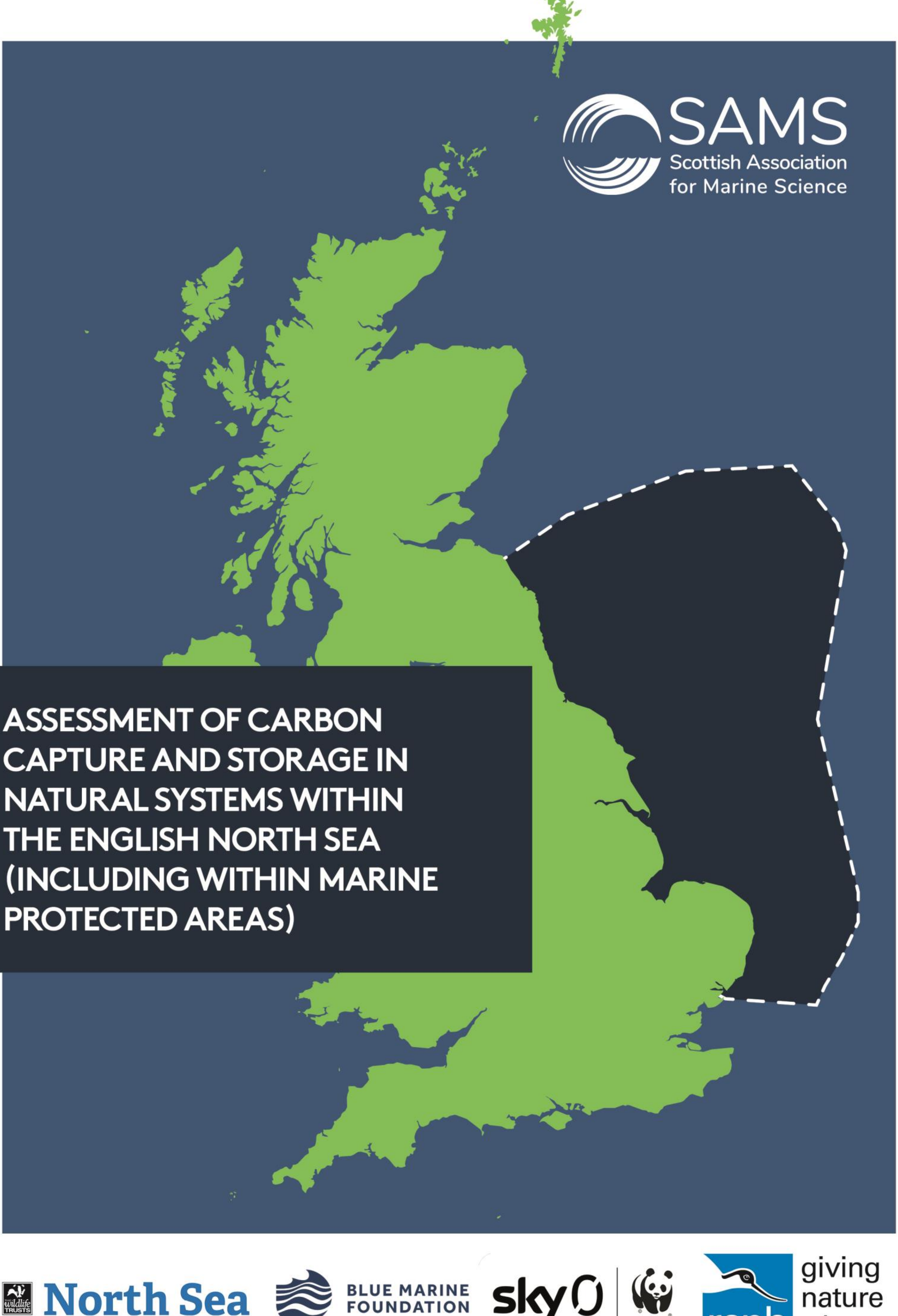

SAMS
Scottish Association for Marine Science

ASSESSMENT OF CARBON CAPTURE AND STORAGE IN NATURAL SYSTEMS WITHIN THE ENGLISH NORTH SEA (INCLUDING WITHIN MARINE PROTECTED AREAS)

The Wildlife Trusts North Sea
BLUE MARINE FOUNDATION
sky Zero
WWF
rspb giving nature a home

Assessment of Carbon Storage and Sequestration Potential Within the English North Sea (Including Within Marine Protected Areas)

Project No: **03745**

Year of publication: **2021**

This report was prepared by:

The Scottish Association for Marine Science (SAMS)

Centre for Environment, Fisheries and Aquaculture (Cefas)

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Recommended Citation: Burrows, M.T., Moore, P., Sugden, H., Fitzsimmons, C., Smeaton, C., Austin, W., Parker, R., Kröger, S., Powell, C., Gregory, L., Procter, W., Brook, T. (2021) Assessment of Carbon Capture and Storage in Natural Systems within the English North Sea (Including within Marine Protected Areas). A North Sea Wildlife Trusts, Blue Marine Foundation, WWF and RSPB commissioned report.

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Acknowledgements

We acknowledge members of the steering committee that contributed to the development of this report, including the Department of Environment, Food, and Rural Affairs (Defra), Joint Nature Conservation Committee (JNCC), and Natural England.

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Acronyms & Abbreviations

BC	Blue Carbon
C:N	Carbon:Nitrogen ratio
EEZ	Exclusive Economic Zone
EUNIS	European Nature Information System
GIS	Geographic Information System
HPMPA	Highly Protected Marine Protected Area
IC	Inorganic Carbon
ICES	International Council for the Exploration of the Sea
JNCC	Joint Nature Conservation Committee
MCZ	Marine Conservation Zone
MMO	Marine Management Organisation
MPA	Marine Protected Area
NE	Natural England
NBN	National Biodiversity Network
NBS	Nature-Based Solution
NVC	National Vegetation Classification
OC	Organic Carbon
OWF	Offshore Wind Farm
P/B	Production/Biomass
PCB	Polychlorinated Biphenyl
PIC	Particulate Inorganic Carbon
POC	Particulate Organic Carbon
SAC	Special Area of Conservation
SACFOR	Superabundant, Abundant, Common, Frequent, Occasional, Rare
SAR	Swept Area Ratio
SPA	Special Protected Area
SoS	Secretary of State
TAZ	Taphonomically Active Zone
TOC	Total Organic Carbon
UNFCCC	United Nations Framework Convention on Climate Change

EXECUTIVE SUMMARY

This report was commissioned by the North Sea Wildlife Trusts, Blue Marine Foundation, WWF and the RSPB to assess the extent, scale, distribution, and potential of the current blue carbon sinks in the English North Sea (i.e. seabed sediments, saltmarsh, kelp forests, seagrass beds and biogenic reefs). The focus was to i) review the current extent and distribution of each blue carbon habitat, ii) estimate the quantity of carbon currently stored within these habitats, iii) establish the average net sequestration rate (i.e. gC $m^{-2} yr^{-1}$), and iv) estimate the potential net total sequestration (i.e. gC yr^{-1}) of each blue carbon habitat.

This analysis synthesises and reviews the most up-to-date scientific literature on fixation, processing, and storage of carbon in the English North Sea, including within Marine Protected Areas (MPAs). Carbon stock densities and rates of production and storage are 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 enhance the seabed and their carbon sequestration potential. Evidence of this nature will contribute to explore the potential of the English North Sea Marine Protected Area (MPA) network to help mitigate against the effects of climate change.

Extents of blue carbon habitats for the North Sea region were derived from available sources. These include the EUNIS level 3 combined map from JNCC, Natural England Marine Habitats and Species Open Data, and recently published estimates of organic carbon (OC) and inorganic carbon (IC) stocks in surface sediments (Smeaton *et al.*, 2021). Where maps of coastal habitats based on surveys were not available, including kelp and seagrass, extents of these habitats were estimated from models.

Limitations of the estimates produced here link primarily to poorly constrained spatial extents of blue carbon habitats at the scales required for this report. For some habitats (intertidal and subtidal sediments), confidence in observational understanding of long-term sequestration is very low, as is that for transport and fate of carbon from macroalgae. Kelp forests in the region, for example, have received little attention compared to the rest of the United Kingdom. Furthermore, the science of understanding the effects of physical disturbance (including trawling) and climate change on these systems is very much in its infancy and new developments will allow a much better-informed outlook for the fate of these stocks and accumulation rates in a changing world and under varying management scenarios.

Direct comparison between these North Sea carbon stores and those in terrestrial vegetation and soils are fraught with difficulty. Carbon stock sizes (MtC) and density per unit area (t/km^2) are assessed differently, over different areas of habitats, and different timescales for storage of reported stocks. Carbon in living material may persist for years or decades, while that buried in soils and marine sediments may last for 100s to 1000s of years. Such lack of comparability renders straight numerical comparisons nearly meaningless. This is even more of a problem when comparing marine and terrestrial stocks, where soils and sediments and the nature of vegetated habitats are so radically different from each other. Depths of soils considered are a vital consideration. Here we consider marine sediments to a depth of only 10cm, while carbon in terrestrial soils is often reported to depths, typically 30cm to a metre or more. Given these caveats, conclusions that the total carbon reported for the area is 19% of that in UK forests (101 Mt vs 529 Mt) should be treated with extreme caution.

Main Findings

- In total, 37.4 million tonnes (Mt) of organic carbon (OC) stocks are found in the region, with 98% of that total stored in sublittoral mud and sand/mud seabed sediments. The 2% (0.8 Mt) of organic carbon found within coastal vegetated blue carbon habitats is predominantly stored in the soils of coastal saltmarshes (76%), with sediment in seagrass beds (16%) and living kelp biomass (8%) forming the remainder. Seabed sediments are thus by far the most important habitat for carbon storage in the English North Sea. However, it is important to note that this analysis considers only surficial sediments, accounting for the top 10 cm of the seabed, and therefore represents a fraction of the overall carbon stored in the full thickness of these sediments. While blue carbon habitats (kelp beds, intertidal macroalgae, saltmarshes and seagrass beds) form only 0.5% of the total area of the region, they disproportionately hold 2% of the total organic carbon stores. Furthermore, 63.0 Mt of inorganic carbon (IC) was estimated within the study area, primarily stored as shell material.

- The MPAs in this study cover over 57 000 km^2, representing 50% of the English North Sea. Stocks of carbon within the MPA network are estimated to hold 19.4 Mt of organic carbon, accounting for 51.9% of the total organic carbon stores in the region, and 26.5 Mt of inorganic carbon, or 42.1% of the total stored across the study area. The network was not initially designated for carbon stocks or storage potential, however, the proportion of organic carbon stocks contained within MPAs (51.9%) is largely in line with the percentage of the study area (50.3%). Inorganic carbon stocks contained within the network account for a smaller proportion (42.1%), as it does not cover areas with the largest stock densities (e.g., coastal regions of the English North Sea).

- Annually, an estimated 1.27 Mt of organic carbon is added to sediment stores across the study area, predominantly within mud and sand/mud seabed sediments. Blue carbon habitats (e.g., kelp beds, intertidal macroalgae, saltmarshes and seagrass beds) store a considerably smaller fraction of this (0.077 MtC/yr; 6% of the total annual value, albeit at a higher rate per unit area), with saltmarsh soils dominating (95%) the accumulation among blue carbon habitat stores. However, this accounts for the standing stock of macroalgae only, which also contribute to carbon storage through subsequent loss and transport of biological material to seabed sediments.

- Growth and reproduction of plant material, with subsequent losses and transport to stores in the seabed, are the primary mechanism for removal of CO_2 by the marine ecosystem in the region. Unlike rates of plant growth, the proportion of plant detritus that reaches storage considered relevant over climatically relevant time-periods is poorly known. Adopting values typically used in ecosystem models, we used a value of 10% of plant material produced to predict the fraction of organic carbon transported from standing stocks and stored within seabed sediments. Under this assumption, 0.94 MtC/yr is thought to be added to the particulate organic carbon (POC) pool each year for transport and incorporation into stores.

- Production of organic carbon by plants in the region is dominated by phytoplankton (0.93 MtC/yr), with much smaller fractions by kelp (12 600 tC/yr), saltmarshes (1 800 tC), seagrass beds (1 400 tC) and intertidal macroalgae (900 tC/yr). Additionally, biogenic reefs are extensive in the region, particularly the subtidal tubeworm *Sabellaria spinulosa*, but such areas are similar to surrounding sediments in their ability to store carbon.

- As stated above, the English North Sea is estimated to store 100.4 Mt carbon (37.4 Mt of organic carbon and 63.0 Mt of inorganic carbon), which equates to 880 tC per km^2. To put this into context, UK forests are estimated to store 529 Mt carbon, or for comparison on a per unit area basis, 5 500 tC per km^2 (**Table 14**). Given the problems with such comparisons, marine sediments may be likely to represent a greater proportion of the UK total under future revised and aligned accounting methods.

- Integrating the understanding of carbon storage provided by marine habitats into decisions relating to marine management would potentially improve the protection provided to these habitats and enhance their capacity to act as carbon sinks. In some cases, where blue carbon habitat is covered by an existing MPA, management measures that have the specific objective of protecting or restoring habitat containing these stocks can be considered alongside primary biodiversity considerations as potential Nature-Based Solutions (NBS) to climate change.
- The main threat to organic carbon stores is physical disturbance of the seabed, for example from demersal fishing activities, deployment of moorings and installation of offshore energy platforms, but the net effects are highly uncertain. Climate change, specifically ocean acidification caused by increased CO_2 concentrations, is likely to have mixed effects on blue carbon capture and storage, negatively impacting on calcareous organisms (that build carbonate skeletons) and carbonate sediments, but potentially benefitting photosynthetic species (such as kelp or other macroalgae).

1 INTRODUCTION

1.1 Rationale and structure of report

In this report, a habitat-oriented approach is used to assess marine carbon stores in the English North Sea and its Marine Protected Areas (MPAs). “Blue carbon” habitats are broadly considered here as essentially all those habitats with significant contributions to the fixation and storage of carbon. Such habitats present in the area are identified and reviewed for their potential to fix and store (sequester) carbon, focussing on the ecology of the key carbon-fixing and habitat-forming species, the dynamics of physical habitats, and quantitative estimates of stocks and rates of carbon fluxes. Exports and imports from these habitats, threats to stocks and fluxes as well as the potential of restoring lost habitats to improve carbon storage and sequestration. Habitat reviews (Section 2) have identified sources of information on known and predicted habitat extent 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. The resulting synthesis and assessment of carbon sequestration capacity will guide conservation and restoration efforts in the region.

Assessing carbon sequestration and storage in the region follows the sequence of combining estimates of area with area-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 stocks (Burrows *et al.*, 2014). This was the first national assessment of its kind, and remains the primary source for information on carbon stocks in the area as habitat-specific estimates continue to be revised (Turrell, 2020). Partitioning blue carbon stocks and processes among MPAs in Scotland informed the role of MPAs in protecting the capacity of coastal seas to sequester carbon (Burrows *et al.*, 2017). Integrating the contribution of UK coastal areas with European shelf waters recently produced a continental shelf-wide assessment of carbon dynamics (Legge *et al.*, 2020) and the first complete mapping of sedimentary carbon across the UK EEZ (Smeaton *et al.*, 2021).

Primary information on the area and location of blue carbon habitats and associated sediment stores have been compiled from existing habitat maps, building on the data sources used in recent reviews of blue carbon by Natural England (Gregg *et al.*, 2021), Defra/Cefas (Parker *et al.*, 2020), and the contribution of MPAs to the protection of carbon stocks (Flavell *et al.*, 2020). Where observed data do not give the extent of habitats or patterns of carbon stored directly, estimates from the predictions of statistical models of habitat suitability (Burrows *et al.*, 2018, Kettle *et al.*, 2020, Wheater *et al.*, 2020) and carbon types stored (Diesing *et al.*, 2017, Smeaton *et al.*, 2021) based on relationships between known records and data layers for physical and biological drivers of species distributions and carbon stored by sediments. Such estimates have been reported for the whole region and for focal areas including MPAs, highlighting 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, and natural processes such as wave-resuspension and river-derived plumes.

Carbon budgets and carbon stores for each blue carbon habitat in the report use the available information on extent and biomass. Net sequestration capacity ($gCm^{-2}yr^{-1}$) of each habitat depends on the balance of processes of net production as reported in the relevant habitat review sections (Section 2) and synthesised in Section 4.7.

The occurrence and extent of blue carbon habitats and sediment stores in Marine Conservation Zones (MCZs), Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) are evaluated and combined with existing work on the contribution of habitats within MCZs (Flavell *et al.*, 2020). The report thus gives a breakdown of carbon stores and sequestration capacity within 26 MPAs (**Table 1**, **Figure 1**), hereby referred to as the English North Sea MPA network.

Table 1. *A list of the MPA network investigated within this study (in alphabetical order).*

Number	Name	Designation
1	Alde, Ore and Butley Estuaries	SAC
2	Aln Estuary	MCZ
3	Berwick to St Mary's	MCZ
4	Berwickshire and North Northumberland Coast	SAC
5	Coquet to St. Mary's	MCZ
6	Cromer Shoal Chalk Beds	MCZ
7	Dogger Bank	SAC
8	Farnes East	MCZ
9	Flamborough Head	SAC
10	Fulmar	MCZ
11	Haisborough, Hammond & Winterton	SAC
12	Holderness Inshore	MCZ
13	Holderness Offshore	MCZ
14	Humber Estuary	SAC
15	Inner Dowsing, Race Bank and North Ridge MPA	SAC
16	Markham’s Triangle	MCZ
17	North East of Farne Deeps	MCZ
18	North Norfolk Coast	SAC
19	North Norfolk Sandbanks & Saturn Reef	SAC
20	Orford Inshore	MCZ
21	Orfordness - Shingle street	SAC
22	Runswick Bay	MCZ
23	Southern North Sea	SAC
24	Swallow Sands	MCZ
25	The Wash and North Norfolk Coast	SAC
26	Tweed Estuary	SAC

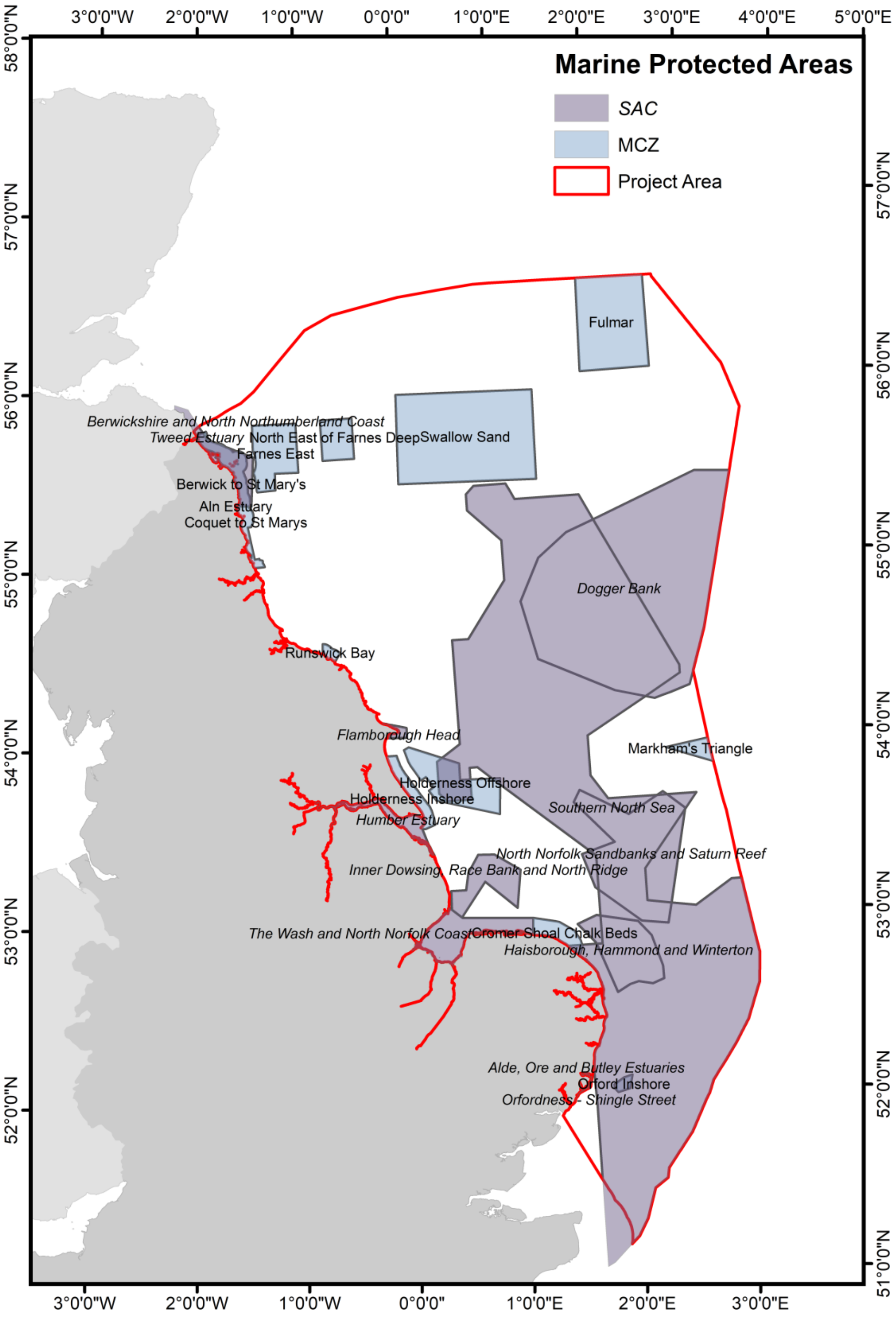

Figure 1. *Map showing the location of the MPA network investigated within this study. MCZs coloured blue, with names in non-italicised labels; SACs coloured purple, with names in italicised labels*

1.2 Project objectives

The main purpose of this report is to provide and assess the extent, scale, distribution, and potential of the current blue carbon sinks in the English North Sea (i.e. saltmarsh, kelp forests, seagrass beds, biogenic reefs, seabed sediments). The specific focus was to

- Review the current extent and distribution of each blue carbon habitat.
- Estimate the quantity of carbon currently stored within each blue carbon habitat.
- Establish the average net sequestration capacity (i.e. gC m^{-2} yr^{-1}) of each blue carbon habitat.
- Estimate the potential net sequestration (i.e. gC yr^{-1}) of each blue carbon habitat.
- Further develop analytical methodology and approaches (based on the work undertaken in Scottish inshore waters) that can be replicated on a wider UK scale.

The results are intended to inform management decisions and identify opportunities to enhance the seabed and their carbon sequestration potential. Evidence of this nature will contribute to explore the potential of the English North Sea MPA network to mitigate against the effects of climate change.

1.3 Project outputs

1.3.1 Inventory of existing carbon stocks for English North Sea blue carbon habitats and associated sediment stores

The completed inventory is summarised in section 4.7.

1.3.2 Maps and GIS datasets giving storage potential

Datasets used in this study are publicly available, except for minor modelled extents used for comparative purposes. These include the EUNIS level 3 combined map from JNCC[1], Natural England Marine Habitats and Species Open Data[2], and organic carbon (OC) and inorganic carbon (IC) stocks following the methodology of Smeaton et al. (2021)[3].

[1] https://jncc.gov.uk/our-work/marine-habitat-data-product-eunis-level-3-combined-map/
[2] https://data.gov.uk/dataset/bfc23a6d-8879-4072-95ed-125b091f908a/marine-habitats-and-species-open-data
[3] https://data.marine.gov.scot/dataset/organic-and-inorganic-carbon-content-surficial-sediments-within-scottish-adjacent-waters

2 REVIEWS OF BLUE CARBON HABITATS

This section reviews the carbon production, storage and sequestration potential for each blue carbon habitat based on existing literature and data. The glossary (**Section 7**) explains technical terms used here.

2.1 Intertidal and subtidal macroalgae

2.1.1 Intertidal species

Large canopy-forming fucoids are likely to make the largest intertidal contribution to carbon production and loss. Based on habitat suitability modelling this macroalgal group can be found throughout the English North Sea (Yesson *et al.*, 2015), with records of seven fucoid species: *Pelvetia canaliculata*, *Fucus spiralis*, *F. vesiculosus*, *F. serratus*, *Ascophyllum nodosum*, *Halidrys siliquosa* and *Himanthalia elongata* being present in the region. There has been a general presumption that intertidal macroalgae have lower productivity than subtidal macroalgae (i.e. kelp) (Mann, 2000), however, a review of the literature suggests intertidal fucoids can be highly productive ranging from 4 – 1800 gC m^{-2} yr^{-1} (Lewis et al 2020). UK estimates of primary productivity are only available for *F. vesiculosus*, *F. serratus* and *A. nodosum* and are based on data collected from mid and north Wales. Rates of primary production varied across seven study sites for all three species with *F. vesiculosus* primary productivity ranging between 166-946 gC m^{-2} yr^{-1} (mean 430 ± 106 gC m^{-2} yr^{-1} SE), *F. serratus* between 222-958 gC m^{-2} yr^{-1} (mean 611 ± 124 gC m^{-2} yr^{-1} SE) and *A. nodosum* between 16-70 gC m^{-2} yr^{-1} (49 ± 10 gC m^{-2} yr^{-1} SE) (Lewis, 2020). The latter values are considerably lower than what has been previously reported for *A. nodosum* (90-935 gC m^{-2} yr^{-1} , (Brinkhuis, 1977, Lamela-Silvarrey *et al.*, 2012), and probably reflects differences in how individual plants were determined. The UK study followed (Baardseth, 1970) and defined an individual as a single shoot arising from a holdfast, whereas other studies have classified an individual as all shoots arising from a holdfast. The site level variability was not related to differences in wave exposure, as while the sites covered a wave exposure gradient there was no consistent relationship between this and rates of primary production (Lewis, 2020). UK estimates of primary productivity do not exist for the other fucoid species in the North Sea region but do exist from Spain for *F. spiralis* (182.5 gC m^{-2} yr^{-1}), *Himanthalia elongata* (989.2 gC m^{-2} yr^{-1}) and *Pelvetia canaliculata* (351 gC m^{-2} yr^{-1}) and Denmark for *Halidrys siliquosa* (5.4 gC m^{-2} yr^{-1}).

