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Scottish Marine and Freshwater Science Vol 11 No 3

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Contents

Blue Carbon Audit of Orkney Waters

J S Porter[1], W E N Austin[2], M T Burrows[3], D Clarke[4], G Davies[4],
N Kamenos[5], S Riegel[2], C Smeaton[2], C Page[4], A Want[1,4]

[1] International Centre for Island Technology, Heriot Watt University Orkney Campus, Robert Rendall Building, Franklin Road, Stromness, Orkney, KW16 3AW
[2] School of Geography & Sustainable Development, University of St Andrews, St Andrews, Fife, KY16 9AL
[3] Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll. PA37 1QA
[4] Aquatera Ltd., Old Academy Business Centre, Stromness, Orkney, KW16 3AW
[5] School of Geographical & Earth Sciences, University of Glasgow, Glasgow, G12 8QQ

Keywords

Blue carbon; inorganic carbon; organic carbon; storage; standing stocks.

Background

In this study, we provide an audit of the potential blue carbon resources present in the coastal waters around Orkney, bounded by the 12 nautical mile limit and including the Loch of Stenness brackish water lagoon. This report builds on previous work by Burrows et al. (2017) in which blue carbon stocks in Marine Protected Areas in Scottish waters were estimated from i) contributions of biological material to the fixation of carbon, also referred to as production, and ii) contributions of sediments to blue carbon storage. The methodology has been further developed here to allow regional-scale estimation of habitat extent and provides estimates of blue carbon associated with habitats and surface sediments.

Main findings

1. The overall estimated blue carbon in Orkney regional waters is 67 Mt.
2. This is divided into 61.4 Mt in sedimentary stores and 5.9 Mt in living biological habitats.
3. The audit found that the largest blue carbon source in Orkney waters came from the inorganic carbon in sediments. This was divided into 59.1 Mt C in inorganic carbon stores and 2.27 Mt carbon in organic stores.

4. In a local geographical context, the coastal waters around Sanday and North Ronaldsay contained large accumulations of organic carbon due to the kelp forest habitats in the shallow coastal zone and carbon deposits in sediments. The maerl beds at Wyre and Rousay also constitute a hotspot of both organic and inorganic carbon. In Scapa Flow, the area to the north-west of Cava Island and also through Gutter Sound represent key areas for blue carbon due to accumulations of horse mussel beds and flame shell nests.
5. In a Scottish context, Orkney waters account for 8.1% of Scottish inshore waters (defined by a 12 nm boundary), holding 67 Mt of blue carbon. In Orkney we find 67 Mt in a sea area of 7,290 km^2. This equates to a density of 9,190 tonnes C per km^2 in Orkney waters. This figure is likely to increase when further data on the thickness of deposits underlying the biological habitats becomes available.

Executive summary

In May 2019, the Scottish Government declared a global climate emergency in response to climatic change linked to elevated CO_2 levels in the atmosphere. The most obvious effects of climate change include increased atmospheric and sea surface temperatures, ocean acidification, and greater occurrences of ‘extreme’ weather events. While the world’s ocean forms the largest natural ‘sink’ for carbon, the rate of capture and storage in sea water is reduced by increasing levels of atmospheric CO_2, rising global temperatures, and stratification of the surface ocean.

The term ‘blue carbon’ has been used to describe carbon stored in the marine environment. As part of the Scottish Government’s objectives to lead the world in adopting evidence-based policies to mitigate climate change, an audit of blue carbon resources has been commissioned for the waters around the Orkney Islands archipelago. This report is the most comprehensive regional audit of blue carbon resources to date.

Blue carbon refers to carbon captured by biological metabolic processes, i.e. in the soft tissues, shells, and skeletons of plants and animals, and buried in the marine environment in sediment. In some regions this may also include carbon of terrigenous origin. In this audit, the evaluation of carbon storage includes shallow habitats created by marine organisms, and also, the resources stored in surface marine sediments. Once living tissue dies, the resulting organic carbon in biological material may be transported, and ultimately deposited and accumulated in seabed sediments. Carbon stocks in sediments that accumulate in this fashion may remain stored over far longer time scales, for example in the hundreds of years to thousands of years and in much larger amounts than stocks found in biological habitats, although the longevity of certain biological features, such as reefs, is poorly understood.

Currently, detailed understanding of blue carbon capture and storage is limited to a few, relatively well-studied coastal ecosystems, including mangroves, saltmarshes and seagrass beds. In Scotland few published papers report on the contribution of marine habitats to blue carbon.

The Orkney Blue Carbon Audit was conducted using a four-stage approach: 1) assessment of habitat abundance based on data collected during *in situ* surveys; 2) mapping of areas of known habitats compiled from various data sources to inform habitat prediction models; 3) determination of carbon content for specific habitats based on recent and current *in situ* sample collection and laboratory analysis; 4) calculation of total organic and inorganic carbon contribution by combining areas and estimated carbon content of known habitats. Methods developed here will help inform similar studies as part of future audits of regional marine resources.

Key blue carbon habitats evaluated in this audit included a wide variety of biological and sedimentary environments. The Orkney Blue Carbon Audit estimated 67 million tonnes (Mt) of blue carbon resources in Orkney, composed of 5.9 Mt in biological stocks and 2.27 Mt organic carbon and 59. 1 Mt the figure for inorganic carbon will increase in future when data gaps on the thickness of sediment deposits underlying biological habitats are addressed (e.g. horse mussel beds, flame shell beds, brittlestar beds, maerl beds) along with information on the extent of shell banks. Organic carbon stock figures are also likely to increase as there are stocks of organic carbon associated with inorganic carbon and trapped in the anoxic layers where carbon becomes recalcitrant.

In biological habitats in Orkney, the most important stocks of blue carbon are found in maerl beds, kelp forest, and seagrass beds (*Zostera*). In particular, maerl beds had the highest contribution of blue carbon to the audit as well as having the highest density of carbon (tonnes per hectare[1]). New research generated for this report has provided greater details on carbon stocks in several habitats, such as saltmarsh, brittlestar beds, and bryozoan thickets.

Knowledge gaps have been identified and suggestions made to prioritise future research. Additional habitat surveys and sample analysis will further reduce uncertainty in evaluating carbon resources. ‘Ground-truthing’ will improve predicted habitat models in locations where real data are not currently available.

While uncertainties remain, the general conclusions presented here on blue carbon resources in Orkney waters are robust. The audit will inform the Orkney Islands Marine Region: State of the Environment Assessment. The extent to which blue carbon issues could be addressed as part of the statutory regional marine planning process will need to be considered through engagement with stakeholders and public consultation.

Informed management could enhance the capacity of key habitats in providing a carbon sink, while at the same time encouraging sustainable use of the marine environment.

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[1] 1 A conversion table for units commonly used throughout the report can be found in Appendix D.

1. Introduction

1.1. Project background

This first regional blue carbon audit has been commissioned by the Scottish Government with the overall aim of developing robust methods to assess blue carbon stocks associated with key habitat types. The Scottish coastline is complex with Scottish inshore territorial waters comprising about 20% (90,404 km^2) of the total area of 462,263 km^2 of Scotland's seas (Marine Scotland, 2019a).

The focus of this regional audit is on Orkney coastal waters primarily bounded by the 12 nautical mile limit. The geographical boundaries of this audit encompass a sea area of some 7290 km^2 and a coastline of approximately 1220 km along the Mean High Water Spring mark, accounting for 8.1% of Scottish territorial waters.

It is estimated that over half of total carbon captured by marine habitats occurs in the relatively shallow coastal waters extending from the shore to the edge of continental shelf (Borges, 2005). Following discussions with the Scottish Government, Scotland's Blue Carbon Forum, and other stakeholders (including the Orkney Islands Council Marine Planning Team), the following additional caveats were included in defining the extent of this Orkney audit (Figure 1.1):

- 12 nautical miles, except for the waters separating Orkney from the neighbouring county of Caithness, i.e. the Pentland Firth. In these areas, Orkney waters are defined up to the midpoint between regions. See also documentation on Scottish Marine Regions and Offshore Marine Regions (Marine Scotland, 2019b).
- Exclusion of the waters surrounding Sule Stack and Sule Skerry.
- Inclusion of the Loch of Stenness. This brackish lagoon is a designated Special Area of Conservation (SAC) featuring saltmarsh habitats.

The complex coastline of Orkney is matched by a diverse range of different biotopes and geological features. Biological habitats include kelp forests, maerl beds, seagrass (*Zostera*) beds, saltmarshes, horse mussel beds, flame shells, brittlestar beds, and bryozoan thickets; geological habitat features include bare rock and a variety of mobile sediments from muds and sands to gravel and boulders.

When undertaking a regional assessment of this type, it is important to bear in mind that key physical factors such as the tidal flow regime and wave exposure, along with the underlying geology will combine to influence the diversity of the communities that thrive by living on and in the habitats in the area.

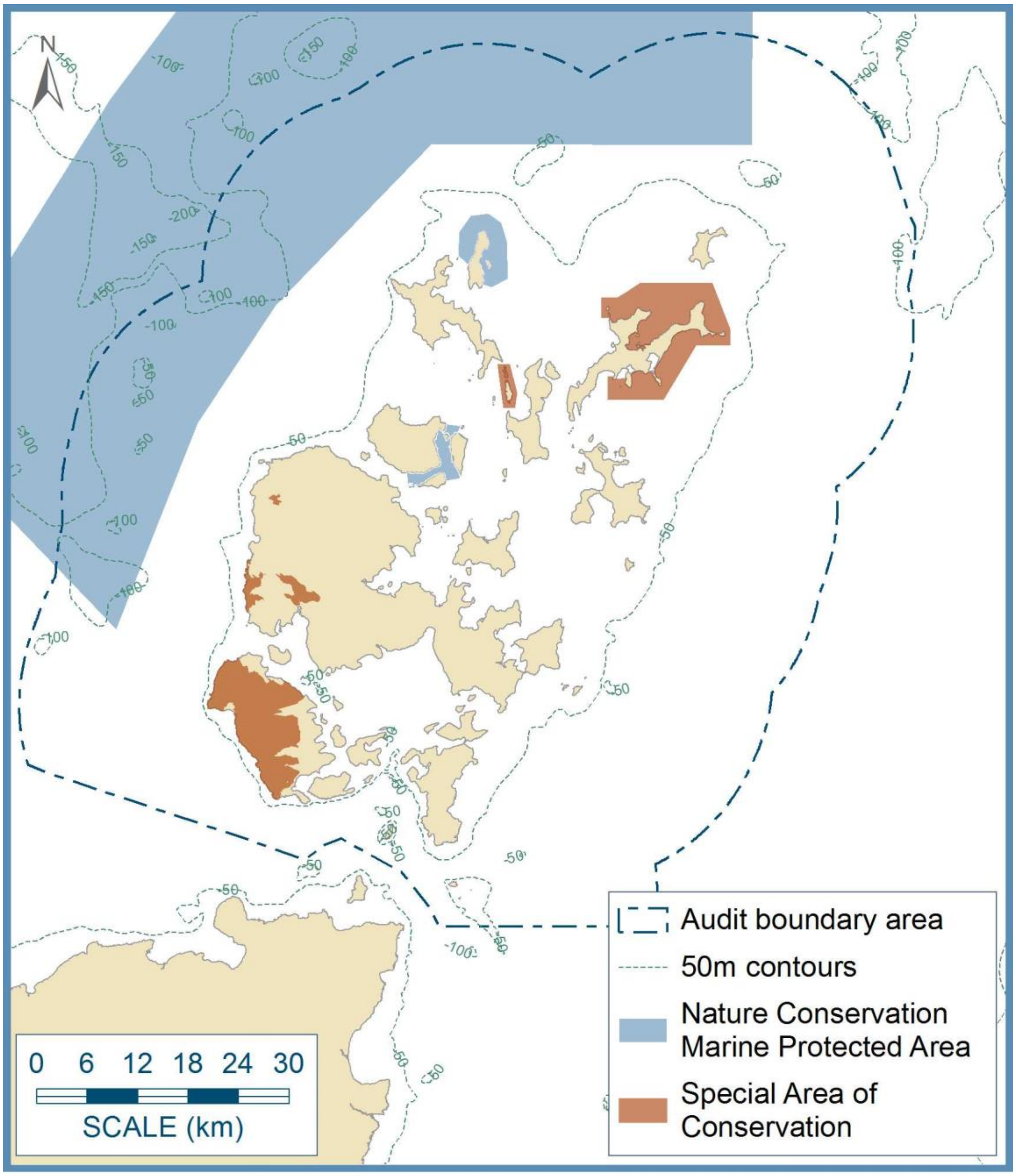

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Figure 1.1: The boundary of the Orkney Blue Carbon Audit. A detailed map with place names can be found in Appendix C.

In this region, two large water masses, the North Sea and the Atlantic Ocean, meet producing a wide range of hydrodynamic conditions. The East Shetland Atlantic Inflow and the Fair Isle Current are major influences, as described by Turrell *et al*. (1996) (Figure 1.2). Tidal heights and times on the west coast of Orkney are dominated by the Atlantic Ocean, while on the east side, tides are dominated by the

North Sea. Within Orkney waters, low tide occurs at markedly different relative times depending on location within the islands. As these large water masses pass through narrow channels strong tidal currents are generated. The Pentland Firth regularly experiences flows of 4 m s^{-1} (Miller, 1994; Goddjin-Murphy *et al*., 2012), acting like a river in the sea as the tide surges from the Atlantic to the North Sea and back again. In contrast, the natural deep-water harbour of Scapa Flow experiences a range of current flow regimes from 3 m s^{-1} at Hoy Sound to <0.5 m s^{-1} in the sheltered embayments.

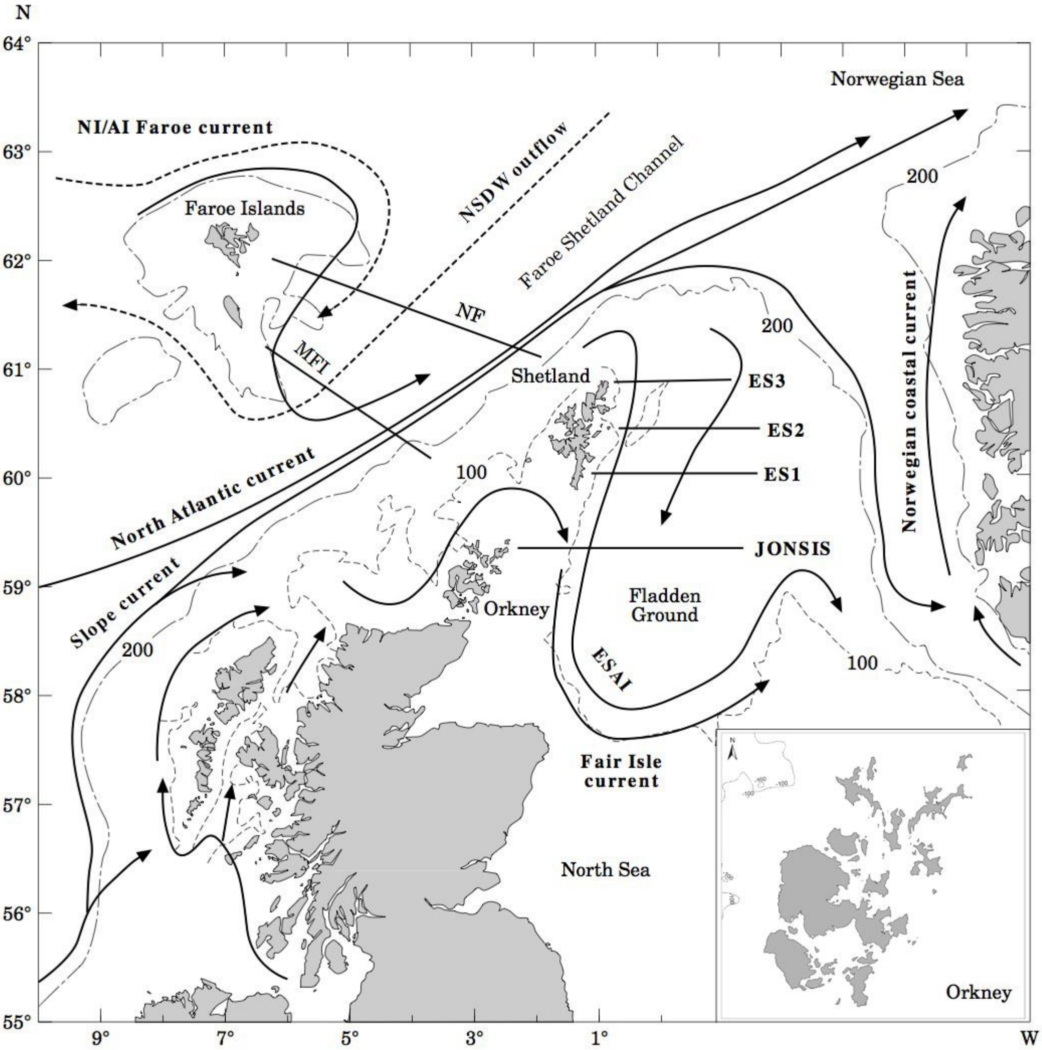

Figure 1.2: Key topographic features of the northern North Sea and adjacent oceanic areas in relation to the location of the standard hydrographic sections. Solid arrows represent surface circulation and broken arrows sub-surface; NF-Nolso-Flugga standard hydrographic section; MFI-Munken-Fair Isle section; Ni/AI-North of Iceland/Arctic intermediate water; NSDW-Norwegian Sea Deep Water (modified from Turrell *et al*., 1996).

With a maximum fetch in excess of 3,000 km, the west coast of Orkney can experience wave heights in excess of 18 m during storm events (EMEC, 2019). In contrast, reduced fetch in Scapa Flow and between islands greatly diminishes wave exposure. This gradient of wave exposure is a key component influencing marine habitat type and extent (Lewis, 1964; Want, 2017).

1.2. Terminology

Describing the dynamics of the ocean carbon sink is complex and requires clarity of terminology. In this report, stores of carbon in living material are referred to as **standing stocks**, stores of carbon in sediments are called **stocks.** The conversion of carbon dioxide to carbon in living material is referred to as **fixation** or **capture**, and the addition of carbon to sediment stocks is referred to as **burial. Sequestration** refers to the addition of carbon to long-term stocks. **Production** refers to the annual amount of carbon captured. A **sink** is where carbon exists in marine sediments where dead organic and inorganic material may be buried.

With the ocean absorbing about one third of atmospheric CO_2 (Woolf *et al.*, 2019), a critical factor in mitigation of elevated CO_2 levels is the rate of carbon sequestration into marine habitats (Doney *et al*., 2009). A major ‘sink’ of carbon exists in marine sediments where dead organic and inorganic material may be buried (referred to as stock). In addition, a significant standing stock is stored within living marine organisms. These organisms include animals and plants that produce calcium carbonate skeletons and shells such as molluscs, corals, and coralline algae, including maerl. In addition, significant amounts of carbon are captured in the soft tissues of all marine organisms including major photosynthesising producers such as kelp, other marine algae (not included in this audit) and *Zostera*. Carbon production by kelp forest is significant, but how much of that goes into the longer-term stores by sequestration, is still unclear.

The identification, and management of such carbon resources are important for allowing us to understand the contribution they make to the overall carbon budget for the region.

This audit provides an estimate of the blue carbon stocks in Orkney coastal waters, based on the latest research and survey work on mapping distributions and measuring of carbon content within the key habitats. The figures generated include designated sites such as the Wyre and Rousay Sound Marine Protected Area (MPA). The inshore waters of Orkney host a range of biological habitats and geological features, many of which (such as horse mussel reefs) may potentially provide high carbon capture rates through the retention of carbon in shell material, as well as the burial of organic carbon in the underlying sediments.

1.3. Project objectives

The objectives of the project were:

- Creation of a database of all available information on blue carbon habitats in Orkney.
- Development and testing of methods allowing estimates of blue carbon using available data. These methods should be readily applicable to other regional and national audits.
- Identification of knowledge gaps and priority targets for future research.
- Assessment of pressures on blue carbon stocks.

It should be noted that carbon sequestration rates are not included as part of this audit. Insufficient data currently exists for many of the key habitats on the processes of sequestration.

2. Methodology

The aim of this study is to produce a first quantitative assessment of the blue organic carbon and inorganic carbon present in the coastal waters of Orkney.

The audit was conducted using a four-stage approach:

1) assessment of abundance of specific blue carbon habitat types based on data collected during *in situ* surveys, i.e. drop-down video, diver surveys, shore surveys;
2) mapping of habitats compiled from publicly available data sources to produce habitat prediction models, to cover geographical areas for which actual survey data was not available;
3) determination of carbon content of habitat types based on past and current sample collection and laboratory analysis using Loss of Ignition (LOI) or volumetric based protocols;
4 calculation of total organic carbon (OC) and inorganic carbon (IC) contributions from each habitat type using the geographical extent estimated from the predictive models (stage 2) and the carbon values generated (stage 3).

Appendix A details the steps taken to achieve this. A caveat of the LOI method for estimating carbon values is that during the burn off of the organic carbon at 550 ºC, carbon is not the only material being lost, e.g. Nitrogen and Phosphorus are also being lost during this process. For some organisms the relative proportions of C, N and P are known and so burn up figures can be adjusted (e.g. blue mussels - see Table 3.6) while for others (e.g. flame shells – Table 3.7) they are not. Using the amount of organic matter (OM) generated from the LOI method will be an overestimate of the amount of organic carbon present in the sample because of the presence of additional elements (Santisteban *et al*., 2004). In some studies, estimation of OC is enhanced by including additional factors. There can also be variability in the results of LOI from different labs; to reduce this variability between studies, a standard protocol was adopted (Heiri *et al*., 2001).

2.1. Data review and blue carbon classification scheme

At the initiation of this study, Scottish Natural Heritage (SNH) supplied existing habitat distribution data in the form of a GIS database (GeMS V2i10 Geodatabase). Further data were acquired from the NBN Atlas (NBN, 2019), SeaSearch (Hirst, pers. comm.), the British Geological Survey (BGS), Cooke Aquaculture, Heriot-Watt University, Scottish Association for Marine Science, University of Glasgow, and the University of St. Andrews.

Table 2.1

Summary of the blue carbon category classification scheme used for this study; these are defined by the pre-existing mapped habitats and sediment types. Note: in Orkney waters, mud has not been mapped in the BGS sediment database.

Biological	Sedimentary
Kelp forest	Gravel
Maerl beds	Gravelly muddy sand
Zostera beds	Gravelly sand
Saltmarshes	Muddy sand
Horse mussel (*Modiolus modiolus*)	Muddy sandy gravel
Flame shell (*Limaria hians*)	Rock
Brittlestar bed (*Ophiothrix fragilis*)	Sand
Bryozoan thicket (*Flustra foliacea*)	Sandy gravel
	Slightly gravelly muddy sand
	Slightly gravelly sand

2.2. Assessment of spatial extents of habitats

Habitat data included both point records and habitats mapped as polygons. In some cases, blue carbon habitat point data had been extrapolated into habitat polygons with attendant spatial data.

A tiered approach was used to deal with the variability in data quality between the blue carbon habitat types, in common with the Burrows *et al*. (2017) report. The data supplied reflected that sampling effort had been concentrated in certain blue carbon habitats, especially where these coincided with priority marine features for protected areas while other habitat types received much less attention. In many studies, attention has been focused on determining area of distribution and organism abundance, rather than the critical third dimension of habitat thickness.

Models of the location and extent of geological and biological habitats were built using data in declining order of quality. Where mapped polygon data were available these were used as the primary data source. Where no polygon data existed, known databases were examined for alternative data. In the case of geological substrate, sediment grain size could be inferred from sediment data held by the BGS. Existing publicly available BGS data (BGS 1:250 000 superficial sediments) were imported into ArcGIS for further analysis. Substrate polygon data were used in preference to point data as a second-tier option. Such alternative data maps were available at a much lower resolution than the SNH polygon data, but the method was preferable to interpolation from point data.

With regards to Kelp forest, *Modiolus modiolus, Zostera marina, Limaria hians, Flustra foliacea and Ophiothrix fragilis* habitats, Maxent models were deployed to create predicted extents from known presence points using various environmental variables predictors as seen in Table 2.2 below. These came from a variety of open source platforms and Aquatera Ltd.'s data bank and research outlets. Presence points of each species were acquired through the MNCR Public Snapshot database and the NBN Atlas Gateway service. Additional details on predictive modelling can be found in the Appendix. In the case of maerl, carbon estimates were based on more extensive point data captured by *in situ* diver observations and drop-down video. Some limited interpolation between point data was used when data points were close together to create an area polygon.

In some cases habitats co-occur, creating the possibility of 'double counting' of carbon particularly in sediments underlying the habitats. For example, in areas where brittlestars overlay horse mussel bed, double counting is avoided because we only have figures for the underlying sedimentary carbon of horse mussels at the present time. In the case where seagrass is growing together with maerl (e.g. at Tingwall), sediment estimates of the latter only are applied to avoid double counting.

Table 2.2

Environmental variables used in predictive modelling of biological habitats used in the Orkney Blue Carbon Audit.

