical terms used here.

2.1 Environmental setting of the ECWA Region

Here blue carbon habitats are described and reviewed in terms of their carbon production, sequestration and storage capacities, first across all regions of the UK and then in the context of the ECWA Region. Process rate estimates are based on the existing literature and available data. Data specific to the ECWA Region are presented following a general review of the relevant ecology and status of each habitat in the UK. Where available, recent reports that have estimated carbon storage, sequestration and short- and long-term stores for UK coastal and marine habitats (Burrows *et al.,* 2014, 2017, 2021; Armstrong *et al.,* 2020; Gregg *et al.,* 2021) (see Table 9) are used as primary sources.

2.1.1 English Channel

The English Channel is a relatively shallow shelf sea lying between England and France. From its entrance in the west between Land's End and the north coast of Brittany, where it is *c.* 160 km wide, it progressively narrows eastward until it reaches the Dover Strait, where it is only 35 km wide. The ECWA study area solely covers the part of the Channel within the UK's EEZ. The depth profile of the Channel decreases from west to east, as a result of which the shallower eastern parts are subject to more wave action, whereas the deeper western parts experience a summer thermocline. The area is tidally dominated, with highest wave amplification in the eastern English Channel and with mean tidal currents of more than 25 cm/s. These oceanographic characteristics influence the ecology of both areas, with similar communities present in both on specific substrates, but with some differences based on species' different ecological tolerances. The predominant habitats are sedimentary. However, within the English Channel, outcropping reef habitats provide habitat for a wide range of attached epifauna and mobile species, and where the rock is soft, chalk and limestone boring species such as piddocks occur. These habitats provide some carbon storage (within the organisms), but this does not represent a long-term carbon store. Chalk habitats formed from marine organisms provide a long-term store of IC. The present-day seafloor sediments comprise both biogenic autochthonous deposits and deposits resulting from the reworking of available pre-existing long-term sediment stores, such as incised-valley fills and sand banks (Reynaud *et al.*, 2003). The western and eastern Channel areas are separated by an area characterised by very high tidal current velocities and by an almost total lack of sandy cover over the boulder pavement that underlies the eastern Channel area (Reynaud *et al.,* 2003). The surficial sediments are currently mobile throughout the whole shelf area, except for the pebbly lag deposits of the central Channel (Reynaud *et al.,* 2003).

Western English Channel

The western half of the English Channel extends from a north–south line between the Isle of White and Cherbourg westwards to the tip of the Cornish peninsula. The water masses in this region are defined as Boreal/Lusitanian and contain some warm water species at the northernmost limit of their range. Species typical of the open-waters seabed habitats penetrate the western half of the English Channel (Glemaréc, 1973). The open seabed and channel habitats typically contain sediment and rock biotopes (although the rock may be covered with sediment in some areas) (Diesing *et al.,* 2015). Rivers supply large quantities of OC to sediments in the Bristol Channel, which allows significant quantities of OC to be trapped (Smeaton *et al.,* 2021). Annex I reefs (defined by the European Environment Agency as ‘natural habitat types of community interest whose conservation requires the designation of special areas of conservation’) occur where rocky areas or concretions made by marine animals arise from the surrounding sea floor. For rock descriptions the reader is referred to Diesing *et al. (*2015).

The western Channel alternates between warmer and cooler states depending on the position of the Boreal/Lusitanian boundary north or south of the Western Approaches. These changes affect the distribution of temperature-sensitive species in the Channel (James *et al.,* 2007).

Large-scale benthic characterisation studies of the English Channel were initiated by Norman Holme and his colleagues (Holme *et al.*, 1961). Between 1958 and 1959 they sampled 167 stations along the southern coast of England, extending from Penzance to Folkstone (Holme, 1961). Fifty of these sites were revisited in July 2006, across a similar spatial range (Hinz *et al.,* 2011). Studies of the central English Channel include those by James *et al. (*2007), Coggan *et al.* (2009) and Dauvin *et al.* (2015).

Eastern English Channel

The eastern English Channel extends from the north–south line between the Isle of White and Cherbourg eastward as far as the Dover Strait, a distance of about 200 km. It has a maximum depth of 60–70 m in the centre of the channel between the Isle of Wight and Cherbourg. The seabed rises gently to the east, reaching a depth of more than 40 m in the centre of the Dover Strait, and it also rises gently to the French and English coasts. The eastern half of the English Channel is considered to be a transition area between the Atlantic Ocean and the North Sea (James *et al.,* 2007). This region corresponds to the eastern limit of Boreal/Lusitanian water masses and the easternmost limit of the range of *Caryophyllia smithii* (Devonshire cup coral) in the Channel, based on the findings of Cabioch and Gentil (1977).

Tidal current velocities expressed as depth-averaged mean spring tidal currents range from less than 0.5 m/s to over 3 m/s. Within the main body of the channel there is a zone of relatively high-velocity tidal currents between Cherbourg and the Isle of Wight. The strong tidal currents in this area winnow away fine sediments, and as a result in the eastern English Channel and coastal margins, areas of gravel and sandy gravel are dominant, with movement and transport of fine sediment and sand to the west and east of this zone and north along the coastal margins.

2.1.2 Western Approaches and Celtic Sea

The Western Approaches and Celtic Sea lie to the west and north of the tip of the Cornish peninsula, respectively. The Celtic Sea is a seasonally stratified, temperate sea that forms part of the north-west European continental shelf. Previous studies of its surface waters have shown that it acts as a net sink of atmospheric CO_2 with a net flux of carbon out of the shelf seawater column, through organic matter export to sediments, or advective exchange with the open ocean (Humphreys *et al.,* 2019). Celtic Sea sediments could form part of this carbon sink, as although they predominantly contain sandy material there is also some organic matter accumulation (Suykens *et al.,* 2011; Diesing *et al.,* 2017).

The Western Approaches is a deeper area than the English Channel, with a seabed depth of more than 100 m across the whole area; the seabed gradually slopes westerly to 200 m, its depth increasing at the edge of the continental slope. Much of the seabed is composed of mixed sand and gravel, with muddy sand being more prevalent in northern parts (Jones *et al.,* 2004). Water masses are defined as Lusitanian (Dinter, 2001). Much of the sea floor area is covered with a thin layer of sediments, mainly sands and muds. In the northern part of the region there are some areas of sandy mud and very small areas of slightly gravelly sandy mud (Jones *et al.,* 2004).

In the Southwest Approaches study area, there is a region characterised by a submarine canyon system (Davies *et al.,* 2014). Submarine canyons and trenches act as depocentres by topographically channelling organic matter, and they may act as conduits transporting sediment and organic matter from the continental shelf to the deep sea (Thurber *et al.,* 2014). They can be areas of enhanced production and diversity as a result of organic matter accumulation (Davies *et al.,* 2014, and references therein). Continental slopes, canyons and deep-sea fans are thought to be the main sinks for OC (de Haas *et al.,* 2002).

Soft-sediment habitats dominate the canyons, with areas of coral garden and cold-water coral reefs. *Desmophyllum pertusum* reef and *Madrepora oculata* with associated mobile and sessile attached species are found on the flank of the Explorer Canyon. Areas also occur with a low-lying coral framework of *D. pertusum* that is predominantly dead, but with small live colonies. A typical reef rubble habitat is characterised by coral fragments as a biogenic gravel inhabited by squat lobster and ophiuroids. Areas of mud and muddy sand are characterised by sea pens and anemones.

A distinct topographical feature is the Haig Fras seamount, a granite intrusion that measures approximately 15 km long and 5 km wide. Boulders and cobbles are present, embedded in sediment at the base of the shoal. Habitats identified on the seamount include high- and moderate-energy circalittoral rock with jewel anemones and Devonshire cup corals, as well as cup, erect and branching sponges (Rees *et al.*, 2020).

2.1.3 Water column processes

Carbon dioxide may be dissolved directly from the atmosphere into the water column, or it may be respired by organisms within the water column. Organic carbon is fixed within marine organisms and excreted. As particles sink through the water column, they are stripped of their easy-to-digest (labile) compounds, releasing nutrients. This process, termed the biological pump, both sequesters atmospheric carbon and releases nutrients that eventually fuel production. Most of the carbon that sinks below 1,000 m is respired in the water column prior to its deposition on the sea floor, leaving only 1% of the carbon fixed at the surface estimated to be deposited on the sea floor (Lutz *et al.,* 2007); thus most of the carbon fixed at the surface is not exported into the deep ocean. The quantity of carbon from the surface water decreases exponentially with increasing water depth (Martin *et al.,* 1987), although the rate of decline is location specific. This flux of particles out of the surface waters provides a pathway for carbon capture from the atmosphere and its transfer to the shelf seabed and the deep sea.

Organic matter plays an important role in productive shelf seas and their contribution to carbon cycles. Dissolved organic matter (DOM) and particulate organic matter (POM) dynamics follow a seasonal cycle in the Celtic Sea (Davis *et al.,* 2019). The quantity of OC is largest during the spring phytoplankton bloom and lowest in autumn. Downward fluxes are dominated by POM during bloom events and by DOM during the stratified summer. In terms of partitioning, 92–96% of OC is in the DOM pool throughout and has potential for off-shelf export of carbon during winter mixing (Davis *et al.,* 2019).

2.2 Habitat extent and distribution

The primary data source used for deriving estimates for habitat extents in the Region was the Natural England Marine Habitats and Species Open Data (see Annex 1. Sources for Habitat Data). This dataset covers most of the seabed in the ECWA Region. It includes high-resolution polygon data at scales that allow the intersection of habitats with MPA boundaries to determine the extent of habitats within each MPA. This analysis permits scaling up of habitat-specific carbon stores and sequestration rates to whole protected areas and the entire ECWA Region itself. Total extents of the main habitat types for the ECWA Region are shown in Table 1.

Table 1. Extents of seabed habitats (in km^2 and as percentage area) in the English Channel and Western Approaches Region derived from Natural England Marine Habitats and Species Open Data supporting the report on carbon storage by habitat for Natural England. Extent values refer to areas where seabed habitats have been mapped. Unmapped areas for habitats account for differences between totals for different types of designations given here and those given elsewhere.

		Area (km²)					Percent area			
		All	MCZ	SAC	SPA	SSSI	MCZ	SAC	SPA	SSSI
EUNIS name										
Littoral habitats - Physical										
Littoral rock and other hard substrata	A1	58.9	20.9	24.9	23.6	35.6	35%	42%	40%	61%
Infralittoral rock and other hard substrata	A3	514.1	100.0	212.6	110.9	49.7	19%	41%	22%	10%
Littoral coarse sediment	A2.1	18.6	3.4	2.9	6.5	7.8	18%	15%	35%	42%
Littoral sand and muddy sand	A2.2	134.9	25.5	80.5	79.6	82.7	19%	60%	59%	61%
Littoral mud	A2.3	389.7	171.2	179.6	311.0	304.6	44%	46%	80%	78%
Littoral mixed sediments	A2.4	21.4	2.0	10.5	15.0	14.7	9%	49%	70%	69%
Littoral habitats - Biogenic										
Coastal saltmarshes and saline reedbeds	A2.5	121.5	14.6	61.1	35.5	35.2	12%	50%	29%	29%
Littoral sediments dominated by aquatic angiosperms	A2.6	9.9	0.2	4.6	11.5	8.7	2%	46%	117%	88%
Littoral biogenic reefs	A2.7	3.2	0.3	1.7	2.1	2.2	10%	53%	65%	69%
Features of littoral sediment	A2.8	0.9	0.1	0.4	1.0	0.9	9%	48%	104%	96%
Sublittoral habitats										
Sublittoral rock and other hard substrata	A4	3505.4	992.8	1383.2	141.0	8.2	28%	39%	4%	0%
Sublittoral sediment	A5	618.7	81.6	256.4	61.6	22.5	13%	41%	10%	4%
Sublittoral coarse sediment	A5.1	15194.3	3540.6	3051.0	621.2	7.3	23%	20%	4%	0%
Sublittoral sand	A5.2	69719.8	11674.0	3346.8	2176.9	108.8	17%	5%	3%	0%
Sublittoral mud	A5.3	9300.3	1211.8	187.1	527.2	40.6	13%	2%	6%	0%
Sublittoral mixed sediments	A5.4	4280.9	769.5	373.6	403.2	28.0	18%	9%	9%	1%
Angiosperm communities in reduced salinity	A5.5	27.3	3.6	19.4	22.2	1.9	13%	71%	81%	7%
Sublittoral biogenic reefs	A5.6	130.1	46.6	76.0	45.1	0.0	36%	58%	35%	0%
Deep seabed	A6	1376.3	329.6	0.0	0.0	0.0	24%	0%	0%	0%
Deep-sea sand	A6.3	82.3	67.9	0.0	0.0	0.0	82%	0%	0%	0%
Deep-sea mud	A6.5	362.8	70.5	0.0	0.0	0.0	19%	0%	0%	0%
Totals		**105871.2**	**19126.8**	**9272.1**	**4595.2**	**759.5**				
			18%	9%	4%	1%				

2.3 Intertidal and subtidal macroalgae

2.3.1 Intertidal species

Background and UK context

Large canopy-forming fucoids are likely to make the greatest *intertidal* contribution to carbon production and loss. Based on habitat suitability modelling this macroalgal group can be found throughout the UK (Yesson *et al.,* 2015), with records of seven fucoid species being present in the Region, namely *Pelvetia canaliculata*, *Fucus spiralis*, *F. vesiculosus*, *F. serratus*, *Ascophyllum nodosum*, *Halidrys siliquosa* and *Himanthalia elongata*. There has been a general assumption that intertidal macroalgae have lower productivity than subtidal macroalgae (i.e., kelp) (Mann, 2000). However, a review of the literature suggests that intertidal fucoids can be highly productive, with values in the range of 4–1,800 g C/m^2/yr (Lewis *et al.,* 2020). UK estimates of primary productivity are only available for *F. vesiculosus*, *F. serratus* and *A. nodosum*, and are based on data collected from mid and north Wales. Rates of primary production varied across seven study sites for all three species; primary productivity of *F. vesiculosus* was in the range of 166–946 g C/m^2/yr (mean ± SE, 430±106 g C/m^2/yr), that of *F. serratus* was 222–958 g C/m^2/yr (611±124 g C/m^2/yr) and that of *A. nodosum* was 16–70 g C/m^2/yr (49±10 g C/m^2/yr) (Lewis, 2020). The latter values are considerably lower than those previously reported for *A. nodosum* (90–935 g C/m^2/yr) (Brinkhuis, 1977; Lamela-Silvarrey *et al.,* 2012), although this probably reflects differences in how individual plants were defined. The UK study conducted by Lewis (2020) in Wales followed Baardseth (1970) and defined an individual plant as a single shoot arising from a holdfast, whereas other studies have defined a single plant as all shoots arising from a holdfast. The site-level variability was not related to differences in wave exposure, as although the sites covered a wave exposure gradient there was no consistent relationship between this and rates of primary production (Lewis, 2020). There have been no published estimates of primary productivity for the other fucoid species in the UK, but such estimates are available from Spain for *F. spiralis* (182.5 g C/m^2/yr, Niell, 1977), *Himanthalia elongata* (989.2 g C/m^2/yr, Niell, 1977) and *Pelvetia canaliculata* (351 g C/m^2/yr, Lamela-Silvarrey *et al*., 2012), and from Denmark for *Halidrys siliquosa* (5.4 g C/m^2/yr, Pedersen *et al.,* 2005). Estimates of fucoid biomass are again restricted to *F. vesiculosus*, *F. serratus* and *A. nodosum*. Values were in the range of 358–634 g C/m^2 (mean ± SE, 536 ± 29 g C/m^2) for *F. vesiculosus*, 241–1,213 g C/m^2 (659±127 g C/m^2) for *F. serratus* and 696–1,649 g C/m^2 (1,033±134 g C/m^2) for *A. nodosum* (Lewis, 2020). Again these values were derived from between seven and nine sites in mid and north Wales.

Information on fucoid detrital production is limited, with information only available for *F. vesiculosus*, *F. serratus* and *A. nodosum*, based on data collected in mid and north Wales. Fucoids lose biomass via three pathways, namely chronic erosion of blade material (including that caused by grazing), whole plant dislodgement and seasonal senescence of reproductive receptacles. Estimates of fucoid detrital production are based on dislodgment and receptacle senescence, and are therefore probably conservative. Whole plant dislodgement ranged from 79–375 g C/m^2/yr (mean ± SE, 148±43 g C/m^2/yr) for *F. vesiculosus* to 18–636 g C/m^2/yr (215±91 g C/m^2/yr) for *F. serratus* and 41–390 g C/m^2/yr (248±57 g C/m^2/yr) for *A. nodosum* (Lewis, 2020). Based on data collected from one site in mid Wales, receptacle senescence contributed an additional 229, 153 and 139 g C/m^2/yr of detrital material from *F. vesiculosus, F. serratus* and *A. nodosum*, respectively. Taken together, detrital production by *F. vesiculosus* contributes on average 377 g C/m^2/yr, that by *F. serratus* contributes 368 g C/m^2/yr and that by *A. nodosum* contributes 387 g C/m^2/yr. These conservative estimates of detrital production are comparable to the amount of detrital material released by *Laminaria hyperborea* (see section 2.3.2). If fucoids lose a similar percentage of biomass via chronic erosion to kelp (*c.* 20%) (Pessarrodona *et al.,* 2018) this would mean that they contribute, on average, approximately 452 g C/m^2/yr. Given that *Himanthalia elongata* and *Halidrys siliquosa* have restricted distributions, and *F. spiralis* and *P. canaliculata* are smaller than the other canopy-forming species, it is likely that *F. vesiculosus*, *F. serratus* and *A. nodosum* contribute the most to intertidal macroalgal carbon production and loss (Burrows *et al.,* 2021).

ECWA Region

Habitat suitability modelling for intertidal fucoid algae in the Region has found that the majority of the coastline is suitable for *Pelvetia canaliculata*, *Fucus spiralis*, *F. vesiculosus*, *F. serratus*, *Ascophyllum nodosum*, *Halidrys siliquosa* and *Himanthalia elongata* (Yesson *et al.,* 2015). There are also records of the invasive species *Sargassum muticum* occurring in some regions of the coastline (Raoux *et al.,* 2021). A review of studies of the productivity of intertidal macroalgae found values in the range of 4–1,800 g C/m^2 (Lewis, 2020). Values for productivity, biomass and carbon storage by the Fucales in the Region follow those for the whole UK, as described earlier. Summaries of the extent, productivity and biomass of these species are presented in Table 2.

Table 2. Intertidal macroalgae habitat extent and rates of carbon accumulation used for the English Channel and Western Approaches Region. Carbon sequestration is measured as a proportion of the production which is released as detritus annually and exported to sediment stores, and ultimately added to long-term carbon stores. Average carbon density and annual rates of production used in Region estimates are shown in bold type.

ECWA region area	111469							***Organic carbon***				
Habitat	Extent (km²)	Component area (km²)	Stock (1000 tC)	Stock (g C/m²)			Production rate (g C/m²/yr)			production (1000t C/yr)	Outflux (1000t C/yr)	Source
				min	max	avg	min	max	avg			
Intertidal macroalgae	45.1	45.1	5.5	85	160	122	125	727	378	17.1	1.7	This report
	45.1	45.1	6.1			134 [1]						Walker 1953; Burrows et al 2014
Intertidal rock	58.9	58.9										Habitat Extent Totals
				Stock (g C/m²)			Production rate (g C/m²/yr)					
Species: whole plants				min	max	avg	min	max	avg			
Fucus vesiculosus				358	634	536	166	946	430			Lewis 2020
Fucus serratus				241	1213	659	222	958	611			Lewis 2020
Ascophyllum nodosum				696	1649	1033	20	70	49			Lewis 2020
Ascophyllum nodosum							90	935				Brinkhuis 1977
Fucus spiralis									183			Habitat Review
Himanthalia elongata									989			Habitat Review
Halidrys siliquosa									5			Habitat Review
Average				**432**	**1165**	**743**	**125**	**727**	**378**			
Species: detritus							min	max	avg			
Fucus vesiculosus - all									377			Lewis 2020
Fucus serratus									368			Lewis 2020
Ascophyllum nodosum									387			Lewis 2020
Stock estimates based on biomass measurement												Burrows, unpublished data

2.3.2 Kelp

Background and UK context

Large stipitate canopy-forming brown algae within the order Laminariales are referred to as kelps. The dominant kelps in the UK are: *Laminaria hyperborea* (Gunnerus) Foslie, 1884; *Laminaria digitata* (Hudson) J.V. Lamouroux, 1813; *Saccharina latissima* (Linnaeus), C.E. Lane, C. Mayes, Druehl & G. W. Saunders, 2006; *Alaria esculenta* (Linnaeus) Greville, 1830; and *Saccorhiza polyschides* (Lightfoot) Batters, 1902 (O'Dell, 2022). The dominant foundation kelp species along most of the UK coastline is *Laminaria hyperborea* (Smale *et al.,* 2020).

ECWA Region

There have been observations of the warm-tolerant species *Laminaria ochroleuca* occurring in the ECWA Region (Smale *et al.,* 2014), but to date the extent of the species and its impacts on carbon sequestration and storage both in the Region and nationwide remain unclear (Schoenrock *et al.,* 2019; Frontier *et al.,* 2022). The majority of habitat suitable for rocky intertidal and subtidal species is in the south-west; the benthic topography of large parts of the south-east is unsuitable for kelps and other attached macroalgae, largely due to the lack of stable and suitable rock habitat (James *et al.,* 2007). The non-native kelp species *Undaria pinnatifida* is also establishing on the lower shore in places in Dorset, Devon and Cornwall.

The extent of kelp habitat in the Region was estimated from a habitat suitability model, further details of which can be found in the English North Sea Blue Carbon Report (Burrows *et al.,* 2021). The model is based on relationships between recorded presence and absence of kelp in Joint Nature Conservation Committee (JNCC) Marine Nature Conservation Review surveys and four environmental predictor variables, namely wave fetch, depth, water column chlorophyll a concentration (from satellite ocean colour data) and sea surface temperature. Given the known limitations on kelp habitats, primarily the presence of suitable rocky habitat at depths suitable for growth, the habitat extent and consequent estimates of store size and sequestration capacity are likely to be upper limits. Values used for sequestration rates were derived from the literature and from averages of published rates documented by Burrows *et al.* (2021), and are presented in Table 3. The total organic carbon in living kelp (102.6 kt) was estimated from a kelp biomass model using an average organic carbon density (60 g C/m^2) over the predicted habitat extent of 1141 km^2. Total production of organic carbon was derived from an average of reported values of area-specific production rates (332 g C/m^2/yr; see the lower part of Table 3) and total predicted habitat extent (1141 km^2). 'Outflux' (see Table 3) is the quantity of particulate organic carbon that is estimated to be added to long-term carbon stores in the Region; taken to be 10% of the total annual production by kelp.

Table 3. Kelp habitat extent and rates of carbon accumulation used for the English Channel and Western Approaches Region. Values used in the Summary are shown in bold.

Habitat	Extent (km²)	Component area (km²)	Stock (1000 tC)	Stock (g C/m²)			Production rate (g C/m²/yr)			production (1000t C/yr)	Outflux (1000t C/yr)	Source
				min	max	avg	min	max	avg			
Intertidal macroalgae	45.1	45.1	5.5	85	160	122	125	727	378	17.1	1.7	This report
	45.1	45.1	6.1			134 [1]						Walker 1954; Burrows et al 2014
Intertidal rock	58.9	58.9										Habitat Extent Totals
				Stock (g C/m²)			Production rate (g C/m²/yr)					
Species: whole plants				min	max	avg	min	max	avg			
Fucus vesiculosus				358	634	536	166	946	430			Lewis 2020
Fucus serratus				241	1213	659	222	958	611			Lewis 2020
Ascophyllum nodosum				696	1649	1033	20	70	49			Lewis 2020
Ascophyllum nodosum							90	935				Brinkhuis 1977
Fucus spiralis									183			Habitat Review
Himanthalia elongata									989			Habitat Review
Halidrys siliquosa									5			Habitat Review
Average				**432**	**1165**	**743**	**125**	**727**	**378**			
Species: detritus							min	max	avg			
Fucus vesiculosus - all									377			Lewis 2020
Fucus serratus									368			Lewis 2020
Ascophyllum nodosum									387			Lewis 2020
Stock estimates based on biomass measurement												Burrows, unpublished data

2.3.3 Maerl

Background and UK context

Maerl is a term for unattached coralline red algae, including the species *Phymatolithon calcareum*, *Lithothamnion corallioides* and *Lithothamnion erinaceum*, albeit with ongoing unpublished genetic studies potentially identifying new species. Maerl beds are made up of live or dead thalli or a varying mixture of both, and can form extensive beds at depths of up to 40 m (Hall-Spencer *et al.,* 2010). These habitats have a complex three-dimensional structure (Hall-Spencer, 1999), and are thus analogous to seagrass beds or kelp forests (Hall-Spencer,, 1999). They have rich biodiversity and act as nursery grounds for commercially important species of fish, crabs and scallops (Kamenos *et al.,* 2004a, 2004b), including queen scallops (*Aequipecten opercularis*) (Hall-Spencer 1999). Maerl is absent from large areas of the UK, including most of the North Sea, the Irish Sea and the eastern English Channel, presumably due to environmental constraints.

Maerl bed distribution in the UK has been described by Hall-Spencer *et al. (*2008). Maerl beds around the coasts of the UK are nearly all on exposed west coasts, where there are no major rivers carrying large quantities of suspended sediment. In Scotland, maerl is widespread along the west coast, in the Western Isles and in Orkney and Shetland. It is also present on the north coast (Loch Eriboll), but is absent from the east coast of Scotland. In Wales it is restricted to a small area of Milford Haven and small patches around the Pembrokeshire islands and the Lleyn peninsula.

Maerl deposits act as a longer-term store for OC and IC and calcifying biota. The maerl species *Lithothamnion corallioides* can be considered to be a key element of carbon and carbonate cycles in the shallow coastal waters where it occurs. The rate of maerl deposit accretion is generally slow (0.25 mm/yr); however, beds can be extensive. Scottish species-specific accretion rates were found to be in the range of 420–1,432 g $CaCO_3/m^2/yr$ in one study (Freiwald and Henrich, 1994, cited in Burrows *et al.,* 2014). Available irradiance is the main factor influencing the primary production of maerl, and accounts for more than 94% of the carbon fluxes for assessed maerl beds (Martin *et al.,* 2006). As a consequence, variations in irradiance that result from anthropic impacts and climatic changes (e.g., albedo, variations in water height or turbidity) could exert an influence on maerl.

Calcification and primary production responses to irradiance in *L. coralloides* were measured in summer 2004 and winter 2005 in the Bay of Brest (Martin *et al.,* 2006). Net primary production reached 1.5 µmol C/g dry wt/hr in August, and was twice as high as in January and February. Maximum calcification rates ranged from 0.6 µmol/g dry wt/hr in summer 2004 to 0.4 µmol/g dry wt/hr in winter 2005. Estimated daily net production and calcification reached 131 µg C/g dry wt and 970 µg $CaCO_3$/g dry wt, respectively, in summer 2004, and 36 µg C/g dry wt and 336 µg $CaCO_3$/g dry wt in winter 2005. The net primary production of natural *L. corallioides* populations in shallow waters was estimated to be 10–600 g $C/m^2/yr$, depending on depth and algal biomass. The mean annual calcification of *L. coralloides* populations ranged from 300 to 3,000 g $CaCO_3/m^2/yr$.

Live maerl deposits on the west coast of Scotland can reach a depth of at least 60 cm, with some dead deposits being found at significantly greater depths (Kamenos, 2010). Burrows *et al.* (2014) applied an annual (inorganic) carbon sequestration rate of 0.074 kg/m^2 for the purpose of their Scottish study. Welsh maerl covers a very small area, limited to Milford Haven, and is currently classed as ‘degraded’. Therefore, it is unlikely that Welsh maerl contributes substantially to carbon sequestration in Welsh waters.

In similar environmental conditions, the production of maerl beds corresponds to approximately one-third that of seagrass beds. Maerl communities are therefore relatively productive ecosystems, relevant to the functioning of temperate coastal ecosystems (Martin *et al.,* 2005; Hall-Spencer *et al.,* 2008).