Estimates of fucoid standing stock is again restricted to *F. vesiculosus*, *F. serratus* and *A. nodosum*. Values ranged from 358-634 gC m^{-2} (mean 536 ± 29 gC m^{-2} SE) for *F. vesiculosus*, 241^{-1} 213 gC m^{-2} (mean 659 ± 127 gC m^{-2} SE) for *F. serratus* and 696^{-1} 649 gC m^{-2} (mean 1033 ± 134 gC m^{-2} SE) for *A. nodosum* (Lewis, 2020). These values were again derived from between 7 and 9 sites in mid and north Wales.

Information on fucoid detrital production is limited with information only existing for *F. vesiculosus*, *F. serratus* and *A. nodosum* based on data collected in mid and north Wales. Fucoids lose biomass via three pathways: chronic erosion of blade material, whole plant dislodgement and seasonal senescence of reproductive receptacles. Estimates of fucoid detrital production are based on dislodgment and receptacle senescence and are therefore likely conservative. Whole plant dislodgement ranged from 79-375 gC m^{-2} yr^{-1} (mean 148 ± 43 gC m^{-2} yr^{-1} SE) for *F. vesiculosus*, 18-636 gC m^{-2} yr^{-1} (mean 215 ± 91 gC m^{-2} yr^{-1} SE) for F. serratus and 41-390 gC m^{-2} yr^{-1} (mean 248 ± 57 gC m^{-2} yr^{-1} SE) for A. nodosum (Lewis 2020). Based on data collected from one site in mid Wales, receptacle senescence contributed an additional 229, 153 and 139 gC m^{-2} yr^{-1} of detrital material from *F. vesiculosus*, *F. serratus* and *A. nodosum*, respectfully. Combined, detrital production by *F. vesiculosus* contributes on average 377 gC m^{-2} yr^{-1} , *F. serratus* 368 gC m^{-2} yr^{-1} and *A. nodosum* 387 gC m^{-2} $yr^{-1.}$ These conservative values 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 as kelp (~20%, Pessarrodona *et al.*, 2018) this would mean that fucoids contribute, on average, approximately 452 gC m^{-2} $yr^{-1.}$

Given that *H. elongata* and *H. 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.

Table 2**. Intertidal macroalgae: Summary values for organic carbon fixation and export from kelp beds in the English North Sea project region. The upper part of the table gives estimates for carbon stock and sequestration capacity for intertidal macroalgae. The lower part of the table shows specific rates of production based on growth and experimental measurements of detritus production. Stock carbon density estimates in the middle of the table represent those for dense stands of each species. These values are overestimates for the entire rocky foreshore and have been adjusted by assumed percentage cover values (Note [1]) and recalculated from coast-wide measurements of wet weight of macroalgae from data collected in Scotland (Note [2]). Values used in synthesis studies are shown in* ***bold.

				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	22.6	22.6	2.8	85	160	122	125	727	378	8.5	0.9	This report
	22.6	22.6	5.0			223 [1]						Walker 1953; Burrows et al 2014
Intertidal rock	12.2	12.2										Habitat Extent Totals

	Stock (g C/m²)			Production rate (g C/m²/yr)			
Species: whole plants	min	max	avg	min	max	avg	
Fucus vesiculosus	358	634	536	166	946	430	Lewis 2020
Fucus serratus	241	1213	659	222	958	611	Lewis 2020
Ascophyllum nodosum	696	1649	1033	20	70	49	Lewis 2020
Ascophyllum nodosum				90	935		Brinkhuis 1977
Fucus spiralis						183	Habitat Review
Himanthalia elongata						989	Habitat Review
Halidrys siliquosa						5	Habitat Review
Average	432	1165	**743**	125	727	**378**	
Species: detritus				min	max	avg	
Fucus vesiculosus - all						377	Lewis 2020
Fucus serratus						368	Lewis 2020
Ascophyllum nodosum						387	Lewis 2020
Stock estimates based on biomass measurement							Burrows, unpublished data

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

2.1.2 Kelp

Kelp forests can be found from Flamborough Head, Yorkshire up to the Scottish Border. The dominant kelp along the English North Sea coast is *Laminaria hyperborea* which forms extensive reefs in the shallow subtidal. *Laminaria digitata* dominates intertidally and while this species is likely to make less of a contribution to coastal carbon cycling than *L. hyperborea* its contribution is still likely important (King *et al.*, 2020). Other species of kelp that occur in this region are *Saccharina latissima*, which is limited to more wave sheltered areas, *Alaria esculenta*, which is limited to more wave exposed areas and the warm-tolerant kelp *Saccorihiza polychides*, which is only found on the Farne Islands within the English North Sea Region. These species are unlikely to make a significant contribution to kelp carbon cycling, but where estimates exist they have been provided. This review will therefore focus on *L. hyperborea* and *L. digitata*.

Kelps are highly productive with estimated primary productivity for *Laminaria* spp. ranging between 110 and 1780 gC m^{-2} yr^{-1} (Mann, 2000). More recent studies focusing on *L. hyperborea* in the United Kingdom estimated the net primary productivity (measured by lamina extension) ranged from 166 – 738 gC m^{-2} yr^{-1} (mean 340 ± 48 gC m^{-2} yr^{-1} SE) with rates 1.5 times higher in the cooler northern regions (north and west Scotland) compared to warmer southern regions (southwest Wales and England, Smale *et al.*, 2020). Across the same sites kelp standing stock (a product of plant density and size) was estimated to range between 208^{-1} 709 gC m^{-2} (mean 640 ± 94 gC m^{-2} SE) with values 2.5 times higher in the cooler northern sites than the warmer southern sites. Interestingly, these differences were primarily driven by the greater size/biomass of kelp individuals in the north rather than differences in kelp density (Pessarrodona *et al.*, 2018). Primary productivity and standing stock were negatively correlated with temperature and positively correlated with light levels (Smale *et al.*, 2020). Across the same geographic area, *L. digitata* primary production was estimated between 135 – 402 gC m^{-2} yr^{-1} (mean 262 gC m^{-2} yr^{-1}) with higher values again found in the cooler northern regions (King *et al.*, 2020). Standing stock was greater in the cooler northern sites (north: 278 gC m^{-2}; south: 79 gC m^{-2}) during the peak growth season, but there was no difference in *L. digitata* standing stock during the reduced growth period (north: 166 gC m^{-2}; south: 113 gC m^{-2}) (King et al., 2020). The study-wide average for *L. digitata* standing stock of 159 gC m^{-2} is significantly lower than that observed for *L. digitata* in the eastern English Channel (403 gC m^{-2} yr^{-1}) (Gevaert *et al.*, 2008).

A review of the fate of kelp production estimated that ~80% is exported as detritus or dissolved organic matter, with little consumed in-situ. Kelp detritus is produced via the erosion of the lamina (an almost continuous process) as well as whole plant loss via dislodgement. *L. hyperborea* also produces a seasonal pulse of detritus via loss of its old growth collar in what is termed as 'May' cast on account of the time of year that it occurs (Pessarrodona et al., 2018). In the UK, it has been estimated that *L. hyperborea* contributes 104 - 568 gC m^{-2} yr^{-1} (mean 301 gC m^{-2} yr^{-1}) of particulate organic carbon via these three combined detrital pathways, with the highest rates of detrital production in cooler norther waters (Smale *et al.*, In review). It is estimated that ~50% of detrital biomass production in the UK is via whole plant dislodgement with May cast and chronic erosion accounting for approximately 30% and 20%, respectively (Pessarrodona et al., 2018). Again for the UK it has been estimated that >94% of the kelp detritus produced is either exported or rapidly turned over, although with regards to the later point kelp detritus has been shown to persist for >16 weeks in UK waters (Smale *et al.*, In review) with evidence to suggest that detrital breakdown is faster in warmer waters (Filbee-Dexter *et al.*, In review).

While the northern portion of the English North Sea supports extensive kelp forests, such forests have received little attention compared to the rest of the United Kingdom. There are therefore no direct measures of kelp carbon production and loss for this region. Based on the cool, clear waters in part of this region it is likely that kelp forests have rates of primary productivity, standing stock and detrital production similar to rates in north and west Scotland.

2.1.3 Fate of macroalgal detritus

Exported macroalgal detritus plays an important role in coastal food webs where it can be consumed by suspension feeders, detrital grazers and general consumers of organic matter. While only a very limited amount of macroalgal derived carbon is likely to remain in-situ, macroalgal detritus has the potential to be transported and stored in receiving habitats such as seagrass meadows, saltmarshes, deep (400m) coastal areas (Filbee-Dexter *et al.*, 2018), continental shelf and slope (1800m depth) and deep sea sediments (up to 4000m depth and 4800 km from the nearest coastline) (Krause-Jensen & Duarte, 2016, Ortega *et al.*, 2019) where the material has the potential to be sequestered (Filbee-Dexter *et al.*, 2018, Smale *et al.*, 2018). Indeed, a study off Plymouth Sound, south-west England estimated macroalgal derived sequestration rate of 8.77 ± 9.85 gC m^{-2} yr^{-1} into coastal sediments (Queirós *et al.*, 2019). While it is highly likely that a proportion of the macroalgal detritus produced does end up sequestered, there are still high levels of uncertainty regarding the fate and turnover of this material. From a UK perspective the role that kelp plays as a long-term carbon donor is likely to be a function of the shelf conditions adjacent to kelp forests, sea-bed characteristics, current and wave driven hydrodynamics and the biochemical composition of different macroalgal species and tissues.

Globally kelps and fucoids are threatened by a range of anthropogenic stressors operating at local to global scales. It has been estimated that 38% of ecoregions globally have experienced loss of kelp, however, there is large scale regional variability (Krumhansl *et al.*, 2016). Within Europe, reductions in macroalgal abundance have been attributed to the direct effects of ocean warming (Fernández, 2016), marine heatwaves (Filbee-Dexter *et al.*, 2018) as well as interactions between ocean warming and eutrophication (Moy & Christie, 2012) and ocean warming and harvesting (Raybaud *et al.*, 2013). Within the UK there has been fluctuations in the abundance of kelp and fucoids (Yesson *et al.*, 2015), but evidence for broad-scale losses are limited and are restricted to the west Sussex coastline. Localised losses of macroalgae have been reported in the English North Sea as a result of historic industrial activity (e.g. depositing mine waste on the Northumberland and North Durham coastline) with Hyslop *et al.* (1997) determining that macroalgal species richness and biomass was reduced on the most impacted beaches. Ongoing research is monitoring these kelp populations and also testing restoration techniques along this coastline. Into the longer-term, modelling suggests that kelp and fucoid populations in the English North Sea are likely to remain stable (Assis *et al.*, 2017, Jüterbock, 2013), although species such as *S. polychides* may increase its range in southern parts of the study area (Assis *et al.*, 2017). While kelp populations may remain more stable the strong link between temperature and carbon production and loss it likely to see primary productivity and detrital production reduce, perhaps following patterns observed in southwest England and Wales.

Estimates of coastal temperate phytoplankton primary productivity range between 100 and 300 gC m^{-2} yr^{-1} (Mann, 2000). Total primary production from micro- and macroalgae in UK coastal waters may therefore be similar: 8000km^2 of kelp habitat could produce 10 MtC/yr at 1300 gC/m^2/yr, while phytoplankton at 100 gC/m^2/yr may produce 13MtC/yr from 133000 km^2 of sea <20km from the coast within the UK EEZ, and 73MtC/yr from the 770000 km^2 in the whole UK EEZ. Kelp may therefore account for 45% of primary production in UK coastal waters, and 12% of the entire UK EEZ marine production.

Table 3. *Kelp beds: Summary values for organic carbon fixation and export from kelp beds in the English North Sea project region. The upper part of the table gives estimates for carbon stock and sequestration capacity in kelp beds, based on habitat extent and process rates given in the lower part of the table. Values used in synthesis studies are shown in* ***bold.***

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
North Sea Net Gain area	113947	379	225.4			594			**332**	**126.1**	12.6	Habitat Review average rate * [model area > 0.5kg/m2 w/w]; Queiros et al 2019
Kelp beds		**379**	**58.4**			**154**			685	126.1		From *L. hyperborea* habitat model: average stock density x extent
									685	259.9		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. digitata				79	278	179	135	402	262	0.1		King et al 2020
L. digitata						403						Gevaert et al. 2008
Detritus production												
L. hyperborea							104	568	301			Smale et al in review

2.2 Saltmarshes

Saltmarsh habitats are dynamic environments that naturally accrete or erode and form on intertidal mudflats and sand. The rate of marsh development is dependent on the rate of sediment supply (from both marine and terrestrial sources), how sheltered the marsh is and the topography of the marsh (Adam, 1993). As a result of the dynamic nature of saltmarsh habitats there can be high rates of carbon turnover, especially at lower shore heights that are often in the earlier stages of succession and have less vegetative cover. At higher shore elevations, which can be dominated by floristically diverse assemblages, soil carbon contents can be higher and turnover rates are slower. Saltmarsh habitats are considered net carbon sinks.

Saltmarsh habitats occupy quite large areas to the south of the English North Sea region but occupy smaller areas to the north of the region. The largest saltmarshes are situated within the estuaries of Norfolk, Lincolnshire and southern Yorkshire and include large marsh systems in the Wash and the Humber Estuary (May & Hansom, 2003). Smaller areas of saltmarsh can be found along the Durham and Northumberland coastline. Saltmarshes on the east coast of the UK are generally characterised by a deep organic-rich clay substratum with limited grazing activity (Beaumont *et al.*, 2014). Approximately 15% of UK saltmarsh habitats have been lost since 1945 (Cooper *et al.*, 2001), with much of this loss occurring in estuaries and inlets. The drivers of decline are largely due to marsh drainage for agricultural and industrial development as well as marsh loss through the loss of tidal inundation due to the placement of hard coastal defence (Blackwell *et al.*, 2004, Morris *et al.*, 2004). While evidence suggests that saltmarsh habitat extent is still decreasing at the UK scale, comparing data collected by the Environment Agency between 2005-2008 with data collected by The Nature Conservancy Council (1989) suggests that saltmarsh habitat extent has increased by 10.3% and 34.5% in the Anglian and Northeast region (Environment Agency 2011). While it would appear saltmarsh extent in the region is recovering there are also active efforts to restore saltmarsh habitat in the region.

It has been established that saltmarsh restoration provides a sustained sink for atmospheric CO_2 (Burden *et al.*, 2013). However, it has been suggested that while managed realignment does provide some carbon benefit, there are varying levels of success with regard to biodiversity (Mieszkowska *et al.*, 2013) and restoration may not provide the same ecosystem services as a natural saltmarsh system. The saltmarsh along the Northumberland coast, specifically at sites in Alnmouth and Warkworth, are partly restored saltmarsh habitat to increase the extent of the remaining habitat here. The 'Northumberland 4shores' restoration project took place between 2006-2009 to successfully restore areas of saltmarsh that was lost in the 1970s.

Based on 36 samples collected from nine saltmarshes in Essex, above ground vegetative biomass was estimated 470 ± 390 g m^{-2} which equates to 282 ± 234 gC m^{-2} (Beaumont *et al.*, 2014). Based on data from the same sites estimated soil bulk density was 0.448 ± 0.03 g cm-3 of which carbon soil density was 0.0244 ± 0.0004 and 0.0116 g cm^{-3} (based on soil carbon content of 5.45 and 2.6%) for soils 0-30 cm and 30-100 cm depth, respectively (Beaumont *et al.*, 2014). In the region soil carbon ranged between 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 at between 62^{-1} 96 gC m^{-2} yr^{-1} with rates differing between high and low marsh, but not in a consistent manner (Callaway *et al.*, 1996). While 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 C content of 5.45% estimated for east coast sediments between 0-30cm (Beaumont *et al.*, 2014). These values are within those estimated by others for the UK (66 – 196 g C m-2 yr-1, Adams *et al.*, 2012, Burrows *et al.*, 2014, Cannell *et al.*, 1999, Chmura *et al.*, 2003) and with global estimates (151 g C m-2 yr-1, Duarte *et al.*, 2005).

A study by Ford *et al.* (2019) investigated the vegetation and soil characteristics as a predictor of soil organic carbon stocks in Welsh Saltmarshes. They found that 44% of the variation in surface soil carbon could be attributed to vegetation community and soil type. Higher carbon stocks were attributed to *Juncus gerardii* and *J. maritimus* plant communities (40–60 tC.ha^{-1}) whilst lower carbon stocks were attributed to *Atriplex* and *Puccinellia* communities (20–50 tC.ha^{-1}). Sandy soils were also found to store less carbon (29 tC ha^{-1}) than non-sandy soils (43 tC ha^{-1} , to 10 cm depth).

As mentioned above there is a differential in carbon sequestration between natural and restored saltmarsh habitat where the average carbon stock of natural ecosystems is higher (range 12.7-69 kgC m^{-2}; n=85; average 40.3 kgC m^{-2}) than that of restored saltmarshes ($10.1^{-2}5$ kgC m^{-2}; n=12; average 18.6 kgC m^{-2}), It is however, suggested that the time elapsed since restoration plays a part in the stock 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 contribute to the stock capacity of the saltmarsh (Gregg *et al.*, 2021).

For protected areas we will be able to use NVC data collected as part of condition monitoring as well as details on soil characteristics to provide more accurate estimates of saltmarsh community structure, productivity and ultimately sequestration potential based on Ford et al. (2019). The saltmarshes of the Northumberland coast support vegetation communities including *Juncus gerardii*, *Atriplex prostrata*, *Atriplex littoralis* and *Puccinella maritima* and are established on non-sandy soils. The saltmarshes found in this area are classified as lower and middle saltmarsh communities (SM4–15, and SM27) via the NVC, including pioneer marshes (Boorman, 2003).

Table 4. *Saltmarshes: Summary values for organic carbon stock and storage rates in the English North Sea project region. Saltmarsh extent estimates vary among different data sources and assumptions as to the landward boundary of the region (mean high water or saltmarshes habitats adjoining the coast <2km away). The lower part of the table gives C-stock density estimates for natural and restored saltmarshes. Values used in synthesis studies are shown in* ***bold.***

Habitat	Extent (km²)	Component area (km²)	Stock (OC 1000 t)	Stock density (g C/m²)			Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr)			Storage capacity (1000t C/yr)	Source
				min	max	avg	min	max	avg				min	max	avg		
Saltmarshes: vegetation		171.1	747.4	48	516	282							62	196	129.0	96.4	CEH Land Cover Map; Habitat Review (Calloway et al 1996)
Saltmarshes: soil		121.7	531.5	1270	6900	4085										68.6	EA Saltmarsh Extent dataset; Gregg et al 2021
Saltmarshes: soil		**132.7**	**579.5**	1270	6900	**4085**										74.8	Natural England Open Data
Saltmarshes: vegetation		132.7					42	235	**138**	**18.3**	**1.8**	**72.9**					Kirwan et al 2009, assuming d/w 25% C
Stock estimates				Stock (kg C/m3)													
Natural saltmarsh				12.7	69	40.9											Gregg et al 2021
Regenerated saltmarsh				10.1	25	17.6											Gregg et al 2021

2.3 Seagrass beds

Seagrass meadows can play an important role in carbon sequestration with many acting as net sinks of carbon (Duarte & Cebrián, 1996, Duarte *et al.*, 2010). Habitat extent of seagrasses in the English North Sea is limited and they are not likely to make substantial contributions to net carbon storage in this region. Notwithstanding this we will use the literature to estimate standing stock, carbon production and loss and sequestration potential. The contribution of seagrasses to global oceanic carbon storage has been quantified in several recent studies but these studies have focussed on a few species and sites (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 issues associated with this global estimation however, due to the high belowground accumulation of carbon in particular species, such as *Posidonia oceanica*, and differences in environmental conditions (Röhr *et al.*, 2018). Global seagrass sediment carbon storage is estimated to average 83,000 Mg km^{-2}, equivalent to a total global blue carbon storage of 19.9 × 109 Mg (Fourqurean *et al.*, 2012, Macreadie *et al.*, 2013).

The high carbon accumulation of seagrass meadows is due to their capacity to reduce water flow and wave energy resulting in trapped sediment particles and a reduction in sediment resuspension (Agawin & Duarte, 2002, Bos *et al.*, 2007, Fonseca & Cahalan, 1992, Gacia & Duarte, 2001, Gacia *et al.*, 2002, Hendriks *et al.*, 2008, Kennedy *et al.*, 2010, Kristensen & Holmer, 2001, Pedersen *et al.*, 2011, Vichkovitten & Holmer, 2004). In addition, below surface sediments associated with seagrass meadows are often hypoxic enabling the slow decomposition of organic material (Enríquez *et al.*, 1993, Fourqurean & Schrlau, 2003, Holmer *et al.*, 2009, Kennedy *et al.*, 2010, Kristensen & Holmer, 2001, Pedersen *et al.*, 2011, Vichkovitten & Holmer, 2004).

The environmental conditions of a region can have significant effects on carbon storage capacity of seagrass meadows and whilst global estimations serve to highlight the importance of seagrass meadows as a blue carbon habitat (Röhr *et al.*, 2018), a regional approach provides more meaningful estimate for natural capita management approaches taken at a local level.

Seagrass meadows in the UK are classified as nationally scarce and sparsely distributed (Hiscock et al., 2005; Jones and Unsworth, 2016). *Zostera marina* and *Z noltii* are the most abundant seagrass species found in the UK with *Z. marina* the dominant species occurring predominately in the sublittoral, whilst *Z. noltii* occurs intertidally (Wilkinson and Wood, 2003). Seagrass meadows are estimated to cover 8,493 ha in the UK (84 km^2) but this coverage is not uniform with only 720 ha thought to be located along the English North Sea region: Northumbria – 680 ha; Norfolk – 42 ha) (Green *et al.*, 2018, Green *et al.*, 2021) estimated sedimentary stocks (up to 30 cm) ranging from 29.4 tC ha^{-1} to 114.02 tC ha^{-1} in the western English Channel where as in comparison Lima et al. (2020) found 33.8 ± 18.5 MgC ha−1 in the top 30 cm of sediment. Green *et al.* (2018) extrapolated carbon stocks to 100 cm depth, resulting in an average of 66,337 tC and an estimated UK wide stock of between 108,427 tC and 221,870 tC, substantially higher than previous estimates by Garrard and Beaumont (2014) of between 8050 tC and 16,100 tC for European sedimentary seagrass stocks (Gregg *et al.*, 2021). The work by Lima *et al.* (2020) provides an estimate of the contribution to the carbon stock in the living biomass of seagrass meadows between 0.07 tC ha^{-1} and 0.5 tC ha^{-1} for six locations within the Solent, in addition to the underlying sedimentary values (Gregg *et al.*, 2021).

Carbon stocks stored in the upper 50 cm of sediment under *Z. marina* and *Z. noltii* have been measured between 22.7 tC ha^{-1} and 107.9 tC ha^{-1} with a mean of 57 tC ha^{-1} across seven sites in Scotland (Potouroglou, 2017). Based on these figures the total estimated carbon stock in seagrass sediment is 91,200 tC across the whole of Scotland. The global average sedimentary carbon stock for seagrass ecosystems is 194.2 tC ha^{-1} , compared to 2.52 tC ha^{-1} stored in living biomass, two-thirds of which is found within the roots and rhizomes of the plant (Fourqurean *et al.*, 2012, Garrard & Beaumont, 2014).

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

Given that environmental conditions can heavily influence the carbon stocks of seagrass meadows and that no data currently exists for the English North Sea region we propose taking a conservative approach to our estimation of seagrass carbon stocks for the English North Sea using medium stock estimations based on the data from other areas in the UK.

