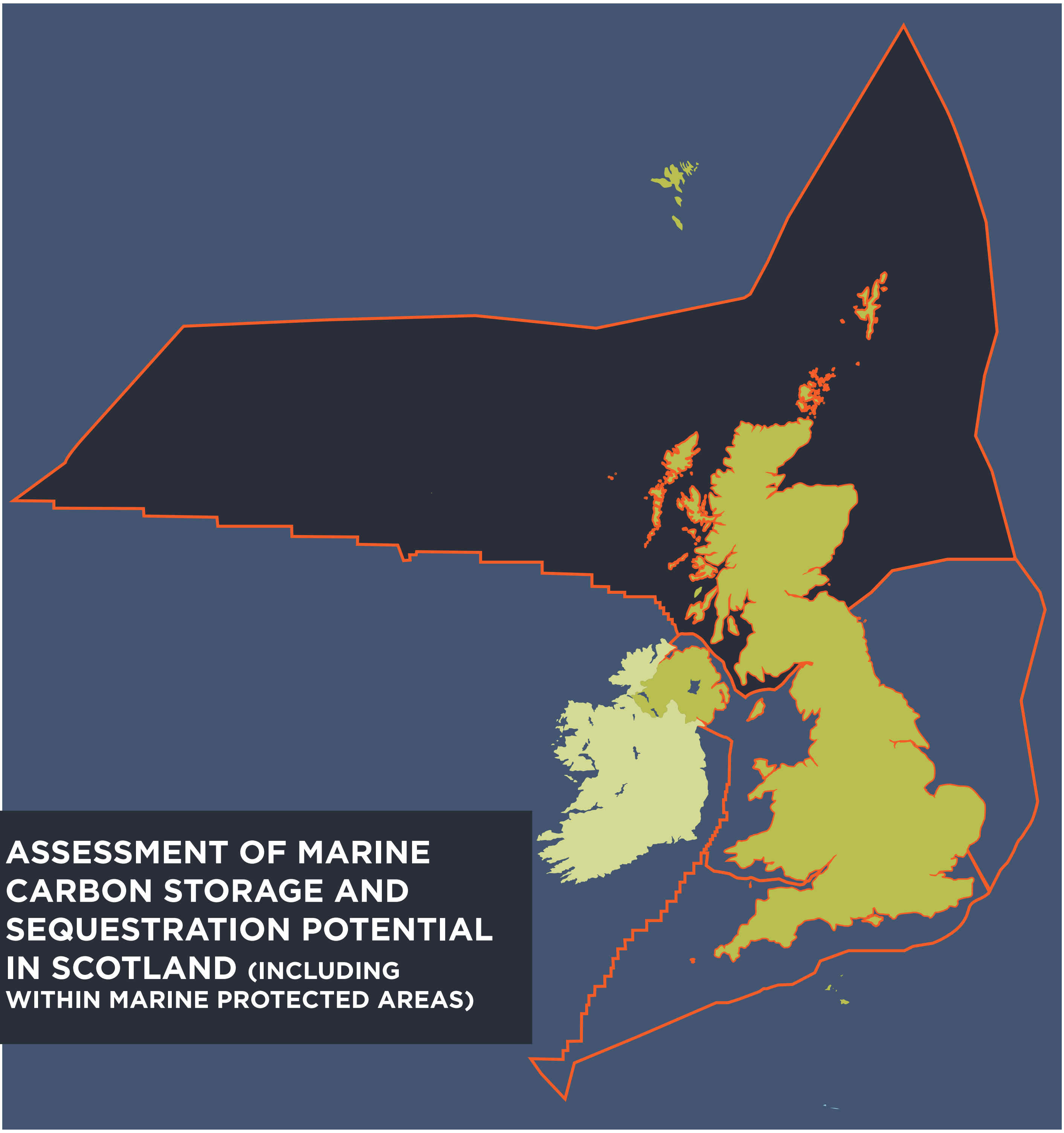
THE UNITED KINGDOM'S BLUE CARBON INVENTORY:

SAMS

University of St Andrews

Marine Biological Association



ASSESSMENT OF MARINE CARBON STORAGE AND SEQUESTRATION POTENTIAL IN SCOTLAND (INCLUDING WITHIN MARINE PROTECTED AREAS)

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The United Kingdom's Blue Carbon Inventory:

Assessment of Marine Carbon Storage and Sequestration Potential in Scotland (Including Within Marine Protected Areas)

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Assessment of Marine Carbon Storage and Sequestration Potential in Scotland (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 Scotland's seas. It forms part of the UK's Blue Carbon Inventory alongside regional reports that focus on the English North Sea (Burrows *et al.,* 2021), the English Channel and Western Approaches Region (Burrows *et al.,* 2024a) and the Irish Sea and Welsh Coast Region, the latter of which includes coastlines in Northern Ireland, England and Wales (Burrows *et al.*, 2024b). The present report also draws on and updates information provided by the most recent Scottish blue carbon report (Cunningham and Hunt, 2023). As in the previous reports, the main objective was to assess the present extent and distribution of habitats, with emphasis on those that are identified as blue carbon habitats. Further aims were to evaluate the blue carbon potential of Scotland's seas 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) of 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 network to help mitigate against the effects of climate change.

The extents of blue carbon habitats for Scotland's seas were derived from available open sources, including the EUNIS level 3 combined map from the Joint Nature Conservation Committee (JNCC), individual habitat publications and datasets (Austin *et al*., 2021; Smeaton *et al*., 2022a,b), and recently published estimates of OC and IC stores in surface sediments (Smeaton *et al*., 2021).

Main Findings

• Scotland's seas out to the limits of the continental shelf[1] cover an area of **617,000 km²**, which is the largest sea-surface area of all nations in the UK, and an area around six times as large as Scotland itself. The majority of the analysis presented in this report covers the area within Scotland's Exclusive Economic Zone (EEZ), which covers an area of approximately 462,315 km^2. Only a subset (437,883 km^2) of the latter area has been mapped for its carbon stores, so the values reported here exclude the region beyond the EEZ and include only mapped areas of the EEZ.

• **Carbon in long-term stores** is carbon that is locked away from atmospheric circulation for significant time periods (generally over 100 years). In total, **152.3 million tonnes (Mt) of OC in long-term stores** are found in the region, with 99.7% of that total stored in seabed sediments. However, it is important to note that **this analysis considers only surficial sediments in the top 10 cm of the seabed**, and therefore represents a fraction of the overall carbon stored in the full thickness of these sediments. The remaining 0.3% (**423,000 t**) of OC

[1] https://marine.gov.scot/data/facts-and-figures-about-scotlands-sea-area-coastline-length-sea-area-sq-kms

in long-term stores is in coastal vegetated blue carbon (CVBC) habitats: **368,000 t C** in the soils of coastal saltmarshes and **32,000 t C** in sediment in seagrass beds. Seabed sediments are thus by far the most important habitat for carbon storage in Scotland.

• **Carbon in short-term stores** is that which is temporarily fixed or removed from atmospheric circulation for less significant time periods (e.g., in living biomass). Coastal vegetated blue carbon habitats (kelp beds, intertidal macroalgae, saltmarshes and seagrass beds) account for only **0.8%** of the total area of the region, and only **0.3%** of the total OC in long-term stores, and they account for **0.07%** of annual accumulated OC in the region. In total, **1,042,000 t C** are stored as living kelp biomass and **50,000 t C** as biomass of intertidal macroalgae.

• 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[2]), 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 have to be addressed.

• Marine protected areas will be referred to throughout this report simply as 'protected areas', to avoid confusion with the Marine Protected Area designation in Scotland. Protected areas – that is, Marine Protected Areas (MPAs), Special Areas of Conservation (SACs), Special Protection Areas (SPAs) and marine areas of Sites of Special Scientific Interest (SSSIs) accounting for overlapping designations – in this region cover **207,000 km^2**, representing **33.5%** of the area of Scotland's seas out to the continental shelf limits (617,000 km^2). Long-term stores of carbon in the top 10 cm of sediments within the protected areas are estimated to contain **76 Mt of OC**, accounting for 50% of the total OC in the region, and **510 Mt of IC**, accounting for 36% of the total IC across the region.

• Offshore MPAs and SACs contain the largest proportion of OC and IC long-term stores because of their much larger extent compared with inshore protected areas.

• Littoral protected areas, 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. Protected areas with predominantly rocky habitats have less OC in long-term stores and lower accumulation rates but do support carbon stores as living biomass in extensive kelp beds that contribute carbon to neighbouring areas of sediment.

• Inshore sediments, including west coast sea lochs and the Minch, the Clyde Sea and inner parts of the Moray Firth and Firth of Forth, have rich OC deposits in their sediments (over 0.8 kg C/m^2, compared with values that are typically less than 0.2 kg C/m^2 in offshore areas).

• Annually, an estimated **9.5 Mt of OC** are added to sediment long-term stores across Scotland's seas, predominantly within mud and sand/mud seabed sediments. Due to the lack of direct measurements of carbon accumulation in the area and the high variability of the values reported in the literature, this estimate must be treated with **low confidence** (see Section 2.7.4).

• Coastal vegetated blue carbon habitats (kelp beds, intertidal macroalgae, saltmarshes and seagrass beds) accumulate **7,900 t C/yr** of OC, much less than seabed sediments (0.08% of the total annual value), albeit at a higher rate per unit area. Saltmarsh soils account for the majority (68%) of the annual accumulation by these CVBC habitats. Macroalgae contribute to carbon storage through subsequent loss and transport of biological material to seabed sediments at relatively uncertain rates.

• Growth and reproduction of algae and plants, with subsequent losses and transport to long-term 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 detritus that

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[2] www.ceh.ac.uk/our-science/projects/uk-saltmarsh-code

reaches long-term stores (carbon accumulated for climatically relevant time periods) has been little studied. Reflecting values typically adopted in ecosystem models, a value of 10% of plant material produced was used to predict the fraction of OC derived annually from accumulated living biomass and stored within seabed sediments. Although the actual percentage is uncertain, based on this assumption an annual accumulation rate of **50 Mt C/yr** in living plant biomass may result in **5.0 Mt C/yr** being added from marine sources to the particulate organic carbon (POC) pool for transport and incorporation into surface stores and longer-term stores.

• Production of POC exported to long-term stores (10% of the total production of carbon as living biomass) is dominated by **phytoplankton** (**5.02 Mt C/yr**) in Scotland, with **kelp** (**160,000 t C/yr)** and **intertidal macroalgae** (**14,000 t C/yr**) the next largest contributors. Estimates of the amount of carbon fixed and exported to sediment annually by **saltmarsh plants (810 t C/yr**) and **seagrass beds (570 t C/yr)** are small relative to the annual totals accumulated in their soils (**6,600 t C/yr for saltmarshes** and **2,100 t C/yr for seagrasses**).

• 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 such 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 a blue carbon habitat is covered by an existing protected area designation, management measures that have the specific objective of protecting or restoring habitat which contains such carbon stores can be considered alongside primary biodiversity considerations as potential nature-based solutions (NBS) to mitigate the impacts of climate change.

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Acronyms and Abbreviations

ASSI	Area of Special Scientific Interest
BAP	Biodiversity Action Plan
BGS	British Geological Survey
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CVBC	Coastal vegetated blue carbon (habitat)
Defra	Department of Environment, Food and Rural Affairs
EEZ	Exclusive Economic Zone
EQR	Ecological Quality Ratio
EUNIS	European Nature Information System
GIS	Geographic information system
IC	Inorganic carbon
ICES	International Council for the Exploration of the Sea
IPCC	Intergovernmental Panel on Climate Change
JNCC	Joint Nature Conservation Committee
MCZ	Marine Conservation Zone
MDS	Multidimensional scaling
MNR	Marine Nature Reserve
MPA	Marine Protected Area (a designated area in Scotland)
Mt	Million tonnes
NBN	National Biodiversity Network
NBS	Nature-based solutions
NVC	National Vegetation Classification
OBIS	Ocean Biodiversity Information System
OC	Organic carbon
PMF	Priority Marine Feature
POC	Particulate organic carbon
ROV	Remotely operated vehicle

RSPB	Royal Society for the Protection of Birds
SAC	Special Area of Conservation
SAMS	Scottish Association for Marine Science
SEPA	Scottish Environment Protection Agency
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
TWTs	The Wildlife Trusts
UAV	Unoccupied aerial vehicle
UK	United Kingdom
USA	United States of America
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 stores in UK seas including within protected areas.[3] 'Blue carbon' ecosystems are broadly considered here to be all those ecosystems that make significant contributions to the fixation and/or 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- and long-term stores and of rates of carbon fluxes. The report considers exports from and imports to these habitats, and threats to these 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 and divided into four regions, namely the English North Sea Region (Burrows *et al*., 2021), the English Channel and Western Approaches Region (Burrows *et al*., 2024a), the Irish Sea and Welsh Coast Region (Burrows *et al*., 2024b) and Scotland (this report[4]). These reports are combined 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 reports of the assessment of carbon capture and storage in the English North Sea Region (Burrows *et al*., 2021), the English Channel and Western Approaches Region (Burrows *et al.,* 2024a) and the Irish Sea and Welsh Coast Region (Burrows *et al.,* 2024b) that accompany this report. Further partitioning of blue carbon among protected areas into short- and long-term stores and accumulation processes has 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 sediment long-term stores has been compiled from existing habitat maps, building on the data sources used in recent reviews of blue carbon in Scotland by NatureScot (Cunningham and Hunt, 2023) and in England and Wales by Natural England (Gregg *et al*., 2021) and Defra/Cefas (Parker *et al*., 2021). Where observed data do not give the extent of habitats or patterns of carbon

[3] In this report the term 'protected area' is used to avoid confusion with the Marine Protected Area designation that exists in Scotland, and the abbreviation 'MPA' is used to refer to that designation.

[4] The area covered by this report, referred to simply as Scotland, covers Scotland's seas out to the limits of the continental shelf limits (617,000 km^2). The majority of the analysis presented within this report however covers the area within Scotland's Exclusive Economic Zone (EEZ), which covers an area of approximately 462,315 km^2. Only a subset (437,883 km^2) of the latter area has been mapped for its carbon stores, so the values reported here exclude the region beyond the EEZ and include only mapped areas of the EEZ (which represent 94.7% of the EEZ).

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 in sediments. Such estimates have been reported for the whole region and for focal areas, including protected areas. 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 natural processes such as wave-driven sediment resuspension and river-derived plumes.

Carbon budgets and 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 sediment stores are evaluated in protected areas, including Nature Conservation Marine Protected Areas (hereafter referred to as MPAs) in Scotland, Marine Conservation Zones (MCZs) in England, Wales and Northern Ireland, Marine Nature Reserves (MNRs) in the Isle of Man Territorial Seas, Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) in all devolved administrations, as well as the marine areas of Sites of Special Scientific Interest (SSSIs) in devolved administrations, and Areas of Special Scientific Interest (ASSIs) in Northern Ireland (see Figure 1). This regional report is the final one in a series of four and gives a breakdown of carbon short- and long-term stores and sequestration capacity within 36 MPAs, 106 SACs, 96 SPAs and 399 SSSIs in Scotland (see Table 15).

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 habitats (saltmarsh, kelp forests, seagrass beds, biogenic reefs and seabed sediments) in the UK-. The specific aim for this region was to update the existing blue carbon assessment for Scotland (Burrows *et al.,* 2014), incorporating the most recent review (Cunningham and Hunt, 2023), by:

- reviewing the current extent and distribution of each blue carbon habitat
- estimating the quantity of carbon currently stored within each blue carbon habitat
- establishing the average net sequestration rate (in g C/m^2/yr) of each blue carbon habitat
- estimating the potential net sequestration (in g C/yr) of each blue carbon habitat
- estimating the quantity of carbon stored in and potential carbon sequestration rates of protected areas in the UK and Isle of Man (MPAs, MCZs, MNRs, SACs, SPAs SSSIs and ASSIs)
- further developing 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 seabed habitats. Evidence of this nature will contribute to exploration of the potential of the UK’s protected areas to help to mitigate the effects of climate change by capturing and storing carbon.

Maps of major carbon stores and the associated blue carbon habitats are presented throughout this report. These include regional maps for sediment organic carbon (see Figure

10) and inorganic carbon (see Figure 11), and detailed maps of selected habitats for the areas included in the case studies of Cromarty Firth and Loch Craignish (see Section 4).

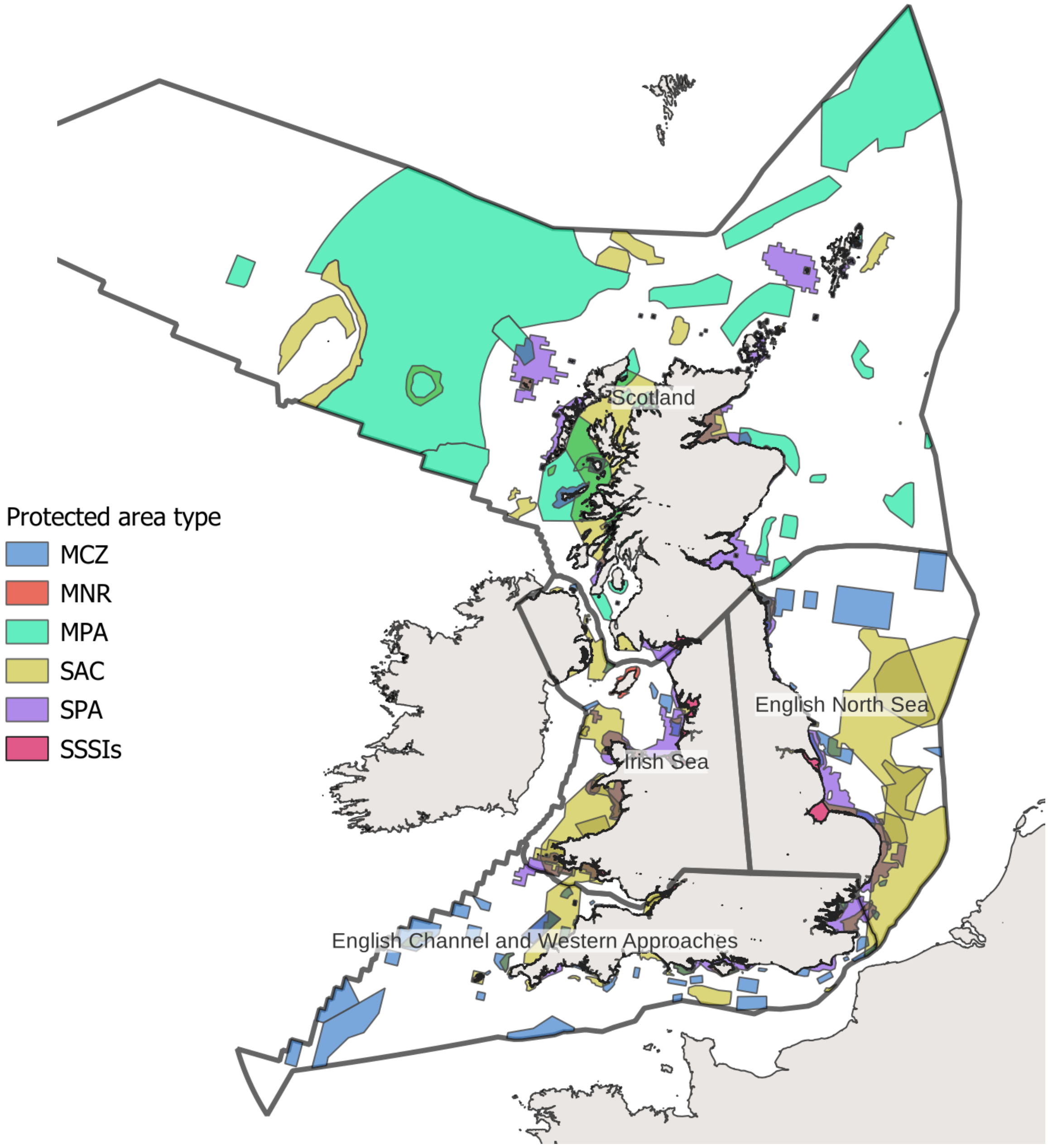

Figure 1. The UK's protected areas, showing the four UK Blue Carbon Inventory regions. Protected area types include Marine Conservation Zones (MCZs) in England and Wales, Marine Protected Areas (MPAs) in Scotland, Marine Nature Reserves (MNRs) in the Isle of Man Territorial Seas, Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) in all devolved administrations, coastal Sites of Special Scientific Interest (SSSIs) in England, Wales and Scotland, and Areas of Special Scientific Interest (ASSIs) in Northern Ireland.

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 protected areas

Sources of habitat information that were used for the blue carbon habitats of Scotland are listed in Annex 1. Biotope and EUNIS codes for polygons were assigned to blue carbon habitats (see Table 1). The primary data source used for deriving estimates for habitat extents in the Region was the EMODnet Seabed Habitats data (EUSeaMap 2019). Assessments of habitats in the Scotland report used this dataset rather than the Natural England Marine Habitats and Species Open Data that were used for the other regional reports. In Scotland, EUSeaMap lacks detailed information on inshore biogenic and coastal vegetated habitats, but gives more complete coverage offshore than the Natural England Marine Habitats and Species Open Data. EUSeaMap includes high-resolution polygon data at scales that allow the intersection of habitats with protected area outlines to determine the extent of habitats within each protected area. This analysis permits scaling up of habitat-specific carbon stores and sequestration rates to whole protected areas and all of Scotland's seas. Additional information on habitat extents was derived from literature reports and from the NatureScot GeMS database for mapped habitats, particularly where those habitats were designated as Priority Marine Features (PMFs) for conservation.

After merging with the habitat datasets, the combined protected area–habitat shapefiles were used for area calculations of habitat categories within each protected area. Extents (in km^2) were estimated for MPAs, SACs, SPAs and SSSIs by summing the areas of their component polygons in GIS, and after reading shapefiles using the R statistical package.

1.3.2 Carbon stores in protected areas

Carbon in stores for the entire region and its individual protected areas was estimated from existing spatial data. Organic carbon (OC) and inorganic carbon (IC) 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 Figure 10 and Figure 11) covered most of the UK's Exclusive Economic Zone (EEZ) and were cropped to Scotland. For each protected area (MPAs, SACs, SPAs and SSSIs), values were extracted from these gridded datasets by re-projecting protected area shapefiles to the same coordinate system as the carbon density maps (ETRS89) and selecting those grid cells that lay inside the protected area polygons using the 'extract' function of *terra* library in R (see Hijmans, 2022). Total carbon (OC and IC) for each Region and for each protected area was calculated as the product of average carbon density per unit area (in g C/m^2/yr) and the total area of the Region or protected area.

1.3.3 Carbon accumulation from habitat-specific assimilation rates in protected areas

As in previous assessments (Burrows *et al*., 2014, 2017), area-specific process rates 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 protected areas, the EUSeaMap 2019 data layer (see Annex 1) was first cropped to Scotland, and the intersection between this layer and the protected areas 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 protected area 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 protected area, and the average rate of accumulation when divided by the extent of the protected area (see Section 3.2.4).

2 Blue Carbon Ecosystems of Scotland

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 Scotland

In this section, blue carbon habitats are described and reviewed in terms of their carbon production, sequestration and storage capacities in the context of Scotland. Process rate estimates are based on the existing literature and available data. Data specific to Scotland are presented following a general review of the relevant ecology and status of each habitat in the UK. Where relevant, recent reports that have estimated carbon storage, sequestration and carbon 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 8) are used as primary sources.

2.2 Habitat extent and distribution

EMODnet Seabed Habitats data (EUSeaMap 2019; see Annex 1) cover most of the seabed in Scotland, but notably exclude the seafloor immediately adjacent to the coastline. EUSeaMap includes high-resolution polygon data at scales that allow the intersection of habitats with protected area outlines to determine the extent of habitats within each protected area. This analysis permits scaling up of habitat-specific carbon stores and sequestration rates to whole protected areas and the entire area of Scotland itself. However, the absence of nearshore habitat information impairs the assessment of habitat types in such locations in protected areas, so the data presented here must be viewed bearing this in mind. Total extents of the main habitat types for Scotland estimated in this way are shown in Table 1.

Table 1. Extents of seabed habitats in Scotland derived from EUSeaMap 2019. Percentage areas are the percentage of each habitat type within the region's protected areas, and values in the bottom row are the percentages of the total area of the Region covered by each type of protected area. Extents presented here reflect the total area of mapped seabed, but not necessarily the total area of the region. Total areas of the different types of protected area do not take into account overlapping designations.