Table 4 Storage and sequestration values used in Welsh and Scottish estimates of carbon storage and sequestration by maerl beds.

Reference	Parameter	Value
Armstrong *et al.*, 2020	Biomass of live maerl, *Phymatolithon calcareum*	90 g/m^2*
Armstrong *et al.*, 2020	Soil biomass	12,400 g/m^2 (top 60 cm, for live and dead maerl beds)
Armstrong *et al.*, 2020	Sequestration	9.5 g m^2/yr**
Martin *et al.*, 2006	Net primary production	10–600 g C/m^2/yr
Martin *et al.*, 2006	Mean annual calcification	300–3000 g $CaCO_3$ m^2/yr

*This was 20% of the value applied by Burrows *et al.* (2014), as Welsh beds are dominated by *P. calcareum*, which sequesters approximately 20% less than *Lithothamnion glaciale*, and also as Welsh beds are considered to be degraded.

** This represents the minimum sequestration rate quoted for *P. calcareum* by Burrows *et al.* (2014).

ECWA Region

In southern Britain, maerl beds (including live or dead thalli) consist of *Phymatolithon calcareum* and *Lithothamnion corallioides*. *L. corallioides* is replaced in Scotland by *L. glaciale* (Hall-Spencer, 1995). *P. calcareum* is both the most widely distributed and the most abundant maerl species in the UK. Measurements of the extents of maerl beds in the ECWA region are rare, but there are observations of live beds in south-west England.

Living maerl (including *L. corallioides*) grows on the St Mawes Bank in the Fal Estuary, currently the largest known area of maerl beds in England (15.9 km^2, 11,500 tC inorganic). Maerl has also been reported from the mouth of the Helford River, and deep deposits of dead maerl (described as sub-fossil) are known in other parts of Carrick Roads and in Falmouth Bay, indicating that maerl formerly covered a much wider area. There is research underway to asess the extent of maerl beds along the south coast of Cornwall too, from Falmouth Bay up to St Austell bay where large deposits of both live and dead maerl have been reported. Maerl beds have also been reported from Dorset (*P. calcareum*; Irvine and Chamberlain, 1994), and small amounts occur in the Isles of Scilly and Lundy (Hall-Spencer *et al.,* 2008), but the extent of these beds have not been mapped.

2.3.4 Fate of macroalgal detritus

Most seaweed-dominated habitats export carbon as detritus, and an understanding of the fate of this material is important, given the quantities involved. Macroalgae are highly productive, and much effort has been made to understand the productivity of key species (see Table 5). Long-term carbon storage (beyond that of biomass) is largely governed by the production, transport, degradation and eventual sedimentation of the detritus produced by macroalgal ecosystems (Krumhansl and Scheibling, 2012; Trevathan-Tackett *et al.,* 2015; Krause-Jensen and Duarte, 2016). Macroalgae grow on hard substrates where carbon burial is precluded, and they do not have root systems to stabilise sediments, so carbon storage in this blue carbon habitat is different from that in seagrass and saltmarsh systems, and mainly dependent on the annual production of large amounts of detritus. In south-west England the amount of macroalgal-derived carbon transferred to sediments has been estimated to be

9 g C/m^2 macroalgal habitat/yr (Queirós *et al.,* 2019). While this accumulation rate may allow estimation of the total quantity of macroalgal-derived OC added to sediments, here only the fraction of detritus relative to other sources (mainly phytoplankton) has been calculated (see Table 19).

*Table **5**. Estimates of primary productivity of three key macroalgal species in the UK. From O'Dell (2022).*

Species	Productivity (g C/m^2/yr)	SD	SE	*n*[1]	References
Laminaria digitata	480	550	120	20	Gunnarsson, 1991; Krumhansl and Scheibling, 2012; Smith, 1988
Laminaria hyperborea	330	430	7	42	Kain, 1977; Gunnarsson, 1991; Jupp and Drew, 1974; Luning, 1969; Pessarrodona *et al.,* 2018; Sjotun *et al.,* 1996; Smale *et al.,* 2016
Saccharina latissimi	290	40	11	12	Borum *et al.,* 2012; Brady-Campbell *et al.,* 1984; Krumhansl and Scheibling, 2012; Johnston *et al.,* 1977

[1] *n* refers to the number of data points used to calculate mean values, standard deviation (SD) and standard error (SE).

2.4 Saltmarsh

Background and UK context

Coastal saltmarshes may be defined as areas that are vegetated by herbs, grasses or low shrubs and which border saline water bodies (Adam, 1990). Saltmarshes form in low-energy or sheltered environments with shallow water, and the rate of formation depends upon the degree of exposure, the topography of the nearshore seabed and the supply of suspended sediment (Long and Mason, 1983). Saltmarsh extent in natural conditions is broadly governed by a combination of physical parameters, most importantly sediment supply, tidal regime, salinity, wind and wave action. A relatively flat intertidal topography that slopes gradually toward the intertidal channels provides the most suitable location for saltmarsh development (Zedler, 1984). As a result of the dynamic nature of saltmarsh habitats there can be high rates of carbon turnover, especially at lower shore heights, which are often in the earlier stages of succession and have less vegetative cover.

Within a saltmarsh habitat complex, halophytic plant species and communities display a transition from marine to terrestrial habitat. There is general agreement that the main factors affecting the zonation of halophytic plant species within a saltmarsh habitat relate to frequency of tidal inundation and the associated effects of salinity and tidal scouring. Each species has a different tolerance to tidal flooding, and as a result different species have different, although often overlapping, vertical ranges. Different communities are therefore apparent at different tidal elevations. At higher shore elevations, which can be dominated by floristically diverse assemblages, soil carbon content can be higher and turnover rates are slower.

Routine monitoring of saltmarsh is undertaken for the post-EU successors to the Water Framework Directive and Habitats Directive, and SSSI site assessment. The Water Framework Directive saltmarsh index is based on saltmarsh extent (current proportion of historical extent and extent change), proportions of zones present, dominant zone extent as a proportion of the total extent, and taxa number as a proportion of a historical reference. These measurements are combined to derive an Ecological Quality Ratio.

Saltmarsh habitats are considered to be net carbon sinks that are formed through capture of CO_2 from the surrounding air and water column by the plants that subsequently store this carbon in their roots and rhizomes. At the same time, saltmarsh plant roots physically bind together soil particles and encourage rhizome-inhabiting microbes to do the same, trapping organic material (Ford *et al.,* 2016). The exudation of captured carbon and organic material into the soil creates an anaerobic, carbon-rich sediment (Reid and Goss, 1981, cited in Ford *et al.,* 2016). This has the ability to accumulate carbon without reaching saturation (i.e., anaerobic conditions slow the rate of decomposition) and can potentially store carbon over millennial timescales (Stewart *et al.*, 2023).

However, as these habitats are dynamic, and can be subject to die-back and physical remobilisation at intervals of decades or centuries (Burrows *et al.,* 2014), they may not be capable of storing carbon over very long timescales. Carbon sequestration rates vary between complexes, with variability related to numerous factors, including hydroperiod (time spent submerged), salinity, nutrient input (i.e., from pollution) and suspended sediment supply (Nelleman *et al.,* 2009). Substrate type and thickness are also important factors in saltmarsh sequestration potential, with clay soils widely recognised as good long-term stores of OC, due to the efficient adsorption of organics to clay particles (Ford *et al.,* 2019). Plant community composition and plant diversity are also important, as they largely determine root properties such as biomass, sediment turnover and carbon exudate rate. Ford *et al. (*2016) suggest that species-rich saltmarshes have a reduced soil erosion rate and may therefore sequester carbon for longer than marshes, which are less species-diverse. Similarly, the relationship between soil stabilisation and plant diversity was found to be stronger in erosion-prone sandy soils compared with resilient clay soils (Ford *et al.,* 2016).

It is thought that saltmarshes have a higher carbon burial rate per unit area than any other blue carbon habitat (Stewart *et al.*, 2023). Sequestration rates in UK saltmarshes are in the range of 64–219 g C/m^2/yr (Adams *et al.,* 2012), with typical figures of around 120–150 g C/m^2/yr (Beaumont *et al.,* 2014). Burrows *et al. (*2014) used a value of 210 g C/m^2/yr for their Scottish study. A Welsh study conducted in 2015 by Ford *et al.* (2019) sampled 23 saltmarsh sites to determine long-term carbon stores. Plant and soil characteristics were analysed for each site, and the carbon store was determined for each of the sampling locations (51 in total across the 23 sites). Values from the study by Ford *et al. (*2019) contributed to the store estimates used in this report (see Table 9).

It has been established that saltmarsh restoration provides a sustained sink for atmospheric CO_2 (Burden *et al.,* 2013). Based on 36 samples collected from nine saltmarshes in Essex, above-ground vegetative biomass was estimated to be 282±234 g C/m^2 (Beaumont *et al.,* 2014). Based on data from the same sites, estimated soil bulk density was 0.448±0.03 g/cm^3, of which carbon soil density was 0.0244 g/cm^3 and 0.0116 g/cm^3 (based on soil carbon content of 5.45% and 2.6%) for soil depths of 0–30 cm and 30–100 cm, respectively (Beaumont *et al.,* 2014). In the region, soil carbon was in the range of 1–5% on the mudflat and lower saltmarsh dominated by pioneer species, and 3–5% in the more vegetated middle and higher saltmarsh (Andrews *et al.,* 2008).

Marsh accretion rates on the east coast of England have been estimated to be 62–196 g C/m^2/yr, with rates differing between high and low marsh, but not in a consistent manner (Callaway *et al.,* 1996). Although Callaway *et al. (*1996) do not provide carbon accumulation rates, these values were based on the total mineral and organic accumulation rates, with carbon accumulation rates based on a soil carbon content of 5.45% estimated for east coast sediments at depths of 0–30cm (Beaumont *et al.,* 2014). The rates reported by Callaway *et al. (*1996) for marsh accretion are similar to those estimated by others for the UK, namely 66–196 g C/m^2/yr (Cannell *et al.,* 1999; Chmura *et al.,* 2003; Adams *et al.,* 2012; Burrows *et al.,* 2014), and to global estimates, namely 151 g C/m^2/yr (Duarte *et al.,* 2005).

There is a differential in carbon sequestration between natural and restored saltmarsh habitat, with the average carbon density of natural ecosystems being higher (range 12.7–69 kg C/m^2; n = 85; average 40.3 kg C/m^2) than that of restored saltmarshes (10.125 kg C/m^2; n = 12; average 18.6 kg C/m^2) (Gregg *et al.,* 2021). However, it is suggested that the time that has elapsed since restoration plays a part in determining the storage capacity of the saltmarsh in question. In addition to time since restoration, other factors such as management practice (including grazing) and the type of soil in the area can also have an impact on the storage capacity of the saltmarsh (Gregg *et al.,* 2021).

Saltmarshes in Wales and on the west coast of the UK generally have a shallow organic-rich clay layer (less than 1 m) underlain by sandy substrate, and are frequently grazed by livestock (May and Hansom, 2003, cited in Beaumont *et al.,* 2014), whereas the marshes of the south and east UK coasts are characterised by a deep (more than 10 m) organic-rich clay substrate, and are most commonly ungrazed (Beaumont *et al.,* 2014).

ECWA Region

The extent of saltmarshes in the UK has been recently mapped. Available data was downloaded from the Environment Agency (EA) database, with maps produced from aerial photography between 2016 and 2019, and updated in July 2022 (Environment Agency, 2022) (see Annex 1. Sources for Habitat Data). Clipping the layer by the ECWA Region results in a total area of 102.2 km^2 (see Figure 2). Saltmarsh restoration sites within the Region include Medmerry. Table 6 shows the extents within regions. The Severn Estuary is recorded within the Midlands region. For saltmarsh, it is estimated that there are around 1,400 ha within the Severn Estuary cSAC (Natural England and Countryside Council for Wales, 2009) (see Figure 2).

According to the Environment Agency (2022), the reation of saltmarsh through realignment and regulated tidal exchange (RTE) sites contributed to 88 ha of marsh extent gain, primarily at sites on the North Norfolk coast and within Suffolk and Essex estuaries. In contrast, considerable marsh erosion was found along the outer Thames and Essex coast. Solent and South Downs Habitat Compensation and Restoration Programme (HCRP) region had a net gain of 18.6 ha of saltmarsh overall (a 1.4% gain), including the realignment and RTE sites. However, this value does not show the scale of local changes within this region. There were 184.46 ha of new growth (gains) compared with 217.29 ha of lost saltmarsh in the Solent and South Downs HCRP region. The breach at the Medmerry managed realignment site has resulted in a gain of 51 ha for this region. If gains (and losses) within Medmerry and other realignment sites are excluded, this region had a net loss of 34.75 ha (a 2.6%) loss. Most of the losses were observed within the Solent.

South Wessex HCRP region lost 16 ha of saltmarsh, which represented 2.5% of the total saltmarsh habitat in this region. This loss can be attributed to a net loss (18 ha) observed in Poole Harbour between 2008 and 2014. Significant patches of saltmarsh loss were observed within Holes Bay on the seaward edge currently occupied by pioneer and *Spartina* zones.

The area of the Severn HCRP region located within the South West Environment Agency Region saw a substantial gain of 220 ha. Over 200 ha of the marsh gained in this region was created within the Steart managed realignment and Otterhampton RTE sites located in the Parrett estuary. An increase in saltmarsh extent (23.93 ha) was observed within the area of the Severn HCRP region that overlaps the Midlands Environment Agency Region (from above Sharpness). The gains (20.41 ha) in this area can be attributed to widespread, patchy change outside of realignment sites.

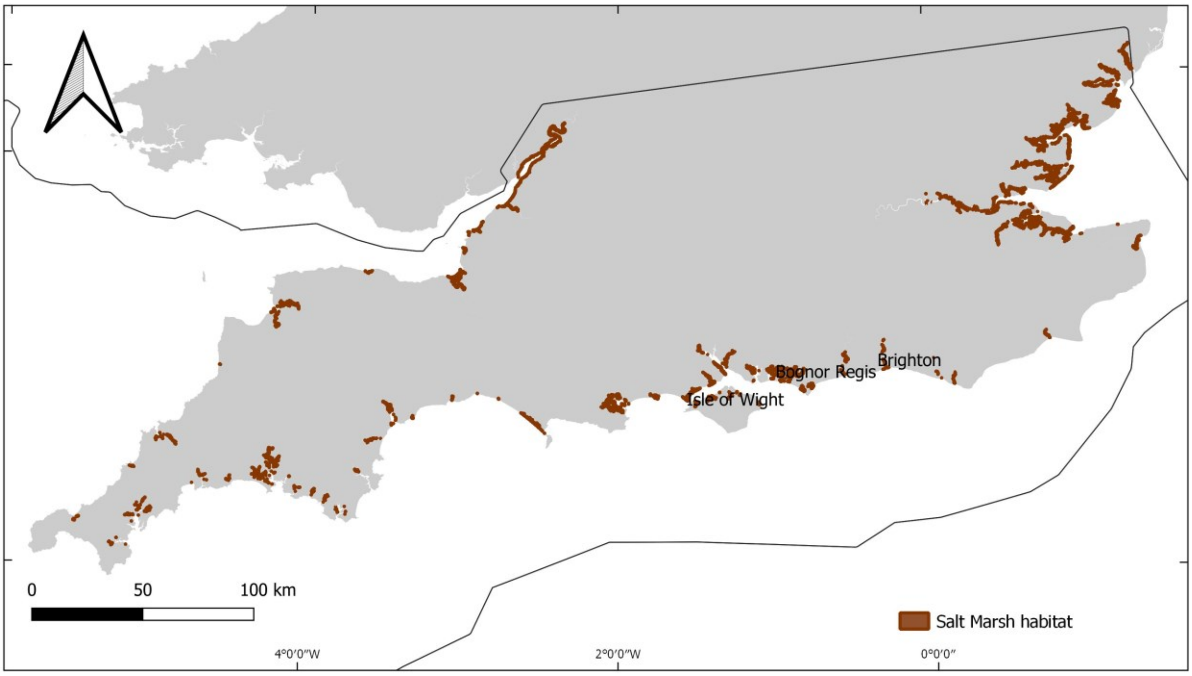


Figure 2. Saltmarsh extent in the English Channel and Western Approaches Region. Clipped from the recent Environment Agency dataset. © Environment Agency 2022.

Table 6. Aerial extent of saltmarsh within English Habitat Compensation and Restoration Programme (HCRP) regions and the English Channel and Western Approaches region of this report, comparing baseline and latest extents. Numbers in parentheses indicate net change (ha and percentage values) when managed realignment sites are excluded. © Environment Agency 2022.

EA Region	HCRP region	Baseline extent (ha)	Latest extent (ha)	Net change (ha)	Net change (%)
Midlands (Severn)	Severn	746.21	770.17	23.96 (20.44)	3.21% (2.83%)
South West	Devon and Cornwall	935.84	990.84	550 (27.94)	5.88 (3.33%)
	South Wessex	647.79	631.79	–16 (–16)	–2.47 (–2.47)
	Severn	282.15	502.13	219.98 (15.77)	77.96 (5.66)
South East	Solent and South Downs	1,346.36	1,364.92	18.56 (–34.75)	1.38 (–2.6)
	South East	1,425.83	1,502.17	76.34 (76.34)	5.35 (5.35)
	Thames	551.85	606.62	54.77 (46.00)	9.92 (8.34)

Carbon storage

Zonation of saltmarshes (as described in Table 7: Pioneer, Mid-low, Upper, Reedbed, *Spartina*, Unclassified and Un-vegetated) has been mapped in 75 out of the 111 waterbodies that contain saltmarsh in England. The largest area of saltmarsh in England is in the low-mid zone. The upper zone is the second largest zone in England, and the Severn HCRP has the largest proportion of upper saltmarsh compared with other areas. Devon and Cornwall waterbodies also have large extents of upper saltmarsh.

Spartina species account for less than 10% of England’s saltmarsh, and the greatest extents of this zone are found in the Anglian and Solent and South Downs regions. In the Anglian region the *Spartina* zone accounts for less than 10% of the total marsh area, and is typically very much a component of the marsh rather than a dominant constituent of the sward. *Spartina* species are much more prevalent in the Severn and Solent and South Downs HRCP regions, comprising 50% of saltmarsh in the latter.

Pioneer and reedbed zones each represent less than 5% of England’s total saltmarsh habitat. The pioneer zone in England was found in low abundance in almost all waterbodies that were categorised. However, due to the mapping protocols used there is potential for pioneer marsh to be underestimated as a result of its low density and fragmented nature. Some waterbodies had relatively large proportions of reedbed.

Saltmarsh extents for the ECWA Region are shown in Table 7.

Table 7. Extent of each zone in saltmarshes in England’s Environment Agency regions and Habitat Compensation and Restoration Programme (HCRP) regions in the English Channel and Western Approaches Region. (% of total below). © Environment Agency 2022.

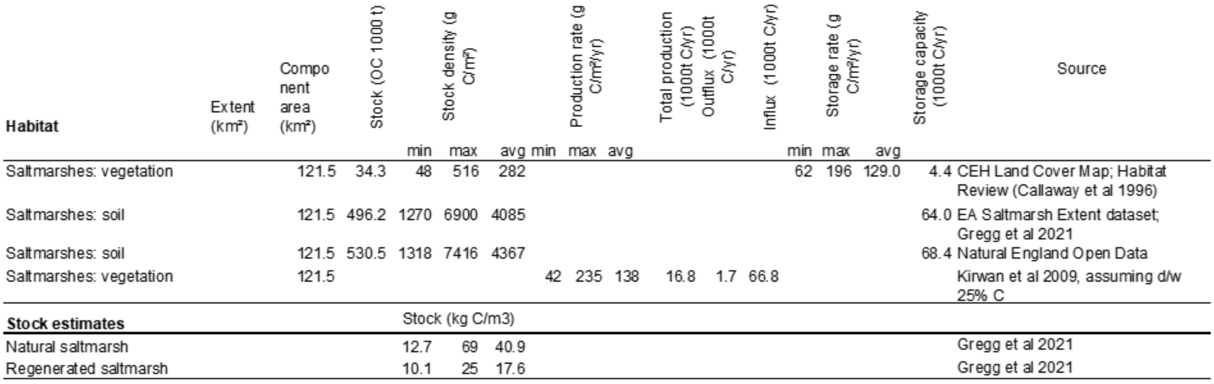
Environment Agency Region	**HCRP region**	**Pioneer (ha)**	**Mid-low (ha)**	**Upper (ha)**	**Reedbed (ha)**	***Spartina* (ha)**	**Unclassified (ha)**	**Un-vegetate**
Anglian	East Anglia	895.2	8,553.6	2,068.3	106.9	996.6	641.5	91.7
South East	Solent and South Downs	20.0	384.0	148.4	73.0	632.3	98.8	9.3
	South East	0.0	0.0	0.0	0.0	0.0	1,502.2	0.0
	Thames	17.1	312.9	192.7	8.1	71.4	2.3	2.2
South West	Devon and Cornwall	24.5	248.4	315.3	107.4	55.2	222.8	17.3
	South Wessex	5.2	197.3	163.8	135.9	23.5	99.1	8.4
	Severn	11.4	97.0	173.9	32.3	135.5	24.1	28.0
Midlands	Severn	8.4	191.0	404.4	35.3	119.2	7.0	4.9

Table 8. Organic carbon storage for a range of habitats. From Gregg et al. *(2021).*

Habitat	**Sediment carbon (t C/ha)**	**Sediment depth (cm)**	**Vegetation carbon (t C/ha)**	**Conf-idence (high, med, low)**	**References**
Sand dunes	9.5 (4–15)	15	5 (n = 3)	Low	Beaumont *et al.,* 2014; Gregg *et al.,* 2021
Saltmarsh	59[a–e] (20–134)	10–30	13[a]	Med	[a]Beaumont *et al.,* 2014 [b]Ford *et al*., 2012; [c]Burden *et al*., 2013; Ford *et al*., 2019; [e]Burden *et al*., 2019 (all cited in Gregg *et al.,* 2021)
Intertidal sediments (sandflats and mudflats)	English 12[a–c] [0.13[a]–1.72[a]] [5.5[b]–18.4[b]] Welsh [20[c]–89[c]] Scottish	English 20[a] Welsh 10[b] Scottish 50[c]	N/A	Low	[a]Trimmer *et al*., 1998 [b]Armstrong *et al*., 2020 [c]Potouroglou *et al*., 2017
Seagrass	39[ab] [6.7[b]–114.2[a]]	30	0.3[b] [0.07[b]–0.5[b]]	Low	[a]Green *et al*., 2018; [b]Lima *et al*., 2020
Kelp	N/A	N/A	6.7[a–c] [1.37–11.987[a]	Low	[a]Pessarrodona *et al*., 2018 [b]Smale *et al*., 2016 [c]Gevaert *et al*., 2008
Subtidal sediment	–1.12[ab]		0.07[a]–2.16[a]		[a]Queirós *et al*., 2019; measured values from the English Channel [b] De Haas *et al*., 1997; estimated value for the North Sea

Rates of carbon accumulation for saltmarshes are taken from the habitat reviews in Section 0, and are summarised in Table 9.

Table 9. Saltmarsh habitat extent and rates of carbon accumulation used for the English Channel and Western Approaches Region.



Habitat	Extent (km²)	Component area (km²)	Stock (OC 1000 t)	Stock density (g C/m²)			Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr)			Storage capacity (1000t C/yr)	Source
				min	max	avg	min	max	avg				min	max	avg		
Saltmarshes: vegetation		121.5	34.3	48	516	282							62	196	129.0	4.4	CEH Land Cover Map; Habitat Review (Callaway et al 1996)
Saltmarshes: soil		121.5	496.2	1270	6900	4085										64.0	EA Saltmarsh Extent dataset; Gregg et al 2021
Saltmarshes: soil		121.5	530.5	1318	7416	4367										68.4	Natural England Open Data
Saltmarshes: vegetation		121.5					42	235	138	16.8	1.7	66.8					Kirwan et al 2009, assuming d/w 25% C
Stock estimates				Stock (kg C/m3)													
Natural saltmarsh				12.7	69	40.9											Gregg et al 2021
Regenerated saltmarsh				10.1	25	17.6											Gregg et al 2021

Habitat	Extent (km²)	Component area (km²)	Stock (OC 1000 t)	Stock density (g C/m²)			Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr)			Storage capacity (1000t C/yr)	Source
				min	max	avg	min	max	avg				min	max	avg		
Saltmarshes: vegetation		121.5	34.3	48	516	282							62	196	129.0	4.4	CEH Land Cover Map; Habitat Review (Calloway et al 1996)
Saltmarshes: soil		121.5	496.2	1270	6900	4085										64.0	EA Saltmarsh Extent dataset; Gregg et al 2021
Saltmarshes: soil		121.5	530.5	1318	7416	4367										68.4	Natural England Open Data
Saltmarshes: vegetation		121.5					42	235	138	16.8	1.7	66.8					Kirwan et al 2009, assuming d/w 25% C
Stock estimates				Stock (kg C/m3)													
Natural saltmarsh				12.7	69	40.9											Gregg et al 2021
Regenerated saltmarsh				10.1	25	17.6											Gregg et al 2021

2.5 Seagrass beds

Background and UK context

Seagrass beds (*Zostera marina* and *Zostera noltii* in the UK) can play an important role in carbon sequestration, with many acting as net sinks of carbon (Duarte and Cebrián, 1996; Duarte *et al.,* 2010), notably *Posidonia* species. The contribution of seagrasses to global oceanic carbon storage has been quantified in several recent studies, but that research focused on only a few species and sites (Greiner *et al.,* 2013; Macreadie *et al.,* 2013; Serrano *et al.,* 2014; Miyajima *et al.,* 2015; Dahl *et al.,* 2016; Röhr *et al.,* 2016; Gullström *et al.,* 2018). However, there are some caveats associated with this global estimation, largely due to the high rates of below-ground accumulation of carbon in certain species, such as *Posidonia oceanica*, and differences in environmental conditions (Röhr *et al.,* 2018).

Seagrass beds sequester OC in shoots and leaves, below-ground rhizomes and seagrass detritus accumulated in the soil. Non-seagrass carbon is deposited mainly from the water column (suspended particulate carbon) (Kennedy *et al.,* 2010). This process is enhanced by the presence of the seagrass canopy and its effect in slowing current flow over the sediment surface (Gacia *et al.,* 2002; Hendriks *et al.,* 2008). Organic carbon derived from macroalgae and phytoplankton is much more labile than seagrass-derived OC, especially compared with below-ground biomass (Klap *et al.,* 2000; Nielsen *et al.,* 2004). Yet, once incorporated within the soil compartment, where low oxygen levels inhibit microbial activity (Trevathan-Tackett *et al.,* 2017), remineralisation of allochthonous OC is reduced, leading to a significant contribution to the long-term OC deposits that develop in seagrass soils (global average of 50%) (Kennedy *et al.,* 2010).

Seagrasses export a substantial portion of their primary production, in both particulate and dissolved organic form, but the fate of this export production remains unexplained in terms of seagrass carbon sequestration. Available evidence on the fate of exported seagrass carbon

(Duarte *et al.,* 2005) indicates that this represents a significant contribution to carbon sequestration, both in sediments outside seagrass beds and in the deep sea. The reported evidence implies that the contribution of seagrass beds to carbon sequestration has been underestimated as a result of only including carbon burial within seagrass sediments (Duarte *et al.,* 2005).