Table 5. *Seagrasses: Summary values for organic carbon stock and storage rates in the English North Sea project region. Seagrass extent estimates are widely different, largely depending on whether modelled estimates (likely overestimates) or observations (likely underestimate) are used. Values used in synthesis studies are shown in* ***bold.***

Habitat	Extent (km²)	Component area (km²)	Standing stock (1000 t)	Stock (g C/m²) (<0.3m depth)			(<0.1m)	Production rate (g C/m²/yr)			Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Storage rate (g C/m²/yr)			Storage capacity (1000t C/yr)	Source
				min	max	avg	avg	min	max	avg				min	max	avg		
North Sea NG	113947	87.6	209.3	2940	11402	7171	2390										8.79	JNCC Model under NDA: P(saltmarsh)>0.5
Seagrass		**49.3**	**117.9**	2940	11402	7171	**2390**										**4.95**	Natural England Blue Carbon Data
		7.2	17.2	2940	11402	7171	2390							10.5	48.3	**100.4**	0.72	Habitat Review
										274	**13.5**	**1.4**						from increase in dry mass of *Zostera marina*; Godshalk & Wetzel 1978; Sand-Jensen 1974
		49.3																

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

2.4 Biogenic reefs (inc. tubeworms and horse mussels)

Reefs occur widely around the UK coast and are found in both inshore and offshore waters. There is a far greater range and extent of rocky reefs than biogenic concretions. Only a few invertebrate species can develop biogenic reefs, and these have a restricted distribution and extent in the UK. The definition of biogenic reefs used in this review will follow that of Holt *et al.* (1998) as summarised in Burrows *et al.* (2014) to provide a consistent approach to the estimates of the carbon sequestration potential of biogenic reefs. In the English North Sea area, the following taxa were identified as potentially important in the formation of biogenic reefs:

- *Sabellaria* spp
- *Modiolus modiolus*
- *Mytilus edulis*
- *Serpula vermicularis*

Biogenic reefs are primarily believed to contribute via the build-up of sedimentary carbon (Lovelock & Duarte, 2019). Common throughout the English North Sea they are found in both intertidal and subtidal areas. Dense aggregations of *Sabellaria spinulosa* have been reported in Northumberland and North Yorkshire (Connor *et al.*, 1997) and the southern North Sea (Dörjes, 1992). *Modiolus modiolus* has been reported throughout the region, with some evidence of bed formation off the shores of Northumberland, Teeside and Yorkshire. Dense aggregations have been noted around offshore structures. Individuals are regularly reported South of the Humber, but reef forms are believed unlikely (Tyler-Walters, 2007). *Mytilus edulis* has a widespread distribution throughout the English North Sea occurring from the intertidal to the shallow subtidal. Mussel bed reefs occur naturally along shorelines where suitable substrata for attachment are found (Coolen *et al.*, 2020). While *Serpula vermicularis* is present, there is little evidence from the literature to support formation of reefs in the English North Sea. Sixteen records collected between 1986 and 2014 describe scarce samples or record individuals in very low numbers (NBN Atlas, 2021).

Modelling these habitats is uncertain and data relatively scarce, a recent review undertaken by Natural England stated that no values measured in the English context could be found (Gregg *et al.*, 2021). Attempts have been made to predict distributions and extents in Scotland (Gormley *et al.*, 2013) and, more recently, English restoration potential intertidally (MMO, 2019), although this focussed on *Ostrea edulis* and *Sabellaria alveolata*, species not currently present in ‘reef’ form in the study area.

Despite the paucity of data, most agencies acknowledge that biogenic reefs have important structural and functional characteristics; they form ‘Habitat Features of Conservation Importance’ in both Marine Conservation Zones and Special Areas of Conservation. Biogenic reefs provide coastal protection and contribute to the build-up of sediments (Lovelock & Duarte, 2019). The biogenic reef building organisms summarised in this review are all suspension-feeders on phytoplankton, zooplankton or suspended detritus. The collective suspension-feeding activity constitutes a potentially important pathway for the accelerated flux of organic carbon from the water column to the sea floor (Burrows *et al.*, 2014, Hily, 1991). Shell growth, the accumulation of dead skeletal material and its subsequent breakdown (carbonate taphonomy) are thereafter the primary processes determining the sequestration capacity of these biogenic habitats, although recent research has suggested that calcification during shell development releases CO_2 resulting in a potential source of CO_2 (Gregg *et al.*, 2021, Lovelock & Duarte, 2019). This debate should be acknowledged, but the focus of this review will be on the potential of calcareous skeletal material to act as a carbon store.

2.4.1 Sabellaria sp. Reefs

Sabellaria spinulosa biogenic habitats allow many other associated species to become established and act to stabilize cobble, pebble and gravel. Fauna can be more than twice as diverse, with almost three times the abundance of proximate areas (NRA, 1994). The reefs are of particular significance for nature conservation when they occur on sediment or mixed substrata areas as they enable a range of other species to occur that would not otherwise be found in such areas. In the English North Sea, they are best known to form in the sedimentary areas to the South, for example extensive reefs are located at Haisborough Tail, Haisborough Gat and between Winterton Ridge and Hewett Ridge. Reefs rise to heights of between 5cm to 10cm from the surrounding coarse sandy seabed, tube structures covering 30^{-1} 00% of the sediment. Some parts of the reefs appear to be acting as sediment traps, with exposed tube height accordingly reduced within the core parts of reefs.

Abundant *Sabellaria spinulosa* agglomerations have also consistently been recorded within the boundary of the Inner Dowsing, Race Bank and North Ridge SAC (Foster-Smith & Hendrick, 2003). Survey data indicate that reef structures are concentrated in certain areas of the site, with a patchy distribution of crust-forming aggregations across the site. The main areas of S. spinulosa reef are found along the Lincolnshire coast south of Skegness at Lynn Knock and Skegness Middle Ground (south-east part of the site); just north of Docking Shoal bank; and associated with the southern edge of Silver Pit (in the northern area of the site) (Foster-Smith & Sotheran, 2003, Limpenny *et al.*, 2010, Woo, 2008); Brutto, 2009).

Saturn Reef, in the North Norfolk Sandbanks, was first discovered in 2002, consists of thousands of fragile sand-tubes. This structure qualifies as Annex I Reef according to European Commission interpretation (CEC, 2007). In 2003, the Saturn reef covered an area approximately 750m by 500m just to the south of Swarte Bank, varying in density over this area (Cordah, 2003). Nearby the Wash and North Norfolk Coast East Anglia, Lincolnshire SAC hosts diverse *Sabellaria* structures, including reefs which stand up to 30 cm proud of the seabed and which extend for hundreds of metres (Foster-Smith & Sotheran, 2003). The reefs are thought to extend into The Wash where super-abundant *S. spinulosa* occurs and where reef-like structures such as concretions and crusts have been recorded. The site is the only currently known location of well-developed stable Sabellaria reef in the UK; diverse and productive habitats support many associated species (including epibenthos and crevice fauna) that would not otherwise be found in predominantly sedimentary areas. As such, the fauna is quite distinct from other biotopes found in the site. Associated motile species include large numbers of polychaetes, mysid shrimps, the pink shrimp *Pandalus montagui*, and crabs (see overview (Holt et al., 1998)).

In their 2014 review, Burrows et al conclude that the tubes constructed by the reef-building polychaetes *Sabellaria alveolata* and *S. spinulosa* consolidate sediments (Naylor & Viles, 2000), rather than accreting calcium carbonate like *Serpula vermicularis*. They conclude that *Sabellaria* reefs rearrange sand and shell and should be considered to have the same blue carbon potential as the surrounding sediments. As no contradictory studies could be found in the literature, these reefs will not be considered further here, but future work to investigate the contribution of associated communities is highly recommended.

2.4.2 Horse mussel (*Modiolus modiolus*)

The accumulated relict shells of the large bivalve *Modiolus modiolus* may provide important repositories of biogenic carbonate. The horse mussel *Modiolus modiolus* is widely distributed in the shallow subtidal areas of the English North Sea, and reports describe offshore beds, but details are absent. Many records of isolated individuals or sparse, low-density populations exist, but beds dense enough to be regarded as biogenic reefs are formed in some localities. The NBN database records 33 high-density samples (SACFOR Abundant or Superabundant, or n>50) at 22 sites from the Farnes to the Thames (NBN database, 2021). The most frequently reported beds seem to exist on rough ground off the Humber, Flamborough, Tees and the Farne Islands. Some may exist off north Norfolk, as *M. modiolus* was collected here for comparison of trace metals with those from more polluted locations (Richardson *et al.*, 2001). However, over large parts of the geographic range of this habitat there is at present too little evidence to determine Modiolus abundance or extents in the North Sea. Without such information it is not possible to provide estimates of the area covered by the *M. modiolus* bed habitat or the proportion it makes up of the English North Sea. Data derived from Scottish examples are included below for comparison.

Noss Head is considered the largest bed in Scotland. Density of living *M. modiolus* was recorded as patchy but the SACFOR category of Superabundant (10-90 individuals m^{-2}) was recorded at several stations (Hirst et al., 2012). In the English North Sea, superabundance has been recorded at St Luke (4950,BW006) offshore, River Don (Tyne Estuary, Phillips Petroleum. (Tees Estuary), by the wreck of Ocean Prince (UK6899, at Robin Hood's Bay N. Yorks, at Flamborough Headland (Nab Cap, North Cliff and Selwicks Bay), Danes Dyke, Dimlington Drift, Titchwell and Brancaster Beach; Norfolk, and in wreck and offshore locations down to Essex (NBN Database 2021).

Burrows *et al.* (2017) used a mean thickness of 75 cm of *M. modiolus* beds to calculate blue carbon contributions These calculations were based on field sampling which provide a more robust estimate of the underlying carbonate stores due to accurate measurements of the depth of a given reef (Porter et al., 2020). These estimates reported 2219 gCaCO3 m^{-2} and a 12% inorganic carbon percentage of CaCO3, with a final area-specific stock estimate of 4000 g IC m^{-2} (Burrows *et al.*, 2014). Porter *et al.* (2020) reported a mean value of 13.78 ± 6.6 S.D. gC (as organic matter) per individual by performing LOI burn ups. They reported that no empirical data were available on the relative contributions of Carbon, Phosphorus and Nitrogen in the tissue and therefore based their calculations on data available for *Mytilus edulis* (Oliver et al 2018) adjusting the value by 45.98% to account for the N and P components. While these estimates may prove useful, without extent data it remains impossible to estimate carbon stocks at English sites. Remarkably little data exist.

For the sake of comparison, the density of living horse mussels in the Noss Head bed varied from Frequent (1-9 10 m^{-2}) to Superabundant (10-90 m^{-2}) (Hirst *et al.*, 2012), which may be comparable with several of the English sites listed above. However, for Noss Head these are augmented by qualitative descriptions, where like Pen Llŷn in North Wales, “characteristic undulating bedforms of ridges and troughs” are described (Hirst *et al.*, 2012, Lindenbaum *et al.*, 2008). No such data were found for England.

Burrows et al 2014 summarise relevant Scottish and Welsh data as follows. No more recent relevant publications were found. Collins (1986) studied a horse mussel bed at ~160^{-1} 90 m depth in the Firth of Lorn (between Mull and Kerrera). *Modiolus modiolus* density was estimated as 125 ind. m^{-2}, indicating a dense population. Grab samples gave a standing stock ("calcimass") attributable to *M. modiolus* of 2219 gCaCO3 m^{-2}.(equivalent to IC) The grabs penetrated to a depth of 5-7 cm, so that this figure represents standing stock in the near-surface layer of the seabed. Applying Collins' (1986) figure to Noss Head (area 385 x 104 m^2) gives an estimated standing stock of ~8543 $tCaCO_3$ in the ~5 cm of superficial sediments, representing ~1025 t stored carbon. If Noss Head supports shelly deposits of similar depth to those at Pen Llŷn (assuming mean depth 75 cm), the carbonate standing stock estimate would increase to ~128,145 t, representing ~15377 t stored carbon. These are likely maximum values, as horse mussel density is not uniform across the extent of the bed, and relict shells will lose mass as a result of chemical dissolution and bioerosion (Akpan & Farrow, 1985); Powell et al., 2006). Nevertheless, Collins' (1986) data provide an insight into the potential standing stock of stored carbon in the Noss Head horse mussel bed.

Net carbon sequestration capacity

In the Firth of Lorn, *Modiolus modiolus* accounted for ~94% of carbonate standing stock in the mussel bed community, but only ~38% of the estimated carbonate production (Collins, 1986). Brachiopods, brittlestars and smaller bivalve species accounted for the remaining community production. The very low production/biomass (P/B) ratio of *M. modiolus* (0.05) was attributed to a long lifespan (~40 years) and slow growth rate. Studies in other localities support a lifespan of at least 20-35 years for *M. modiolus* (Anwar *et al.*, 1990, Comely, 1978, Seed & Brown, 1978)). Size-frequency distributions in three Scottish west coast populations studied by Mair *et al.* (2000) showed no evidence for recruitment in the preceding 5-10 years. Comely (1978) reported very low recruitment rates in two horse mussel beds at low-energy sites, but a higher frequency of juveniles in more energetic conditions. Overall, *M. modiolus* appears to be a long-lived, relatively slow-growing bivalve with very sporadic recruitment, and in consequence has a low area-specific carbonate production rate, estimated as 330 gCaCO3 m^{-2} yr^{-1} in the Firth of Lorn (Collins, 1986), equivalent to ~40 gC m^{-2} yr^{-1}.

As with other skeletal carbonates, the temporal persistence of horse mussel shells after death will be determined by rates of chemical dissolution, bioerosion and physical abrasion (which may be a factor in high-energy environments) (Smith & Nelson, 2003, Zuschin *et al.*, 2003). Mollusc shells from shallow waters of the Scottish west coast are attacked by a variety of bio-eroding organisms, but degradation rates are lower below the euphotic zone where important bioeroders such as endolithic algae and the limpet Acmaea are absent (Akpan & Farrow, 1985). Most carbonate degradation is believed to take place at the sediment-water interface, and long-term preservation (i.e. with the potential to enter the geological record) requires burial below this "Taphonomically Active Zone" (TAZ), typically by a sediment slide or other large-scale physical event (Davies *et al.*, 1989, Walker & Goldstein, 1999). Even at the sediment-water interface, bioerosion on temperate shelves may require a timescale of centuries to several millennia for total shell destruction (Smith & Nelson, 2003), especially for large, robust shells such as those of *Modiolus modiolus*. Smith (1993) predicted a lifespan of 500-2000 years for bivalve shells on the New Zealand shelf. Thick deposits of horse mussel shells, such as occur at Pen Llŷn (and possibly at Noss Head) may therefore not persist for long enough to enter the geological record but will have the potential to store carbon over a timescale of ~1000 years.

2.4.3 Blue mussel (*Mytilus edulis*)

The blue mussel (*Mytilus edulis*) is one of the most common and widespread shallow-water invertebrates of Scottish coastal waters. Its habitat range extends from the high intertidal to the shallow subtidal zone, and from exposed rocky shores to sheltered bays, estuaries and sea lochs. *Mytilus edulis* is one of the most intensively studied marine animals, with a huge primary literature (reviewed by Bayne, 1976, Gosling, 2008), but literature relevant to its potential contribution to blue carbon storage is rather sparse. The spatial extent, density and temporal persistence of blue mussel beds is highly variable, depending on local environmental conditions, but in some areas beds can attain dimensions justifying their classification as biogenic reefs (Holt *et al.*, 1998). *Mytilus* reefs 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 U K, reefs rarely exceed 30-50 cm in thickness, but subtidal examples up to 120 cm thick have been reported (Holt *et al.*, 1998). Blue mussel beds of varying extent occur widely around the coast and exist in several sites within the inshore MPA network.

Mytilus edulis was not included in the Scotland-wide assessment of blue carbon by Burrows et al. (2014) and a comprehensive review of the extensive literature on mussel growth and productivity is beyond the scope of the present report. In optimal conditions Mytilus edulis can reach a shell length of 60-80 mm within two years, but in the high intertidal zone growth rate is significantly lower, and mussels may take 15-20 years to reach only 20-30mm in length (Seed & Suchanek, 1992). Standing stock 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/reef thickness, mussel population size structure and shell growth rate) it is not possible to assign figures for individual MPAs, and blue mussel beds are therefore treated as a “data deficient” category in this study. Stocks and rates of production and sequestration of carbon were assumed to the same as for *Modiolus* beds in the absence of any appropriate alternative information.

2.4.4 Conclusions

Quantitative and qualitative information on biogenic reefs in the English North Sea are scarce, and future research on the potential role of calcifying organisms in carbon sequestration is needed. Burrows’ et al (2014) summary of Scottish blue carbon by habitat is provided below and reinforces the absence of data. Additional habitats were included there. Important gaps are highlighted.

Table 6. *Production rates, sequestration rates and stock densities for common types of shallow water biogenic reefs around the UK. Abbreviations: OC, organic carbon; IC, inorganic carbon.*

Biogenic reefs	Production rate (gC m^{-2} yr^{-1})		Sequestration rate (gC m^{-2} yr^{-1})		Stock (gC m^{-2} yr^{-1})	
	OC	IC	OC	IC	OC	IC
Modiolus modiolus	0	40	0	40	0	4 000
Mytilus	0	40	0	40	0	15
Sabellaria reefs	0	0	0	0	0	0
Serpula vermicularis reefs	0	420	0	420		781
Brittlestars (shelf seas)	0	82	0	82		0
Subcanopy algae	21	0	0	0	22	0

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

To date, no existing climate mitigation initiatives consider the role of shellfish reefs in carbon burial, neither are there standardised methodologies for assessing how shellfish reefs influence coastal and marine carbon cycling (Fodrie *et al.*, 2017). Dense beds of brittlestars have been assessed elsewhere for their carbon potential (Porter *et al.*, 2020), and large beds are also believed to exist around the rocky reefs and shipwrecks of the English North Sea, but as in Scotland, estimates of extent and abundance are scarce (Burrows et al., 2014). Carbon density estimates of 66.2 gC m^{-2} are also highlighted by Porter *et al.* (2020) for bryozoa, including flustra, as potential contributors in Orkney; similar habitats are known to persist in the Northern English North Sea.

Additionally, in contrast to the common view that biogenic reefs are carbon sinks, a review by Fodrie *et al.* (2017) found that biogenic reefs on intertidal sandflats were net sources of CO_2 (7.1 ± 1.2 tCO_2 ha^{-1} yr^{-1}) resulting from predominantly carbonate deposition. Shallow subtidal reefs and saltmarsh fringing reefs (predominantly composed of oyster reefs present at the edge of a saltmarsh) were small net sinks (-1.0 ± 0.4 tC ha−1 yr^{-1} and -1.3 ± 0.4 tC ha^{-1} yr^{-1} respectively) due to the presence of organic carbon rich sediments. Biogenic reefs may facilitate carbon sequestration in other habitats, thus providing an indirect mitigation potential. For example, biogenic reefs fringing saltmarshes have been shown to facilitate the seaward migration of saltmarshes, increasing their carbon storage capacity. To date, no existing climate mitigation initiatives consider the role of biogenic reefs in carbon burial, neither are there standardised methodologies for assessing how biogenic reefs influence coastal and marine carbon cycling (Fodrie *et al.*, 2017, Gregg *et al.*, 2021). These elements deserve consideration.

Overall, data required to estimate the carbon storage capacity of biogenic reefs in the North Sea and similar benthic communities are extremely scarce. Spatial location and extent are unknown for many species and, where reefs are monitored, they are believed to be largely ephemeral. Dynamics of reefs are poorly understood (e.g. *Sabellaria* in the Wash). Published measurements of carbonate production and degradation rates (required for mass-balance estimates of net carbon sequestration) are also rare or non-existent for several of these systems. Significant work is required to produce reliable estimates for biogenic reefs.

Table 7. *Biogenic reefs: Summary values for organic carbon stock and storage rates in the English North Sea project region. NA denotes no data*

			Organic carbon			Inorganic carbon							
North Sea Net Gain area (km²)	113947												
Habitat	Extent (km²)	Component area (km²)	Standing stock (1000 t)	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Stock (1000t C)	Stock (g C/m²)	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Refractory period	Source
Sabellaria spinulosa reefs		248.6				See sediment review, [1]							Habitat review
Modiolus modiolus		NA						40					Habitat review
Mytilus		NA					266	40					Habitat review
Oyster reefs fringing saltmarshes		NA		0.01									Habitat review
				-0.19	[2]								Habitat review

Note [1]. Sabellaria reefs are assumed to have the same C content and storage as surrounding sediment
Note [2]. Oyster reefs are net source of CO2 from carbonate deposition, 1 tCO2/ha * 0.1 * 0.273 = 1 gC/m2

2.5 Sediment

Marine sediments, and particularly deep-sea sediments, are the primary store of biologically derived carbon (both organic and inorganic) within the marine system (Lee *et al.*, 2019). Across a continental shelf (such as the North West-European shelf) and among regional seas (such as the North Sea), some areas store more organic carbon, while others are richer stores of inorganic materials. The significance of intertidal (Jickells *et al.*, 2000, Legge *et al.*, 2020) and subtidal stocks across the UK shelf has been clearly recognised (Diesing *et al.*, 2017, Legge *et al.*, 2020, Luisetti *et al.*, 2019, Parker *et al.*, 2020, Smeaton *et al.*, 2021, Turrell, 2020, Wilson *et al.*, 2018)).

Carbon may be stored as precipitated carbonates or as particulate organics from both terrestrial and fully marine sources. This is largely controlled by input rates (from terrestrial or marine environments; for more information see (Painter *et al.*, 2018); (Smeaton & Austin, 2019) and receiving sediment environment (sediment type, oxygenation) which controls degradation and sediment accumulation rates (Arndt *et al.*, 2013). These materials accumulate in soft sediments in 'shelf deeps', such as accumulation basins on the continental shelf and in basins of sea lochs (Diesing *et al.*, 2021, Smeaton & Austin, 2019). Sediment accumulation rate in such places tends to be faster (Smeaton *et al.*, 2021). It is unclear what processes maintain the accumulation basins on the shelf, or whether any of the rich supply of fresh organic matter becomes refractory and persists on timescales relevant for climate change mitigation.

2.5.1 Setting of the English North Sea and controls on sublittoral carbon

The English North Sea lies within the Greater North Sea ecoregion (ICES ecoregion overview) and is a temperate coastal shelf sea with a permanently thermally mixed water column in the south and seasonal stratification to the north. There are distinct regions within the North Sea which function differently in relation to seabed carbon processing, mainly driven by changes in hydrography coupled to sediment type.

The Southern North Sea (and Dogger Bank) is shallow, with depth ranging from 20m to 50m, and is characterized by large river inputs and strongly mixed water. Temperature at the seabed ranges from 7°C in winter to 17 °C in summer (Painting *et al.*, 2013), with maximum temperatures occurring in August coincident with the maximum temperature of the Rhine and the Thames (Berx & Hughes, 2009). The sediment type in this region is typically sand with some muddy sand in places (Stephens & Diesing, 2015). Due to the coarse sediment type, strong tidal currents, deeper oxygen penetration and larger temperature range at the bed, biogeochemical cycling of POC in this region is comparatively fast with little carbon being stored in the sediments (Painting et al., 2012; (Diesing *et al.*, 2017, Huettel *et al.*, 2014).

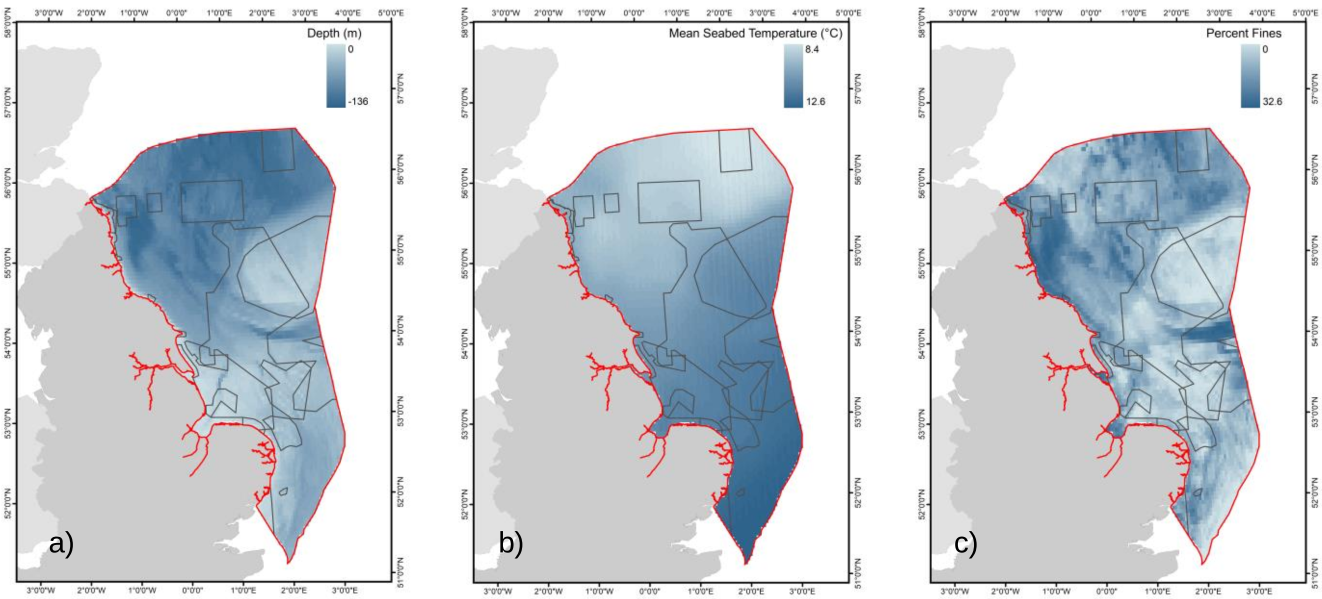

Figure 2. *(a) Depth (GEBCO), (b) seabed temperature and (c) percentage fine sediment (% fines) from Diesing and Stephens (2015), including outlines of the MPA network..*

The English part of the Northern North Sea is deeper, with depths ranging to about 100m, and is more influenced by oceanic inflow from the north. Stratification, which is set up by the onset of warmer spring weather in April/May and typically breaks down with increased wind speeds, storminess and decreasing temperatures in September/October, controls bottom temperatures (which range from only 7 to 8 °C in the central and Northern North Sea; as illustrated in **Figure 2. b**). In deeper areas the seasonal development of stratification controls C turnover rates at the bed and the delivery amount and timing of POC via the spring bloom deposition (in contrast to well mixed shallower areas near the coast or in the Southern Bight). The dominant human activities are fishing and oil and gas production.