Scotland		Area (km²)					Percentage area			
EUNIS name		All	MPA	SAC	SPA	SSSI	MPA	SAC	SPA	SSSI
Littoral habitats - Physical										
Infralittoral rock and other hard substrata	A3	1336.1	144.0	226.7	496.4	0.9	11%	17%	37%	0.1%
Sublittoral habitats										
Sublittoral rock and other hard substrata	A4	14.0	2.0	3.2	2.2	0.0	14%	23%	16%	0.0%
Sublittoral sediment	A5	5479.8	77.1	169.5	964.2	1.7	1%	3%	18%	0.0%
Sublittoral coarse sediment	A5.1	68275.5	10919.0	4139.6	5521.8	2.9	16%	6%	8%	0.0%
Sublittoral sand	A5.2	110712.0	8522.2	2878.7	4835.9	79.1	8%	3%	4%	0.1%
Sublittoral mud	A5.3	59574.9	8213.8	6703.1	2286.4	17.9	14%	11%	4%	0.0%
Sublittoral mixed sediments	A5.4	3430.8	841.5	1337.2	515.9	3.2	25%	39%	15%	0.1%
Deep-sea mud	A6.5	223921.5	109847.1	4365.6	7.7	0.0	49%	2%	0%	0.0%
	NA	5645.93	1474.0	2980.8	1120.1	70.5	26%	53%	20%	1.2%
Totals		**613387.3**	**174922.0**	**30462.0**	**16482.9**	**176.1**				
			29%	5%	3%	0.03%				

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 seven fucoid species being present in Scotland, 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 (mainly 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., 2020). UK estimates of primary production 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 site-level variability was not related to differences in wave exposure (Lewis, 2020). There have been no published estimates of primary production 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), *Himanthalia elongata* (989.2 g C/m^2/yr) and *Pelvetia canaliculata* (351 g C/m^2/yr), and from Denmark for *Halidrys siliquosa* (5.4 g

C/m^2/yr). Estimates of fucoid living biomass are also 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). These values were again derived from between seven and nine sites in mid and north Wales.

Information on fucoid detrital production is limited to *F. vesiculosus*, *F. serratus* and *A. nodosum* 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 dislodgement and receptacle senescence and are therefore probably conservative. Whole plant dislodgement was in the range of 79–375 g C/m^2/yr (mean ± SE, 148±43 g C/m^2/yr) for *F. vesiculosus*, 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. Combined, 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 below). 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).

Scotland

Values for productivity, carbon stored in living biomass and carbon accumulation 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. Production rates measured by Lewis (2020) were obtained at coastal sites in Wales but should still be relevant to Scotland given the relatively similar environmental conditions.

Table 2. Intertidal macroalgal habitat extent and rates of carbon accumulation used for the Scotland blue carbon assessment. The region area is Scotland's portion of the UK's Exclusive Economic Zone (EEZ)[5] for which organic carbon content has been mapped.

Scotland region area	437883 km²							***Organic carbon***					
Habitat	Extent (km²)	Component area (km²)	Stock (1000 tC)	Stock (g C/m²)			Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Source
				min	max	avg	min	max	avg			
Intertidal macroalgae	371.3	371.3	45.4	85	160	122	125	727	378	140.3	14.0	This report
	371.3	371.3	49.8			134 [1]						Walker 1953; Burrows et al 2014
Intertidal rock	0.0	0.0										Habitat Extent Totals

	Stock (g C/m²)			Production rate (g C/m²/yr)			Source
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

Unpublished biomass measurements in Scotland [2].	Stock (g C/m²)			Wet weight (kg/m²)			
Species [3]	min	max	avg	lower shore	upper shore	avg	
All species combined	85	160	122	3.24	2.00	2.83	
F. serratus	0.9	59.4	30.1	1.32	0.02	0.67	Burrows, unpublished data
F. vesiculosus	44.0	44.1	44.0	0.98	0.98	0.98	Burrows, unpublished data
Ascophyllum nodosum	36.0	42.2	39.1	0.94	0.80	0.87	Burrows, unpublished data

Note [1]. Assuming 30% cover of macroalgae and 447 gC/m²/yr

Note [2]. Using w/w x 0.15 x 0.3 to give kg C /m2 (wet mass to dry mass and dry mass to carbon)

Note [3]. Other species all <3g C/m²

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*, *Laminaria digitata*, *Saccharina latissima*, *Alaria esculenta* and *Sacchoriza polyschides* (O'Dell, 2022). The dominant foundation kelp species along most of the UK coastline is *Laminaria hyperborea* (Smale *et al.*, 2020).

Scotland

The current extent of kelp habitat in Scotland is unknown, but widespread surveys in the 1940s and 1950s (Walker, 1954) for the potential industrial harvest of these plants suggested a total biomass of 3.5 Mt wet mass over a habitat extent of 1,100 km^2 where kelp was of viable quantities for harvesting (average 3.1 kg/m^2), with an overall total of 9 Mt wet mass over the entire rocky subtidal zone (8,100 km^2, average 1.1 kg/m^2). These early estimates, despite the

5 https://marine.gov.scot/data/facts-and-figures-about-scotlands-sea-area-coastline-length-sea-area-sq-kms

limitations of the sampling approaches and spatial analyses, were similar to those emerging from models of the extent of habitat suitable for kelp, based on the associations between kelp observations and underlying environmental predictors (Burrows, 2014). However, model predictions remain highly uncertain, especially without good prediction layers. Habitat extent estimates from models usually require a threshold level of predicted abundance or likelihood of presence to be set before summing areas across a model grid. When thresholds for delineating predicted habitats are set low, the predicted extent is large. Yesson *et al.* (2015) predicted that an area of 19,000 km^2 (nearly the area of Wales) was suitable for kelp around the UK, based on the threshold of presence of species in 3 × 3 km areas. In this series of UK regional reports, estimated extents of kelp habitats used the threshold levels of biomass that corresponded to those typical in places where experimental studies have measured production rates (Smale *et al.,* 2020), yet these thresholds may have produced overestimates. For Scotland, a threshold of predicted kelp biomass of 0.5 kg/m^2 produced an estimate of kelp habitat extent of 4,778 km^2 for the region (see Figure 2). A more typical biomass of 10 kg/m^2 for a dense kelp bed gave a smaller estimate of 993 km^2. Whichever is the most appropriate, the plot (see Figure 2) shows the extreme sensitivity of extent estimates to the chosen threshold (here 0.5 kg/m^2).

Combining the extent estimate of 4,778 km^2 with the average modelled carbon density of 218 g C/m^2 for suitable habitat with over 0.5 kg wet weight/m^2 gives a total of 1.04 Mt C stored in living kelp material in Scotland (see Table 3). Using the higher carbon density value of 594 g C/m^2 from literature reports for the same extent of habitat gives a larger total carbon value of 2.8 Mt C stored in living kelp (see Table 3). The value of 2.8 Mt C is an overestimate, as 594 g C/m^2 is likely to be found only in dense kelp stands. A value of 1.04 Mt C in living kelp is adopted here and used in the UK synthesis report. Burrows *et al.* (2014) suggested a smaller value (202,000–404,000 t C) for the same area, based on a much lower OC density for kelp (94–187 g C/m^2) and a smaller extent based on a lower threshold of abundance (2,155 km^2, where $P(\text{Abundance} \geq A) > 0.5$). Greater confidence in these estimates will only be achieved with improved mapping of kelp habitats.

The extent of kelp habitat for this regional report was estimated for this report using a habitat suitability model (for further details, see 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 total carbon in living biomass 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). The data that were used to estimate the contribution of kelp are summarised in Table 3.

The habitat suitability models for kelp in Scotland were developed extensively for a stock assessment for potential sustainable harvesting (Burrows *et al*., 2018). Kelp harvesting is now banned in Scotland under the terms of Section 15 of the Scottish Crown Estate Act 2019.[6]

[6] www.gov.scot/publications/wild-kelp---restrictions-on-removal-questions-and-answers/

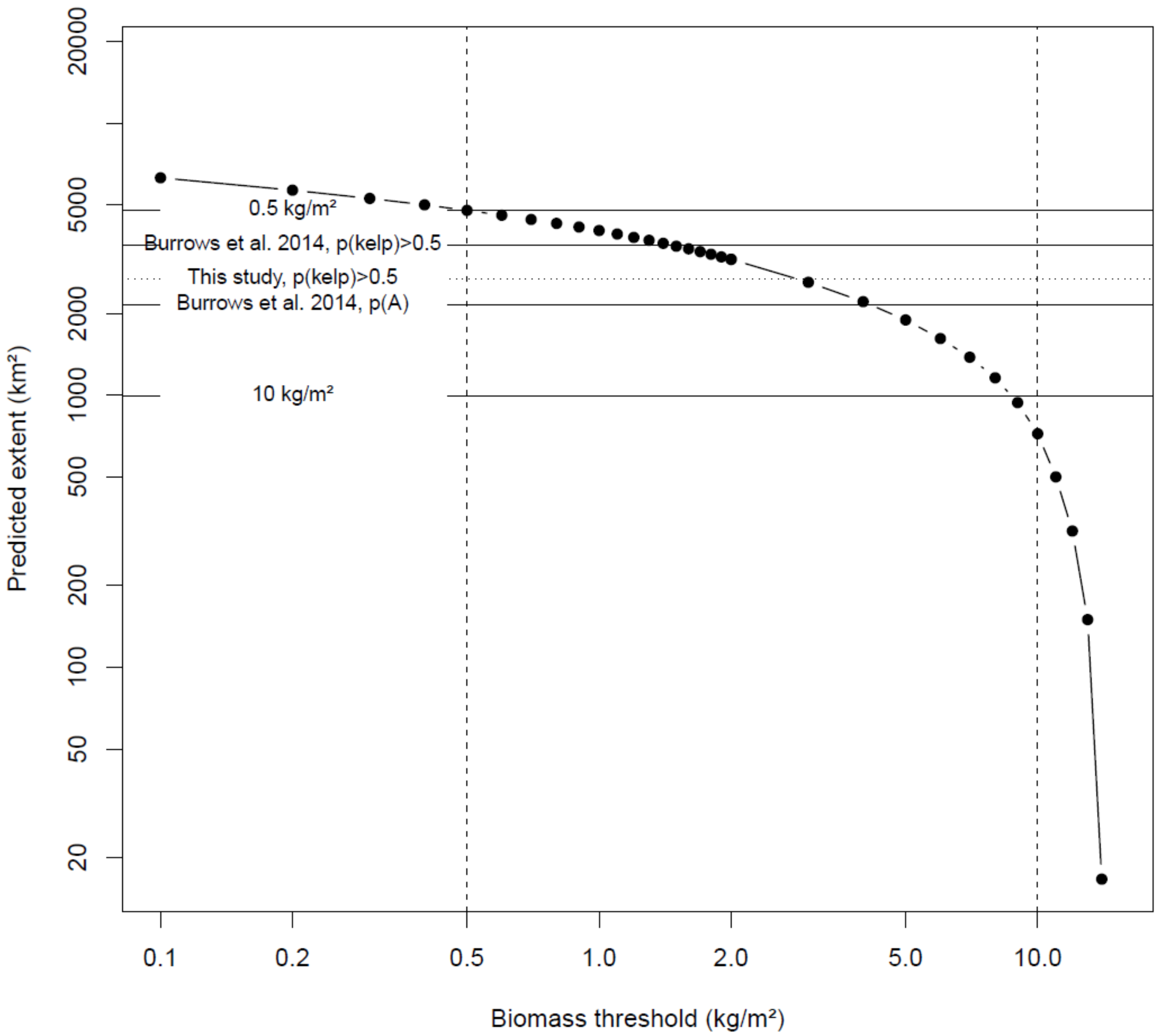

Figure 2. Effects of changing thresholds for extent estimation for kelp (Laminaria hyperborea) *habitat in Scotland. The plot shows the dependence of the predicted extent of kelp habitat on the threshold of predicted abundance. Broken vertical lines represent thresholds of predicted kelp biomass of 0.5 kg/m^2 and 10 kg/m^2, the latter value being more typical of dense kelp beds. Solid horizontal lines represent kelp habitat extents estimated for the same region in previous studies (Burrows* et al.*, 2014).*

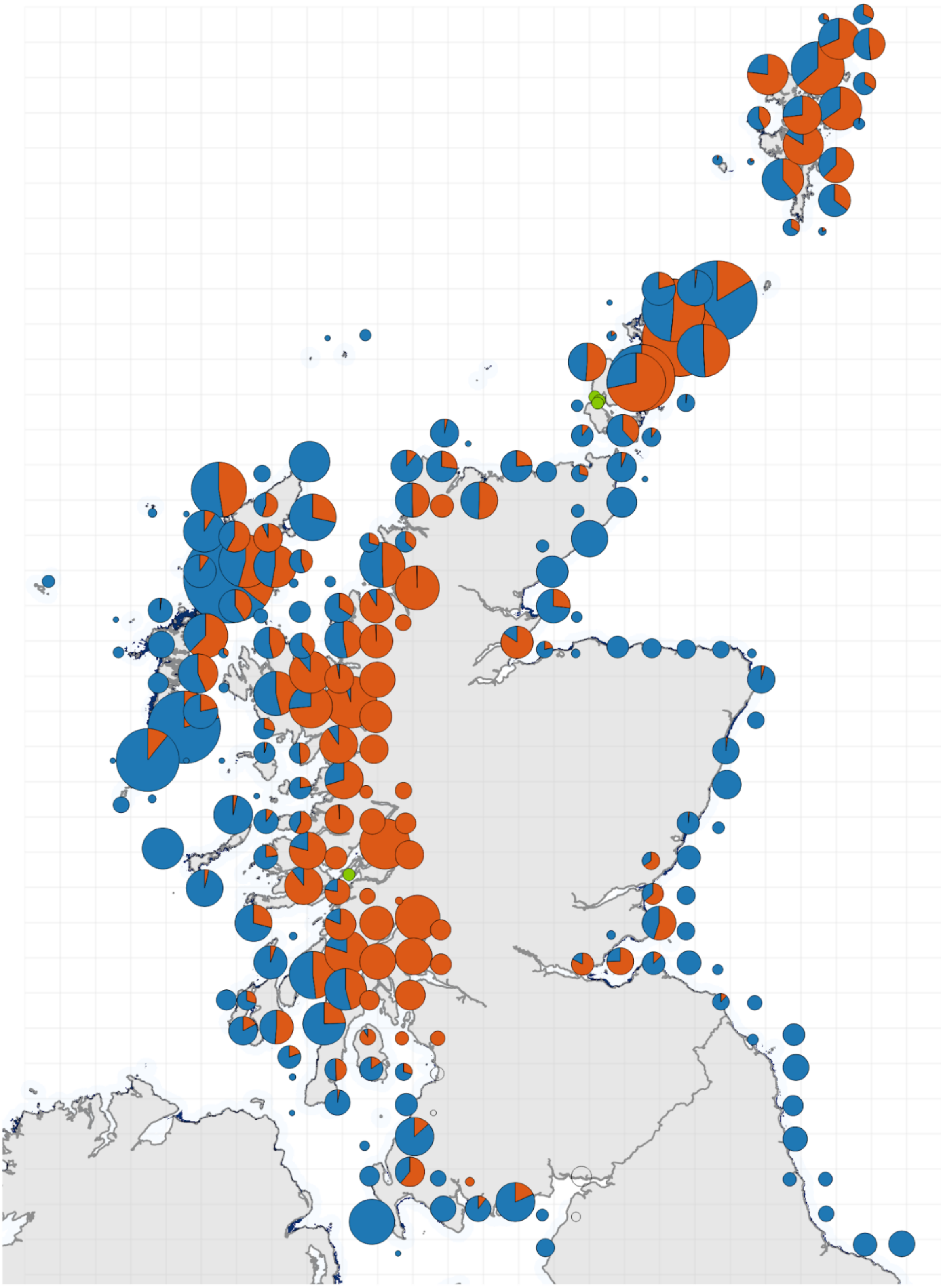

*Figure 3. Predicted distribution of suitable habitat for 'tangle' (*Laminaria hyperborea*) (shown in blue) and sugar kelp (*Saccharina latissima *(shown in orange) around Scotland. Pie charts show the percentage of the total suitable habitat (P (kelp) > 50%) for each species in 20-km grid squares. The size of each circle is scaled to the estimated suitable habitat for the two species combined. From Burrows* et al. *(2018).*

Table 3. Kelp habitat extent and rates of carbon accumulation estimated for Scotland. The region area is Scotland's portion of the UK's Exclusive Economic Zone (EEZ) for which organic carbon content has been mapped. Values used in the ecosystem summary are shown in bold. 'Outflux' is the amount of material exported as particulate organic carbon that is estimated to reach seabed sediment stores.

Sublittoral macroalgae				**Organic carbon**								
Habitat	Extent (km²)	Component area (km²)	Standing stock (1000 t)			Stock (g C/m²)			Production rate (g C/m²/yr)	Total production (1000t C/yr)	Outflux (1000t C/yr)	Source and comments
Scotland	437883	4778	2837.2			594			332	1587.1	158.7	Habitat Review average rate * [model area > 0.5kg/m2 w/w]; Queiros et al 2019
Kelp beds		**4778**	**1041.6**			**218**			**332**	**1587.1**	**158.7**	From *L. hyperborea* habitat model: average stock density x extent
		4778							685	3272.7	327.3	Burrows et al 2014 for average kelp production
						594			**332**		**301**	Habitat Review averages
Fixation from growth rates				min	max	avg	min	max	avg	Proportion of stock		
L. hyperborea				208	1709	**640**	166	738	**340**	0.9		Smale et al 2020
L. hyperborea									**330**			This review (Section 2.2)
L. digitata				79	278	**179**	135	402	**262**	0.1		King et al 2020
L. digitata						**403**						Gevaert et al. 2008
L. digitata									**480**			This review (Section 2.2)
Saccharina latissima									**290**			This review (Section 2.2)
Detritus production												
L. hyperborea							104	568	**301**			Smale et al. 2022

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 (Jenkins *et al.,* 2021). 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 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, 1998).

The distribution of maerl beds 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. 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 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 a study by 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 (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/h in August and was twice as high as in January and February. Maximum calcification rates ranged from 0.6 µmol/g dry wt/h 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, respectively, 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 at least 60 cm thickness, and some dead deposits extend significantly deeper (Kamenos, 2010). Burrows *et al.* (2014) applied an annual IC sequestration rate of 0.074 kg/m^2 for the purpose of their Scottish study.

In similar environmental conditions the productivity of maerl beds is approximately one-third that of seagrass beds. Maerl communities therefore form productive ecosystems that are 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* (20% of the value applied by Burrows *et al.* (2014) due to lower production)
Armstrong *et al.*, 2020	Soil carbon density	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	300–3,000 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* species, which sequester 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).

Scotland

Maerl is widespread along the west coast of Scotland, 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 (see Figure 4). Mapped areas of maerl as a Priority Marine Feature (PMF) in NatureScot's GeMs database (see Annex 1) extend to 31.4 km^2 for maerl beds alone, with a further 13.8 km^2 as a mosaic of maerl and horse mussel (*Modiolus modiolus*) beds, and 14.6 km^2 as a mix of maerl and coarse shell gravel ('Maerl or coarse shell gravel with burrowing sea cucumbers').

Scotland's maerl beds are estimated to contain 720 g C/m^2 of OC to a depth of 25 cm (Mao *et al*., 2020) across their estimated extent of 31.4 km^2. Combining these values gives an estimate of **22,000 t C** stored in the region's maerl beds.

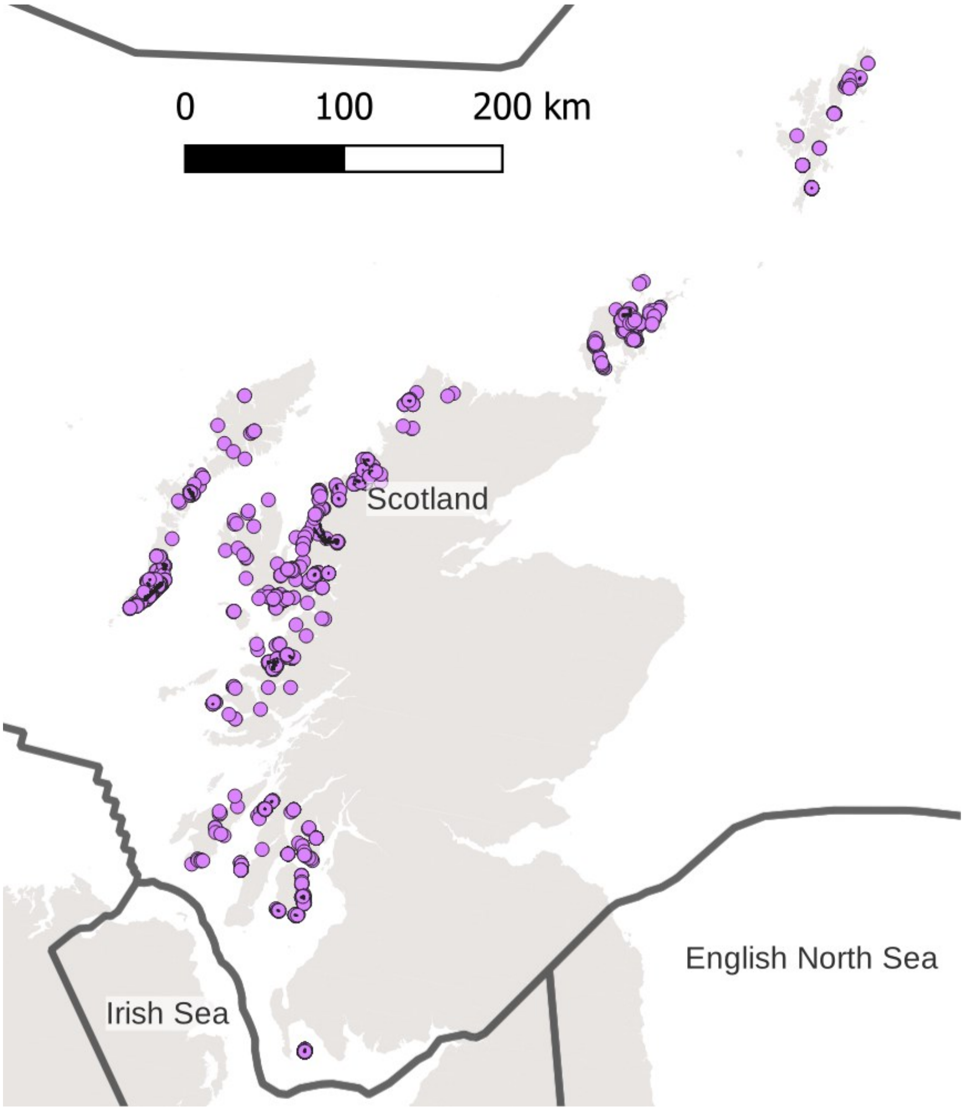

Figure 4. Distribution of maerl records in the NatureScot GeMS database.

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 in living biomass) is largely governed by the production, transport, degradation and eventual sedimentation of the detritus produced by macroalgal ecosystems (Krumhansl & 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 largely 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/yr (Queirós *et al*., 2019).

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

Species	Productivity (g C/m²/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*., 1995; Smale *et al*., 2016
Saccharina latissima	290	40	11	12	Borum *et al*., 2002; Brady-Campbell *et al*., 1984; Krumhansl & 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).

For this report, a value of 10% of annual primary production delivered to sediments as detritus from kelp was adopted in line with the figure assumed for phytoplankton production (Burrows *et al*., 2014, section 3.6.2, p. 46) and with the estimate by Krause-Jensen and Duarte (2016) that, globally, 89% of annual production of macroalgal-derived POC remains in the coastal ocean and, of that, 4.6% is buried in shelf sediments and 95.4% is remineralised. A recent study of POC decomposition in kelp showed that decomposition rates vary considerably with temperature (Filbee-Dexter *et al.,* 2022). Decomposition rates ranged from 0–0.3% per day in the cold north-eastern Atlantic to 2.7% per day in Portugal, with a global average rate of 0.74% per day. These rates suggest that the annual proportion of kelp POC remaining after 1 year is between 48% (0.2% per day) and 0.006% (almost nothing at the 2.7% per day rate), with 6.7% remaining after 1 year at the global average rate of decay. Therefore, although the choice of 10% was initially arbitrary, it is well within the limits of experimental results (10% remaining after 1 year is equivalent to 0.63% per day), and close to emerging findings for decomposition rates of species in Scotland (*Laminaria hyperborea* and *Saccharina latissima*) at prevailing temperatures (see Filbee-Dexter *et al.,* 2022, figure 3).