Species Data		
Presence occurrence points	MNCR Marine Recorder Public Snapshot	NBN Atlas Gateway
Environmental Variables		
Bathymetry	Aquatera Ltd Bathymetry Data Layer	
Wave exposure	Mike Burrows Log10 Wave Fetch Layer	
Fraction of light penetration at seabed	EU SeaMap 2011	
Maximum Tidal Current	Mohammed-Alaa Almoghayer / Heriot-Watt University / Aquatera Ltd - PhD Research (Unpublished)	
Substrate	EMODNet EUSeaMap 2016	
Biozone	EMODNet EUSeaMap 2016	

Following the habitat modelling, spatial data for each habitat and substrate blue carbon category were extracted. Standing stock of carbon was calculated for each habitat in turn, and itemised in this report, using data generated as part of this study or gathered from peer-reviewed literature as identified in Section 3 and 4. Results of the calculations have been tabulated in Section 5. The most valuable habitats and substrates from a blue carbon perspective have been identified following this analysis and are discussed in Section 6.

3. Habitat identification: Biological environments

3.1. Introduction

Habitats identified as having distinct contributions to blue carbon stocks and distinct rates of production and burial follow those of Burrows *et al.* (2014), excluding the production from phytoplankton. Some additional classes are added as habitats of particular local importance as blue carbon habitats. For some habitats, values used for the biomass per unit area (g C m^{-2}), modified by habitat thickness, were taken directly from Burrows *et al.* (2014) (see Annex 1 for more details) which gives details of the literature and methods used to obtain values for each habitat. In other cases, new data were generated.

3.2. Biological habitats

3.2.1. Kelp forest

Estimates of the extent and biomass of five dominant kelp species in the sea around Orkney were made using existing models that describe the associations between presence and abundance of kelp and the main predictors of their presence across the UK (fully described in Annex A in Burrows *et al.*, 2018; Burrows *et al.*, 2014a; Burrows *et al.*, 2014b) (Figure 3.1). The main determinants of kelp presence, abundance and biomass are:

(1) depth, because of the need for light for photosynthesis;
(2) wave exposure, a major influence on the dominant species in the kelp forest;
(3) water clarity, implemented here using satellite-estimated *chlorophyll a* concentrations and influencing the amount of light reaching the sea bed; and
(4) summer average water temperature (Figure 3.2).

The last of these, temperature, does not vary significantly across the Orkney Islands archipelago but is important in determining species presence and abundance at the UK scale, and for considering the future threat to kelp species from climate change. Kelp species in the UK are in the warmer part of their global geographical distributions and are likely to decline or disappear with warming in areas close to their warm distribution limits in SW England. While populations in Orkney are likely to persist with sea temperature rises of up to 2°C, declines in abundance over time are likely following the spatial pattern of reduced abundance from NE Scotland to SW England with increasing summer water temperatures (12-13°C to 16-17°C).

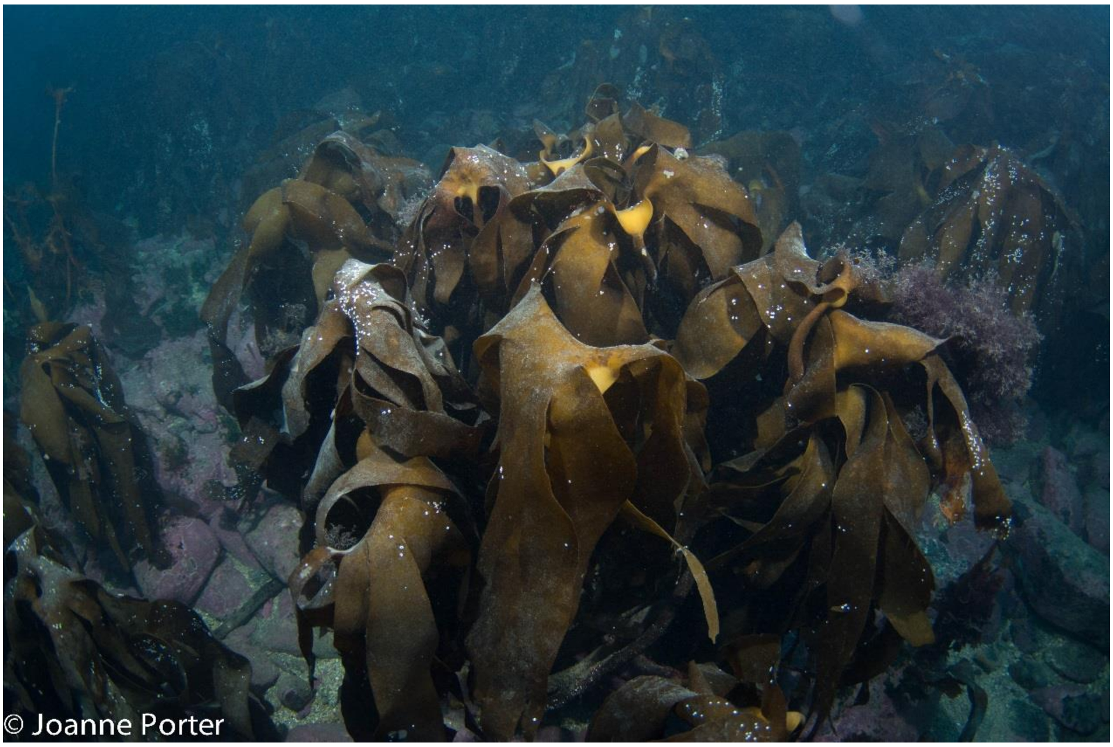

Figure 3.1: *Laminaria hyperborea* can be found in extensive 'forests', this is an example from habitat at Tingwall, north mainland of Orkney.

The existing Generalised Additive Models (GAMs; Wood, 2011) used here had been fitted to data on kelp abundance from the Joint Nature Conservation Committee's Marine Nature Conservation Review, collected mostly during the 1980s and 1990s. Divers surveyed kelp along short transects and assigned them to categories according to the density of stipes per m^2 (Superabundant >9 m^{-2}; Abundant 1-9 m^{-2}; Common 1-9/10 m^{-2}; Frequent 1-9/100 m^{-2}; Occasional 1-9/1,000 m^{-2}; Rare <1/1,000 m^{-2}) (Hiscock, 1996). Kelp was assumed absent if surveys were made in an area, but no kelp was recorded. GAMs predicted the likelihood of kelp presence and were scaled to biomass using a conversion method that predicted associated likelihoods of each abundance category and assigned biomass values to each category (Table 3.1).

Figure 3.2: Extensive debris from *Laminaria* spp. following a winter storm. Warebeth Beach, West Mainland, Orkney. Photo: Joanne S Porter.

Predictive layers were produced using the Aquatera 22-m resolution bathymetry dataset for Orkney as the baseline. Wave fetch was estimated for each grid cell up to 5 km away from the coast and less than 50 m deep. Fetch estimation was achieved using a modified version of the model presented in Burrows *et al.* (2008) and Burrows (2012). The model involved multiple searches (2000) for the nearest land around each cell in random directions and at randomly selected distances up to a maximum of 200 km. Wave fetch was then expressed as the summed distance to the nearest land in the 32 sectors of 11.25° width around each point. The resulting fetch values were calibrated against the existing UK-scale wave fetch layer (200 m scale, Ordnance Survey Great Britain) used in the original fitting of the GAM models (Figure 3.3). This novel wave fetch layer was also used in the Maxent models for the prediction of the extent and location of other biological blue carbon habitats (except saltmarshes).

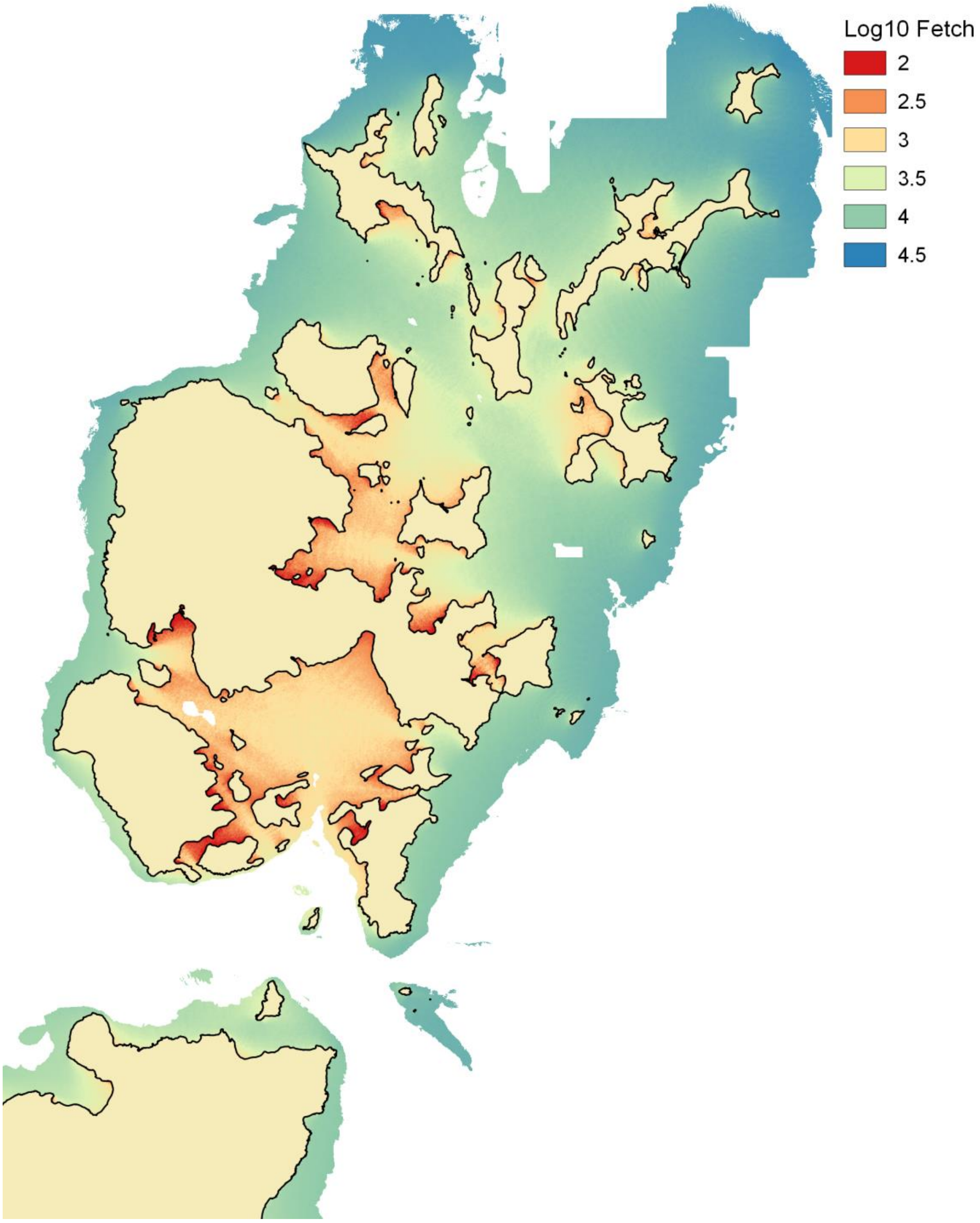

Figure 3.3: Wave fetch for coastal cells around Orkney. Values are expressed as $\log_{10}$ of summed fetch in 32 11.25° sectors, in multiples of 200 m. The maximum fetch value for cells surrounded by 200 km of open sea would be $\log_{10}$ of 32000 or 4.5.

Summer sea surface temperatures (averaged for July, August, September and October) had been found to best predict kelp presence across the UK, and so 1989-2014 values were used from a NEMO-ERSEM (Butenschön *et al.,* 2016) model run obtained from the National Oceanography Centre Southampton. Ocean colour, as *chlorophyll a* in mg m^{-3}, was taken from the MODIS Aqua L3m analysis product for

2002-2010 at 9 km resolution. Temperature and ocean-colour datasets were re-projected, resampled and interpolated into the 22 m resolution depth grid to match the wave fetch and depth datasets. These prediction layers were then presented as new prediction layers for the GAM models for each of the five kelp species, producing the models shown in Figures 3.3-3.5 and Appendix A.

Known records of the occurrence of each of kelp (*Laminaria hyperborea, Saccharina latissima*, *Saccorhiza polyschides, Laminaria digitata*, *Alaria esculenta*) were extracted from the National Biodiversity Network Gateway (https://nbn.org.uk/) in May and June 2019. These occurrence records report only the presence of a particular species of kelp and not the absence of other species. Surveys such as the MNCR were, however, known to have collected information (including abundance) on multiple species and so records were merged by unique latitude, longitude and date combinations to recreate the kelp surveys. Where more than one species was recorded per survey, no data for unreported species were interpreted as true absence. Where only one kelp species was reported for a location, no data were interpreted as that species not having been recorded (i.e. unconfirmed absence). The aim of this process was to allow direct comparison with model predictions. Accuracy of locations of occurrence was rarely sufficient to allow comparison with a 22 m-resolution prediction. Survey locations (see Figure 3.3 for example) were often in depths known not to support kelp populations, and were even on land in some instances.

Notwithstanding the lack of accurate model validation, the predicted extents and patterns of abundance of each species follow observations reasonably well. The model appears credible based on what we know of the general ecology of the species and appears to broadly match the Orkney records shown as symbols. Additional survey data are required in the future to fully validate the model predictions. There are only a handful of kelp biomass estimates from around Orkney: some historical (e.g. ISR surveys, Walker and Richardson 1956) and some recent from the Wildweed report from diver and acoustic/drop down surveys. Most of the other data for kelp presence are not spatially accurate enough to match with model predictions.

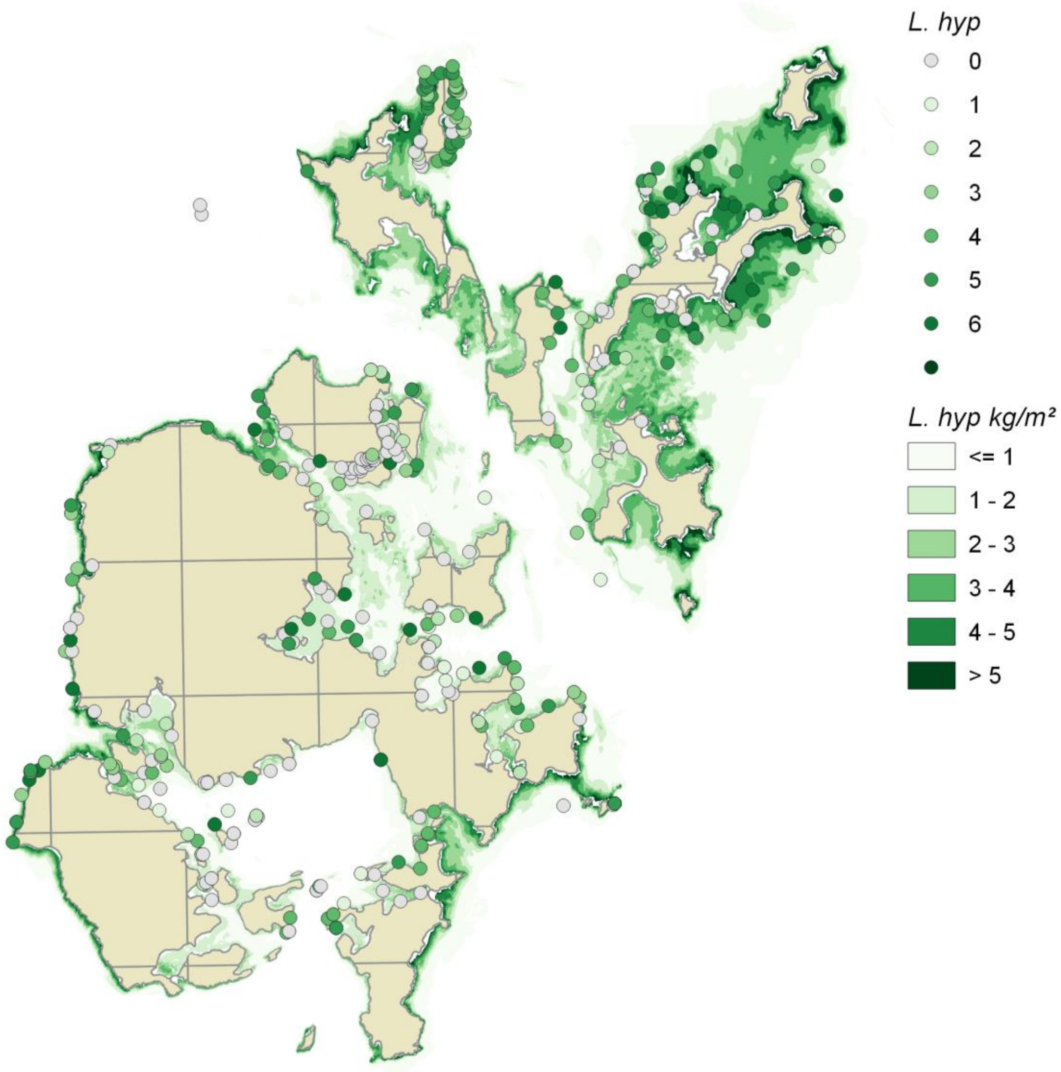

Figure 3.4: Predicted biomass density of *Laminaria hyperborea* across Orkney. Symbols indicate recorded abundance of the species in surveys with absence (0, grey) and categories Rare to Superabundant as integers (1-6).

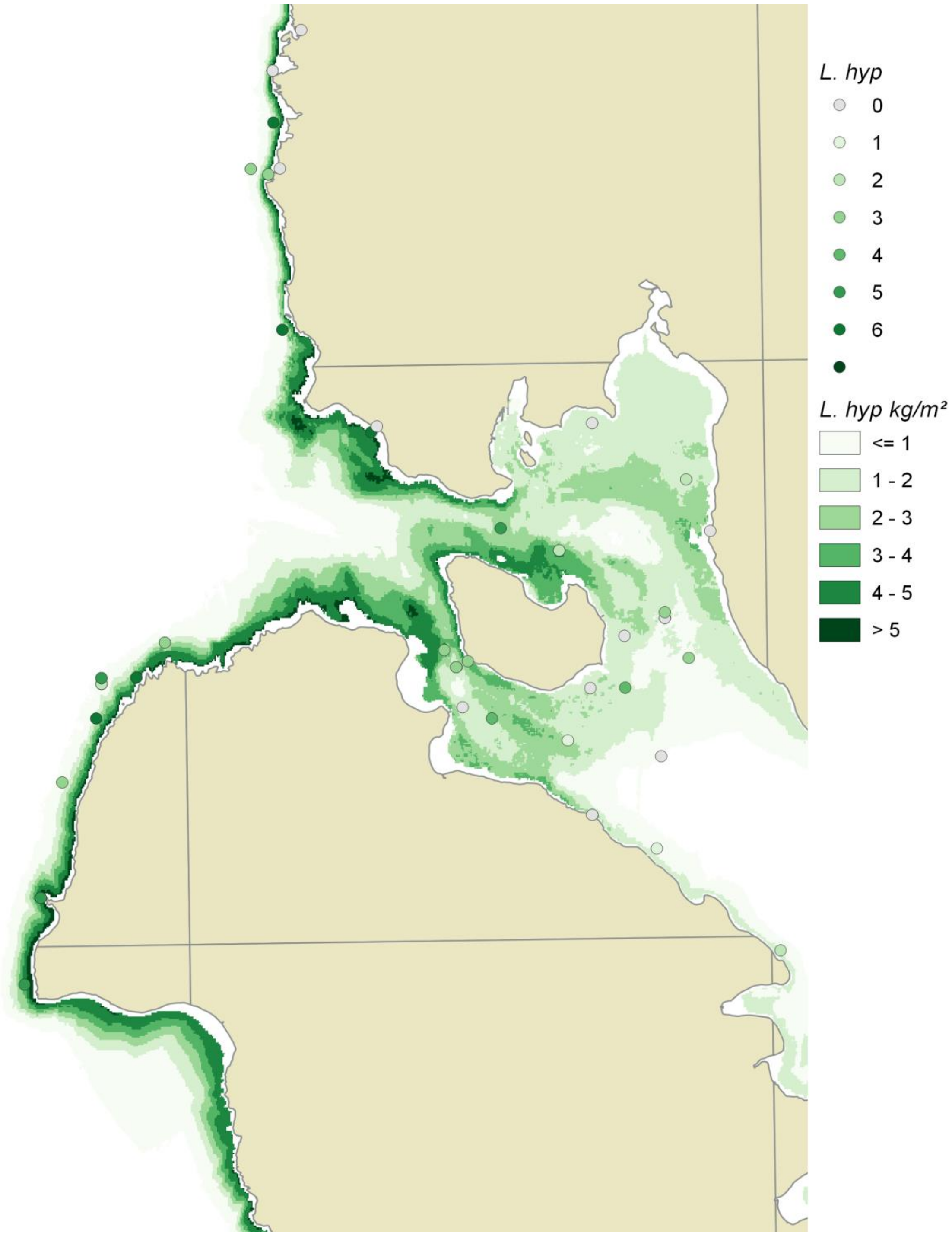

Figure 3.5: Predicted biomass density of *Laminaria hyperborea* around Stromness and the western entrance to Scapa Flow. Symbols indicate recorded abundance of the species in surveys with absence (0, grey) and categories Rare to Superabundant as integers (1-6).

Exposed-coast species *Laminaria hyperborea* (Figure 3.4) and *Alaria esculenta* (Figure A3) were predicted and observed on the outer coasts and were generally less abundant in more sheltered locations. The less prevalent, moderately exposed kelp species, *Saccorhiza polyschides*, tended to be seen more in the vicinity of Scapa Flow and northern Mainland, as well as the more protected parts of Sanday and Westray (Figure A2). Sheltered coastal areas supported higher predicted and observed abundance of sugar kelp *Saccharina latissima* (Figure A4). The ubiquitous shallow water species *Laminaria digitata* was widespread (Figure A5) and notably absent among deeper water observations.

3.2.1.1. Habitat extent, total biomass and standing stocks of carbon

Areas of habitat for each species were taken from the maps of predicted presence. For the common kelp species, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*, areas were summed for places where the species were predicted to be more likely than not to be present (P (Abundance ≥ Rare) >0.5). *Laminaria hyperborea* habitat was predicted to occupy nearly 300 km^2, with sugar kelp *Saccharina latissima* 180 km^2 and *Alaria esculenta* 7 km^2 (Table 3.1). These species were predicted to occupy distinct and largely non-overlapping regions (Figure 3.6), with *Laminaria* and *Saccharina* separated by wave exposure, and *Alaria* habitat restricted to only the most wave-exposed places. Setting a lower threshold of >10% likely to be found gave extent estimates for the rarer species of 5.2 and 2.6 km^2 for *Laminaria digitata* and *Saccorhiza polyschides*, respectively.

Summing values for predicted biomass gave similar rankings for the standing stock of each species to their habitat area (Table 3.1). By far the most kelp carbon standing stock (82%) was projected to be in living *Laminaria hyperborea* (83 000 tC), with the remainder sugar kelp *Saccharina latissima* (14%) and only 4% from *Alaria esculenta*, *Laminaria digitata* and *Saccorhiza polyschides* combined.

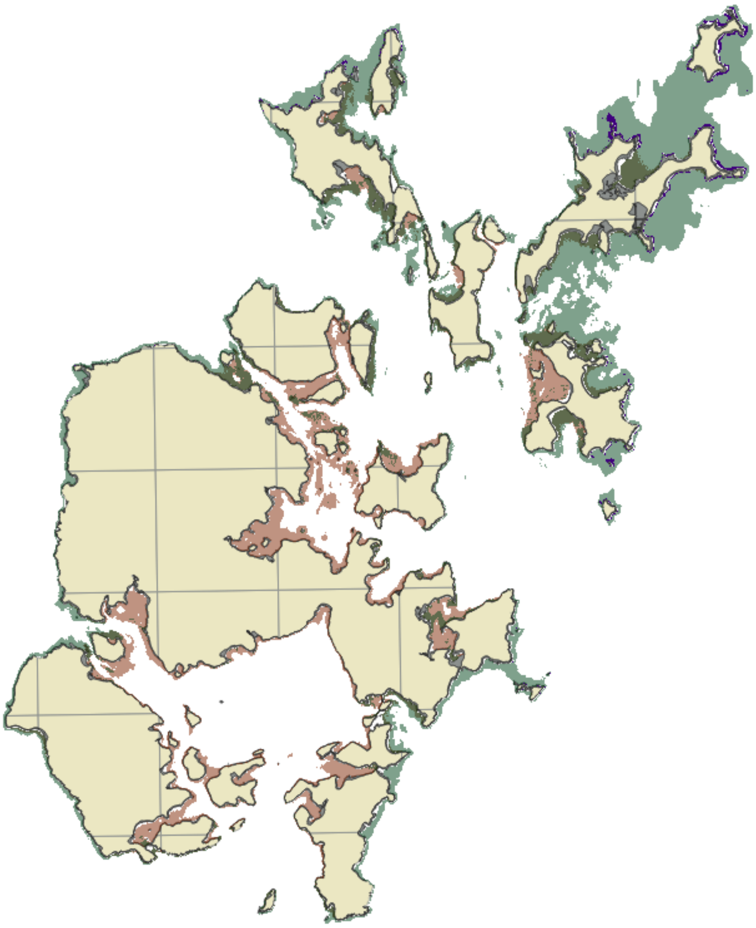

Figure 3.6: Predicted habitat for *Laminaria hyperborea* (green), *Saccharina latissima* (brown), and *Alaria esculenta* (purple), as areas where each species was expected to be more than likely to be present. Overlapping areas with both *Laminaria hyperborea* and *Saccharina latissima* are indicated in dark green.