Deposition centres in the North Sea mainly occur in the Pits (Inner/Outer Silver Pit, Devils Hole) and North of Dogger bank. The Southern Bight region has a mobile bed due to high tidal currents and this prevents long-term depositional areas. The regular mobility of the bed (often daily; (Aldridge *et al.*, 2015, Wilson *et al.*, 2018) and high natural disturbance from waves and tides prevents sediment or carbon deposition long-term and drives rapid carbon cycling. The transition in the physical regimes from South to North and inshore to offshore sets the natural conditions controlling carbon processing and response to pressures, especially in deeper areas of the northern North Sea (~80m) where physical disturbance only results from infrequent storms or human disturbances.

Transport of carbon through the English North Sea from various sources (terrestrial coastal habitats or marine) to longer-term sinks is also a key consideration to understand carbon stocks, sequestration controls and for governance and local management (Luisetti *et al.*, 2020).

There are significant coastal transport pathways along the East coast of England which can act to collect and transport water and any particulates. In the Southern North Sea, these local circulations can then move offshore across the Southern Bight and join channel water moving towards the Dutch and Belgian coast. (Hill et al., 1971; (Brown *et al.*, 2001, Hill *et al.*, 2008). Similarly, the Northern North Sea has pathways set up from coastal circulation, North Atlantic inflow and movement offshore in seasonal jets set-up across north of Dogger bank and out of UK EEZ (Brown et al., 2003). These rates can be significant. Tiessen *et al.* (2017) calculated the East Anglian Plume net transport to be 13 million kg over a tidal cycle (equivalent to 3.5 km dayr^{-1} from the East Anglian coast, AE1221 Final Report). Such transport pathways can therefore move both terrestrially derived and marine POC long distances (Bristow *et al.*, 2012, Weston *et al.*, 2004). These transport pathways overlay and control the mix of carbon source terms and quality found within North Sea sinks available for storage and sequestration long-term. The central Northern North Sea is area away from terrestrial transport pathways and sources (Brown *et al.*, 2003) and inputs and so stocks and sequestration of carbon are potentially fully marine signals.

Generally in the North Sea, TOC concentration and distribution stock are strongly related to % silt/clay (Diesing *et al.*, 2017) and sediment type (Smeaton *et al.*, 2021). This is also related to controls in oxygen penetration, depth/temperature and remineralisation rates.

The transfer and links between stocks and accumulation rates are poorly constrained due to lack of data but the hydrological and sedimentary conditions will set the stock and sequestration / preservation efficiency (Burdige, 2007) and so some key parameters are sedimentation rates, oxygen exposure times (Arndt *et al.*, 2013, Diesing *et al.*, 2021).

2.5.2 Subtidal Particulate Inorganic Carbon (PIC)

Particulate inorganic carbon is deposited in sediments via authigenic precipitation (within the sediment) of calcium carbonate, and from sedimentation of calcium carbonate rich biogenic material (such as coccolithophores) and may be linked to decomposition of organic carbon (Yu *et al.*, 2018).

Examination of the BGS carbonate data suggest, unlike the sediment OC data, that the $CaCO_3$/IC content of the surficial sediment is not related to the sediment type, but more likely related to presence of shell material (Smeaton *et al.*, 2021). The English North Sea IC densities are consistently low across the area as seen in Smeaton *et al.* (2021).

Burial of inorganic carbon linked to the formation of calcium carbonate can account for up to 80% of carbon removed from the carbon cycle (Sun & Turchyn, 2014) but specific information for the English North Sea was not found.

2.5.3 Intertidal areas

Intertidal mud and sandflats are habitats not usually included in blue carbon literature as they do not represent vegetated systems, but they do contain significant organic carbon stores. Intertidal (littoral) muds have potentially significant stores and accumulation capacity due to having conditions ideal for POC preservation (fine grained, depositional, low oxygen penetration).

It is important to understand that the carbon in intertidal mud and sandflats (and indeed subtidal sediments) is not well identified in terms of its age and origin and can be young or recycled or already have been stored for many thousand years. If the latter, then its presence now may not be indicative of storage in the future. Rivers and run-off from land deliver both very refractory carbon (i.e. carbon that is largely protected from being broken down due to being highly inert or already very degraded), which could be stored for many years, but also labile carbon (fresh carbon or carbon which is easily broken down). The labile carbon is likely to be dominant, having a short sediment lifetime measured in months rather than years. Bioturbation and erosion all cause net carbon release. Carbon in intertidal areas and sediments is different to that in saltmarshes where the main burial mechanism is trapping of OM by root systems and little is recycled after the first phase of oxidation near the surface. Mudflats are typically found adjacent to saltmarshes, and therefore can be coupled in their carbon storage ability, for example, carbon flowing out of a saltmarsh may be transported to mudflats.

Carbon concentrations in mud- and sandflats, are predominantly determined by sediment type, along with location and parameters such as the carbon loading of organic matter sources such as river inputs to estuaries and adjacent sea areas. As mentioned above, mudflats are unvegetated by macro-flora, but they can support microphytobenthos biofilms for example consisting of diatoms.

Over the last century significant intertidal areas have been lost through sea level rise and coastal squeeze (the loss of tidal areas seaward of coastal defence structures). This loss of intertidal habitats affects not only carbon transport through estuaries but also carbon concentrations (Jickells *et al.*, 2000). This means that terrestrial loads of POC which had historically been trapped in intertidal areas are now exported to the coastal strip and circulation system. This is particularly evident in the Humber, where 90% of the intertidal areas have been lost.

2.5.4 Key values

Stocks and storage rates are summarised for sediment habitats in Section 4.4, **Table 11** (page 41).

3 HABITAT EXTENTS

Multiple data sources exist for deriving estimates for habitat extents in the region. Mapped outputs for the extents below are presented in Section 5.2

Table 8. *Extents of blue carbon habitats in the North Sea region derived from available sources. NE Open Data and NE_BC data supports the report on carbon storage by habitat for Natural England (Gregg* et al.*, 2021). JNCC combined data comes from a report the evidence base for MPAs (Flavell et al., 2020), also used in a recent report on blue carbon habitats in the UK Secretary of State region by Cefas on behalf of Defra (Parker et al., 2020).*

	NE Open Data		**JNCC Combined data**		**NE_BC data**		**Modelled data**	
EUNIS name	EUNIS code	km²		km²		km²		km²
Littoral habitats - Physical								
Moderate energy littoral rock	A1.2	5.8	A1.2	6.8	A5.3	820.6		
Atlantic and Mediterranean high energy infralittoral rock	A3.1	8.1	A3.1	9.5				
Littoral coarse sediment	A2.1	3.9	A2.1	4.0	A5.2	16.9		
Littoral sand and muddy sand	A2.2	213.4	A2.2	135.0				
Littoral mud	A2.3	116.1	A2.3	24.8	A2.2	214.3		
Littoral mixed sediments	A2.4	10.5	A2.4	12.1				
	A2.2 & A2.3	3.4	A2.2 & A2.3	3.4	A2.3	22.0		
	A2.3 & A2.4	0.3	A2.3 & A2.4	0.3				
	A2.3 & A2.5	3.5	A2.3 & A2.5	195.8				
Littoral habitats - Biogenic								
Coastal saltmarshes and saline reedbeds	A2.5	7.9	A2.5	1.0	Saltmarsh	0.6	Saltmarsh	0.4
Littoral sediments dominated by aquatic angiosperms	A2.6	6.2	A2.6	6.2	Seagrass	49.3		
Littoral biogenic reefs	A2.7	2.6	A2.7	2.6				
Features of littoral sediment	A2.8	0.6	A2.8	0.6				
Sublittoral habitats								
Sublittoral sediment	A5	44.6	A5	47.0				
Sublittoral coarse sediment	A5.1	303.9	A5.1	186.4				
Sublittoral sand	A5.2	533.4	A5.2	212.3				
Sublittoral mud	A5.3	535.5	A5.3	239.9				
Sublittoral mixed sediments	A5.4	1584.4	A5.4	349.9				
	A5.4 & A5.1	21.6	A5.4 & A5.1	21.6				
Sublittoral biogenic reefs	A5.6	274.0	A5.6	248.5	Oyster beds	0.0		
					Kelp	71.7	Kelp [1]	379.48

Notes: [1] Kelp extent based on predicted likelihood of presence of *Laminaria hyperborea* > 0.5 using a model developed for the UK in Burrows *et al.* (2018)

3.1 Habitat descriptions

Table 9. *Description of EUNIS level 2 and level 3 habitats assessed for blue carbon potential (adapted from Thornton et al., 2019).*

EUNIS Level 2	EUNIS Level 3	Habitat name	Description
A2		Littoral sediment	Littoral sediment includes habitats of shingle (mobile cobbles and pebbles), gravel, sand and mud or any combination of these which occur in the intertidal zone.
	A2.1	Littoral coarse sediment	Littoral coarse sediments include shores of mobile pebbles, cobbles and gravel, sometimes with varying amounts of coarse sand.
	A2.2	Littoral sand and muddy sand	Shores comprising clean sands (coarse, medium or fine-grained) and muddy sands with up to 25% silt and clay fraction.
	A2.3	Littoral mud	Shores of fine particulate sediment, mostly in the silt and clay fraction (particle size less than 0.063 mm in diameter), though sandy mud may contain up to 40% sand (mostly very fine and fine sand).
	A2.4	Littoral mixed sediments	Shores of mixed sediments ranging from muds with gravel and sand components to mixed sediments with pebbles, gravels, sands and mud in more even proportions.
	A2.5	Coastal saltmarshes and saline reedbeds	Angiosperm-dominated stands of vegetation, occurring on the extreme upper shore of sheltered coasts and periodically covered by high tides.
	A2.6	Littoral sediments dominated by aquatic angiosperms	Dominants are *Zostera* spp. (intertidal seagrass beds)
A5		Sublittoral sediment	Sediment habitats in the sublittoral near shore zone (i.e.: covering the infralittoral and circalittoral zones), typically extending from the extreme lower shore down to the edge of the bathyal zone (200 m).
	A5.1	Sublittoral coarse sediment	Coarse sediments including coarse sand, gravel, pebbles, shingle and cobbles which are often unstable due to tidal currents and/or wave action.
	A5.2	Sublittoral sand	Clean medium to fine sands or non-cohesive slightly muddy sands on open coasts, offshore or in estuaries and marine inlets.
	A5.3	Sublittoral mud	Sublittoral mud and cohesive sandy mud extending from the extreme lower shore to offshore, circalittoral habitats.
	A5.4	Sublittoral mixed sediments	Sublittoral mixed (heterogeneous) sediments found from the extreme low water mark to deep offshore circalittoral habitats.

4 CARBON STOCKS AND SEQUESTRATION

4.1 Intertidal sediment habitats

There have been many intertidal studies on the short-term processing of nutrients, metals and carbon. However, very few studies report stocks and accumulation rates. A review of literature yielded a range of percentages for organic carbon by weight between 0.1 and 2.23 % (Andrews *et al.*, 2008, Andrews *et al.*, 2000, Trimmer *et al.*, 2000). Carbon stocks (when integrating over a depth of 1 m) ranged from 1.3-35.6 kgC m^{-2} (Adams *et al.*, 2012, Potouroglou, 2017, Thornton *et al.*, 2002, Trimmer *et al.*, 1998). When differentiating between mud and sand, mudflats had an average stock of 19.9 kgC m^{-2} (n=8) while sandy sites only contained 6.5 kgC m^{-2} (n=4).

4.2 Subtidal sediments

4.2.1 Stock values from recent studies

Several published works cite shelf seabed sediment concentrations of organic carbon (to a depth of 10 cm) and provide a comprehensive overview and maps (derived from models) of the shelf seabed POC stocks across UK EEZ and SoS waters. A random forest model predicting the standing stock of organic carbon in the surface sediments of the North-West European continental shelf has been developed (Diesing *et al.*, 2017, Wilson *et al.*, 2018). In the below calculations, the values found have again been extrapolated to a sediment depth of 1 m to align with the other habitats and UNFCCC guidance, though it is likely that this will result in an overestimation due to the generally observed decline of carbon with sediment depth.

Organic carbon content values of 0.02 – 8.86 % have been reported (Burrows *et al.*, 2014, Camacho-Ibar & McEvoy, 1996, De Haas *et al.*, 1997, Hunt *et al.*, 2020, Loh *et al.*, 2008, Queirós *et al.*, 2019, Smeaton & Austin, 2017, Smeaton *et al.*, 2017, Smith *et al.*, 2015) with the very high values found mostly in fjordic environments, and most other environs falling between 0.5-5%. There is a clear link between sediment type, in particular grain size distribution, dry bulk density and organic carbon content, with finer sediments generally containing more carbon but having lower dry bulk densities, as demonstrated for fjordic sediments (Smeaton & Austin, 2019) and the wider shelf sea (Diesing *et al.*, 2017).

In order to estimate global patterns in marine sediment carbon stocks, Atwood and co-workers (2020) collected carbon data from over 12,500 cores. It is worth noting that the burial rates in the different areas included in this collection will be vastly different and thus the age of the carbon accounted for very variable (some core content will be over 300,000 years old). They extrapolated carbon stocks to 1 m depth, divided they data set into Oceanic Provinces and derived carbon stock values of: Continental shelf 35.6 kgC m^{-2}, Other Coastal 6.3 kgC m^{-2}, Continental Slope 11.5 kgC m^{-2}, Abyss/Basin 7.6 kgC m^{-2} and Hadal 8.4 kgC m^{-2}, resulting in a total carbon stock for global marine sediments of 8.9 kgC m^{-2}.

4.2.2 Stock values (to depth of 1 m) based on Cefas data

To refine the review of sedimentary carbon stocks, samples were divided into “mud” and “sand” using a cut-off of 10% fines (particles <64 μm). For muds, a sediment organic carbon stock range of 0.6^{-1} 2.3 kgC m^{-2} with an average of 5.5 kgC m^{-2} (n=33) was found, and for sands a range of 0.4-7.6 kgC m^{-2} with an average of 1.8 kgC m^{-2} (n=90), illustrating the significant correlation between grain size and carbon content.

4.2.3 Stocks from modelled outputs

A large data collection exercise undertaken by Cefas has brought together >1000 carbon concentration measurements in sediments. The modelled carbon stock distribution derived from these observations by Diesing *et al.* (2017). A similar exercise was undertaken by Smeaton et al., 2021 using BGS data. Both POC stock maps are shown in **Figure 3** below, they have contrasting distributions due to the differing datasets used and interpolation or machine learning (Random Forest approaches used). The development of 1 stock map is currently underway.

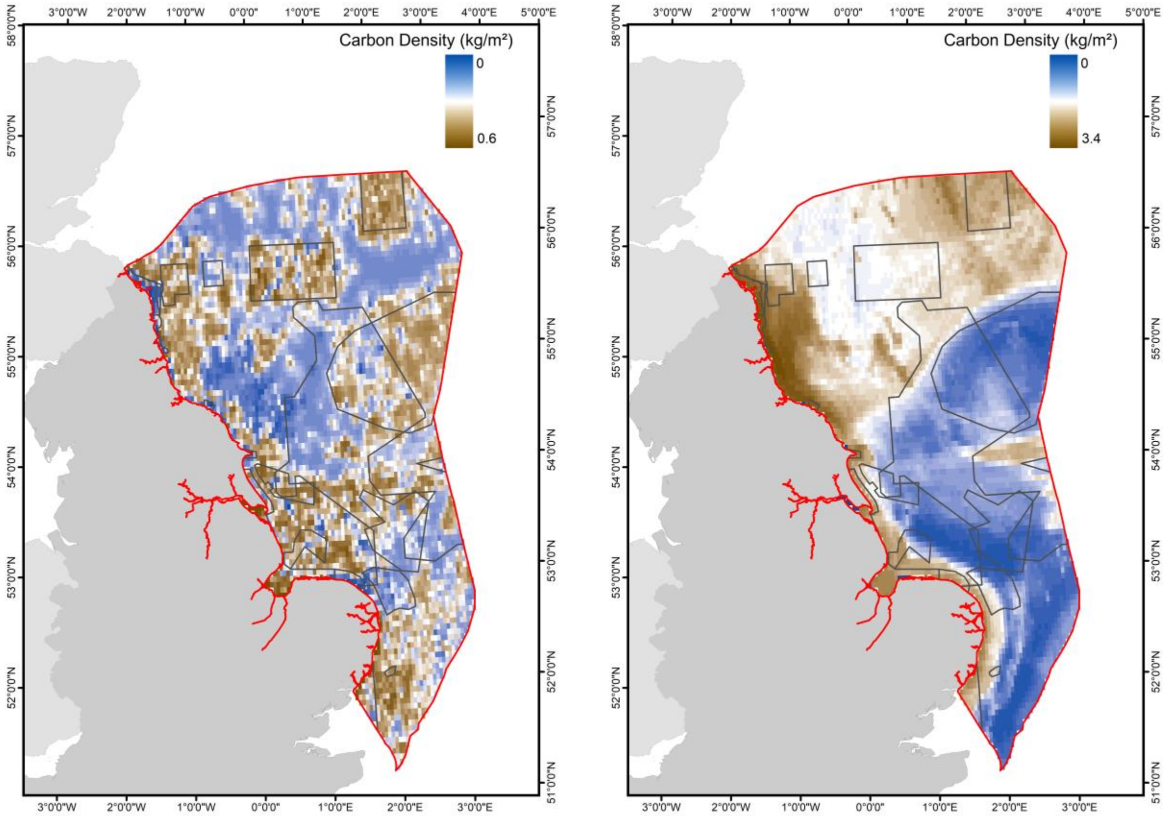

Figure 3. *Stock maps showing organic carbon (OC) density (<10cm depth) from Smeaton et al. (2021) and Diesing et al. (2017), including outlines of the MPA network. Note the change in scale between the two maps.*

4.3 The characteristics of carbon stores

An important feature of understanding the significance of carbon stores and sequestration (mainly for POC) is the composition, lability and hence potential vulnerability of the carbon. This can be controlled by source (terrestrial, marine, phytoplankton, coastal plants) and degradation level.

With the exception of shallow area with sufficient light for photosynthesis such as the Dogger Bank, most of the carbon stored in subtidal sediments is allochthonous i.e. primary production happens elsewhere: on land and in coastal habitats. In shelf seas marine plankton in surface waters are an important carbon source, though much of this carbon is expected to be recycled back within ocean waters. In shallow waters, even away from the coast, microphytobenthos also fix carbon at the sediment surface. Estimated seabed irradiance for the Dogger Bank area is 0.8 mol photons m^{-2} d^{-1} is above the 0.24 threshold light intensity for photosynthesis by surface-living single-celled plants (microphytobenthos) (using mapped data from Gattuso *et al.*, 2020, Gattuso *et al.*, 2006). Fundamentally, linking stored carbon to its source(s) relies on constraining the properties of the source itself: potential sources should be identified and analysed wherever possible, which is more challenging when carbon storage occurs at a distance from the carbon source and molecular properties are modified between source and sink.

The vulnerability of the POC stock to disturbance (when brought into a more degrading environment) or climate change is controlled by the chemical status and reactivity of the carbon stock. The nature of the carbon and associated level of degradation (lability vs recalcitrance) can vary with region (carbon source) and depth in the sediment. This will control whether POC disturbance or relocation will result in degradation and CO_2 emissions. There are many chemical analyses which can describe this carbon composition, lability or vulnerability.

The carbon to nitrogen ratio (C:N) of the carbon may be a useful indicator of carbon lability/age, but source terms can vary between terrestrial input (>10) and marine phytoplankton (6-7). As marine carbon ages, N is depleted by bacteria and C:N ratios increase. Although a proxy for C lability/vulnerability, the interpretation of C:N can be complex and higher levels are generally associated with reduced vulnerability as they are more degraded (refractory marine C) or from terrestrial sources (C4 plants which contain more lignin). C:N ratio of POC stock which has legacy data from monitoring programmes for the region (**Figure 4**) from Wilson *et al.* (2018). It is possible to see that in mobile areas of sands C:N is very low (Wilson et al., 2018). C:N is a good proxy but the blending of terrestrial and marine carbon sources in the North Sea makes it complex.

There are many techniques which can provide insight into this issue (see review by Geraldi *et al.*, 2019).

Other chemical descriptions of POC pools (including isotopic analysis, thermal gradient analysis/carbon stability analysis, alkane fingerprinting) can be combined to give a more rounded understanding of POC stock characteristics, including vulnerability. Limitations in the evidence base beyond C:N ratios makes vulnerability mapping difficult but new data is coming which will aid this to allow vulnerability assessments (and risk when combined with pressure estimates).

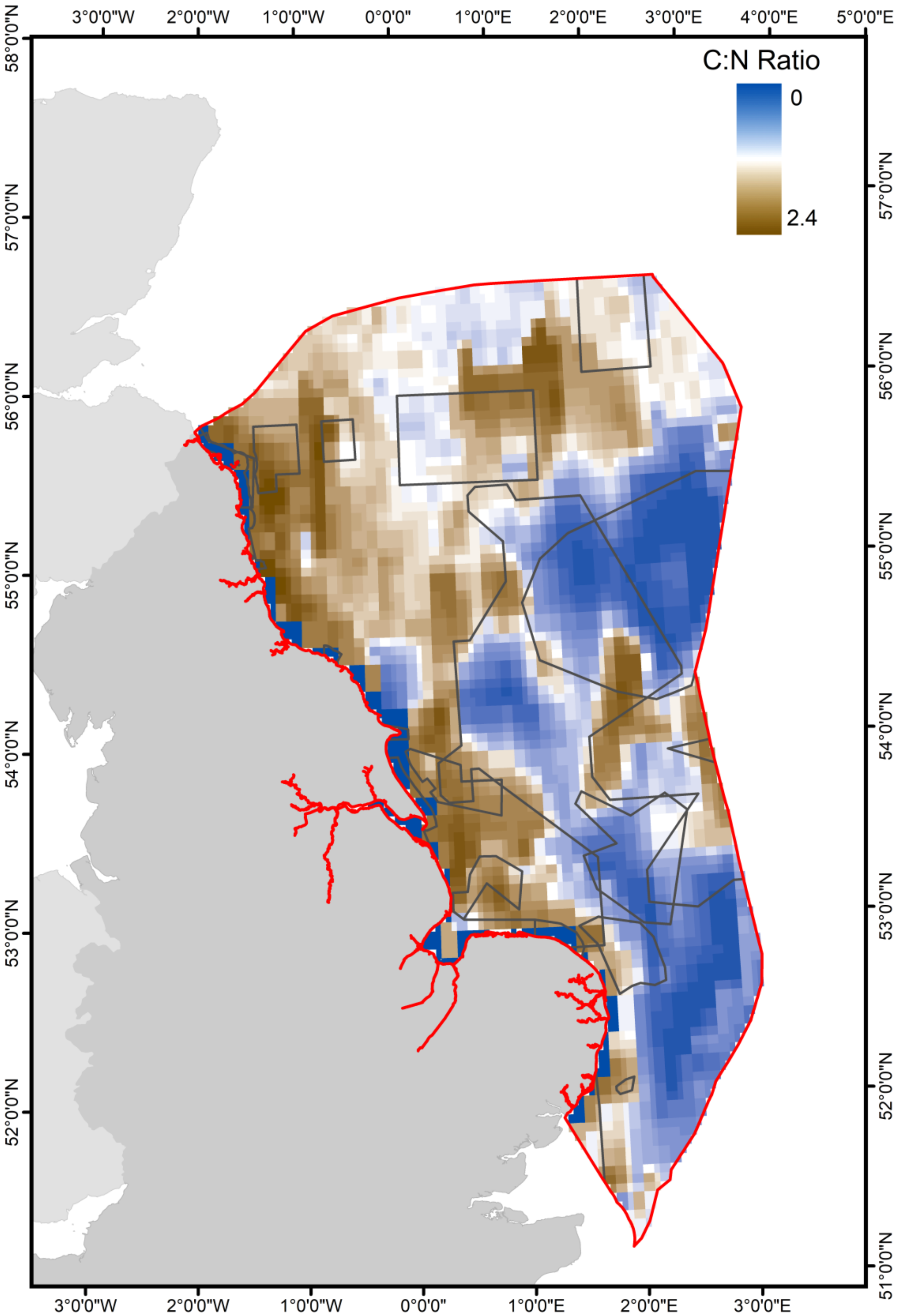

Figure 4. *C:N distributions within North Sea section of Wilson et al. (2018), including outlines of the MPA network.*

4.4 Carbon sequestration

4.4.1 Accumulation rates – Intertidal sediments

The rates of carbon fluxes of intertidal mud sediments were 73.3-93.7 gC m^{-2} yr^{-1} (Adams *et al.*, 2012) with an average of 83.5 (± 10.2) gC m^{-2} $yr^{-1.}$ In their review, Duarte and colleagues (2005) quote 45 gC m^{-2} yr^{-1} , citing Heip *et al.* (1995) and Widdows *et al.* (2004). The Heip *et al.* (1995) paper again is a review and tabulates a large range of carbon burial rates from other papers covering for example locations is the US, Denmark, The Netherlands and Germany. Rates here range from 5 - 1368 gC m^{-2} yr^{-1} , with 212 gC m^{-2} yr^{-1} for Westerschelde as the only North Sea site and no UK sites included. The Widdows paper reports original measurements from Molenplaat station in the Netherlands and gives carbon burial rates from 10-105 gC m^{-2} yr^{-1} over five sites with an average of 53 gC m^{-2} yr^{-1}. This illustrates the high degree or variability and uncertainty in current observations and indicates that the range deducted from the measurements reported for England is not necessarily the overall envelope of flux rates.