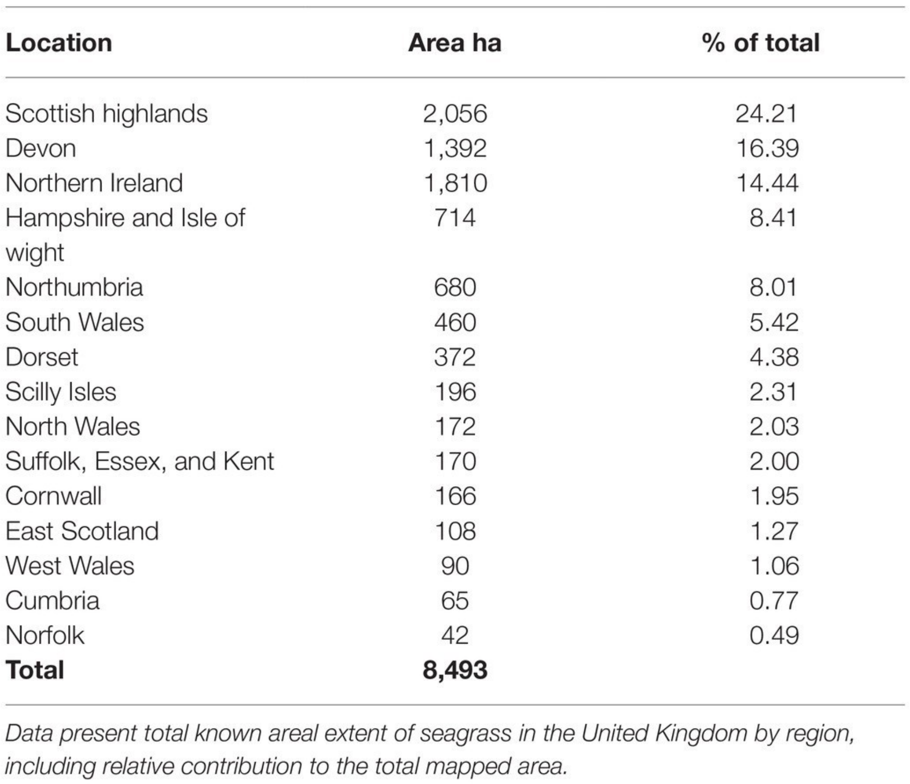
Garrard and Beaumont (2014) estimated that seagrass beds in the UK have a mean biomass of 1.61 t C/ha, using data reported from previous studies conducted in different geographical areas. Long-term carbon stores in the upper 50 cm of sediment under *Z. marina* and *Z. noltii* were found to be in the range of 22.7–107.9 t C/ha, with a mean value of 57 t C/ha, across seven sites in Scotland (Potouroglou, 2017). Based on these figures the total estimated carbon store in seagrass sediment is 91,200 t C across the whole of Scotland.

Carbon sequestration rates of seagrass beds in the UK were estimated to be 2,500 t C/yr by Luisetti *et al.* (2019) and 0.232 Mt C/yr by Green *et al.* (2021). These estimates are based on frequently used accumulation rates in the literature (low rate, 0.044 cm/yr; medium rate, 0.202 cm/yr; high rate, 0.42 cm/yr), where the rate of medium store accumulation (0.024 Mt C/yr^{-}) is used to estimate average annual carbon accumulation (Duarte *et al.,* 2013; Lavery *et al.,* 2013; Macreadie *et al.,* 2013; Miyajima *et al.,* 2015; Röhr *et al.,* 2018). Similar estimates have been made for the carbon sequestration capacity of Scottish seagrass beds (1,321 t C/yr) (Burrows *et al.,* 2014). These estimates relied on values of carbon sequestration for seagrass beds of varying species, from the north-east Atlantic (Fourqurean *et al.,* 2012) and the Mediterranean Sea (Duarte *et al.,* 2005).

Seagrasses are found around the coast of the UK in sheltered areas such as harbours, estuaries, lagoons and bays. *Zostera marina* and *Z noltii* are the most abundant seagrass species found in the UK, with *Z. marina* being the dominant species and occurring predominantly in the sublittoral, whereas *Z. noltii* occurs intertidally (Wilkinson and Wood, 2003). A wasting disease was the cause of a drastic reduction in seagrass beds in the UK in the 1930s. The subsequent recovery has been hampered by increased disturbance by human activity, such as pollution and physical disturbance from anchors and dredging, use of mobile fishing gear and coastal development. Seagrass beds are estimated to cover 8,493 ha (84 km^2) in the UK (Green *et al.*, 2018, 2021). Dense beds of seagrass tend to develop in sheltered areas, but in more exposed sites the beds are usually smaller, patchier and more susceptible to storm damage. Seagrass beds are spatially dynamic, with advancing and retreating edges, causing changes in coverage; the beds expand either through vegetative growth from shooting rhizomes that have survived the winter, or sexually by production of seed. Subtidal *Z. marina* beds in the UK are perennial, and some are believed to persist almost entirely as a result of vegetative growth rather than reproduction by seed. Growth of individual plants occurs during the spring and summer.

The total mapped areal extent of contemporary seagrass records (post-1997) from an OSPAR dataset, the European Union Water Framework Directive (WFD) dataset, and all other contributors includes 47 surveys spanning 20 years, 79% of which are from the last 10 years (Green *et al.,* 2021). In total, the data confirm the presence of 8,493 ha of seagrass in the UK (see Table 10). The occurrence of seagrasses is not uniform. Half of all mapped seagrass occurs in the Scottish Highlands (20%), Devon (16.2%), and Northern Ireland (14.3%). Seagrass extents range from patches of less than 1 m^2 to beds of up to 1,200 ha (in the Cromarty Firth, East Scotland). The average seagrass area recorded is 2.64±32.22 ha. The contemporary data represent the minimum area of seagrasses in the UK, since some beds have certainly gone unreported, as is demonstrated by the recent discovery of extensive beds in Mount’s Bay (east of Penzance, Cornwall) and St. Austell Bay (south coast of Cornwall) (see Section 2.5).

Table 10 Seagrass extents in UK regions. From Green et al. *(2021).*



Location	Area ha	% of total
Scottish highlands	2,056	24.21
Devon	1,392	16.39
Northern Ireland	1,810	14.44
Hampshire and Isle of wight	714	8.41
Northumbria	680	8.01
South Wales	460	5.42
Dorset	372	4.38
Scilly Isles	196	2.31
North Wales	172	2.03
Suffolk, Essex, and Kent	170	2.00
Cornwall	166	1.95
East Scotland	108	1.27
West Wales	90	1.06
Cumbria	65	0.77
Norfolk	42	0.49
Total	**8,493**	

Data present total known areal extent of seagrass in the United Kingdom by region, including relative contribution to the total mapped area.

ECWA Region

Recent focus on the potential of seagrass to help to mitigate climate change has revealed new seagrass beds in the ECWA Region. The areas with the most seagrass in Cornwall, for example, are Mount’s Bay, Fowey, Looe, Falmouth, St Mawes and the Helford Estuary (see Figure 3), with further seagrass beds revealed in recent unpublished studies. A Cornwall Council project has described one of the biggest seagrass beds ever found in UK waters. The newly identified seagrass bed in Mount’s Bay covers 5 km^2, and is larger than all known seagrass beds in Cornwall combined. Researchers from the University of Exeter have mapped seagrass beds in the Fal and Helford Estuaries covering 172 ha. Small areas of seagrass beds also occur in the Severn Estuary, unusually since they occur in an area of mixed cobbles, gravel, sand and mud (Natural England & the Countryside Council for Wales, 2009.

Green *et al.* (2021) used a range of data sources to compile seagrass bed extents in England and Wales. This information has been used here to estimate the extents of seagrass beds across the ECWA Region, showing significant areas of seagrass beds in Devon, Hampshire and the Isle of Wight, Dorset, the Scilly Isles, Cornwall, and Kent (see Table 11).

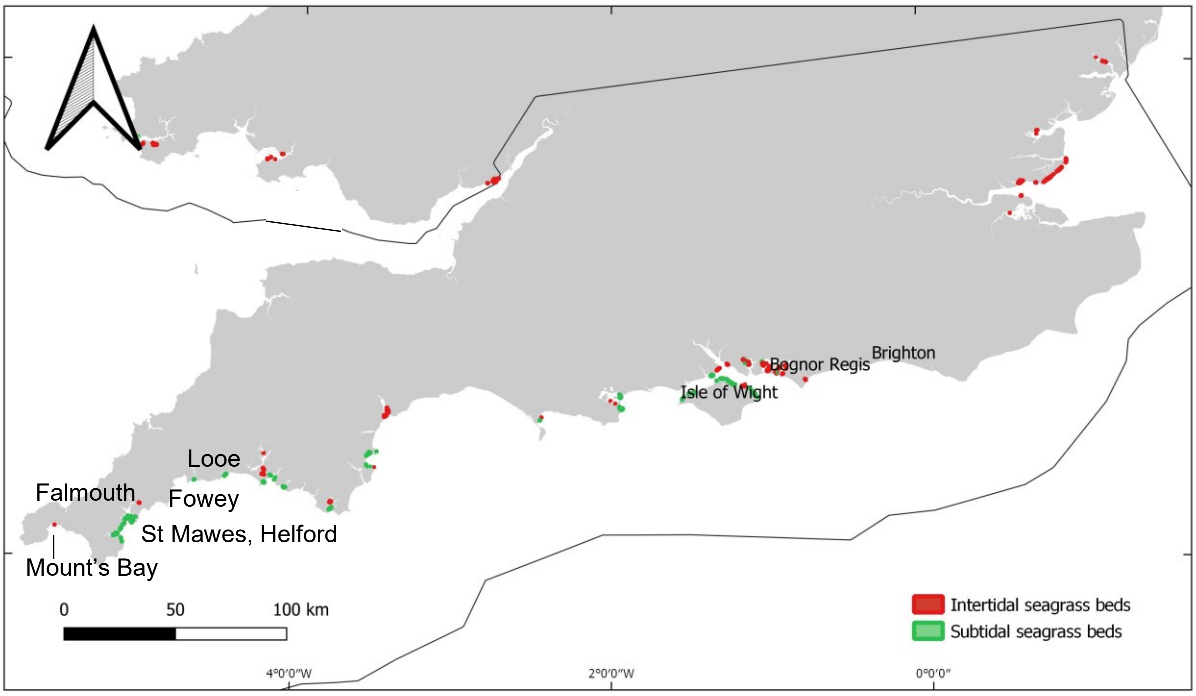


Figure 3. Locations of intertidal and subtidal seagrass beds in the English Channel and Western Approaches Region (excluding the Scilly Isles). From the Natural England habitat polygon database (see Annex 1 for data source).

Table 11 Known extents of seagrass beds in the English Channel and Western Approaches Region. From Green et al. *(2021).*

Location	**Area (ha)**	**Percentage of total UK**
Devon	1,392	24.21
Hampshire and Isle of Wight	714	8.41
Dorset	372	4.38
Scilly Isles	196	2.31
Cornwall[1]	166	1.95
Suffolk,[2] Kent and Essex	170	2.00

[1] An underestimate following the discovery of an extensive seagrass bed in Mount's Bay.

[2] Includes areas in Suffolk outside of the ECWA Region.

Carbon storage

Within the ECWA Region two studies were identified that assessed the blue carbon potential of seagrass beds. Lima *et al. (*2022) analysed total carbon stores from the Isle of Wight, the Solent and adjacent harbours in southern England, including OC stored in sediment and plant material. Four seagrass species and morphological types were identified in the study sites, with *Zostera marina* var. *angustifolia* (hereafter referred to as *Z. angustifolia*) representing the dominant taxon, found in all sample sites apart from Cowes. *Z. angustifolia* formed mixed beds with *Zostera noltii* in Creek Rythe, Hayling Island and Porchester, and mainly monospecific beds in Farlington Marshes and Ryde. *Zostera marina* was found predominantly in Cowes, whereas *Ruppia maritima* was only found in Creek Rythe and Hayling Island, in small mixed patches. Average above-ground biomass and below-ground biomass for all taxa combined were 0.28±0.008 t C/ha and 0.012±0.013 t C/ha, respectively. Sediment from intertidal seagrass beds stored on average 103.12±71.45 t C/ha. This study also compared sediment percentage of OC and percentage of organic matter (OM) within seagrass beds and adjacent, un-vegetated, sampling points, showing that un-vegetated mudflats had higher percentages of OC and OM than seagrass for most sites apart from Hayling Island.

Green *et al. (*2018) sampled 13 *Z. marina* beds along the south-west coast of the UK to assess the variability in sediment long-term stores of OC. The study sites were considered representative of subtidal *Z. marina* beds in the ECWA Region, spanning a gradient of sheltered to exposed sites, varying in formation, size and density, but found along the same latitudinal gradient. Long-term stores of OC integrated across 100-cm depth profiles were similar among all sites (ranging from 98.01±2.15 to 140.24±10.27 t C/ha), with the exception of Drake's Island in Plymouth Sound, which recorded an unusually high OC store (380.07±17.51 t C/ha) compared with the rest of the region. The total biomass of OC in the top 100 cm of the surveyed seagrass beds was 66,337 t C.

Green *et al. (*2021) estimated sedimentary long-term stores (up to 30 cm) ranging from 29.4 t C/ha to 114.02 t C/ha in the western English Channel, whereas Lima *et al. (*2020) reported a value of 33.8±18.5 t C/ha in the top 30 cm of sediment. Green *et al. (*2018) estimated the UK-wide store of OC in seagrass beds to be in the range of 108,427–221,870 t C, which is substantially higher than previous estimates by Garrard and Beaumont (2014) of 8,050–16,100 t C for European sedimentary seagrass long-term stores (Gregg *et al.,* 2021). Store sizes reported from these studies are summarised, alongside values used for carbon accumulation rates in seagrass beds, in Table 13.

Table 12. Reported seagrass carbon stores (biomass) and long-term stores (sediment) in the English Channel and Western Approaches Region.

Reference	**Location**	**Parameter**	**g C/m^2**	**g C/m^2 (<0.1m)**
Lima *et al.,* 2022	Intertidal seagrass, Isle of Wight, Solent and adjacent harbours	Average above-ground biomass	28±8 (*n* = 30)	2.8
		Average below-ground biomass	1.2 ± 1.3 (*n* = 30)	0.12
		Mean carbon stock value for the top 1 m of sediment	11,534±912	1153.4
Green *et al.,* 2018	Subtidal seagrass, Looe, Plymouth, Torbay, Fleet, Studland		14,000±7332	1400.0

Table 13. Seagrass habitat extent and rates of carbon accumulation used for the English Channel and Western Approaches Region.

Habitat	Extent (km²)	Component area (km²)	Standing stock (1000 t)	Stock (g C/m²) (<0.3m depth)			(<0.1m)	Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr)			Storage capacity (1000t C/yr)	Source
				min	max	avg	avg	min	max	avg				min	max	avg		
ECWA	111469		0.0	2940	11402	**7171**	**2390**										0.00	
Seagrass		9.9	23.6	2940	11402	7171	**2390**										0.99	Natural England Blue Carbon Data
		7.2	17.2	2940	11402	7171	**2390**							10.5	48.3	100.4	0.72	Habitat Review
										274	2.7	0.3						from increase in dry mass of *Zostera marina* ;
		9.9																Godshalk & Wetzel 1978; Sand-Jensen 1974

Stock estimates	Stock (t C/ha)			Accumulation (cm/yr)				
	min	max	avg	low	med	high	avg	
Seagrass	29.4	114.0	71.7	0.0440	0.2020	0.4200	0.2220	Green et al 2018, 2021; Luisetti et al 2019
			48.7					Fourqurean et al 2012 (North Atlantic)
	22.7	107.8	65.3					Scotland (Potouroglou, 2017) <0.5m
			33.8					Lima et al 2020

2.6 Biogenic reefs

Table 14 Production rates, sequestration rates and store densities for common types of shallow-water biogenic reefs around the UK.[1] *Based on Burrows* et al. *(2021).*

Biogenic reefs	**Production rate (g C/m²/yr)**		**Sequestration rate (g C/m²/yr)**		**Store density (g C/m²)**	
	OC	**IC**	**OC**	**IC**	**OC**	**IC**
Modiolus modiolus	0	40	0	40	0	4,000
Mytilus edulis	0	40	0	40	0	15
Serpula vermicularis reefs	0	0	0	0	0	0
Sabellaria reefs	0	420	0	420	–	781
Brittlestars (shelf seas)	0	82	0	82	–	0
Subcanopy algae	21	0	0	0	22	0

[1] *Modiolus* beds are assumed to be 75 cm deep, *Mytilus* beds were assigned the same values as *Modiolus* beds. Sources of values and other assumptions are given in Burrows *et al. (*2017).

OC, organic carbon; IC, inorganic carbon.

2.6.1 Blue mussel (*Mytilus edulis*) beds

Background and UK context

Blue mussel beds occur naturally along shorelines where suitable substrata for attachment are found (Coolen *et al.,* 2020). Their habitat range extends from the high intertidal to the shallow subtidal zone, and from exposed rocky shores to sheltered bays, estuaries and sea lochs. The spatial extent, density and temporal persistence of blue mussel beds are highly variable, depending on local environmental conditions, but in some areas these beds can attain dimensions that justify their classification as biogenic reefs (Holt *et al.,* 1998). *Mytilus edulis* beds are composed of layers of living and dead mussels, with a matrix of accumulated sediment and shell debris bound together by networks of byssal threads. In the UK, beds rarely exceed 30–50 cm in thickness, but subtidal examples up to 120 cm thick have been reported (Holt *et al.,* 1998).

Mussels are capable of living for up to 18–24 years. However, the majority of mussels in beds are probably young, consisting of 2- to 3-year-old individuals, due to predation and the dislodgement of clumps of mussels by wave action and storms (Holt *et al.,* 1998). As mussel beds grow in size, individual mussels tend to become attached to other mussels rather than to the underlying substratum, so that large beds may be 'rolled up' and removed by wave action. Therefore mussel beds may vary in size and extent, and show a continuum between thin patchy beds and well-developed beds (Holt *et al.,* 1998). The bed extent and other characteristics may change over time, although beds in sheltered areas may develop and persist over longer timescales.

Blue mussels produce faeces and pseudofaeces which, together with silt, build up rich organic biodeposits under the beds. However, the longevity of these organic-rich biodeposits is likely to be limited as beds change and retract, and therefore they are unlikely to provide a long-term carbon store. *Mytilus edulis* was not included in the Scotland-wide assessment of blue carbon by Burrows *et al. (*2014) for this reason. Under optimal conditions *M. edulis* can reach a shell length of 60–80 mm within 2 years, but in the high intertidal zone the growth rate is significantly lower, and mussels may take 15–20 years to reach only 20–30 mm in length (Seed and Suchanek, 1992). Both biomass and carbonate production rate will therefore be heavily dependent on local conditions, and no single set of values can accurately represent all cases. Without detailed site-specific information (on bed thickness, mussel population size and structure and shell growth rate) it is not possible to assign values for specific beds (and thereby individual MPAs), and blue mussel beds are therefore treated as a ‘data-deficient’ category in this report. Long-term stores and rates of production and sequestration of carbon have been assumed to be the same as those for *Modiolus* beds, in the absence of any relevant alternative information (see Table 4).

ECWA Region

Within the ECWA Region, the available data layers suggest that there are 2.3 km^2 of intertidal blue mussel beds and a further 33 km^2 of mixed species subtidal mussel reefs with *Mytilus* and *Modiolus* (see Section 2.6.2). Mussel beds occur in sheltered areas and are found within MPAs. In areas east of the Isle of Wight, commercial relaying of populations also occurs. These beds are harvested, and therefore their contribution to blue carbon via sediment storage is likely to be limited.

2.6.2 Horse mussel (*Modiolus modiolus*) beds

Background and UK context

Biogenic carbonates are deposited by accumulated shells of the large bivalve *Modiolus modiolus*, and occur in living reefs as well as in areas that were previously occupied. *M. modiolus* is a long-lived, slow-growing bivalve with sporadic recruitment. Although horse mussels are responsible for large amounts of carbonate biomass, the annual IC productivity rates are relatively low, estimated to be 330 g $CaCO_3$/m^2/yr (Collins, 1986). The largest UK bed was recorded in Scotland at Noss Head, but horse mussel beds are found throughout the UK. An average thickness of 75 cm in *M. modiolus* beds is used to calculate underlying carbonate in sediments (Burrows *et al.,* 2017, 2021; Porter *et al.,* 2020). Field sampling in Scottish beds has provided an accurate estimate of calcium carbonate, which can be applied to English sites (Hirst *et al.,* 2012), but to our knowledge no such data are available for English sites. The area-specific storage density estimate adopted in this report is therefore 4,000 g IC/m^2.

ECWA Region

There are records of subtidal mussel beds in the English Channel region, the majority of which lie off the coast of Brighton, Worthing and Bognor Regis. There is also a mapped area of subtidal mussel beds to the south of the Isle of Wight (see Figure 4) and off Portland Bill (to the west, south of Weymouth). These beds are described as permanently submerged, densely packed groups of horse mussels (*Modiolus modiolus*) and/or blue mussels (*Mytilus edulis*) (Natural England, 2015). The mapped areas of mixed reefs of *Mytilus* and *Modiolus* cover 33 km^2 of the Region.

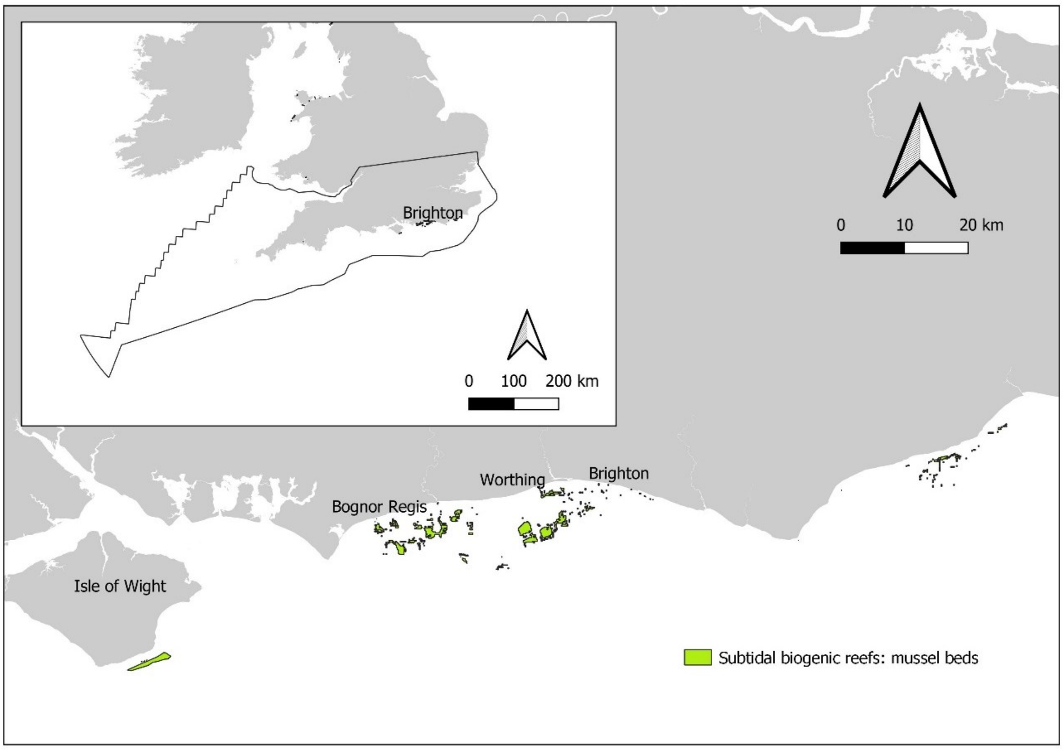


Figure 4. Subtidal biogenic reefs from the Marine Habitats and Species GeoPackage shapefiles; these data are open source and available online (see Annex 1 for link).

2.6.3 Native oyster (*Ostrea edulis*) reefs

Background and UK context

Oyster (*Ostrea edulis*) reefs are usually a net source of CO_2, due to carbonate formation (Fodrie *et al.,* 2017), but shallow subtidal reefs and saltmarsh-fringing reefs (predominantly composed of oyster reefs present at the edge of a saltmarsh) are small net sinks (–1.0±0.4 t C/ha/yr and –1.3±0.4 t C/ha/yr, respectively) due to the presence of OC-rich sediments (Fodrie *et al.,* 2017).

ECWA Region

Significant quantities of native oysters (*Ostrea edulis*) exist in the ECWA Region. The Solent between the Isle of Wight and Hampshire, the River Fal in Truro, Cornwall and parts of the Thames Estuary in London have been listed as the main areas where native oysters are present in the ECWA (Perry and Jackson, 2017). Between 1972 and 2006 the largest European self-sustaining oyster fishery was present in the Solent, supporting 450 vessels and over 700 jobs. In 2007, poor recruitment led to a rapid decline in populations, and in 2013 the fishery was closed to protect what remained of the stock (Harding *et al.,* 2016). Since 2015, the Blue Marine Foundation initiated the Solent Oyster Restoration Project. This involved gathering a coalition of local fishermen, authorities, scientists and other stakeholders as well as other private investors to help. Almost 100,000 oysters have been restored in the Solent since the initiation of the project across 12 restoration sites. The main aim of the project is to reconnect fragmented oyster reefs, and to adopt a ‘seascape’ approach which will benefit other species, as well as blue carbon habitats (Thomas *et al.,* 2022). Work has also begun on the Thames oyster populations, led by the Zoological Society of London, in Essex. The extent of oyster habitats in the region is therefore expected to expand in the coming years (Pogoda *et al.,* 2019).

2.6.4 Cold-water coral (*Desmophyllum pertusum*) reefs

Background and UK context

Cold-water corals (*Desmophyllum pertusum*, also known as *Lophelia pertusa*) typically support a range of other species by providing a three-dimensional structure that can be used both as shelter and as an attachment surface. The living coral framework and accumulations of relict calcareous material collectively represent an IC sink operating over a timescale of thousands of years, based on radiocarbon dating of coral fragments (Douarin *et al.,* 2013, 2014, cited in Burrows *et al.,* 2017). Although its localised occurrence means that the contribution of *D. pertusum* to total carbon storage is likely to be very small, simple calculations of coral mass per unit area based on the reported size of coral mounds (Burrows *et al.,* 2014) gave a store density estimate of 9,375 g/m^2. Rates of accumulation of *D. pertusum* mounds suggested a sequestration rate of 35 g IC/m^2/year (Burrows *et al.,* 2014, cited in Burrows *et al.,* 2017), but releasing CO_2 in the process and thereby not directly mitigating CO_2-driven climate warming.

Cold-water coral reefs and coral gardens may also contribute to carbon sequestration by trapping sediment. Suspension- and filter-feeding macrofauna associated with coral branches intercept organic matter that would otherwise not settle on the sea floor and, through their action as ecosystem engineers, the increased turbulence generated by the coral framework and the depletion of organic matter in the boundary layer augment the influx to the coral community (Thurber *et al.,* 2014).

The carbonate accumulation rates of Challenger Mound are lower than those of tropical shallow-water reefs (4–12% of the carbonate accumulation), but they exceed the carbonate accumulation rates of continental slopes by a factor of 3.9–11.8 (Titschack *et al.,* 2009). White *et al. (*2012) found that cold-water coral reef ecosystems potentially turn over a significant proportion of the annual shelf carbon export in the Norwegian Sea, where reefs are abundant. However, carbon sequestration from this habitat is not currently considered to be significant in the UK (cited in Armstrong *et al.,* 2012).

ECWA Region

Cold-water coral (*D. pertusum*) reefs are only known to be present in the ECWA Region in The Canyons MCZ. This MCZ was designated after consultation with the Joint Nature Conservation Committee (JNCC) in 2013, and is in the far south-west corner of the UK continental shelf within the ECWA region. The site itself is positioned on the shelf edge, where it drops to depths of up to 2,000 m. Important protected features at the site are cold-water corals (including *D. pertusum*), deep-sea beds, coral gardens, burrowing megafauna and sea pens. Two large deep canyons at the shelf edge are within the MCZ; these have been named the Explorer Canyon, which sits in the northern region, and the Dangaard Canyon, which is directly below it. The only known examples of *D. pertusum* were recorded on the northernmost wall of the Explorer Canyon, with other coral species forming coral gardens.

2.6.5 *Sabellaria* reefs

Background and UK context

Sabellaria reefs are listed as a priority habitat under the UK Biodiversity Action Plan (BAP). The reefs are generally formed by two marine polychaete worms, *Sabellaria alveolata* and *Sabellaria spinulosa*, constructing tubes in tightly packed masses with a honeycomb-like appearance, which are 30–50 cm thick. By forming complex structures and reefs, both species provide a biogenic habitat which is often occupied by multiple associated species. Reef construction is not a calcification process, but rather one that binds and 'cements' sand particles to form complex three-dimensional structures (Franzitta *et al.,* 2022). Previous reports have therefore concluded that the blue carbon contribution from *Sabellaria* reefs is negligible, and have generally considered it to be the same as that from the surrounding sediments (Naylor and Viles, 2000; Burrows et al., 2021).