2.4 Saltmarsh

Background and UK context

Coastal saltmarshes may be defined as areas that are vegetated by halophytic (salt-tolerant) 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 near-shore 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 towards 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 (Austin *et al*., 2021). 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-Brexit successors to the European Union 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), the proportions of zones present, the 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 give an Ecological Quality Ratio (EQR).

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).

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 significant timescales (over 100 years). Autochthonous carbon in saltmarshes may decompose over a few decades, whereas the age of the oldest OC can be several millennia, but it is largely transported from other habitats (i.e., it is allochthonous) (Van de Broek *et al.,* 2018). 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 stores of OC due to the efficient adsorption of organic carbon compounds 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 exudation rate. Ford *et al*. (2016) suggest that species-rich saltmarshes have a reduced soil erosion rate and may therefore sequester carbon for longer than less species-diverse marshes. 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 and Williams, 2019). Sequestration rates in UK saltmarsh 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) applied a value of 210 g $C/m^2/yr$ for their Scottish study.

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 mean 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 soils at 0–30 cm and 30–100 cm depth, 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 in the range of 62–196 g C/m^2/yr, with rates differing between high and low marsh, although 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 between 0–30 cm (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).

Primary production by saltmarsh plants across Scotland remains unknown (Miller *et al*., 2023), but the rate is likely to be less than the global value of 273 g C/m^2/yr used in previous reports (Chmura *et al*., 2003).

There is a differential in carbon sequestration between natural and restored saltmarsh habitat, with the average carbon store 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). It is, however, suggested that the time that has elapsed since restoration plays a part in determining the carbon 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).

Scotland

Scotland's saltmarshes are well mapped (Haynes, 2016) and have been intensively studied in recent years with regard to their OC storage and sequestration/accumulation capacity (Smeaton *et al*., 2022a,b; Miller *et al*., 2023). Haynes (2016) identified 77.0 km^2 of saltmarshes in Scotland, of which 58.4 km^2 consisted of saltmarsh vegetation, with 8.7 km^2 of swamp and 9.9 km^2 of other vegetation or land cover types. The most extensive saltmarshes occur around the Solway Firth in south-west Scotland, and the Moray Firth, Firth of Tay and Firth of Forth, with smaller saltmarshes fringing the upper reaches of sea lochs and sheltered inlets on the west coast. East coast saltmarshes in more open coastal localities occur around coastal basins, such as Findhorn Bay and Montrose Basin, and in estuaries, such as the Rivers Ythan and Spey.

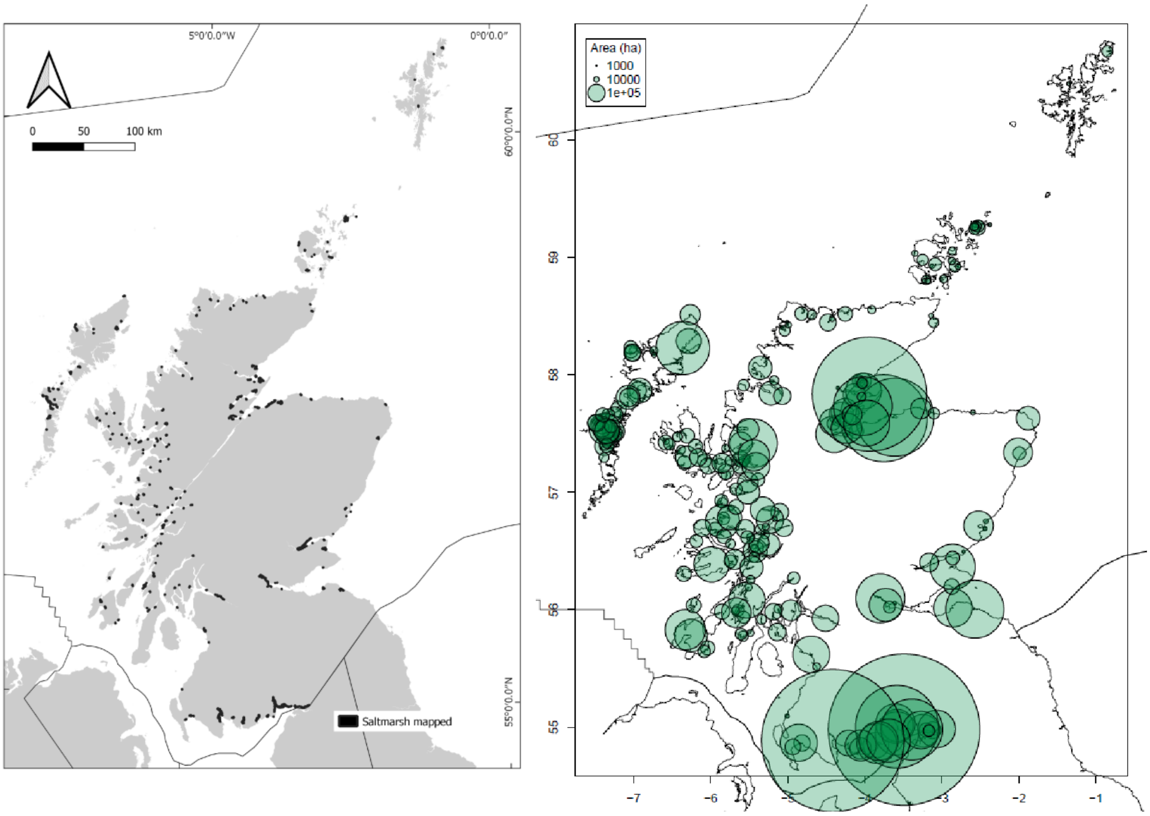

Figure 5. Saltmarshes in Scotland from a recent review by Austin et al. *(2021, using data from Haynes, 2016). (left) The left-hand image shows locations of mapped saltmarshes, and the right-hand image shows relative areas of named saltmarshes. From a recent review by Austin* et al. *(2021), using data from Haynes (2016).*

Table 6. Extent of community types in Scotland's saltmarshes. From Haynes (2016).

NVC	Area (ha)	Description
SM1	8	*Zostera* communities
SM2	< 1	*Ruppia maritima* saltmarsh community
SM6	83	*Spartina anglica* saltmarsh community
SM8	279	Annual *Salicornia* saltmarsh community
SM9	12	*Suaeda maritima* saltmarsh community
SM10	51	Transitional low-marsh vegetation with *Puccinellia maritima*, annual *Salicornia* species and *Suaeda maritima*
SM12	92	Rayed *Aster tripolium* stands
SM13	1,610	*Puccinellia maritima* saltmarsh community
SM14	18	*Halimione portulacoides* saltmarsh community
SM15	< 1	*Juncus maritimus–Triglochin maritima* saltmarsh community
SM16	3,197	*Festuca rubra* saltmarsh community
SM17	4	*Artemisia maritima* saltmarsh community
SM18	50	*Juncus maritimus* saltmarsh community
SM19	18	*Blysmus rufus* saltmarsh community
SM20	35	*Eleocharis uniglumis* saltmarsh community
SM23	1	*Spergularia marina–Puccinellia distans* saltmarsh community
SM27	7	Ephemeral saltmarsh vegetation with *Sagina maritima*
SM28	351	*Elymus repens* saltmarsh community
Total	5,840	

Extents of saltmarsh vegetation types for the Scottish Region from Haynes (2016) (see Table 6) show that most saltmarshes are dominated by *Festuca rubra* (SM16) and *Puccinellia maritima* (SM13).

Carbon storage

The comprehensive study by Miller *et al.* (2023) reported storage of OC in Scotland's 58.7 km^2 of saltmarshes to be 1.15±0.21 Mt OC, based largely on Hayne's extent estimates (Haynes, 2016) and new analyses of the carbon content of vegetation and sediment cores. Surface layers ('Fibrous peat', 'Humified peat') had higher percentages of OC (5–30%) than basal layers ('Basal Unit') (0.7–9%), but lower bulk densities (0.3–0.6 g/cm^3, compared with 0.4–2.1 g/cm^3 for basal layers). High OC content with low bulk density layers extended to 10–30 cm below the surface of the soil, and below that the basal layer represented pre-saltmarsh habitat (tidal flat) with little connection with the saltmarsh soils.

Miller *et al*. (2023) also examined the source of the OC stored in four Scottish saltmarshes using isotopic signatures and found that 50–90% of the carbon stored in saltmarsh sediments was of terrestrial origin. Lower tidal levels of saltmarshes had higher proportions of carbon of marine origin.

The recent focus of research activity on saltmarshes in Scotland and elsewhere in the UK considerably increases confidence in the estimates of OC storage and accumulation in these habitats (Smeaton *et al.,* 2022a,b). Organic carbon per unit area was estimated to be 17.9±3.5 kg/m^2 for complete depth of saltmarsh soil, where soil depth is greater than 10 cm, and 6.31±1.56 kg/m^2 for the top 10 cm. Above-ground biomass of saltmarsh plants was in the range of 0.09–0.28 kg C/m^2, with below-ground biomass in the range of 1.33–1.65 kg C/m^2 (see Table 7).

For comparability with coastal marine sediments, the values of stores reported here extend only to the top 10 cm of sediment, despite the broader recommendation of 1 m depth by the Intergovernmental Panel on Climate Change (IPCC). Organic carbon in coastal sediments is often determined from surface grabs, and extrapolation of surface values to sediments at depths below 10 cm is problematic (Graves *et al.*, 2022). It was estimated by Miller *et al*. (2023) that saltmarshes in Scotland contain 1.15 Mt OC over the full depth of sediments. Using the OC content of saltmarsh plants mapped using the National Vegetation Classification (NVC) scheme, Austin *et al*. (2021) estimated that the top 10 cm of sediment in Scotland's saltmarshes contain 0.368±0.091 Mt OC. This value is higher than the figure of 87,000 t C used here, as it is calculated from literature-reported OC densities and the estimated extent of saltmarshes in Scotland (see Table 7).

Rates of carbon accumulation for saltmarshes in Scotland (see Table 7) have also been estimated by Miller *et al*. (2023) based on stratigraphy and dating of sediment cores from four representative locations (Dornoch Point, Morrich More around the Dornoch Firth, Skinflats in the Firth of Forth, and Wigtown in the Solway Firth). Estimated OC accumulation rates in saltmarsh sediments ranged from 29 g $C/m^2/yr$ to 198 g $C/m^2/yr$, with a mean value of 113.5 g $C/m^2/yr$, and the total accumulation per year across Scotland was calculated by Miller *et al*. (2023) to be 4,385±481 t C/yr. For this report, which was produced before the study by Miller *et al*. (2023) was published, the carbon accumulation rate in saltmarsh sediments was calculated from literature-reported accumulation rates and the estimated extent to be 6,600 t C/yr, with total production from saltmarsh plants being 810 t C/yr, similarly calculated.

Table 7. Saltmarsh habitat extent and rates of carbon accumulation used for the Scotland report. Values used in the regional summary are shown in bold.

Habitat	Extent (km^2)	Component area (km^2)	Stock (OC 1000 t)	Stock density (g C/m²) min	max	avg	Production rate (g C/m²/yr) min	max	avg	Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr) min	max	avg	Storage capacity (1000t C/yr)	Source
Saltmarshes: vegetation	58.4	58.4	10.8	90	280	185	42	235	138	8.1	**0.81**					0.0	Haynes 2016; Miller et al 2023; Smeaton et al 2022a,b; Kirwan et al 2009.
Saltmarshes: soil	58.4	58.4	87.0	1330	1650	1490						**6.6**	**29**	**198**	**113.5**	**6.6**	Miller et al 2023; Smeaton et al 2022a,b
	58.4	58.4	368	3640	6570	6000											Austin et al 2021 (using NVC classes)

2.5 Seagrass beds

Background and UK context

Seagrasses in the UK (*Zostera marina, Zostera noltii* and the salt-tolerant tasselweed *Ruppia maritima*) can play an important role in carbon sequestration. In other parts of the world seagrass beds act as net sinks of carbon (in the Mediterranean, notably *Posidonia* species) (Duarte and Cebrián, 1996; Duarte *et al*., 2010). The contribution of seagrasses to global oceanic carbon storage has been quantified in several recent studies, but that research focused on species and locations outside the UK (Dahl *et al*., 2016; Greiner *et al*., 2013; Gullström *et al*., 2018; Macreadie *et al*., 2013; Miyajima *et al*., 2015; Röhr *et al*., 2016; Serrano *et al*., 2014). There are some caveats associated with this global estimation, however, largely due to the high rates of below-ground accumulation of carbon in certain species which are not found in the UK, such as *Posidonia oceanica*, and differences in environmental conditions (Röhr *et al*., 2018).

Seagrass beds sequester OC in shoots, leaves and below-ground rhizomes, and as seagrass detritus accumulated in the soil. Deposition of POC from the water column (Kennedy *et al.,* 2010) 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 rhizome material (Enriquez *et al.,* 1993; Klap *et al.,* 2000; Nielsen *et al.,* 2004). Yet, once incorporated in the soil, 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 unaccounted for 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 suggests that the contribution of seagrass beds to carbon sequestration has been underestimated by only including carbon burial within seagrass sediments (Duarte *et al*., 2005).

Garrard and Beaumont (2014) estimated a mean biomass carbon density of 1.61 t C/ha for all seagrass beds in the UK, using data reported from previous studies conducted in different geographical areas. Carbon sequestration rates of seagrass beds in the UK have been estimated to be 24,000 t C/yr by Green *et al.* (2021) and 2,500 t C/yr by Luisetti *et al.* (2019), with potentially 232,000 t C/yr from historical undamaged seagrass meadows (Green *et al.,* 2021). These estimates are based on frequently used accretion rates in the literature (low rate, 0.044 cm/yr; medium rate, 0.202 cm/yr; high rate, 0.42 cm/yr), with medium rates of carbon accumulation (2,400 t C/yr^{-}) being 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 for Scotland (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 (Duarte *et al.,* 2005), albeit based on studies of *Posidionia* species and therefore less applicable to the UK.

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 human disturbance, such as pollution and physical disturbance from 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. The occurrence of seagrasses is not uniform. Seagrass extents range from patches of less than 1 m^2 to beds of up to 1,200 ha (Cromarty Firth, East Scotland). 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).

Scotland

Scotland hosts the second largest extent of mapped seagrass habitats in the UK, with a total area of 20.9 km^2 (Green *et al*., 2021; Cunningham and Hunt, 2023), compared with 26 km^2 for the Irish Sea and Welsh Coast Region, 9.9 km^2 for the English Channel and Western Approaches Region and 8.9 km^2 for the English North Sea Region. The extent of seagrass is almost equally divided into subtidal areas (mainly *Zostera marina,* 10.9 km^2) and intertidal areas (*Zostera noltii,* 10.0 km^2). In total, 26 known locations of seagrass beds in Scotland currently lie within protected area boundaries.

The largest areas of mapped seagrass in Scotland are in the Outer Hebrides (Sounds of Harris and Barra) and on the east coast in the Cromarty Firth (notably Nigg Bay and Udale Bay) and Dornoch Firth (see Table 8).

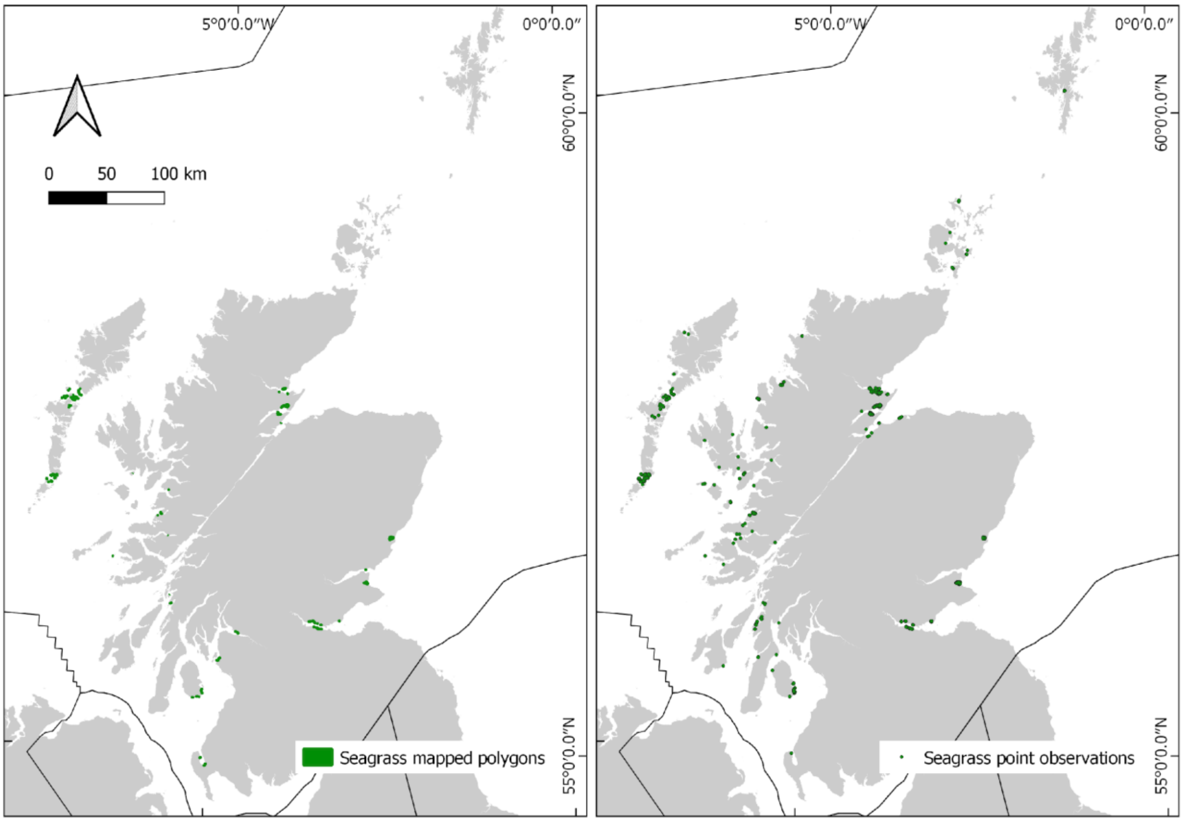

Figure 6. Locations of seagrass beds in Scotland. Left-hand image shows the mapped polygons of seagrass (current known extent). Right-hand image contains point-source data for observed seagrass in Scotland. Shapes are not to scale.

Table 8. Extent of Scotland's seagrass beds mapped as Priority Marine Features (PMFs). From NatureScot GeMS data (see Annex 1).

Location	Area (ha)	Latitude	Longitude
Sound of Harris	661.21	57.72	–7.14
Outer Cromarty Firth	323.97	57.72	–4.07
Sound of Barra	300.26	57.08	–7.34
Montrose Basin	279.54	56.71	–2.50
Dornoch Firth and Morrich More	116.98	57.84	–4.09
South Arran	65.87	55.48	–5.08
Eden Estuary	55.92	56.36	–2.86
Lower Forth Estuary	33.18	56.01	–3.51
North Uist	24.75	57.64	–7.18
Sound of Arisaig (Loch Ailort to Loch Ceann Traigh)	23.90	56.85	–5.79
Largs Channel (Fairlie Roads)	19.29	55.74	–4.88
Middle Forth Estuary	19.23	56.05	–3.60
Clyde Estuary – Outer	10.80	55.95	–4.62
Loch Ryan	10.48	54.94	–5.02
Treshnish Isles	3.05	56.50	–6.42

Location	Area (ha)	Latitude	Longitude
Loch Craignish	2.35	56.16	–5.57
Kinghorn to Leith Docks	1.48	56.06	–3.21
Firth of Tay and Eden Estuary	1.47	56.47	–2.85
Kildonan Beach	0.83	55.44	–5.14
Rosemarkie Bay	0.65	57.59	–4.11
Kilmory Beach	0.34	55.43	–5.21
Inverie Bay, Knoydart	0.13	57.04	–5.68
Port an t-Salainn on north-east side of Shuna Island	0.03	56.22	–5.59
Loch Sunart	0.03	56.68	–5.66
Camas nan Gall, Soay Island	0.02	57.15	–6.21

Carbon storage

Carbon stores in Scotland's seagrass beds have been assessed in two recent studies (Potouroglou, 2017; Potouroglou *et al*., 2021). Organic carbon stores in the top 50 cm of sediment in *Z. marina* and *Z. noltii* beds in Scotland are reported to range from 22.7 t C/ha to 107.9 t C/ha, with a mean of 57 t C/ha across seven sites (Potouroglou, 2017), and a mean of 54.8 t C/ha over ten locations (see Table 9). In this report, OC stores stated for these habitats have been based on scaling of published values for OC densities per unit area stored in the upper 50 cm of sediment to just the top 10 cm of sediment. The total estimated OC stored in seagrass sediment is thus 32,300 t C for the top 10 cm of sediments in 20.9 km^2 of seagrass beds in Scotland (see Table 9). Carbon accumulation per year for seagrasses in the region was estimated to be 2,100 t C/yr based on their total extent (20.9 km^2) and reported area-based rates of accumulation (see Table 9).

Table 9. Seagrass habitat extent and rates of organic carbon accumulation used for the Scotland

Habitat	Component area (km²)	Organic carbon total (1000 t)	Organic carbon density (g C/m²)			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
437883 (region)			min	max	avg		avg	avg				min	max	avg		
Scotland			2940	11402	**7171**	0.3	**1547**								0.00	
Seagrass (total)	19.6	30.3														NatureScot GeMS V10 i26
Seagrass (total)	**20.9**	**32.3**													2.10	Cunningham & Hunt 2023
								274	5.7	0.6	1.52					from increase in dry mass of *Zostera marina* ; Godshalk and Wetzel, 1978; Sand-Jensen, 1974
Seagrass (intertidal)	10.0	15.5										10.5	48.3	100.4	1.00	SMA2020
Seagrass (subtidal)	10.9	16.8														Cunningham & Hunt 2023

OC content estimates	Organic carbon density (t C/ha)					Accumulation (cm/yr)				
	min	max	avg			low	med	high	avg	
Seagrass -sediment: Scotland	29.4	114.0	71.7	0.3	23.9	0.044	0.202	0.420	0.222	Green et al 2018, 2021; Luisetti et al 2019
Seagrass - sediment: global			139.7	1.0	14.0					Fourqurean et al 2012
Seagrass - sediment: Scotland	22.7	107.8	65.3	0.5	13.1					Scotland (Potouroglou, 2017) <0.5m
	14.9	105.7	54.8	0.5	11.0					Potouroglou et al., 2021, Scotland <0.5m
			33.8							Lima et al 2020
Seagrass - vegetation: global	2.0	3.0	2.5	0.1	2.5					Fourqurean et al 2012

2.6 Biogenic reefs

The role of calcium-carbonate-forming biogenic reefs, such as mussel beds and cold-water corals, in climate mitigation through accumulation of carbon stores is complex (Turrell *et al.,* 2023). Such structures may facilitate the accumulation of organic material derived from other sources or produced by the reef-building species themselves (e.g., pseudofaeces from live mussels). Importantly, however, carbon dioxide is released by these habitats through the process of calcification during construction of the skeletal material that forms the biogenic reefs themselves, as shells, coral or worm tubes. This effect means that such habitats are generally viewed as net producers of CO_2 (Frankignoulle *et al.*, 1994) and, as such, not blue carbon habitats in the traditional sense. However, biogenic reefs are extremely important as species-rich, high-biodiversity habitats that support wider ecological communities through habitat provision and food supply (e.g., serpulid reefs attracting fishes and invertebrate mobile predators) (Poloczanska *et al.*, 2004). As such, many of these habitats have high conservation value (they are Priority Marine Features in Scotland), and their presence has led to the identification and designation of the present network of protected areas in the region. As a result of the focus on these habitats, much of their occurrence has been recorded and mapped (see Table 10).