Table 3.1

Estimated total biomass and standing stocks of kelp species in Orkney.

Species	Habitat area hectares [a]	1000 tonnes wet weight	1000 tonnes organic C [c]	Scale [d]	kg m^{-2} per abundance class (R,O,F,C,A,S)
Alaria esculenta	730 [a]	43	1.9	4	c(0.0003,0.003,0.03,0.3,3,3)
Laminaria digitata	520 [b]	18	0.8	4	c(0.0003,0.003,0.03,0.3,3,3)
Saccorhiza polyschides	260 [b]	24	1.1	4	c(0.0003,0.003,0.03,0.3,3,3)
Saccharina latissima	18000 [a]	311	14.0	3	c(0.0002,0.002,0.02,0.2,6,6)
Laminaria hyperborea	29200 [a]	1845	83.0	2	c(0.0017,0.0083,0.083,0.83,8.3,25)
Total	48710	2241			

Notes: [a] where species is >50% likely to be present, [b] >10% likely to be present. [c] assuming that dry weight is 15% of fresh weight, and a 30% carbon content of dry matter (from Krumhansl and Scheibling, 2011). [d] Biomass scale from Burrows *et al.* (2017).

3.2.2. Maerl beds

The location of maerl observations were obtained from survey (observational) records including *Phymatolithon calcareum* and *Lithothamnion glaciale* (Marine Scotland, 2019c) (Figure 3.7). These included some presence/absence data without extent (Figure 3.8). To generate bed extent, mapped maerl locations were assessed by individuals with local expert knowledge. Only sites classed as “beds” were retained (rather than accumulations of a few small pieces). Beds were defined as per Burrows *et al.* (2014) covering areas greater or equal to 10,000 m^2. Where extent was known (multiple adjacent observational data in SNH surveys and expert observation) this was defined by polygonal area. Where extent was not known, the average extent from Burrows *et al*. (2014) 10,000 m^2 was applied.

Figure 3.7: Example of habitat classified as a maerl bed for this report, photographed at Tingwall, north mainland, Orkney.

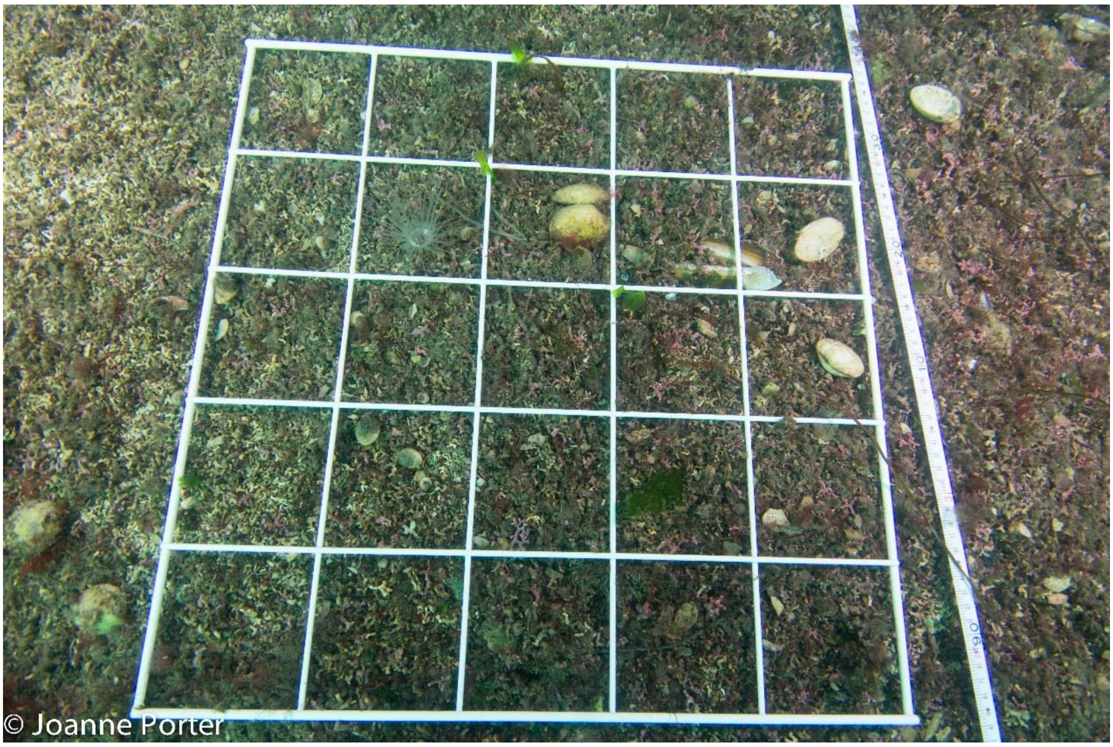

Figure 3.8: Quadrat-based quantification of maerl surface abundance, image taken by Heriot Watt Scientific Dive team at Weddell Sound, Scapa Flow, Orkney. Quadrat size is 0.5 m^2.

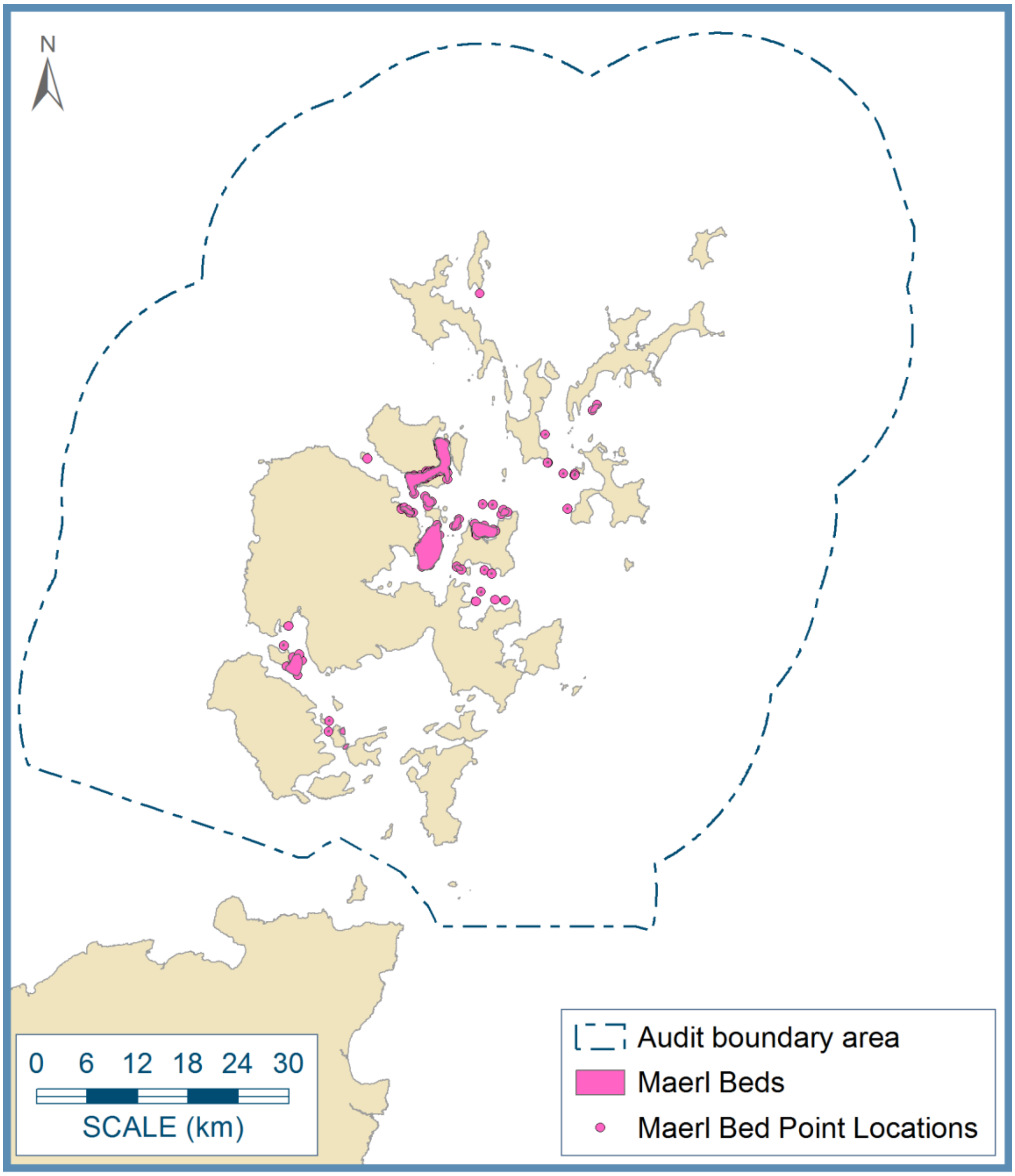

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Figure 3.9: Maerl bed habitat (*Phymatolithon calcareum* and *Lithothamnion glaciale*) generated from SNH survey observations and local expert knowledge for extent. These distributions do not include observations of single or small numbers of thalli which are less likely to be large contributors to maerl TOC.

3.2.2.1 Maerl bed thickness

Very little information is available on maerl bed deposit thickness in Orkney waters, with the exception of the Wyre sound bed, which preliminary observations suggest has a mean thickness of at least 117.5 cm (Sanderson, Porter and Want, pers. comm.). Thus, while assessing organic and inorganic carbon, accumulations in the top 25 cm were used (see below) apart from Wyre sound where the thickness of

117.5 cm was used. These are still likely underestimates of the organic and inorganic carbon buried in Orkney maerl beds and thus provide the minimum value we can expect until more widespread deposit thickness data become available.

3.2.2.2 Organic carbon

Average total organic carbon (TOC) in the top 25 cm of maerl beds has been recently calculated for Scottish maerl beds at 7.38 tonnes TOC ha^{-1} (0.000723 tonnes m^{-2}) (Mao *et al*., 2019); this was applied to the maerl bed extent to generate Orkney maerl bed TOC with the exception of Wyre sound where this was extrapolated to its recorded thickness (117.5 cm). We note this extrapolation does not therefore include temporal variation in organic carbon accumulation and breakdown.

3.2.2.3 Inorganic carbon

Net inorganic carbon production by maerl bed-forming coralline algae is 22 g $C_{inorganic}$ m^2 y^{-1} (Van der Heijden and Kamenos, 2015) and the historic accumulation rate of Orkney maerl beds is estimated at 80 mm ky^{-1} (Van der Heijden and Kamenos, 2015; Farrow *et al*., 1984). Together with maerl bed thickness, these suggest inorganic carbon standing stocks plus stocks combined of 323,180 g $C_{inorganic}$ m^{-2} for Wyre sound and 68,750 g $C_{inorganic}$ m^{-2} for all other Orkney maerl beds assuming deposit thicknesses of 120 and 25 cm respectively.

Table 3.2

Estimated areal extent and standing stocks plus stocks of maerl in Orkney.

	Areal extent in hectares	**Thickness of maerl bed**	**Tonnes OC m^{-2} (Mao *et al*., 2019)**	**Total OC (1000 t)**	**Tonnes IC m^{-2} (Mao *et al*., 2019)**	**Total IC (1000 t)**
Wyre Sound	1120	120 cm	0.003469	38.8	0.32318	3618.5
Rest of Orkney beds	2526	25 cm	0.000738	18.6	0.06875	1736.8
Total	3645		0.004207	57.5	0.39193	5355.2

3.2.3. Seagrass beds *(Zostera)*

In Scotland, members of the seagrass genus *Zostera* typically occur from the lower saltmarsh limit (*Zostera noltii*) into the sublittoral zone (*Zostera marina*) (Figure 3.10) down to approximately 10 m below the surface (Burrows *et al*., 2014). Laffoley and Grimsditch (2009) suggested that although the seagrasses only cover a relatively small area of the global ocean floor (~1%), they are responsible for about 15% of the total carbon storage in the ocean (these figures include *Posidonia* species). Furthermore, these authors state that the slow turnover time of seagrass biomass and its sediment trapping and binding capacity makes this habitat an important sink for carbon with an average net sequestration rate of 83 g C m^{-2} y^{-1}, translating into global storage of 27-40 Tg C y^{-1}.

Regarding the estimation of standing stocks of blue carbon contained in Orcadian *Zostera* beds, there are no currently available data for *Zostera* in Orkney waters. Röhr *et al*. (2016) reported values from the Baltic Sea area where organic carbon values were integrated to include the top 25 cm of sediment. This study reported organic carbon values of 627 g C m^{-2} in Finland *Zostera* (averaged over 10 beds) and almost six times more in Denmark *Zostera* (averaged over 10 beds) at 4324 g C m^{-2}. A further publication on the blue carbon storage capacity of temperate seagrass meadows was published by Röhr *et al*., (2018). In this study three *Zostera marina* locations were studied in the Eastern Atlantic region including Ireland, France and Portugal but these data were aggregated together and so not considered suitable for use in the Orkney audit due to the wide latitudinal variation in the sites. From the Röhr *et al*. papers two key points arise: firstly, there is a great deal of variation in the organic carbon values between beds and between geographical regions; therefore, a large element of uncertainty is introduced when extrapolating from one bed to another. Secondly, there is a great deal more carbon stored in the underlying sediment than in the plants themselves and so it is essential to incorporate this aspect into programmes of work when *Zostera* beds are being sampled.

In this audit direct contact with Dr Maria Potouroglou resulted in the provision of some data on Scottish *Zostera* from her PhD Thesis (Napier University, 2017). Estimates of organic carbon from the sediment of both intertidal *Zostera marina* and *Zostera noltii* meadows were provided to a sediment thickness of 100 cm. Samples of vegetated and unvegetated plots were sampled across seven broad locations down the east coast of Scotland including Forth, Tay, Montrose, Beauly, Moray, Cromarty and Dornoch. The mean organic carbon stock across the seven locations for the top 100 cm of sediment was 114 Mg C ha^{-1} (Appendix B). Further to this, there has been one small study estimating the organic carbon from subtidal sediment of *Zostera marina* meadows produced, from samples taken in 2017 as part of an ongoing PhD project (Whitlock, in prep.). Samples of vegetated and unvegetated plots were sampled near Eynhallow, Orkney. The Eynhallow meadow was chosen as it is one of the known subtidal *Zostera* meadow in Orkney where seagrass beds are the dominant habitat. The Tingwall meadows is dominated by maerl making organic carbon estimates more difficult to retrieve, it is not included in the calculations here for that reason. The mean organic carbon stock for the top 100 cm of sediment from the subtidal *Zostera* meadow was 77.94 Mg C ha^{-1}. Both intertidal and subtidal *Zostera* studies used a regression equation from Potouroglou (2017) to convert organic matter via the loss on ignition method (at a 500 °C burn) into organic carbon content. The two studies emphasise the difference in carbon content between intertidal and subtidal *Zostera* meadows, therefore both have been applied within this audit to produce the most accurate audit of the Orkney *Zostera* meadows at this time.

With respect to the calculation of the areal coverage of *Zostera* in Orkney waters we first referred to the Scottish Natural Heritage commissioned report No. 765 (2014) which contained information regarding the presence of *Zostera* beds in Orkney (Thomson *et al*., 2014). In this report, the team used a combination of predictive modelling using the Maxent approach along with ground-truthing of some of the predicted points using a WEMo wave exposure model (NOAA, 2019). In the discussion of that report it was noted that overlaying known presence of *Zostera* on the predictive map for Orkney highlights that *Zostera* is predominantly found not only at specific depths and wave exposures, but that offshore slope is very important and that its inclusion in future models would improve the accuracy of the Orkney model. This was taken into consideration in Maxent in the new model we generated for this audit, however there was not a huge difference between the results whether that raster layer was included or not.

Figure 3.10: *Zostera* in Orkney, photographed off Tingwall harbour, north mainland. (Image: Dr Richard Shucksmith).

The extracted areal extent for the *Zostera* from the predictive model was 14.23 km^2. Carbon estimates for Zostera are presented in Table 3.3.

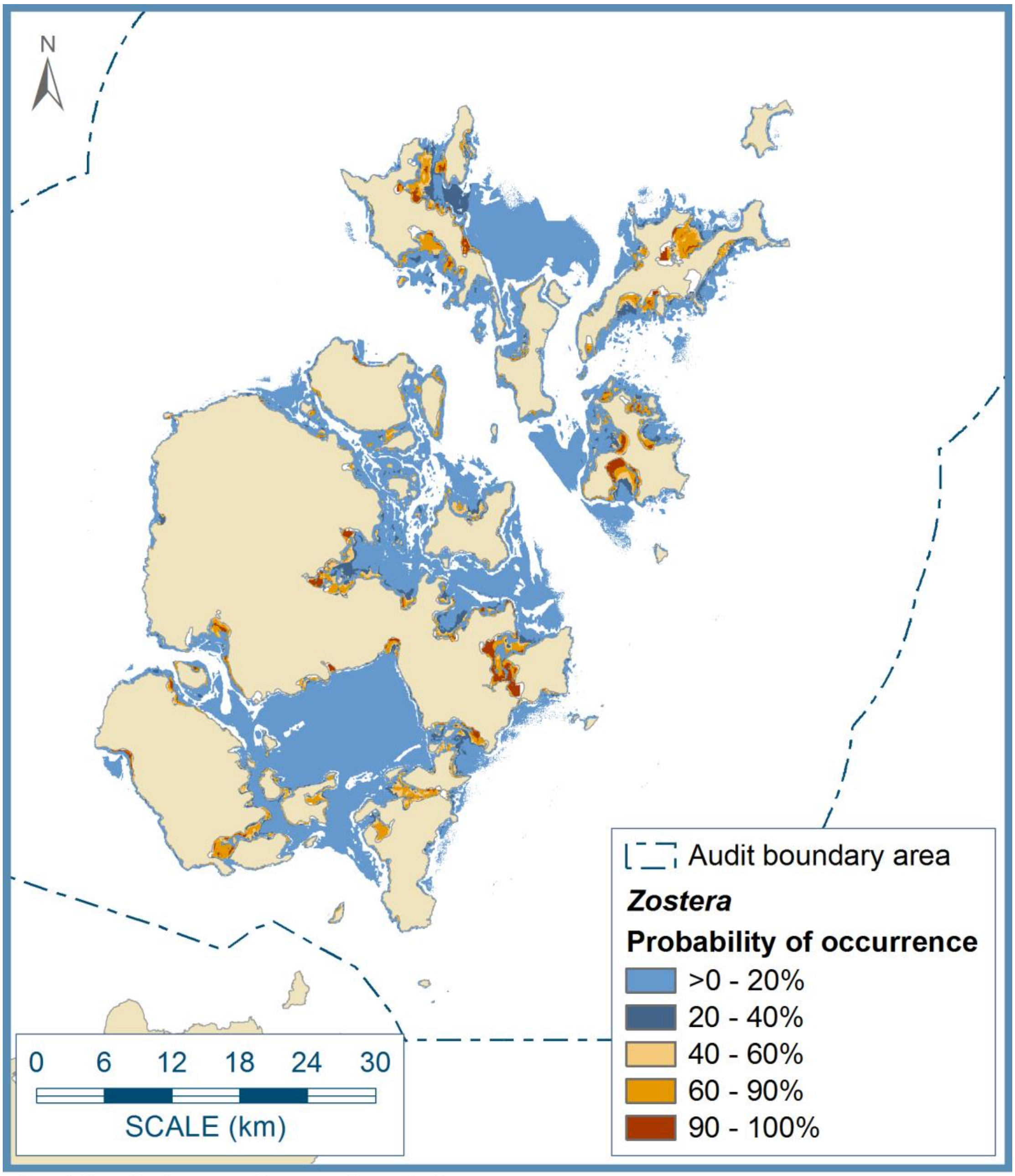

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Figure 3.11: Maxent predictive model for *Zostera* in Orkney waters.

Table 3.3

Estimated areal extent and standing stocks plus stocks of *Zostera* in Orkney.

Species	Areal extent of *Zostera* in hectares	Mg of OC in top 100 cm of intertidal sediment per hectare (Potouroglou, 2017)	Mg of OC in top 100 cm of subtidal sediment per hectare (Whitlock, in prep.)	Total organic carbon (1000 t)
Zostera marina	1243		77.94	96.8
Zostera noltii	180	114		20.5
Total	1423			117.3

3.2.4. Saltmarshes

Saltmarshes are coastal wetland situated on sheltered coastlines from the Arctic to the tropics but are most common in temperate regions. Approximately 3% of the Scottish coastline is covered by saltmarsh occupying 5840 ha (58.4 km^2) (Haynes, 2012). The larger Scottish saltmarshes are mainly concentrated in the low-lying estuaries of the eastern and south-west coasts, with a large number of small highly restricted marshes located at the heads of sea lochs and in embayment's in the west and north of the country.

The Orkney Islands have a sparse coverage of saltmarsh, extending to 55.05 ha (0.55 km^2) (Haynes, 2012) (Figure 3.12). The marshes are all estuarine in nature with the majority being situated behind spits of land providing a level of protection not found on exposed coastlines (Figure 3.13).

Figure 3.12: Saltmarsh at Waulkmill Bay, Orkney (Image: Simone Riegel).

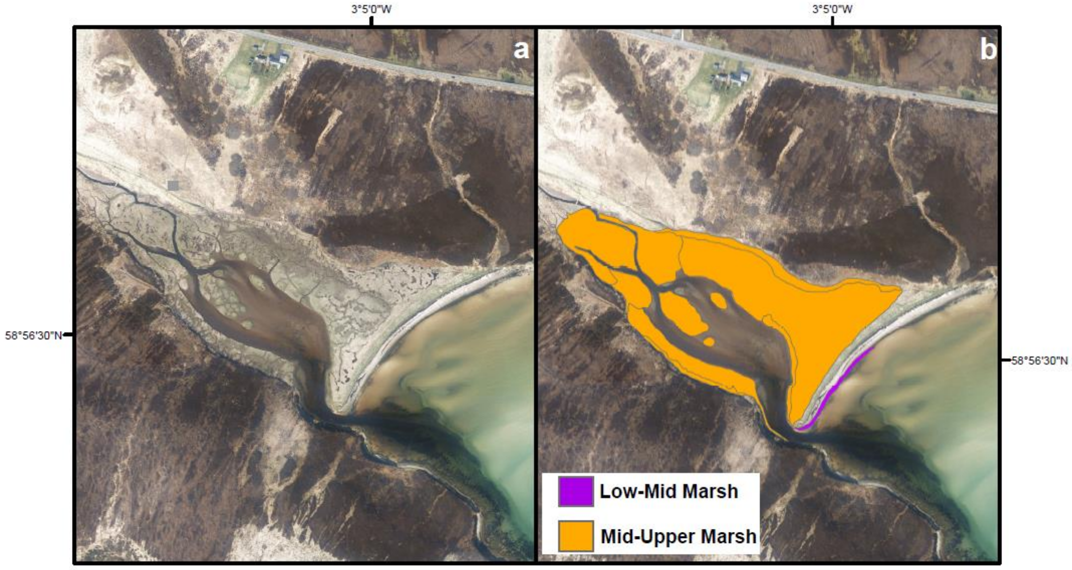

Figure 3.13: Waulkmill marsh (5.54 ha) a typical example of the saltmarshes found on the Orkney Islands (a) Aerial photo of the marshes (b) Spatial extent (HabMoS) of the saltmarsh.

The spatial extent of the saltmarsh was assessed using data accessed through the Habitat Map of Scotland (HabMoS). By comparing the HabMoS data to aerial photos (*Digimap: aerial*) inconsistences were identified between the two data sets. Within the HabMoS data clifftop sites were identified as saltmarsh (Figure 3.14). These clifftop sites were covered by saline tolerant vegetation similar to that of saltmarsh habitats but do not have any significant underlying soil and to include them as part of this audit would result in a small overestimation of the quantity of OC held with the Orkney saltmarshes.