ECWA Region

The Severn Estuary has areas of biogenic reefs formed by the tube-dwelling polychaete worm *Sabellaria alveolata*. *S. alveolata* reefs in the UK are predominantly an intertidal habitat, but the Severn Estuary is one of the few places where *S. alveolata* reefs occur extensively in the subtidal as well as the intertidal zone. Subtidal *Sabellaria* reefs are currently recorded in the area between Cardiff and Weston, and there are also intertidal reef features further upstream (Natural England and Countryside Council for Wales, 2009). Patches of intertidal *S. alveolata* reef occur throughout the estuary, although it tends to be more common on the English side. The subtidal *S. alveolata* tends to be in the outer parts of the estuary, south-west of a line between Clevedon and Newport. The exact distribution of subtidal *S. alveolata* reef in the Severn Estuary is not known, partly due to the difficulties in sampling this habitat. An extensive area of *Sabellaria* reefs is also mapped east of the Dengie National Nature Reserve.

2.7 Sediments

2.7.1 Background and UK context

Seabed habitats develop through the prevailing hydrographic regime (tides, waves and residual currents) together with the underlying physiography and geology (Eliott *et al.,* 1998).

Organic detritus and phytoplankton are incorporated into the sediments via direct settlement and accumulation on the sediment (sedimentation), where labile and semi-labile dissolved and particulate matter is consumed by macrofauna and micro-organisms. The activities of benthic organisms promote the uptake of dissolved OC and suspended organic particles via bio-irrigation (flushing of sediments) and bioturbation (burrowing activities) that incorporate within the sediment organic matter that has been deposited at its surface. Respiration by the benthic community remineralises carbon as CO_2.

Where carbon is biologically inert (i.e., refractory) it may accumulate over timescales of thousands of years in deeper, less disturbed sediments (Aldridge *et al.,* 2017). Within offshore seabed sites in the Celtic Sea, POC is relatively uniform down to 25 cm, with a tendency to increase with depth due to decreasing porosity (Aldridge *et al.,* 2017). Some pools of OC may be historical in areas such as The Canyons, where they have accumulated over long time periods.

2.7.2 ECWA Region

Sediments in the eastern English Channel

Evidence for the geology and biology of the eastern English Channel is provided by the South Coast Regional Environmental Characterisation and the partially overlapping Eastern English Channel Marine Habitat Map (EECMHM) study (James *et al.,* 2007), which explored 5,600 km^2 of the seabed to provide context for identification of new sites for aggregate extraction. These studies explore the seabed between Dungeness and Poole. A wide variety of seabed habitats are present, including fine mud in low-energy areas, and bedrock exposures of sandstone, mudstone, limestone and chalk (James *et al.,* 2010).

Although bedrock of solid geology underlies the whole central and eastern English Channel, it is only where it is exposed or covered by thin sediment that rock will influence seabed habitat. Outcrops and areas covered by thin sediment veneers occur over a relatively large proportion of the area. Areas of chalk are extensive. Elsewhere the seabed is composed of thicker Quaternary and mobile sediment (James *et al.,* 2007). Modern input of sediment to the central and eastern English Channel is minimal, and the natural supply is reduced as a result of river management and coastal protection (James *et al.,* 2010).

Gravel and sand habitats cover extensive subtidal and offshore areas of the eastern English Channel (Jones *et al.*, 2004). Where these are stable in deeper offshore areas (depths of over 30 m), diverse faunal communities are present. Few areas of mud-dominated sediment are present, due to bed shear stress across much of the eastern English Channel area.

Sandy sediments are widespread throughout the eastern English Channel in regions of moderate to strong tidal currents that prevent finer particle sediments from settling. Mobile and clean sands are characterised by a robust and impoverished fauna. In areas of extensive sand in the eastern parts of the Channel, tidal currents create bedforms, including mega-ripples, sand waves and sandbanks. These can be numerous and extensive over large areas, or may occur as isolated or small group features on gravel or rocky seabeds (James *et al.,* 2010). In eastern parts of the region, sand bank areas extend up to 30 km in length and can rise over 40 m above the seabed. Sandbank crests may shoal or come within 5 m of the surface at spring tides.

There are also extensive systems of sediment-infilled paleochannels incised into bedrock. Rock and thin sediment extend over much of the northern parts of the Channel where sand streaks, patches, sand ribbons and mega-ripple trains are more common, and rock is particularly extensive in the south-west. Coarse sediment dominates in the central southern region, with sandy sediment increasing in significance to the east and encompassing all of the south-east region, where there is an extensive sand wave field.

Sublittoral mixed sediments become more prevalent in the south and west of the eastern English Channel. Subtidal chalk also occurs in this region (Downie and Curtis, 2014).

Sediments in the western English Channel and Western Approaches Region

In the western English Channel the boulder pavement that underlies the region is largely exposed or has a thin covering of sediment, particularly in some coastal areas where this consists of non-living maerl (carbonate skeletal fraction). The carbonate fraction in the superficial sediments is composed of shelly gravel – that is, skeletal grains derived from littoral shelf faunas and algae, mainly pelecypods and bryozoans at depth (Bouchet *et al.,* 1978, cited in Reynaud *et al.,* 2003).

In the Celtic Bank area of the Western Approaches the sediment cover is thicker than in the Channel. Sands in the Celtic Bank area are several tens of metres thick and covered by poorly sorted gravelly sandy muds. Most of the carbonate skeletal fraction of these sediments is transported (as tidal bedload) from present-day coastal areas of Brittany, as has been demonstrated for bryozoans (Bouysse *et al.,* 1979) and molluscan faunas (Reynaud *et al.,* 1999). Muddy deposits and mound-like boulder accumulations have been recorded only in the northern part of the Western Approaches. The shelf–slope transition, at around 200,220 m, is characterised by calcareous muds and ooze, locally composed of more than 80% of foraminiferal tests (Reynaud *et al.,* 2003). The deepest part of the ECWA Region is The Canyons Marine Conservation Zone (MCZ), located more than 330 km from Land's End, Cornwall. It encompasses an area of 661 km^2 and covers a depth range of 100–2,000 m below sea level.

2.7.3 Carbon storage

Analyses of the carbon content of historical BGS sediment cores by Smeaton *et al. (*2021) have produced spatial maps of OC and IC across most of the UK's Exclusive Economic Zone (EEZ). For this region, these maps show considerable variation in both OC density (see Figure 5) and IC density (see Figure 6).

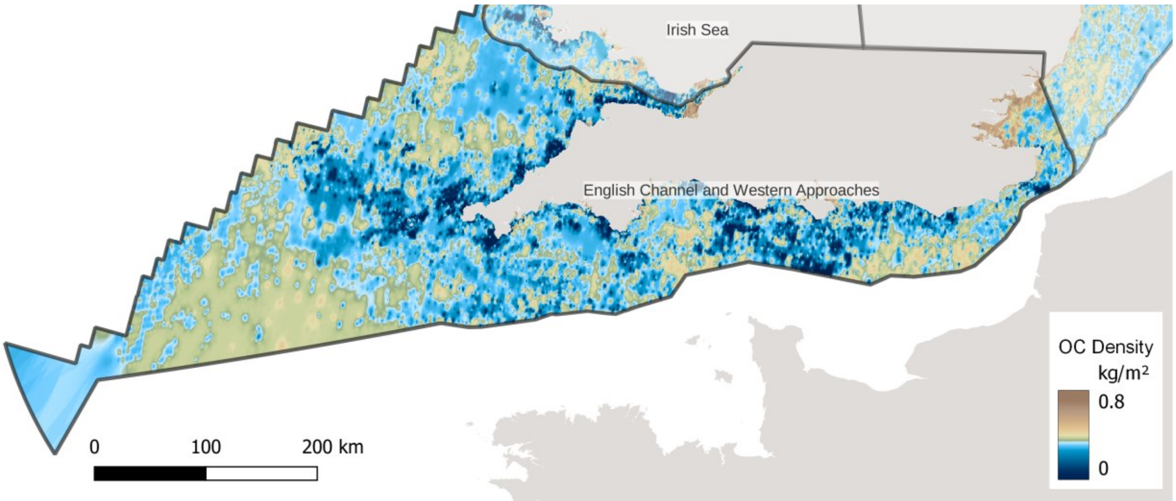


Figure 5. Organic carbon density in the top 10 cm of marine sediments in the English Channel and Western Approaches Region. Data from Smeaton et al. *(2021).*

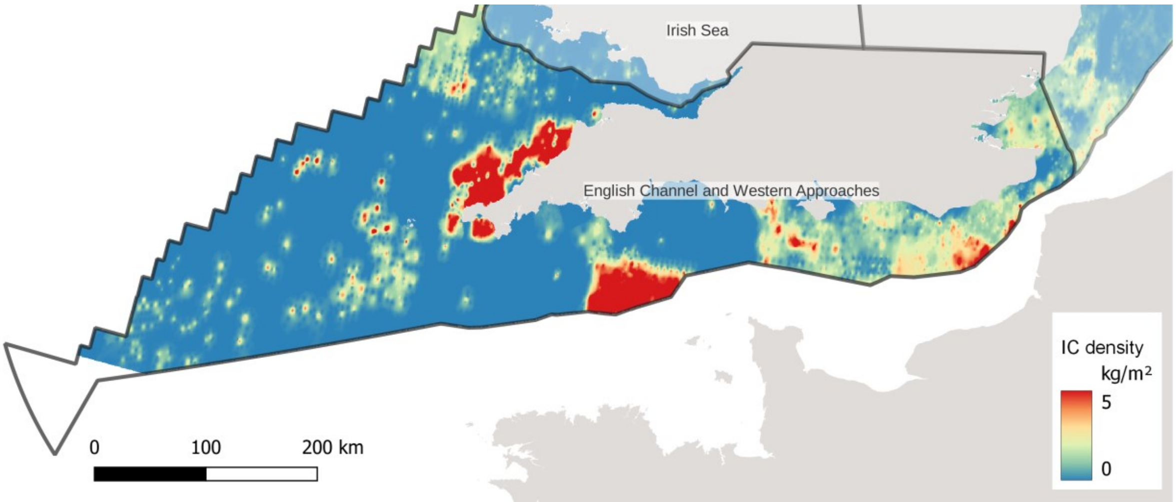


Figure 6. Inorganic carbon density in the top 10 cm of marine sediments in the English Channel and Western Approaches Region. Data from Smeaton et al. *(2021).*

Organic carbon density (see Figure 5) is higher in surface sediments in the middle of the English Channel, in deeper areas of the outer continental shelf extending northwards towards the Bristol Channel. Highest OC density is found in sediments in the upper Bristol Channel and coastal areas off Kent and Essex. Lower OC densities are found in tide-swept areas (see Figure 7) off the coasts of Cornwall and North Devon, particularly around the rocky headlands of Land's End, the Lizard peninsula, Bolt Head, and Trevose and Hartland Points in the north. Inorganic carbon is very patchily distributed in the region, with extensive areas in mid Channel, the Straits of Dover and the Bristol Channel, and very low values elsewhere (see Figure 6).

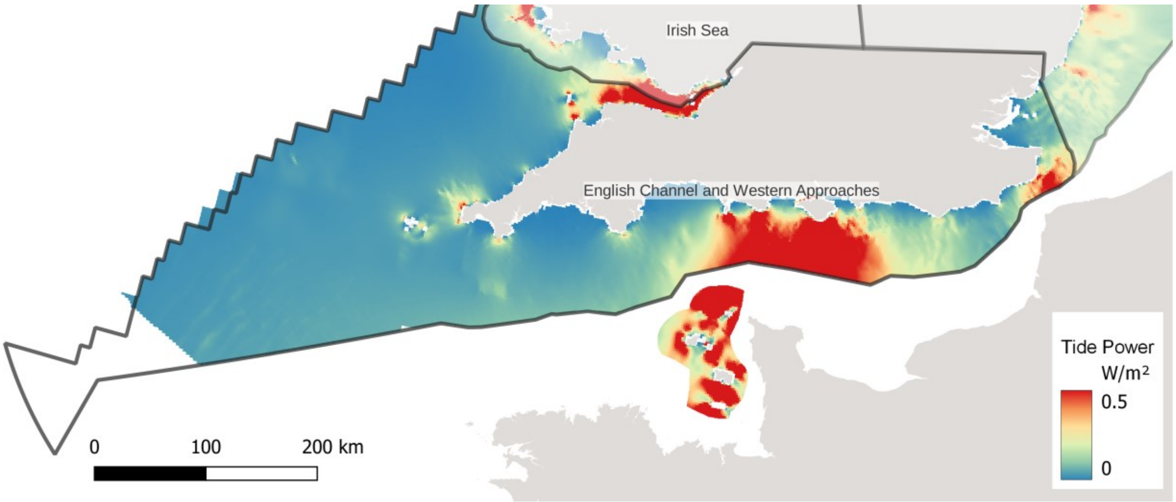


Figure 7. Tidal power in the English Channel and Western Approaches Region. Data from the UK Atlas of Marine Renewables (a free resource hosted by ABPmer, 2022).

Sedimentation of POC transfers CO_2 from the atmosphere to the seabed, where it may be stored long term (from decades to centuries), mitigating increases in atmospheric CO_2 levels associated with climate change. Coarse sandy sediments allow water to flow freely through the upper parts of the sediment. This results in oxygen penetration allowing rapid carbon cycling and therefore low carbon storage in these sediments (Alonso *et al.,* 2012). Mud content and distance from the shore are factors that influence the OC content of sediments (Diesing *et al.,* 2017). Coarse sands do not have such high OC densities as inshore dense muds and vegetated habitats (see Table 16). Diesing *et al. (*2017) measured POC in UK shelf sediments. They found that the highest POC concentrations are associated with gravelly mud, mud and sandy mud. Conversely, sands, gravel and sandy gravel exhibit the lowest POC concentrations. Offshore sands are much less likely to provide this service at high levels than are inshore mud and vegetated habitats, but may support a large store due to the broad extent of these habitats. Distance from the shore is also a factor influencing POC, due to the importance of terrestrial inputs. Particulate OC is higher in mud sediments (Diesing *et al.,* 2017), and mud content has been used as a proxy for OC storage by Hooper *et al. (*2017), based on studies by de Falco *et al.* (2004), McBreen *et al.* (2008) and Serpetti *et al.* (2012).

There are existing studies of intertidal sediments within the ECWA Region. Direct measurements of OC in this Region include two studies by Trimmer *et al. (*1998, 2012). Trimmer *et al.* (1998) reported OC storage density (to a depth of 20 cm) of 13.33–171.75 g C/m^2 or 0.13–1.72 t C/ha (originally reported as 1.11–14.30 mol/m^2) for sites in the lower part of the Ouse estuary (cited in Gregg *et al.,* 2021).Cundy and Croudace (1995) measured total OC and carbonate (i.e., IC) at two sites with contrasting sediments and energy environments in Poole Harbour.

Wood *et al. (*2015) collected surface sediment samples across English mud and sandflats in Essex and around Morecambe Bay. The available data show that the percentage of carbon (dry weight) contained in intertidal flat sediments is in the range of 0–7.5%, with the average for Essex samples being 2.5% and the average for Morecambe Bay sites being 0.4%, and there is a clear correlation between mud and carbon content. Furthermore, the samples had a relatively high $CaCO_3$ content, in the range of 1.3–23%. Carbon can be assumed to account for 12% of the mass of $CaCO_3$. Measurements from these studies are shown in Table 15.

Table 15 Direct measurements of sediment carbon in the English Channel and Western Approaches Region.

Reference	Area	Sediment	Sediment carbon (t C/ha)	Organic carbon (%)	$CaCO_3$ (%)
Trimmer *et al.,* 1998	Great Ouse Estuary	Lower estuary silt clays	0.13–1.72	0.44–2.23 (% dry weight)	–
		Lower estuary fine to very fine sands		0.1–0.37 (% dry weight)	–
Trimmer *et al.,* 2012	Blackwater Estuary, Essex		0.13–11.72		
Wood *et al.,* 2015[1]	Essex	Mudflat (*n* = 396)		5.85 avg (% dry weight)	13.31 avg (% dry weight)
Cundy and Croudace, 1995	Poole Harbour: Wytch Farm	Area of fine sediment, backed by *Spartina* sp. salt marsh. Sheltered location next to Corfe River		1–20.1	0.1–0.9
Cundy and Croudace, 1995	Poole Harbour: Bramble Bush Bay, near harbour entrance	Area of sandy sediment, backed by mixed salt marsh		0.1–10.5	0.2–1.5

[1] Cited in Armstrong *et al.* (2020), but no reference is provided.

Carbon accumulation rates used to project OC sequestration across the ECWA Region are summarised in Table 16. By attributing an area-specific carbon accumulation rate (g C/m^2/yr) to each EUNIS 2012 habitat code, it was possible to estimate whole-Region and MPA-specific average and total rates of carbon accumulation in sediments. Ideally, measurements of local sediment accumulation rates would be combined with local OC density estimates to give a locally determined rate of carbon accumulation. Here, however, single values for carbon accumulation rates were used for each habitat type across the whole Region. Table 16 also shows typical values for OC density from literature sources, but these values are presented for comparison purposes only. Carbon density estimates for sediments in the Region were solely derived from those presented by Smeaton *et al.* (2021) (see Figure 5 in this report).

Table 16. Habitat- and area-specific estimates of organic carbon density and accumulation in marine sediments in the English Channel and Western Approaches Region.

			Stocks													Sequestration				
			%OC		1m depth kgC/m²					0.1m depth gC/m²			**Sediment** cm/yr			**Carbon Accumulation** gC/m²/yr				
EUNIS code	Habitat	Sediment type	min	max	min	max	Avg	SD	n	min	max	Avg	min	max	Avg	min	max	Avg	Source	Comment
A1	Intertidal	Rock					0					0			0			0		Logical zero
A2.1	Intertidal	Coarse					0.0					0			0.000			0.0		
A2.2	Intertidal	Sand			1.3	18.6	6.5	4	4	130	1860	650			0.989			45.0	Duarte et al 2005	
A2.3	Intertidal	Mud			5.4	35.6	19.9	4	8	540	3560	1990	1.939	0.376	0.599	73.3	93.7	83.5	Adams et al., 2012; Potouroglou, 2017; Thornton et al., 2002; Trimmer et al., 1998	
A2.4	Intertidal	Mixed																42.8		
A2.5	Coastal saltmarshes and saline reedbeds																	129.0	CEH Land Cover Map; Habitat Review (Callaway et al 1996)	
A2.6	Intertidal/Sı	Seagrass beds																100.4	Habitat Review	
A2.7	Intertidal	Biogenic reef: mussel beds/Sabellaria					0.0					0			0.000			0.0		Not known
A2.8	Littoral	Rock					0					0			0			0.0		Logical zero
A3	Intertidal	Rock					0					0			0			0.0		Logical zero
A4	Circalittoral	Rock					0					0			0			0.0		Logical zero
A5	Sublittoral	All																0.2	De Haas et al 1997	
A5	Sublittoral	All	0.02	8.86															Habitat review	
A5	Sublittoral	All			0.6	6.1	2.6			64	608	264							Diesing et al 2017	min/max as 5%/95%iles
A5	Sublittoral	All			2.8	4.0	3.3			279	402	329							Smeaton et al 2021	min/max as 5%/95%iles
A5.1	Sublittoral	Coarse																		
A5.2	Sublittoral	Sand			0.4	7.6	1.8			40	760	180						0.2	Cefas data	
A5.2	Sublittoral	Sand	0.02	0.1	0.5	2.6	1.6			52	260	156				0.1	0.3	0.2	Burrows et al 2014	
A5.3	Sublittoral	Mud														0.2	2.7	1.1	Diesing et al 2021	
A5.3	Sublittoral	Mud	1.5	8	39.0	208.0	123.5			3900	20800	12350	0.068	0.200	0.180	18.7	291.6	155.2	Burrows et al 2014	
A5.3	Sublittoral	Mud			0.6	12.3	5.5			60	1230	550							Cefas data	
A5.4	Sublittoral	Sand/mud																59.0	Queiros et al 2019	English Channel L4: EUNIS A5.4 from NE habitats data
A5.4	Sublittoral	Sand/mud														0.1	1.1	0.5	Diesing et al 2021	
A5.4	Sublittoral	Sand/mud	1.5	4	39.0	104.0	71.5			3900	10400	7150	0.168	0.206	0.101	46.0	150.0	50.6	Burrows et al 2014	
A5.5	Sublittoral	Maerl																0.0		
A5.6	Sublittoral	Subtidal biogenic reefs: mussel beds																0.0		Not net carbon sequesterin
A6																				
A6.1	Deep	Rock					0					0			0			0.0		Logical zero
A6.2	Deep	mixed substrata																		
A6.3	Deep	Sand			3.9	17.8	10.9			390	1780	1085	0.001	0.002	0.002	0.0	0.2	0.1	Burrows et al 2014	Continental Slope
A6.4	Deep	Muddy sand																		
A6.5	Deep	Mud																		
	Oceanic	Continental shelf					35.6					3560							Atwood et al 2020	
		Other Coastal					6.3					630							Atwood et al 2020	
		Continental Slope					11.5					1150							Atwood et al 2020	
		Continental Slope			3.9	17.8	10.9			390	1780	1085	0.001	0.002	0.002	0.0	0.2	0.1	Burrows et al 2014	
		Abyss/Basin					7.6					760			0.000				Atwood et al 2020	
		Hadal					8.4					840			0.000				Atwood et al 2020	

Table 17. Habitat- and area-specific estimates of inorganic carbon density and accumulation in marine sediments in the English Channel and Western Approaches Region.

			Stocks							**Inorganic carbon Sequestration**			
			%IC	0.1m depth kgC/m²			0.1m depth gC/m²			**Accumulation rate** gC/m²/yr			
EUNIS code	Habitat	Sediment type	Avg	min	max	Avg	min	max	Avg	min	max	Avg	Source
A1	Intertidal	Rock											
A2.1	Intertidal	Coarse											
A2.2	Intertidal	Sand											
A2.3	Intertidal	Mud											
A2.4	Intertidal	Mixed											
A2.5	Coastal saltmarshes and saline reedbeds												
A2.6	Intertidal/S	Seagrass beds											
A2.7	Intertidal	Biogenic reef: mussel beds/Sabellaria											
A2.8	Littoral	Rock											
A3	Intertidal	Rock											
A4	Circalittoral	Rock											
A5	Sublittoral	All											
A5	Sublittoral	All											
A5	Sublittoral	All											
A5	Sublittoral	All	8%	0.04	1.697	0.55	44	1697	554	1.18	5.58	3.38	Smeaton et al 2021; Accumulation scaled as 10% Burrows et al 2014 estimates
A5.1	Sublittoral	Coarse											
A5.2	Sublittoral	Sand											
A5.2	Sublittoral	Sand	80%						26880	11.8	55.8		Burrows et al 2014
A5.3	Sublittoral	Mud											
A5.3	Sublittoral	Mud											
A5.4	Sublittoral	Sand/mud											
A5.4	Sublittoral	Sand/mud											
A5.5	Sublittoral	Maerl											
A5.6	Sublittoral	Subtidal biogenic reefs: mussel beds											
A6													
A6.1	Deep	Rock											
A6.2	Deep	mixed substrata											
A6.3	Deep	Sand											
A6.4	Deep	Muddy sand											
A6.5	Deep	Mud											
	Oceanic	Continental shelf											
		Other Coastal											
		Continental Slope											
		Continental Slope											
		Abyss/Basin											
		Hadal											

3 Carbon Stores and Accumulation Rates across the ECWA Region and its Marine Protected Areas

As in the North Sea Region, the MPAs in the ECWA region were not designated for protection of carbon in short- and long-term stores but for biodiversity features. Here the quantities of carbon stored in sediments within the ECWA MPAs are reviewed for the assessment of their conservation value and coverage by existing designations, and the identification of potential hotspots.

3.1 Carbon in short- and long-term stores across the ECWA Region

The top 10 cm of marine sediments in the whole ECWA Region contain 35.8 Mt OC and 90.5 Mt IC (see Table 18).

3.2 Marine protected areas (MPAs)

Compared with the 45% area coverage of MPAs in the English North Sea Region of the UK (Burrows *et al.,* 2021), the ECWA MPAs cover a smaller proportion of the area of the region, totalling 32%, with MCZs accounting for 17%, SACs for 10%, SPAs for 4% and SSSIs for 1% of the total area of 111,000 km^2 (rounded up here to avoid spurious implied accuracy) (see Table 18 and Figure 8). The percentages of total long-term OC stores falling inside MPAs broadly follow the percentages of the total area covered by MCZs, SACs, SPAs and SSSIs. MCZs cover 17% of the region's OC in long-term stores (6.2 Mt OC), SACs cover 9% (3.1 Mt OC), SPAs cover 5% (1.8 Mt OC) and SSSIs cover 1% (0.3 Mt OC) of the total OC (35.8 Mt). Quantities of sediment IC in MPAs are such that MCZs cover 11% of total IC in the region (9.6 Mt IC), SACs cover 21% (19.0 Mt IC), SPAs cover 5% (4.7 Mt IC) and SSSIs cover less than 1% (0.4 Mt IC).