In summary, the inclusion of the deposition of sedimentary carbon, as well as carbon stored in shell material, balanced with the release of carbon through respiration and calcification, suggests that these habitats are unlikely to be significant carbon sinks in the context of global climate change mitigation. However, the recovery of biogenic reefs is likely to facilitate the accretion of carbon stores that are nevertheless important in conservation management (Turrell *et al.,* 2023).

Table 10. Extents of biogenic reefs mapped as Priority Marine Features (PMFs) in Scotland. The values shown do not reflect the total extent of the habitats in the region.

Priority Marine Feature	Area (km^2)
Northern sea fan and sponge communities	903.5
Native oysters	675.9
Maerl beds	31.4
Maerl or coarse shell gravel with burrowing sea cucumbers	14.6
Maerl beds and horse mussel beds (mosaic)	13.8
Flame shell beds	10.5
Horse mussel beds	10.2
Cold-water coral reefs	6.2
Blue mussel beds	4.4
Coral gardens	2.5
Serpulid aggregations	1.1

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 long 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 carbon in living 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 protected areas), and blue mussel beds are therefore treated as a 'data-deficient' category in this report. 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).

Scotland

Mapped blue mussel beds in Scotland are shown in Figure 7. Both subtidal and intertidal beds are widespread throughout the Region (12.4 km^2 of intertidal beds and 23.1 km^2 of subtidal beds, including the mapped PMFs in Table 10).

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 stores, the annual IC production 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 stores (see Burrows *et al.,* 2017, 2021; Porter *et al.,* 2020). Field sampling in Scottish beds has provided an accurate estimate of calcium carbonate (see Hirst *et al.,* 2012). The area-specific store density estimate used in this report is 4,000 g IC/m^2.

Scotland

Large *M. modiolus* beds occur in Scotland, the most extensive ones being off Noss Head (410 ha) and in the Moray Firth (318 ha) (see Figure 7).

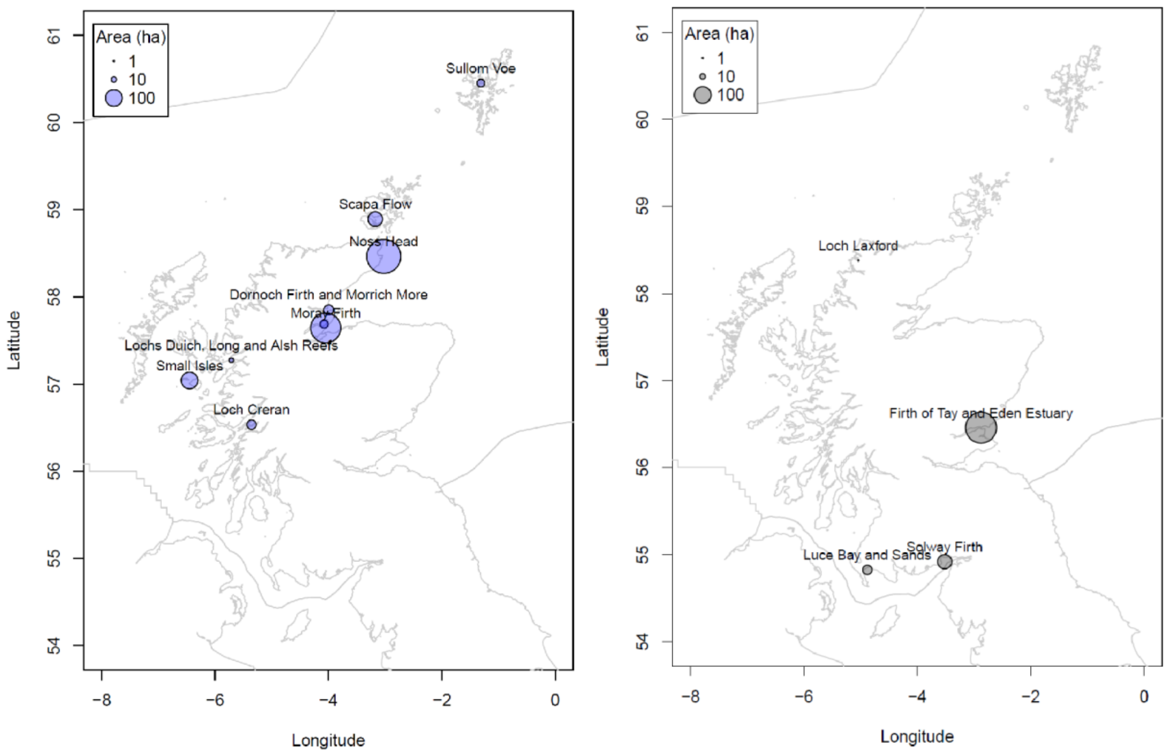

*Figure 7. Locations of mapped areas of horse mussel (*Modiolus modiolus*) beds (left) and blue mussel (*Mytilus edulis*) beds (right) in Scotland. From the NatureScot GeMS database.*

2.6.3 Native oyster (*Ostrea edulis*) reefs

Background and UK context

Native oyster (*Ostrea edulis*) reefs are usually considered to be 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).

Scotland

Native oysters (*O. edulis*) are found throughout the Region (see, for example, the NBN Gateway), but are not recorded as reef-forming seabed habitats.

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

Background and UK context

Cold-water corals (*Desmophyllum pertusum*, formerly 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 from the Mingulay Reef complex (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 suggest a sequestration rate of IC of 35 g C/m^2/year

(Burrows *et al.,* 2014), 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 seafloor, 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).

Scotland

In Scottish seas there are records of cold-water corals (*D. pertusum*) forming on continental slopes off the west coast within depth ranges of 200–400 m. There are also observations of reefs forming off the islands of Barra and Mingulay in slightly shallower water (above 150 m). This region of reef is thought to cover an area of approximately 100 km^2, and it has been estimated to be 4,000 years old (Douarin *et al*., 2013, 2014). The reefs are currently protected as the East Mingulay SAC, and there is a complete ban on trawling from some regions of the Darwin Mounds SAC (east of Rockall). The combined protected areas cover an area of approximately 1,400 km^2 (see Figure 8).

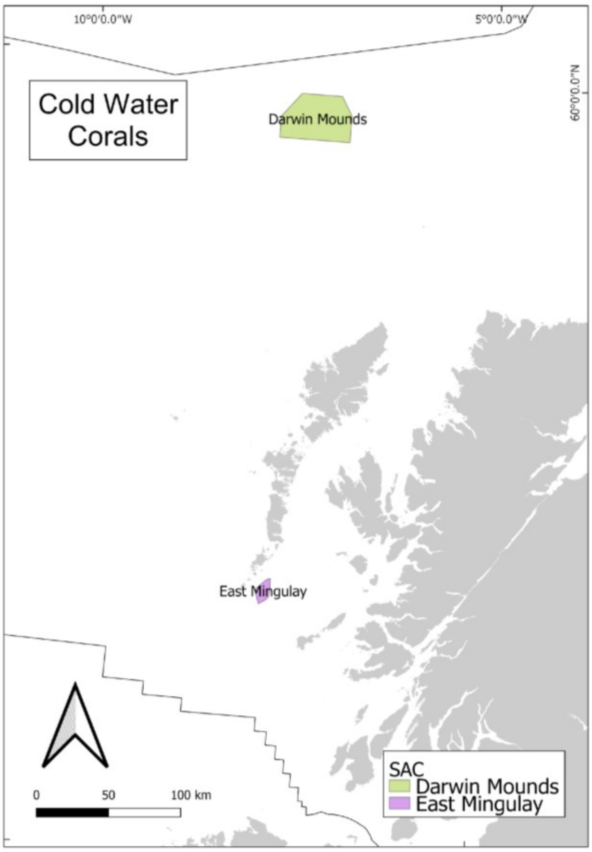

Figure 8. Protected areas designated for the presence of cold-water corals (both are SAC designations).

2.6.5 *Sabellaria* reefs

Background and UK context

Sabellaria reefs are listed as a priority habitat under the UK Biodiversity Action Plan (BAP, Holt *et al.*, 1998), but are not designated as a PMF in Scotland. 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).

Scotland

There are multiple observations of *S. alveolata* and *S. spinulosa* in Scotland, but these species are only thought to form reefs in a few areas. *S. alveolata* reefs have been found on the coast of the Solway Firth, and more recently significant *S. spinulosa* reefs have been found on the east coast of Scotland (Pearce and Kimber, 2020). The new *S. spinulosa* sites were found off the Moray Firth during remotely operated vehicle (ROV) surveys close to Peterhead and Fraserburgh.

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 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 burrowing activities (bioturbation) 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 and have accumulated over time periods of up to 10,000 years (Eglinton *et al*., 1997; Austín *et al*., 2021a).

2.7.2 Scotland

The seabed in Scotland is diverse in its composition. There are large areas of exposed rock west of the Outer Hebrides around Uist and the southern part of Harris. Belts of fine mud can be found nearshore in the Minch, around Argyll and Bute and in the Clyde Sea (see Figure 9). This contrasts with sediments on the east coast, which are largely sandy and coarse grained (see Figure 9).

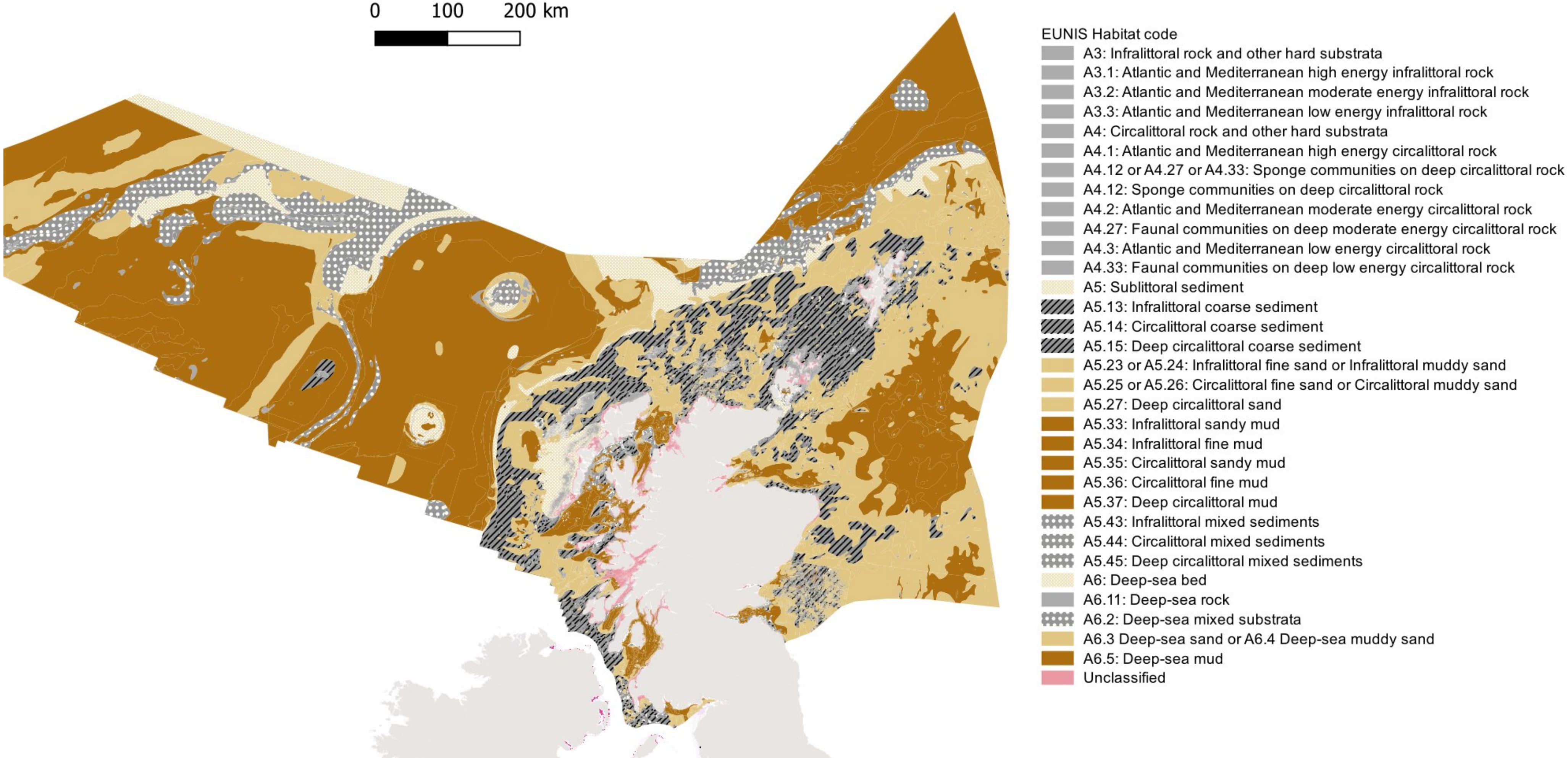

Figure 9. Seabed habitat classification from the EUSeaMap (2019) polygon dataset. Note the predominance of unclassified areas in coastal regions.

2.7.3 Carbon stores in seabed sediments

Analyses of the carbon content of historical British Geological Survey (BGS) sediment cores by Smeaton *et al.* (2021) have produced spatial maps of OC and IC across most of the UK's EEZ. For Scotland, these maps show considerable variation in OC density (see Figure 10 and Figure 11).

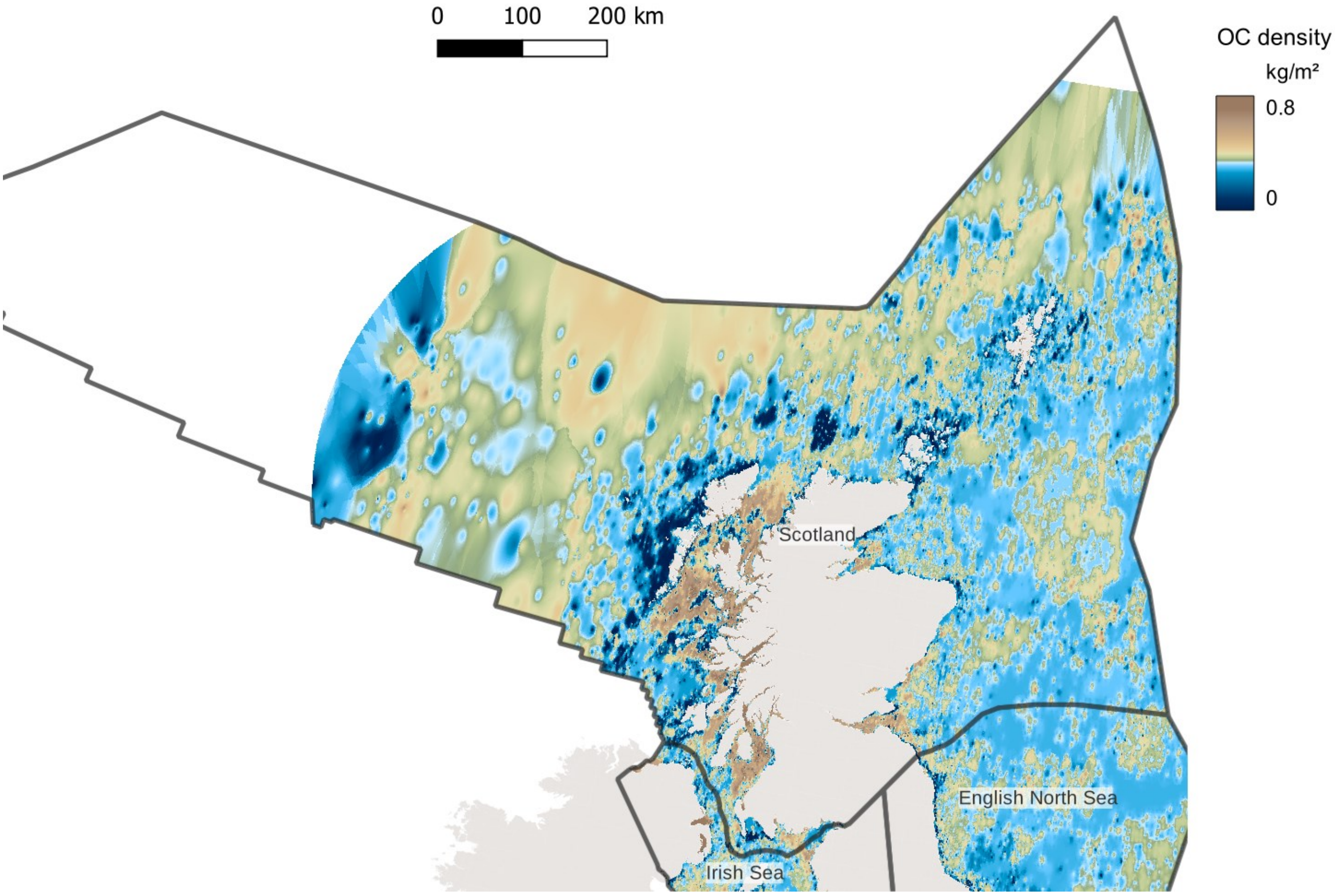

Figure 10. Organic carbon density in the top 10 cm of marine sediments in Scotland. Mapped areas for organic carbon extend to the Exclusive Economic Zone (EEZ) limit of the UK, whereas the Scotland area of this report (black outline) extends to the Continental Shelf limit. Data from Smeaton et al*. (2021).*

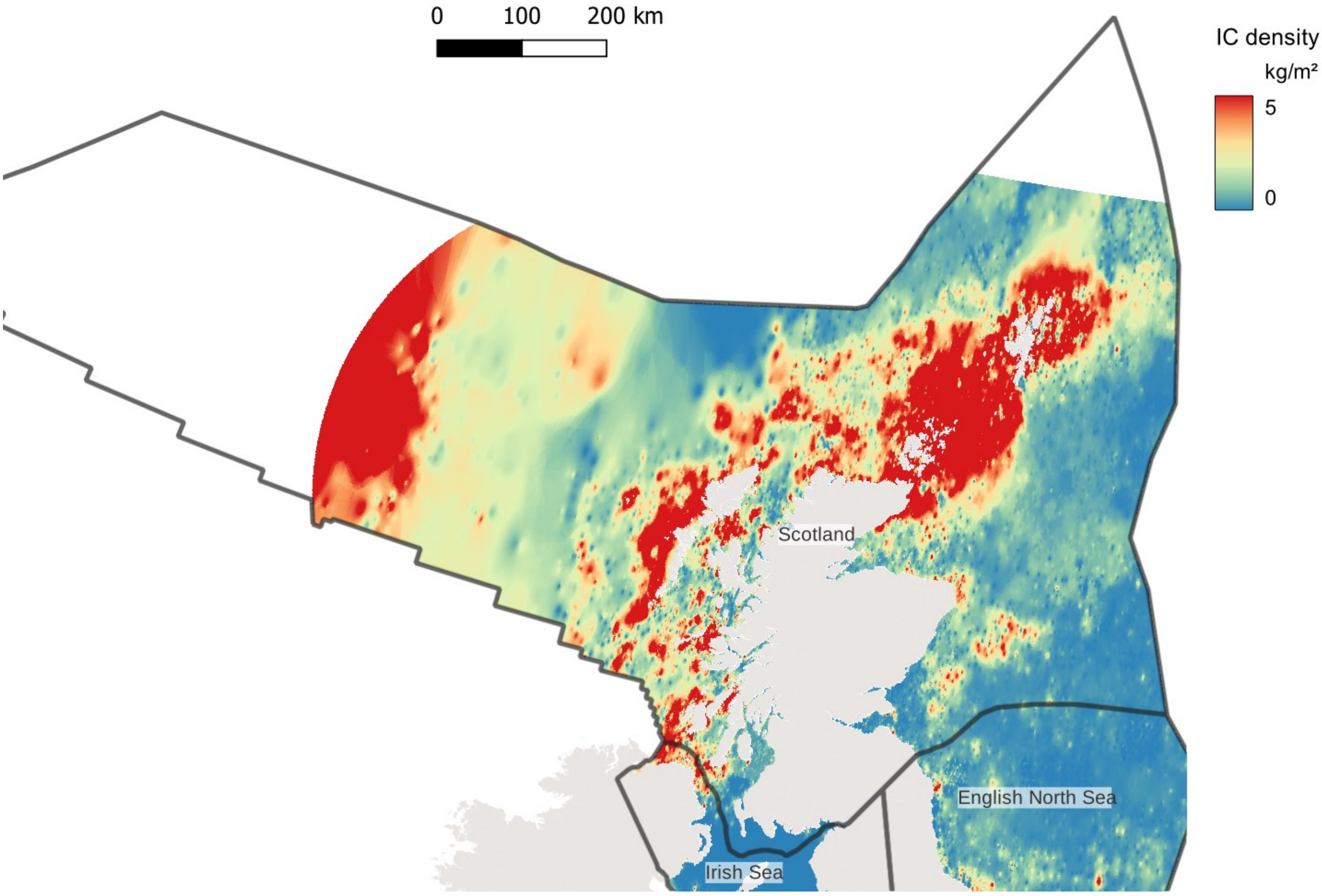

Figure 11. Inorganic carbon density in the top 10 cm of marine sediments in Scotland. Mapped areas for organic carbon extend to the Exclusive Economic Zone (EEZ) limit of the UK, whereas the Scotland area of this report (black outline) extends to the Continental Shelf limit. Data from Smeaton et al*. (2021).*

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 mud and vegetated habitats (see Table 11). Diesing *et al*. (2017) modelled patterns of POC in UK shelf sediments. The highest POC concentrations are associated with gravelly mud, mud and sandy mud. Conversely, sands, gravel and sandy gravel have the lowest POC concentrations. Offshore sands do not have such high OC densities (in g C/m^2) as inshore mud and vegetated habitats, but may support a larger total store due to the greater extent of these habitats. Areas of high tidal flows (see Figure 12) tend to have lower densities of sediment OC, but often have much higher densities of IC in the form of shelly material. Distance from the shore is also a factor influencing POC, due to the importance of terrestrial inputs, with sediments in enclosed fjordic sea lochs having a much higher density of OC (Smeaton *et al*., 2017) and a greater proportion of carbon from terrestrial sources (Smeaton and Austin, 2017, 2022). Across Scotland's sea lochs, 52±10% of the OC in the surficial sediments is terrestrial (Smeaton and Austin, 2022). Particulate organic carbon density 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 referenced studies by de Falco *et al.* (2004), McBreen *et al.* (2008) and Serpetti *et al.* (2012).

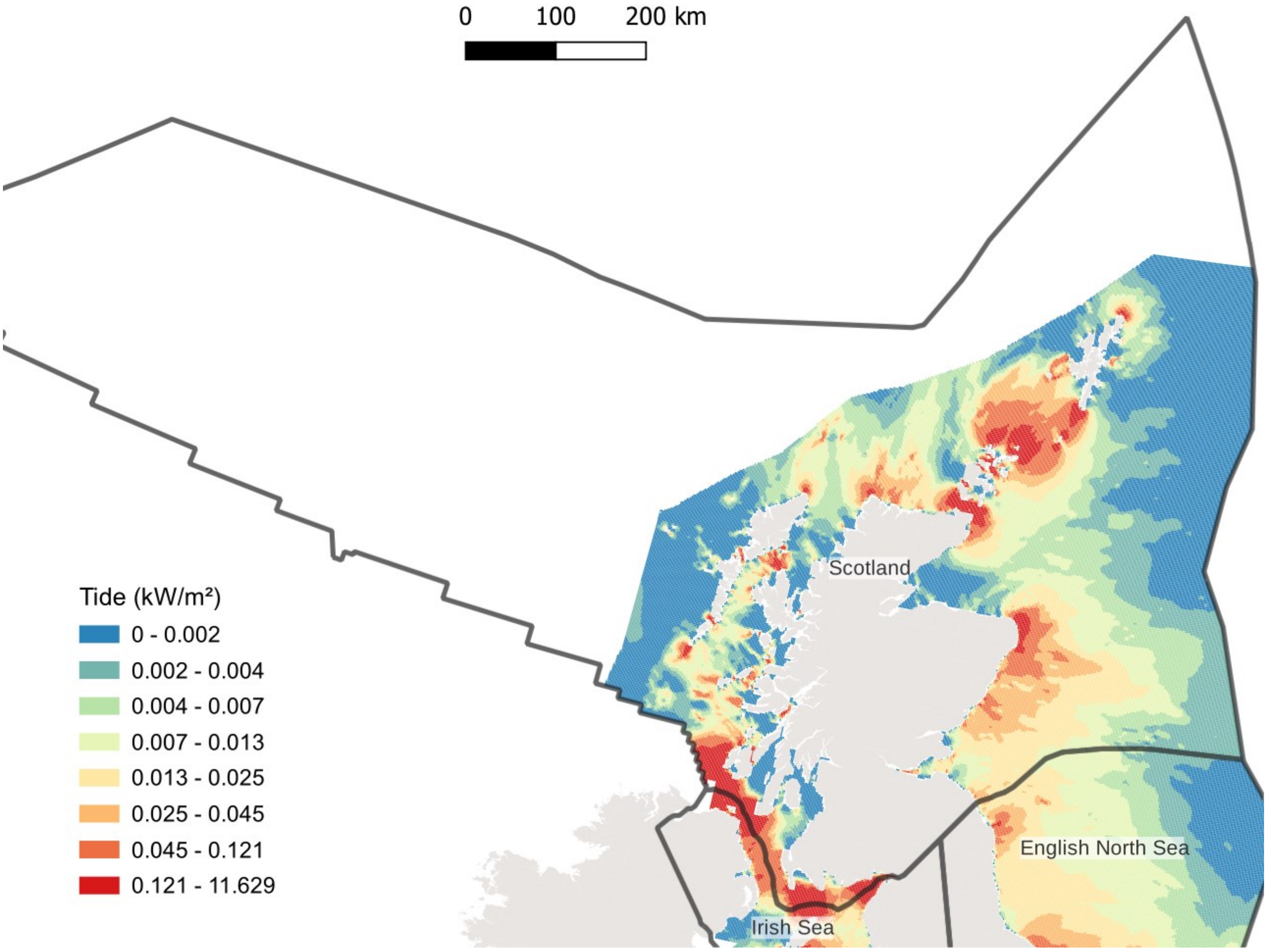

Figure 12. Tidal power in Scotland. Data from the UK Atlas of Marine Renewables (a free resource hosted by ABPmer, 2022). Tidal power is derived from the cube of the average current speed (see Atlas of UK Marine Renewable Energy Resources: Technical Report, ABPMer 2008).