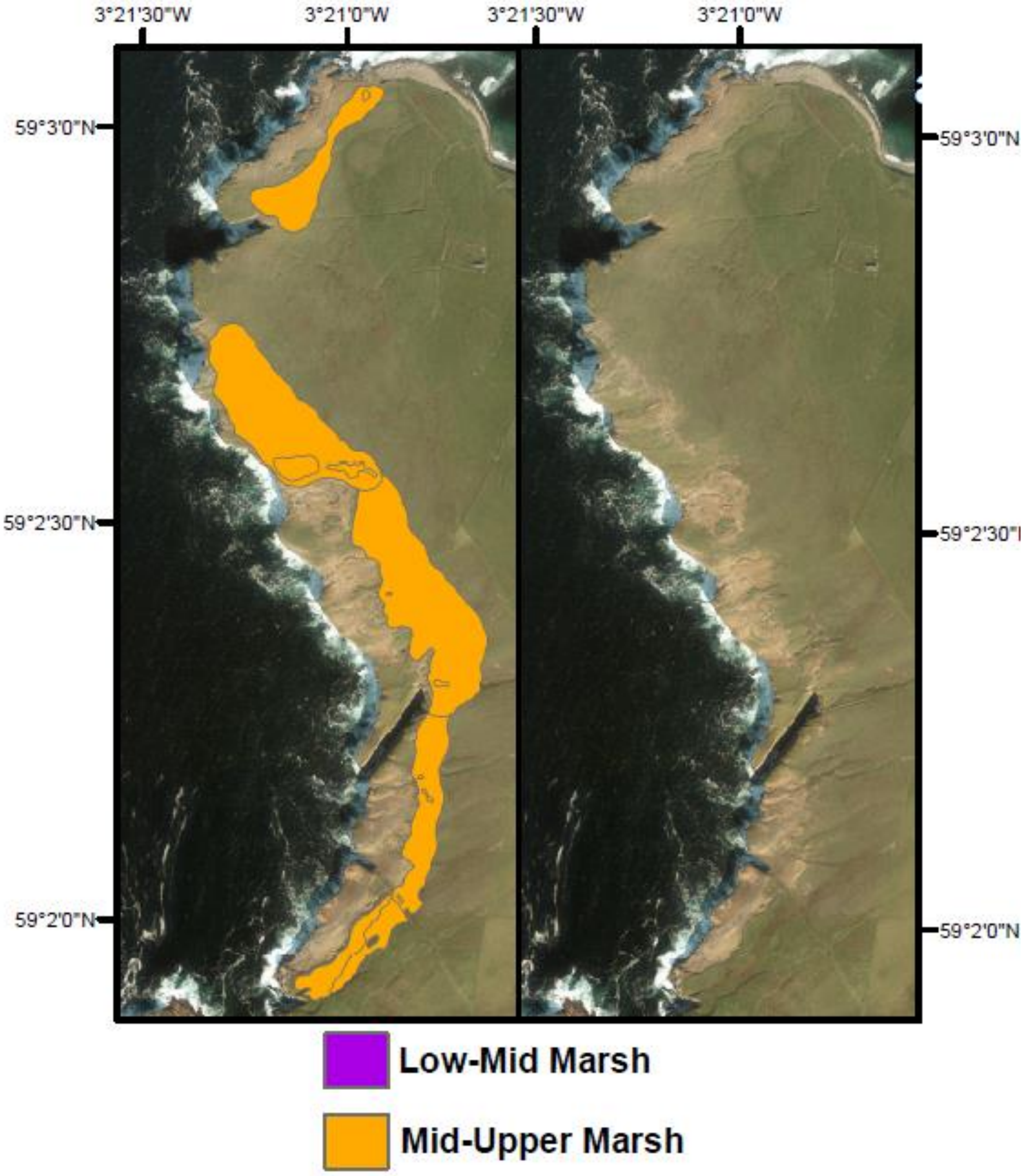

Figure 3.14: An example of the misidentification of saltmarsh habitat on the Orkney Islands (a) HabMoS saltmarsh extent (b) Aerial photograph illustrating that the site is on a clifftop south of the Bay of Skaill.

All saltmarshes identified in the HabMoS were checked against aerial photos to assure that all saltmarsh was correctly classified. Through this process the spatial extent of saltmarsh on the Orkney Islands was revised to 48.94 ha (0.49 km^2).

3.2.4.1 Saltmarsh carbon values

Globally it has been shown that saltmarsh habitats can trap several orders of magnitude more OC per area unit than the world's forests (McLeod *et al*., 2011). It is estimated that globally saltmarshes soils store between 0.4-6.5 Gt OC (Duarte *et al*., 2013) with a further 4.8-87.3 Mt OC being buried annually (McLeod *et al*., 2011). The global average saltmarsh store of OC is 162 tonnes ha^{-1} (Pendleton *et al*., 2012) with an estimated 218 ± 24 g OC m^{-2} y^{-1} being sequestered (McLeod *et al*., 2011).

To determine OC values for the saltmarsh found on the Orkney Islands two saltmarshes were sampled in April 2019 as part of the NERC C-SIDE project (C-SIDE, 2019). The saltmarshes at the Loch of Stenness (58.975343, -3.248660) and Waulkmill marsh (58.942162, -3.086477) were the focus of the sampling where a total of 17 and 11 gouge cores (3 cm diameter) were collected at each site, respectively. The samples were returned to the University of St Andrews for analysis with key data (Table 3.4).

Table 3.4

Physical property and elemental data from two Orkney saltmarshes provided by the C-SIDE project to allow the calculation of OC stocks

Saltmarsh	**Saltmarsh Area**	**Saltmarsh Thickness**	**Dry Bulk Density**	**OC Content**	**Soil OC Stock**	**OC Density**
	(ha)	**(m)**	**(kg m^{-3})**	**(%)**	**(tonnes)**	**(tonnes ha^{-1})**
Stenness	3.77	0.18 ± 0.11	420 ± 200	14.64 ± 7.98	417 ± 66	110 ± 17.5
Waulkmill	5.54	0.18 ± 0.17	390 ± 170	16.59 ± 8.29	645 ± 135	116 ± 24

To calculate the quantity of OC held within the Orkney saltmarshes the average OC density for the two surveyed marshes (113 ± 20.9 tonnes ha^{-1}) was applied to the saltmarsh areal coverage (48.94 ha) to calculate the total saltmarsh OC stock of 5569 ±1022 tonnes (Table 5.1).

3.2.5. Horse mussel (*Modiolus modiolus*)

The horse mussel *Modiolus modiolus* is well represented in shallow subtidal waters around Orkney (Mair *et al*., 2000) (Figure 3.15). Some records are of isolated individuals or of sparse, low-density populations, but areas where the number of individuals is dense enough to be regarded as beds are formed in at least three localities in the region. Records of horse mussel beds in the region have increased recently as Marine Protected Area (MPA) search feature surveys have applied modern habitat mapping methods to poorly known regions of the Scottish seas (Hirst *et al*., 2012; Moore *et al*., 2012, 2013). In Orkney waters *Modiolus* beds have been recorded within Scapa Flow close to the wreck of SMS Karlsruhe (Sanderson *et al*., 2014) covering an area of around 0.2 km^2 (Figure 3.16). Off the small island of Copinsay an area of 0.42 km^2 has been recorded (Hirst *et al*., 2012). In total the extent of the known beds and other patches modelled in Orkney waters give rise to a total estimate of 38.28 km^2 of *Modiolus* coverage. Currently a limited number of the predicted areas have been ground truthed by a series of drop down video surveys, *in situ* diver video or photography. This is almost certainly an underestimate of the full extent, and further survey in future will no doubt add to the knowledge of the extent, connectedness and thickness of sedimentary deposits underlying the habitat in Orkney regional waters (Mackenzie *et al*., 2018).

Modiolus modiolus is a large bivalve with a robust shell, and where it occurs in dense beds the accumulated relict shells may be important repositories of biogenic carbonate. In the Burrows *et al.* (2017) report, a mean thickness of 75 cm of *Modiolus* beds was used to calculate blue carbon contributions based on field sampling. It is possible that the Orkney deposits are thicker than 75 cm but until core samples are conducted, it is difficult to estimate the full extent of the underlying carbonate stores. This knowledge gap represents a very significant underestimate of the carbon storage attributable to horse mussel beds.

Figure 3.15: Example of a feeding horse mussel (*Modiolus modiolus*) at the site of the shipwreck of Karlsruhe, west of Cava Island, Orkney.

Density of living *M. modiolus* within the Orkney beds is patchy but the SACFOR category of Superabundant (10-90 individuals m^{-2}) was recorded at several stations at the Karlsruhe site (Sanderson *et al*., 2014), Copinsay and Pentland Firth (Hirst *et al*., 2012).

Figure 3.16: Clumps of horse mussels at the Karlsruhe bed, overlain by dense aggregation of the brittlestar *Ophiothrix fragilis*.

Previous Inorganic carbon estimates were reported by Burrows *et al*. (2014) based on 5-7 cm deep grab samples of 2219 g $CaCO_3$ m^{-2} and a 12% inorganic carbon percentage of $CaCO_3$. The estimates were based on a bed of 75 cm thickness. From this a calculation was made of 4000 g IC m^{-2} as the area-specific stock estimate (Burrows *et al.,* 2014). This estimate was used in the audit for Inorganic Carbon.

Despite extensive literature review, no measurements could be found for the amount of organic carbon present within the tissue of horse mussels. This knowledge gap was addressed in the audit by performing LOI burn ups on a modest number of horse mussels (n=6) (Length = 86-111 mm, Mean length = 99.66 mm, Standard Deviation = ± 8.63) collected from the bed adjacent to Cava Island.

From the LOI results a mean value of 13.78 ± 6.6 S.D. g C (as organic matter) per individual was calculated. No data are available for horse mussels regarding the relative contribution of Carbon, Nitrogen and Phosphorus in the tissue or the shell. In Table 3.5 a summary of mean values is given from the recent review by Olivier *et al*. (2018) for the closely related genus *Mytilus*. In the absence of empirical data on C N P ratios for horse mussel tissue, in the audit we base calculations for organic carbon in horse mussel tissue on the value of 45.98% of the dry weight. This was used to adjust the value for tissue organic carbon obtained in the LOI method to account for the N and P components.

Table 3.5

Chemical composition (carbon (C), nitrogen (N), phosphate (P) (% dry weight) of shellfish, organised by species of mussel and average values. A dash indicates no value presented. Table adapted from Olivier *et al*., 2018.

Species	Tissue C	Tissue N	Tissue P	Reference
Mytilus edulis	45.98	11.40	0.708	Zhou *et al*. (2002)
Mytilus edulis	-	10.6	0.80	Haamer (1996)
Mytilus edulis	-	8.1	1.24	Cantoni *et al*. (1977)
Mytilus galloprovincialis	-	6.2	-	Miletic *et al*. (1991)
Mussel mean (± 1SE)	45.98	9.08 ± 1.19	0.92 ± 0.16	Olivier *et al*. (2018)

The areal extent of horse mussel bed in Orkney waters was modelled using the Maxent method. A caveat of the model in this instance is that because there were no estimates of horse mussel presence in depths of more than 50 m, the model was not able to predict whether the presence of horse mussels beyond the 50 m contour. This does not mean that there are not any horse mussels present in those depths, just that the model cannot predict them due to the lack of data.

Figure 3.17 illustrates the results from the model. Using a probability of occurrence value of >0.9 the predicted area of horse mussel reef in Orkney waters is 38.28 km^2. Estimated areal extent and standing stocks plus stocks of horse mussel carbon in Orkney are shown in Table 3.6.

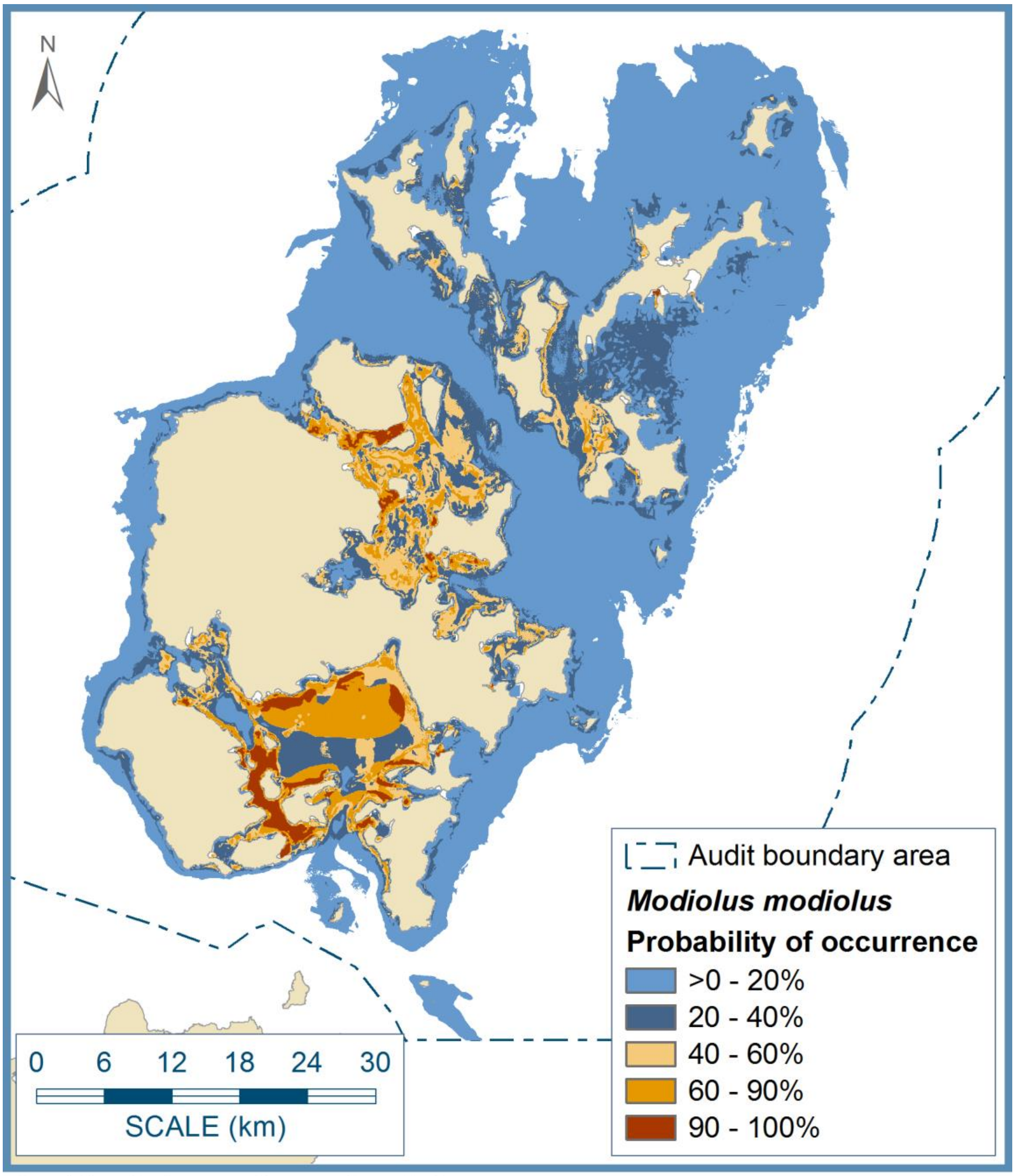

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Figure 3.17: Maxent model illustrating the predicted extent of horse mussel beds in Orkney regional waters.

Table 3.6

Estimated areal extent and standing stocks plus stocks of carbon in horse mussel habitats in Orkney.

Areal extent hectares	Abundance of individuals m^{-2}	Inorganic Carbon m^{-2} (Burrows *et al.*, 2014) in g (top 75 cm)	Inorganic Carbon (1000 t) in top 75 cm	Organic carbon tissue g m^{-2}	Organic carbon (tissue) (1000 t)
3828	SACFOR Super Abundant (10-90 individuals m^{-2})	4000	153.1	348.63	13.35

3.2.6. Flame shell (*Limaria hians*)

The flame shell *Limaria hians* is an epifaunal bivalve that constructs a “nest” made of secreted protein byssus threads (Figure 3.18). Woven in amongst the threads are pieces of shell and algae. Sediment gets trapped among the nest material and is used to help form the galleries that are built by the flame shell (Hall-Spencer and Moore, 2000a) (Figure 3.19).

Figure 3.18: Flame shell (*Limaria hians*) among nest material comprising the red seaweed *Phylophora crispa*.

In dense populations these nests can form continuous reef-like structures up to 50 cm thick and several hectares in extent.

Figure 3.19: Flame shell (*Limaria hians*) nests forming continuous reef-like structure in Gutter Sound, Scapa Flow.

Limaria nest samples were gathered by Heriot Watt Scientific Dive Team from the ‘Mystery Block’ location at Lyness, using four replicate 21 cm depth buckets with a diameter of 21 cm, as macrofaunal cores. These were pushed down by hand into the sediment, twisted around to enable capturing of the nest material and then lids were carefully manoeuvred into place to retain the collected material. These sealed bucket cores were recovered to the surface and landed onto the survey vessel. A limitation of this method is that it does not sample any deeper than 21 cm into the nest and sediment surface. Thicker nest material and the deposits laid down underneath the surface sediment could extend much further and need to be investigated in future studies to ascertain the sediment thickness and its carbon content. Detailed analysis of the collected material was conducted back at the laboratory

Each bucket was emptied into a large sorting tray and examined thoroughly by hand, to sort out the *L. hians* individuals from within the nest structures. This process of sorting through material was repeated several times to ensure that all *Limaria* were separated from the nest material and the number of *L. hians* was counted for each of the core samples. The mean number of *L. hians* per core was 46 ± 18.3 S.D. (N=4) (Hood, 2016).

A total of 45 whole individuals of *L. hians* from across the size range were selected and weighed. Each individual was then separated into tissue and shell material and the wet weight of these components recorded. Sub- samples of wet nest material were also weighed. All these samples were oven-dried at 100 ºC for 24 hours, then reweighed to obtain a dry weight, before going into a carbon burn-up in the muffle furnace. A standard LOI protocol was used to derive carbon values for *Limaria* shell, tissue and nest material. Average organic and inorganic carbon values were measured. For *Limaria* shell the amount of carbon was 83.9% inorganic and 16.1% organic carbon. The ratio of overall inorganic to organic carbon in the *Limaria* individuals (tissue and shell combined) works out at an average of 77% organic carbon to 23% inorganic carbon. Average organic carbon of shell and tissue per *Limaria* individual was 0.716 g (N=45, Standard Deviation = 0.205). Average Inorganic carbon per *Limaria* individual was 0.197 g (N=45, Standard Deviation = 0.23).

Nest materials contained a mixture of stones, shell fragments, algae and associated invertebrate fauna all held together by copious protein-based byssus threads. The ratio of shell:stone:byssus:algae in the nest material was 1:4.4:9.1:2) across the 4 replicate bucket core samples. From the replicate carbon burn ups of nest material minus the stones, the OC represented 36% of the dry weight, with IC representing 64%.

The carbon values of the shell, tissue and the nest material were scaled up and combined to estimate the amount of carbon per square metre. A caveat here is that the OC values generated during the LOI are not adjusted for the presence of N and P due to a lack of data on the proportions of those within *Limaria* tissue.

Areal extent of the *L. hians* was modelled using the Maxent tool, and checked by comparing with *in situ* spot records or extent records from either diver or drop down video surveys. Mean density of L. *hians* individuals was estimated at 412 m^{-2} (Hood, 2016). In Figure 3.20, the areal extent of *L. hians* cover is illustrated. Using a Probability of Occurrence level of >0.9, an area of 17.99 km^2 is predicted for the extent of *L. hians* nest cover in Orkney regional waters. Estimated areal extent and standing stocks *of L.hians* in Orkney are shown in Table 3.7.

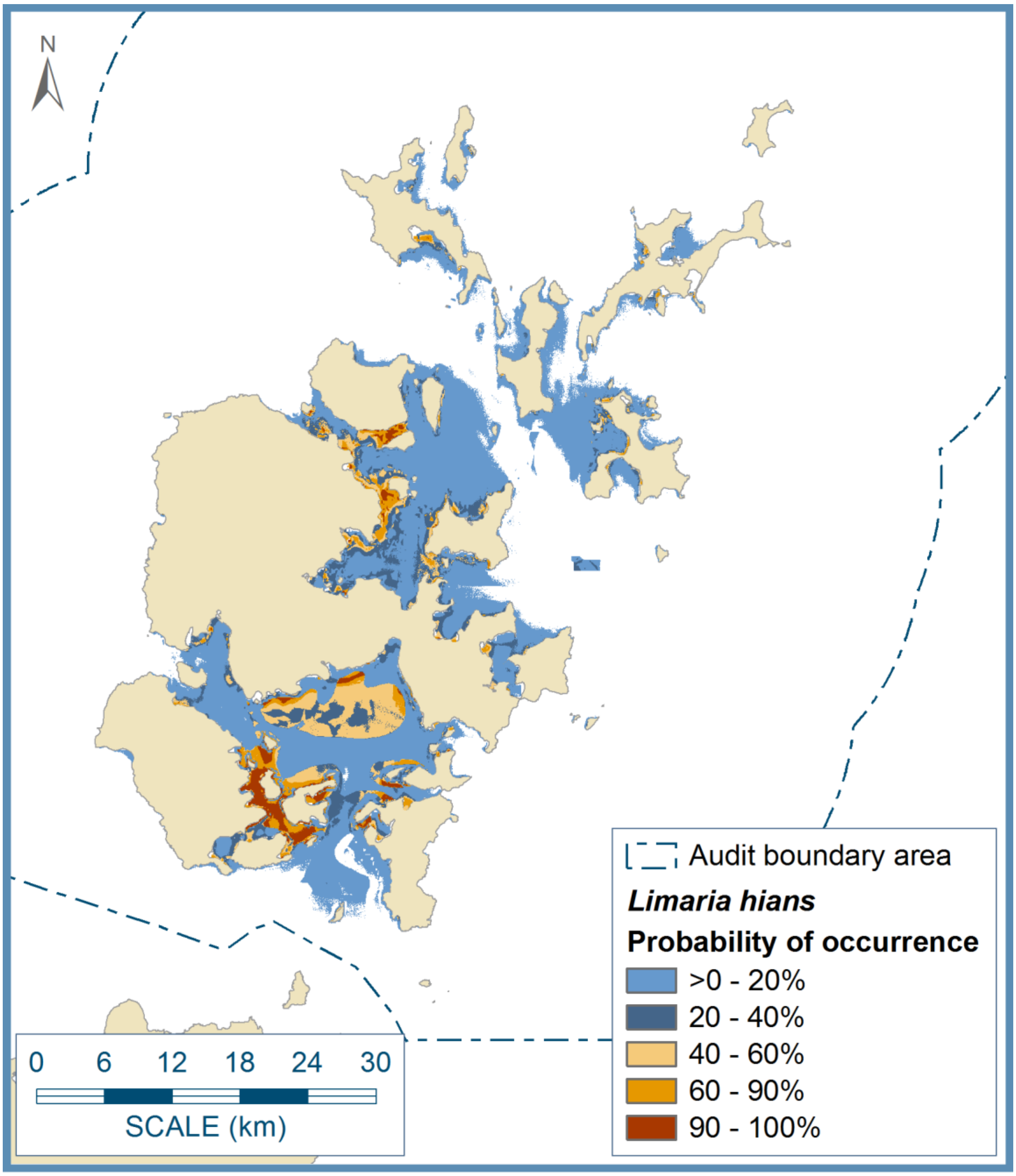

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Figure 3.20: Areal extent of *Limaria hians* in Orkney regional waters as predicted by Maxent model.

Table 3.7

Estimated areal extent and standing stocks of Flame shells in Orkney. Note that Total Carbon is a combined figure including shell, tissue and nest carbon values. This is calculated from the top 21 cm of nest material.

Areal extent hectares	Estimated number of individuals m^{-2}	Total number of individuals	OC 1000 t	IC 1000 t	Total Carbon (*Limaria hians* and nest material) (1000 t)
1799	412	7,411,880,000	1.1	6	7.1

3.2.7. Brittlestar beds

It is common to find dense beds of brittlestars in Scottish inshore waters. This is particularly the case in west coast sea loch environments, however, extensive brittlestar beds have also been reported from Orkney and Shetland waters (Hughes, 1998) (Figure 3.21). In Orkney waters, the main bed-forming species is *Ophiothrix fragilis*, which forms dense accumulations on the hulls of shipwrecks and on the seabed (Figure 3.22).

Figure 3.21: Dense *Ophiothrix fragilis* bed overlying horse mussel bed off Cava Island, Scapa Flow, Orkney with the predatory Seven-armed seastar (*Luidia ciliaris*).

Figure 3.22: Dense aggregations of *Ophiothrix fragilis* on the hull of the SMS Karlsruhe, off Cava Island, Scapa Flow, Orkney.

Brittlestars are not recognised as a Priority Marine Feature and are not designated under other protective status categories. As such, estimates of brittlestar extent and abundance are sparse in Scottish waters (Burrows *et al.,* 2014). From a blue carbon perspective brittlestars are significant, as they have an endoskeleton of calcareous plates. As they are often abundant in benthic marine environments it is likely that they may play an important role in the marine carbon cycle (Lebrato *et al*., 2010). A study by Migne *et al*. (1998) in the Dover Strait recorded a range in the density of individuals over a twelve-month period in June 1992 to June 1993 between 31 to 1188 individuals m^{-2}. The mean abundance was 476 ± 400.7 (N=26), showing that the density of the brittlestars between the sample stations was highly variable. Carbon burn ups gave an estimate of 66.2 g C m^{-2}. In Orkney waters a large brittlestar bed was surveyed north of Cava Island. As no previous data on the brittlestar abundance were available for Orkney waters and in view of the high variability recorded by the Migne study (1998), a single *in situ* diver transect (25 m) across the brittlestar bed adjacent to the Karlsruhe wreck was undertaken in March 2019 by Heriot Watt Scientific Dive team. A series of high-resolution photo quadrats were obtained (N=10) (Figure 3.23). This allowed zooming in to the image and counting the disks of the brittlestars. Subsequent analysis of the digital images allowed the calculation of an average abundance per 0.5 m^2 quadrat of *Ophiothrix fragilis* along the transect, of 59.9 ± 38.4 S.D. brittlestars (N=10) scaling up to 240 individuals m^{-2}.