While the literature search for this topic has not yet been as extensive as for some of the other habitats to date, it is likely that significant gaps in both coverage and carbon stocks and flux numbers exist. Important aspects to consider would be the status of the intertidal flats, i.e. whether they are stable or eroding and what the age profile and origin (terrestrial or marine) of the organic carbon content is. Even less is known about sandflats than mudflats and both systems require additional observations.

4.4.2 Accumulation rates - Sublittoral sediments

Literature sources include only 2 publications for carbon accumulation rates in sublittoral sediments in the North Sea; (De Haas *et al.*, 1997, Diesing *et al.*, 2021, drawing heavily on De Haas also). Therefore, the confidence in these data are low.

Very few published works cite carbon flux measurements within the English North Sea, SoS or even UK EEZ waters. One study in the North Sea (De Haas *et al.*, 1997) gives an average estimate of 0.2 gC m^{-2} yr^{-1} but with many samples as ND (not determinable) in sandy substrates. Even in muddier substrates this is challenging due to disturbance of the upper sediment layers. The numbers in De Haas are very low compared to a value measured on the South coast of the UK~ 59 gC m^{-2} yr^{-1} (Queirós *et al.*, 2019). Carbon burial rates are often limited due to the lack of deeper carbon concentration measurements and sedimentation rates derived from Pb210 or another dating technique. The evidence base for carbon burial (relating to stocks) in the offshore therefore remains poor and additional observations are required across much of the shelf area. It should be noted, that in some instances where dating techniques have been applied, no clear profiles were obtained. This was likely due to either the widespread impact of trawling which mixes sediment layers or to slow sedimentation rates. It is possible in future work that ‘refuge areas’ that can’t be trawled (e.g. around infrastructure or in protected areas) may provide data for ‘background carbon stocks’ removing the impact of trawling, thus allowing a more accurate dating procedure to estimate accumulation rates.

In the above reporting for habitat extents and associated habitat stores/sequestration we have used the EUNIS level classification across the BC habitats for comparability. However, the link between this EUNIS level and sediment classification can be complex, especially across boundaries linked to permeability and carbon processing.

The classical Folk classification scheme (Folk, 1954) has 16 classes ranging between gravel to fine grained muddy sediments, the scheme can be devolved and simplified to either 7 or 5 classes (Kaskela *et al.*, 2019). The EUNIS level classification scheme describes marine sediments as course, mixed, sand to muddy sand and mud (Table 1), these classes correspond to the simplified 5 folk classes outlined by Kaskela et al., (2019). The classification scheme and number of classes used to describe sediments can potentially have a significant impact on the calculation of sedimentary C stocks and C burial estimations. By condensing the number of sediment classes, the data required to calculate sedimentary C stocks (i.e. dry bulk density and OC content) is also grouped resulting in an increased spread of data resulting in larger errors likely leading to both under and overestimations in both sedimentary C stocks and burial estimates. To date there have been no studies directly exploring the potential issues arising from the use of different classification schemes to determine sedimentary C stocks but comparison of studies across the same geographic area can provided insights. Using the simplified 5 folk scheme Smeaton and Austin (2019) estimated that the surficial sediments (top 10cm) of Scottish and Northern Irish fjords hold 4.2 ± 0.5 and 0.9 ± 0.1 Mt of OC respectively; Smeaton et al. (2021) repeated the analysis using the full 16 folk scheme and estimated that 3.9 ± 0.6 and 1.6 ± 0.2 Mt of OC is stored in Scottish and Northern Irish fjords sediments. It is important to note that Smeaton et al. (2021) had access to an increased quantity of OC and dry bulk density data which is a potential reason for the difference in the estimates, but it is also highly likely the different way the sediments where mapped played a role in the diverging sedimentary OC stock estimates. Further work is required to fully understand the impact of sediment classification in calculating sedimentary OC stock and estimating burial rates.

4.4.3 Modelling to address stock and sequestration predictions

Statistical models are data-driven models that can be used to interrogate and develop relationships between POC/IC stock or sequestration and key controlling parameters. These can then be spatialised to produce interpolated maps (Smeaton *et al.*, 2021) or maps can be developed using machine learning approaches such as Random Forest modelling (Diesing *et al.*, 2017, Diesing *et al.*, 2021). Maps produced by these methods are shown in **Figure 3** and **Figure 4**. Both methods generally have good prediction power and accuracy and require existing data across the area of interest (sometimes limited to <10cm depth) and are based on present-day measurements so predictions of change can be difficult.

Mechanistic models combine many individual processes and inter-relationships within a dynamic and evolving representation of the seabed system and so features are allowed to emerge over time. They require good validation but are good for predicting change. Coupled physical-biogeochemical models such as (GETM-BFM, GOTM-ERSEM) can give predictions for hundreds of variables covering ecosystem states and fluxes, including benthic and pelagic biomass in various functional groups, nutrient concentrations and the fluxes of carbon through various forms. They can also provide integrated outputs of processes which cannot be easily observed within monitoring programmes and look at dynamics and changes. These models include carbon parameters within the seabed but are focused on seasonal dynamics so stock/burial of carbon can be poorly constrained. 1D diagenetic models such as OMEXDIA (Soetaert *et al.*, 1996) may offer better predictions of stock and sequestration in the North Sea but often results are not interrogated with stock and sequestration as an aim (De Borger *et al.*, 2021). All these models need good validation data and coupling with observations to be of future use in predicting spatial variability of stocks/sequestration and changes under climate or human forcing.

Most statistical and mechanistic approaches to date have been focused on POC so information on IC is more limited.

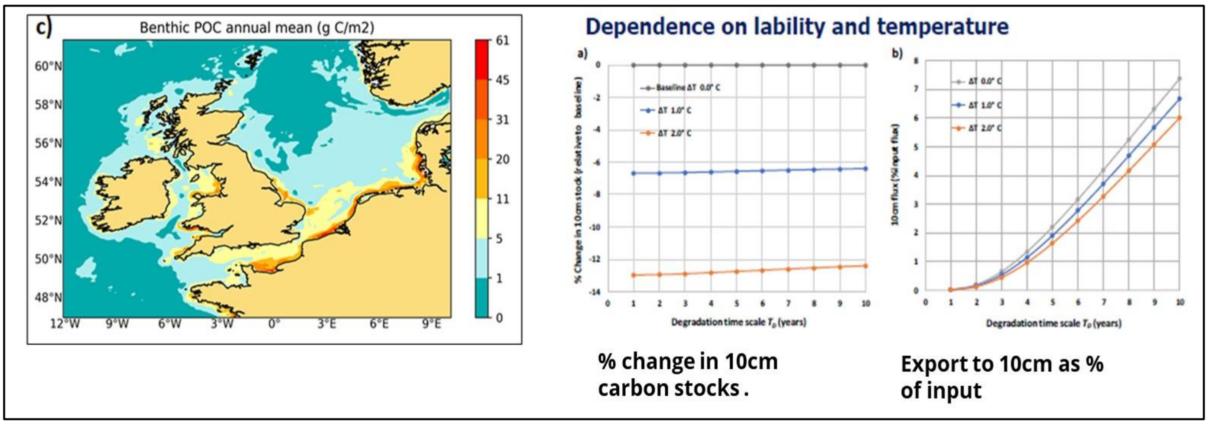

Figure 5. *Example outputs from ERSEM for North Sea and Omexdia (sensitivity assessments for C lability and temperature impact on stock and export) for an example North Sea test site.*

4.4.4 Key values for sediment carbon stocks and storage rates

Table 10. *Habitat-specific information on organic and inorganic carbon stocks and associated rates of storage for the English North Sea study area and other similar habitats, summarised from Section 4. Values from other studies (Atwood et al., 2020, Burrows et al., 2014, Queirós et al., 2019) are presented for comparison with those used in this study.*

			Organic carbon																Inorganic carbon											
			Stocks										Sequestration						Stocks							Sequestration				
			%OC		1m depth kgC/m²					0.1m depth gC/m²			Accumulation rate gC/m²/yr						%IC	0.1m depth kgC/m²			0.1m depth gC/m²			Accumulation rate gC/m²/yr			
EUNIS code	Habitat	Sediment type	min	max	min	max	Avg	SD	n	min	max	Avg	min	max	Avg	Source	Comment		Avg	min	max	Avg	min	max	Avg	min	max	Avg	Source
A2.3	Intertidal	Mud			5.4	35.6	19.9	4	8	540	3560	1990	73.3	93.7	83.5	Adams et al., 2012; Potouroglou, 2017; Thornton et al., 2002; Trimmer et al., 1998													
A2.2	Intertidal	Sand			1.3	18.6	6.5	4	4	130	1860	650			45.0	Duarte et al 2005													
A5	Sublittoral	All	0.02	8.86												Habitat review													
A5	Sublittoral	All			0.6	6.1	2.6			64	608	264				Diesing et al 2017	min/max as 5%/95%iles												
A5	Sublittoral	All			2.8	4.0	3.3			279	402	329				Smeaton et al 2021	min/max as 5%/95%iles		8%	0.04	1.697	0.55	44	1697	554	1.18	5.6	3.38	Smeaton et al 2021; Accumulation scaled as 10% Burrows et al 2014 estimates
A5	Sublittoral	All													0.2	De Haas et al 1997													
A5.2	Sublittoral	Sand			0.4	7.6	1.8			40	760	180				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			80%						26880	11.8	56		Burrows et al 2014
A5.3	Sublittoral	Mud			0.6	12.3	5.5			60	1230	550				Cefas data													
A5.3	Sublittoral	Mud	1.5	8	39.0	208.0	123.5			3900	20800	12350	18.7	291.6	155.2	Burrows et al 2014													
A5.4	Sublittoral	Sand/mud													59.0	Queiros et al 2019	English Channel L4: EUNIS A5.4 from NE habitats data												
A5.4	Sublittoral	Sand/mud	1.5	4	39.0	104.0	71.5			3900	10400	7150	46.0	150.0	50.6	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	0.0	0.2	0.1	Burrows et al 2014													
		Abyss/Basin					7.6					760				Atwood et al 2020													
		Hadal					8.4					840				Atwood et al 2020													

***Table 11**. Carbon stocks and storage rates for sediment types in the North Sea region. Stocks are calculated by (a) combining average stock density estimates (gC/m²) and estimated habitat extents, and (b) directly from modelled carbon values across the region by Smeaton et al 2021 and Diesing et al 2017.*

				Organic carbon						***Inorganic carbon***					
	North Sea Net Gain area	113947		<0.1m											
EUNIS code	**Habitat**	Extent (km²)	Component area (km²)	Stock (1000 t)	Stock (g C/m²)			Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Stock (1000t C)	Stock (g C/m²)			Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)
					min	max	avg				min	max	avg		
A2	**Littoral sediment**	292.3		**14.2**					**1.0**						
A2.1	Littoral coarse sediment		144.5					0	0.0						
A2.2	Littoral sand and muddy sand		11.4	7.4	130	1860	650	45.0	0.5						
A2.3	Littoral mud		3.4	6.8	540	3560	1990	83.5	0.3						
A2.4	Littoral mixed sediments		0.3					45.0	0.0						
A2.2 & A2.3	Littoral sand and mud		3.5					45.0	0.2						
A2.3 & A2.4	Littoral mud and mixed sediments		0.0												
A2.3 & A2.5	Littoral mud & Coastal saltmarshes and saline reedbeds		129.2												
A5	**Sublittoral sediment**	113674.1	31.0	**18037**					**1189.5**	**62975**	44	1697	554	3.38	384.2
A5.1	Sublittoral coarse sediment		19866.0												
A5.2	Sublittoral sand		83036.3	14947	40	760	180	0.2	16.6						
A5.3	Sublittoral mud		5618.6	3090	60	1230	550	155.2	872.0						
A5.4	Sublittoral mixed sediments		5100.6					59	300.9						
A5.4 & A5.1	Sublittoral coarse and mixed sediments		21.6												
A5.6	**Sublittoral biogenic reefs**	273.2	273.2												
Area weighted averages					32	613	158	10.42							
Modelled values															
A5	Diesing et al 2017	112505		29722			264								
A5	Smeaton et al 2021	113947		37500			329			62975	44	1697	553		

4.5 Risks to carbon stocks

Carbon stock and sequestration in the seabed are controlled by several interacting variables within shelf seas namely, input from terrestrial sources, generation by fixation in water-column (relating to hydrography, depth and temperature) and deposition to the seabed. Balance between these sources and supply will depend on proximity to land and transport pathways across the North Sea region.

Once at the bed, the creation of particulate organic carbon (POC) stocks and accumulation is controlled by seabed conditions. Sediment type controls oxygenation in the upper layers of the seabed, temperature controls carbon degradation rates and the faunal community can mix carbon into the bed and control turnover. The biggest control is permeability and switch between diffusive and advectively controlled sediments. This is largely between sands and muds as controlled by % fines at ~ 5-8% for English waters (Parker *et al*., in prep).

Ultimately, POC stock levels are controlled by a balance between input, overall degradation / respiration (controlled by temperature, carbon lability, faunal community, and sedimentation/accumulation, Burdige *et al*., 2007). These key factors also control long-term sequestration i.e. annual climate mitigation service and vary in space across the English shelf.

Any pressure, human or climate driven, which alters the input of carbon to the bed (directly or indirectly through carbon input or addition of carbon rich sediment) or changes degradation rates in the upper parts of the sediment will affect overall stock and burial or long-term sequestration rates (Burdige, 2007). Physical disturbance can alter carbon degradation pathways and rates through increased exposure to oxygen (resuspension) but also by physical mixing and relocation through the sediment column. Disturbance can also impact the biological assemblage, which in turn can mediate carbon degradation through differing redox pathways and direct consumption. Similarly, changes in inputs or carbon amount and quality as well ambient seabed temperatures can alter carbon bacterial degradation and change seabed carbon stocks.

In the North Sea, carbon stocks and sequestration potential are at risk from multiple pressures, both climate driven and from anthropogenic activities. The exact impact of these pressures, specifically the impact on carbon, for habitats and sediments included in this study is largely unknown. However, it is clear that the North Sea region experiences significant anthropogenic pressures from fishing activity, oil and gas infrastructure, offshore renewable installations, and dredge disposal, among others, the combined influence of which may have an impact on carbon stores. The potential impacts of several impacts is discussed briefly below.

4.5.1 Offshore energy and dredge disposal

Oil and gas installations may affect carbon stores due to restrictions of activities, such as trawling, within exclusion zones around them. The impact on carbon stocks and sequestration has not been addressed but is planned under upcoming INSITE II projects, which are investigating the INfluence of man-made Structures In The Ecosystem. There are approximately 650 subsurface and 280 surface installations within the English North Sea. Similarly, the influence of Offshore Wind Farms (OWFs) on carbon stocks has not yet been studied in this region. The net impact over various timescales of construction versus longer term fisheries exclusion, which potentially may preserve stocks and allow recovery, is unclear. **Figure 6** below illustrates the location of offshore energy installations within the English North Sea, which are primarily concentrated in the southern portion of the project area.

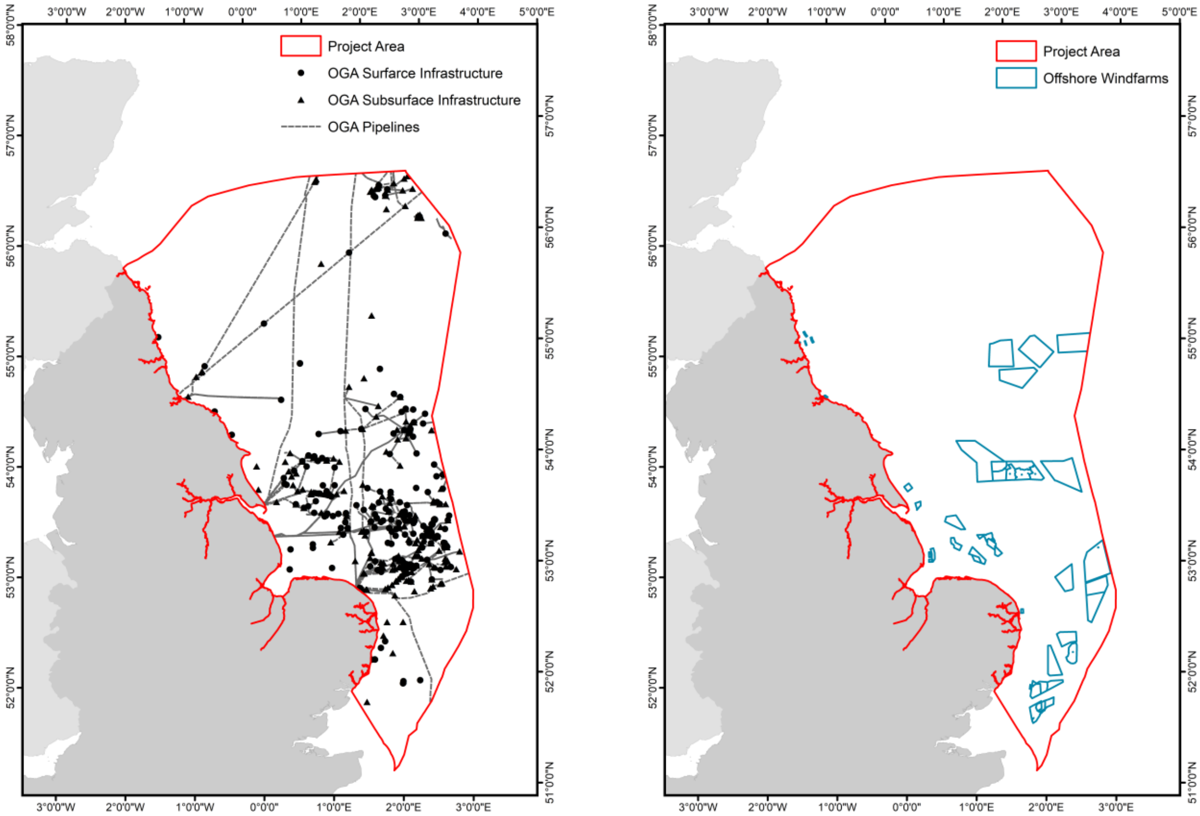

Figure 6. *(Left) Locations of Offshore oil and gas infrastructure and pipelines in the North Sea from the Oil and Gas Authority. (Right) Locations of Offshore Windfarms (Crown Estate).*

Dredge disposal is spatially restricted (<0.01% of the English North Sea area) but can cause significant changes to sediment dynamics in localised areas, building large stocks to great depths (>10 m). Maintenance disposal relocates sediments from higher carbon environments (e.g. ports and estuaries) and increases POC stock locally within the disposal area by doing so. However, this may also influence wider carbon storage dynamics through subsequent transport processes.

For almost all the above activities there are very few studies which have measured carbon stocks or sequestration under pressure levels or recovery. This is an evidence gap relevant to carbon management but also natural capital considerations which needs to be addressed.

Mapping of human pressure levels do indicate a level of risk to a habitat and the climate regulation service. However, the overall effect on service delivery (carbon stocks and burial) will be a non-linear link between pressure, mode of action (fishing gear specific, type of disposal, dredging), habitat type and setting and the vulnerability of the carbon present. Ultimately, any pressure which alters the input of carbon to the bed or changes degradation rates in the upper parts of the sediment will affect overall stock and burial rates (Burdige, 2007). Impact on condition will depend on the distribution of ecosystem services and pressure from different fishing fleets (or other activities), and this will vary in both space and time. Some human activities may act to decrease pressure (e.g. OWFs) but can also increase/focus pressure, such as through the management of fishing fleet distributions.

4.5.2 Fishing (bottom towed gears)

The impact of fisheries on blue carbon stocks in this region is being addressed in a separate project and has therefore not been examined in detail here. However, fishing activity may have an impact on blue carbon in this region as demersal trawling is by far the most extensive activity within the North Sea (60.06% of area affected with a SAR range of 0 to 9 impacts per year) although it is focused on areas of muddier substrates, such as on the Dogger Bank. **Figure 7** below shows the Swept Area Ratio (SAR) and carbon pressure across the study area.

Trawling using bottom gear physically changes the sediment via two mechanisms: firstly, the trawl doors penetrate into the bed, turning the sediment over, burying fresh sediment underneath older layers (De Borger *et al.*, 2021, Duplisea *et al.*, 2001), rather like a plough turns the soil over in a field, and can lead to visible trawl marks on the sea floor; secondly, the hydrostatic force between nets/gear and bed resuspends the top layer of sediment into the water column (O'Neill & Summerbell, 2016, Tiano *et al.*, 2021). In addition, some fishing gears are designed to disturb and resuspend greater amounts of sediment in order to force benthic fish and shellfish into the water column.

The magnitude and direction of the effect of fishing pressure on carbon stocks and fluxes is hugely dependent on local conditions (e.g. sediment type, bed morphology, depth, temperature, currents, weather conditions, seasonal stratification, type and number of animals living in and on the sediment) and on the fishing type (e.g. gear type, trawl speed, trawl frequency, how long the area has been a trawling fishery for) and for this reason it is difficult to quantify relative effects of this type of pressure.

There remains high uncertainty on the impacts of fishing to carbon stocks and hence burial rates (Kroger *et al.*, 2018, Legge *et al.*, 2020). In part this is due to a lack of observational data linking fishing pressure and stock and burial responses. It is also a complex pressure with several interacting mechanisms namely resuspension (which may decrease stocks and create emissions (Luisetti *et al.*, 2019, Sala *et al.*, 2021)); faunal mortality (which may increase burial) and direct mixing or relocation of carbon (which may increase or decrease stocks/burial). As a result, the net effect of trawling on seabed carbon condition is highly uncertain (Kroger *et al.*, 2018, Legge *et al.*, 2020). The complexity of the processes also makes prediction of pressure effects on ecosystem service delivery and condition very difficult. The historic and spatial/temporal variability of pressure distributions must also be considered (Dinmore et al., 2003; Sciberras et al., 2016).

In combination, this lack of evidence associated with understanding the effect of trawling pressure on carbon stock and sequestration makes predictions of changes in pressure levels or removal (and associated recovery) very low confidence, especially in light of displacement effects.

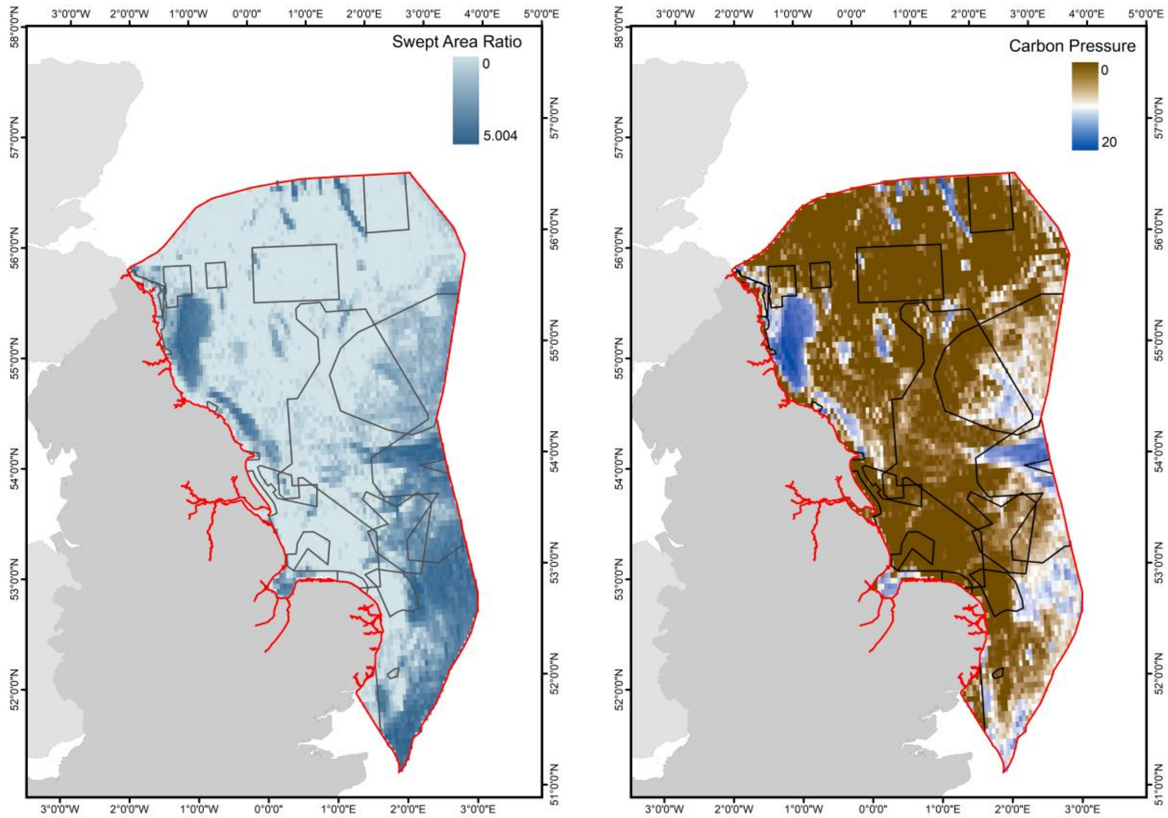

Figure 7. *Swept Area Ratio (left) and comparative carbon pressure (right) according to Diesing et al. (2021) carbon stock levels for each scenario. The absolute pressure is the product of the absolute carbon stock and the swept-area ratio for each grid square.*

4.5.3 Climate change

Any pressure which influences the input and processing of carbon within the seabed will alter supporting stock and burial rates. Climate change is a wide-scale and potentially significant pressure (gradual) type forcing factor which could alter ecosystem service delivery and condition. Changes associated with climate change include increased temperature, changes in primary production and water column carbon generation and altered carbon input to the bed, oxygen concentrations and within bed carbon-processing rates. These will all vary according to location on the shelf linked to hydrography, sediment type and depth, as well as seasonally. Generally, work has shown (Kroger *et al.*, 2018, Legge *et al.*, 2020, van der Molen *et al.*, 2013) that in some areas stock and burial rates will decrease as a result of climate change, but this conclusion remains highly uncertain.