2.7.4 Rates of carbon accumulation in sediments

Carbon accumulation in Scotland's seabed sediment is not well understood. The lack of region-specific data on accumulation rates necessitates the use of data from comparable locations elsewhere (see Table 11), based on the earlier review of sediment accumulation rates by Burrows *et al*. (2014) and other reviews and recent studies (Duarte *et al*., 2005; Queirós *et al*., 2019; Atwood *et al*., 2020). Rates of accumulation for each EUNIS habitat type derived in this way were used with extents of mapped habitats (see Figure 9) to obtain a total of 9.5 Mt OC/yr added to sediments in the Region (see Table 13). This value mainly represents the accumulation in a single habitat (EUNIS code A5.2 Sublittoral mud) (see Table 13). The rate of OC accumulation for sublittoral mud that was used by Burrows *et al*. (2014) and in this report was derived from a study in Quebec that reported values of 19 and 292 g C/m^2/yr, giving an average of 155 g C/m^2/yr (St-Onge and Hillaire-Marcel, 2001). As the authors of that study point out, the sedimentation rates in their study area may be exceptionally high. That said, rates of carbon accumulation in Scottish fjords have been reported to be 146 g C/m^2/yr (Overnell and Young, 1995), with similarly high rates being reported from mud habitats in the Skaggerak, namely 130 g C/m^2/yr (Jørgensen *et al.*, 1990) and 26–120 g C/m^2/yr (Stahl *et al.*, 2004).

A more recent study has shown that large areas of the Scottish Region of the North Sea have very low rates of sediment deposition, particularly in the southern part of the Region where surface disturbance by waves and currents may be greater than elsewhere (Aldridge *et al.*, 2015), resulting in very little OC burial in those areas (Diesing *et al.*, 2021). Rates of accumulation predicted from that study follow sediment types (see Figure 13), and as expected higher rates are associated with mud habitats and lower rates with sand and coarse sediment habitats. However, predicted accumulation rates from Diesing *et al*. (2021) (see Figure 13) are nearly two orders of magnitude smaller than the values used in the analysis presented here. The typical maximum value of 4 g C/m^2/yr for OC accumulation in sublittoral mud habitats in the area is only 3% of the value used here (155 g C/m^2/yr) (see Table 11), and is much closer to the literature-reported values used here for sublittoral sand (0.2 g C/m^2/yr). Using average OC accumulation rates for Scotland, part of Diesing's dataset (0.63 g C/m^2/yr) gives a total annual accumulation of 79,200t C/yr from a subset of 20% (126,000 km^2) of the Region; this is just 0.8% of the 9.5 Mt/yr total estimated from the larger value for accumulation in sublittoral mud. The discrepancy between these two estimates, combined with the absence of experimental measurements, confers considerable uncertainty on the value for OC accumulation in the Region per year. There is greater confidence about accumulation rates in Scotland's fjordic sea lochs, with a value of 57.1±10.9 g C/m^2/yr, giving a total of 84,000 tonnes of OC deposited per year (Smeaton and Austin, 2022).

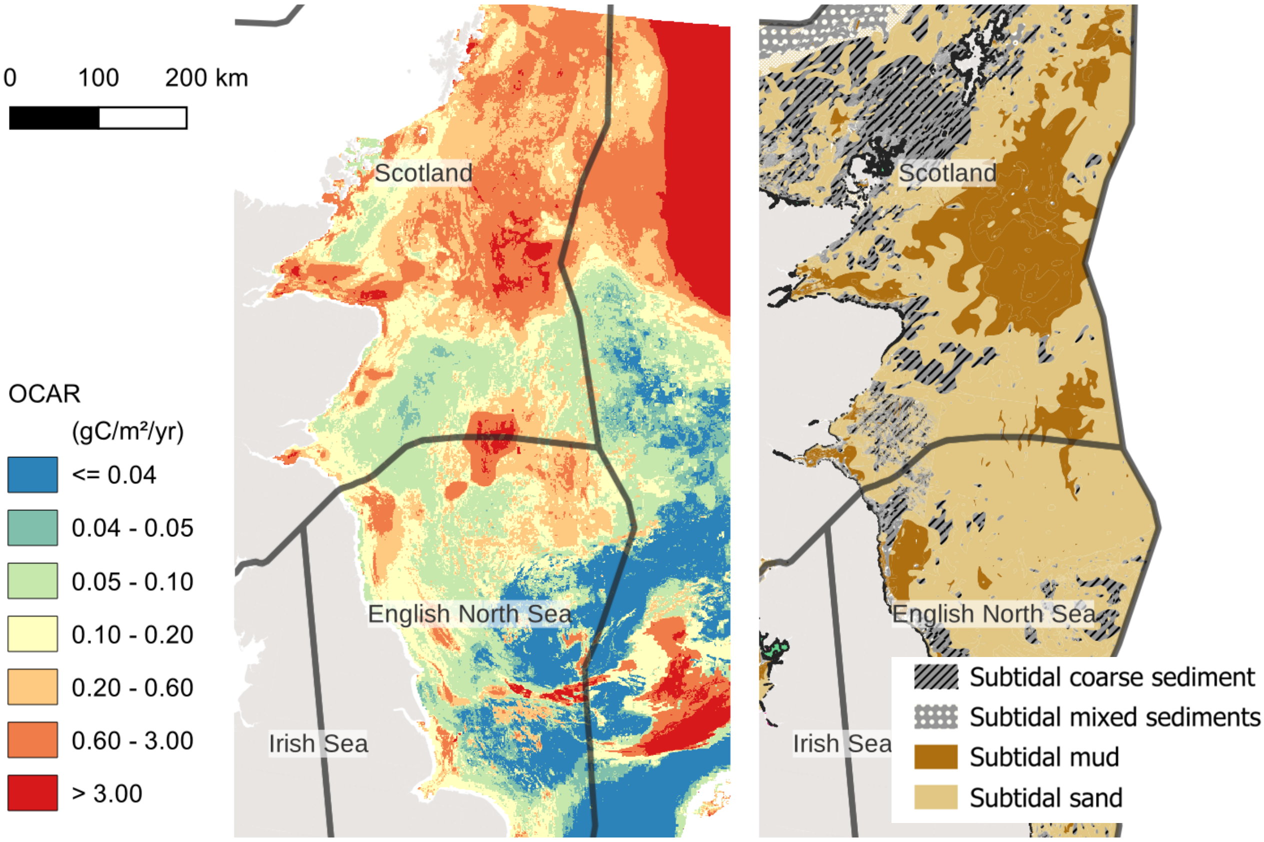

Figure 13. Sediment organic carbon accumulation rates in the North Sea, from Diesing et al. *(2021) (left). EUSeaMap 2019 seabed habitat types (right).*

Table 11. Habitat- and area-specific estimates of organic carbon density and accumulation in marine sediments in Scotland, from relevant literature sources. The table summarises data used in calculations. Columns with a grey background give values of organic carbon over 1 m depth of sediments. Columns with a blue background give reported values for organic carbon accumulation rates. New values for organic carbon accumulation rates in sublittoral mud habitats are highlighted in pale orange, contrasting with the previously used values (Burrows et al., *2014), which are highlighted in dark orange.*

			%OC		1m depth kgOC/m²					0.1m depth gOC/m²			**Sediment** cm/yr			**Carbon Accumulation** gOC/m²/yr			
EUNIS code	Habitat	Sediment type	min	max	min	max	Avg	SD	n	min	max	Avg	min	max	Avg	min	max	Avg	Source
A1	Intertidal	Rock					0					0			0			0	
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																	0.0	CEH Land Cover Map; Habitat Review (Callowa
A2.6	Intertidal/Su	Seagrass beds																100.4	Cunningham & Hunt 2023
A2.7	Intertidal	Biogenic reef: mussel beds/Sabellaria					0.0					0			0.000			0.0	
A2.8	Littoral	Rock					0					0			0			0.0	
A3	Intertidal	Rock					0					0			0			0.0	
A4	Circalittoral	Rock					0					0			0			0.0	
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
A5	Sublittoral	All			2.8	4.0	3.3			279	402	329							Smeaton et al 2021
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														0.1	1.1	0.5	Diesing et al 2021
A5.4	Sublittoral	Sand/mud																59.0	Queiros et al 2019
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	
A6																			
A6.1	Deep	Rock					0					0			0			0.0	
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
A6.4	Deep	Muddy sand																	
A6.5	Deep	Mud			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
	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 12. Habitat- and area-specific estimates of inorganic carbon density and accumulation in marine sediments in Scotland.

EUNIS code	Habitat	Sediment type	%IC	0.1m depth kgIC/m²			0.1m depth gIC/m²			**Accumulation rate** gIC/m²/yr			
			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/Su	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											
A5.3	Sublittoral	Mud											
A5.4	Sublittoral	Sand/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											

Table 13. Organic carbon density and rates of accumulation in marine sediments in the Scotland. Values were obtained from the reviews listed in Table 11 and Table 12. Values for organic carbon accumulation rates in sublittoral mud and mixed sediment habitats are highlighted in orange. Values in bold in the 'Extent' column indicate summed areas of component habitats. The bold value in the 'Storage capacity' column is the sum of storage rates for component habitats (A5.2, A5.3 and A5.4). Blank areas indicate that no information was available from the data sources used for this analysis.

Sediment stores by component habitats				<0.1m					
			(Habitat)		***Organic carbon***				
	Scotland Region	437883.3	km²						
EUNIS code	**Habitat**	Extent (km²)	Component area (km²)	Stock (1000 tOC)	Stock (g OC/m²) min	max	avg	Storage rate (g OC/m²/yr)	Storage capacity (1000t OC/yr)
A2	**Littoral sediment**								
A2.1	Littoral coarse sediment								
A2.2	Littoral sand and muddy sand				130	1860	650	45.0	
A2.3	Littoral mud				540	3560	1990	83.5	
A2.4	Littoral mixed sediments							45.0	
A2.2 & A2.3	Littoral sand and mud							45.0	
A2.3 & A2.4	Littoral mud and mixed sediments								
A2.3 & A2.5	Littoral mud & Coastal saltmarshes and saline reedbeds								
	Sublittoral	**247487.0**							
A4	Sublittoral rock		14.0						
A5	**Sublittoral sediment**		5479.8	52694					**9470.6**
A5.1	Sublittoral coarse sediment		68275.5						
A5.2	Sublittoral sand		110712.0	19928	40	760	180	0.2	22.1
A5.3	Sublittoral mud		59574.9	32766	60	1230	550	155.2	9246.0
A5.4	Sublittoral mixed sediments		3430.8					59.0	202.4
A5.4 & A5.1	Sublittoral coarse and mixed sediments								
A5.6	Sublittoral biogenic reefs								
A6	**Deep sea**	**358918.3**							
A6	Deep seabed		35331.5						
A6.1	Deep-sea rock								
A6.2	Deep-sea mixed		47095.6						
A6.3	Deep-sea sand		52569.7	57038	390	1780	1085	0.1	6.8
A6.5	Deep-sea mud		223921.5	242955	390	1780	1085	0.1	29.1
NA	**Not mapped**	5645.9	5645.9						
Area weighted averages					32	636	213	15.68	
Modelled values									
	Mapped habitat extent	617385							
	Smeaton et al 2021	437883		151845			347		

3 Carbon Stores and Accumulation Rates across Scotland and its Protected Areas

As with the other regions in this series of blue carbon assessments, the protected areas in Scotland were not designated for protection of their carbon stores, but for their biodiversity features. Here the quantities of carbon stored in sediments within the boundaries of Scotland's protected areas (MPAs, SACs, SPAs and SSSIs) 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 Scotland

The top 10 cm of marine sediments in the 438,000 km^2 of Scotland up to the UK's EEZ limit that have been mapped for their carbon content (Smeaton *et al.*, 2021) contain 151.8 Mt OC and 1,020.7 Mt IC (see Table 14). The mapped region of OC and IC sediments is 70% of the total 617,000 km^2 of the Region up to the Continental Shelf limit.

3.2 Protected areas

Protected areas in Scotland cover 35% of the total region to the Continental Shelf boundary not accounting for overlapping designations. MPAs account for 28%, SACs for 5%, SPAs for 3%, SSSIs for 0.1%, and fractional parts of MCZs within the region boundaries for less than 0.01% of the total area (617,000 km^2) of the Region (see Table 14 and Figure 13). The percentages of total OC stores that fall inside protected areas broadly follow the percentages of the total area covered by MPAs, SACs, SPAs, SSSIs and the two MCZs that overlap with English waters south of the Scottish marine border. Protected areas contain 28% of the region's OC stores (64.8 Mt OC), SACs contain 8% (12.2 Mt OC) and SPAs contain 2% (3.5 Mt OC), with small stores of OC in SSSIs (0.25 Mt OC), and large areas of SSSIs remaining unmapped. Together, after merging areas of overlapping designations (Burrows *et al.*, 2024c), these protected areas contain 76.1 Mt in superficial sediments (depth less than 0.1 m) in the region. MPAs contain 367 Mt of the total sediment IC in the region, SACs contain 106 Mt IC and SPAs contain 26 Mt IC. The IC content of SSSIs is largely unmapped (see Table 14).

Table 14. Sediment carbon stores and accumulation rates throughout Scotland . Carbon store density values were extracted from maps published by Smeaton et al. *(2021) covering the Continental Shelf region (see *mapped habitat), excluding outer EEZ areas (see Figure 10). Per-area organic carbon accumulation rates were derived from habitat reviews (see Table 11 and Table 13), and protected area totals were calculated as the product of these rates and protected area extents. Substrate was determined from the largest area of component habitat (see Figure 9). Only SACs, SPAs and SSSIs with an area of over 2 km^2 are listed. Summed areas and carbon stores of protected area types do not account for overlapping designations. Total extents of regions and protected areas refer to the extent of mapped areas for which habitat information is available, and do not necessarily cover the entire extent of the named features.*

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr^{-1})
Scotland (* mapped sediment carbon)		437,883	0.347	2.331	**151.84**	**1,020.73**		
Total area of Scotland[1]		617,368					0.22	134.1
All MCZs		2	0.276	0.004	0.00	0.00	29.09	0.1
All MPAs		175,186	0.421	3.031	64.63	365.16	26.60	1362.5
All SACs (57 < 2 km^2 not listed)		32,413	0.370	2.806	12.20	105.15	13.37	1122.7
All SPAs (35 < 2 km² not listed)		18,521	0.278	3.653	5.88	55.21	8.69	386.5
All SSSIs (350 < 2 km² not listed)		636	0.311	2.442	0.25	0.79	2.00	3.0

[1] Total area of mapped habitat in Scotland

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr^{-1})
Marine Conservation Zones (MCZs)								
Solway Firth	Sand	1	0.217	0.007	0.00	0.00	0.20	0.0
South Rigg	Sand	1	0.334	0.000	0.00	0.00	57.97	0.1
Marine Protected Areas (MPAs)								
West of Scotland	Mud	107,079	0.369	2.273	39.49	243.42	0.22	24.1
North-east Faroe-Shetland Channel	Mud	23,759	0.372	0.736	8.84	17.48	0.24	5.8
Sea of the Hebrides	Mud	10,039	0.415	2.599	4.16	26.10	79.57	758.2
Faroe-Shetland Sponge Belt		5,281	0.364	0.965	1.92	5.09	0.92	4.8
The Barra Fan and Hebrides Terrace Seamount	Mud	4,374	0.380	1.699	1.66	7.43	0.28	1.2
North-west Orkney	Coarse	4,368	0.335	6.882	1.46	30.06	6.28	27.4
West Shetland Shelf	Coarse	4,085	0.364	2.573	1.49	10.51	0.08	0.3
Southern Trench	Coarse	2,398	0.326	1.875	0.78	4.50	52.35	124.9
Geikie Slide and Hebridean Slope	Mud	2,217	0.359	1.342	0.80	2.98	0.11	0.3
Firth of Forth Banks Complex	Coarse	2,130	0.332	1.321	0.71	2.81	1.26	2.7
East of Gannet and Montrose Fields	Sand	1,840	0.329	0.157	0.61	0.29	48.56	89.3
Hatton-Rockall Basin	Mud	1,257	0.000	0.000	0.00	0.00	0.13	0.2
Central Fladen	Mud	925	0.349	0.425	0.32	0.39	147.45	136.3
North-east Lewis	Sand	907	0.392	2.554	0.36	2.32	49.96	43.3
Small Isles	Mud	803	0.422	2.437	0.34	1.96	79.68	58.7

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr-1)
Loch Sunart to the Sound of Jura	Mud	741	0.576	2.612	0.43	1.94	61.89	4.7
Clyde Sea Sill	Sand	712	0.373	1.522	0.27	1.08	32.26	22.5
Wester Ross	Mud	599	0.536	1.323	0.32	0.79	86.67	24.5
South Arran	Mud	280	0.496	0.944	0.14	0.26	99.69	25.2
Shiant East Bank	Mixed	252	0.320	4.413	0.08	1.11	28.41	7.1
Turbot Bank	Coarse	251	0.334	2.557	0.08	0.64	0.05	0.0
Fetlar to Haroldswick	Coarse	216	0.217	7.061	0.05	1.52	0.36	0.1
Norwegian Boundary Sediment Plain	Sand	164	0.305	0.256	0.05	0.04	0.19	0.0
East Caithness Cliffs	Coarse	114	0.270	6.517	0.03	0.74	0.04	0.0
Upper Loch Fyne and Loch Goil		88	0.938	0.894	0.08	0.08	0.00	0.0
Monach Isles		62	0.047	8.968	0.00	0.55	0.17	0.0
Loch Sunart	Mud	49	1.215	1.230	0.06	0.06	154.20	0.9
Loch Sween		41	0.710	7.051	0.03	0.29	2.83	0.0
Lochs Duich, Long and Alsh	Coarse	37	0.866	2.640	0.03	0.10	20.61	0.1
Papa Westray		33	0.084	9.968	0.00	0.33	0.00	0.0
Loch Carron		23	0.809	1.416	0.02	0.03	0.00	0.0
Wyre and Rousay Sounds		16	0.226	6.409	0.00	0.10	0.00	0.0
Mousa to Boddam		13	0.145	2.267	0.00	0.03	0.01	0.0
Loch Creran		12	1.034	0.733	0.01	0.01	0.00	0.0
Red Rocks and Longay (Urgent MPA)		12	0.426	1.168	0.01	0.01	3.13	0.0
Noss Head	Coarse	8	0.114	11.322	0.00	0.09	0.00	0.0
Special Areas of Conservation (SACs)								
Inner Hebrides and the Minches	Mud	13,694	0.466	2.403	6.38	32.91	83.39	913.4
North West Rockall Bank	Mud	4,188	0.248	6.915	1.04	28.96	17.18	72.8
East Rockall Bank	Mud	3,697	0.352	4.742	1.30	17.53	0.53	2.0
Wyville Thomson Ridge		1,740	0.401	0.788	0.70	1.37	0.01	0.0
Moray Firth	Sand	1,511	0.370	1.091	0.56	1.65	71.35	97.8
Anton Dohrn Seamount		1,429	0.371	2.173	0.53	3.10	0.11	0.2
Darwin Mounds	Sand	1,378	0.419	0.059	0.58	0.08	0.11	0.2
Pobie Bank Reef	Coarse	966	0.248	7.744	0.24	7.48	1.91	1.8
Solan Bank Reef	Coarse	856	0.050	3.959	0.04	3.39	0.03	0.0
Stanton Banks	Coarse	818	0.178	4.091	0.15	3.35	4.15	3.4
Luce Bay and Sands	Coarse	469	0.217	0.000	0.10	0.00	0.10	0.0
St Kilda	Coarse	244	0.183	6.387	0.04	1.56	0.09	0.0
Solway Firth	Sand	219	0.315	0.091	0.07	0.02	16.26	2.6
Firth of Lorn		201	0.323	3.142	0.06	0.63	0.00	0.0
Firth of Tay and Eden Estuary	Sand	145	0.414	0.233	0.06	0.03	0.43	0.0
Sound of Barra		119	0.222	1.661	0.03	0.20	5.75	0.1
East Mingulay	Mud	115	0.488	2.094	0.06	0.24	144.34	16.6
Sanday		106	0.154	10.516	0.02	1.11	0.00	0.0

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr⁻¹)
Berwickshire and North Northumberland Coast	Sand	70	0.284	1.457	0.02	0.10	27.72	1.8
Dornoch Firth and Morrich More	Mud	65	0.401	0.818	0.03	0.05	112.88	0.9
Sunart	Mud	50	1.237	1.225	0.06	0.06	154.24	0.9
Sound of Arisaig (Loch Ailort to Loch Ceann Traigh)	Mud	43	0.476	1.765	0.02	0.08	155.20	2.0
Monach Islands		32	0.031	9.145	0.00	0.29	0.18	0.0
Ascrib, Isay and Dunvegan	Mixed	23	0.797	2.157	0.02	0.05	52.32	0.4
Braemar Pockmarks	Mud	23	0.323	0.222	0.01	0.01	155.20	3.5
Sullom Voe	Mixed	23	0.487	3.623	0.01	0.08	50.55	0.3
Lochs Duich, Long and Alsh Reefs	Coarse	18	0.799	3.247	0.01	0.06	17.36	0.1
Treshnish Isles	Coarse	18	0.024	7.709	0.00	0.14	64.69	0.4
Papa Stour		18	0.126	8.063	0.00	0.14	0.00	0.0
Loch nam Madadh		14	0.734	3.755	0.01	0.05	4.86	0.0
South-East Islay Skerries	Mixed	14	0.278	3.215	0.00	0.04	53.55	0.0
Loch Creran		12	1.027	0.740	0.01	0.01	0.00	0.0
Eileanan agus Sgeiran Lios mor		10	1.058	1.462	0.01	0.01	0.00	0.0
Loch Laxford		8	0.810	4.055	0.01	0.03	0.00	0.0
Loch of Stenness		8	0.274	6.481	0.00	0.05	0.00	0.0
Scanner Pockmark	Mud	7	0.321	0.793	0.00	0.01	155.20	1.0
Faray and Holm of Faray		7	0.057	10.245	0.00	0.07	0.00	0.0
North Uist Machair		6	0.277	3.225	0.00	0.02	0.00	0.0
Yell Sound Coast		5	0.335	5.112	0.00	0.03	3.32	0.0
Mousa		5	0.022	4.291	0.00	0.02	0.00	0.0
North Rona		5	0.024	8.973	0.00	0.04	0.00	0.0
North Channel	Mud	4	0.286	0.003	0.00	0.00	63.14	0.3
Culbin Bar	Sand	4	0.438	0.671	0.00	0.00	0.20	0.0
Isle of May		3	0.036	3.194	0.00	0.01	0.03	0.0
Loch Moidart and Loch Shiel Woods		2	0.938	1.522	0.00	0.00	0.00	0.0
Moine Mhor		2	0.705	3.129	0.00	0.01	0.00	0.0
Hoy		2	0.268	5.580	0.00	0.01	0.19	0.0
South Uist Machair		2	0.360	2.269	0.00	0.00	0.00	0.0
Tayvallich Juniper and Coast		2	0.723	7.946	0.00	0.01	0.00	0.0
Rum		2	0.247	4.169	0.00	0.01	0.00	0.0
Special Protection Areas (SPAs)								
Seas off St Kilda	Coarse	3,984	0.330	1.990	1.31	7.93	8.77	35.0
Seas off Foula	Coarse	3,415	0.334	5.037	1.14	17.20	0.29	1.0
Outer Firth of Forth and St Andrews Bay Complex	Sand	2,723	0.400	0.433	1.09	1.18	60.31	159.4
Moray Firth	Sand	1,763	0.333	1.520	0.59	2.68	40.30	65.6
West Coast of the Outer Hebrides		1,318	0.152	4.752	0.20	6.26	0.73	0.6