Table 18. Sediment carbon in long-term stores and accumulation rates in the English Channel and Western Approaches Region and its marine protected areas (MPAs). Carbon store density values were extracted from maps published by Smeaton et al. *(2021). Per-area organic carbon accumulation rates were derived from habitat reviews, and MPA totals were calculated as the product of these rates and MPA extents. Substrate was determined from the largest area component habitat. Only SSSIs with an area of over 3 km^2 are listed.*

Name	**Substrate**	**Area (km^2)**	**OC density (kg/m^2)**	**IC density (kg/m^2)**	**OC store (1,000 t)**	**IC store (1,000 t)**	**OC accumulation (g C/m^2/yr)**	**OC accumulation (kt/yr)**
English Channel/Western Approaches		111,469	0.322	0.812	**35,839**	**90,473**	16.66	1,766.27
All MCZs		19,246	0.281	0.669	6,202	9,640	19.02	248.97
All SACs		10,948	0.286	0.877	3,098	18,993	22.15	79.21
All SPAs		4,780	0.468	0.667	1,822	4,747	62.12	142.00
All SSSIs		697	0.455	0.662	276	411	63.55	43.21
Marine Conservation Zones (MCZs)								
South-West Deeps (East)	Sediment	4,675	0.360	0.226	1,681	1,056	0.17	0.776
Greater Haig Fras	Sediment	2,048	0.337	0.384	691	786	44.35	90.817
South-West Deeps (West)	Sediment	1,835	0.324	0.041	594	76	0.47	0.857
Western Channel	Sediment	1,615	0.307	0.000	496	0	1.44	2.316

Name	Substrate	Area (km^2)	OC density (kg/m^2)	IC density (kg/m^2)	OC store (1,000 t)	IC store (1,000 t)	OC accumulation (g $C/m^2/yr$)	OC accumulation (kt/yr)
South-West Approaches to Bristol Channel	Sediment	1,129	0.336	1.430	379	1,614	0.19	0.219
Offshore Brighton	Sediment	861	0.351	0.626	303	539	0.20	0.082
The Canyons	Sediment	665	0.335	0.092	223	61	0.04	0.011
Offshore Overfalls	Sediment	594	0.258	0.969	153	576	0.03	0.008
Cape Bank	Sediment	474	0.138	0.878	66	416	0.00	0.002
North-East of Haig Fras	Sediment	465	0.358	0.023	166	11	67.06	31.166
East of Haig Fras	Sediment	401	0.310	0.036	124	15	0.20	0.080
North-West of Jones Bank	Sediment	400	0.351	0.000	140	0	151.60	60.604
Hartland Point to Tintagel	Rock	304	0.108	6.514	33	1,980	0.38	0.114
Blackwater, Crouch, Roach and Colne Estuaries	Sediment	284	0.549	1.176	156	334	73.17	20.147
Purbeck Coast	Sediment	282	0.164	0.955	46	270	19.64	5.302
South of Celtic Deep	Sediment	279	0.304	0.078	85	22	10.25	2.857
Goodwin Sands	Sediment	277	0.326	0.208	90	58	5.26	1.456
Skerries Bank and Surrounds	Sediment	249	0.299	0.001	74	0	15.20	3.774
Foreland*	Sediment	242	0.260	0.947	63	230	0.02	0.006
Inner Bank	Sediment	199	0.310	1.308	62	260	19.65	3.912
Beachy Head East	Sediment	195	0.240	0.399	47	78	1.08	0.210
South Dorset	Rock	193	0.131	0.002	25	0	0.00	0.000
Albert Field	Rock	192	0.261	2.553	50	489	0.00	0.000
North-West of Lundy	Sediment	173	0.326	0.116	56	20	0.00	0.000
West of Wight-Barfleur	Sediment	137	0.354	0.000	49	0	34.86	4.785
South of the Isles of Scilly	Sediment	132	0.290	1.355	38	179	0.20	0.026
East of Start Point	Sediment	115	0.312	0.000	36	0	0.20	0.004
Bideford to Foreland Point	Sediment	104	0.137	0.317	14	33	3.97	0.353
Padstow Bay and Surrounds	Rock	90	0.098	2.017	9	182	0.34	0.031
Bembridge	Sediment	75	0.315	0.023	24	2	44.52	3.323
Thanet Coast	Sediment	64	0.280	2.033	18	129	22.47	1.421
Medway Estuary – Zone 2	Sediment	61	0.555	0.429	34	26	77.26	4.763
Medway Estuary – Zone 1	Sediment	60	0.555	0.429	33	26	76.30	4.612
Whitsand and Looe Bay	Sediment	52	0.199	0.000	10	0	8.03	0.401
Swale Estuary	Sediment	51	0.569	1.365	29	70	68.33	2.963
Kingmere	Sediment	48	0.182	1.596	9	76	8.69	0.137
Chesil Beach and Stennis Ledges	Sediment	38	0.259	0.000	10	0	29.01	0.999
Folkestone Pomerania	Sediment	34	0.314	0.052	11	2	0.64	0.022
Lundy	Sediment	31	0.099	0.000	3	0	0.04	0.001
Isles of Scilly sites: Bristows to the Stones	Sediment	28	0.021	0.000	1	0	0.01	0.000
Morte Platform	Sediment	25	0.073	0.000	2	0	0.00	0.000
Beachy Head West	Rock	24	0.237	0.083	6	2	1.26	0.028
Runnel Stone (Land's End)	Sediment	20	0.260	0.902	5	18	0.23	0.005
Torbay	Rock	20	0.240	0.000	5	0	36.88	0.258
Other MCZs (34)		6	0.250	0.526	53	3	32.08	0.124
Special Areas of Conservation (SACs)								
Bristol Channel Approaches/ Dynesfeydd Môr Hafren*	Sediment	4,803	0.290	2.586	1,392	12,420	0.18	0.846
Wight-Barfleur Reef	Rock	1,373	0.222	1.685	305	2,314	0.00	0.000
Southern North Sea*	Sediment	551	0.335	0.680	185	374	0.20	0.110
Margate and Long Sands*	Sediment	534	0.336	1.779	180	950	0.20	0.108
Haig Fras	Sediment	478	0.294	1.136	141	542	7.90	3.776
Essex Estuaries	Sediment	461	0.518	1.344	239	620	52.36	23.195

Name	**Substrate**	**Area (km^2)**	**OC density (kg/m^2)**	**IC density (kg/m^2)**	**OC store (1,000 t)**	**IC store (1,000 t)**	**OC accumulation (g C/m^2/yr)**	**OC accumulation (kt/yr)**
Severn Estuary/Môr Hafren*	Sediment	458	0.464	0.107	213	49	52.33	23.262
Start Point to Plymouth Sound and Eddystone	Sediment	341	0.146	0.625	50	213	7.61	2.583
Studland to Portland	Sediment	332	0.163	0.735	54	244	19.18	6.175
Lyme Bay and Torbay	Rock	313	0.214	0.007	67	2	12.67	2.570
Land’s End and Cape Bank	Sediment	302	0.098	2.032	30	614	0.01	0.002
Isles of Scilly Complex	Sediment	268	0.149	0.220	40	59	1.63	0.340
South Wight Maritime	Sediment	199	0.264	0.387	52	77	27.24	5.325
Lizard Point	Rock	140	0.085	2.044	12	286	0.06	0.009
Solent Maritime	Sediment	112	0.492	0.013	55	1	62.18	6.808
Bassurelle Sandbank	Sediment	67	0.321	2.211	22	148	0.17	0.012
Plymouth Sound and Estuaries	Sediment	64	0.380	0.022	24	1	70.91	2.232
Fal and Helford	Sediment	64	0.292	0.000	19	0	17.26	0.982
Lundy	Sediment	31	0.099	0.000	3	0	0.04	0.001
Thanet Coast	Sediment	28	0.258	2.347	7	66	19.49	0.534
Chesil and the Fleet	Sediment	16	0.320	0.000	5	0	28.60	0.184
Braunton Burrows	Sediment	13	0.331	0.941	4	13	45.00	0.148
Solent and Isle of Wight Lagoons	Sediment	0	0.496	0.000	0	0	106.25	0.009
West Wales Marine/Gorllewin Cymru Forol	Sediment	0	0.293	0.151	0	0	0.20	0.000
Special Protection Areas (SPAs)								
Outer Thames Estuary*	Sediment	1,887	0.404	1.542	762	2,911	15.06	28.143
Solent and Dorset Coast	Sediment	880	0.337	0.806	297	709	21.31	17.999
Skomer, Skokholm and the Seas off Pembrokeshire*	Sediment	586	0.323	0.246	189	144	66.83	39.148
Dungeness, Romney Marsh and Rye Bay	Sediment	395	0.343	1.308	136	517	49.25	16.857
Falmouth Bay to St Austell Bay	Sediment	258	0.306	0.162	79	42	2.71	0.678
Isles of Scilly	Sediment	129	0.129	0.204	17	26	3.22	0.353
Severn Estuary*	Sediment	127	0.503	0.103	64	13	60.28	7.072
Foulness (Mid-Essex Coast Phase 5)	Sediment	97	0.510	1.305	49	126	12.23	1.136
Chichester and Langstone Harbours	Sediment	51	0.534	0.000	27	0	64.38	3.257
Poole Harbour	Sediment	32	0.540	1.523	17	49	111.76	3.201
Medway Estuary and Marshes	Sediment	32	0.567	0.484	18	15	88.52	2.836
Stour and Orwell Estuaries	Sediment	31	0.572	0.550	18	17	91.34	2.737
Solent and Southampton Water	Sediment	30	0.524	0.010	16	0	71.05	2.106
The Swale	Sediment	29	0.561	1.143	16	33	81.35	2.343
Blackwater Estuary (Mid-Essex Coast Phase 4)	Sediment	28	0.588	0.921	16	26	95.33	2.299
Hamford Water	Sediment	26	0.577	0.823	15	22	43.69	1.024
Dengie (Mid-Essex Coast Phase 1)	Sediment	25	0.509	1.356	13	34	82.54	2.103
Thames Estuary and Marshes	Sediment	22	0.582	0.496	13	11	83.69	1.861
Benfleet and Southend Marshes	Sediment	22	0.566	0.307	12	7	37.58	0.696
Exe Estuary	Sediment	19	0.468	0.000	9	0	77.18	1.185
Tamar Estuaries Complex	Sediment	16	0.599	0.000	10	0	86.03	1.356
Thanet Coast and Sandwich Bay	Sediment	13	0.371	1.620	5	21	48.98	0.641
Colne Estuary (Mid-Essex Coast Phase 2)	Sediment	12	0.539	1.051	7	13	85.73	0.936
Portsmouth Harbour	Sediment	12	0.539	0.000	7	0	68.02	0.819

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (1,000 t)	IC store (1,000 t)	OC accumulation (g C/m²/yr)	OC accumulation (kt/yr)
Crouch and Roach Estuaries (Mid-Essex Coast Phase 3)	Sediment	7	0.545	0.724	4	5	95.73	0.571
Chesil Beach and The Fleet	Sediment	5	0.342	0.000	2	0	107.50	0.026
Deben Estuary	Sediment	4	0.754	0.000	3	0	87.46	0.353
Pagham Harbour	Sediment	3	0.438	1.219	1	4	79.92	0.256
Dorset Heathlands	Sediment	0	0.457	2.112	0	0	45.00	0.004
Wealden Heaths Phase 2	Rock	0	0.000	0.000	0	0	0.00	0.000
Sites of Special Scientific Interest (SSSIs)								
Foulness	Sediment	97	0.510	1.303	49	126	12.17	1.130
Severn Estuary	Sediment	79	0.467	0.175	0	0	57.75	4.063
Bridgwater Bay	Sediment	48	0.579	0.000	28	0	64.19	3.076
Poole Harbour	Sediment	32	0.541	1.508	17	48	111.76	3.201
Chichester Harbour	Sediment	32	0.508	0.001	16	0	61.41	1.958
Medway Estuary and Marshes	Sediment	32	0.567	0.496	0	0	88.08	2.981
The Swale	Sediment	29	0.561	1.143	16	33	81.29	2.341
Blackwater Estuary	Sediment	28	0.584	0.897	0	0	97.85	2.607
Dengie	Sediment	25	0.509	1.356	13	34	82.54	2.103
South Thames Estuary and Marshes	Sediment	22	0.582	0.496	13	11	83.69	1.865
Benfleet and Southend Marshes	Sediment	22	0.566	0.308	12	7	37.50	0.696
Dungeness, Romney Marsh and Rye Bay	Sediment	22	0.340	1.630	7	35	44.80	0.937
Stour Estuary	Sediment	21	0.571	0.564	12	12	87.76	1.734
Langstone Harbour	Sediment	19	0.566	0.000	11	0	69.40	1.305
Exe Estuary	Sediment	17	0.470	0.000	8	0	76.84	1.103
Colne Estuary	Sediment	15	0.544	1.060	8	16	95.09	1.289
Hamford Water	Sediment	13	0.561	0.706	7	9	102.83	1.024
Taw-Torridge Estuary	Sediment	12	0.327	0.515	4	6	45.71	0.260
Portsmouth Harbour	Sediment	12	0.539	0.000	0	0	67.92	0.812
Orwell Estuary	Sediment	10	0.574	0.478	6	5	98.49	1.009
Tamar-Tavy Estuary	Sediment	10	0.603	0.000	6	0	93.32	0.900
Crouch and Roach Estuaries	Sediment	7	0.548	0.726	0	0	95.33	0.564
Hurst Castle and Lymington River Estuary	Sediment	7	0.559	0.000	4	0	91.29	0.624
Thanet Coast	Rock	7	0.272	2.500	0	0	17.14	0.192
Blue Anchor to Lilstock Coast	Sediment	6	0.412	0.011	3	0	69.38	0.075
Sandwich Bay to Hacklinge Marshes	Sediment	6	0.467	0.844	3	5	79.02	0.461
Chesil and The Fleet	Sediment	5	0.341	0.000	2	0	92.14	0.026
North Solent	Sediment	5	0.562	0.031	3	0	72.23	0.393
Lynher Estuary	Sediment	5	0.588	0.000	3	0	86.98	0.369
Hythe to Calshot Marshes	Sediment	5	0.535	0.000	2	0	91.95	0.401
Deben Estuary	Sediment	4	0.754	0.000	3	0	87.46	0.353
Ryde Sands and Wootton Creek	Sediment	4	0.536	0.000	0	0	44.78	0.181
Braunton Burrows	Sediment	4	0.353	0.974	1	0	45.00	0.126
Lee-on-the Solent to Itchen Estuary	Sediment	3	0.555	0.000	2	0	49.08	0.183
Pagham Harbour	Sediment	3	0.438	1.219	1	4	79.92	0.256
Newtown Harbour	Sediment	3	0.472	0.064	0	0	79.95	0.313
St John's Lake	Sediment	3	0.611	0.000	2	0	57.18	0.149
Marsland to Clovelly Coast	Rock	3	0.178	1.181	0	3	1.92	0.004
Lower Fal and Helford Intertidal	Sediment	2	0.395	0.000	0	0	40.09	0.176

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (1,000 t)	IC store (1,000 t)	OC accumulation (g C/m²/yr)	OC accumulation (kt/yr)
Boscastle to Widemouth	Sediment	2	0.058	7.669	0	16	13.70	0.013
Upper Fal Estuary and Woods	Sediment	2	0.000	0.000	0	0	68.90	0.160
Sheppey Cliffs and Foreshore	Sediment	2	0.576	0.784	1	2	77.66	0.146
Holehaven Creek	Sediment	2	0.667	0.865	1	0	82.94	0.136
Northam Burrows	Sediment	2	0.341	0.979	1	2	40.14	0.059
Seaford to Beachy Head	Rock	2	0.208	0.112	0	0	1.10	0.002
Bracklesham Bay	Sediment	2	0.385	0.647	1	1	31.65	0.030
Erme Estuary	Sediment	2	0.211	1.026	0	2	37.69	0.044
Christchurch Harbour	Sediment	2	0.344	0.000	1	0	55.02	0.064
Exmoor Coastal Heaths	Rock	1	0.047	0.000	0	0	7.50	0.004
Other SSSIs (191)		0	0.252	0.805	8	33	20.14	1.310

*Indicates MCZs, SACs and SPAs that have been clipped as their boundary crosses into other regional zones. No SSSIs have been clipped in this report, which is visualised in Figure 1.

Figure 8. Marine protected areas in the English Channel and Western Approaches Region, showing total organic carbon (OC) and inorganic carbon (IC) in long-term stores per marine protected area (data from Table 18).

3.2.1 Habitat extents within MPAs

The extents of habitats across the network of MPAs (MCZs, SACs, SPAs and SSSIs) were derived using GIS processing to subset the whole Region habitat information (the Natural England Open Data habitat data layer) to the areas of the MPAs. Total areas of habitat types are shown in Table 16, and the size of associated carbon stores and the corresponding OC accumulation rates are shown in Table 18. More detailed information on habitat types is given in Section 2.2, and extents of designated features are shown in Tables 16 and 17 and described in Sections 2.3–2.7.

3.2.2 Visualising patterns of stores and accumulation rates across MPAs

There are 372 separate MPAs (78 MCZs, 24 SACs, 30 SPAs and 240 SSSIs) in the ECWA Region, each of which contains more than one habitat type, making simple comparisons among them based on inspection of tabulated data extremely difficult. Marine protected areas span habitats ranging from deep seabed to coastal rock and saltmarsh, with offshore MPAs covering larger areas, and shallow and intertidal (circalittoral) MPAs being generally smaller. However, the patterns of carbon storage among these varied and widely different MPAs can be visualised using ordination techniques known as non-metric multidimensional scaling (MDS) (see Figure 9), based on the composition of habitats within each MPA boundary. The ordination analysis separated small, shallow coastal areas on the right of the MDS plots from large, deep offshore areas on the left of the plots. Marine protected areas composed of rocky and coarse sediment habitats were placed at the bottom of the plots, while those composed predominantly of mud seabed were placed towards the top, with those composed of sand and coarse sediments placed halfway up. With regard to the variation in total area of each MPA, offshore (‘sublittoral’) MPAs (see Figure 9a) tend to be much larger than inshore (‘littoral) ones, with the largest of these composed mostly of sand and coarse sediment (see Figure 9b).

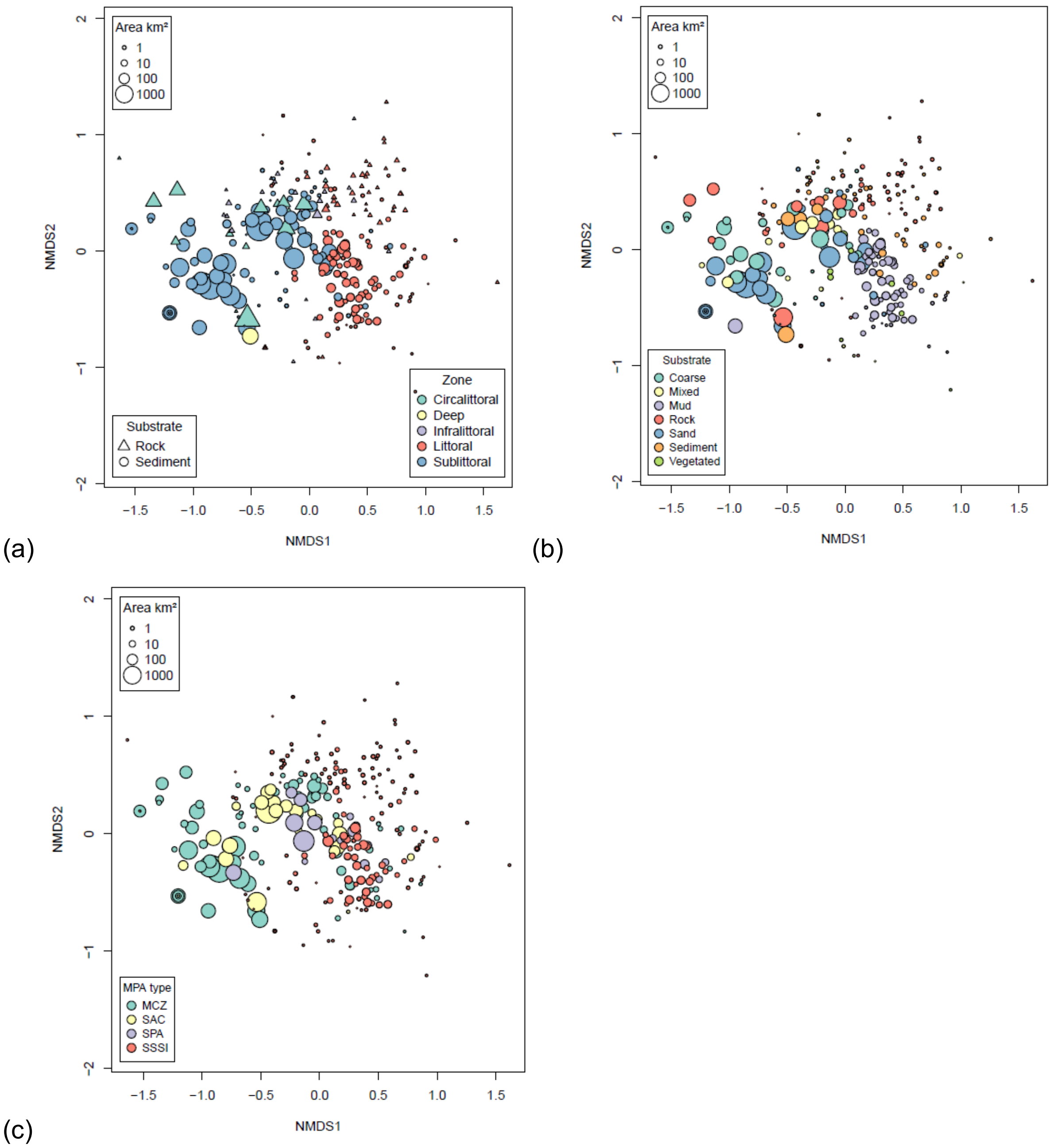


Figure 9. Ordination of the area-based composition of habitat types across the English Channel and Western Approaches Region MPAs using non-metric multidimensional scaling. Each symbol represents a single MCZ, SAC, SPA or SSSI, with the size of the symbol indicating the area of each MPA: (a) the type of symbol denotes the seabed type, and the colour denotes the depth zone; (b) the colour denotes the substrate type; (c) the colour denotes the MPA type.

SSSIs are much smaller than SACs and MCZs, and appear exclusively in coastal areas (see Figure 9c). Although relative areas of MPAs are easy to grasp without the need for this graphical approach, the patterns of carbon storage and accumulation are more complex, and will be addressed in Sections 3.2.3 and 3.2.4.

3.2.3 Carbon in long-term stores in the ECWA Region's MPAs

The amount of carbon in long-term stores in each MPA (see Table 18) depends on the kinds of habitat present. Using the Natural England GIS data for seabed habitats across the Region (see Table 1), the extent of each habitat type present in each MPA was estimated. Although the resolution of the habitat information often exceeded the resolution of the available sediment carbon data (see Figure 5), the mix of habitats and dominant habitat by area were good indicators of the value of the MPAs in terms of OC density (see Figure 10) and total OC store. Small inshore MPAs, mostly SSSIs (see Figure 10c), had the highest OC density values (see Figure 10a), and were composed mainly of mud habitats (see Figure 10b). Marine protected areas with predominantly rocky habitats had unexpectedly significant OC density values from the matching of the interpolated point sampling of OC in sediments to the seabed habitat map information. This was probably due to the proximity of OC-rich coastal mud habitats to rocky areas, as is seen in other locations, such as Scottish sea lochs.

Despite the variation in OC density across the MPAs, with a tendency towards higher OC densities in shallow coastal muddy areas, the total OC store was much larger in the more extensive offshore MPAs, particularly those MCZs and SACs that contained sand and coarse sediment (see Figure 11).

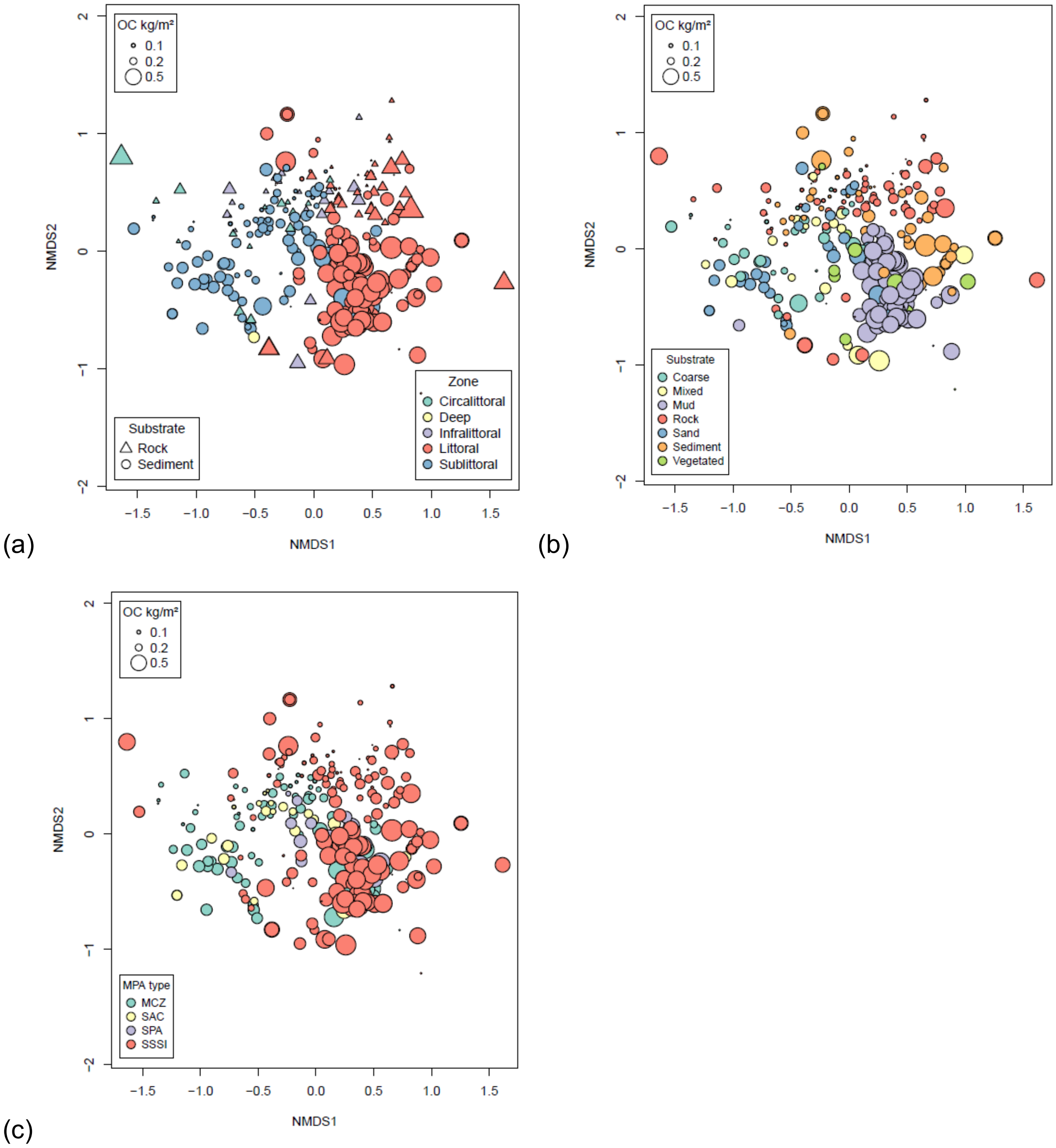
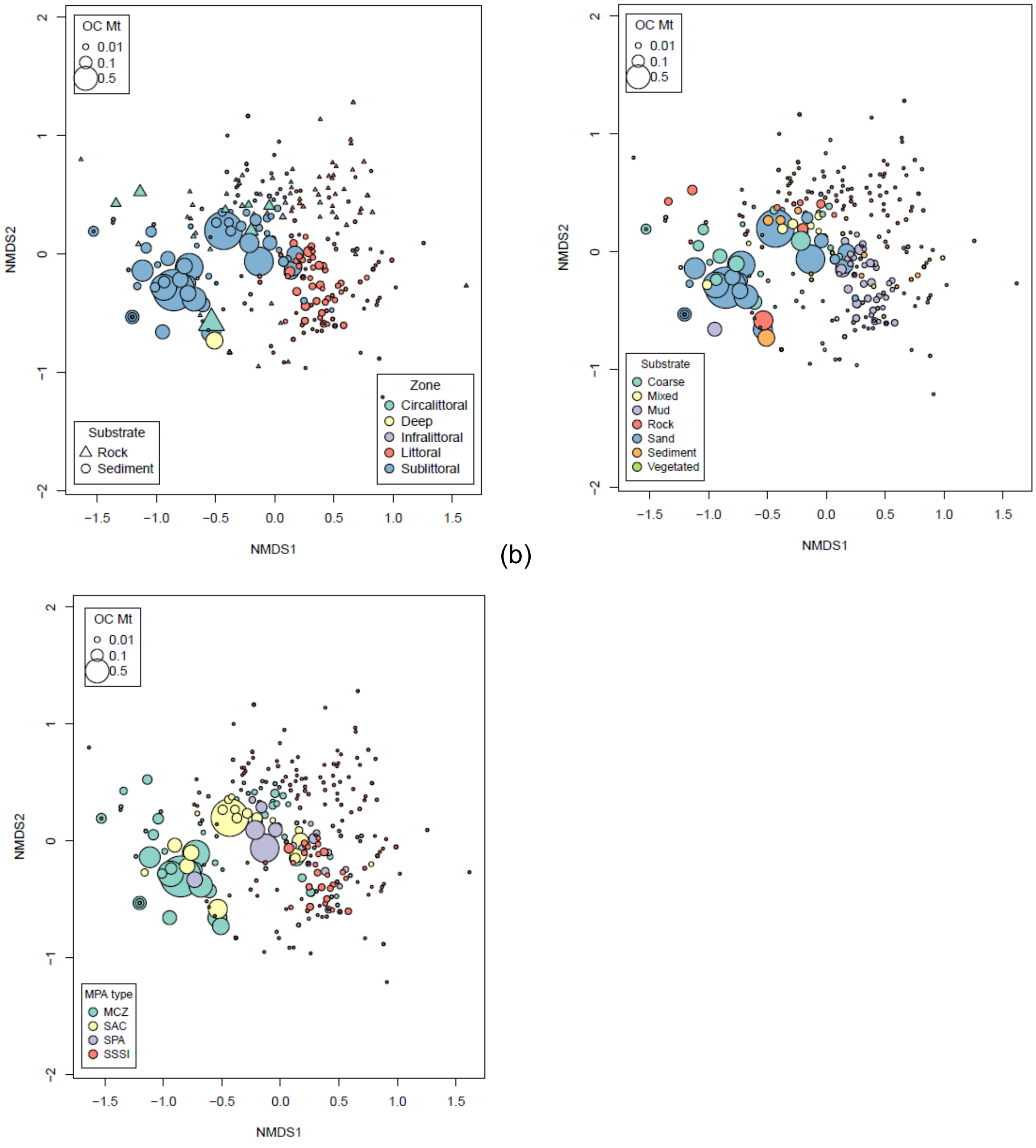


Figure 10. Ordination of the area-based composition of habitat types across the English Channel and Western Approaches Region MPAs using non-metric multidimensional scaling. Each symbol represents a single MCZ, SAC, SPA or SSSI, with the size of the symbol representing the average organic carbon (OC) content (in kg/m^2) in the top 10 cm of sediment:

(a) the type of symbol denotes the seabed type, and the colour denotes the depth zone; (b) the colour denotes the substrate type; (c) the colour denotes the MPA type. Zone and substrate types in (a) and (b) are taken from EUNIS 2012 habitat descriptions.