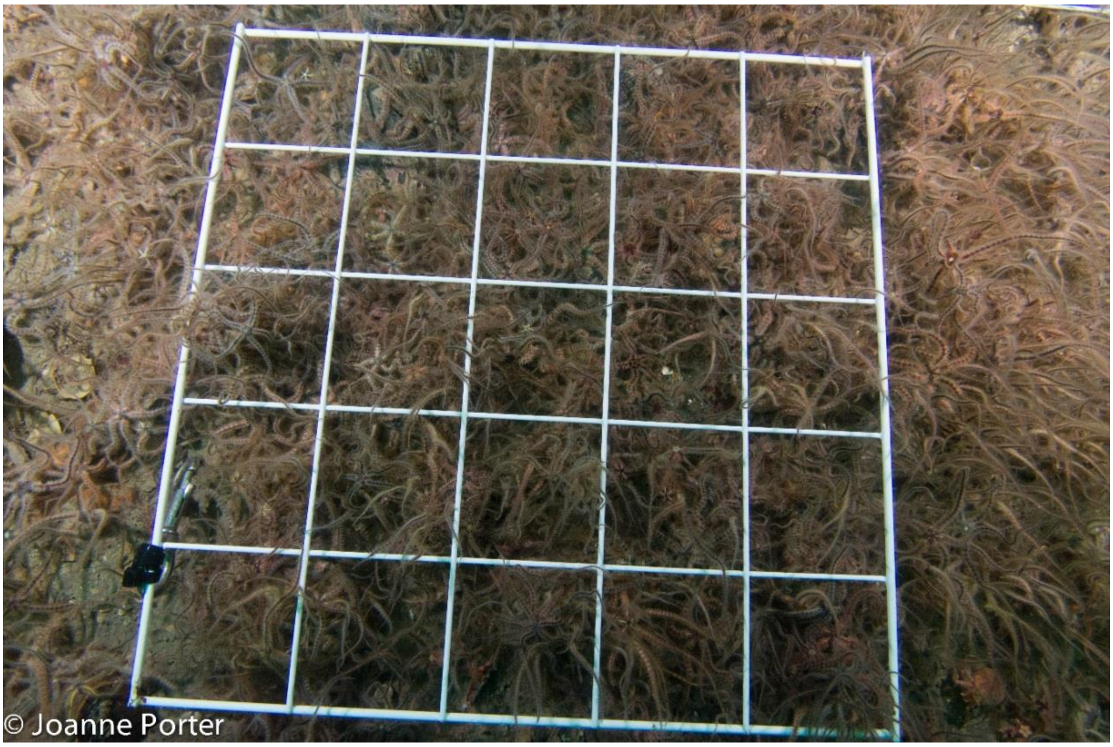

Figure 3.23: Dense *Ophiothrix fragilis* overlying clumps of the horse mussel *Modiolus modiolus* along a 25 m transect line adjacent to the wreck of SMS Karlsruhe, Scapa Flow, Orkney.

Carbon LOI burn up experiments gave an average total carbon content (organic carbon plus inorganic carbon added together) of 0.566 g C per brittlestar (N=5); OC represented 41.7% of total C and IC represented 58.3%.

Using Maxent, the predicted distribution of *Ophiothrix fragilis* in Orkney waters is 47.56 km^2 (Figure 3.24). Estimated areal extent and standing stocks of brittlestar beds in Orkney are shown in Table 3.8. These estimates do not account for the underlying sediment stocks on which the brittlestar beds are lying, and hence the numbers presented here will be an underestimate of the total carbon within the habitat. In areas where brittlestars overly horse mussel bed, sediment estimates of carbon are estimated only on the basis of horse mussel sediment thickness. In future work, it may be useful to consider areas with co-occurring habitats to be analysed and compared against ‘pure’ *Modiolus* and ‘pure’ brittlestar estimates. This may help to elucidate the relative contribution of each habitat type to the carbon measurements in these co-occurring habitat types.

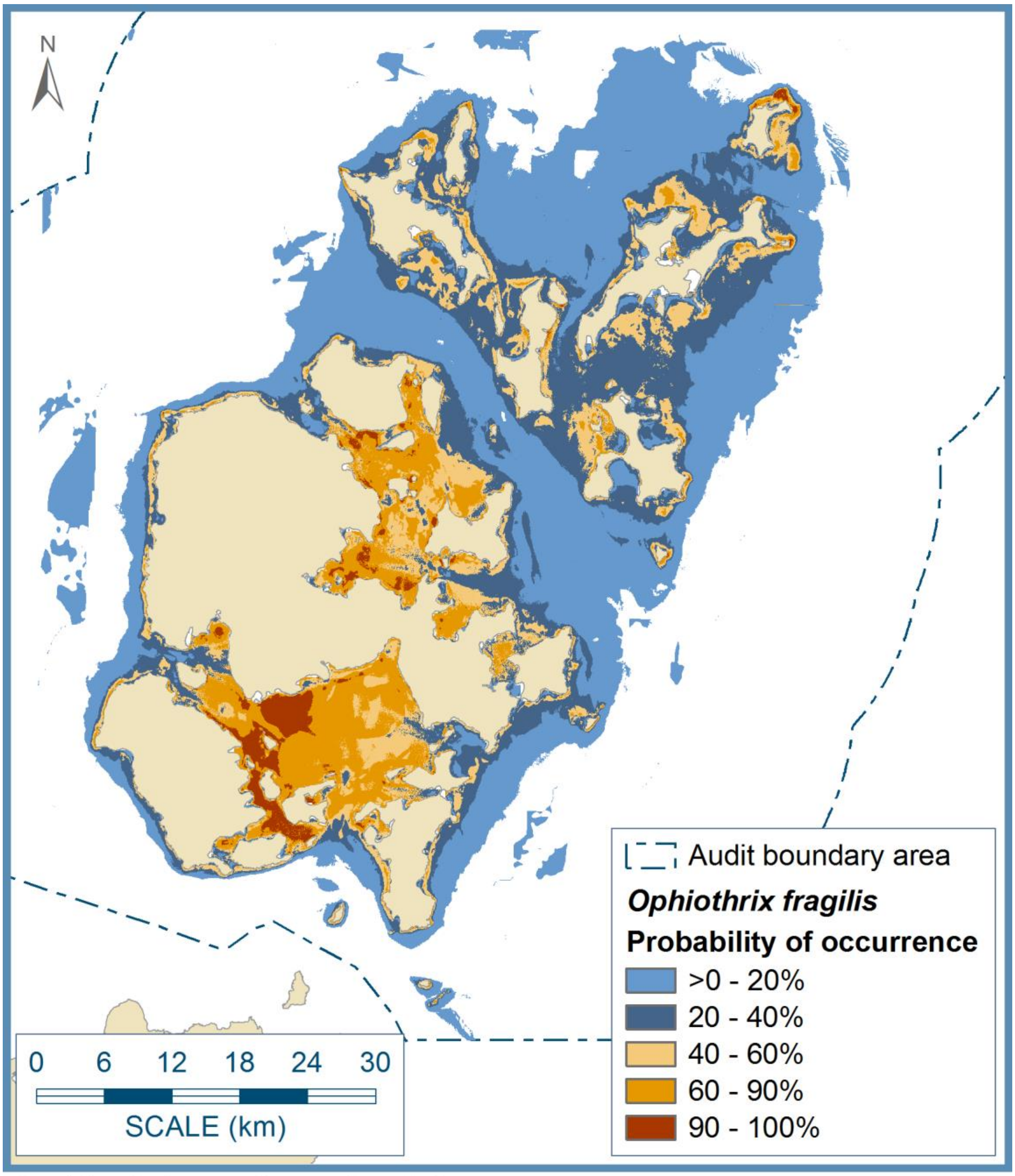

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Figure 3.24: Maxent model prediction of extent of *Ophiothrix fragilis* in Orkney waters.

Table 3.8

Estimated areal extent and standing stocks of brittlestar beds in Orkney.

Areal extent of Ophiothrix fragilis hectares	Number of individuals / m^2	Total number of individuals	Organic Carbon (1000 t)	Inorganic Carbon (1000 t)	Standing stock Carbon (1000 t)
4756	240	11,414,400,000	2.71	3.79	6.5

3.2.8. Bryozoan thicket

In surveys of Orkney waters by SNH and by Seasearch, observations of bryozoan communities have recorded two main types of thickets or turfs. The first of these is dominated by the large erect colonies of species such as *Flustra foliacea* (also known as Hornwrack) (MarLIN, 2019a) and its closely related species *Securiflustra securifrons* (Figure 3.25). These species are found attached to bedrock or large boulders, cobbles and shells. They are tolerant to scour and often flourish in strong tidal flow conditions, such as those experienced around parts of the Orkney coastline. There are for example dense aggregations of *Flustra foliacea* on bedrock and boulders around the wreck of the fishing trawler James Barrie in the mouth of Hoxa Sound (Scapa Flow Wrecks, 2019). The second type of bryozoan thicket or turf is a relatively short turf found as an understorey in kelp forest and/or as a coating on the surfaces of deeper rocky reef, boulders and cobbles (Figure 3.26). This type of turf often consists of species mixes with *Bugulina flabellata*, *Scrupocellaria reptans, Crisia* species, *Bicellariella ciliata* and *Cellaria* species (Figure 3.27). There is a third type of Bryozoa thicket occurs in wider Scottish waters beyond Orkney, particularly off the west coast, which is dominated by those with coral like colony structures or twiggy branched structures, for example *Pentapora foliacea* or *Omalesecosa ramulosa*. This third type of thicket may form an important component in future regional audit projects. In the Orkney Blue Carbon Audit our focus is on the most dominant type i.e. the first one described, in this case, *Flustra foliacea*. It should also be noted that there is a current lack of data on the carbon content of many species of Bryozoa. Our estimate of the contribution of bryozoan thicket to the Blue Carbon stores of Orkney will necessarily be an underestimate, however, it is useful to undertake an initial estimate. This will be the first of its kind, as Bryozoa don’t have any kind of conservation designation status and so have not been the subject of previous search feature work. The skeleton of *Flustra foliacea* comprises a mix of calcium carbonate and of chitinous material (Figure 3.28). This blend of materials gives the colonies a flexibility, allowing them to flex and bend in strong tidal conditions, well suited to the hydrodynamic conditions around Orkney’s coastline.

Figure 3.25: Thickets of *Flustra foliacea* besides the wreck of the trawler ‘James Barrie’ in Scapa Flow, Orkney (Image: Bob Anderson).

Figure 3.26: Mixed bryozoan crusts and turf on bedrock and boulders, typical of habitats along the west coast of Orkney.

Figure 3.27: *Crisia*-dominated Bryozoan turf among Jewel Anemones, typical of submerged bedrock and pinnacle habitats off Orkney west coast.

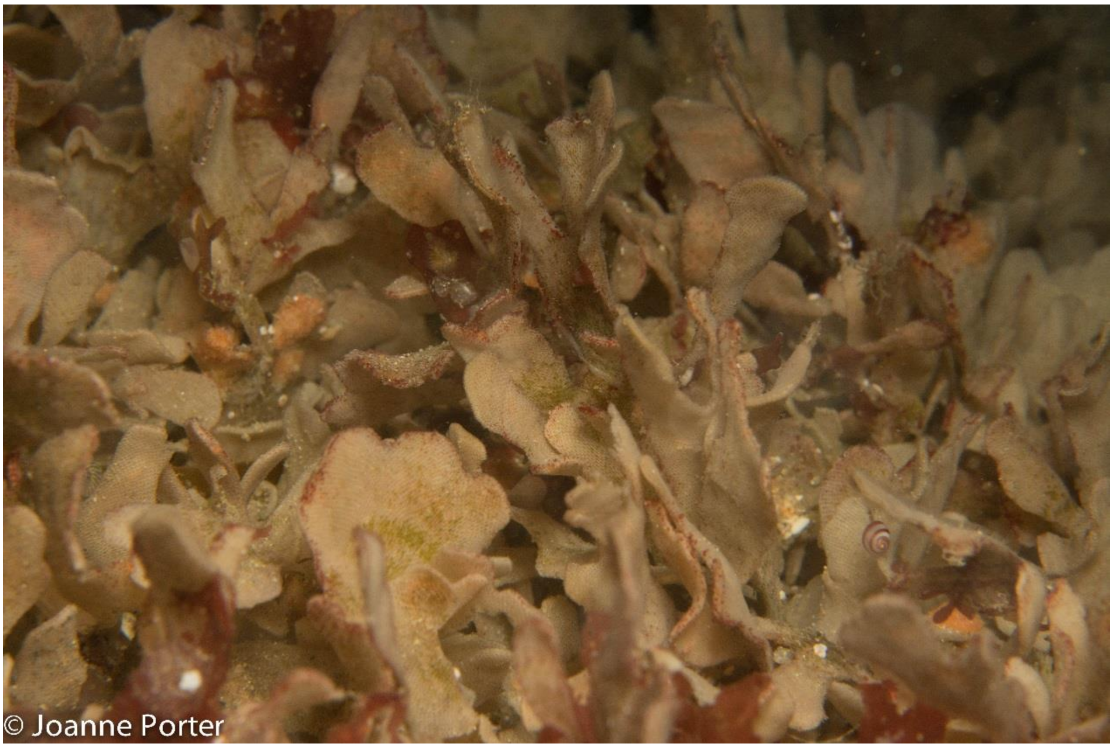


Figure 3.28: A dense turf of the bryozoan *Flustra foliacea* in Orkney waters.

Using *in situ* diver surveys, data were collected on the density of *Flustra foliacea* using estimates of percentage cover in 10 x 10 cm quadrats. Average number of

Flustra foliacea fronds and average wet weight of material per quadrat were also recorded. LOI analysis was performed to determine the amount of organic and inorganic carbon in replicate subsamples taken from *Flustra foliacea* colonies. The average total carbon of *Flustra foliacea* is 0.701 kg m^{-2}.

The areal extent of *Flustra foliacea* dominated bryozoan thicket was estimated by using a Maxent predictive model (Figure 3.30). The overall predicted cover as extracted from the model was 94.16 km^2 with 47.4 ton C (Table 3.9).

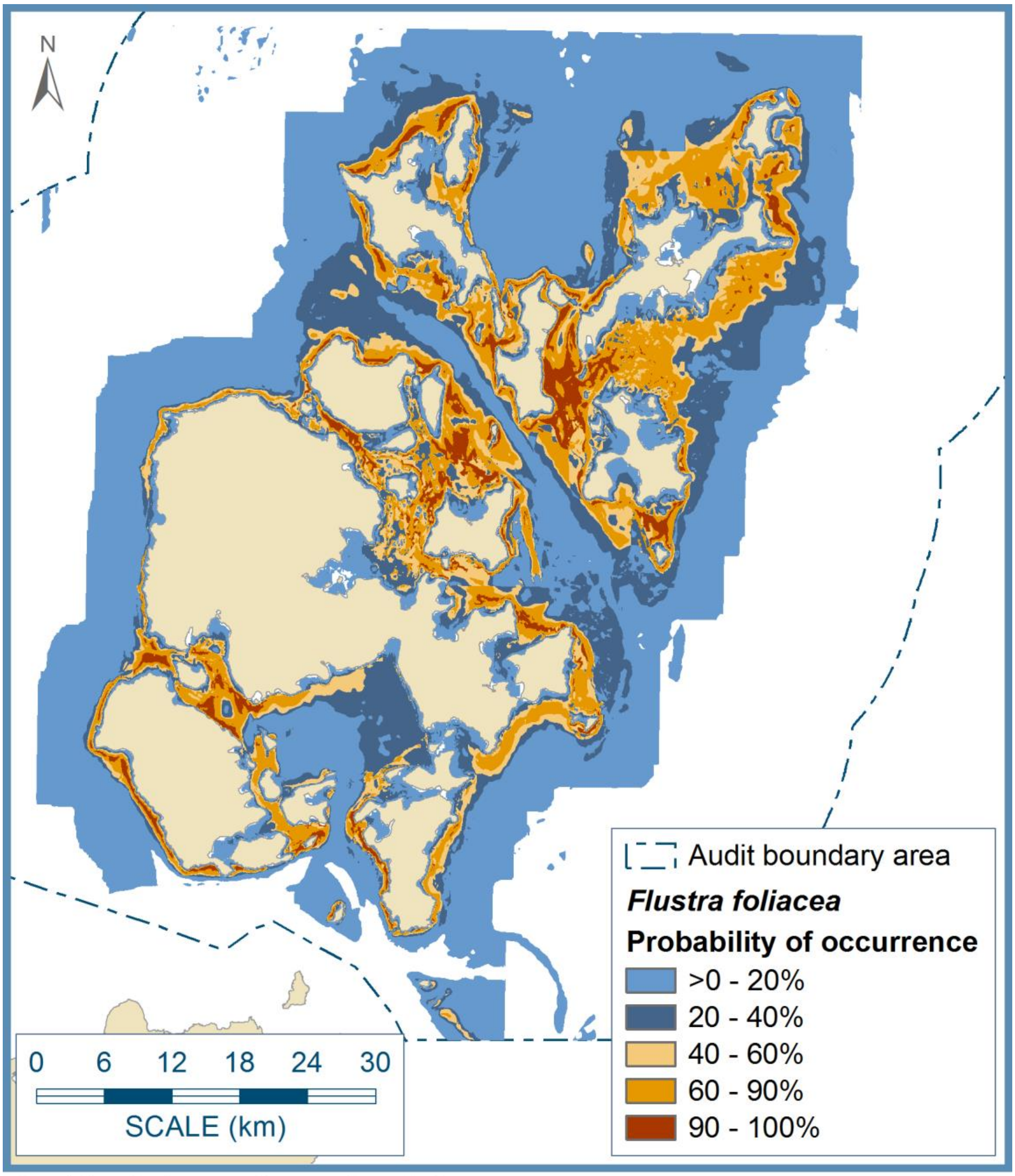


Figure 3.30: Maxent predicted model of *Flustra foliacea* extent in Orkney waters.

Table 3.9

Estimated areal extent and standing stocks of *Flustra foliacea* in Orkney.

Areal extent of *Flustra foliacea* hectares	OC/IC g m^{-2}	Organic Carbon (1000 t)	Inorganic Carbon (1000 t)	Standing Stock of C (1000 t)
9416	473/30	44.6	2.8	47.4

4. Habitat identification: Sedimentary environments

4.1. Introduction

Marine sediments are known to be environments where large quantities of C are trapped and stored over long periods of time (> 10^3 y) (Hedges, 1995; Smeaton *et al*., 2016, 2017). Currently there is no global estimate of the quantity of C stored in sediments but within Scottish territorial waters it is estimated that 592 Mt of OC and 1738 Mt of IC are stored in the top 10 cm of the sediment (Burrows *et al*., 2014, 2017). Furthermore, the sea lochs (fjords) of Scotland are estimated to store 252.4 ± 62 Mt OC and 214.7 Mt of IC in their postglacial sediments (Smeaton *et al*., 2017).

These sedimentary environments do not directly capture CO_2 from the atmosphere rather they are recipients of C from other environments. The source of the C buried in these sediments is derived from marine (Santschi *et al*., 1990; Glud, 2008; Krause-Jensen and Duarte, 2016), terrestrial (Bianchi, 2011; Bauer *et al*., 2013; Smeaton and Austin, 2017; Cui *et al*., 2017) and geological sources (Dicken *et al*., 2014; Galy *et al*., 2017). Globally it is estimated that marine sediments bury approximately 160 Mt OC y^{-1} (Hedges *et al*., 1995; Smith *et al*., 2014) with non-deltaic shelf sediments such as those found surrounding the Orkney Islands representing 42% of this total. The quantity of IC being buried in sediments globally remain poorly constrained.

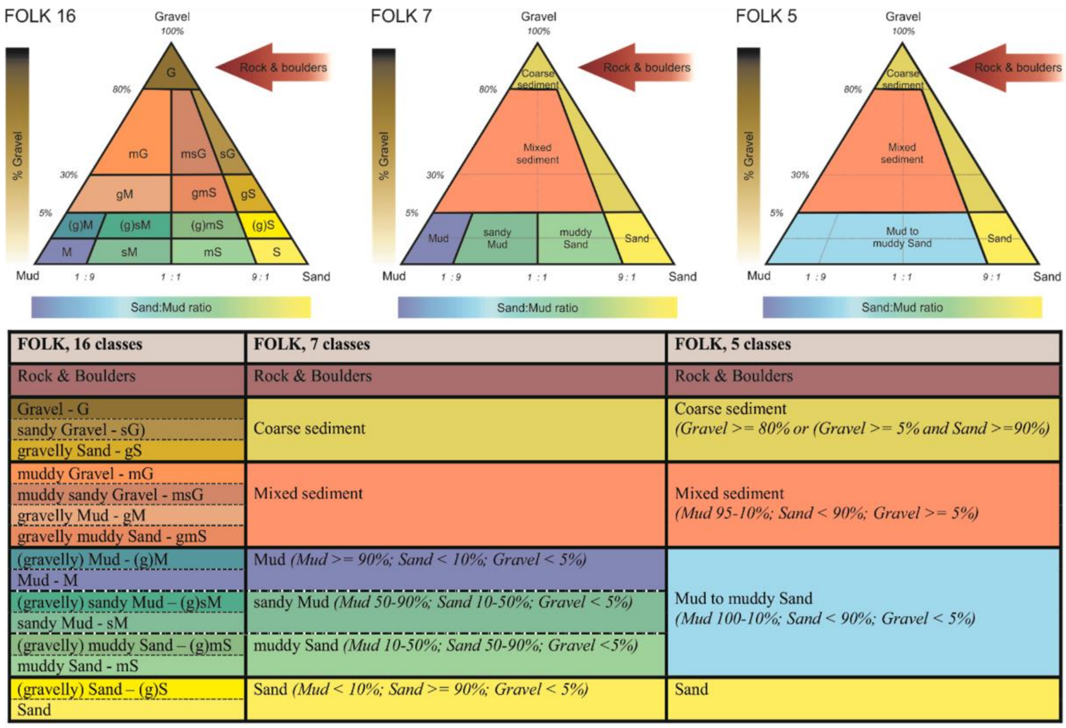
Within Scottish waters there are very few data available on the rate at which C is buried in marine sediments therefore it is currently not possible to include annual C burial rates for Orkney; instead, the focus of the audit is to quantify the C held within the surficial sediments surrounding the Orkney Islands.

4.2. Substrate identification and spatial extent

The Folk sediment classification scheme (Folk, 1954) was chosen as it is internationally prevalent, allowing this audit to benefit from existing sedimentological and OC data (i.e. BGS sediment maps). Furthermore, by using the Folk classification scheme the outputs from the mapping can be easily integrated and compared with other such studies (e.g. Diesing *et al*., 2017).

The Folk sediment classification can be used at three resolutions comprising 16, 7 and 5 classes (Figure 4.1) (Kaskela *et al*., 2019). Where existing data resolution allowed, the most detailed Folk classification was used.

4.2.1. Sediment type (folk classification)



FOLK, 16 classes	**FOLK, 7 classes**	**FOLK, 5 classes**
Rock & Boulders	Rock & Boulders	Rock & Boulders
Gravel - G sandy Gravel - sG) gravelly Sand - gS	Coarse sediment	Coarse sediment *(Gravel >= 80% or (Gravel >= 5% and Sand >=90%)*
muddy Gravel - mG muddy sandy Gravel - msG gravelly Mud - gM gravelly muddy Sand - gmS	Mixed sediment	Mixed sediment *(Mud 95-10%; Sand < 90%; Gravel >= 5%)*
(gravelly) Mud - (g)M Mud - M	Mud *(Mud >= 90%; Sand < 10%; Gravel < 5%)*	Mud to muddy Sand *(Mud 100-10%; Sand < 90%; Gravel < 5%)*
(gravelly) sandy Mud – (g)sM sandy Mud - sM	sandy Mud *(Mud 50-90%; Sand 10-50%; Gravel < 5%)*	
(gravelly) muddy Sand – (g)mS muddy Sand - mS	muddy Sand *(Mud 10-50%; Sand 50-90%; Gravel <5%)*	
(gravelly) Sand – (g)S Sand	Sand *(Mud < 10%; Sand >= 90%; Gravel < 5%)*	Sand

Figure 4.1: The Folk sediment triangle and the hierarchy of Folk classification (15, 6 and 4 classes), plus an additional class “rock and boulders,” indicated by the arrow) used in the EMODnet Geology project (from Kaskela *et al.*, 2019).