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr⁻¹)
Coll and Tiree	Coarse	794	0.236	3.416	0.19	2.71	27.08	17.1
Solway Firth	Sand	779	0.376	0.102	0.29	0.08	64.34	43.1
Sound of Gigha	Coarse	363	0.346	1.578	0.13	0.57	17.30	4.1
Rum	Mud	360	0.483	1.743	0.17	0.63	116.00	35.7
Scapa Flow	Mixed	318	0.243	6.632	0.08	2.11	54.11	12.7
St Kilda	Coarse	281	0.186	6.095	0.05	1.71	0.10	0.0
East Mainland Coast, Shetland		233	0.256	6.425	0.06	1.50	1.57	0.3
North Orkney		212	0.203	6.592	0.04	1.40	0.00	0.0
Fetlar	Coarse	144	0.211	6.708	0.03	0.97	3.17	0.4
North Caithness Cliffs	Coarse	141	0.250	7.895	0.04	1.11	0.09	0.0
East Caithness Cliffs	Coarse	114	0.270	6.522	0.03	0.74	0.04	0.0
Forth Islands	Mixed	97	0.431	1.000	0.04	0.10	51.23	4.6
Hoy	Coarse	87	0.230	5.400	0.02	0.47	0.04	0.0
Mingulay and Berneray		69	0.113	4.531	0.01	0.31	0.13	0.0
The Shiant Isles	Coarse	68	0.329	4.881	0.02	0.33	0.00	0.0
North Rona and Sula Sgeir		67	0.099	6.677	0.01	0.45	0.00	0.0
Foula	Coarse	67	0.154	9.245	0.01	0.62	0.02	0.0
Fair Isle	Coarse	63	0.250	6.369	0.02	0.40	0.01	0.0
Ythan Estuary, Sands of Forvie and Meikle Loch	Sand	61	0.285	0.847	0.02	0.05	0.20	0.0
Firth of Tay & Eden Estuary	Sand	60	0.467	0.283	0.03	0.02	0.18	0.0
Firth of Forth	Mixed	59	0.478	0.458	0.03	0.03	32.91	0.2
Cape Wrath	Sand	58	0.301	4.734	0.02	0.27	0.09	0.0
Flannan Isles		58	0.038	4.001	0.00	0.23	0.01	0.0
Canna and Sanday	Coarse	54	0.283	2.032	0.02	0.11	70.61	2.7
Buchan Ness to Collieston Coast	Sand	52	0.275	1.386	0.01	0.07	0.16	0.0
Hermaness, Saxa Vord and Valla Field	Coarse	52	0.248	6.414	0.01	0.33	0.00	0.0
Rousay		49	0.101	8.869	0.00	0.43	0.00	0.0
Sule Skerry and Sule Stack		39	0.169	6.090	0.01	0.24	0.02	0.0
Bluemull and Colgrave Sounds		38	0.325	4.985	0.01	0.19	0.00	0.0
Copinsay	Coarse	35	0.240	8.871	0.01	0.31	0.02	0.0
West Westray		34	0.212	9.559	0.01	0.33	0.02	0.0
Troup, Pennan and Lion`s Heads	Coarse	32	0.260	3.958	0.01	0.13	0.00	0.0
Dornoch Firth and Loch Fleet	Sand	31	0.404	0.852	0.01	0.03	58.99	0.2
Noss	Coarse	30	0.244	5.599	0.01	0.17	0.06	0.0
Cromarty Firth		30	0.510	0.505	0.02	0.02	0.00	0.0
Handa	Coarse	29	0.214	2.765	0.01	0.08	0.00	0.0
Ailsa Craig	Mud	27	0.634	0.438	0.02	0.01	141.01	3.5
Calf of Eday		25	0.171	8.045	0.00	0.20	0.00	0.0
Sumburgh Head	Coarse	24	0.249	1.839	0.01	0.04	0.00	0.0
North Colonsay and Western Cliffs	Coarse	24	0.261	2.181	0.01	0.05	3.99	0.0
Inner Moray Firth		19	0.494	0.526	0.01	0.01	0.00	0.0

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr⁻¹)
Inner Clyde Estuary		17	0.470	0.779	0.01	0.01	0.00	0.0
St Abb`s Head to Fast Castle		16	0.153	1.342	0.00	0.02	20.83	0.3
Moray and Nairn Coast	Sand	14	0.466	0.697	0.01	0.01	0.20	0.0
Fowlsheugh	Coarse	13	0.212	1.515	0.00	0.02	0.09	0.0
East Sanday Coast	Coarse	13	0.226	9.975	0.00	0.13	0.00	0.0
Loch of Inch and Torrs Warren		11	0.317	0.000	0.00	0.00	0.00	0.0
Gruinart Flats, Islay		10	0.792	3.299	0.01	0.03	0.00	0.0
North Uist Machair and Islands		10	0.254	3.328	0.00	0.03	0.00	0.0
Montrose Basin		8	0.533	0.134	0.00	0.00	0.00	0.0
Sleibhtean agus Cladach Thiriodh (Tiree Wetlands and Coast)		6	0.187	5.056	0.00	0.03	0.00	0.0
Oronsay and South Colonsay		5	0.286	4.471	0.00	0.02	0.00	0.0
Marwick Head		5	0.025	4.927	0.00	0.02	0.00	0.0
South Uist Machair and Lochs		3	0.191	2.295	0.00	0.01	0.00	0.0
Bridgend Flats, Islay		2	0.424	2.461	0.00	0.01	0.00	0.0
Monach Isles		2	0.021	9.085	0.00	0.02	0.20	0.0
Sites of Special Scientific Interest (SSSIs)								
Upper Solway Flats and Marshes	Sand	155	0.323	0.088	0.05	0.01	28.96	2.6
Firth of Forth	Mixed	61	0.463	0.558	0.03	0.03	32.59	0.2
Inner Tay Estuary	Sand	36	0.562	0.336	0.02	0.01	0.20	0.0
Cromarty Firth		29	0.506	0.516	0.01	0.01	0.00	0.0
Cree Estuary		25	0.581	0.000	0.01	0.00	0.00	0.0
Inner Clyde		17	0.468	0.782	0.01	0.01	0.00	0.0
Dornoch Firth		17	0.408	0.786	0.01	0.01	0.00	0.0
East Sanday Coast	Coarse	14	0.220	9.968	0.00	0.14	0.00	0.0
Culbin Sands, Culbin Forest and Findhorn Bay	Sand	13	0.472	0.700	0.01	0.01	0.20	0.0
Morrich More	Sand	13	0.431	0.864	0.01	0.01	49.98	0.1
Torrs Warren – Luce Sands		11	0.317	0.000	0.00	0.00	0.00	0.0
Tayport – Tentsmuir Coast	Sand	11	0.299	0.150	0.00	0.00	0.18	0.0
Beauly Firth		11	0.534	0.441	0.01	0.00	0.00	0.0
Gruinart Flats		10	0.774	3.308	0.01	0.03	0.00	0.0
Eden Estuary		9	0.355	0.236	0.00	0.00	0.00	0.0
Loch an Duin		8	0.450	2.690	0.00	0.02	2.96	0.0
Montrose Basin		8	0.533	0.134	0.00	0.00	0.00	0.0
Durness		7	0.217	2.898	0.00	0.02	0.00	0.0
Oronsay and South Colonsay	Coarse	7	0.275	4.754	0.00	0.03	0.00	0.0
Sleibhtean agus Cladach Thiriodh		6	0.180	4.274	0.00	0.03	0.00	0.0
Borgue Coast	Mud	5	0.339	0.000	0.00	0.00	153.48	0.0
Central Sanday		4	0.279	10.378	0.00	0.04	0.00	0.0
Longman and Castle Stuart Bays		4	0.491	0.754	0.00	0.00	0.00	0.0

Name	Substrate	Area (km²)	OC density (kg/m²)	IC density (kg/m²)	OC store (Mt)	IC store (Mt)	OC accumulation (g C/m²/yr)	OC accumulation (kt yr⁻¹)
Sunart	Mud	4	1.109	0.018	0.00	0.00	155.20	0.0
Luskentyre Banks and Saltings		4	1.255	1.418	0.00	0.01	0.00	0.0
Tong Saltings		3	0.365	2.069	0.00	0.01	0.00	0.0
Baleshare and Kirkibost		3	0.265	2.824	0.00	0.01	0.00	0.0
Moine Mhor		3	0.685	3.217	0.00	0.01	0.00	0.0
Loch Moidart		3	0.878	0.000	0.00	0.00	0.00	0.0
Barry Links	Sand	3	0.289	0.143	0.00	0.00	0.20	0.0
Kentra Bay and Moss		3	0.818	0.000	0.00	0.00	0.00	0.0
Northton Bay		3	0.000	0.000	0.00	0.00	0.00	0.0
Southannan Sands		3	0.436	1.330	0.00	0.00	0.00	0.0
Whiteness Head		2	0.316	0.564	0.00	0.00	0.00	0.0
Munlochy Bay		2	0.463	0.442	0.00	0.00	0.00	0.0
Machairs Robach and Newton		2	0.268	2.386	0.00	0.01	0.00	0.0
Eoligarry		2	0.385	2.011	0.00	0.00	0.00	0.0
Bridgend Flats		2	0.424	2.461	0.00	0.01	0.00	0.0
Monach Isles		2	0.020	9.152	0.00	0.02	0.20	0.0
Upper Solway Flats & Marshes	Sand	2	0.278	0.027	0.00	0.00	0.20	0.0
Crossapol and Gunna		2	0.207	3.508	0.00	0.01	0.00	0.0
Monifieth Bay	Sand	2	0.302	0.142	0.00	0.00	0.14	0.0
Rum		2	0.293	2.445	0.00	0.00	0.00	0.0
Berwickshire Coast (Intertidal)		2	0.128	1.833	0.00	0.00	0.05	0.0
Barns Ness Coast		2	0.163	1.109	0.00	0.00	0.19	0.0
Balranald Bog and Loch nam Feithean		2	0.369	5.426	0.00	0.01	0.00	0.0
Ruel Estuary		2	1.048	0.334	0.00	0.00	0.00	0.0
Maidens to Doonfoot		2	0.173	0.817	0.00	0.00	0.00	0.0
Auchencairn and Orchardton Bays		2	0.484	0.000	0.00	0.00	0.00	0.0

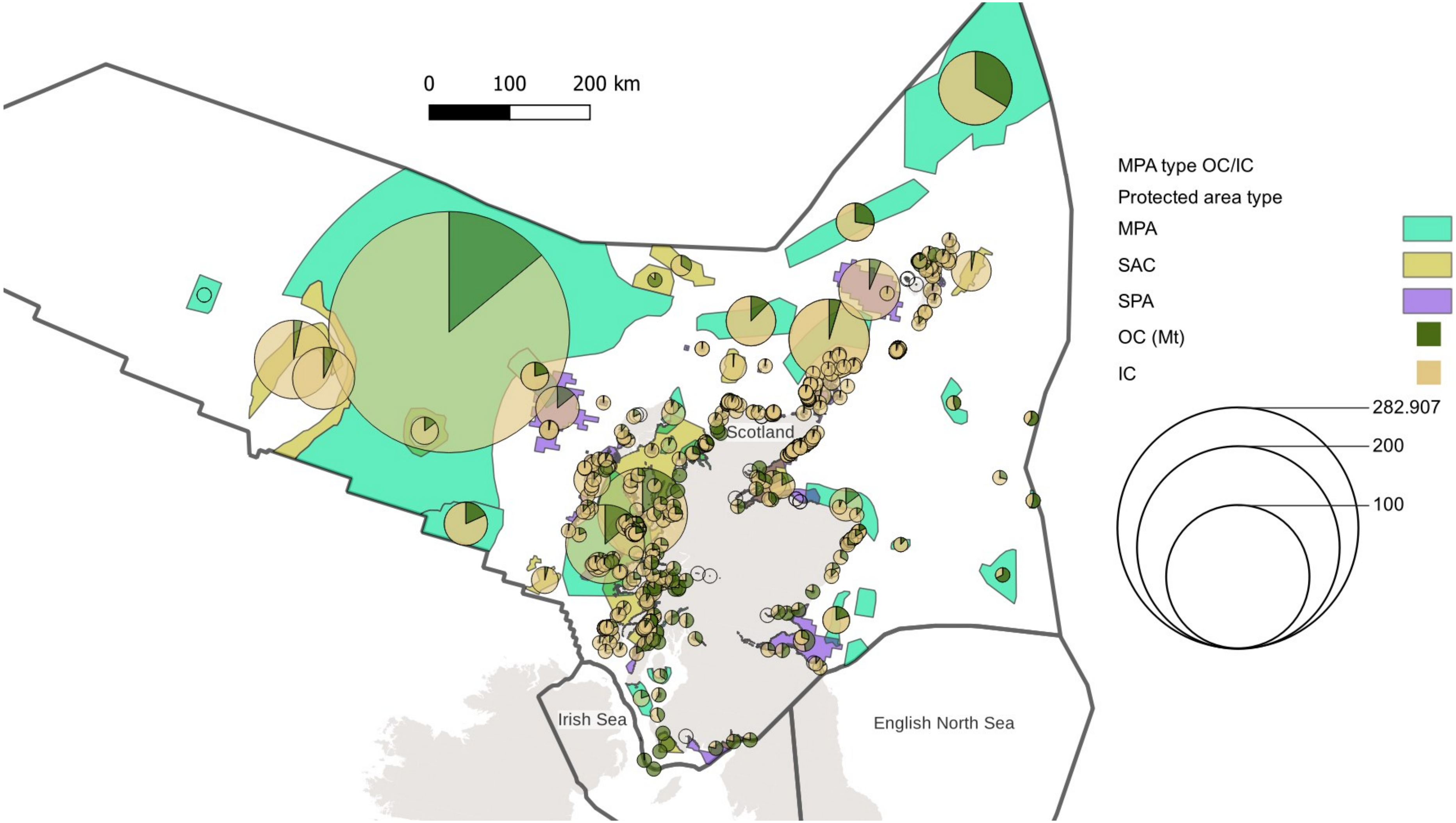

Figure 14. Protected areas in Scotland, showing total organic carbon (OC) and inorganic carbon (IC) stores per protected area (data from Table 14). The size of each pie chart shows the quantity of carbon stores (in Mt) in each protected area. Zero estimated carbon store values for areas unmapped for sediment OC beyond the EEZ limit and close inshore (see Figure 10) are shown as empty circles.

3.2.1 Habitat extents within protected areas

The extents of habitats across the network of protected areas (MPAs, SACs, SPAs and SSSIs, with small portions of MCZs, in boundary areas) were derived using GIS processing to subset the habitat information for the whole Region (see Figure 9) to the boundaries of its protected areas (see Figure 1). Total areas of habitat types are shown in Table 1, and the size of associated carbon stores and the corresponding OC accumulation rates are shown in Table 14. More detailed information on habitat types is provided in Section 2, with reviews of the information available for each habitat and their total extent in Scotland.

3.2.2 Visualising patterns of carbon stores and accumulation rates across protected areas

In total, 639 separate protected areas are included in Scotland (36 MPAs, 106 SACs, 96 SPAs, two portions of MCZs and 399 SSSIs), each of which contains more than one habitat type, making simple comparisons among them based on inspection of tabulated data extremely difficult. Protected areas span habitats ranging from deep seabed to coastal rock and saltmarsh, with offshore protected areas being larger, and shallow and intertidal circalittoral ones being generally smaller. The patterns of carbon storage among these varied and widely different areas can be visualised using ordination techniques known as non-metric multidimensional scaling (MDS) (see Figures 15 to 18), based on the composition of habitats within each area boundary. The ordination analysis separated small, shallow coastal areas (infralittoral) on the right of the MDS plots from mid-sized (sublittoral) areas and large, deep offshore areas to the left of the plots. Protected areas composed of rocky and coarse sediment habitats were placed at the right of the plots, with those composed predominantly of mud seabed towards the left, and those composed of sand and coarse sediment halfway up. Offshore and deep protected areas (Sublittoral, Deep; see Figure 15a) tend to be much larger than inshore ones (Circalittoral), with the largest of the deeper protected areas composed mostly of mud and coarse sediment (see Figure 15b).

3.2.3 Organic carbon stores and accumulation rates across Scotland's protected areas

The amount of carbon stored in each protected area (see Table 14) depends on the kinds of habitat present. Using the EUSeaMap 2019 data for seabed habitats across the region (see Table 1), the extent of each habitat type present in each protected area was estimated. Although the resolution of the habitat information often exceeded the resolution of the available sediment carbon data (see Figure 10), the mix of habitats and dominant habitat by area were good indicators of the value of the protected area in terms of OC density (see Figure 16) and total OC store. Small inshore protected areas, mostly SSSIs (see Figure 16c), had the highest OC density values (see Figure 16a), and unlike other regions were composed mostly of rock habitats (see Figure 16b). Protected areas with predominantly rocky habitats were unexpectedly rich in OC (see Figure 16a). 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 set of protected areas, with a tendency towards higher OC density in shallow coastal muddy areas, the total OC store was much larger in the more extensive offshore protected areas (see Figure 17a).

Estimated area-specific rates of OC accumulation in sediments, using habitat-specific accumulation rates and summed across the within-protected area habitat extents to give the values shown in Table 14, can also be visualised in this framework. The protected areas with high OC density tended to be those with the highest estimated carbon accumulation rate (Pearson's correlation coefficient $r = 0.36$, $n = 271$; compare Figure 15 with Figure 17). This association was expected, since the latter measure was driven strongly by the presence of rapidly accumulating mud habitats in each protected area.

3.2.4 Summary of marine organic carbon stores across the Scotland's protected areas

Coastal (infralittoral) protected areas with predominantly rocky seabed characteristics (triangles in Figure 15a) are generally small (less than 100 km^2 in area, and typically 1–50 km^2), with relatively small OC stores (see Figure 17a) and low rates of OC accumulation despite having high OC densities per unit area (see Figure 16a). The smallest of these coastal protected areas are the SSSIs (see Figure 16c).

Further offshore, sublittoral protected areas are of intermediate size (hundreds to thousands of km^2) (see Figure 15a) with mostly coarse sediment habitats (see Figure 15b), with a mix of designations among MPAs, SACs and SPAs, but no SSSIs (see Figure 15c). Such areas have lower OC densities per unit area (see Figure 16) than coastal areas, but contain larger OC stores (see Figure 17). Sublittoral protected areas have relatively large annual OC accumulations (see Figure 18) because of their greater area and the occurrence of mud habitats associated with more rapid rates of carbon accumulation.

Protected areas in the deepest part of the region are much larger (thousands to tens of thousands of km^2), with almost entirely sedimentary habitats. Their much greater size results in larger OC stores (see Figure 17a) despite having lower OC densities per unit area (see Figure 16) than shallower inshore areas. The quantities of OC accumulated per year in such areas (see Figure 18) are less than in sublittoral areas.

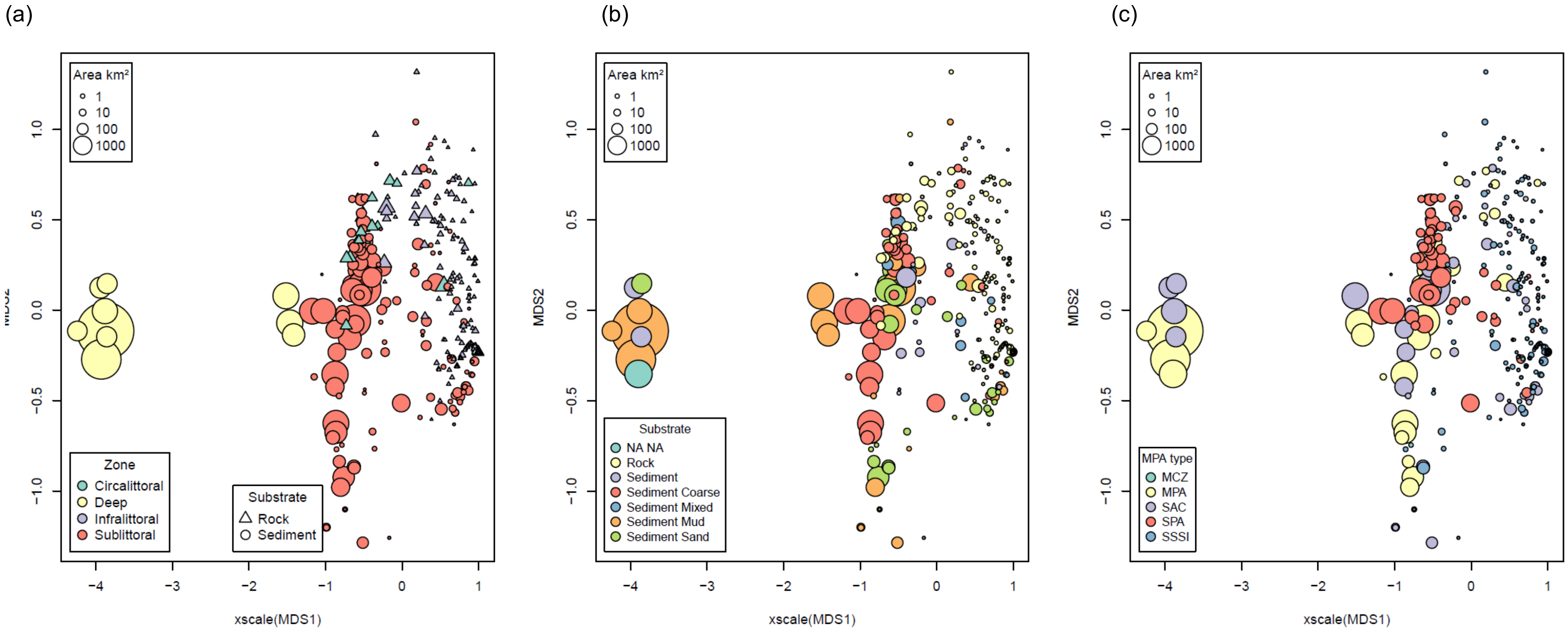

Figure 15. Ordination of the area-based composition of habitat types across the Scotland's protected areas using non-metric multidimensional scaling. Each symbol represents a single MCZ, MPA, SAC, SPA or SSSI, with the size of the symbol representing the extent (in km²) of each protected area: (a) the 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 type of marine protected area. Zone and substrate types in (a) and (b) are taken from EUNIS 2019 habitat descriptions.