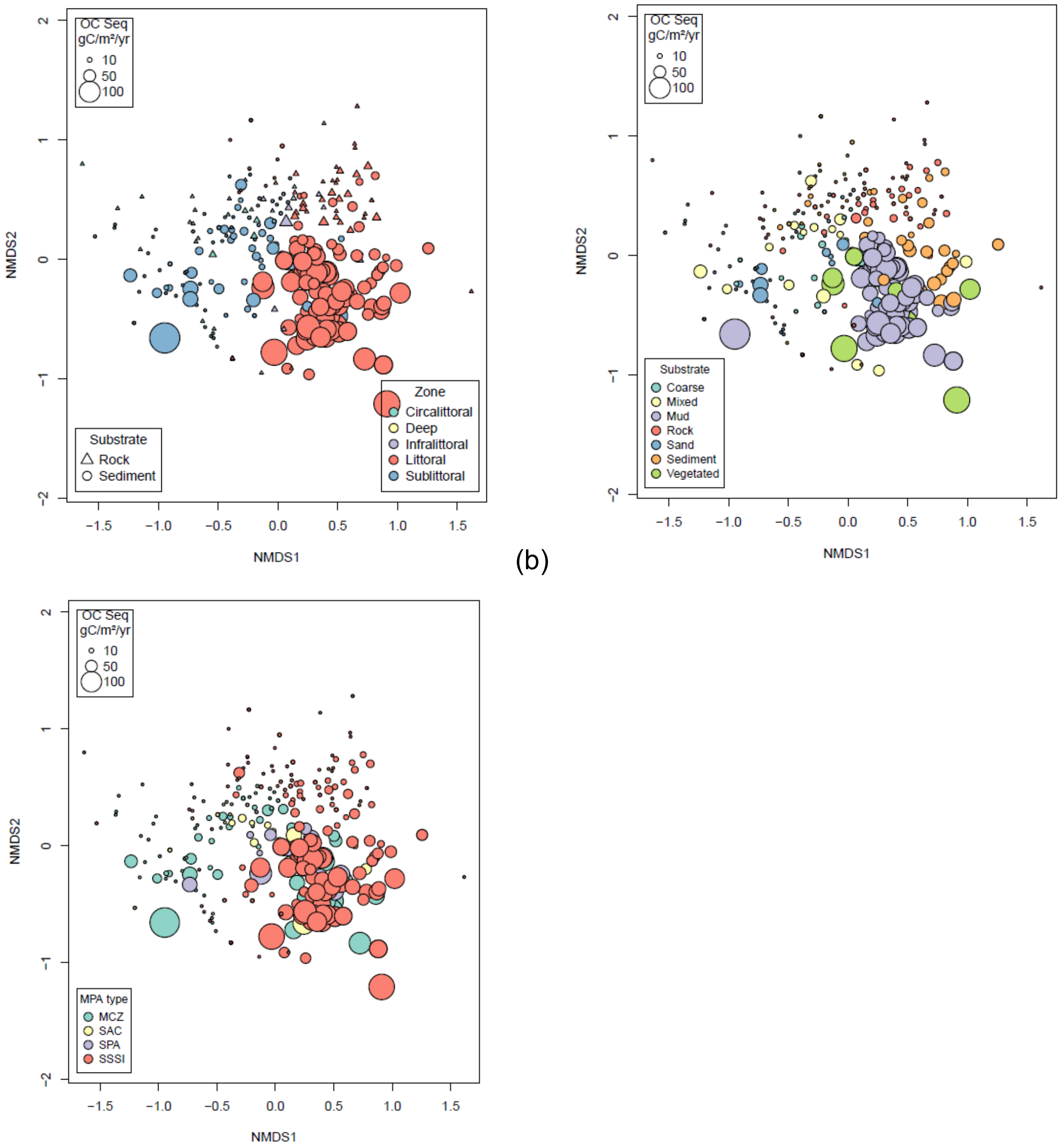


(a) (b) (c)

Figure 11. Ordination of the area-based composition of habitat types across the English Channel and Western Approaches Region MPAs using non-metric multidimensional scaling. Each symbol represents a single MCZ, SAC, SPA or SSSI, with the size of the symbol representing the total organic carbon (OC) store (in Mt) in the top 10 cm of sediment: (a) the type of symbol denotes the seabed type, and the colour denotes the depth zone; (b) the colour denotes the substrate type; (c) the colour denotes the MPA type.

3.2.4 Rates of carbon accumulation across the ECWA Region's MPAs

Estimated area-specific rates of OC accumulation in sediments, using habitat-specific accumulation rates from Table 18 and summed across the within-MPA habitat extents to give the values in Table 18, can also be visualised in this framework. The MPAs with high OC density tended to be those with the highest estimated carbon accumulation rate (Pearson's correlation coefficient *r* = 0.69, *n* = 322; compare Figure 10 with Figure 12). This association was expected, as the latter measure was driven strongly by the presence of rapidly accumulating mud habitats in each MPA.



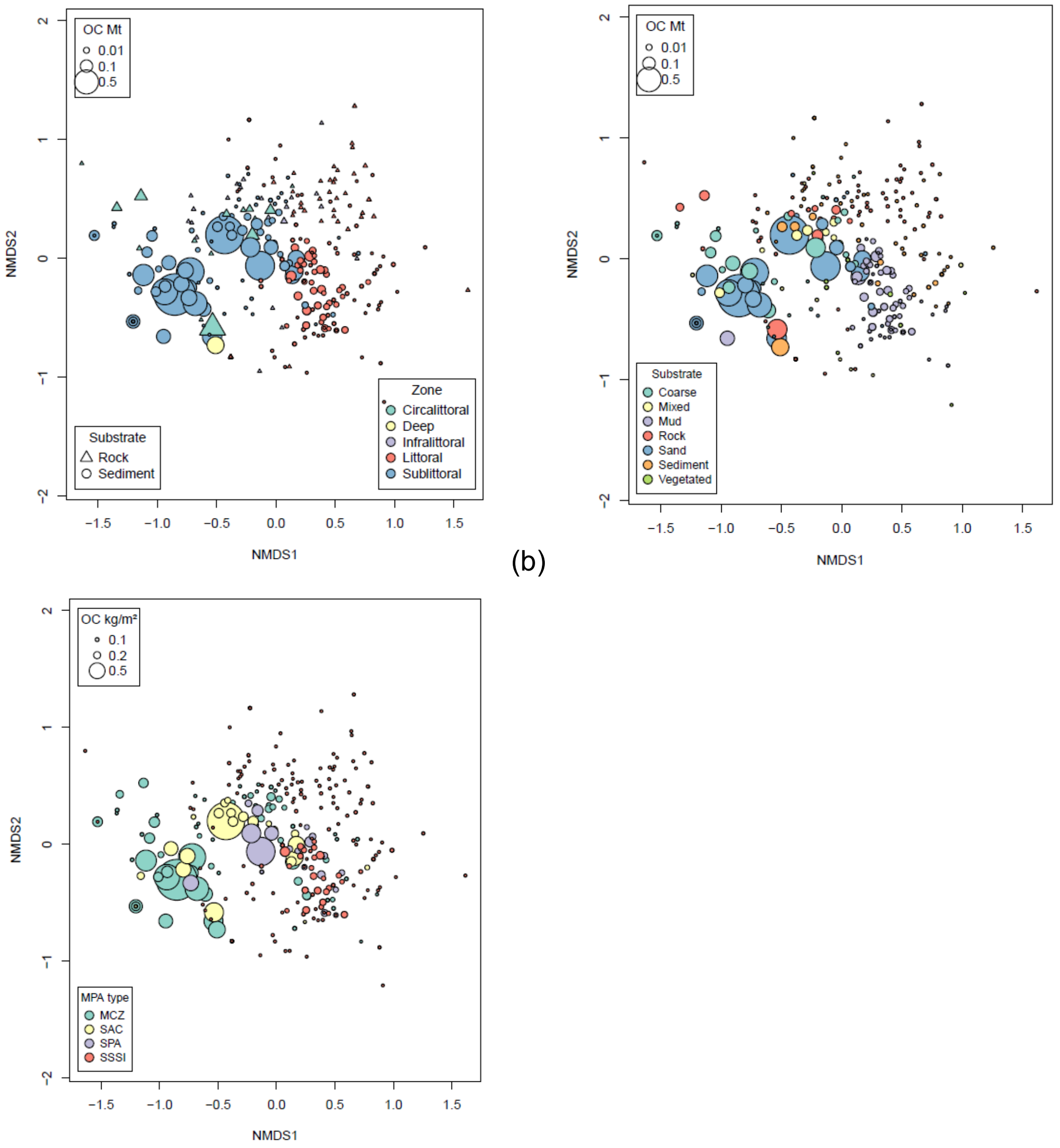
(a)

(b)

(c)

Figure 12. Ordination of the area-based composition of habitat types across the English Channel and Western Approaches Region MPAs using non-metric multidimensional scaling. Each symbol represents a single MCZ, SAC, SPA or SSSI, with the size of the symbol representing the sediment organic carbon (OC) accumulation rate (in g C/m^2/yr): (a) the type of symbol denotes the seabed type, and the colour denotes the depth zone; (b) the colour denotes the substrate type; (c) the colour denotes the MPA type.

Combining the MPA-specific estimates of OC accumulation based on their component habitats with the total extents of each MPA gave their OC sequestration capacity (see Figure 13). Although the large offshore MPAs (MCZs and SACs) still dominated the list, those MPAs with predominantly littoral mud (including many SSSIs; see Figure 13c) were also important. The higher OC densities in their sediment and the more rapid rates of carbon accumulation make the smaller inshore MPAs (SSSIs) disproportionately important as carbon-accumulating locations.



(a)

(b)

(c)

Figure 13. Ordination of the area-based composition of habitat types across the English Channel and Western Approaches Region MPAs using non-metric multidimensional scaling. Each symbol represents a single MCZ, SAC, SPA or SSSI, with the size of the symbol representing the total sediment organic carbon (OC) accumulation rate (in Mt/yr): (a) the type of symbol denotes the seabed type, and the colour denotes the depth zone; (b) the colour denotes the substrate type; (c) the colour denotes the MPA type.

3.3 Ecosystem-scale carbon budget

Summarising the dynamics of carbon in short- and long-term stores across the main blue carbon habitats and seabed sediments (see Table 19) shows the relative importance of each component. Although some elements remain unknown, these values demonstrate the overriding importance of phytoplankton as the primary source of carbon (and it is assumed to have a habitat roughly the same size as the sediment or seafloor area) and sublittoral sediments as the main store of OC in the ECWA Region.

Table 19. Summary of short- and long-term carbon stores and sequestration capacity in the English Channel and Western Approaches Region. The values shown summarise carbon in short- and long-term stores with extent estimates from the habitat reviews (see Sections 2.1–2.6), and the description of sediment carbon stores (see Section 2.7). Grey background indicates that either no data are available or there is insufficient evidence to present values with confidence. The lower part of the table lists contributions by blue carbon habitats. Method 1 is described in Section 2.7.3 (see also Burrows et al.*, 2021).*

English Channel and Western Approaches		**Organic carbon**									**Inorganic carbon**					
Habitat	Extent (km^2)	Organic carbon total (Mt C) [0.1m depth]	Organic carbon density (g C/m^2)	Production rate (g C/m^2/yr)	Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m^2/yr)	Storage capacity (1000t C/yr)	Storage timescale (half life)	Stock (Mt C) [1m depth]	Stock (kg C/m^2) [1m depth]	Storage rate (g C/m^2/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Phytoplankton	111469			81	9069	907										
All sediment (Method 1)	111469	35.8	322				1730	17.4	1730		90	0.8	3.4	341		
Biogenic habitats	1396	0.7		298	416	42	67		67							
Total / Average	112865	36.5		84	9485	949	1798		1798		90			341		
Long-term stores		36.4														

		Organic carbon									**Inorganic carbon**					
Habitat	Extent (km^2)	Organic carbon total (Mt C) [0.1m depth]	Organic carbon density (g C/m^2)	Production rate (g C/m^2/yr)	Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m^2/yr)	Storage capacity (1000t C/yr)	Storage timescale (half life)	Stock (1000t C)	Stock (kg C/m^2)	Storage rate (g C/m^2/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Vegetated habitats																
Kelp beds	1141.3	102.6	90	332	379.1	37.9		0	0							
Intertidal macroalgae	45.1	6.1	122	378	17.1	1.7		0	0							
Seagrass beds	9.9	23.6	2390	274	2.7	0.3	0.7	100.4	1.0							
Saltmarshes	121.5	530.5	4367	138	16.8	1.7	66.8	129.0	68.4							
Maerl beds	15.9	11.5	720													
Biogenic reefs																
Modiolus / Mytilus beds	35.3															
Sabellaria reefs	27.0															
Total	1396.0	674.3		298	415.7	41.6	67.5	11.9	69.4	0.0						
Long-term stores		565.6														

3.3.1 Organic carbon (OC)

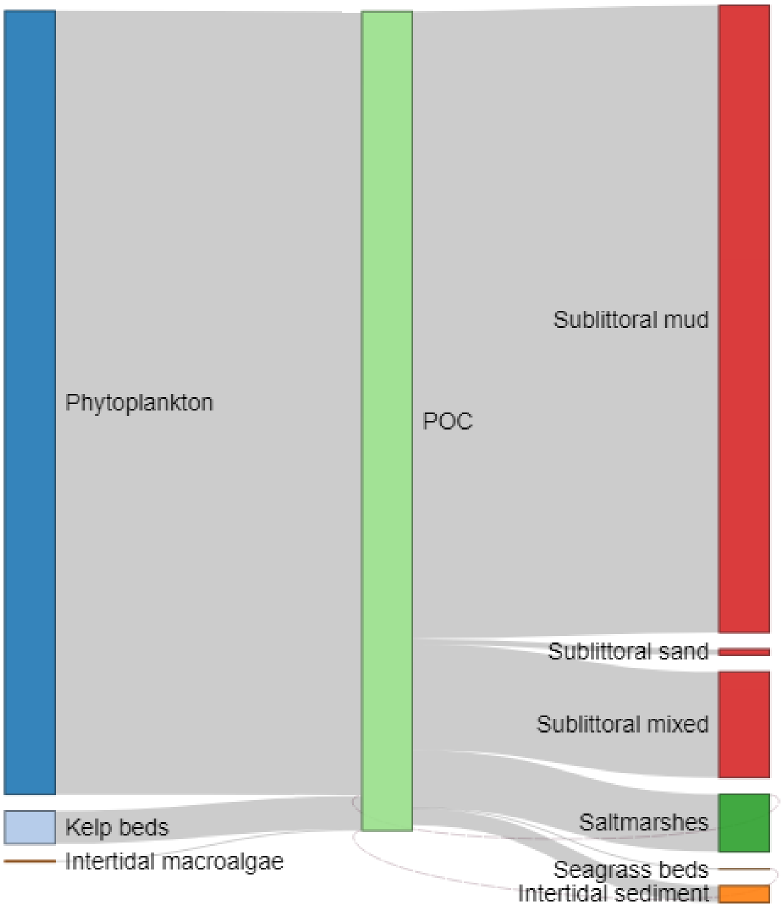


Figure 14. Annual flows of organic carbon from sources to short- and long-term stores in the English Channel and Western Approaches Region, based on values presented in Table 19, and shown as a Sankey diagram with flows from left to right. The heights of each block represent the flows into and out of each carbon source or sink, with the sum of particulate organic carbon (POC) produced annually from phytoplankton (green central bar) estimated to be 907,000 t C (0.91 Mt C/yr) for reference. Total inputs of POC to stores (1.74 Mt C/yr) have been scaled to match estimated total outputs from primary producers (0.95 Mt C/yr).

Flows of OC from sources to stores (see Figure 14) show the dominant contribution of phytoplankton over coastal vegetated habitats (blue carbon in the original sense). Elsewhere it has been assumed that 10% or less of annual production of organic material as plant growth and reproduction is exported as POC. Given this percentage and the estimated total production from phytoplankton in the Region using values reported in the literature (81 g C/m^2/yr), a total of 0.91 Mt C may be added to the POC pool each year by phytoplankton. Annual macroalgal and plant growth and losses in blue carbon habitats contribute 42,000 t C to POC, with kelp beds potentially accounting for most of this POC (38,000 t C), followed by saltmarshes (1,700 t C), intertidal macroalgae (1,700 t C) and seagrasses (300 t C). The annual export of POC from blue carbon habitats (kelp, seagrass and saltmarsh) is 9% of the combined total exported by phytoplankton and blue carbon habitats.

The accumulation of OC in blue carbon habitats and sediment stores is estimated independently of estimated exports of POC, being largely calculated from sediment accumulation rates. Unlike the North Sea region (Burrows *et al.*, 2021), the total estimated import of OC to sediment stores based on habitat-specific carbon accumulation rates (1.80 Mt

C/yr; see Table 19, Influx) is much greater than the estimated total exports of OC from primary producers (phytoplankton and coastal vegetation export 0.95 Mt C/yr as detritus to the POC pool; see Table 19, Outflux). Blue carbon habitats, particularly saltmarshes, accumulate OC at a faster rate than offshore sediments.

3.3.2 Inorganic carbon (IC)

Inclusion of IC in an audit such as this can be misleading, since the overriding consideration must be that the calcification process that produces the shell material which forms the bulk of this carbon store releases CO_2, and therefore cannot contribute positively to a greenhouse gas inventory (Frankignoulle *et al*., 1994). However, information on the extent of the IC stores and their dynamics remains important, since the dissolution of already formed calcium carbonate material can increase alkalinity, absorbing dissolved CO_2 and countering ocean acidification. Using only a single value for IC accumulation in sediments (see Table 19) produces an estimate of IC accumulation in the ECWA Region of 0.34 Mt C/yr. That estimate must be seen as highly uncertain due to relatively low confidence, as it is based on rates from outside the Region.

3.4 Risks to carbon in long-term stores

In this section, multiple pressures on the existing carbon in long-term stores are discussed, most of which are viewed as being the result of use of the environment, or the exploitation of ecosystem services within the study region. Conservation objectives can vary according to region and MPA designation, but here the pressures discussed are those that relate to the use of the environment and, specifically, the risks they pose to conservation or preservation of the carbon in long-term stores that they might disturb (Knights *et al*., 2013).

3.4.1 Climate change

Overall, the impacts of climate change on blue carbon ecosystems and the habitats that they provide can be variable, depending on the location (e.g., latitude) and type of change (e.g., temperature, acidification). Blue carbon provides an opportunity to mitigate the effects of change, while at the same time being potentially vulnerable to certain changes (Lovelock and Reef, 2020). Some impacts, such as available irradiance, might have a major influence on the primary production of features such as maerl, and can explain more than 94% of the carbon fluxes for assessed maerl beds (Martin *et al.,* 2006). Consequently, variation in irradiance provoked by anthropic impacts and climatic changes (albedo, variations in the water height or turbidity) could exert an influence on maerl. Elevated temperatures across the ECWA Region may cause some species to decline and others to flourish (e.g., the warm-tolerant kelp *Laminaria ochroleuca*) (Smale *et al.,* 2014; Schoenrock *et al.,* 2019). Sea-level rise might be exacerbated by certain coastal defence systems reducing the space available for systems to expand and deepening beaches, an effect known as coastal squeeze (Burden *et al.,* 2020). Other factors, such as restoration programmes, could increase the area occupied by blue carbon systems (multiple programmes are under way). Additional exchange of atmospheric CO_2 with the oceans (ocean acidification) could increase the capacity for features such as seagrass to photosynthesise, and thereby potentially enhance survival rates (Lowell *et al.,* 2021) and carbon sequestration for certain species (Garrard and Beaumont, 2014). There are some uncertainties about what specific impacts will be felt by blue carbon ecosystems in the region (Lovelock and Reef 2020), but it is important to have a clearer understanding of the protections afforded by MPAs and the pressures that they are under (Schmidt *et al.,* 2022).

3.4.2 Natural disturbance

The level of natural disturbance to which habitats are exposed varies considerably, and is influenced by wave action, depth, currents and factors such as sediment cohesion. One impact of climate change is the intensification of natural disturbances which might lead to more frequent and intense weather events.

3.4.3 Fishing

Trawling and dredging of the seabed with mobile fishing gears causes an increase in sediment resuspension and a subsequent increase in turbidity of the water column. An increase in turbidity causes a decline in the penetration depth of light, as well as an increase in sedimentation rates once the resuspended particles settle back out of the water column. In addition, deposition in other more vulnerable areas is possible. Increased turbidity of the water column has direct consequences for the fauna, mainly by affecting food availability.

Penetration of gear parts into the seabed depends on the pressure that the gear part exerts on the seabed, and is mainly determined by the shape and mass of the gear (Noack, 2017). The map provided in Figure 15 takes into consideration gear size to identify the intensity of abrasion and sub-surface abrasion resulting from mobile fishing gears. The area of intense activity includes the eastern and western parts of the English Channel and parts of the Western Approaches and Celtic Sea. The degree of impact on blue carbon stored within sediments (the main habitat affected) is unclear, and will be partially determined by the depth of carbon stored and the degree of natural disturbance to sediments. There is currently some debate in the literature about the extent of disturbance that mobile fishing gear causes to carbon stores in the seabed (Sala *et al.,* 2021: Epstein *et al.,* 2022). Further evidence is needed to precisely quantify the amount of carbon that is lost through trawling and dredging.

The interaction of the effects of natural variation and bottom fishing on seabed communities across the North Sea and English Channel was assessed by Diesing *et al. (*2013). Natural disturbance was determined by estimating the number of days each year that the seabed was disturbed by tides and waves. Disturbance of the seabed was considered to occur if energy acting on the seafloor exceeded certain energy thresholds; these levels varied depending on the type of sediment (i.e., gravel, sand or mud). The study found that the effects of natural disturbance were strongly correlated with depth, with a higher frequency and magnitude of disturbance in shallower waters. In areas where higher frequencies of natural disturbance were modelled, the frequency exceeded that of bottom fishing activity. The probability that natural disturbance is greater than fishing disturbance varies spatially across the English Channel. Fishing disturbance remains below natural disturbance levels in areas close to the coast and in shallow areas, but high levels of significant fishing disturbance occur across the eastern and western Channel.

Deep circalittoral seabed, which is below the wave base and typically aphotic, is mainly limited to the western English Channel.

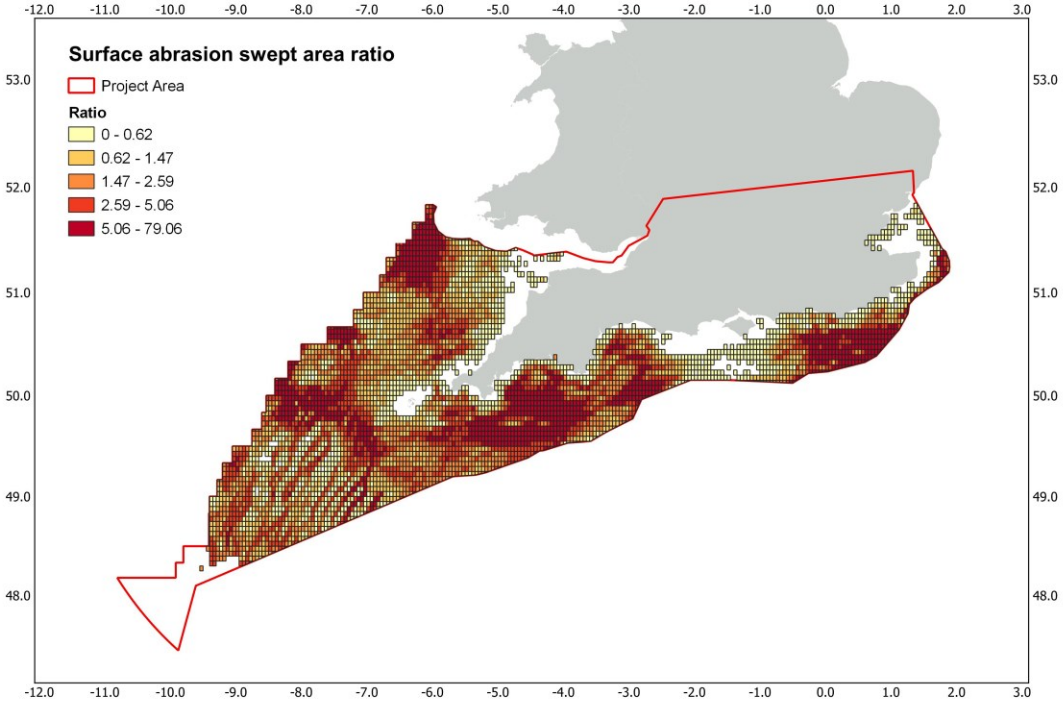


Figure 15. Surface abrasion extent in the English Channel and Western Approaches Region. From OSPAR (2018).

3.4.4 Aggregate extraction

Approximately 20 Mt of sand and gravel are dredged from the seabed in England and Wales each year; in 2021 alone, 21 Mt of sand and gravel were dredged (Tillin *et al.,* 2011; The Crown Estate, 2022). The coarse and sandy sediments in the eastern part of the English Channel are targeted for aggregate extraction (see Figure 16). This region is characterised by high tidal currents, resulting in low levels of OC within the fine sands that are characteristic of this area. Aggregate extraction will release and re-suspend finer particles through direct disturbance or sorting and grading of extracted sediments. Fine plumes are observed behind dredgers, and these will be redistributed and may remain in the water column for some time, given the high levels of water movement. Blue carbon habitats are not targeted for aggregate extraction. Consequently, this source of physical disturbance, which occurs in highly disturbed areas through fishing and natural processes (Diesing *et al.,* 2013), is unlikely to significantly alter carbon capture and storage within the eastern English Channel.

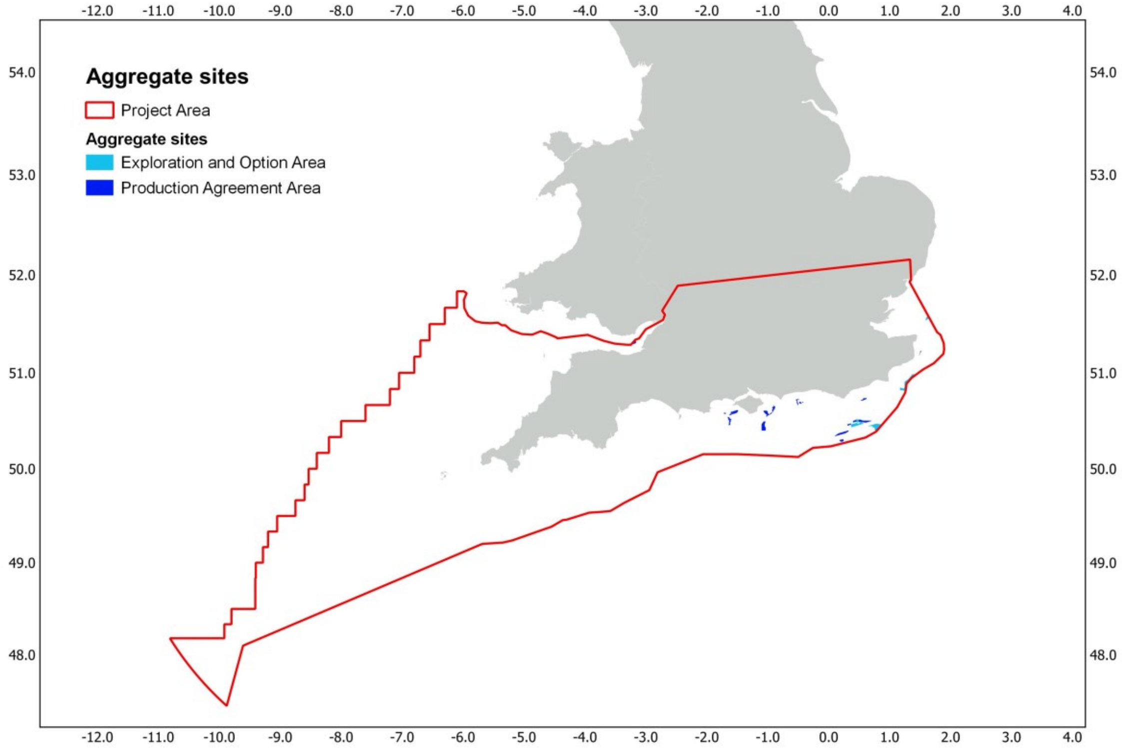


Figure 16. Aggregate extraction sites in the English Channel and Western Approaches Region.