4.2.1.1. Sediment spatial distribution (BGS 250k)

The sediment type data were extracted from the 250k BGS SeaBed Sediment Map (*accessed from: Digimap: Geology*) and used to map the spatial distribution of the different sediment types within the 12 nm zone around the Orkney Islands (Figure 4.2)

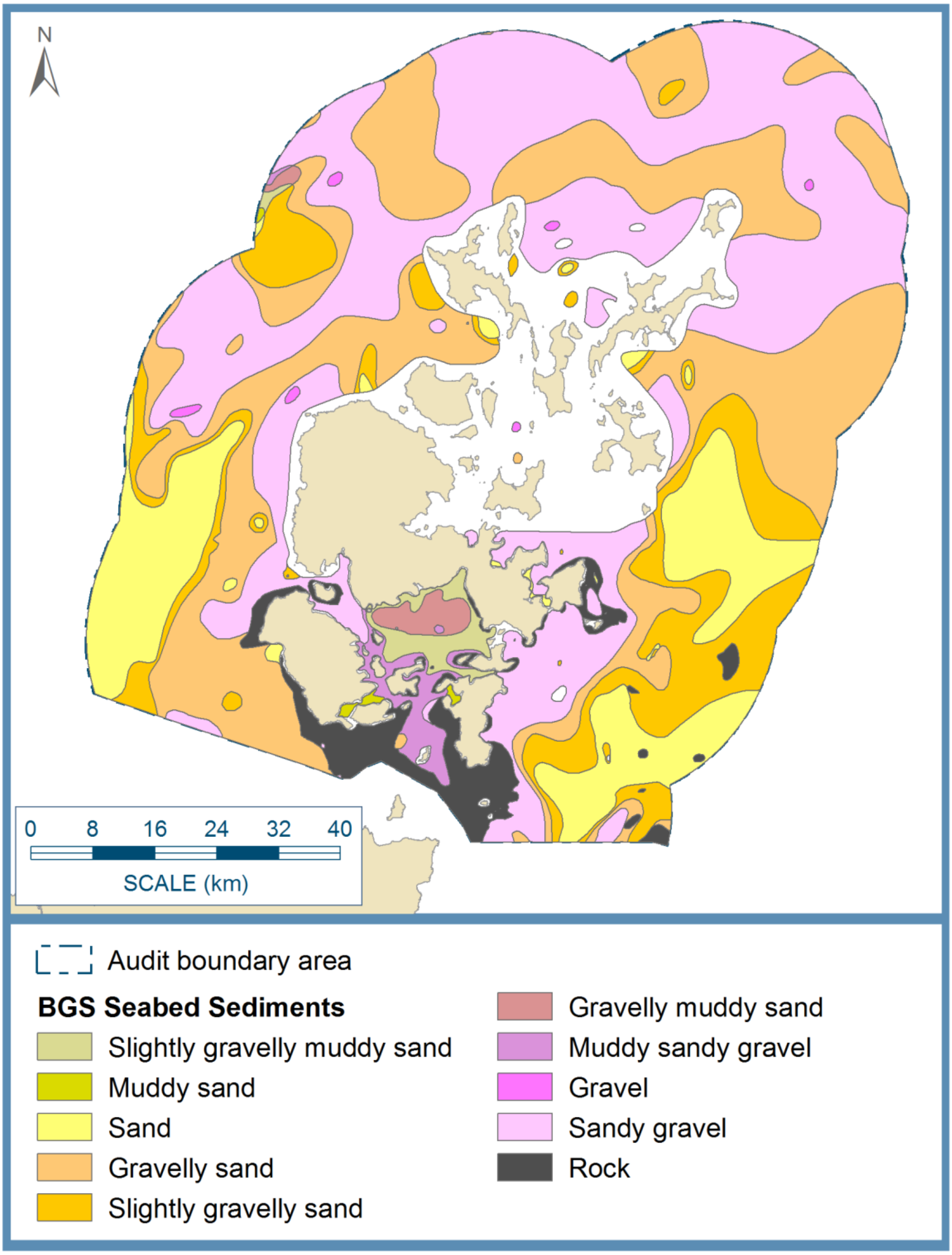


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Figure 4.2: Spatial distribution of the different sediment types surrounding Orkney derived from the 250k BGS SeaBed Sediment Map (*Accessed from: Digimap: Geology*). See Figure 4.3 for details of the central unmapped region.

The sediments around Orkney can be classified as 10 separate sediment types (Table 4.1) in accordance with the Folk classification (Folk, 1954). In total the BGS data covers an area of 6250 km^2 leaving an area of 1040 km^2 between the islands unmapped at this resolution (Figure 4.2).

Table 4.1

Areal extent of the different sediment types found with the 12 nm zone surrounding Orkney.

Sediment Type	Areal Extent (km^2)	Sediment Type	Areal Extent (km^2)
Gravelly Muddy Sand	55	Sandy Gravel	2293
Gravel	13	Slightly Gravelly Muddy Sand	78
Gravelly Sand	1932	Slightly Gravelly Sand	723
Muddy Sandy Gravel	82	Sand	806
Muddy Sand	9	Rock	259

4.2.1.2. Sediment spatial distribution (BGS 1:1 Million)

To map the sediment type in the 1040 km^2 area between the islands a coarser resolution (1:1 million) sediment map was utilised (Figure 4.3).

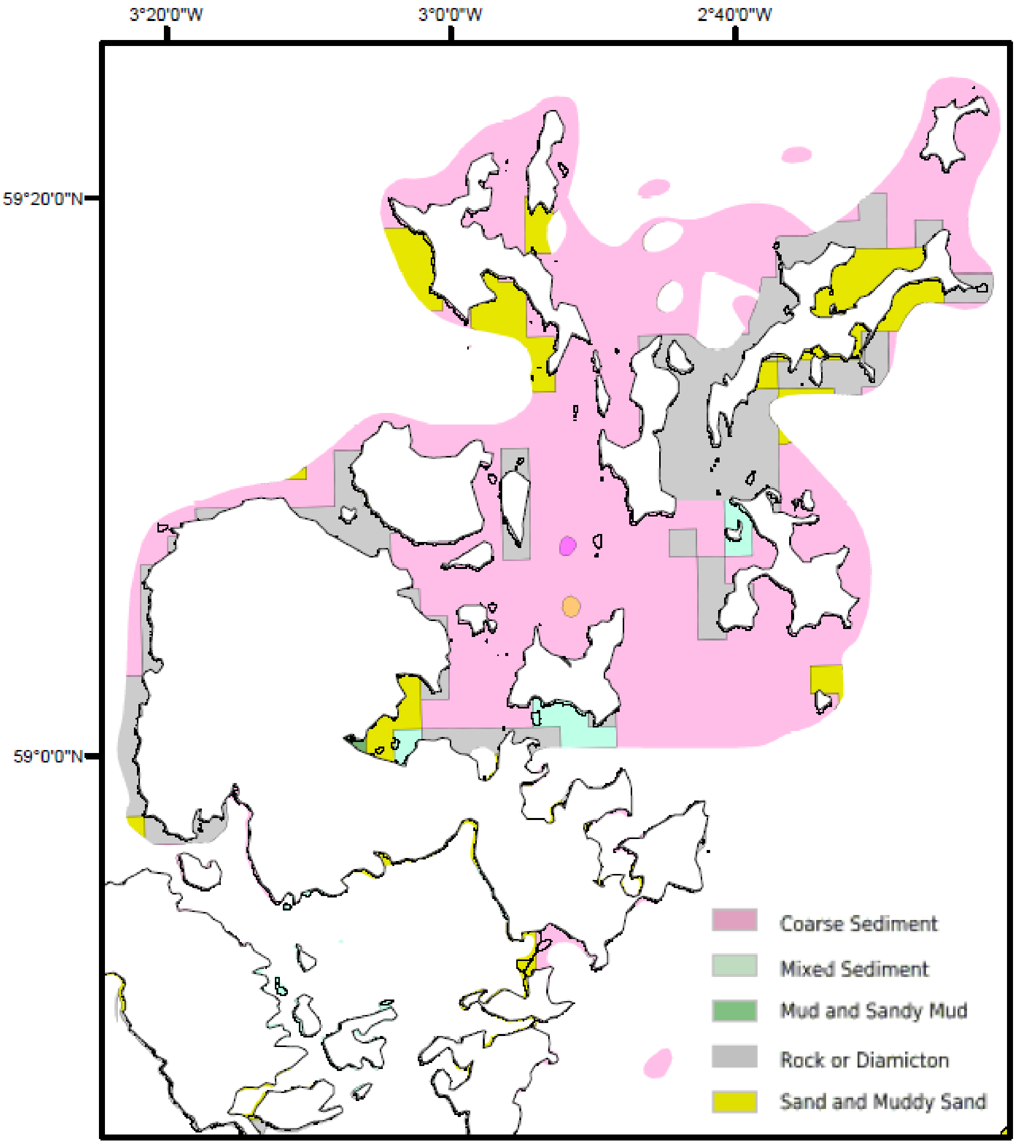

Figure 4.3: Spatial distribution of the different sediment types within the unmapped region between the islands of Orkney derived from the 1:1 million BGS Sediment Map (*Accessed from: BGS Offshore Geoindex*)

The data were accessed through the BGS Offshore Geoindex, unlike the 250K BGS SeaBed sediment map that uses the full Folk classification this lower resolution map uses the simpler 5 Folk classification (Figure 4.1). Within the unmapped region four seabed types were identified (Table 4.2)

Table 4.2

Areal extent of the different sediment types found within 1040 km^2 area between the islands of Orkney.

Sediment Type	**Areal Extent (km^2)**
Coarse Sediment	689
Sand and Muddy Sand	94
Mixed Sediment	51
Rock	207

4.2.2. Sediment thickness

In this audit a conservative approach has been taken, with only the top 10 cm of sediment included in the calculations, as there are limited data on sediment thickness, dry bulk density and OC content beyond the surficial sediments. Through examination of the limited legacy seismic reflection data (1970s) from the area the sediment thickness varies between approximately 2 to 20 m which is supported by the BGS Quaternary Deposits Map which suggests that around Orkney the majority of the sediment is between 5 to 20 m thick. Therefore, it is recognised that stocks reported here represent a small fraction of full-thickness sedimentary carbon stocks.

4.3. Geological Blue Carbon Values

4.3.1. Data availability and quality

4.3.1.1. Organic carbon

Within the 12 nm boundary of the study there are few OC data available that are representative of the whole 12 nm area. Previous sampling of Orkney sediments has been undertaken for specific reasons such a Polycyclic Aromatic Hydrocarbon (PAH) monitoring (Webster *et al*., 2001) which found surficial sediment OC values of between 0.1 and 5% across nine coastal sites. Additionally, monitoring of local aquaculture sites is undertaken regularly, though data from around such sites cannot be used because of the increased organic matter loading associated with the aquaculture but the control sites used in this monitoring are potentially an important data resource. Cooke Aquaculture provide data for 26 control sites which are regularly monitored, 24 of these sites only had % organic matter (OM) content measured by Loss on Ignition (LOI). The organic matter content of these samples ranges between 0.58 and 4.65 % OM. The other two sites have OC data which ranges between 0.43-0.75% OC. Both the aquaculture and the PAH monitoring (Webster *et al*., 2001) data comes from near shore environments and is not representative of the sediments found within the 12 nm zone which is largely similar to continental shelf in nature (Figure 4.2).

Currently there is a knowledge gap in terms of the bulk density and OC content of sediment in the Orkney area and therefore generic values from the adjacent North Sea area were applied (Diesing *et al.,* 2017).

4.3.1.2. Carbon values for geological substrate type

Below the dry bulk density values and the associated OC values derived from North Sea (Deising *et al*., 2017).

Table 4.3

Dry bulk density (kg m^{-3}) and OC (%) values for each of the 9 Folk classes derived from North Sea samples (Diesing *et al*., 2017). The lower and upper bounds of our estimates (based on the 5th and 95th percentiles).

	Dry Bulk Density (kg m^{-3})				OC (%)			
Substrate Type	**P5**	**P95**	**Mean**	**SD**	**P5**	**P95**	**Mean**	**SD**
Mud	536	624	580	29	0.59	1.11	0.88	0.2
Sandy Mud	646	1011	828	120	0.54	1.11	0.78	0.21
Muddy Sand	1111	1429	1323	99	0.27	0.92	0.54	0.22
Sand	1454	1535	1511	25	0.1	0.5	0.24	0.12
Slightly gravelly sandy mud	789	1030	945	73	0.55	0.93	0.67	0.16
Slightly gravelly muddy sand	1192	1433	1357	80	0.32	0.82	0.54	0.22
Slightly gravelly sand	1467	1534	1512	21	0.07	0.43	0.22	0.11
Gravelly mud	845	1080	1011	102	0.7	1.69	0.91	0.51
Gravelly muddy sand	1287	1447	1397	51	0.3	0.77	0.49	0.23
Gravelly sand	1486	1534	1515	16	0.12	0.44	0.23	0.1
Muddy Gravel	1234	1394	1314	125	0.62	0.62	0.62	0.01
Muddy sandy gravel	1438	1510	1482	25	0.16	0.45	0.29	0.1
Sandy gravel	1492	1534	1521	13	0.12	0.35	0.19	0.09
Gravel	1511	1535	1529	8	0.13	0.25	0.18	0.05

The data extracted from Diesing *et al*. (2017) can be directly applied to the sediment data from the 250K BGS SeaBed sediment data but the dry bulk density and OC (Table 4.3) does not directly map onto the 1:1 million scale sediment data. To remedy this, different sediment types were reclassified using the simplified 5 Folk classes and mean values for dry bulk density and OC data calculated (Table 4.4).

Table 4.4

Dry bulk density (kg m^{-3}) and OC (%) values for sediment classified using the 5 Folk Class scheme. The lower and upper bounds of our estimates (based on the 5th and 95th percentiles).

	Dry Bulk Density (kg m^{-3})				OC (%)			
Substrate Type	**P5**	**P95**	**Mean**	**SD**	**P5**	**P95**	**Mean**	**SD**
Coarse Sediment	1496	1534	1522	12	0.12	0.35	0.16	0.08
Sand and Muddy Sand	1129	1331	1253	64	0.31	0.78	0.49	0.17
Mixed Sediment	1177	1354	1291	83	0.45	0.90	0.56	0.21

4.3.1.3. Inorganic carbon

BGS collected significant numbers of surficial sediment samples during the 1970s and 80s, and, as part of this programme, carbonate content of the sediments was regularly analysed. All carbonate data for the 12 nm zone around Orkney were extracted from the BGS Offshore Geoindex (Figure 4.4).

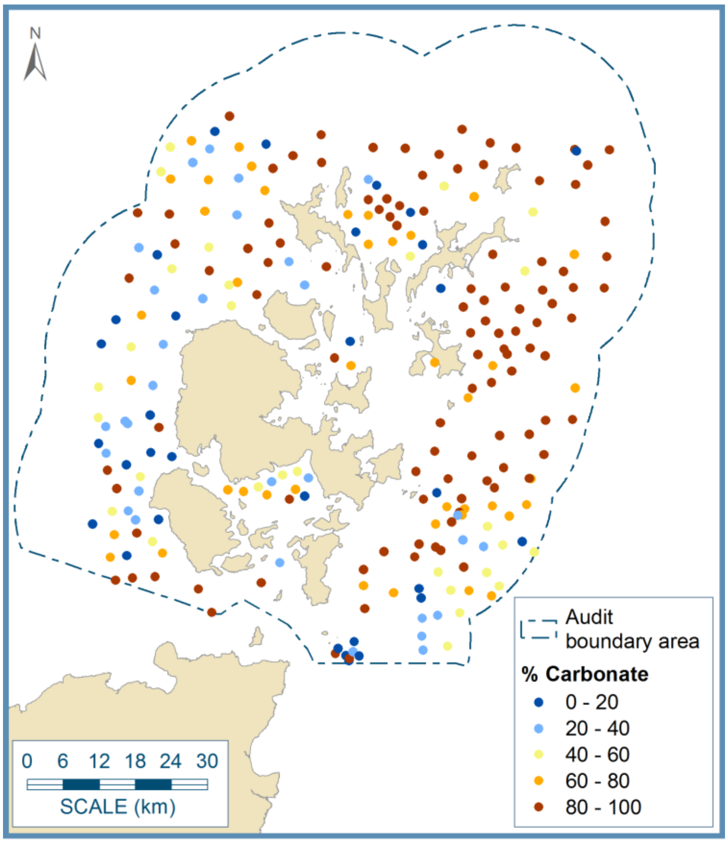

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Figure 4.4: Carbonate content of surficial sediment (data accessed from: *BGS Offshore Geoindex*).

4.4. Calculations

4.4.1. Organic carbon stocks

calculations. The sedimentary spatial maps provided the area (km^2) of the different sediment types (Table 4.1, 4.2). Multiplying the area by a uniform thickness of the sediment (0.1 m) allows the volume of sediment to be calculated. The sediment volume is converted to mass (kg) by multiplying it by the appropriate dry bulk density (kg m^{-3}) value (Table 4.3, 4.4). Using the %OC for each sediment type, the total OC held within the surface 10 cm of the sediment was calculated.

4.4.2. Inorganic Carbon Stocks

The carbonate data extracted from the BGS Offshore Geoindex was initially corrected to %IC (12% of $CaCO_3$ is C). The IC data were linked to the underlying sediment type (Figures 4.2 and 4.3) for each point, allowing IC values to be associated with different sediment types (Table 4.5). The same calculation method discussed in Section 4.4.1 was then used to estimate the quantity of IC stored in the surficial sediments.

Table 4.5

IC (%) values for each of the sediment types found around Orkney derived from the BGS point data (Figure 4.4) and the lower and upper bounds of our estimates (based on the 5th and 95th percentiles).

	IC (%)			
Substrate Type	**P5**	**P95**	**Mean**	**SD**
	1:250K Scale			
Gravelly Muddy Sand	3.11	5.94	4.56	1.02
Gravel	0.45	6.87	2.07	2.06
Gravelly Sand	2.05	8.25	6.70	1.58
Muddy sandy gravel	6.79	7.54	7.17	0.53
Sandy Gravel	0.23	8.20	5.38	2.51
Slightly Gravelly Muddy Sand	3.14	3.36	3.25	0.15
Slightly Gravelly Sand	2.43	8.08	6.20	1.68
Sand	0.16	7.67	5.19	2.22
	1:1 Million Scale			
Coarse Sediment	0.91	7.77	4.72	2.05
Sand and Muddy Sand	3.11	5.94	4.56	1.02
Mixed Sediment	6.79	7.54	7.17	0.53

4.4.3. Sedimentary C density

The OC and IC density was calculated by normalizing the C stocks by the areal extent of each of the sediment types; the C density estimates were then applied to the sediment type map (Figure 4.2) to allow wide-scale mapping of the concentration of carbon (tonnes ha^{-1}) across Orkney waters (Figure 4.5).

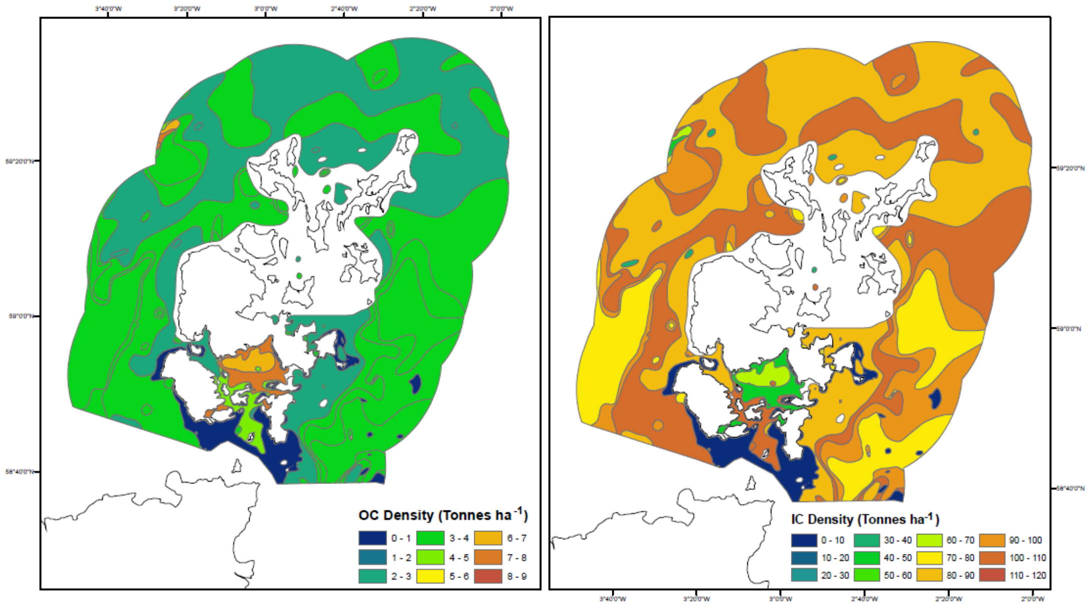

Figure 4.5: Carbon density (Area normalized Carbon Values; tonnes ha^{-1}) across the surficial sediments (top 10 cm) within the study area (a) OC density (b) IC density.

5. Blue carbon results of Orkney Waters

5.1. Carbon audit results

In Table 5.1 the results from the audit are given by biological habitat type following the classification scheme described in Section 2. In Table 5.2 and 5.3, the results are given for OC and IC, respectively, from surficial sediments in Orkney.

Table 5.1

Minimum estimated Carbon estimates for biological habitats in Orkney.

	Hectares	**OC Stock***	**OC Density**	**IC Stock**	**IC Density**
		(1000 t)	**(tonnes ha^{-1})**	**(1000 t)**	**(tonnes ha^{-1})**
Kelp Forest	48710	100.8	2.07	NA	NA
Maerl Beds	3645	57.5	15.77	5,355.2	1,469.1
Zostera Beds	1423	117.3	114/78**	M	M
Saltmarsh	48.94	5.6 ± 1.0***	112.8 ± 20.9***	NA	NA
Horse Mussel	3828	13.35	3.48	153.1	39.9
Flame Shell	1799	1.1	0.61	6.0	3.3
Brittlestar Beds	4756	2.71	0.56	3.79	0.79
Bryozoan Thicket	9416	44.6	6.6	2.8	0.29
Total (Biological)		342.96		5520.89	
Overall Total (OC+IC)		5863.85			

Note: *OC values for flame shells, brittlestars and bryozoans are derived using the Loss on Ignition method. ***Z. noltii*/*Z. marina*. ***Saltmarsh error defined here as Standard Deviation of the mean. NA-Not applicable. M-not measured.

Significant caveats arise from these numbers as have been itemised specifically within each of the habitat sections. In general, these fall into two major areas. Firstly, it is important to note that the lack of data on the thickness of sediment underlying the biological habitats is a key data gap and therefore the numbers reported here will be an underestimate. Secondly, the areal extent of some habitats is not well documented and therefore we are reliant on predictive habitat models to produce the areal extent figures. While a conservative approach has been taken to the predictive mapping by using a cut-off point of 0.90 (see also the AUC confidence levels reported in Appendix A), the predictive model result is based on where the habitat is predicted to be suitable for the organism in question as calculated from the raster layers. This is not the same as knowing that the organism is actually there. There may be some reason why an organism is not able to fulfil the predicted niche even if the model identifies the location as suitable. The only way to prove the accuracy of the model is to go and survey the sites that have been predicted. We did this to a certain extent by splitting our known data points between a training set and a testing set. The testing sets did sit within the predicted areas of the models, however, the sparseness of the available test points still means that there are some areas of the predicted habitat that are not well covered by test points. Ground-truthing of these in future would improve the robustness of the predicted models. A ‘heat-map’ showing total carbon resources found in biological habitats identified in the Orkney Blue Carbon Audit is provided in Figure 5.1. Significant areas of blue carbon are found around the islands of Sanday and North Ronaldsay due to the dense stands of kelp forest in those areas. Less extensive but nonetheless carbon rich deposits are shown through Wyre and Rousay Sound due to the maerl beds there.

Table 5.2

Surficial sediment (top 10 cm) OC stocks (Mt) and OC density (tonnes ha^{-1}).

Substrate Type	Mean OC Stock (Mt)	OC Stock Range (Mt)	Mean OC Density (tonnes ha^{-1})	OC Density Range (tonnes ha^{-1})
1:250K Scale				
Gravelly Muddy Sand	0.038 ± 0.018	0.021 – 0.061	6.85 ± 3.21	3.86 – 11.14
Gravel	0.004 ± 0.001	0.003 – 0.005	2.75 ± 0.76	1.96 – 3.84
Gravelly Sand	0.673 ± 0.293	0.345 – 1.304	3.48 ± 1.52	1.78 – 6.75
Muddy Sandy Gravel	0.035 ± 0.012	0.019 – 0.056	4.30 ± 1.48	2.30 – 6.80
Muddy Sand	0.006 ±0.003	0.003 – 0.012	7.14 ± 2.91	3.00 – 13.15
Sandy Gravel	0.663 ± 0.314	0.411 – 1.231	2.89 ± 1.37	1.79 – 5.37
Slightly Gravelly Muddy Sand	0.057 ± 0.023	0.030 – 0.092	7.33 ± 2.99	3.81 – 11.75
Slightly Gravelly Sand	0.240 ± 0.120	0.074 – 0.477	3.33 ± 1.66	1.03 – 6.60
Sand	0.292 ± 0.146	0.117 – 0.619	3.63 ± 1.81	1.45 – 7.68
1:1 Million Scale				
Coarse Sediment	0.168 ± 0.084	0.127 – 0.366	2.43 ± 1.22	1.85 – 5.32
Sand and Muddy Sand	0.058 ± 0.020	0.033 – 0.097	6.16 ± 2.17	3.54 – 10.36
Mixed Sediment	0.037 ± 0.014	0.027 – 0.062	7.20 ± 2.71	5.30 – 12.12
Total	2.271 ± 1.048	1.209 – 4.382	3.11 ± 1.44	1.66 – 6.01

Table 5.3

Surficial sediment (top 10 cm) IC stocks (Mt) and IC density (tonnes ha^{-1}).