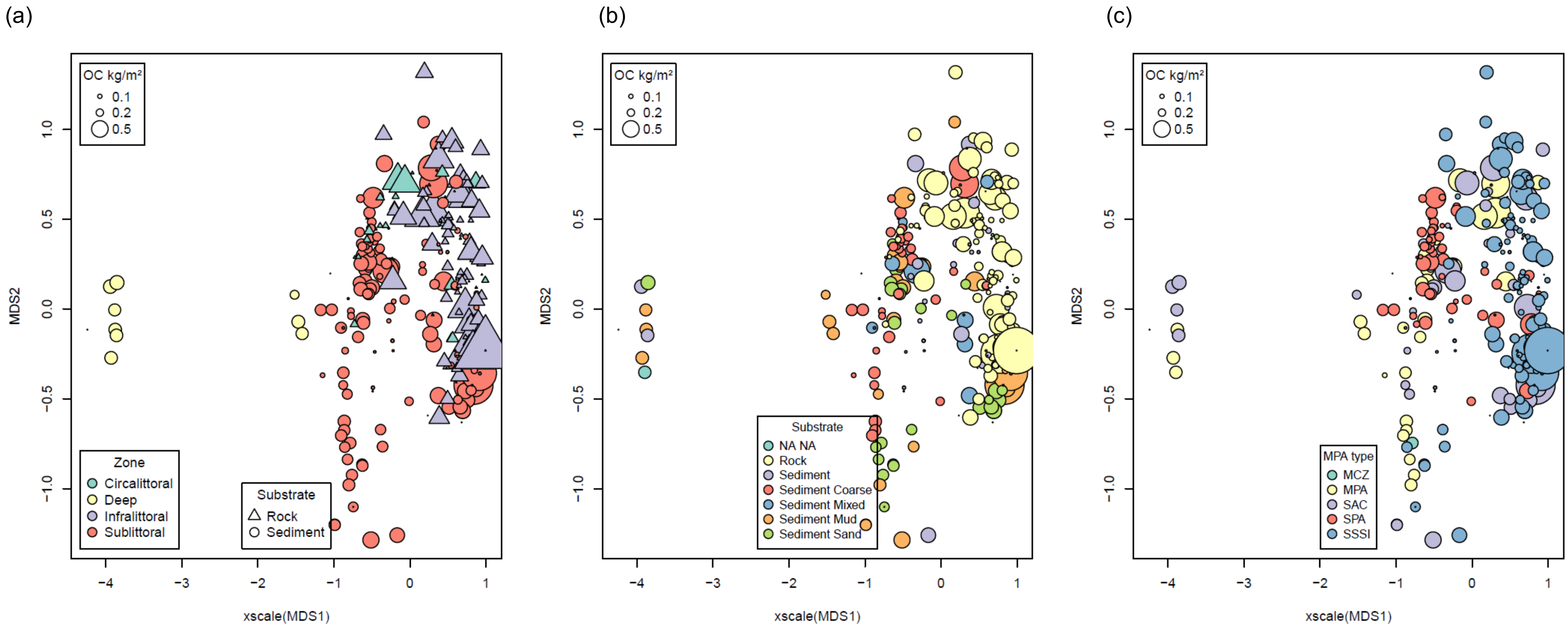

Figure 16. Ordination of the area-based composition of habitat types across Scotland's marine protected areas using non-metric multidimensional scaling. Each symbol represents a single MCZ, MPA, SAC, SPA or SSSI, with the size of the symbol representing the average organic carbon (OC) content (in kg/m^2) 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 type of protected area. Zone and substrate types in (a) and (b) are taken from EUNIS 2019 habitat descriptions.

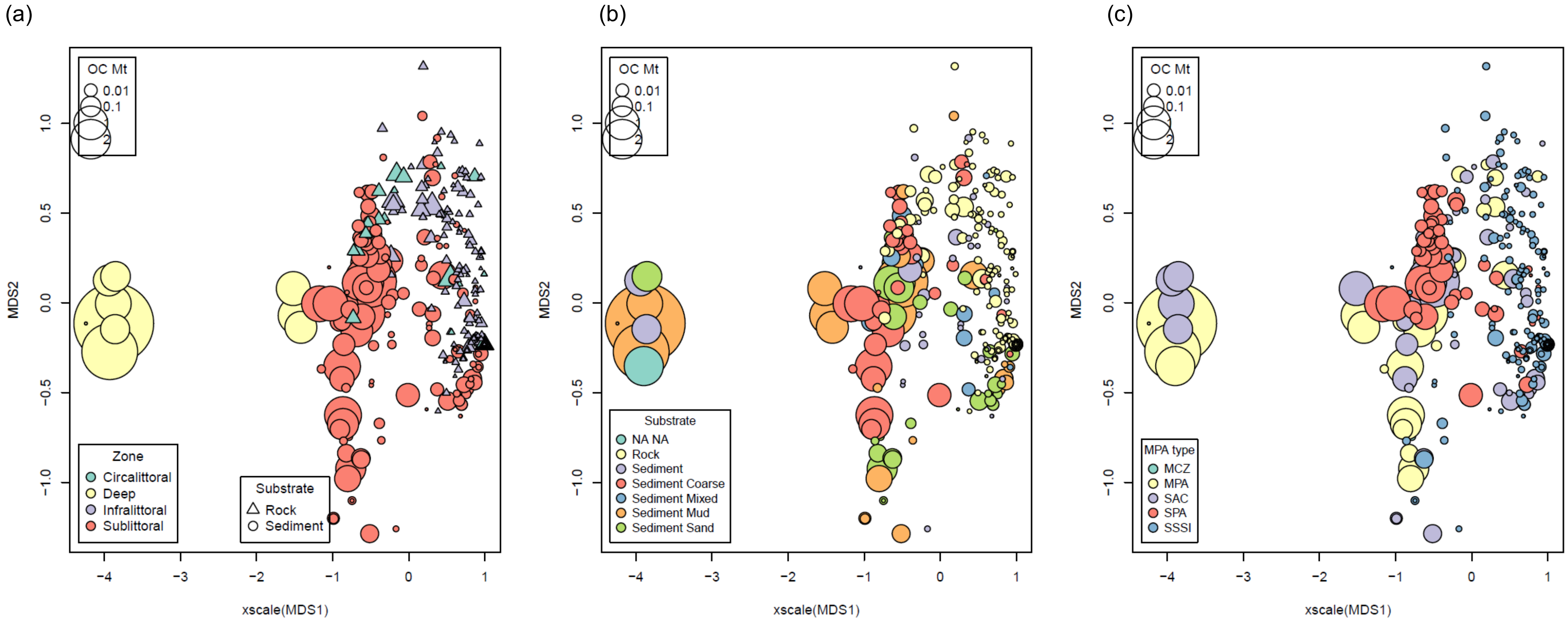

Figure 17. Ordination of the area-based composition of habitat types across Scotland's protected areas using non-metric multidimensional scaling. Each symbol represents a single MCZ, MPA, SAC, SPA or SSSI, with the size of the symbol representing the total sediment organic carbon (OC) store (in Mt) in 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 type of protected area.

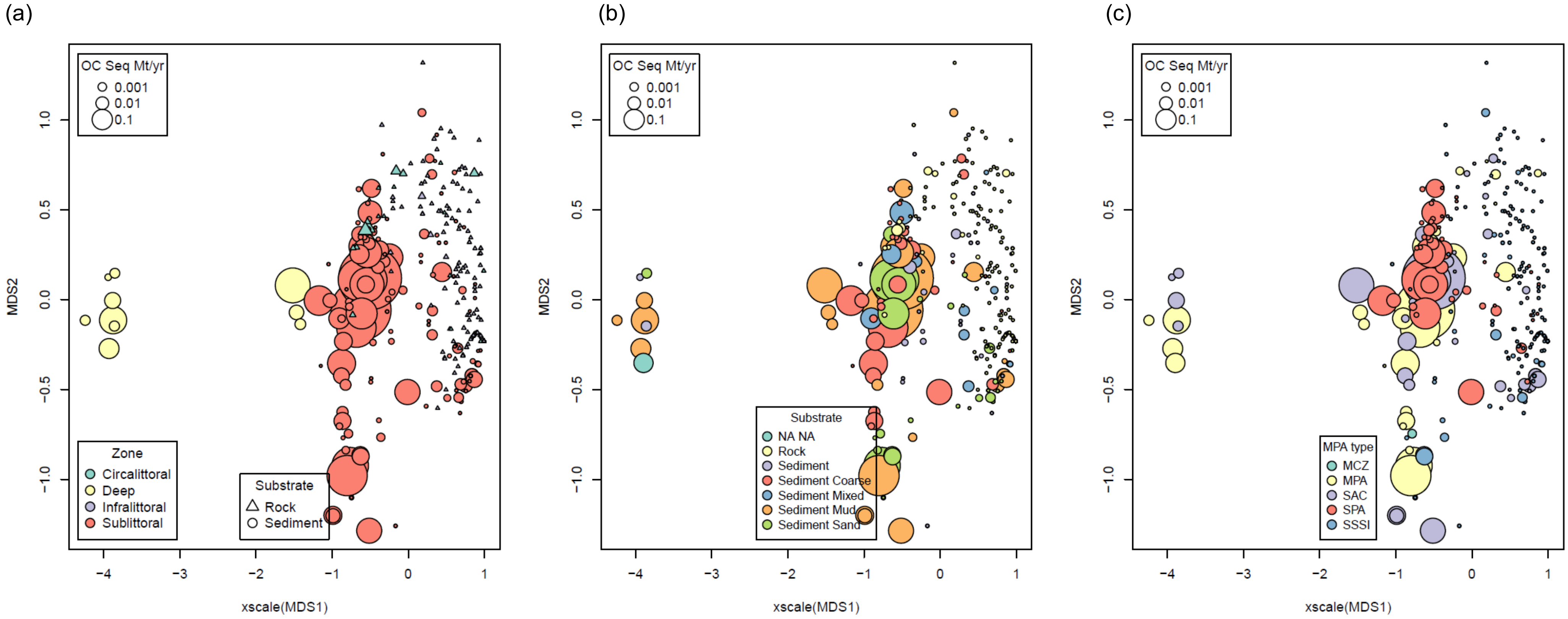

Figure 18. Ordination of the area-based composition of habitat types across Scotland's protected areas using non-metric multidimensional scaling. Each symbol represents a single MCZ, MPA, SAC, SPA or SSSI, with the size of the symbol representing the total sediment organic carbon (OC) accumulation rate (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 type of protected area.

3.3 Ecosystem-scale carbon budget

Summarising the dynamics of carbon short- and long-term stores across the main blue carbon habitats and their associated sediment stores (see Table 15, column 3) shows the relative importance of each component. Although some elements remain unknown, these values show the overriding importance of phytoplankton and sublittoral sediments as the primary carbon source and the carbon short- and long-term store, respectively, in Scotland.

Table 15. Summary of carbon stores and sequestration capacity in Scotland. The values shown summarise the carbon store and extent estimates presented in 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). 'Long-term stores' refers to carbon in the seabed and in sediments associated with saltmarshes and seagrasses.*

Scotland 2023			***Organic carbon***								***Inorganic carbon***					
Habitat		Extent (km²)	Organic carbon total (Mt C) [0.1m depth]	Organic carbon 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)	Stock (Mt C) [0.1m depth]	Stock (kg C/m²) [0.1m depth]	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Phytoplankton		617385			81	50233	5023									
All sediment	(Method 1)	437883	151.8	347				90	0.2	90	1021	2.3	3.38	837		
Biogenic habitats		5228	1.514	290	329	1741	174	7		7						
Total / Average			153.4		83	51974	5197	98		98	1021			837		
Long-term stores			152.3													

Scotland 2023		***Organic carbon***								***Inorganic carbon***					
Habitat	Extent (km²)	Organic carbon total (1000t C)	Organic carbon 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)	Stock (1000t C)	Stock (kg C/m²)	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Vegetated habitats															
Kelp beds	4777.6	1041.6	218.0	332	1587.1	158.7		0	0						
Intertidal macroalgae	371.3	49.8	122	378	140.3	14.0		0	0						
Seagrass beds	20.9	32.3	1547	274	5.7	0.6	1.5	100.4	2.1						
Saltmarshes	58.4	368.0	1490	138	8.1	0.8	5.8	113.5	6.6						
Maerl beds	31.4	22.6	720												
Biogenic reefs															
Serpulid reefs	1.1														
Modiolus modiolus	10.2														
Maerl beds and Horse mussel beds (mosaic)	13.8														
Blue mussel (*Mytilus edulis*) beds	4.4														
Native oysters*	0.0														
Flame shell beds	10.5														
Cold-water coral reefs	6.2														
Honeycomb worm (*Sabellaria alveolata*) reefs	1.1														
Total	5228.2	1514.3		329	1741.2	174.1	7.3	1.7	8.7						
Long-term stores		422.91													

* Unknown

3.3.1 Organic carbon (OC)

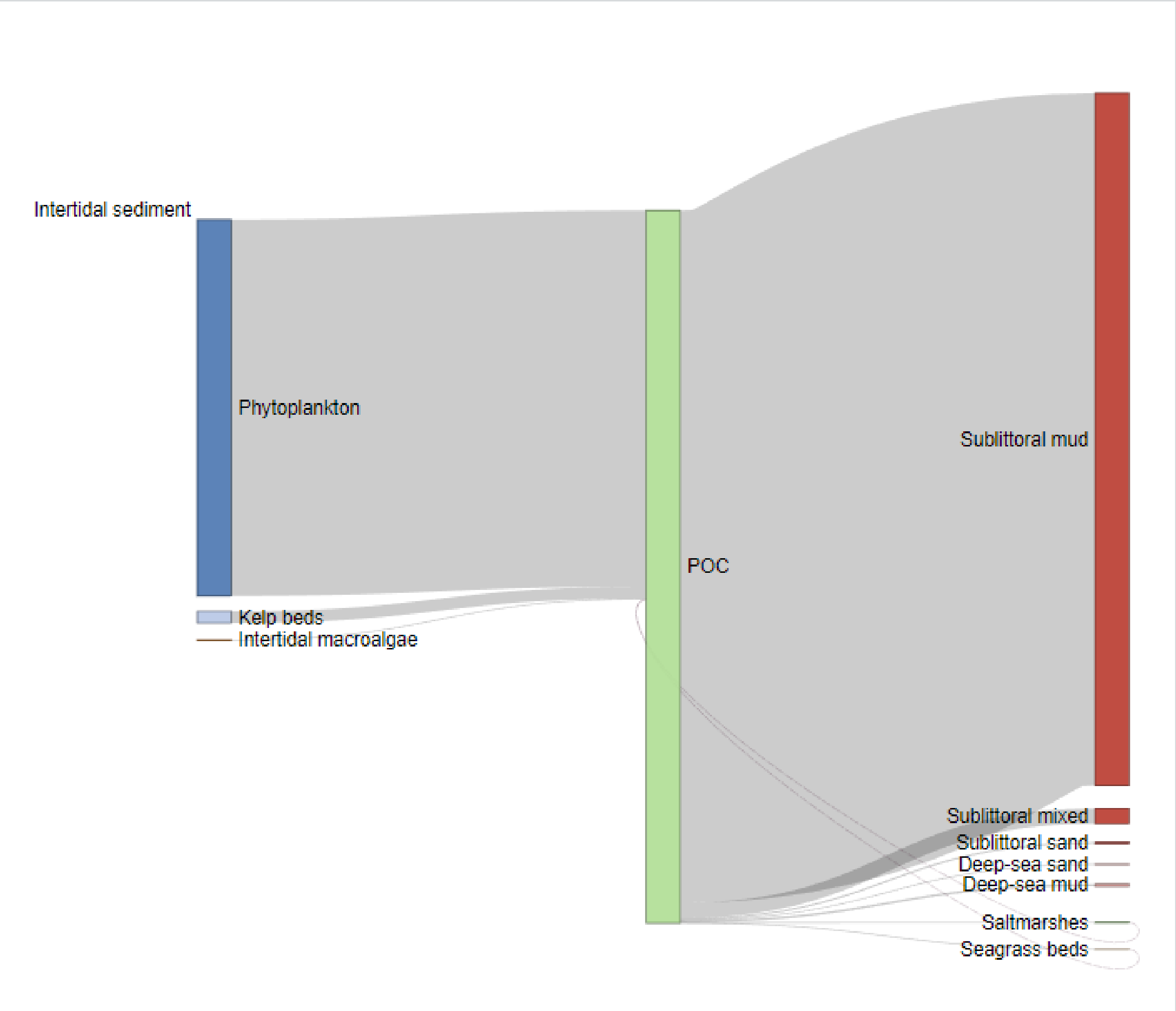

Figure 19. Annual flows of organic carbon from sources to stores in Scotland, based on values presented in Table 15, and shown as a Sankey diagram with flows from left to right. The heights of each block represent the flows into and out of each carbon source or sink, with the sum of particulate organic carbon (POC) produced annually from phytoplankton (green central bar) estimated to be 5,023,000 t C (5.0 Mt C/yr) for reference. Estimated total inputs of POC to stores (9.5 Mt C/yr) exceed calculated total outputs from primary producers (5.0 Mt C/yr).

Flows of OC from sources to short- and long-term stores (see Figure 19 and Figure 20) 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 the 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 5.0 Mt C may be added to the POC pool each year by phytoplankton. Annual plant growth and losses in blue carbon habitats contribute 174,000 t C/yr to POC, with kelp beds potentially providing most of this POC (159,000 t C/yr), followed by intertidal macroalgae (14,000 t C/yr), saltmarshes (800 t C/yr), and unknown amounts from seagrasses.

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 English North Sea Region and the Irish Sea and Welsh Coast Region (Burrows *et al*., 2021, 2024b), the total estimated import of OC to sediment stores in Scotland, based on habitat-specific carbon accumulation rates (9.5 Mt C/yr; see Table 15, Influx), is much greater than that estimated for total exports of OC from primary producers (phytoplankton and coastal vegetation export 5.0 Mt C/yr as detritus to the POC pool; see Table 15, Outflux). This imbalance suggests that imports of OC to sediments from outside the region's marine habitats may be particularly important, including OC from land runoff as well as that transported in from other marine regions. Blue carbon habitats, particularly saltmarshes, accumulate OC at a faster rate than offshore sediments.

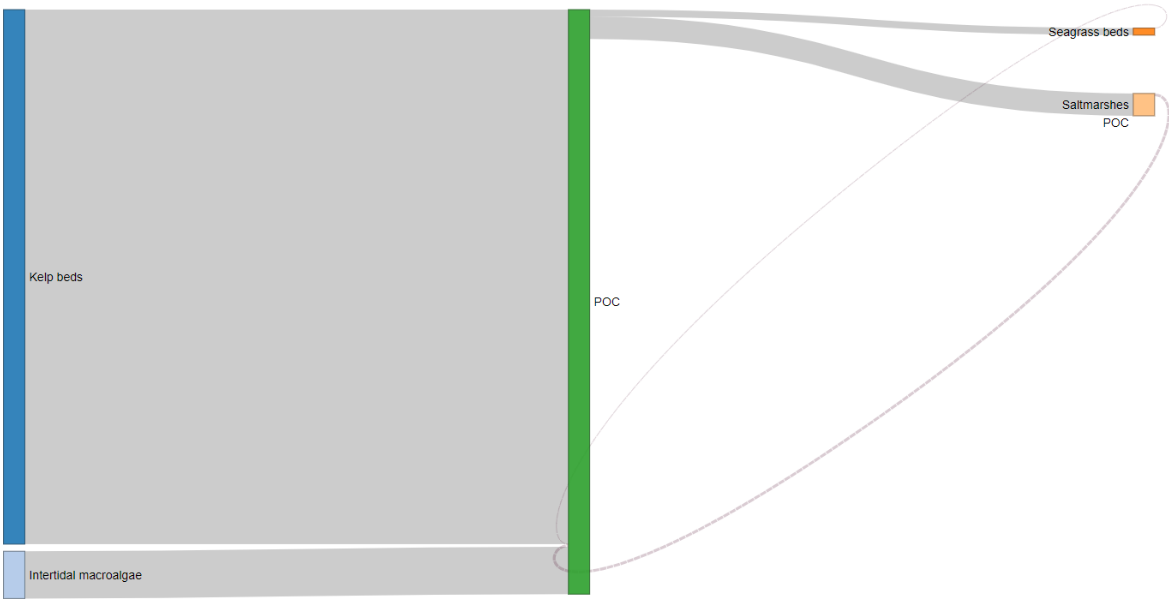

Figure 20. Organic carbon flows in Scotland's coastal vegetated blue carbon habitats.

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 and dynamics of the IC stores remains important, since the dissolution of already formed calcium carbonate material can increase alkalinity, absorbing dissolved CO_2 and countering ocean acidification.

3.4 Updating Scotland's 2014 blue carbon budget

Much new information and research relevant to the understanding of Scotland's blue carbon resources has emerged since the first attempt at a nationwide assessment in 2014 (Burrows *et al*., 2014), and the re-evaluation of blue carbon stores relative to the set of protected areas in Scotland in 2017 (Burrows *et al*., 2017). Recalculated total sediment (the top 10 cm depth) OC stores in 2023 were much smaller (152 Mt C) than the earlier estimate (592 Mt C) (see Table 16). The two reports used different methods to calculate OC stores. In 2014, habitat-specific values for OC densities derived from literature reviews and mapped extents of different substratum types from BGS data were used, whereas in 2023 published spatially modelled gridded data on OC density (Smeaton *et al*., 2021) were directly used. The latter approach has the advantages of allowing estimates of carbon stores for specific areas, such as protected areas and different assessment regions, and of using location-specific measurements of OC density.

Phytoplankton remains by far the largest source of OC in the 2023 assessment (see Table 16), albeit estimated over a larger area than in 2014. The total estimated POC production from primary producers in the region was less than the total estimated to be added to surface sediments in both the 2014 and 2023 assessments. The discrepancy between POC production and accumulation in sediments was greater in 2023 (5.2 Mt C/yr POC produced vs. 9.5 Mt C/yr accumulated) than in 2014 (3.9 Mt C/yr produced vs. 5.7 Mt C/yr accumulated). The reason for this difference remains unknown, but it may be due to uncertainty about the percentages of OC delivered to sediments and estimates of rates of accumulation, or to a missing component of the overall input of POC to the environment (e.g., riverine inputs).

Estimates of total short- and long-term stores of OC as living material and stored in sediments in CVBC habitats were revised upwards between the two reports (0.495 Mt OC in 2014, compared with 1.514 Mt OC in 2023). Extents of CVBC habitats did vary between the two assessments (see Table 17). The increase in estimated stored OC in Scotland between 2014 and 2023 was largely due to the use of (1) different threshold criteria to determine kelp habitat extent from the highly uncertain habitat-suitability-model maps (see Section 2.3.2), (2) improved bathymetry layers for predictions in 2023, and (3) a different approach to applying OC density values to estimated extents of kelp habitat. Saltmarsh extents in 2023 were reduced relative to those in 2014, largely due to the much improved information on their occurrence following a comprehensive review in 2016 (Haynes, 2016). There can be much greater confidence in the 2023 estimates of OC short- and long-term stores in saltmarsh, as multiple detailed and extensive studies of Scotland's saltmarshes have been conducted since 2017 (see Miller *et al*., 2023, and references therein). The 2014 report used a global average value (210 g C/m^2/yr) (Chmura *et al*., 2003) for saltmarsh carbon accumulation, and this is now considered to be inappropriate for Scotland. The use of lower, locally derived storage rates (113 g C/m^2/yr) (Miller *et al*., 2023) and a slightly reduced extent resulted in a lower estimate of the total carbon stored annually in Scotland's saltmarshes (14,200 t C/yr in 2014, compared with 4,400 t C/yr in 2023) (see Table 17).

Like saltmarshes, Scotland's seagrass beds have received increasing attention since the 2014 report (Potouroglou, 2017; Potouroglou *et al*., 2021), and as a result there can be greater confidence in the 2023 estimates of extent (up from 15 km^2 to 21 km^2) and annual carbon storage (up from 1,300 t C/yr to 2,100 t C/yr).

Much greater emphasis was placed on IC and OC stores and accumulation rates in biogenic habitats in 2014 than in 2023, largely due to feedback emphasising the potentially net negative contribution to carbon stores. Biogenic habitats are potential sources of CO_2 due to the generation of dissolved CO_2 during the calcification of skeletal structural material when such habitats are being formed (see Section 2.6). Although IC stores remain important as long-term stores of carbon in the marine environment, and perhaps more importantly as high-biodiversity habitats (Turrell *et al*., 2023), reporting of the total stores has been limited to the IC content of sediments for the 2023 assessment. Carbon dioxide is released during construction of the calcium carbonate skeletons of biogenic reef-forming species (Frankignoulle *et al*., 1994), which means that such stored carbon cannot be viewed as helping to mitigate CO_2 release caused by human activities. Using data from gridded values of IC density (in g C/m^2) (Smeaton *et al*., 2021), total IC stores in sediments were estimated to be 1,021 Mt C in 2023, a much lower value than the figure of 1,739 Mt C provided in 2014.