Process models (ecosystem type, ERSEM) are the main means of predicting climate change impacts with some improvement in bed characterisation and processing. Linking spatial (3D) and point (1D) process, models with appropriate parameterisation data (from targeted observations) will allow improved predictions of the likely impact of climate forcing on the magnitude and distribution of carbon stocks and burial rates and associated condition and ES delivery indicators. The spatial scales of these models may be much higher resolution than the habitat information or units.

Changes are predicted to be biggest in Northern North Sea as temperature limitation creates stock degradation under warming temperatures and greater recycling in the upper water column which depletes supply to the bed (van der Molen *et al.*, 2013). Sensitivity results show that temperature increases may decrease stock of carbon in the top 10cm (~ by 6%) per degree increase in water temperature and decreases export flux (below 10cm boundary), by <10% decrease per degree (Aldridge pers comm).

4.6 Carbon stores contained within the current MPA network

The MPA network in the North Sea has not been designated for carbon provision (or climate regulation) but for biodiversity considerations. This section therefore reviews the role of the seabed within the existing network in terms of its provision of co-benefits (with biodiversity) for carbon stock and sequestration.

Total carbon stocks and accumulation rates are broken down by total regional area, content and areas within MPAs in **Table 12**. The values are also presented diagrammatically in **Figures 10 to 12**, which show the amounts of organic and inorganic carbon, as well as accumulation rates, by relative proportion in each MPA.

The surficial (top 10 cm) OC stock in the Net Gain study area is estimated to be 37.4 ± 4.11 Mt C, which represents 52.64% of the OC stored in Secretary of State waters and 14.26% of the OC stored in the UK EEZ. The surficial IC stock in the Net Gain study area is estimated at 62.98 ± 9.96 MtC, which represents 0.77 % of the IC stored in secretary of state waters and 5.44% of the IC stored in the UK EEZ.

The seabed lying within MPAs represent roughly 50% of the Net Gain study area and contains approximately 51% of the OC stocks and 42% of the IC stocks. The whole area sequesters roughly 39 Kt C yr^{-1} (from GIS analysis using Diesing et al., 2021), which is ~0.05% of the total stock annually. Seabed areas that lie within MPAs are estimated to contribute approximately 42.9% of this total.

In general, the seabed within MPAs of the largest areas contain the largest total organic and inorganic carbon stocks. Organic carbon stocks calculated using the spatial modelling technique developed by Smeaton *et al* (2021) within the MPA network are dominated by the Southern North Sea (11.68 Mt OC) and Dogger Bank (4.25 Mt OC), with lesser amounts stored in Swallow Sand (1.74 Mt OC), Greater Wash (1.14 Mt OC) and North Norfolk Sandbanks and Saturn Reef (1.13 Mt OC). Similarly, inorganic stocks within the MPA network are led by the Southern North Sea (17.51 Mt IC) and Dogger Bank (5.85 Mt IC), with Berwick to St Mary's (2.31 Mt IC), North Norfolk Sandbanks and Saturn Reef (2.10 Mt IC), the Greater Wash (2.079 Mt IC), and the Outer Thames Estuary (1.30 Mt IC) also containing large stocks.

Accumulation rates within the MPA network are topped by the Southern North Sea (4.95 kt yr^{-1}), with lesser amounts accumulated by Berwick to St Mary's (1.74 kt yr^{-1}), the Greater Wash (1.60 kt yr^{-1}), Swallow Sand (1.32 kt yr^{-1}), and Dogger Bank (1.15 kt yr^{-1}), although this is not proportional by size as with overall carbon stocks. In contrast, the smaller sites accumulate a small fraction of carbon across the study area, including Orford Inshore (0.01 kt yr^{-1}), Kentish Knock East (0.01 kt yr^{-1}), Markham's Triangle (0.03 kt yr^{-1}), Flamborough Head (0.04 kt yr^{-1}), and Runswick Bay (0.05 kt yr^{-1}), which also contain much smaller stocks overall.

Accumulation rates per unit area tend to be highest in the smaller MPAs close to the North East coast of England (e.g. Berwickshire and North Northumberland Coast, Flamborough Head, Northumberland Marine, Berwick to St Mary's, Teesmouth and Cleveland Coast), which may indicate a large input of terrestrial carbon to this region. Lower accumulation rates are found at Southern Bight marine sites, reflecting the distance from terrestrial sources of carbon in terms of input (mainly from marine sources) and shallower, coarser substrates reflecting the higher physical disturbance and oxygenation of the seabed. Further offshore, muddier, deeper and colder seabed conditions (MPAs such as Fulmar) may also have significant potential carbon co-benefits per unit area. The blending of terrestrial and marine carbon input and receiver site characteristics which creates stock and accumulation rates, across the North Sea needs to be fully understood to allow assessment of regional scale carbon provision as well as the present role of the MPA network within this.

Similarly, when carbon density (i.e. stock per unit area) is considered, the role of sediment type and hydrography in controlling stock and accumulation becomes far more relevant, with shallow, advective sediments like those at Dogger Bank, Southern North Sea and North Norfolk Sandbanks holding relatively little OC stock per unit area compared to deeper, colder, muddier sites like Swallow Sand, Fulmar, North East of Farnes Deep and Farnes East. This is reflected in the OC and IC density maps in ***Figure 8*** and ***Figure 9***, respectively. For comparison, these are presented alongside OC and IC density maps for the entire study area in Annex 2.

The surficial sediment OC and IC stock estimates (***Figure 8*** and **Figure 9**; **Table 12**) for the MPAs and SACs in the study area are a product of spatial modelling for the entire UK EEZ (Smeaton et al., 2021a). The spatial model utilised ~70,000 point observations (grainsize, dry bulk density, OC and IC) in conjunction with simple kriging interpolation (Cressie, 1990) with Gaussian geostatistical simulations (Li and Heap, 2014). To validate the spatial model, OC values were extracted from the outputted OC map and compared to the ground-truthing datasets with the coefficient of determination (R^2) being utilized to test the performance of the model. In addition, cross-validation of the results were undertaken in the $_{\text{BLOCK}}$CV package (Valavi et al., 2019) to negate underestimations of errors due to the possibility of spatial autocorrelation between the model outputs and the validation dataset. The quality of the output from this approach is directly linked to the quantity of data in the area. The study area has good spatial coverage of bulk density, OC and IC data (Smeaton et al., 2021a) but with all areas there are gaps especially with the bulk density and OC data that hinder the estimation of OC and IC stocks.

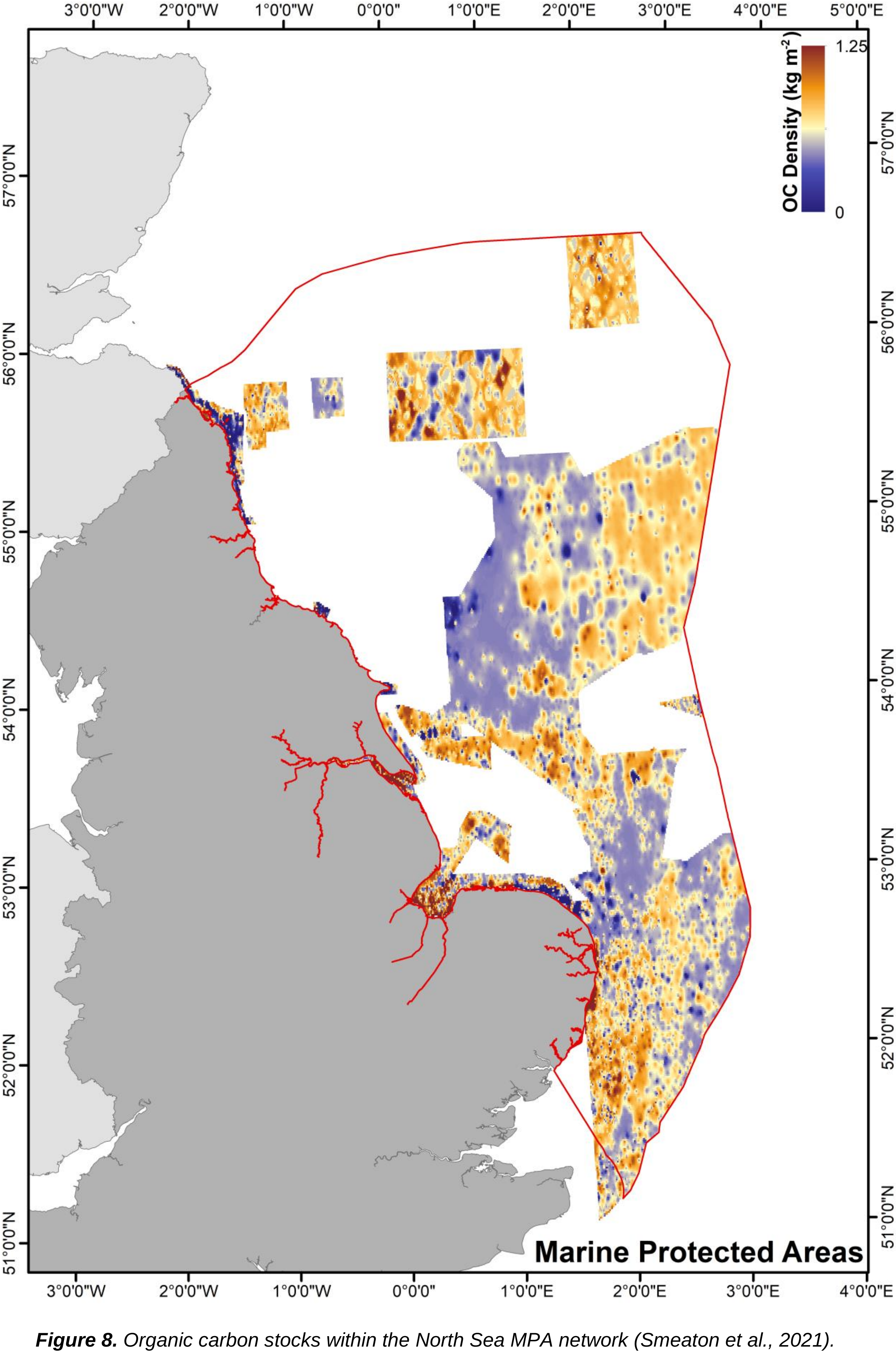

Figure 8. *Organic carbon stocks within the North Sea MPA network (Smeaton et al., 2021).*

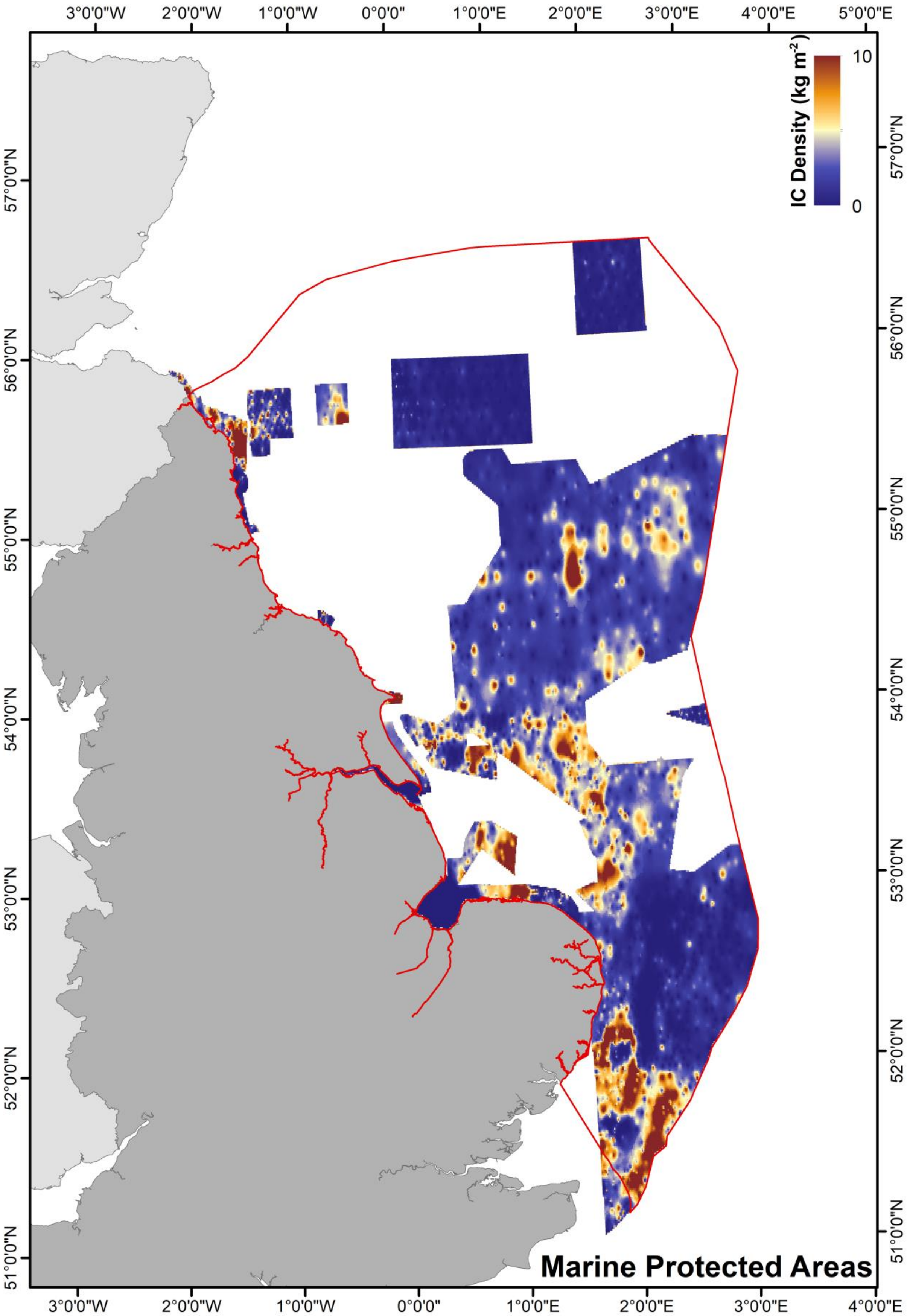

Figure 9. *Inorganic carbon stocks within the North Sea MPA network (Smeaton et al., 2021).*

Table 12. *Total carbon stocks within the whole study area and its MPA network. Method 1 = sediment classification (Smeaton et al., 2021), Method 2 = Spatial Modelling (Smeaton et al., 2021).*

	Area	Method 1	Method 2		Accumulation
	(km²)	**OC Stock (Mt)**	**OC Stock (Mt)**	**IC Stock (Mt)**	**(kt yr⁻¹)**
Study Area *(English North Sea; Net Gain)*	113 947	75.43	37.40	62.98	38.89
Marine Protected Areas*	57 307	37.97	19.40	26.52	16.70
% in MPAs	50%	50%	52%	42%	43%
Marine Conservation Zones (MCZ)					
Farnes East	944.6	0.674	0.352	0.405	0.43
North East of Farnes Deep	491.4	0.311	0.158	0.421	0.13
Swallow Sand	4 745.1	3.100	1.741	0.409	1.32
Fulmar	2 438.4	1.641	0.934	0.193	0.75
Markham's Triangle	200.4	0.132	0.065	0.038	0.03
Holderness Offshore	1 175.6	0.767	0.423	0.865	0.4
Kentish Knock East	96.4	0.028	0.032	0.005	0.01
Orford Inshore	72.0	0.034	0.026	0.006	0.01
Berwick to St Mary's	1 916.7	2.689	0.450	2.307	1.744
Coquet to St Mary's	601.6	1.027	0.153	0.102	0.8
Cromer Shoal Chalk Beds	374.0	0.194	0.093	0.124	0.16
Holderness Inshore	366.8	0.209	0.124	0.209	0.24
Runswick Bay	72.0	0.090	0.015	0.032	0.051
Special Area of Conservation – Offshore (SAC)					
Dogger Bank	12 344.2	8.018	4.248	5.847	1.15
Haisborough, Hammond and Winterton	1 470.0	0.994	0.429	0.571	0.25
Inner Dowsing, Race Bank and North Ridge	845.3	0.864	0.292	0.881	0.27
North Norfolk Sandbanks and Saturn Reef	3 610.1	2.566	1.134	2.097	0.4
Southern North Sea	36 428.0	24.986	11.679	17.509	4.95
Special Area of Conservation – Offshore (SAC)					
Humber Estuary	652.7	0.551	0.136	0.039	0.44
Flamborough Head	54.5	0.046	0.010	0.255	0.044
The Wash & North Norfolk Coast	1 077.2	0.760	0.356	0.346	0.57
Berwickshire & North Northumberland Coast	366.6	0.291	0.143	0.888	0.74

*NB There are several MPAs included in the English North Sea that could not be included as the carbon data available does not intersect with these protected areas. This includes the Alde, Ore and Butley Estuaries SAC, Tweed Estuary SAC, North Norfolk Coast SAC, and Aln Estuary MCZ. Overlaps among areas results in the combined area and carbon stocks of MPAs being less than the sum of the values for individual MPAs.

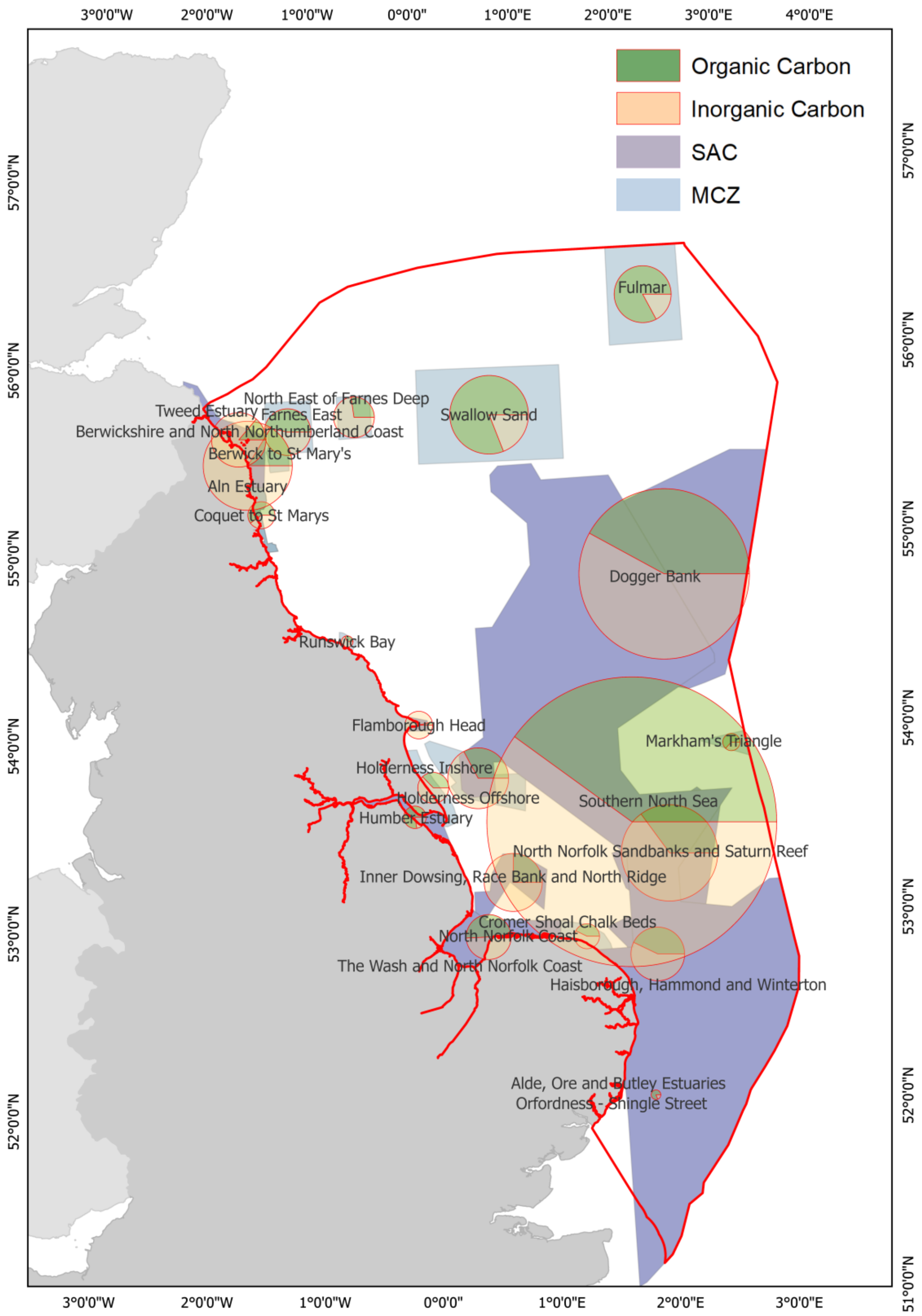

Figure 10. *Summary of blue carbon stocks across the English North Sea MPA network. Pie charts show the relative proportions of organic (green) and inorganic (yellow) blue carbon stocks, with their size scaled to the total carbon stored by each MPA to a maximum 29.19 Mt (Southern North Sea SAC). Total carbon stored are calculated using Spatial Modelling (Smeaton et al., 2021).*

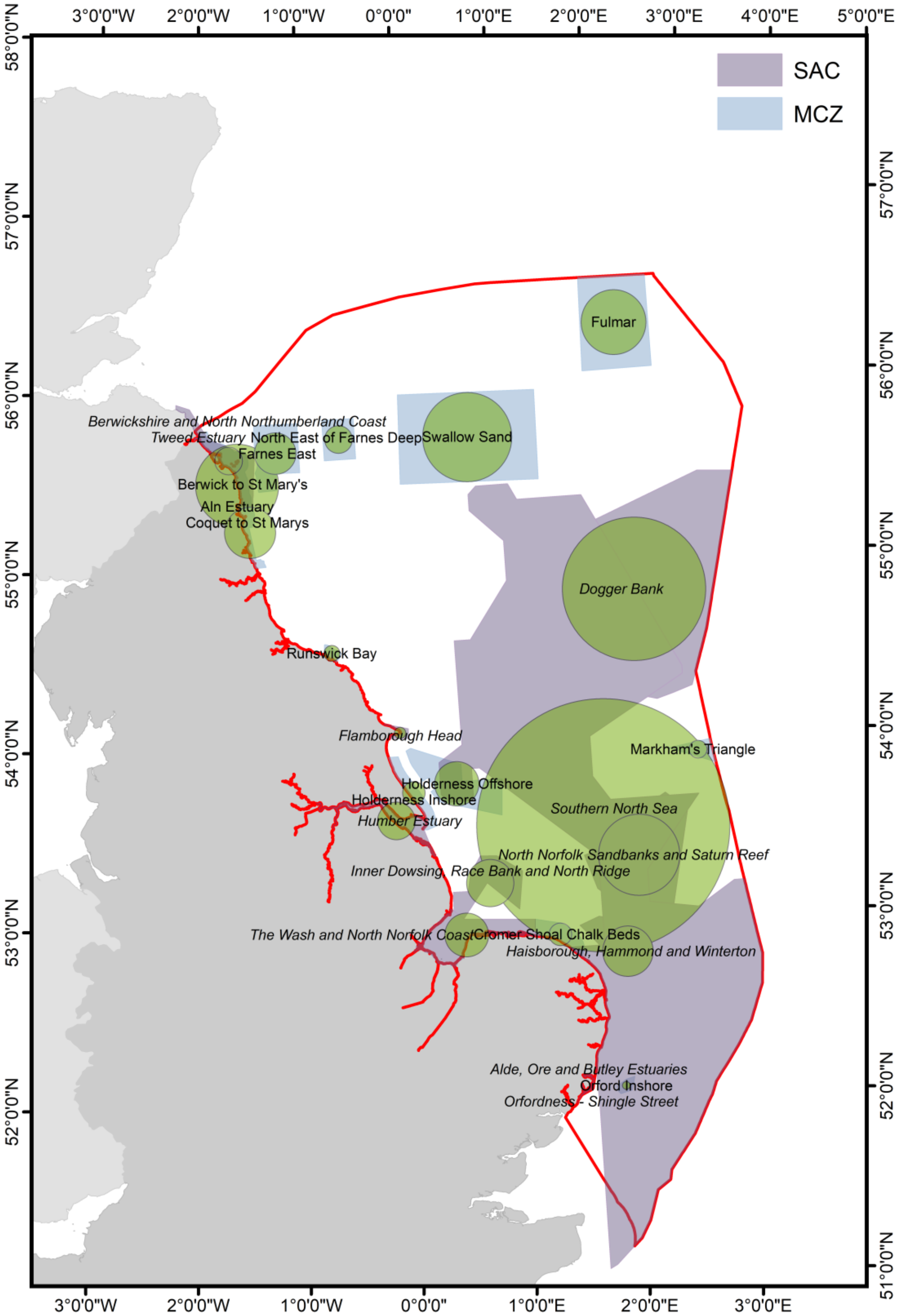

Figure 11. *Summary of blue carbon stocks across the English North Sea MPA network, scaled to organic blue carbon stocks stored by each MPA to a maximum 24.97 Mt (Southern North Sea SAC). Total carbon stored are calculated using sediment classification (Smeaton et al., 2021).*