3.4.5 Offshore renewables

Offshore renewable energy installations currently consist of wind farms in the eastern part of the ECWA Region (see Figure 17), with a smaller area to the north of Cornwall and another planned for the area west of the Bristol Channel. However, use of marine renewable energy is set to increase, and south-west England has various schemes in place to develop wind, wave and tidal energy. The Crown Estate have determined significant areas of the Celtic Sea as Project Development Areas for floating offshore wind development.

The impacts of offshore energy infrastructure and development on benthic or blue carbon habitats are poorly understood. Prominent gaps in current knowledge include (1) potential changes in primary production which could have a knock-on effect on filter feeders, all brought about by altered hydrodynamics, (2) non-native species introductions or range expansions due to increased boat traffic and foreign infrastructure, and (3) benthic community effects due to noise and vibrations caused by boats and during construction (Dannheim *et al.,* 2020). However, it has been pointed out by some authors that artificial reefs created by the foundations of wind turbines can increase species abundance and richness, and that biodiversity loss in soft sediments is minor (Li *et al.,* 2023). It has also been suggested that there may be a marine protected area effect which results from the infrastructure around wind farms in an area where fishing and other disturbance is not permitted or possible (Ashley *et al.,* 2014).

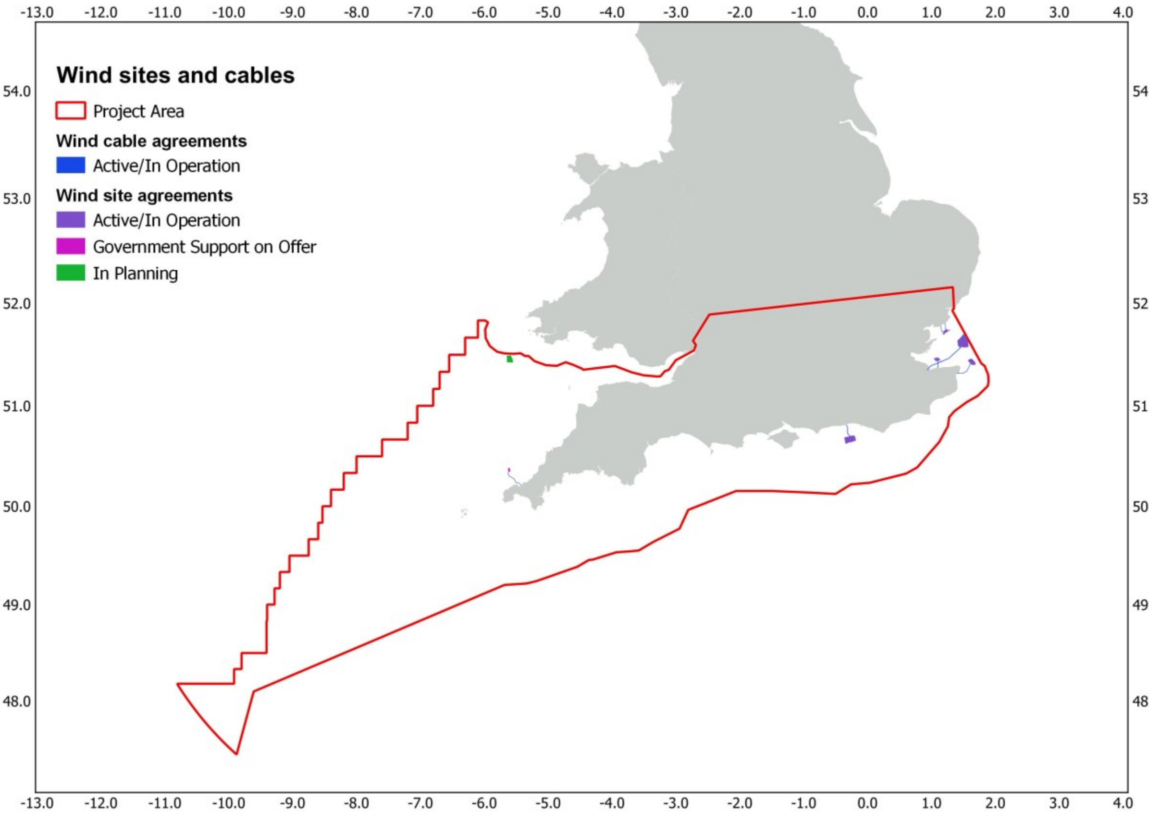


Figure 17. Offshore wind installations in the English Channel and Western Approaches Region.

3.4.6 Anchoring and mooring

Recreational and commercial anchoring and mooring has the potential to damage MPA features through abrasion of the surface of the seabed, penetration of the seabed, and causing habitat change from one habitat type to another (through the introduction of artificial hard substrate in the form of mooring blocks). Exposure to anchoring and mooring may alter carbon storage and sequestration in similar ways to other physical disturbance. However, the evidence for impacts is limited for habitats other than seagrass beds. Griffiths *et al. (*2017) assessed the sensitivity of MPA features to these pressures and the level of exposure. Summaries of exposure to pressures arising from anchoring and mooring activities were produced for MPA sites (170 sites with sensitive features assessed). Exposure to anchoring and mooring within MPA sites was generally low, and extremely patchy. Risk of impacts was also generally low (due to large features and small footprint), but in some cases sensitive features may be vulnerable due to very high levels of exposure (e.g., Bembridge, St Helen's Road Anchorage). Mitigation measures are mostly voluntary, since few organisations have statutory power to manage anchoring of either recreational or commercial vessels, as the requirements for maritime safety override conservation issues. Voluntary measures for the management of anchoring generally involve a diversity of sea users, including responsible authorities as well as recreational and commercial interests, and may be 'owned' locally or by national organisations. Licensing for mooring by the Marine Management Organisation (MMO), The Crown Estate (TCE) and other licensing authorities considers site designations.

3.5 Opportunities

There are initiatives to restore saltmarsh through managed realignment and other techniques which aim to mitigate and offset saltmarsh loss, as well as active programmes in the Solent and in the Fal Estuary in Cornwall which are aimed at restoring seagrass meadows to their former state. As of March 2022, the largest seagrass restoration project in England (led by

Natural England) had planted approximately 70,000 seed bags over 3.5 hectares of seabed, including the Isles of Scilly, Plymouth Sound and the aforementioned projects. As the Environment Agency's (2022) saltmarsh report states: "Environment Agency Regional Habitat Compensation and Restoration Programme (HCRP) leads have been assigned throughout England to develop and deliver schemes to meet the requirements detailed in the Habitats Regulations Assessments (HRAs) of Shoreline Management Plans (SMPs) and aligned to the Environment Agency's National Flood and Coastal Erosion Risk Management Strategy. These programmes work collaboratively and strategically to monitor long-term habitat change at regional level and mitigate against loss through habitat compensation (see Hardiman, 2018)."

Another cross-Defra restoration initiative, known as ReMeMaRe, aims to reverse the decline of estuarine and coastal habitats by Restoring [seagrass] Meadow, [salt] Marsh and [oyster] Reef. ReMeMaRe have produced a set of handbooks[1] that provide guidance on restoration approaches such as managed realignment.

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[1] www.gov.uk/government/news/restoration-handbooks-published-to-give-best-practice-advice-on-creating-new-estuarine-and-coastal-habitats

4 Case Study: Plymouth Sound National Marine Park

4.1 Introduction

Plymouth Sound and its associated tributaries comprise a complex site of marine inlets. The ria systems entering Plymouth Sound (St John's Lake and parts of the Tavy, Tamar and Lynher), the large bay of the Sound itself, Wembury Bay, and the ria of the River Yealm are of international marine conservation importance due to their wide variety of salinity conditions, sedimentary and reef habitats, wave exposure and water depth. The high diversity of habitats and conditions gives rise both to communities that are representative of ria systems and to some unusual features, including abundant southern Mediterranean-Atlantic species which are rarely found in Britain.

There is a wide range of protection designations and blue carbon habitats within Plymouth Sound. The Sound's waters are recognised for their national and international importance for wildlife and heritage through designations as an MCZ and Natura 2000 sites (SAC and SPA), and they contain protected wreck sites and intertidal SSSIs. Plymouth Sound was also designated as the first National Marine Park in the UK. The multiple stakeholder involvements, ecological importance and novel management measures that are in place make Plymouth Sound an ideal candidate for further discussion.

The Plymouth Sound and Estuaries European Marine Site (EMS) is made up of the Plymouth Sound and Estuaries SAC and the Tamar Estuaries Complex SPA (see Figure 18). The conservation objectives which apply to the SAC are to ensure that, subject to natural change, the integrity of the site is maintained or restored as appropriate and that the site contributes to achieving the favourable conservation status of its qualifying features.

Six different Annex 1 habitats are designated as protected features of the Plymouth Sound and Estuaries SAC, namely Atlantic salt meadows, estuaries, large shallow inlets and bays, mudflats and sandflats not covered by seawater at low tide, sandbanks which are slightly covered by seawater all the time, and reefs. Seagrass (*Zostera marina*) beds are a sub-feature of four of these habitats in Plymouth Sound, and are one of the reasons for the SAC designation. The primary areas of subtidal sandbanks are found at the mouth of the River Yealm (Cellars Cove and Red Cove, although Tomb Rock is now also known to be significant in extent). In addition, there are known seagrass beds at Cawsand Bay and Drake's Island, with more ephemeral beds at Firestone Bay and Jennycliff Bay. Intertidal *Zostera noltii* beds are also present in the region (Curtis, 2012).

Section 4.2 discusses the unique features of Plymouth Sound, with specific emphasis on blue carbon ecosystems, the habitats they provide and new management practices that are in place. Management practices aim to maximise the conservation of the features while allowing various users to continue to benefit from the ecosystem services in the region.

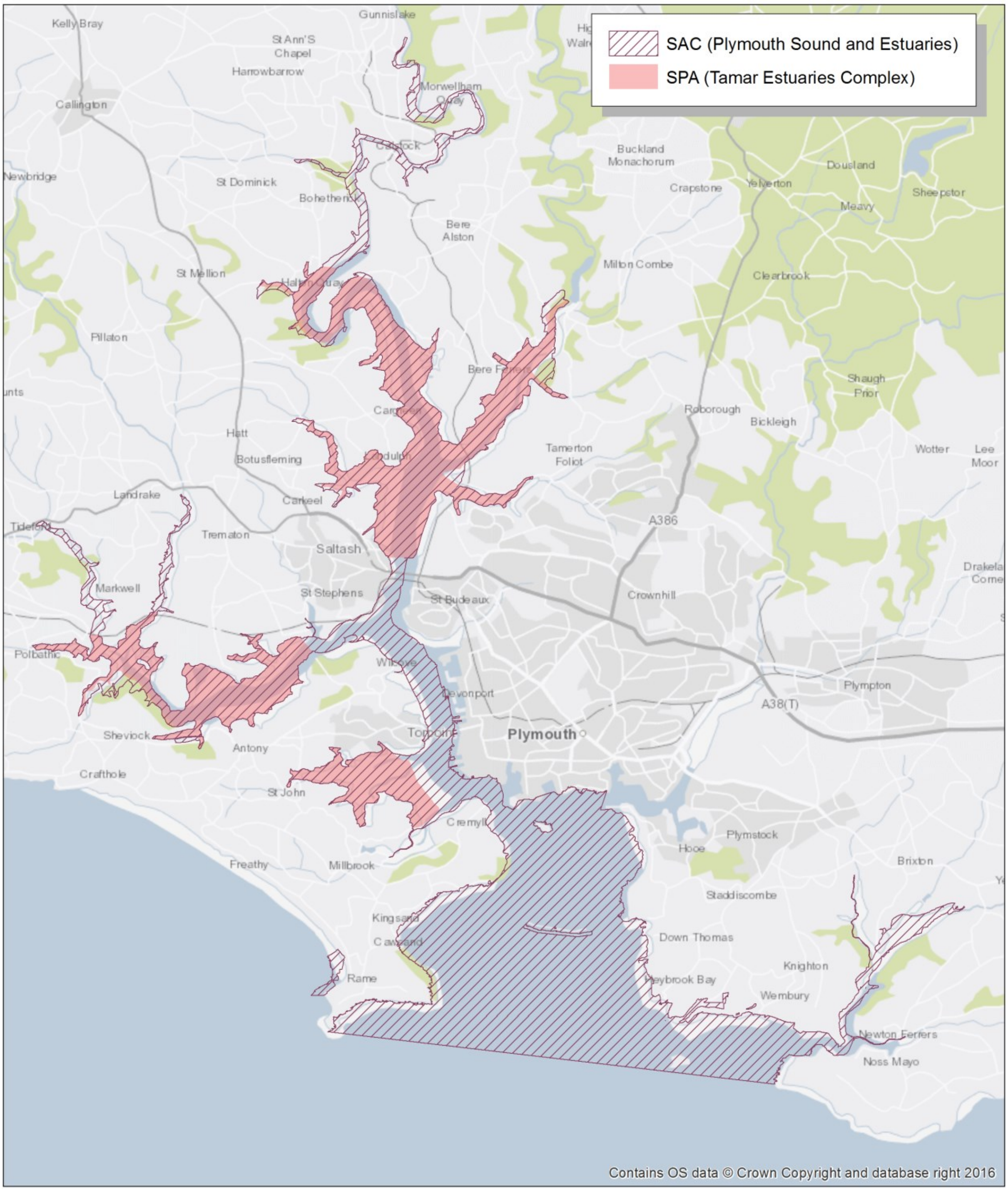

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Figure 18. Plymouth Sound and Estuaries conservation designations.

4.2 Data sources and methodology

Datasets for this project were identified using Google® and Google Scholar® searches and checked on EMODnet. Relevant papers and information were also identified through the searches and review undertaken as part of the ECWA Region review. The designated and non-designated feature extents were based on analysis by Griffiths *et al.* (2017). As the SAC, SPA and National Marine Park designations overlap, the Plymouth South SAC feature extents were adopted to define the area of interest.

4.2.1 Plymouth Sound and Estuaries SAC habitat extents

Habitat extents for the Plymouth Sound and Estuaries SAC were collated by Griffiths *et al.* (2017). The extent of designated and non-designated features is shown in Figure 19 and in Table 20.

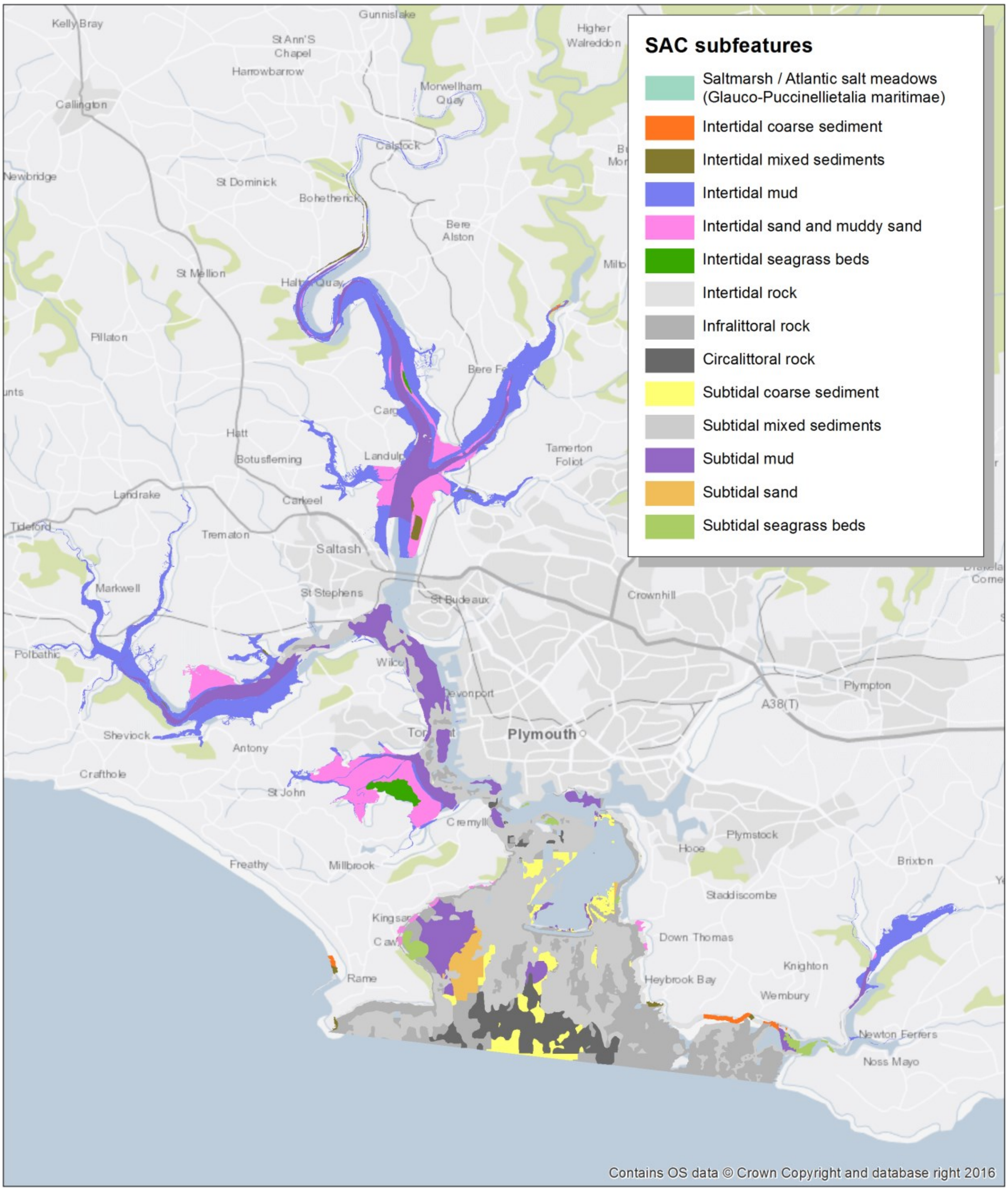

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Figure 19. Designated habitat features of the Plymouth Sound and Estuaries SAC.

Table 20 Habitat extents for designated and non-designated features of the Plymouth Sound and Estuaries SAC. From Griffiths et al. *(2017).*

Feature	**Habitat extent (km^2)**	**Habitat extent (ha)**
Designated features	**39.8**	**3,980.3**
Coastal saltmarshes and saline reedbeds	2.1	205.5
High-energy circalittoral rock	0.1	13.8
High-energy infralittoral rock	1.4	139.5
High-energy littoral rock	0.2	16.5
Intertidal coarse sediment	0.1	12.8
Intertidal mixed sediments	0.3	25.4
Intertidal mud	8.6	857.7
Intertidal rock	0.5	53.1
Intertidal sand and muddy sand	3.7	369.8
Littoral seagrass beds	0.4	39.9
Low-energy littoral rock	0.4	42.1
Moderate-energy littoral rock	0.0	0.3
Sublittoral coarse sediment	1.8	182.7
Sublittoral mixed sediment	11.9	1,185.3
Sublittoral mud	7.0	701.2
Sublittoral sand	0.8	83.2
Subtidal seagrass beds	0.5	51.5
Non-designated features	**10.3**	**1,034.0**
Blue mussel beds	0.2	20.3
Low-energy circalittoral rock	0.0	3.1
Low-energy infralittoral rock	0.1	7.2
Moderate-energy circalittoral rock	2.7	268.0
Moderate-energy infralittoral rock	7.2	723.1
Not applicable	0.0	0.1
Sublittoral sand	0.1	12.3
Total	50.1	5,014.3

4.2.2 Blue carbon habitats

The key vegetated habitats occurring within Plymouth Sound are saltmarsh, seagrass and kelp. Methods to measure the extent and assess the condition of the seagrass beds, and to restore their condition, have been the focus of several projects in the region. Seagrass beds have been mapped and the percentage cover categorised; the habitat extents in different locations within Plymouth Sound are listed in Table 20 and mapped in Figure 19. Most of the seagrass bed extent consists of very sparse cover (Curtis, 2012). However, dense seagrass occurs at Drake’s Island, where Green *et al*. (2018) found unusually high carbon-store densities (380.07±17.51 t C/ha) compared with the rest of the region (see Figure 20).

Table 21 Seagrass bed extents and percentage cover. From Curtis et al. *(2012).*

Cover (%)	**Drake's Island**	**Cawsand Bay**	**Cellars Cove**	**Red Cove (North)**	**Red Cove (South)**	**Tomb Rock**	**Jennycliff**	**Firestone Bay**	**Total (m^2)**
76–100 (dense)	12,503	497	29,815	8,794	3,054	0	0	0	54,663
51–75 (moderate)	11,785	17,141	12,936	5,874	2,650	815	56	15	51,272
26–50 (sparse)	8,713	29,560	6,585	5,470	2,823	10,083	768	1,901	65,903
5–25 (very sparse)	11,206	72,541	7,673	6,050	2,920	55,423	13.554	5,691	161,518
Total (m^2)	44,207	119,739	57,009	26,188	11,447	66,321	838	7,607	333,356

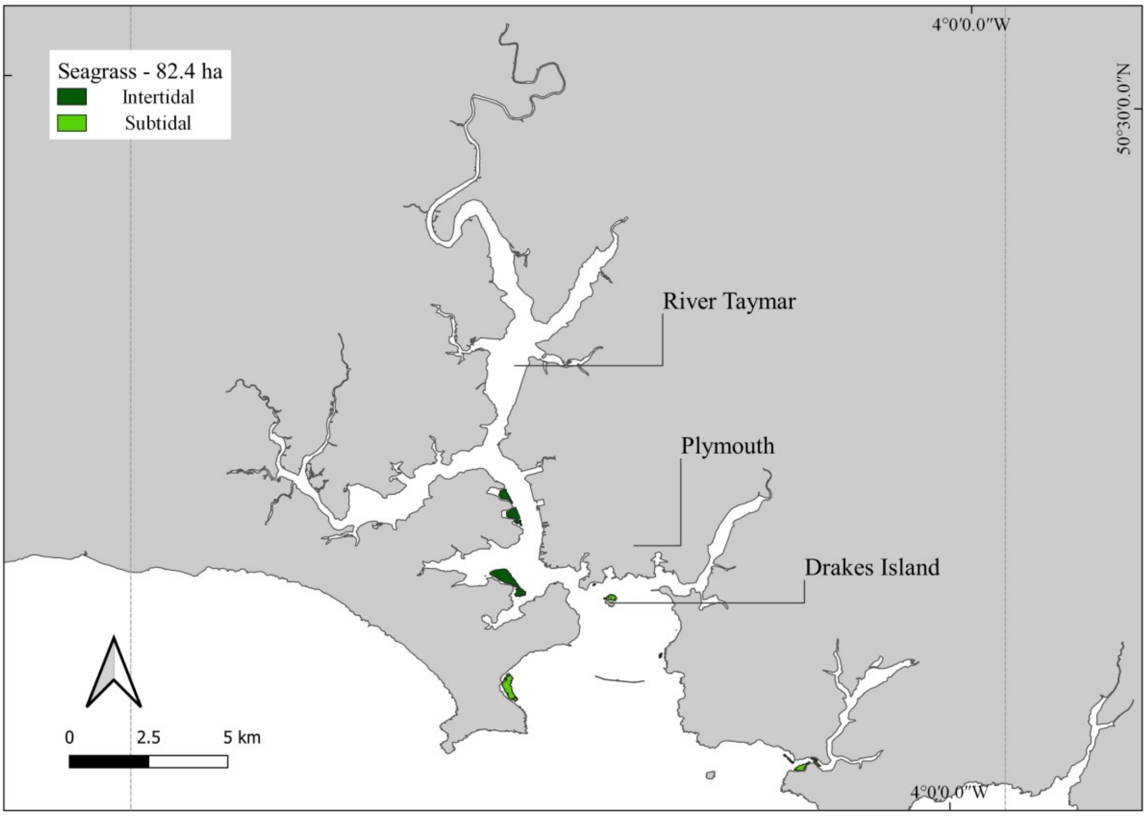

Figure 20. Current knowledge of seagrass beds within Plymouth Sound (based on recently produced spatial extents from the Environment Agency, available online). Griffiths et al. *(2017) previously estimated that the total extent of seagrass beds was 91.4 ha (51.5 subtidal beds and 39.9 littoral beds).*

4.2.3 Kelp beds

Extensive kelp beds are present in Plymouth Sound (see Figure 21), and these were surveyed in 2012. The role of macroalgae in organic matter export to deeper sediments was explored by Queirós *et al.* (2019). Sampling at Station L4 (a sandy mud site, approximately 48 m deep and 13 km south-southwest of Plymouth) identified traces (eDNA) corresponding to 148 distinct macroalgal taxa belonging to 34 orders of red, green and brown algae, with communities within the SAC at Rame Head more connected to the offshore site than those opposite Plymouth Hoe. The 13-month study estimated that the average magnitude of net macroalgal POC sequestration at L4 is 0.73 mol C/m^{2}/yr (8.75 g C/m^{2}/yr), as part of a net POC sequestration rate of 4.89 mol C/m^{2}/yr (58.74 g C/m^{2}/yr). Based on local *Laminaria hyperborea* detrital production rates, it was estimated that as much as 4–9% of macroalgal POC released annually as detritus from the Plymouth Sound area may become sequestered in deep coastal sediments (Queirós *et al.*, 2019).

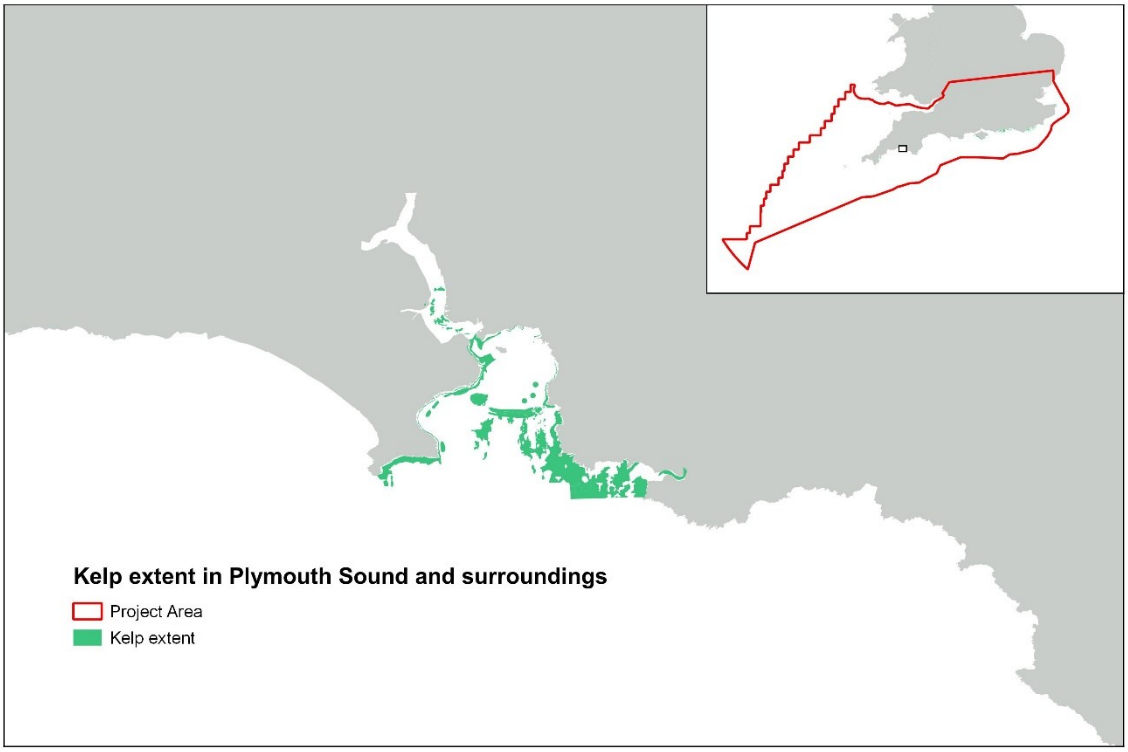

Figure 21. Kelp extent in Plymouth Sound and surrounding areas, based on EMODnet data (2012).