Table 16. Comparison of organic carbon assessments: stores and accumulation rates from this report (top) and Burrows et al*. (2014) (bottom).*

Scotland 2023			***Organic carbon***								***Inorganic carbon***					
Habitat		Extent (km²)	Stock (Mt C) [0.1m depth]	Stock (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)	Stock (Mt C) [0.1m depth]	Stock (kg C/m²) [0.1m depth]	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Phytoplankton		617385			81	50233	5023									
All sediment	(Method 1)	437883	151.8	347				9471	15.7	9471	1021	2.3	3.38	837		
Biogenic habitats		5228	1.514	290	328	1736	174	8		8						
	Total / Average	622614	153.4		83	51968	5197	9479		9479	1021			837		

Scotland 2014	(2023 units)	*Organic carbon*								*Inorganic carbon*					
Habitat	Extent (km2)	Stock (Mt C) [0.1m depth]	Stock (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)	Stock (Mt C) [0.1m depth]	Stock (kg C/m²) [0.1m depth]	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Phytoplankton	469960			81	39009	3900.9	0							1.09	0.00
Shelf Sediment: Coarse (top 10cm)	115004	13.2					1383	0.2	18	798		1.05	0.12		0.27
Shelf Sediment: Fine (top 10cm)	171660	509.9					2065	41.1	7049	468		0.84	0.14		0.40
Offshore Sediment (shelf/deep)	183296	58.3					2205	0.1	23	472		0.95	0.17		0.43
Sealochs: Mud	847	10					10	155.2	131						0.00
Biogenic habitats	2283	0.495		662	1770	1.8	0		15	0.58		109	0.00093		
Total	473089	591.9		84	40780	3903	5663		7238	1739			0.44	1.09	1.09

Table 17. Carbon stores and accumulation rates estimated for coastal blue carbon habitats in Scotland in this report (published in 2024) (top) and by Burrows et al. *(2014) (bottom).*

Scotland 2023		**Organic carbon**								**Inorganic carbon**					
Habitat	Extent (km²)	Organic carbon total (1000t C)	Organic carbon 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)	Stock (1000t C)	Stock (kg C/m²)	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Vegetated habitats															
Kelp beds	4777.6	1041.6	218.0	332	1587.1	158.7		0	0						
Intertidal macroalgae	371.3	49.8	122	378	140.3	14.0		0	0						
Seagrass beds	20.9	32.3	1547	274	5.7	0.6	1.5	100.4	2.1						
Saltmarshes	58.4	368.0	1490	138	8.1	0.8	5.8	113.5	6.6						
Maerl beds	31.4	22.6	720												
Biogenic reefs															
Serpulid reefs	1.1														
Modiolus modiolus	10.2														
Maerl beds and Horse mussel beds (mosaic)	13.8														
Blue mussel (*Mytilus edulis*) beds	4.4														
Native oysters*	0.0														
Flame shell beds	10.5														
Cold-water coral reefs	6.2														
Honeycomb worm (*Sabellaria alveolata*) reefs	1.1														
Total	5228.2	1514.3		329	1741.2	174.1	7.3	1.7	8.7						
	Long-term stores	422.91													

* Unknown

Scotland 2014	(2023 units)	Organic carbon								Inorganic carbon					
Habitat	Extent (km2)	Standing stock (1000t C)		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)	Standing stock (1000t C)		Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Vegetated habitats															
Kelp beds	2154.8	475		685	1732.4	1732.4				0					
Intertidal macroalgae	24.1	11.8		685	19.3	19.3				0					
Maerl beds	7.1									440.6		74	0.5		
Seagrass beds	15.9			261	4.2			83	1.3	0					
Saltmarshes	67.5	8.6		210	14.2			210	14.2	0					
Biogenic reefs															
Modiolus modiolus bed (Noss Head)	3.9									15.4		40	0.1540		
Limaria	1.4									0.1					
Lophelia pertusa reef (Darwin Mounds)	1.4									13.5		5	0.0072		
Lophelia pertusa reef (Mingulay)	5.4									112.0		35	0.1890	0	0
Serpula vermicularis reefs	1.3									1.0		420	0.0546	0	0
Brittlestar beds (shelf seas)												82			
Totals	2282.7	495.0		1841.0	1770.1	1751.7	0.0		15.4893	582.6	0.0		0.9	0.0	0.0

Note: *Desmophyllum pertusa* in this report is the revised name for *Lophelia pertusa*.

3.5 Updating Scotland's 2017 estimates of blue carbon in protected areas

The previous estimates (Burrows *et al*., 2017) of 9.4 Mt OC and 47.8 Mt IC inside Scotland's protected areas (MPAs, SACs, SPAs and SSSIs) were much lower than the values estimated in this report (see Table 14) (OC: 64.6 Mt in MPAs, 12.2 Mt in SACs, 5.9 Mt in SPAs and 0.25 Mt in SSSIs; IC: 365 Mt in MPAs, 105 Mt in SACs, 55 Mt in SPAs and 0.8 Mt in SSSIs). Apart from the differences in the methods of calculation of sedimentary stores for the 2017 and 2023 reports, the main difference in these values for total stores inside protected areas arises from the fact that the earlier report considered inshore areas only (19 MPAs and 29 SACs, 11,350 km^2), whereas this report covered a much larger area (MPAs, 174,900 km^2; SACs, 30,500 km^2; SPAs, 16,500 km^2; SSSIs, 176 km^2) (see Table 1).

4 Case Study: Loch Craignish and the Cromarty Firth

4.1 Introduction

The geography of the west coast of Scotland contrasts with that of the east coast. The west coast has sea lochs, the highlands and islands and extensive rocky shores, whereas the east coast is more of an arable region with large fields of farmland, rich soils and different topography. On the east coast of Scotland there are several firths, many of which are designated for their bird populations, mudflats and sandbanks. One such area on the east coast is the Cromarty Firth. The importance of Nigg Bay as a nature hotspot in the Cromarty Firth was recognised as early as the 1940s, and at the present time serves as part of an RSPB reserve. The Cromarty Firth was first notified in 1974, and later, in 1978, a National Nature Reserve was established in Nigg Bay. The SSSI was re-notified in 1988, and most recently in March 2011, and is currently also an SPA. As well as its extensive saltmarsh and mudflat habitats, the SPA designation also aims to protect 15 bird species (see Figure 21).

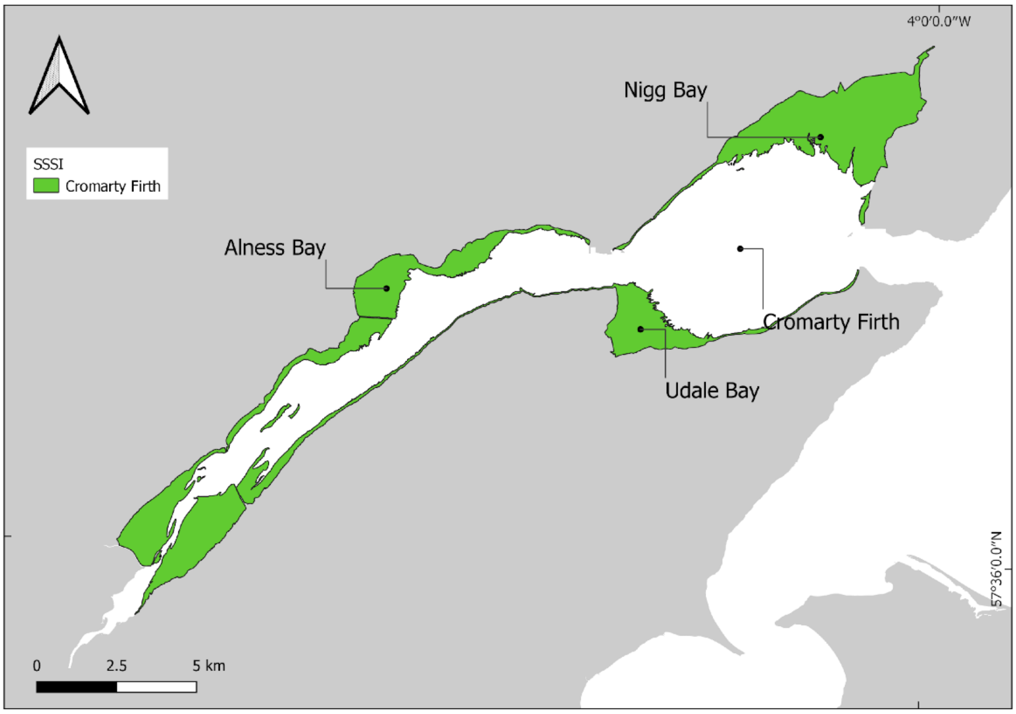

Figure 21. The SSSI designations (denoted by green areas) within the Cromarty Firth, protected for their bird populations and for their extensive mudflats and saltmarsh. The intertidal seagrass species is also protected in the Firth.

In contrast to the Cromarty Firth, Loch Craignish is a small south-west-facing sea loch on the west coast of Scotland (see Figure 22). It currently has no designations or protected area status, but is nestled between the Firth of Lorn SAC and the Inner Hebrides and the Minches SAC, which both overlap with the Loch Sunart to the Sound of Jura MPA (see Figure 22). The regions surrounding Loch Craignish are protected for a variety of reasons. The Inner Hebrides and the Minches SAC was selected for the harbour porpoise (*Phocoena phocoena*, an Annex II species). The Firth of Lorn has 'reefs' formed by multiple Annex I habitats that are the main reason for the site selection. Several species exist in the SAC, such as the sponges *Mycale lingua* and *Clathria barleii*, and the featherstar *Leptometra celtica*, which is often associated with deeper water but is present in the area because of the high-energy tidal flows.

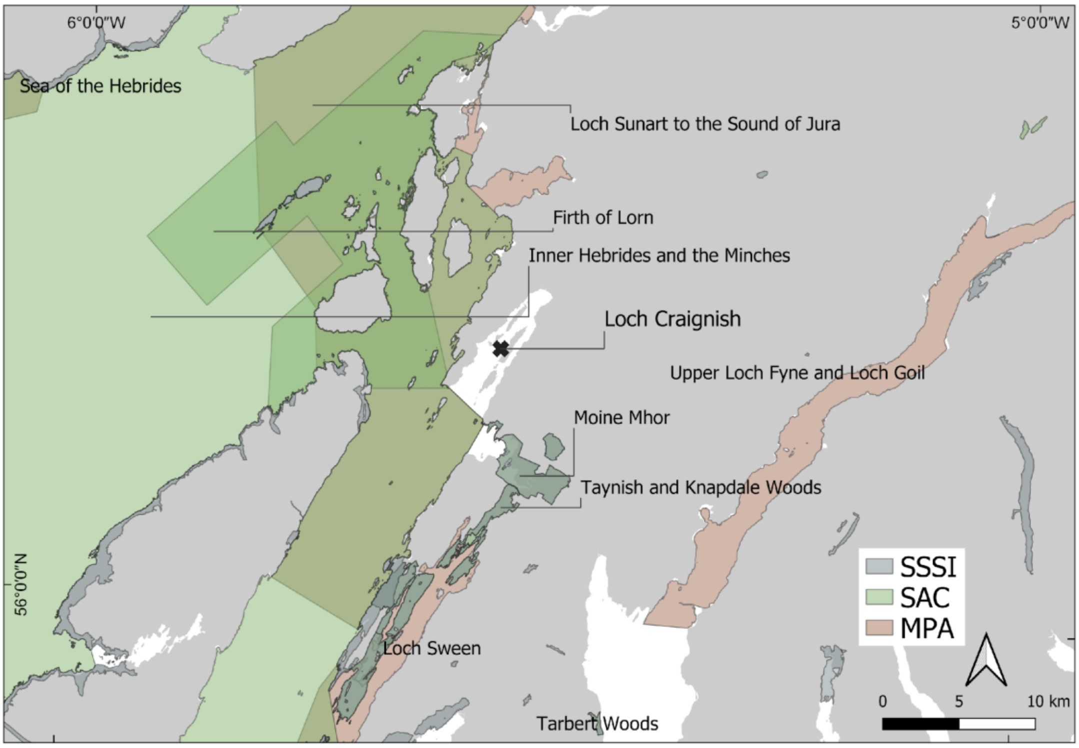

Figure 22. Loch Craignish is located in between several designated areas, but to date has not been given any protected status.

4.1.1 Current knowledge of seagrass at both sites

Both the Cromarty Firth and Loch Craignish are home to seagrass beds. Seagrass beds are a PMF, a UK BAP habitat, and recognised as threatened and declining under the OSPAR Convention (see Section 2.5). Seagrass wasting disease, bottom disturbance and nutrient loading are considered to be major factors underlying the decline of seagrass species in the UK and throughout Europe (Green *et al.*, 2021). These factors were discovered in the late 1930s when widespread loss of *Z. marina* was first observed (see Section 4.2). The potential historical loss of seagrass in the UK has been recently estimated, but the true extent of loss remains unknown (Green *et al.*, 2021). Given the recognised importance of seagrass, a concerted effort to restore lost habitat is under way in multiple locations within the UK and globally.

In 2015, two bays in the Cromarty Firth were surveyed by the Scottish Environment Protection Agency (SEPA), namely Udale Bay and Nigg Bay (see Figure 21). The surveys found 1,258,764 m^2 of seagrass in Udale Bay and 1,979,807 m^2 of seagrass in Nigg Bay, making these two bays the largest known area of seagrass coverage in Scotland to date (Potouroglou *et al.*, 2021). However, the surveys did not include Alness Bay or the bays next to Dalmore and Invergordon, which also contain significant amounts of seagrass. Current knowledge of the extent and distribution of seagrass in the Cromarty Firth means that it is one of the most important areas for the species in Scotland. The main species observed are *Zostera noltii, Zostera marina var. angustifolia* and the less common *Ruppia maritima. Ruppia maritima* is not strictly a seagrass, but rather a salt-tolerant aquatic plant often referred to as widgeon grass or beaked tasselweed. The most abundant species in the area is *Z. noltii*, which inhabits the intertidal mudflats of the firth. This species is described as ephemeral, and is often not visible in the winter months.

In Loch Craignish, all known meadows of *Zostera marina* (as well as other blue carbon habitats in the loch) have recently been mapped by the Scottish Association for Marine Science (SAMS) in collaboration with the community-led restoration charity Seawilding (see Figure 23). The seagrass mapping project involved initial surveys with unmanned aerial vehicles (UAVs, i.e., drones), followed by the use of high-resolution satellite imagery, drone photogrammetry and also ground-truthing by snorkel/paddle board surveys led by citizen scientists. There are observations of *Z. noltii* beds in Loch Craignish, but they are sparse and not as dense as the *Z. marina* beds. In total, 56,000 m^2 (5.6 ha) of dense *Z. marina* beds have now been mapped in Loch Craignish (see Figure 23). These more recent, community-driven efforts have found seagrass in places where it was previously unknown. For example, existing shapefile data (used in the present report and from the GeMS habitat database) have only 26,000 m^2 of seagrass meadows. These findings showcase how citizen science can work in collaboration with research to improve current knowledge of these important habitats. In addition, the findings show that current estimates of the extent and distribution of seagrass may be significantly underestimating the true coverage and therefore the amount of carbon stored. The seabed meadows in Loch Craignish, for example, were underestimated by 43%.

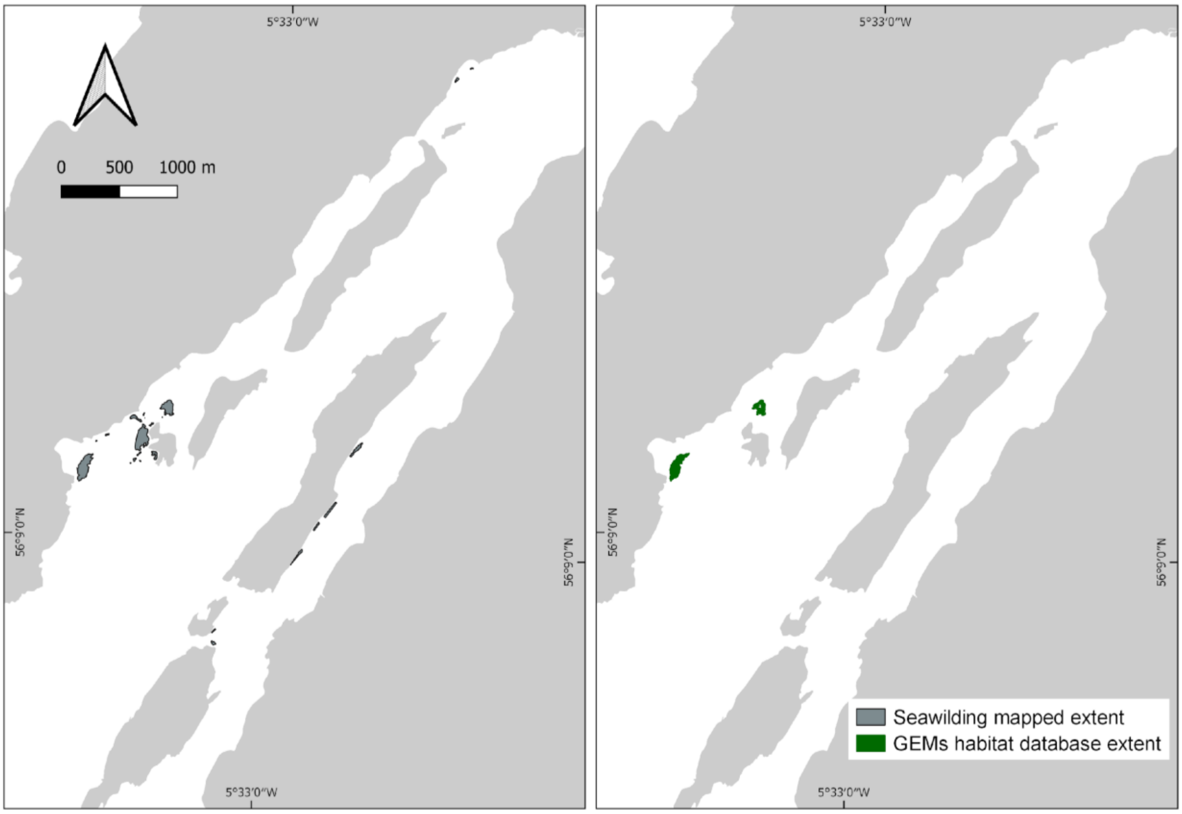

*Figure 23. The extent of blue carbon habitats in Loch Craignish. Seagrass patches were verified using either unoccupied aerial vehicles (UAVs) images or stand-up paddleboarders by the local citizen-led group Seawilding, with assistance from the Scottish Association for Marine Science (SAMS). The true extent of seagrass (*Z. marina*, left-hand image) in Loch Craignish is close to 5.6 ha, but databases (right-hand image) have only mapped 2.4 ha.*

4.2 Historical evidence of seagrass decline in Scotland

There is limited recent robust evidence of seagrass decline in Scotland. Older records of seagrass extent in the UK are generally based on the work of Cotton (1933), Butcher (1934) and Wilson (1949). Gradual loss of *Zostera* species in the Tay Estuary was noted as early as

1934 (Butcher, 1934), but little evidence is available for other estuaries. However, even earlier, in his texts about Loch Creran, a sea loch on the west coast of Scotland, Anderson Smith (1887) noted the occurrence of bays of seagrass meadows which are currently not present on modern databases or visible in high-resolution satellite layers.

> We came at length to a grand sweep of the fine bay, which has now been so left by the sea that a graceful curve of green *Zostera marina* borders it.
>
> (Anderson Smith, 1887)

> Wading at lowest tide among beds of *Zostera marina*, amid bouldery and ware-grown surroundings.
>
> (Anderson Smith, 1887)

The importance of *Zostera* species has been documented since the 1930s, when there was growing interest in the species, particularly as a source of nutrients for the base of the food web in coastal regions. Russell (1932) pointed out that *Zostera* banks are the main source of organic matter for benthic organisms, polychaetes and even fish. Later, Cotton (1933) discussed the economic value of a species that binds sand and mud in estuaries and bays as well as providing food for ducks, geese and swans.

4.3 Managing and restoring seagrass habitats in both sea lochs

It is clear that restoring a certain area or enhancing the extent of a blue carbon habitat will result in a proportionate increase in carbon fixation, storage and stores, depending on the species and the success of the scheme.

Seagrass restoration is progressing throughout the UK. Although many projects are undertaking active research into suitable and effective techniques to maximise the success of schemes in different localities, it is also important to establish an appropriate baseline for restoration to target. The present report shows that the extents of the seagrass meadows in both the Cromarty Firth and Loch Craignish are underestimated. In view of the uncertainty about the true extent of seagrass meadows throughout Scotland (and indeed in the rest of the UK), more effective mapping and monitoring is needed. Successful collaborations between research and citizen science projects (as demonstrated by the citizen science group SeagrassSpotter[7]) can be helpful here. A recent push by Project Seagrass to try to improve the volume of point-source data across the UK led to the addition of multiple data points where seagrass was previously unknown or had not been officially recorded.

In Loch Craignish, *Z. marina* is being replanted in a trial area of 5,000 m^2 (0.5 ha) in a sheltered bay. Initial trials adopted techniques previously used in seagrass planting projects in North Wales and the Solent. The first stage involves collection of mature seeds from plants. The seeds are extracted and placed in small hessian bags filled with locally sourced sediment and re-deployed in the restoration site. As the seeds produce shoots the bags decompose, and the young seagrass plants continue to grow. Subsequently, direct planting of seeds using various methods was trialled, and most recently (in 2023) a technique involving the direct transplantation of clods (including rhizomes) was tested. Repeat surveys will inform future restoration projects about the best practices to adopt for *Zostera marina* plants.

On the east coast, restoration of *Zostera noltii* presents different challenges. This species is much smaller than *Z. marina*, and the seeds are difficult to collect and manipulate. Some studies have made successful attempts to transplant mature plants (see Valle *et al.,* 2015). Finding suitable donors for intertidal muddy flats is difficult, and the time required for donor beds to recover from clod removal is an important consideration.

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[7] https://seagrassspotter.org

4.4 Lessons learned from seagrass restoration projects

Several lessons relating to blue carbon can be learned from seagrass restoration projects and the collaborative efforts that are under way. First, the true extent of seagrass (as well as some other blue carbon ecosystems) in Scotland is unknown. However, with the help of restoration projects, citizen science, modern mapping techniques and the use of drones to take aerial photographs there is potential to rapidly improve our knowledge of these vital blue carbon habitats. Secondly, the benefits that are gained from restoration projects are still being monitored and evaluated. Not only do blue carbon habitats benefit, but also there are potential biodiversity gains, as well as sediment stabilisation, water quality management and nutrient removal benefits. Again, citizen science surveys combined with scientific analysis of sediment carbon dynamics, biodiversity changes and other aspects of seagrass physiology, growth and survival will improve the success of seagrass restoration projects and our knowledge of the additional benefits of these projects.

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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).
labile carbon	Sugars, proteins and other carbon compounds that are easily used by marine bacteria.
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, which are used by living organisms in the structure of their cells and as a source of energy.
particulate organic carbon (POC)	Organic carbon that is in the form of solid particles, derived from dead plant material.
refractory carbon	High-molecular-weight and structurally complex compounds that are difficult for marine organisms to use (e.g., lignin, humic acid).
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	Any solid particles that have settled under the action of gravity after formerly being suspended in liquid.
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?
Saltmarsh Extent & Zonation	www.data.gov.uk	Environment Agency	Environment Agency	Open Government Licence 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
C20220127_AnnexI_Reefs_v8_3_OpenData	https://hub.jncc.gov.uk/assets/8f886e47-31d6-477e-9240-65ac42bee709		Joint Nature Conservation Committee (JNCC)	Limitations on public access. 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

Title	Data source	Data sub-source	Data owner	Restrictions	Permissions request needed?
Geodatabase of Marine features adjacent to Scotland (GeMS)	https://opendata.nature.scot/maps/0e722e3e911e424f8dacac5a587c0dfb/about	NatureScot	NatureScot and JNCC	These datasets are available under the Open Government Licence (OGL)	No