Substrate Type	Mean IC Stock (Mt)	IC Stock Range (Mt)	Mean IC Density (tonnes ha^{-1})	IC Density Range (tonnes ha^{-1})
1:250K Scale				
Gravelly Muddy Sand	0.350 ± 0.078	0.22 – 0.473	63.70 ± 14.25	40.03 – 85.95
Gravel	0.041 ±0.041	0.009 – 0.137	31.65 ± 31.50	6.80 – 105.45
Gravelly Sand	19.611 ± 4.625	5.885 – 24.450	101.51 ± 23.94	30.46 – 126.56
Muddy Sandy Gravel	0.871 ± 0.064	0.801 – 0.934	106.26 ± 7.85	97.64 – 113.85
Muddy Sand	0.039 ± 0.002	0.002 – 0.043	43.00 ± 2.04	2.56 – 48
Sandy Gravel	18.764 ± 8.754	10.745 – 28.843	81.83 ± 38.18	46.86 –125.79
Slightly Gravelly Muddy Sand	0.344 ± 0.016	0.226 – 0.375	44.10 ± 2.10	28.97 –48.14
Slightly Gravelly Sand	6.778 ± 1.837	0.170 – 8.961	93.74 ± 25.40	2.35 –123.95
Sand	6.321 ± 2.704	0.188 – 9.489	78.42 ± 33.54	2.33 –117.73
1:1 Million Scale				
Coarse Sediment	4.949 ± 2.149	0.938 – 8.214	71.82 ± 31.19	13.62 – 119.22
Sand and Muddy Sand	0.537 ± 0.120	0.412 – 0.841	57.14 ± 12.78	43.82 –89.42
Mixed Sediment	0.472 ± 0.035	0.408 – 0.521	92.56 ± 6.84	79.94 – 102.11
Total	59.08 ± 20.43	20.01 – 83.28	81.03 ± 28.01	27.44 – 114.23

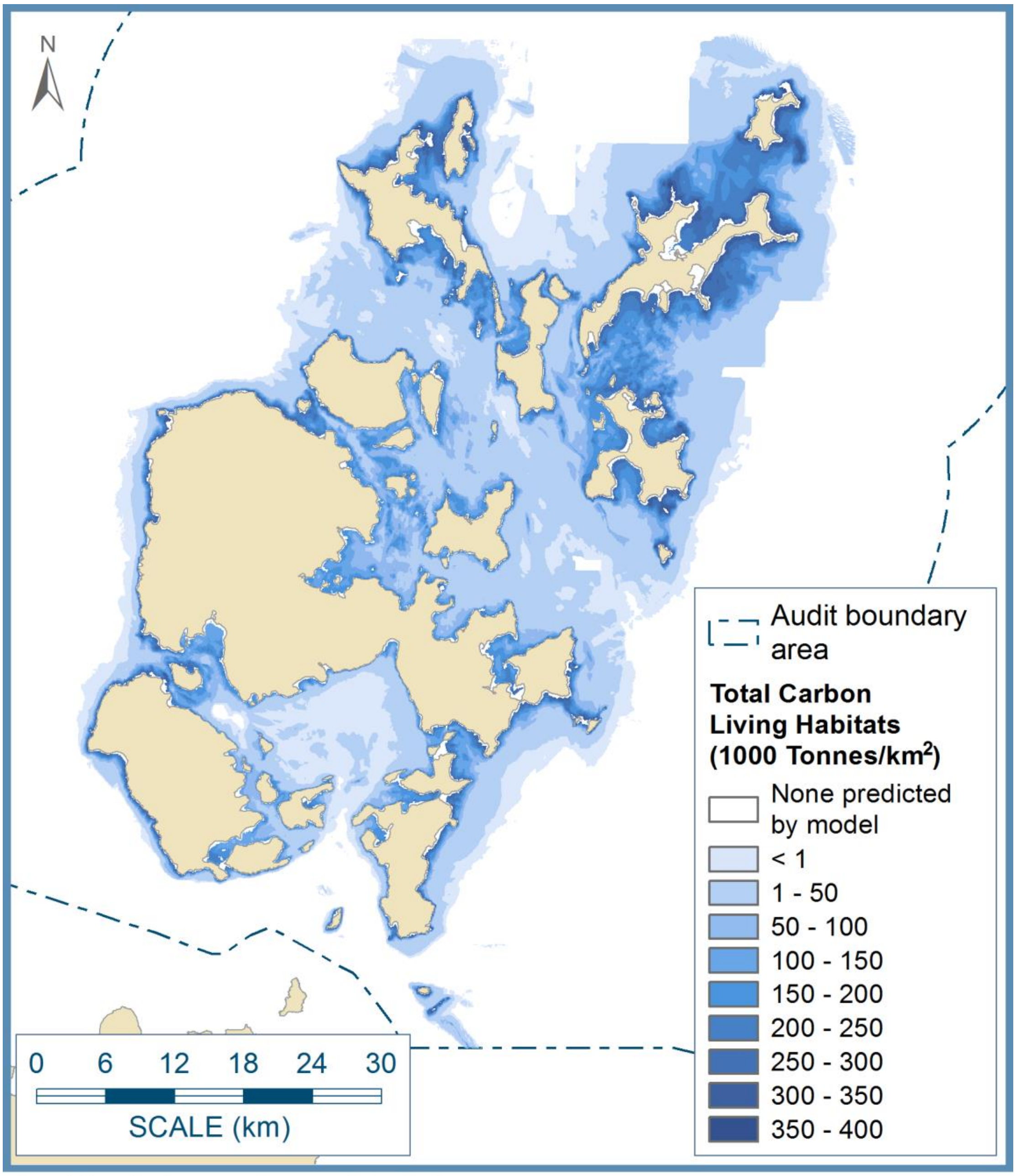

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Figure 5.1: A 'heat-map' of total carbon resources found in biological habitats in Orkney.

5.2. Uncertainty analysis

In order to assess the uncertainty associated with the estimates of blue carbon in Orkney waters we applied the Delta method. This involves multiplying together the sources of error (calculated as standard error). There are three main sources of potential error in this audit approach; biomass density estimates, blue carbon biomass estimates and areal extent estimates. In general, of these, the blue carbon estimates have the least error associated with them, followed by the biomass density estimates and then the areal extent being the major source of error as for all the habitats except for maerl and saltmarsh, the areal extent is based on the MAXENT predictive modelling. In these cases we have assumed a coefficient of variance of 25%.

In Table 5.4 there is a summary of the uncertainty calculations performed for the living habitats. These figures indicate that the highest levels of uncertainty are found with the kelp forest and horse mussel habitats. With the inclusion of further survey data points it is likely that the uncertainty associated with these numbers could be reduced.

Table 5.4

Summary of uncertainty calculations for living habitats contribution to blue carbon audit estimates.

All figures in thousand tonnes				
			95% CI	
Habitat	**Total C**	**SE**	**Lower**	**Upper**
Kelp Forest	100.85	36.19	29.91	171.78
Maerl Beds	5412.70	1353.18	2760.48	8064.92
Zostera Beds	117.3	29.33	59.81	174.79
Saltmarshes	5.60	0.72	4.19	7.01
Horse Mussel	166.47	41.62	84.90	248.03
Flame Shell	7.10	1.77	3.62	10.58
Brittlestar Bed	5.69	1.86	2.05	9.33
Bryozoan thicket	47.38	14.22	19.51	75.25
Total	5863.85	1354.98	3252.22	8563.74

6. Discussion of the Orkney blue carbon audit

6.1. Blue carbon assessment across the Orkney Region

This report provides details on the first regional audit of blue carbon resources. Methods developed here are readily transferable for application to other regional audits. While this audit is based on the latest available survey data and carbon analysis, detailed studies of some key habitats are limited. In certain cases, carbon content has been estimated from samples out-with Orkney waters and model predictions of distribution are used to estimate the coverage of key habitat types. This is ground-truthed where possible with actual observations. New research has provided greater details on carbon stocks in several habitats, such as saltmarsh, brittlestar beds, and bryozoan thickets. Knowledge gaps are identified, and suggestions made to prioritise future research. While further studies will increase the accuracy of blue carbon estimates, the general findings presented here on blue carbon resources in key habitats in Orkney waters are sufficiently robust to provide important guidance to marine management policy-makers.

6.1.1. Carbon standing stocks

In this audit estimates have been made of the standing stock of key blue carbon habitat types known to be prevalent in Orkney waters. The overall total blue carbon, including surface sediments, in Orkney waters is estimated to be 67 million tonnes. This is a minimal estimate of the blue carbon resource going out to the 12 nm limit, given that it has not been possible to assess the full extent of the range out to 12 nm for some habitats due to limitations of available data for predictive modelling. In Orkney we find 67 Mt in a sea area of 7,290 km^2. This equates to a density of 9,190 tonnes C km^{-2} in Orkney waters. This contribution is likely to increase when further data on the thickness of deposits underlying the biological habitats becomes available.

6.1.2. Sequestration rates

The focus of the blue carbon audit was to develop for the first time an estimate of the standing stock of blue carbon in Orkney waters. For standing stocks to be maintained in future, it is also important to have an understanding of the annual rate at which blue carbon is produced, as well as understanding time-scales necessary for sequestration into long term storage. For many habitat types determination of sequestration rates is not currently possible owing to gaps in critical data. Data gaps necessary to allow sequestration rates determination are highlighted in Table 6.1.

6.1.3. Carbon budgets: Production versus sequestration

In future it would be useful to work towards an understanding of the production and sequestration rates of the key habitat types, so that sources and sinks of blue carbon, and the dynamics between them, can be better understood.

6.1.4. Current blue carbon protection measures

Currently, there are five protected sites in the waters defined in the Orkney Blue Carbon Audit. While each of the four fully marine protected sites form part of the Orkney Carbonate Production Area, the sites were designated wholly on their biodiversity value and no consideration was given to the role played in carbon cycling. This network of MPAs and SACs, however, contains several habitats identified in this audit as important resources of blue carbon (Figure 1.1). The Wyre and Rousay Sounds MPA has been designated for three functionally linked protected features; the maerl beds and the kelp and seaweed communities on sublittoral sediment thrive in the tide-swept channels, forming a large-scale intermixed habitat mosaic. The maerl beds are also considered an integral part of the Orkney carbonate production system. The Papa Westray MPA has been designated to protect the cliffs and near-shore waters used for breeding and foraging by black guillemots (*Cepphus grylle*). The Sanday SAC was primarily selected for the presence of the Annex I habitat of rocky reefs which provide substrate for extensive forests of *Laminaria* spp. In addition, the waters within this SAC feature dense turfs of bryozoan and hydroids, and important beds of *Modiolus* and brittlestars below the kelp zone. The primary reason for selection of the Faray and Holm of Faray SAC is for protection of habitats important to breeding colonies of the Grey seal (*Halichoerus grypus*). Extensive kelp forests are located within this SAC.

6.2. Pressures on blue carbon resources

A summary of pressures on blue carbon resources is presented in Table 6.1. Some of the key pressures on the carbon stored in sediment and the carbon in organisms are discussed in further detail below.

6.2.1. Pressures on carbon stored in sediment

Multiple pressures arise from current management practices of the marine environment, most notably from the physical disturbance of the seabed. Where significant sedimentary carbon stores exist and where the stocks are high, there may be a greater risk of turning these long-term carbon stores into carbon sources. The generally high IC contents of the sedimentary carbon resource may allow Orkney waters to effectively buffer some of the negative impacts of ocean acidification and the risks, apart from certain key habitats where calcifying organisms may be particularly vulnerable, are deemed to be relatively low. Deoxygenation of inshore Orkney waters in the near future is unlikely due to the combination of the relatively shallow and tidally well-mixed waters, which are well-exchanged with the atmosphere. This may not be the case for deeper waters further offshore. Sea-level rise is likely to play an increasingly important role in driving coastal erosion and Orkney's saltmarsh habitats and blue carbon resources are therefore likely to come under increasing pressure unless effective coastal management and coastal realignment opportunities are in-place. Pressures and risks are highlighted in Table 6.1, following from the Marlin (2019b) webpages.

6.2.2. Pressures on carbon stored in organisms

6.2.2.1. Deoxygenation

Deoxygenation of coastal waters, such as that experienced in parts of the Clyde Sea means that animals which sequester carbon could die off. Some animals are more tolerant to deoxygenation than others, but shellfish, for example, which cannot move out of a layer of deoxygenated water will suffocate. There have been studies of the impact of deoxygenation related to instances of toxic algal blooms - where the blooms decompose and sink to the sea bed, the biological oxygen demand increases in the water layers close to the sea bed and mass mortality of a wide range of organisms has been noted. This has been observed in Killary harbour on the west coast of Ireland where periodic bouts of algal bloom associated with deoxygenation occur (Silke *et al*., 2005). Recovery does occur but, depending on the type of organism and its rate of growth, this can take years or decades. From a blue carbon perspective, deoxygenation events could lead to a sudden release of carbon into the system when large quantities of plant and animal materials start to decompose simultaneously. On the other hand if a zone is fully anoxic, decomposition will not occur and so the likelihood then is that carbon will be buried and stored. Understanding the tipping points is key to being able to manage the resource in future.

6.2.2.2. Acidification

It is now well documented that organisms which have a carbonate shell or skeleton are vulnerable to the impact of ocean acidification (Ciais *et al*., 2013; Koch *et al*., 2013; Brodie *et al*., 2014). In terms of the blue carbon habitat types in this study, horse mussel beds, flame shell beds, maerl, brittlestars and Bryozoa would be particularly vulnerable to ocean acidification. *Limaria* shells are composed largely of aragonite, and so are likely to be more vulnerable than horse mussel shells whose shells comprise layers of both aragonite and the more robust calcite. Studies on maerl revealed a short-term reduction in calcification rates in sea water with lower pH conditions (this was not sustained over longer periods, Form and Riebesell, 2012). In contrast, it has been shown that macro-autotrophs such as *Zostera* and macroalgae such as kelps may do better than calcified or coralline algae in terms of being able to withstand the impacts of ocean acidification (Koch *et al*., 2013). Indeed, fleshy macroalgae show increased growth rates in reduced pH (Kroeker *et al*., 2013).

6.2.2.3. Temperature

Warming of the oceans is underway and is occurring more quickly in the Arctic waters than in other regions. As Orkney is situated close to the Northern Periphery and Arctic region, warming will also be taking place here, but at a slower rate. In general, some marine organisms will be able to tolerate the warming conditions better than others will and so the likely impact will be a decrease in the abundance less tolerant ones and an increase in the more tolerant species. In terms of blue carbon habitats, it will depend very much on the rate of increase in water temperature and the adaptability of the organisms. If the maximum temperatures experienced by each species across their range give their temperature limits, then the difference between local temperatures and such maxima give the ‘thermal safety margin’ for each species (Sunday *et al*., 2014). The fate of kelp and maerl may be quite different in a warmer (and more acidic) future north-eastern Atlantic (Brodie *et al*., 2014). Maerl beds may die out altogether, while kelp forests will persist around Orkney until sea temperature have increased above present-day values to those currently experienced at the warm range edge of the species. For the kelps *Laminaria hyperborea* and *Saccharina latissima* for example, these thermal maxima are around 15.5 °C annual average sea surface temperature. Compared to present-day Orkney average sea temperatures of 10 °C, this gives thermal safety margins of around 5.5 °C for each species, implying that the climate can warm by this amount before the species become locally extinct, however. There will be associated issues around the decline of densities as the limit is reached. This will impact the ability of the kelp forest to maintain the level of standing stock and the contribution to burial and longer term sequestration. That said, however, seaweed populations away from range edges can also suffer under warming due to local adaptation to cooler temperatures (Bennett *et al*., 2015).

6.2.3. Pressures caused by land use changes

Blue carbon resources in Orkney waters occur in close proximity to the terrestrial environment. This means that land use practices could potentially have a significant influence on the supply of carbon to the biological and sediment habitats referred to in this audit. Increases in terrestrial carbon input may result in changes to the turbidity of the water and consequently reduced light penetration. This in turn will have an impact on the capacity of the biological habitat to cycle and store carbon. An increase in the quantity of terrestrial carbon coming into the coastal seawaters will mean a higher rate of sedimentation.

Table 6.1

Summary table of pressures on living blue carbon habitat types. (+) indicates a positive impact; (-) indicates a negative impact; (?) indicates impact unknown or not accessed) (MarLIN, 2019b). Temp. = temperature; Deoxy. = deoxygenation; Physical = dredging, pile-driving, etc.; Shading. *Based on data for *Laminaria hyperborea*; ** High sensitivity to organic enrichment; not sensitive to nutrient enrichment; not assessed for transition elements and organo-metal contamination, hydrocarbons, synthetic compounds, radionuclides; ***Based on the biotope *Ophiothrix fragilis* and/or *Ophiocomina nigra* brittlestar beds on sublittoral mixed sediment; ****Based on *Flustra foliacea*.

Habitat type	**Temp. increase**	**Salinity increase**	**Salinity decrease**	**Deoxy.**	**Physical**	**Shading**	**Chemical pollution**
Kelp forest*	Moderate -	Moderate -	?	?	-	-	Very low/non sensitive -
Maerl beds	Medium -	?	High -	High -	-	-	?**
Zostera beds	Not sensitive	Very low -	?	Very low -	-	-	Very low-very high (nutrients) -
Saltmarshes (pioneer)	Very low -	Very low -	?	Very low -	-	-	Low – high (hydrocarbons) -
Horse mussel beds	High -	?	High -	Very low -	-	?	Very low-high (synthetics) -
Flame shell beds	Not sensitive	High -	High -	?	-	?	?
Brittlestar beds***	Not sensitive	Medium -	Medium -	Low -	-	?	?
Bryozoan thicket****	+ and -	?	?	?	-	?	?

6.3. Knowledge gaps and priority research areas

During the development of the Orkney Blue Carbon Audit it has become apparent that there are a number of knowledge gaps which would be important to address in future work, to improve the usefulness of the work (Table 6.2).

Table 6.2

Knowledge gaps identified during the Orkney Blue Carbon Audit.

Habitat type	Knowledge gaps to be addressed
Kelp forest	Further ground truthing of the predicted habitat models Lack of knowledge on the fate and burial of kelp detritus in Orkney waters
Maerl beds	Further ground truthing of the predicted habitat models and in particular the extent of maerl beds and their health Further work needed on understanding the depth of carbonate sediment underlying the maerl beds (Figure 6.2) Lack of knowledge on age of maerl sediments
Zostera beds	Further ground truthing of the predicted habitat models Lack of organic/inorganic carbon values specific to Orkney waters Further work needed on understanding the depth of sediment underlying the maerl beds Lack of knowledge on growth rates of local *Zostera* beds
Saltmarshes	Further ground truthing of the mapped saltmarsh habitats. Further work needed to understand the depth of organic rich sediment underlying the modern saltmarsh Lack of knowledge on the age and sequestration rates of local marshes
Horse mussel beds (*Modiolus modiolus*)	Further ground truthing of the predicted habitat models and addition of data regarding sites deeper than 50 m.

	Further work needed on understanding the depth of carbonate sediment underlying the horse mussel beds Lack of knowledge on age of the horse mussel sediments Lack of organic carbon values for the tissue and shell components of horse mussels Lack of knowledge of growth rates in Orkney waters
Flame shell beds (*Limaria hians*)	Further ground truthing of the predicted habitat models Further work needed on understanding the depth of carbonate sediment underlying the flame shell beds Lack of knowledge on age of the flame shell sediments
Brittlestar beds (*Ophiothrix fragilis*)	Further ground truthing of the predicted habitat models Further work needed on understanding the depth of carbonate sediment underlying the brittlestar beds as appropriate Lack of knowledge on growth rates in Orkney waters
Bryozoan thickets (*Flustra foliacea*)	Further ground truthing of the predicted habitat models Further work needed to understand the carbon contribution of the other types of bryozoan dominated animal turfs in Orkney waters Lack of knowledge on growth rates in Orkney waters
Sediment	Further ground truthing of the mapped sediments. Further work needed to understand the depth of sediments associated with each mapped unit. Further work needed, particularly in the finer-grained sediments, to understand the organic carbon content. Lack of knowledge on the age and burial rates of carbon associated with each sediment type.

6.4. Availability of accurate geological data

Future outlook – detailed multibeam surveys of the seabed, supported by ground-truthing (grab sampling and camera drops), will greatly enhanced the mapping of sedimentary carbon contents in the Orkney area. In particular, further effort to map and quantify carbon accumulation and storage in some of the depositional environments where fine-grained sediments accumulate is a priority.

7. Conclusions

7.1. Main findings from the work

The main purpose of this report is to develop methods for auditing blue carbon resources at the regional scale, using Orkney coastal waters as a case example. During the development of the audit process we reviewed and collated the data sources available to us, identified gaps in the data sources and endeavoured to fill them where possible by appropriate available means, in order to provide a first assessment of the resource.

1. The blue carbon present in Orkney regional waters is estimated at 67 Mt. The total inorganic carbon stores hold 64.6 Mt while the total organic carbon stores hold 2.7 Mt.
2. Approximately 11 times more carbon was found in the inorganic stores in sediment than in the biological habitats. This comprised 2.27 Mt organic carbon and 59.1 Mt inorganic carbon in sediments.
3 In biological habitats 5.9 Mt carbon was estimated. The largest carbon source from the biological habitats in the audit came from maerl bed, mainly due to the large amount of inorganic carbon content present in the 1.2 m thick maerl deposits at Wyre Sound.
4. Orkney waters account for 8.1% of the Scottish coastal waters and hold an estimated 67 Mt of blue carbon stores. The total organic and inorganic carbon estimate from blue carbon habitats in Scottish waters as reported in Burrows *et al*., 2014 is 1756 Mt across the 200 nautical mile area (470,000 km^2). This equates to a density of 373.62 tonnes C km^{-2}. In Orkney we find 67 Mt in a sea area of 7,290 km^2. This equates to a density of 9,190 tonnes C km^{-2} in Orkney waters. This contribution is likely to increase when further data on the thickness of deposits underlying the biological habitats becomes available. These resources are derived from a range of important biological habitats. Appropriate recognition and management of these habitats is key to the future maintenance and sequestration of the Orcadian blue carbon resource.

7.2. Pressures on the resources

7.2.1. Pressures on the blue carbon resources

Significant overall pressures on blue carbon resources include increase in temperature and decrease in the pH of seawater leading to ocean acidification. In 2010-13 a study in Australian waters showed that marine heatwaves caused the loss of more than 90% of kelp forests making up the north-western tip of the Great Southern Reef. This resulted in a loss of the rock lobster and abalone fisheries, worth about $10bn to the Australian economy. The death of the kelp caused a functional extinction of 370 square kilometres of rocky cool-climate reefs (Wernberg *et al*., 2016). These temperate rocky reef systems are functionally similar to those of Scottish waters, and it is likely that with increased incidence of heatwaves we could also lose areas of these ecosystems and consequently their ability to sequester carbon. Regarding increases in the pH of seawater a whole plethora of experimental studies have shown that plants and animals which have a skeleton composed of calcium carbonate will have a reduction of the ability to produce a calcified skeleton as the pH of seawater increases. In experimental work on horse mussels the cumulative impact of temperature and pH was tested, showing that temperature was the stronger of the drivers when it came to the ability to acclimate (Mackenzie, 2017).

7.2.2. Pressures on the sequestration of the blue carbon resources

Sequestration of carbon into long term stores can be impacted in a number of ways, depending on the specific habitat. For the plant based blue carbon resources such as kelp forest, maerl, *Zostera* and salt marsh, photosynthesis is key to the capture of carbon. Impacts which prevent photosynthesis from occurring will therefore impact on the sequestration ability. Activities which cause an increase in turbidity to coastal waters such as resuspension of sediments from dredging activity, increased inputs of organic material from coastal or land-based activity, and erosion from land caused by unstable soils and flooding could all cause reduction in capture. Physical loss of the habitats would also mean that the capture rates would be reduced. Increased storminess is likely to impact capture rates in that it could cause either damage or reduction in habitat and reduction in water clarity, meaning reduced opportunity for photosynthesis and carbon capture. Where the damage is reversible, it is possible that habitats may recover over time; kelp is more likely to recover within years, whereas maerl may take decades to recover. Introduction of shading as part of construction activities will impact the ability for successful photosynthesis. Pollution in the form of organ-metallic compounds such as TBT may impact molluscs e.g. horse mussels in terms of their ability to reproduce effectively. This will cause a decline in functional populations over a period of years. In terms of the sedimentary resources, activities which damage the physical integrity of the resource may cause a release of carbon back into the ecosystem, and consequently impact on the balance of the long-term storage capacity.

7.3. Knowledge gaps and recommendations for future work

In view of the knowledge gaps highlighted in Table 6.2, recommendations for future work would include a programme of sediment coring for the various habitat types to understand the thickness of the sediment and to ascertain carbon content. For example, at the Wyre Sound maerl bed preliminary data has shown that cores collected by divers were containing maerl of a thickness up to 120 cm as shown in Figure 7.1. In the audit we could confidently apply this figure to the Wyre Sound maerl bed; it was not appropriate at this stage to apply it to the other Orkney maerl beds given the lack of field data for those locations where so far cores of 25 cm have been performed. Inevitably this means there is likely to be an underestimate of the maerl blue carbon resource. This type of issue also applies to other habitats e.g. horse mussels, brittlestar beds, where there is currently no available data regarding thickness of the underlying carbonate sediments. As an additional example Saltmarsh habitat average values are largely calculated from research conducted in Australia and Louisiana (USA) (Duarte *et al*., 2013). The marshes in these regions are highly organic in contrast to organo-mineral marshes of north-west Europe. Therefore, it is unlikely that these data are applicable to the saltmarsh found in Scotland.