4.2.4 Saltmarsh

Saltmarsh is a relatively uncommon feature in the south-west of England; of the site characters listed for the SAC, it accounted for approximately 5% of the total. The Plym Estuary to the east of Plymouth is home to the Saltram saltmarsh, which is managed by the National Trust. Saltmarshes within Plymouth Sound are defined as Atlantic salt meadows which support (among others) the only known UK populations of triangular club-rush (*Schoenoplectus triqueter)*. Other unusual species are present, too; for example, stands of sea purslane (*Halimione portulacoides)* have been recorded in the area. The marshes in the area are also home to glasswort (*Salicornia* species), sea aster (*Tripolium pannonicum*), wild celery (*Apium graveolens*) and lesser sea-spurrey (*Spergularia marina*). Coverage of saltmarsh in Plymouth Sound is estimated to be 2.1 km^{2}, which stores over 9,200 t OC (see Figure 22 and Table 22).

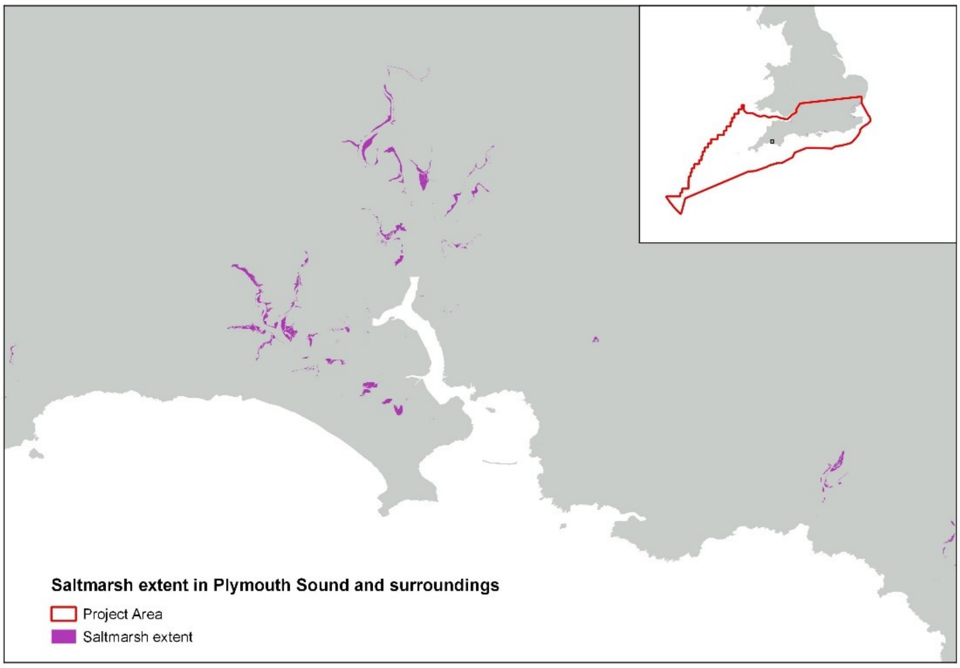

Figure 22. Saltmarsh in Plymouth Sound and surrounding areas, based on EMODnet data (2012).

4.3 Carbon storage and sequestration

Carbon storage and sequestration rates were analysed based on the methodology outlined in Section 1 and on the review of blue carbon habitats (see Section 2). Total amounts of carbon in long-term stores for vegetated and non-vegetated habitats are shown in Tables 22 and 23, respectively. Littoral and sublittoral mud are estimated to support the largest carbon stores as a function of both the greater extent of these habitats and their capacity compared with other sedimentary habitats. The amount of carbon stored within subtidal mud is similar in magnitude to that stored within saltmarshes.

Table 22. Carbon storage rates for vegetated habitats within Plymouth Sound.

Habitat	**Extent (km²)**	**Store (1,000 t OC)**	**Store density (g C/m²)**			**Storage capacity (1,000 t C/yr)**
			Min	**Max**	**Avg**	
Saltmarshes: vegetation	2.1	9.17	48	516	282	1.18302
Saltmarshes: soil	2.1	9.17	1,270	6,900	4,085	1.18302
Littoral seagrass	0.4	0.96	2,940	11,402	7,171	0.040158
Sublittoral seagrass	0.5	1.20	2,940	11,402	7,171	0.050197
Intertidal macroalgae	0.4	0.05	84,663	160	122	

Table 23. Carbon storage rates for unvegetated (sedimentary) habitats within Plymouth Sound.

EUNIS code	Habitat	Area (km^2)	Store (1,000 t C)	Store density (g C/m^2)			Storage rate (g C/m^2/yr)	Storage capacity (1,000 t C/yr)
				Min	Max	Avg		
A2	**Littoral sediment**							
A2.1	Littoral coarse sediment	0.1					0	0
A2.2	Littoral sand and muddy sand	3.7	2.405	130	1,860	650	45	0.1665
A2.3	Littoral mud	8.6	17.114	540	3,560	1,990	83.5	0.7181
A5	**Sublittoral sediment**							
A5.1	Sublittoral coarse sediment	1.8						
A5.2	Sublittoral sand	0.9	0.162	40	760	180	0.2	0.00018
A5.3	Sublittoral mud	7.0	3.85	60	1,230	550	155.2	1.0864
A5.4	Sublittoral mixed sediments	11.9					59	0.7021

4.4 Risks and opportunities

4.4.1 Management

The Tamar Estuaries Consultative Forum (TECF) is a partnership of organisations and local authorities with statutory responsibility for the management of the Plymouth Sound and Tamar Estuaries MPAs. TECF and its advisory bodies, the Port of Plymouth Marine Liaison Committee (PPMLC) and the Wembury Marine Conservation Area Advisory Group (WAG), provide an effective and collaborative framework for managing the MPAs while recognising the commercial, defence and recreational importance of the site. TECF has delivered a single management plan for the site. The 11 funding partners pay Plymouth County Council to coordinate and deliver the TECF service. TECF have commissioned work on the site, including a review of recreational activities, and have supported projects such as the installation of eco-moorings to reduce impacts on seagrass.

4.4.2 Human activities

Plymouth Sound hosts a range of uses, including fishing, marine science, military dockyards supporting the refurbishment of nuclear submarines and warships, and the development of fully Wi-Fi-enabled underwater testing areas for autonomous marine vehicles. Plymouth Sound is also notable for recreational activities; it is a key diving area that hosts a range of wrecks, including the *HMS Scylla*, which was purposefully sunk in 2004 to create an artificial reef off the Cornish coast.

4.4.3 Fishing activities

Subtidal rock and reef communities have been categorised as ‘red’ risk against all demersal towed gear and towed dredges in the Marine Conservation Zone Assessment[2] for the Devon and Severn Inshore Fisheries and Conservation Authority (IFCA). In January 2014 this IFCA introduced the Mobile Fishing Permit Byelaw, which prohibits the use of towed gear within the European Marine Site (EMS).

Risks to seabed habitats, including seagrass beds, include activities such as potting. Potting is a fishing activity which often occurs where seagrass is found. Although potting activities are generally low impact when compared with demersal towed gear, there is potential for this activity to damage the seagrass, which is not physically robust (D’Avack *et al.,* 2019). There is limited evidence on the impact of potting on seagrass. However, based on the physical characteristics of pots, it is considered that if they are consistently set and hauled in seagrass beds they have the potential to cause damage by leaf shearing, which damages the meristems (and thereby reduces growth) (Marbà *et al.,* 2004), and by uprooting plants. They can also cause damage by smothering and light attenuation if soak times are particularly long (Roberts *et al.,* 2010).

Previous studies have shown that potting can also cause surface abrasion which damages or removes the rhizomes, leaves and stems of the seagrass plant, which are above the surface, and damages the roots, which are only shallowly buried (D’Avack *et al.,* 2019). Damage can be caused during the setting of pots, during movement of gear on the benthos due to tide, current and storm activity, and as the gear is hauled if it is dragged laterally when lifted (Walmsley *et al.,* 2015).

4.4.4 Anchoring and mooring

Anchoring and mooring occur throughout Plymouth Sound (see Figure 23). Subtidal seagrass beds in the Sound have been assessed as being at high risk from chain abrasion from anchoring and mooring, largely resulting from the placement of navigation marks rather than commercial and recreational anchoring and mooring (although there are some gaps in the data regarding recreational anchoring) (Griffiths *et al.,* 2017). When an anchor and chain are pulled up and dragged over the bottom, following the movement of the boat, the anchor cuts seagrass leaves and pull the rhizomes from the seabed, forming an anchor scar. This damage is exacerbated by wave action. Chains attached to anchors from moored boats leave bare patches, typically 1–4 m^2 in diameter (Collins *et al.,* 2010). Given the risk to seagrass within Plymouth Sound, initiatives to manage and reduce impacts are being trialled, with TECF supporting the testing and introduction of eco-moorings that reduce abrasion from chains by using floating ropes. Where these extend and enhance the condition of the seagrass beds these projects will also enhance blue carbon capacity (see Section 4.4.8).

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[2] www.devonandsevernifca.gov.uk/content/download/3698/28479/file/TAM-MCZ-001%20Intertidal%20habitats,%20mussel%20&%20oyster.pdf

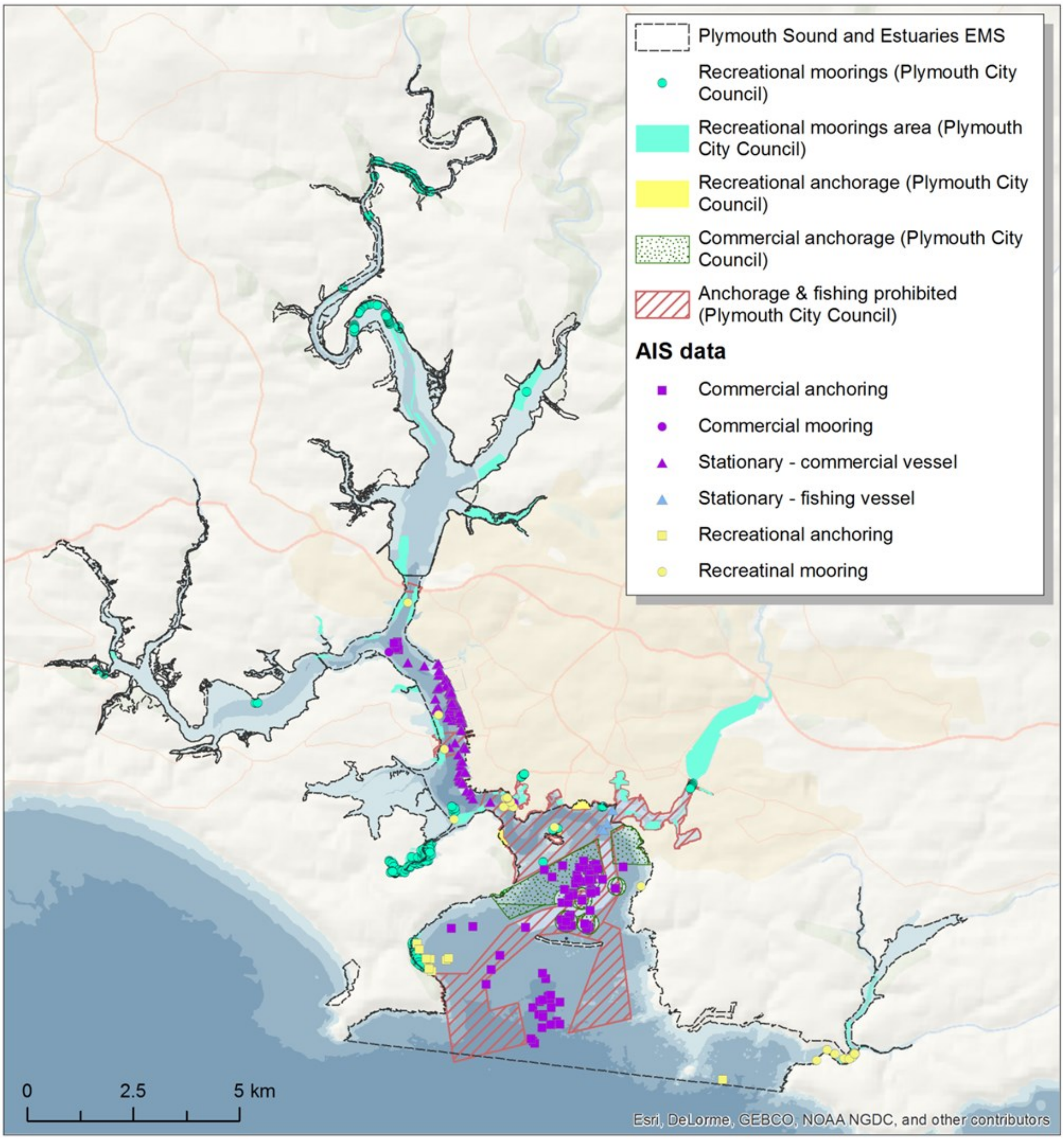

Figure 23. Anchoring and mooring within Plymouth Sound. From Griffiths et al. (*2017).*

4.4.5 Recreational activities

The site's proximity to the city of Plymouth provides water users with infrastructure to support boating communities and many access points for users to engage in a range of activities, such as swimming, bait digging, crab tiling and kayaking. Recreational activities can adversely affect habitats and disturb species, primarily through noise, abrasion/penetration of the seabed, litter, organic enrichment, contamination (with synthetic compounds/organometals/hydrocarbons/PAHs), spread of non-indigenous species, physical change (to a different seabed type) and introduction of light. Projects to assess the level of recreational activity found higher levels of recreation activity/infrastructure in management areas where there was a concentration of slipways, car parks, marinas, moorings and swimming areas serving the population centres of Kingsand and Cawsand, Saltash, Torpoint and Plymouth within the EMS. The most popular marine-based recreational activities were canoeing/kayaking, angling, sailing and swimming (Langmead *et al.,* 2017). Overall, these activities are unlikely to affect accumulation and stores of blue carbon, with the exception of anchoring and mooring resulting from recreational sailing (see Section 4.4.4).

4.4.6 Bait collecting

Areas of mudflat within Plymouth Sound may be subject to intensive bait digging that turns over the sediment and removes target species. Attendees at a workshop to characterise activities within Plymouth Sound reported that four different types of bait for recreational fishing were being collected within the Plymouth Sound and Estuaries EMS. These were mackerel, worms (lugworm and ragworm), prawns and recently moulted shore crab ‘peelers’ (via crab tiling) (Langmead *et al.,* 2017). The locations for these bait-collecting activities are very different for each target (see Figure 24): worms are collected in the Tamar, St John’s Lake and the Lynher, and also in the Plym; prawns are collected around the Hoe and central Tamar; most crab tiling activity takes place in the Tamar around Saltash, St Budeaux up to Tamerton, and also in the Plym. Bait digging can have impacts on many key species, including non-target macrofaunal species (Watson *et al.,* 2007). Evidence of impacts on blue carbon systems in the UK is scarce. Sediment destabilisation and remineralisation of OC content is likely to occur, and has been suggested in tropical seagrass (Dahl *et al.,* 2022) and saltmarsh areas (Raw *et al.,* 2021) in relation to bait digging.

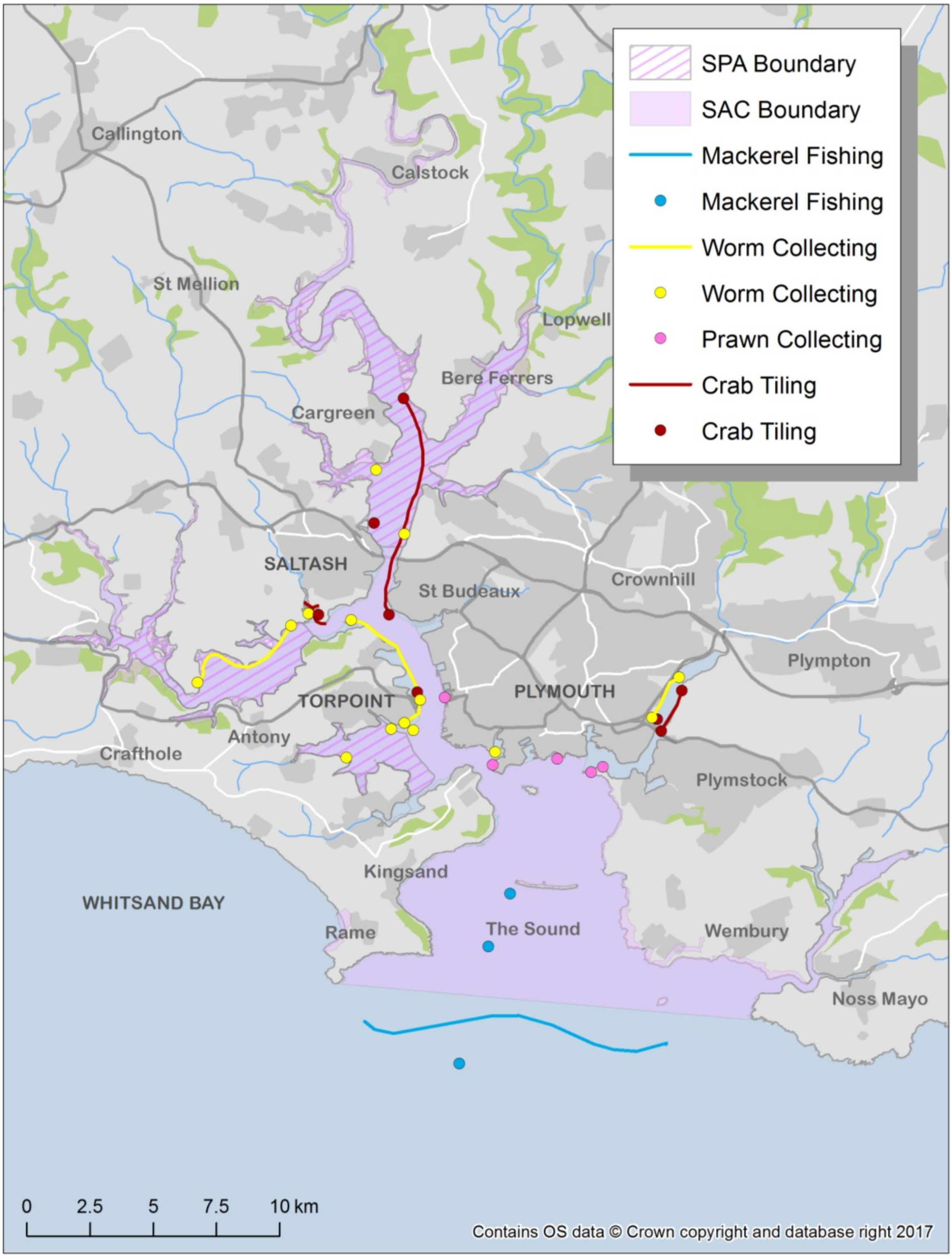

Figure 24. Bait-collecting sites around the Plymouth Sound SAC as reported by survey respondents (Langmead et al.*, 2017).*

Managing and restoring seagrass habitats in Plymouth Sound

LIFE Recreation ReMEDIES is a four-year marine conservation partnership project that aims to protect and restore the seabed in five SACs in southern England. It is funded by the EU LIFE programme and led by Natural England in partnership with the Royal Yachting Association, the Marine Conservation Society, the Ocean Conservation Trust and Plymouth

City Council/Tamar Estuaries Consultative Forum. ReMEDIES stands for Reducing and Mitigating Erosion and Disturbance Impacts affEcting the Seabed. The aims of the project are:

- to promote awareness of seabed habitats, their importance and their vulnerabilities
- to work together to reduce impacts on the seabed from recreational activities
- to restore and protect sensitive habitats for the benefit of nature and people.

ReMEDIES aims to restore a total of 8 ha of seagrass beds, consisting of 4 ha in Plymouth Sound and 4 ha in the Solent. This is England's largest seagrass planting effort. In April 2021 one of the project partners, the Ocean Conservation Trust, began the planting work by deploying 16,000 seagrass seed bags and 2,200 seedling bags across an area of almost 1 ha in the southern part of Jennycliff Bay, Plymouth Sound.

A Voluntary No Anchor Zone (VNAZ) is in place around the newly planted seagrass meadow in Jennycliff Bay, to help to protect it from anchoring disturbance from recreational boats. The King's Harbour Master Plymouth has issued a notice to mariners which includes location details and charts. Marker buoys will be installed around the area to provide sailors with a visual indication of the VNAZ when out on the water. Voluntary No-Anchor Zones are intended to help boaters make an informed choice about where to anchor. Safety is paramount, and the zone is not intended to limit safe anchorage when this is needed. However, during smooth sailing, boaters are asked to observe the VNAZ and explore alternative safe anchorages nearby.

4.4.7 Eco-mooring trial

Areas of subtidal seagrass overlap with anchoring and mooring locations. To reduce damage to seagrass beds, the TECF has contributed funding to install a trial eco-mooring solution developed by the Community Seagrass Initiative (CSI) as part of a wider trial in multiple locations in south-west England. It was installed in July 2016 in Cawsand Bay, and the CSI has conducted regular monitoring of the seagrass around the mooring to establish whether the solution has helped to minimise the impacts of standard moorings, and to assess any improvements in habitat condition.

4.4.8 Lessons learned from the management of Plymouth Sound

Despite being one of the more active recreational and fishing areas in the south-west of England, Plymouth Sound is now recognised for its ecological importance. The region hosts kelp forests, saltmarshes and seagrass beds, which are all important habitats that provide ecosystems implicated in blue carbon storage. The recently introduced levels of protection and collaboration with local stakeholders show that industry and environmental policy can work together to promote and enhance the ecosystem services even in regions with multiple users. Innovative schemes that will function alongside restoration efforts to reduce impacts and improve the potential for success have been implemented, such as ecological moorings for boats. Opportunities include efforts to restore important -habitat-providing ecosystems, such as seagrass, and trials to implement new and innovative mooring schemes and no-anchor zones. With the introduction of increasing numbers of restoration schemes at a national level, multiple lessons can be learned from the management of Plymouth Sound.

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6 Glossary

basin	A large depression in which sediments are accumulated, or a tectonic, circular, syncline-like depression of strata.
blue carbon	Carbon that is stored and sequestered in coastal and marine ecosystems, including tidal and estuarine salt marshes, seagrass beds and mangrove forests, associated sediment stores and biogenic reefs. For the purposes of the present report, this definition has been extended to include the geological substrate on which the marine ecosystem has developed.
carbon accumulation rate	The rate at which carbon reaches the seabed sediment, expressed in g $C/m^2/yr$ (grams of carbon per square metre per year).
carbon fixation (or capture)	The conversion of carbon dioxide (CO_2) into carbon compounds by plants.
Continental Shelf	A region of submerged rock of the same type, at depths (of up to a few hundred metres) that are shallow compared with those in the ocean. Around Scotland is a wide area of shelf reaching about 120 metres at its outer edge (deeper in a few glacier dredged troughs); the shelf seas, including the North and Malin Seas, are the waters over this shelf.
dry bulk density	The dry weight of sediment per unit volume of soil. It takes into account both the solids and the pore space, and is expressed as g/cm^3.
estuary	An area where fresh water comes into contact with seawater, usually in a partly enclosed coastal body of water; a mix of fresh and salt water where the current of a stream meets the tides.
gravel	Coarse-grained sediment, mainly consisting of particles larger than 2 mm in diameter, and including cobbles and boulders.
inorganic carbon (IC)	Carbon dioxide (CO_2) gas, dissolved CO_2 and bicarbonate (HCO_3^-) and carbonate (CO_3^{2--}) ions; particulate compounds of carbonate, such as calcium carbonate ($CaCO_3$, also known as chalk).
influx	The rate of arrival of carbon to long-term stores, usually as particulate organic carbon (POC) to seabed sediments or saltmarsh soils, from the combined available sources of POC (such as phytoplankton, macroalgae, saltmarsh plants etc.).

long-term carbon stores	Carbon that is considered to be locked away from atmospheric circulation for significant time periods (generally over 100 years).
mud	A sediment that consists mainly of grains with a diameter of less than 0.06 mm. It is a general term that refers to mixtures of sediments in water, and applies to both clays and silts.
organic carbon (OC)	Compounds of carbon, nitrogen and hydrogen and, in some cases, oxygen and sulphur, used by living organisms in the structure of their cells and as a source of energy.
outflux	The rate of production of carbon for long-term storage, usually particulate organic carbon (POC) either exported to other habitats, such as from kelp or phytoplankton to seabed sediments, or stored locally, such as from saltmarsh vegetation to saltmarsh soils.
particulate organic carbon (POC)	Organic carbon that is in the form of solid particles, derived from dead plant material.
rock	An extensive geological term, but limited in hydrography to hard, solid masses on the Earth's surface that rise from the bottom of the sea. Rock may be either completely submerged or project permanently, or at times, above water.
sand	Medium-grained sediment with a diameter range of 0.063–2 mm. This is the most common sediment on the Continental Shelf.
sea loch (fjord)	A former glacial valley, with steep walls and a U-shaped profile, now occupied by the sea.
sediment accumulation rate (SAR)	The rate at which sediment builds up on the seabed, expressed in cm/yr.
sedimentation	The process of deposition of mineral grains or precipitates in beds or other accumulations.
sequestration	The process of addition of solid carbon to the carbon store.
short-term carbon stores	Carbon that is temporarily fixed or removed from atmospheric circulation for less significant time periods (e.g., in living biomass). 'Store' as a verb refers to carbon added to either short-term or long-term stores.

Annex 1. Sources for Habitat Data

Table A1. Sources for habitat data

Title	Data source	Data sub-source	Data owner	Restrictions	Permissions request needed?
Seastar DORIS (DORset Integrated Seabed survey)	Dorset Wildlife Trust: Peter Tinsley PTinsley@dorsetwildlifetrust.org.uk	n/a	Dorset Wildlife Trust	Creative Commons by Attribution (CC-BY). Permission received from Peter Tinsley <PTinsley@dorsetwildlifetrust.org.uk>	No
Saltmarsh Extent & Zonation	www.data.gov.uk	Environment Agency	Environment Agency	Open Government License www.data.gov.uk/dataset/0e9982d3-1fef-47de-9af0-4b1398330d88/saltmarsh-extent-zonation	No
EUSeaMap	www.emodnet-seabedhabitats.eu/about/euseamap-broad-scale-maps/	EMODnet	European Marine Observation and Data Network (EMODnet) Seabed Habitats initiative (www.emodnet-seabedhabitats.eu), funded by the European Commission	Credit: Licensed under CC-BY 4.0 from the European Marine Observation and Data Network (EMODnet) Seabed Habitats initiative (www.emodnet-seabedhabitats.eu), funded by the European Commission	No

Title	Data source	Data sub-source	Data owner	Restrictions	Permissions request needed?
C20220127_AnnexI_Reefs_v8_3_OpenData	https://hub.jncc.gov.uk/assets/8f886e47-31d6-477e-9240-65ac42bee709		Joint Nature Conservation Committee (JNCC)	No limitations on public access. Use constraints: Available under the Open Government Licence v3. Attribution statement ‘Contains JNCC data © copyright and database right 2021’	No
Natural England Marine Habitats	www.data.gov.uk/dataset/bfc23a6d-8879-4072-95ed-125b091f908a/marine-habitats-and-species-open-data	Defra	Natural England	These datasets are available under the Open Government Licence (OGL)	No