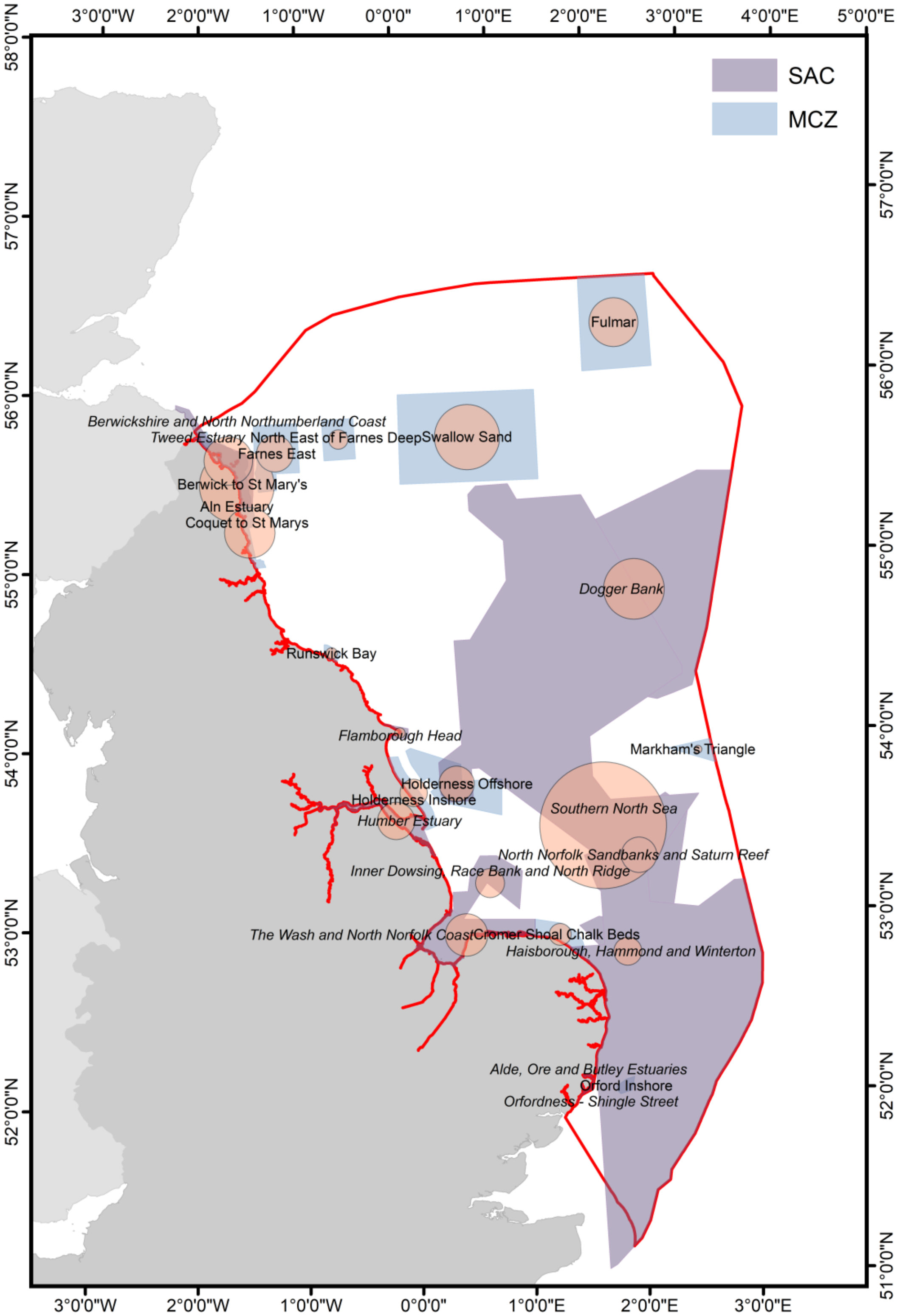

Figure 12. *Summary of blue carbon accumulation rates across the English North Sea MPA network, scaled to accumulation rates by each MPA to a maximum 4.95 Kt yr-1 (Southern North Sea SAC).*

In summary, the seabed within the MPA network contains significant stocks of carbon and sequestration potential, with 46% of carbon stocks (combined OC and IC) and 43% of carbon sequestration in the region in offshore MPAs (**Table 12**). The network was not initially designated for carbon stocks or storage potential, but for biodiversity considerations. This biodiversity focus is evidenced by some high stock/sequestration areas not included within the MPA areas., As such, it does not cover some of areas with potentially the largest stock densities (e.g. the northern portion of the study area). However, the existing network can offer considerable present day co-benefits for carbon and potentially in future if any management actions relating to biodiversity protection and recovery are implemented.

4.6.1 Potential future MPA management:

The existing MPA network was not designated with carbon considerations in mind and not all are actively managed via regulation of human activities.

It should be noted that the outcomes of any MPA management for carbon are still quite uncertain due to lack of understanding of pressure impacts and recovery trajectories, both for carbon parameters but also associated biodiversity considerations, all of which are context specific, controlled by seabed physical conditions.

Furthermore, overall confidence in the carbon estimates presented here are low due to the poor evidence underpinning levels of sequestration within this region, which is limited to (only one paper, De Haas *et al.*, 1997) and dominance of the Norwegian trench in the modelling approach used by Diesing *et al.* (2021).

The effectiveness and even net effect of any management measures to reduce carbon stock loss (prevent emissions) and protect sequestration by disturbance (such as trawling) depends on a full understanding of carbon vulnerability (lability) and stock dynamics (relic vs a maintained stock). These are poorly understood parameters across the area, although targeted observations will improve this.

Additionally, pressure re-distribution into differing seabed areas and associated impact on carbon stock and accumulation (linked with biodiversity) is also a significant uncertainty and risk associated with increased protection or management of existing MPAs based on carbon stocks. This is especially true as significant carbon stocks sit in areas adjacent to some existing MPAs (e.g. Dogger Bank – to North and South), which would be affected by displacement of fleet activity and could subsequently increase the risk to these unprotected stocks.

4.7 Ecosystem-scale carbon budget

Summarising the dynamics of carbon stocks across the main blue carbon habitats and their associated sediment stores (**Table 13**) shows the relative importance of each component. While some elements remain unknown, these values show the overriding importance of phytoplankton and sublittoral sediments as the primary source and store of carbon respectively in the region.

Table 13. *Summary of carbon stocks and sequestration capacity in the study region. Values here summarise those presented in the habitat reviews (Section 2), extent estimates (Section 3) and the description of sediment carbon stores (Section 4). Shaded cells indicate no data or insufficient evidence to present values with confidence. The lower part of the table gives contributions by blue carbon habitats.*

English North Sea 2021			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) [1m depth]	Stock (g C/m²) [1m depth]	Storage rate (g C/m²/yr)	Storage capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)
Phytoplankton		113947			81	9271	927									
All sediment	(Method 1)	113947	37.5	329				1190	10.4	1190	63.0	553	3.4	384		
	(Method 2) [	112505	29.7	264]												
Biogenic habitats		584	0.8		285	165	17	77		77						
	Total / Average	114531	38.3		82	9437	944	1266		1266	63			384		

		Organic carbon								Inorganic carbon					
Habitat	Extent (km²)	Stock (1000t C)	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 (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	379.5	58.4	154	332	126.1	12.6		0	0						
Intertidal macroalgae	22.6	3.0	122	378	7.5	0.9		0	0						
Seagrass beds	49.3	117.9	2390	274	13.5	1.4	3.6	100.4	5.0						
Saltmarshes	132.7	579.5	4085	138	18.3	1.8	72.9	129.0	74.8						
Biogenic reefs															
Modiolus modiolus beds	NA														
Sabellaria reefs	NA														
Total	584.1	758.8		285	165.4	16.6	76.5	37.8	79.7						

4.7.1 Organic carbon

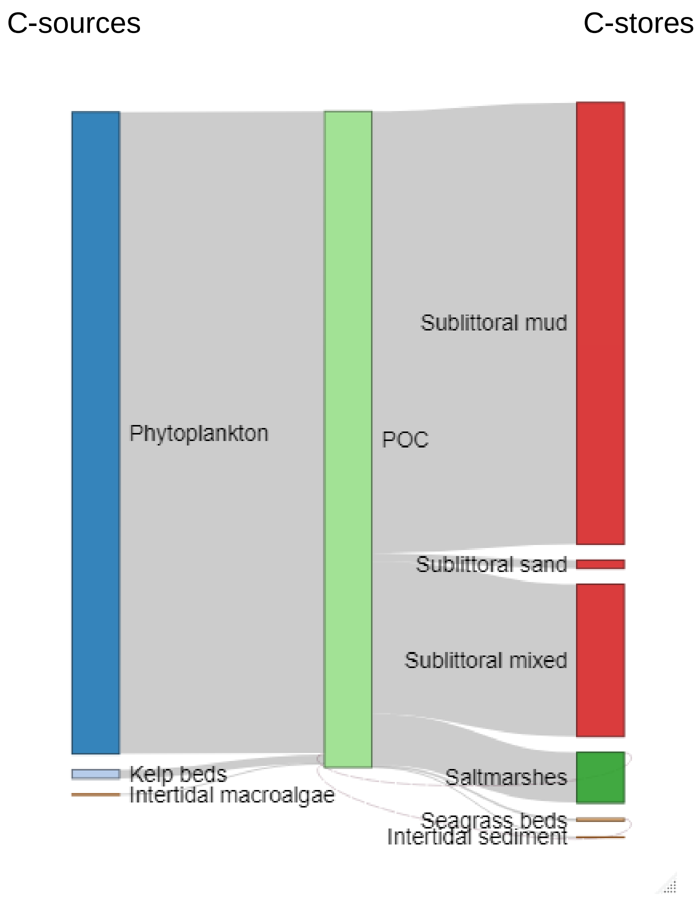

Figure 13. *Annual flows of organic carbon from sources to stores in the region, based on values presented in Table 13 and shown as a Sankey diagram with flows from left to right. Heights of each block represent the flows into and out of each carbon source or sink, with the sum of particulate organic carbon (POC) produced annually from phytoplankton (green central bar) estimated as 927 000 tC (0.93 MtC/yr) for reference. Total inputs of POC to stores (1.27 MtC/yr) have been scaled to match estimated total outputs from primary producers (0.94 MtC/yr).*

Carbon stocks across the region vary widely in magnitude among the component habitats and contributing elements of the ecosystem (**Table 13**). For organic carbon stocks, the dominant fraction (98%) is in surface marine sediments, with a total of 37.5 MtC in the top 10cm of the sediment. The remaining 2% of organic carbon stocks, 0.76 Mt C, is spread among the coastal vegetated blue carbon habitats, primarily in saltmarshes (0.58 MtC) followed by seagrass beds (0.12 Mt C). Macroalgae habitats (kelp 0.06 Mt C; intertidal macroalgae 3000 tC) host the remaining organic carbon stock as living material. Fixation of carbon by macroalgae (mostly kelp, tC yr^{-1}) exceeds that of vegetation in saltmarshes and seagrass beds by almost an order of magnitude due to the greater extent and production rate. Macroalgae beds store no carbon beyond that in living plants, while the carbon present in vegetation is combined with sediments in saltmarshes and seagrass beds, resulting in a far greater stock density. Rates of accumulation of carbon in these sediments exceed rates of production by the seagrass and saltmarsh plants, suggesting that much of the carbon stored is imported (allochthonous, denoted Influx in **Table 13**, vs autochthonous, shown as Outflux).

Seabed sediments are thus by far the most important habitat for carbon storage in the region. Nonetheless, while blue carbon habitats (kelp beds, intertidal macroalgae, saltmarshes and seagrass beds) form only 0.5% of the total area of the region (584 km^2 of the total 114000 km^2), they do hold 2% of the total organic carbon stores.

Flows of organic carbon are also quite different among the components of the ecosystem (**Figure 13**). Contributions of plants and phytoplankton as primary producers to the pool of particulate organic carbon are very hard to estimate, but elsewhere (Burrows *et al.*, 2014), it has been assumed that around 10% or less of annual production of organic material as plant growth and reproduction is exported to the sediment as particulate detritus. Given this percentage and estimated total production from phytoplankton in the region using reported literature values (81 gC m^{-2} yr^{-1}), we estimate that 0.93 MtC may be added to the POC pool each year by phytoplankton. Annual plant growth and losses in blue carbon habitats contributes 17 000t C to POC, with kelp beds potentially providing 75% of this POC (12 600tC), followed by saltmarshes (11%, 1800 tC), seagrasses (8%,1400 tC) and intertidal macroalgae (5%, 900 tC). The annual export of POC from blue carbon habitats is about 2% of the total exported by phytoplankton and BC habitats combined.

The accumulation of organic carbon in blue carbon habitats and sediment stores is estimated independently from estimated exports of POC, being largely calculated from sediment accumulation rates. Yet the total estimated import of OC to these stores (1.27 MtC/yr, **Table 13**, Influx) is very similar to that of total OC exports from primary producers (phytoplankton and coastal vegetation export 0.94 MtC/yr as detritus to the POC added to stores, **Table 13**, Outflux); a reassuring convergence of values. Notably, blue carbon habitats, particularly saltmarshes, form a greater percentage of OC accumulations with 6% (0.077 MtC) of the total OC accumulation (1.27 MtC/yr). Blue carbon habitats are therefore around 12 times more important as accumulators of carbon stores than their relative area (0.5%) suggests.

4.7.2 Inorganic carbon

Much less information is available for inorganic than organic carbon stocks and flows in the region (Section 2.5). Data available (Section 1.1.1) suggests, that despite a lower percentage of carbonate than in shelly sands of regions further north, 63.0 MtC is stored in sediments in the region. No accumulation rates for inorganic carbon (IC) are presented in the reviews of habitats and stores (Sections 2 and 4) but storage rates from an earlier study (Burrows *et al.*, 2014) scaled to the lower proportion of carbonate in the region (3.4 gC/m^2/yr, **Table 13**) suggest that up to 0.38 MtC/yr may be stored as inorganic carbon each year.

4.7.3 Confidence and uncertainty

While a relatively high degree of confidence can be assigned to the broad picture presented by these values, particularly in terms of the approximate relative habitat extents and carbon stock sizes, it is important to highlight those elements where lack of data from the region and information on processes is lacking, reducing confidence in values presented. A good example is the lack of information on organic carbon accumulation rates in the region. One study cites a rate of 0.2 gC m^{-2} yr^{-1} (De Haas *et al.*, 1997), while another in a comparable coastal area of the English Channel (Queirós *et al.*, 2019) reports 59 gC m^{-2} yr^{-1}, the latter being a value closer to that used in the original audit of Scotland's carbon stocks (51 gC/m^2/yr, Burrows *et al.*, 2014). Changes in the lower estimate of organic carbon estimation would produce large changes in the estimate of 1.27 MtC/yr total sequestration in the region. Sublittoral sand comprises 73% of the area of the region (**Table 11**) yet contributes only 1% (17 000 tC of 1.27 MtC) of the quantity of organic carbon being stored each year.

Similarly, the mapping approaches which provide spatial variability maps of stock and sequestration (Diesing et al., 2017; Smeaton et al., 2021 and Diesing et al., 2021) all have inherent uncertainties due to interpolation methods or modelling approaches. The confidence in these predictions, and hence overview of carbon within the region will be improved by systematic (to reduce bias) additional observations of key carbon stock and sequestration parameters. This is also true for the coastal habitats (Parker et al., 2020).

Although a future aim of this type of assessment would be to facilitate the management of seabed regions for associated carbon co-benefits (along with biodiversity) there are some key evidence gaps which remain which will prevent outcomes of future management of human activities to remain highly uncertain. These relate to:

- Evidence of carbon source and lability which will control response to climate or human disturbance pressures and hence vulnerability
- Understanding of dynamics of carbon stocks and sequestration (and relationship between stock and sequestration) to inform protection or recovery predictions.
- Understanding between biodiversity and carbon parameters (both in control, pressure and release scenarios)
- Understanding of displacement behaviour under activity management and associated carbon / biodiversity trade-offs

Similarly, the lack of information on inorganic carbon accumulation rates for the region reduces confidence in the estimate of IC stored per year for the region. Given the claim that up to 80% of the carbon removed from the carbon cycle can be as inorganic carbon (Sun & Turchyn, 2014), this would appear to be an important knowledge gap.

4.7.4 Comparison with UK carbon stocks

Direct comparison of carbon stock sizes (MtC) and density (t/km^2) are fraught with difficulty, since methods of assessment, areas compared and timescales for storage of reported stocks are almost never similar enough to justify comparison. This is even more of a problem in comparing marine and terrestrial stocks, where soils and sediments and the nature of vegetated habitats are so radically different from each other. Depths of soils considered are a vital consideration, with terrestrial figures often extending to 1m or 30cm depth, while here we consider sediments to only 10cm depth.

Notwithstanding these overriding caveats, **Table 14** below presents values for broad visualisation of the relative magnitudes of key quantities.

***Table 14**. Comparisons of carbon stores in the English North Sea region with UK terrestrial habitats, using data from Cornelius et al. (2020). Carbon stocks in the English North Sea represent a relatively small fraction of the UK total (1) but can be seen as nearly 20% of those held in UK forests and woodlands.*

UK Terrestrial Carbon stocks							**English N Sea OC**			
	MtCO2e	MtC	Area km2	t/km2	g/m2	% total C	% C density	%UK Land area		Source
Total UK C stocks (1)	16231	4426	242000	18289						
Peatlands	10193	2780	29040	95727			0.3%	12%		
Grasslands	1941	529	96800	5469			6.0%	40%		
Grazing lands	1334	364								
Forests and woodland	1932	527	31460	16749			2.0%	13%		
Croplands	826	225	93400	2412			13.6%	39%	93400	
						(vs total)				
English North Sea OC	137	37	113947	329	329	0.8%		47%		
English North Sea IC	231	63	112505	264	264	1.4%				
English North Sea Total C	369	101		593	593	2.3%				
						19%	(vs forests)			

5 OUTPUTS

Details and links to data sources used in the report are given here.

5.1 Dataset availability

As discussed in Section 1.3, datasets used in this study are publicly available, except for minor modelled extents used for comparative purposes. These include the EUNIS level 3 combined map from JNCC[4], Natural England Marine Habitats and Species Open Data[5], and organic carbon (OC) and inorganic carbon (IC) stocks following the methodology of Smeaton et al. (2021)[6]

5.2 Maps

Mapped outputs are presented in Annex 1, for EUNIS Level 2 and Level 3 habitats/ sediments.

[4] https://jncc.gov.uk/our-work/marine-habitat-data-product-eunis-level-3-combined-map/
[5] https://data.gov.uk/dataset/bfc23a6d-8879-4072-95ed-125b091f908a/marine-habitats-and-species-open-data
[6] https://data.marine.gov.scot/dataset/organic-and-inorganic-carbon-content-surficial-sediments-within-scottish-adjacent-waters

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7 GLOSSARY

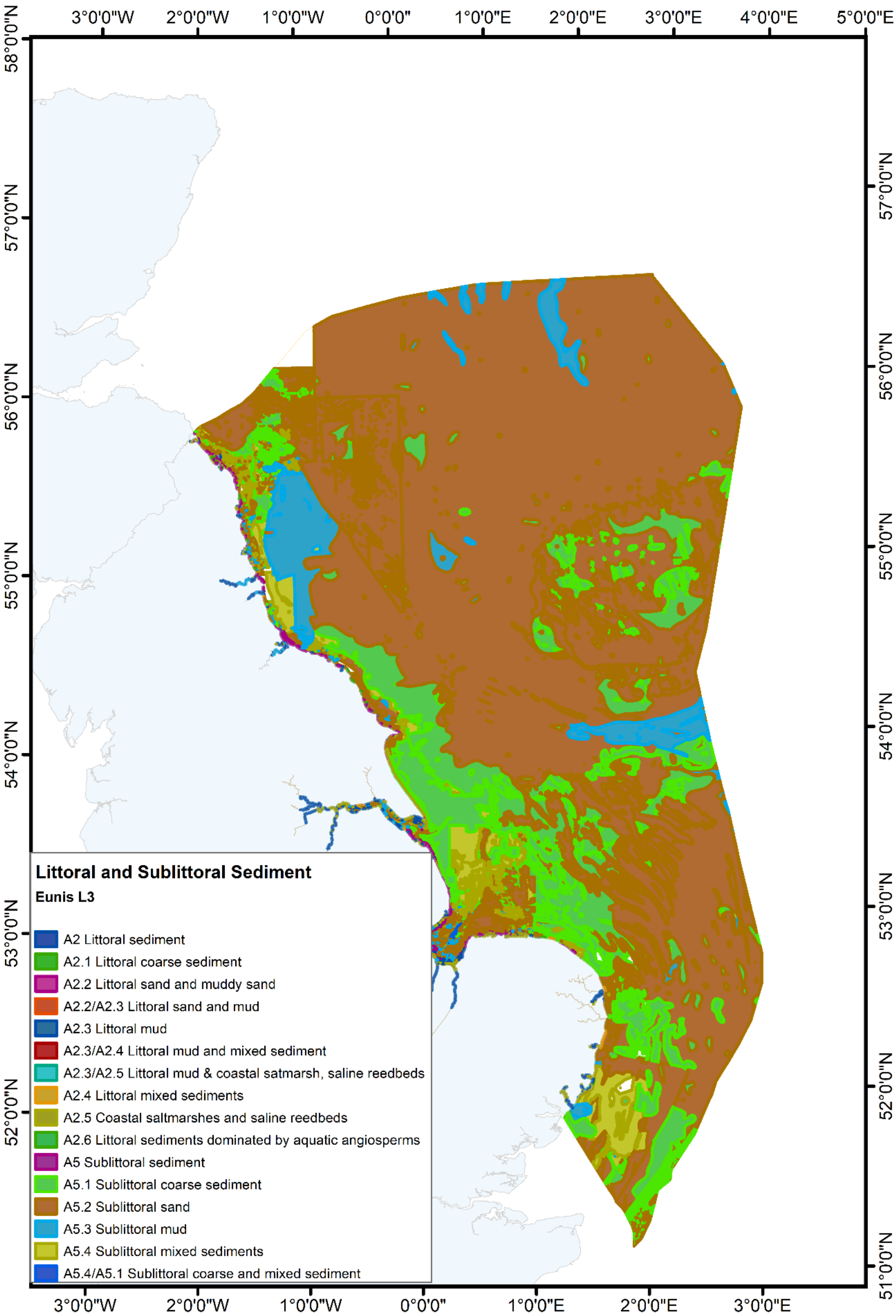
^{210}Pb	^{210}Pb is a radioactive isotope in the ^{238}U decay chain which can be used to date sediment up to 100 years old.
Basin	A large depression in which sediments are accumulated, or a tectonic circular, syncline-like depression of strata.
Blue Carbon	Carbon stored and sequestered in coastal and marine ecosystems, including tidal and estuarine salt marshes, seagrass meadows, and mangrove forests'. For the purposes of this study, 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 is reaches the seabed sediment, expressed in g C m^{-2} yr^{-1}.
Carbonate	A mineral composed mainly of carbonate (CO_3^{--}) ions with calcium (Ca) and may also include magnesium (Mg), iron (Fe) and other elements. Carbonate also refers to rock or sediments derived from debris of organic materials composed mainly of calcium carbonate such as shells or corals.
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	Bulk density is defined as the dry weight of sediment per unit volume of soil. Bulk density considers both the solids and the pore space; 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.
Fixation (or capture)	The conversion of carbon dioxide to solid carbon by animals and plants.
Gravel	Coarse-grained sediment, containing mostly particles larger than 2 mm in size and including cobbles and boulders.
Inorganic Carbon (IC)	Carbon dioxide (CO_2) gas, dissolved CO_2 and the ions bicarbonate (HCO_3^-) and carbonate (CO_3^{--}); particulate

	compounds of carbonate, e.g. calcium carbonate (Chalk, $CaCO_3$).
Labile carbon	Consists of sugars, proteins and other compounds easily used by marine bacteria.
Mud	A sediment having predominance of grains with diameters less than 0·06 mm. The term is a general term referring to mixtures of sediments in water and applies to both clays and silts.
Organic Carbon (OC)	Compounds of carbon, nitrogen and hydrogen and, in some cases, oxygen and sulphur, used by living organisms in the structure of their cells and as a reservoir of energy.
POC	Particulate Organic Carbon
Refractory carbon	Consists of high molecular weight and structurally complex compiunds that are difficult for marine organisms to use (e.g. lignin, humic acid, etc.).
Rock	An extensive geological term, but limited in hydrography to hard, solid masses of the Earth's surface rising from the bottom of the sea, either completely submerged or projecting permanently, or at times, above water.
Sand	Medium-grained sediment with a size 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 material that has settled out of a state of suspension in liquid.
Sediment Accumulation	The rate that sediment builds up on the seabed rate (SAR). expressed in cm yr^{-1}
Sedimentation	The process of deposition of mineral grains or precipitates in beds or other accumulations.
Sediment Trap	Sediment traps are containers that placed in the water column to collect particles falling toward the sea floor.
Sequestration	The process of addition of solid carbon to the standing stock.
Standing stocks	Stores of solid carbon in sediments.

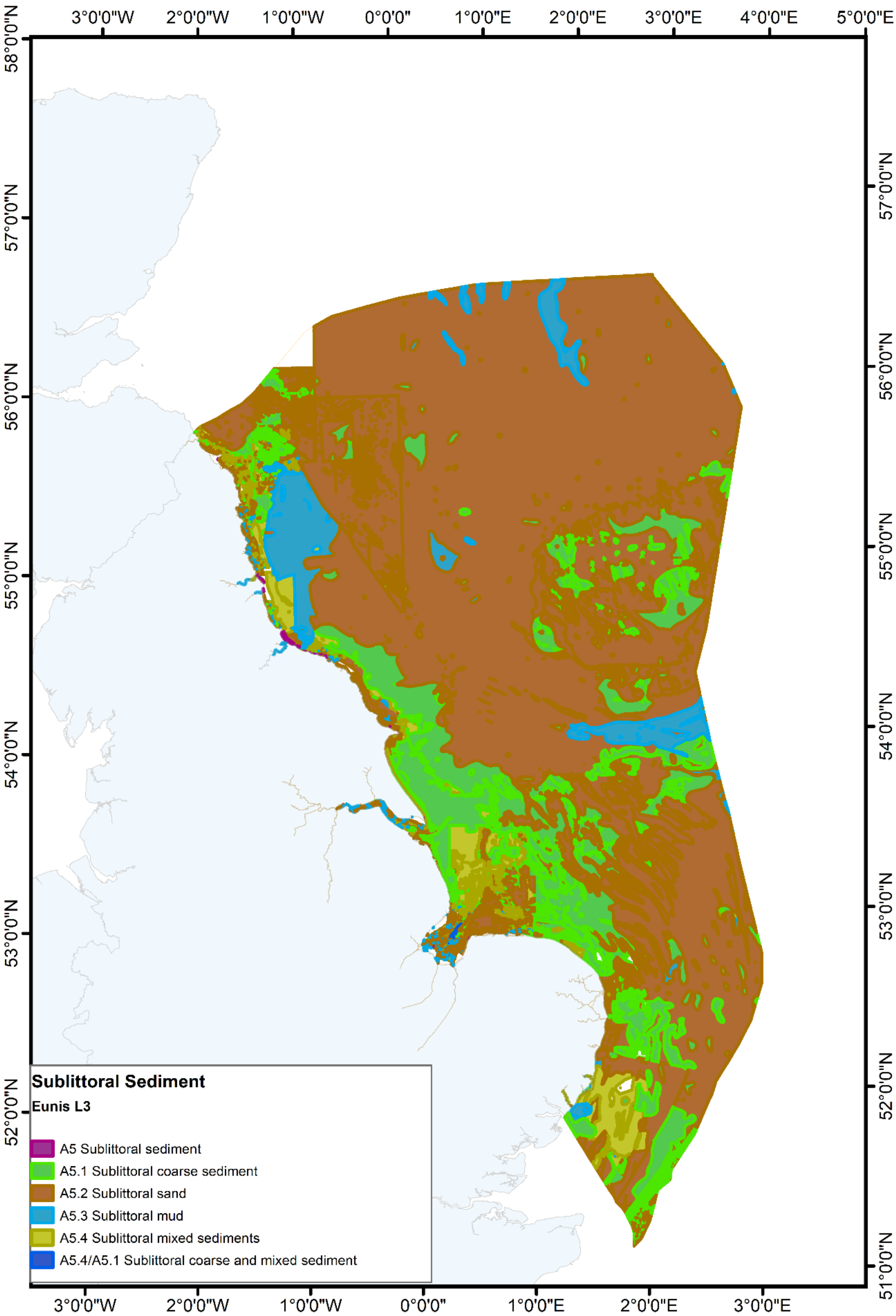
8 ANNEX 1 – EUNIS L2 & L3 MAPS

EUNIS level 2 and level 3 seabed habitat maps are presented below for the English North Sea.

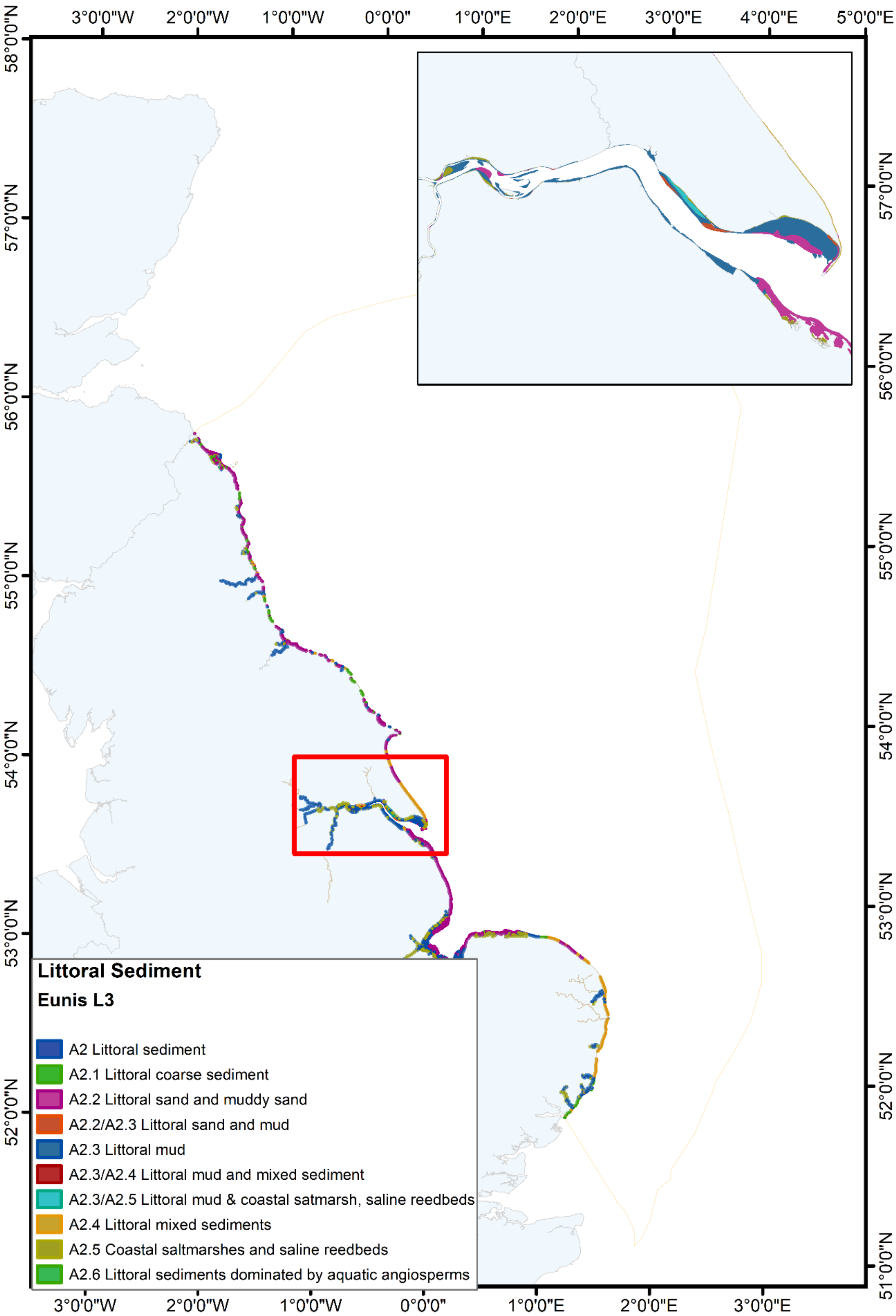
8.1.1 Habitat Extents – EUNIS L3



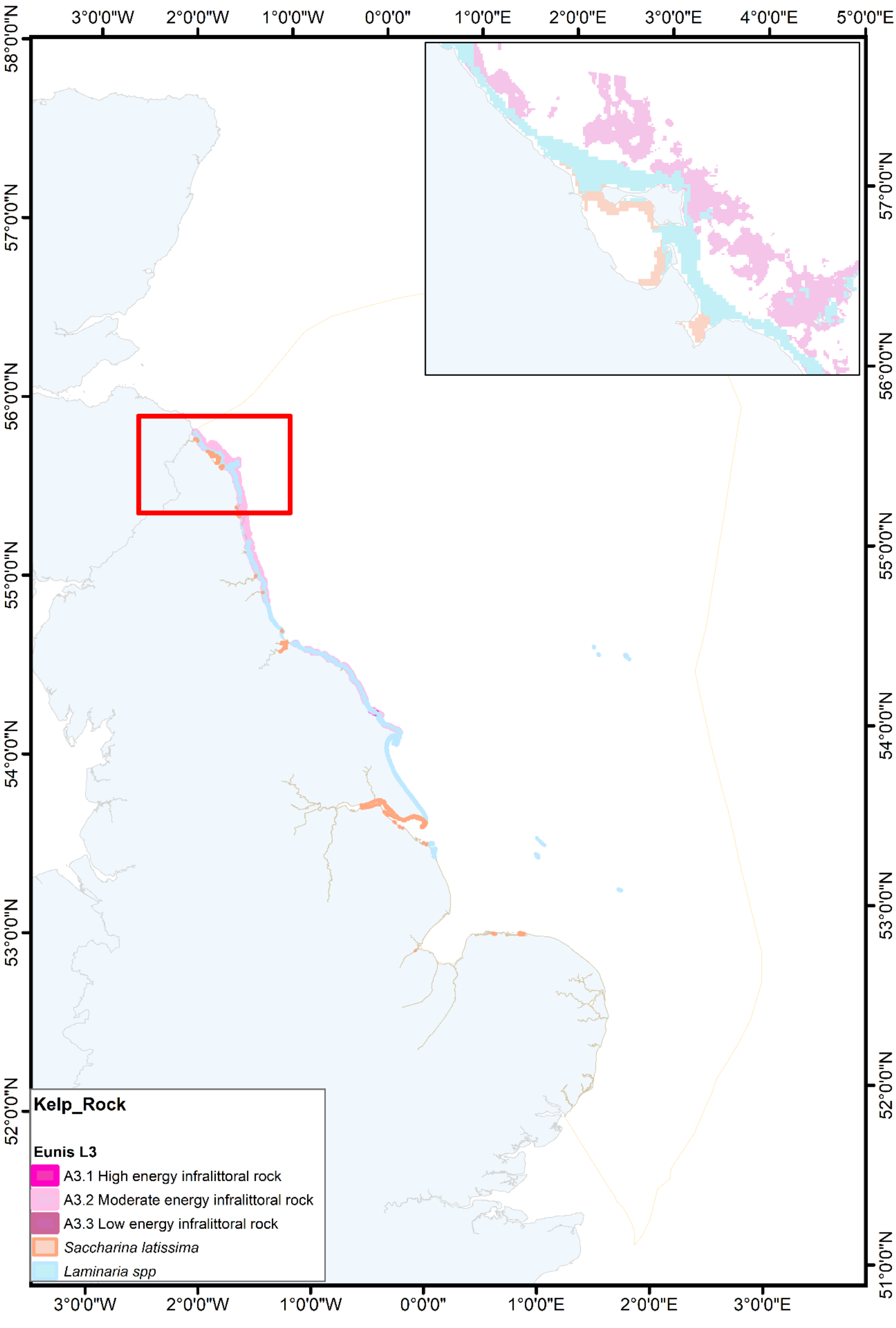
8.1.2 Sublittoral sediments (A5)



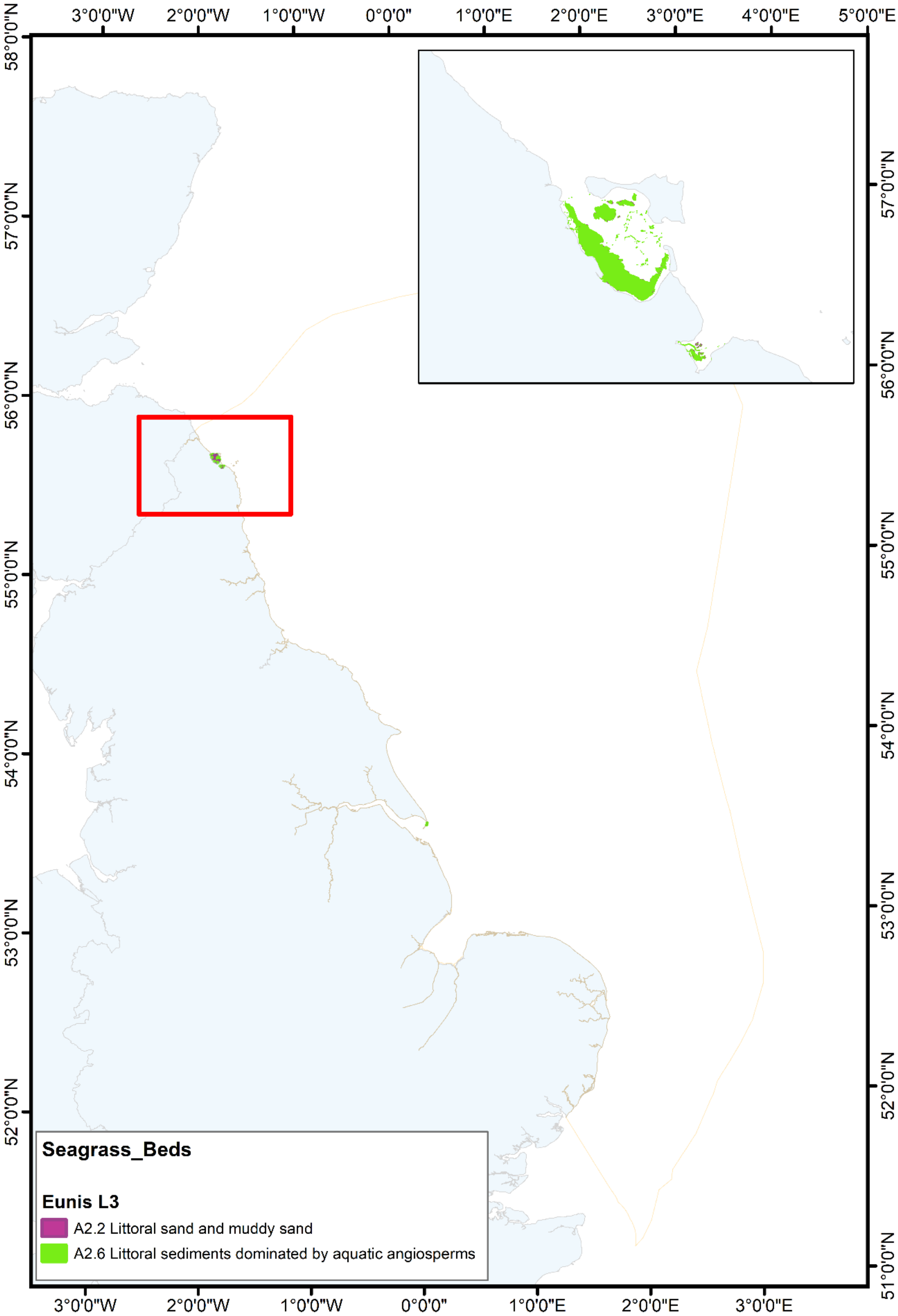
8.1.3 Littoral sediments (A2)



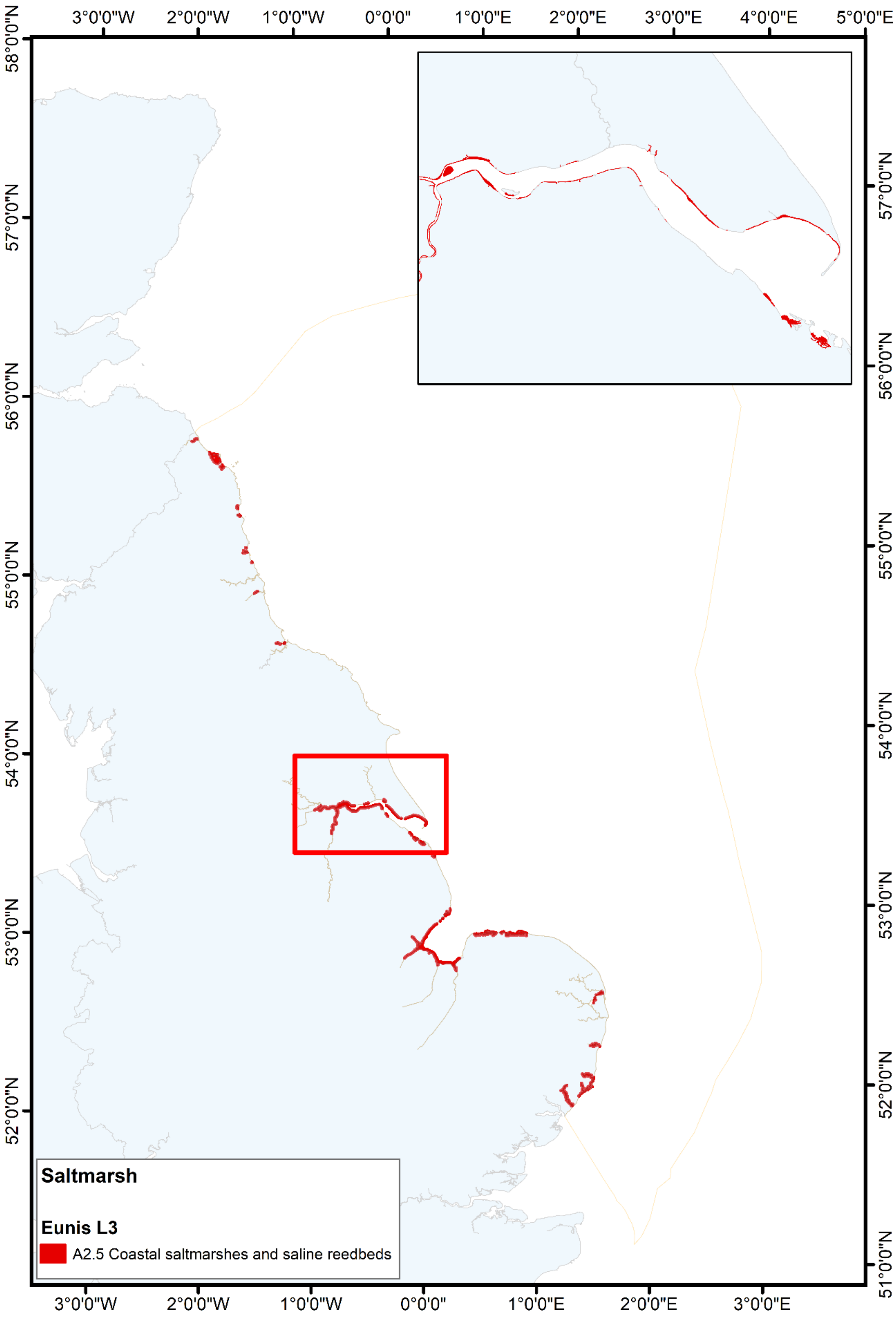
8.1.4 Kelp biomass and species



8.1.5 Seagrass



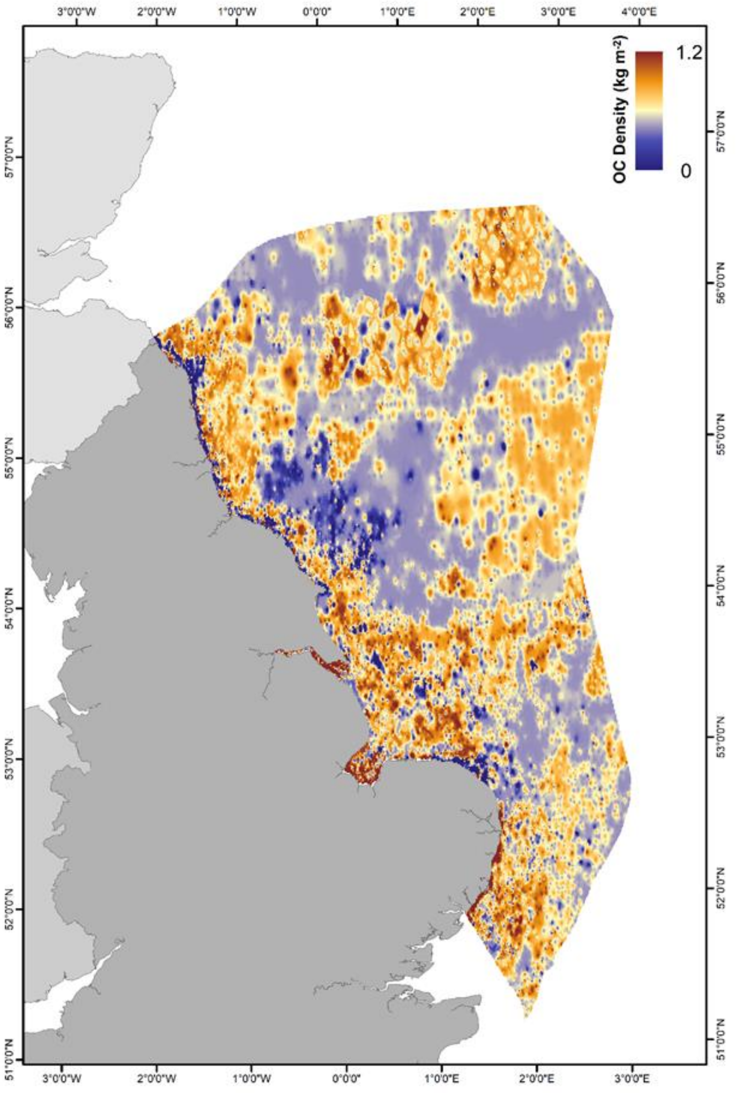
8.1.6 Saltmarsh

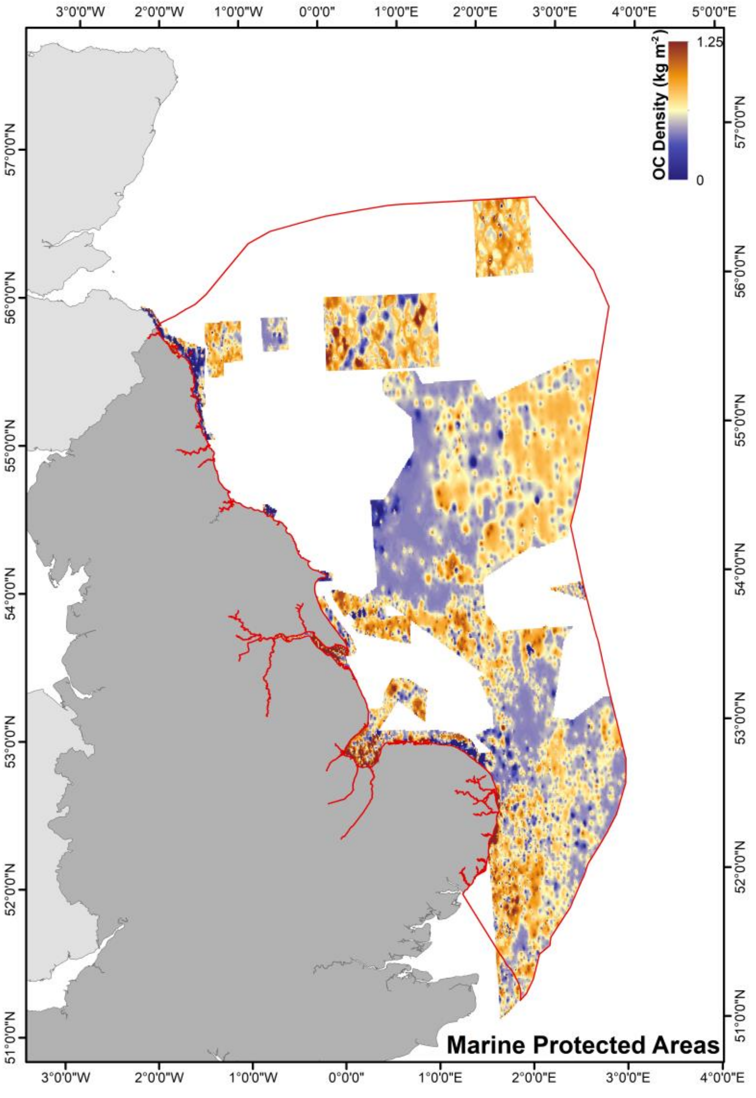


9 ANNEX 2 – CARBON DENSITY MAPS

Carbon density maps are presented below for comparison between the MPA network and study area.

9.1.1 Organic Carbon





9.1.2 Inorganic Carbon