A further significant knowledge gap exists regarding the understanding of the longer-term sequestration of blue carbon in Orkney waters. The lack of information on growth rates of the organisms in this region and also a general lack of knowledge on burial rates of organic material into sediments precludes estimates from being calculated at this point in time. Going forward, an understanding of sequestration rates is imperative so that these can be incorporated alongside carbon estimations for terrestrial components to generate a holistic carbon budget for the region. It will be important in the future to focus investigations into identifying the major sources and sinks of carbon and how they may be impacted spatially and temporally, to be able to incorporate into mitigation activities.

Figure 7.1: Cores collected by Heriot Watt Scientific Dive team from Wyre Sound showed maerl deposits in excess of 1.2 m (Image taken by Dr Bill Sanderson).

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10. Appendices

Appendix A - Maxent modelling methodology

Maxent modelling uses the principle of maximum entropy on species presence-only data to predict or estimate a group of functions that link environmental variables and habitat suitability in order to approximate the probable geographic distribution (Philips *et al*., 2006). This approach is the most suitable when the primary species data are historical observations.

Presence data for each species were filtered for quality assurance ensuring that outliers and spurious records were sense-checked (Records with Validity Confidence) and records with SACFOR scale values of “S” (Superabundant), “A” (Abundant) and “C” (Common). These are the levels of abundance which are believed correlate to densities for each species that form ‘beds’. These were then imported into the R ‘workspace’ using the ‘sf’ package, subsequently presence points for each species were randomly sampled into a training set (80%) and a testing set (20%) for testing validity of the model.

The environmental variables already existed in a Raster format and were imported into R using the ‘raster’ package, all layers were resampled to the Aquatera Ltd bathymetry layer so that all rasters shared the same extent and resolution. All of these layers were then combined into a rasterstack ready to be used in the Maxent model, these can be viewed in Fig A1 in the appendix.

Training subsets of each species presence points were then modelled with the rasterstack using the Maxent function in the ‘dismo’ package, the model was then used to predict the probable occurrence of the species throughout the rasterstack. The models were then evaluated using the testing subsets and 1000 randomly sampled background points of the raster stack to gain an AUC value for each model, these can be viewed in Table A1 in the appendix. The predicted maps were then exported as ‘.tif’ raster files for visualisation and extent analysis.

To obtain a spatial extent for each species raster cells were extracted which had probability of occurrence >= 0.9, and the area of these cells was calculated within a GIS application.

Table A1

Maxent model outputs and performance metrics.

Species	**N Points Training**	**N Points Testing**	**Area (km2)**	**AUC Model Score**
Ophiothrix fragilis	215	54	47.560	0.9383
Limaria hians	19	5	17.99	0.9234
Zostera marina	31	8	14.23	0.9619
Flustra foliacea	40	10	94.15	0.9363
Modiolus modiolus	98	24	38.28	0.9206

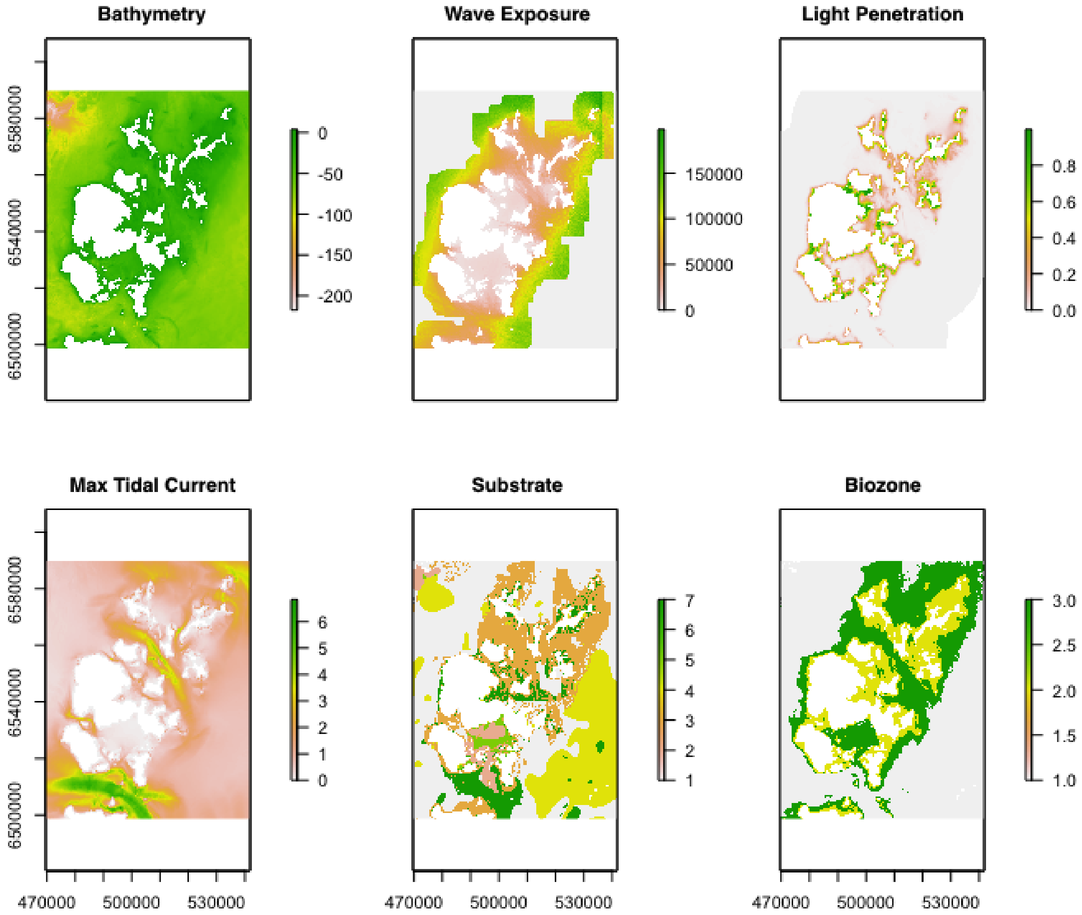


Figure A1: Environmental variables used in rasterstack for Maxent modelling.

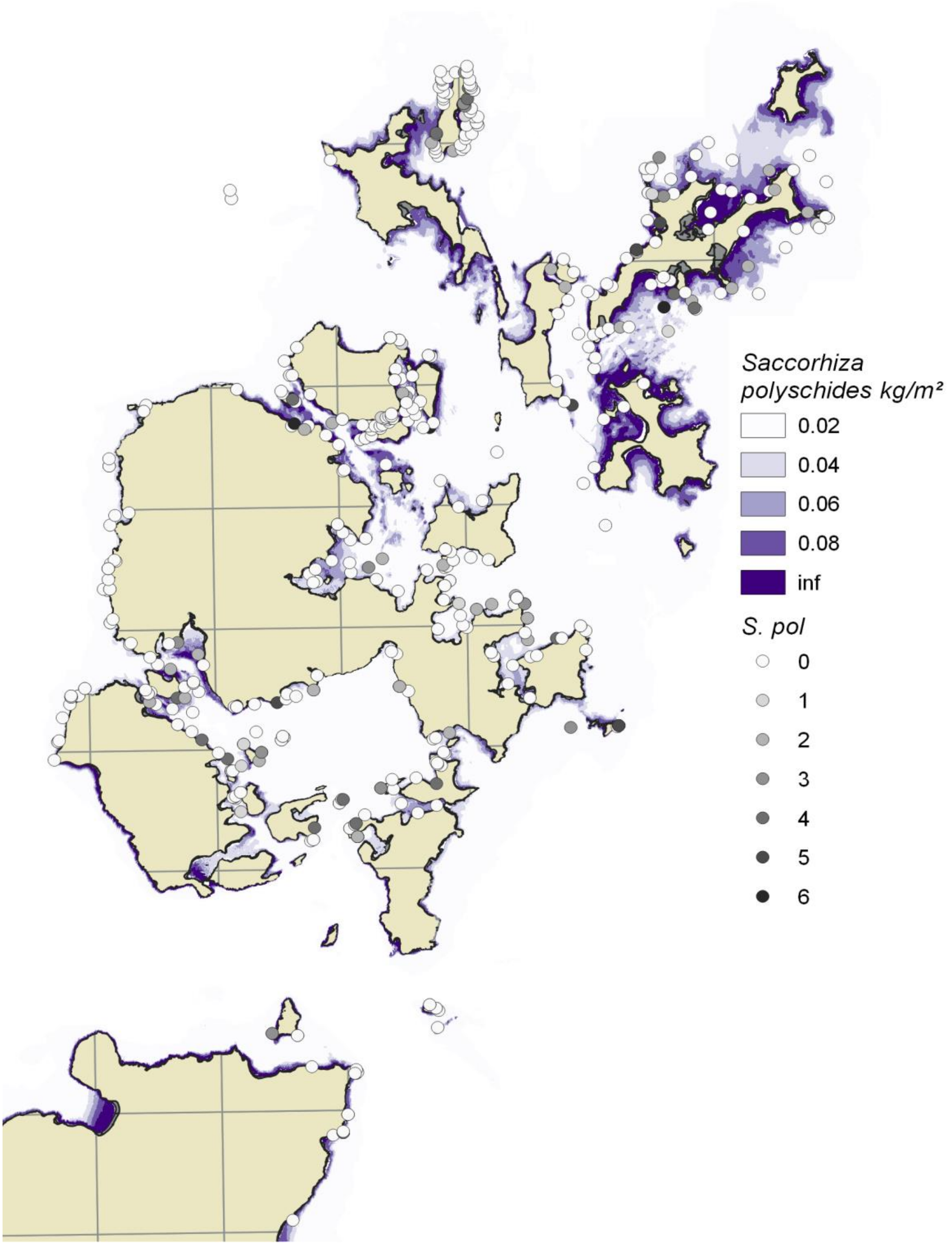


Figure A2: Predicted biomass density of *Saccorhiza polyschides* across Orkney. Symbols indicate recorded abundance of the species in surveys with absence (0, white) and categories Rare to Superabundant as integers (1-6).

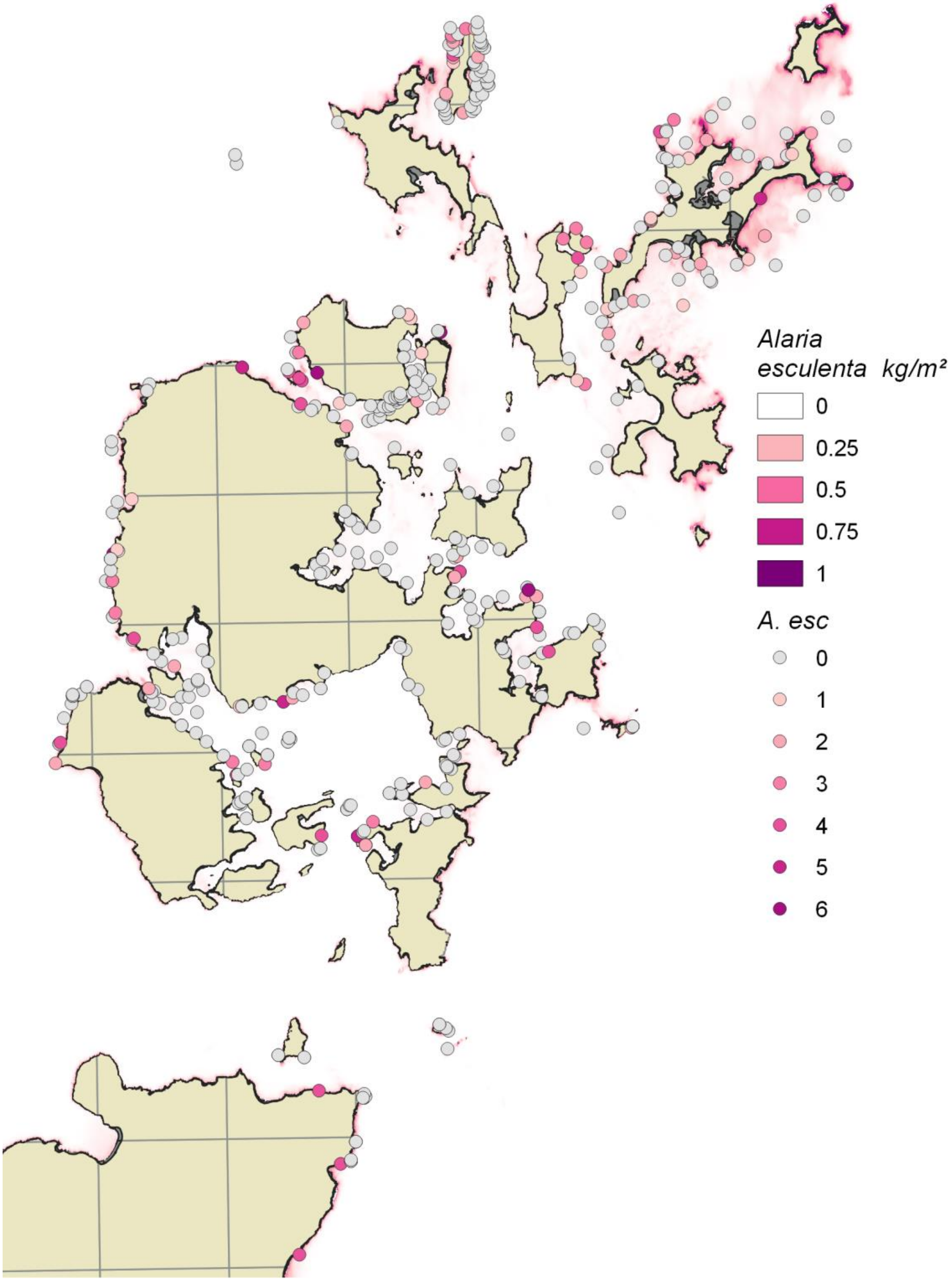


Figure A3: Predicted biomass density of *Alaria esculenta* across Orkney. Symbols indicate recorded abundance of the species in surveys with absence (0, white) and categories Rare to Superabundant as integers (1-6).

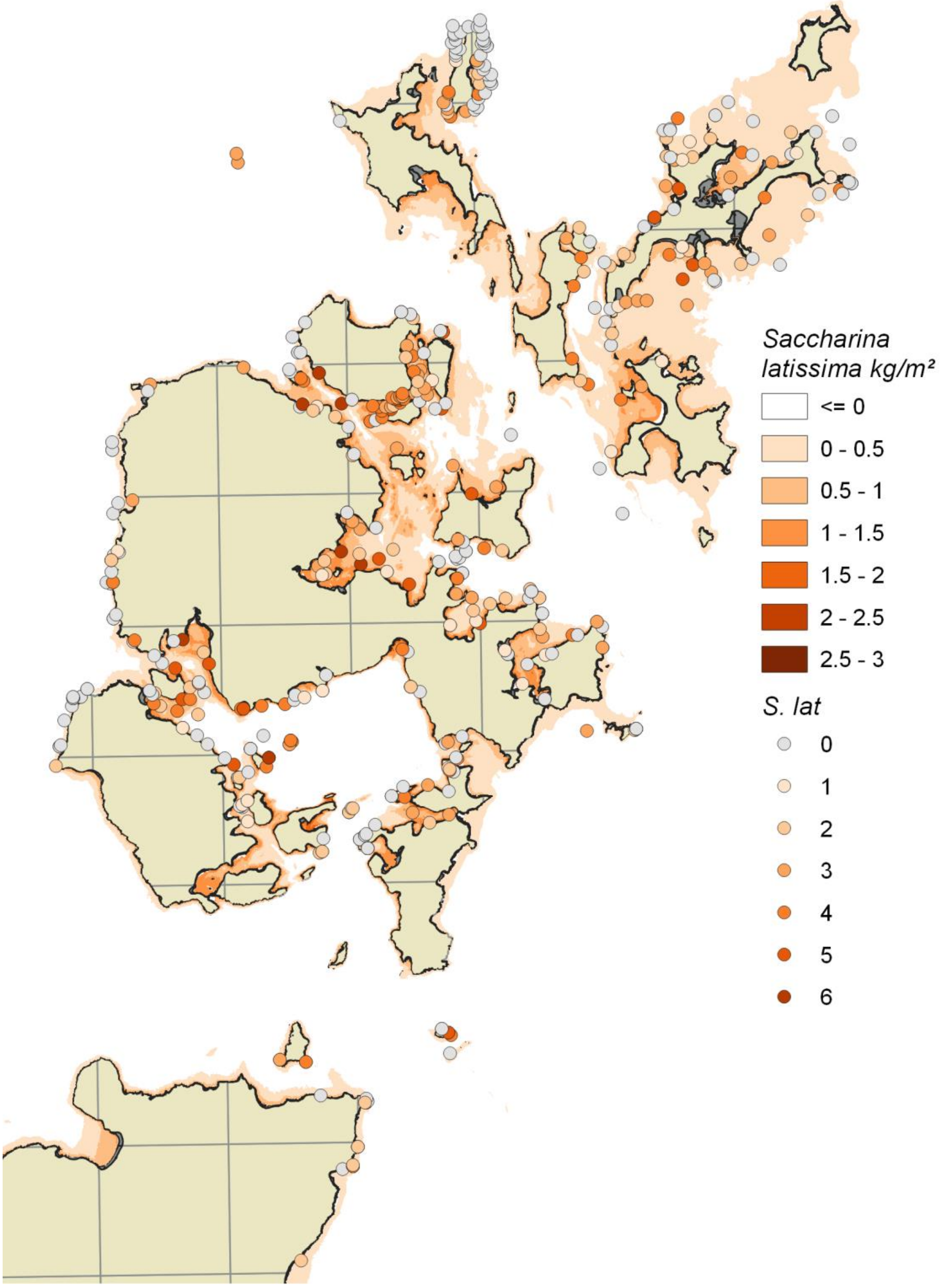


Figure A4: Predicted biomass density of *Saccharina latissima* across Orkney. Symbols indicate recorded abundance of the species in surveys with absence (0, white) and categories Rare to Superabundant as integers (1-6).

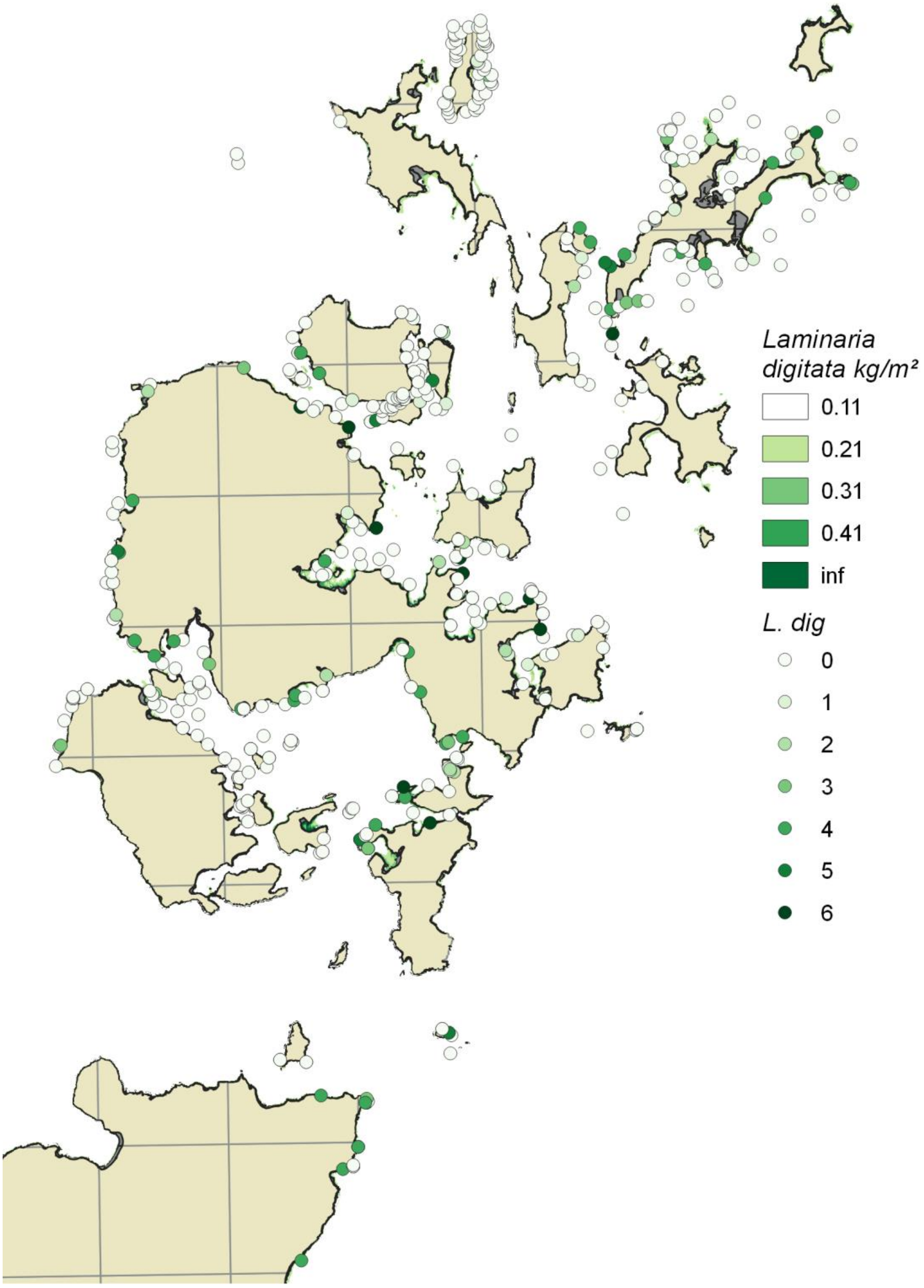


Figure A5: Predicted biomass density of *Laminaria digitata* across Orkney. Symbols indicate recorded abundance of the species in surveys with absence (0, white) and categories Rare to Superabundant as integers (1-6).

Appendix B - Scottish *Zostera* information

Scottish *Zostera* information kindly provided by Dr Maria Potouroglou from her PhD thesis (2017): Assessing the role of intertidal seagrasses as coastal carbon sinks in Scotland. Doctoral Thesis. Edinburgh, Scotland, UK: Edinburgh Napier University. Retrieved from http://researchrepository.napier.ac.uk/Output/975386
We sampled both seagrass (either *Zostera noltii*, or *Zostera marina*, or mixed) and control (unvegetated) plots from the areas shown below.

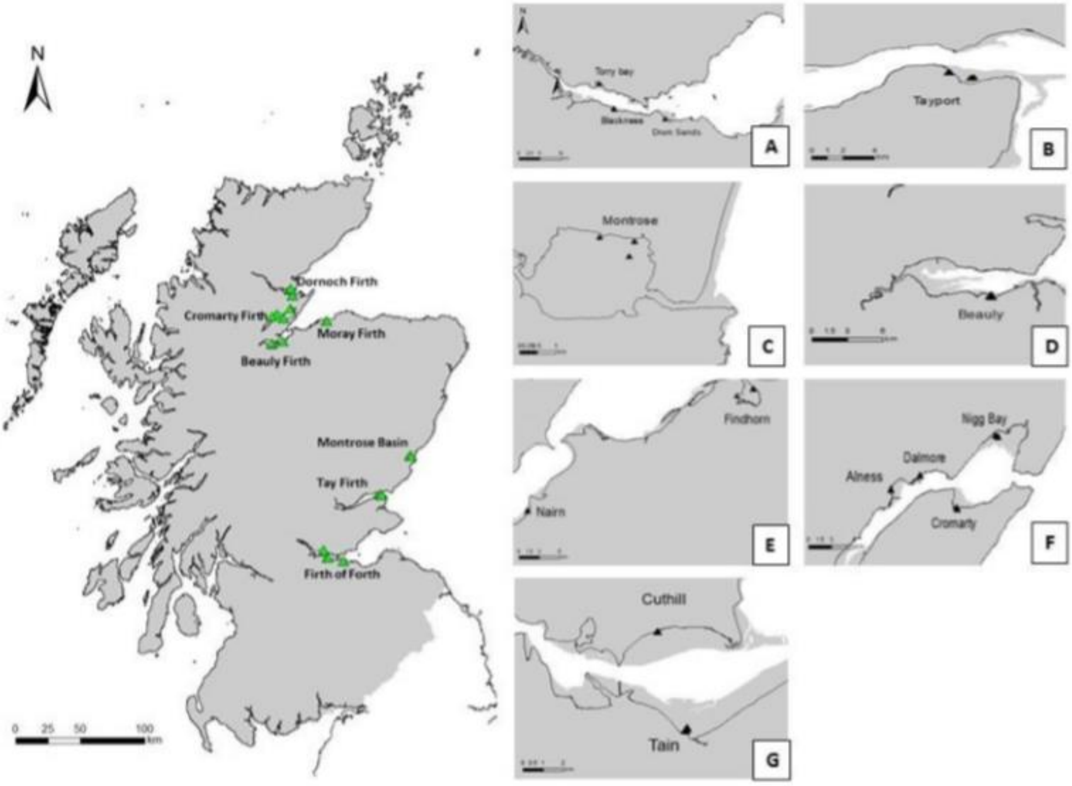


Figure B1: Study area showing locations of seagrass survey sites and sub-sites A-G along the East coast of Scotland (A: Firth of Forth, B: Tay Estuary, C: Montrose Basin, D: Beauly Firth, E: Moray Firth, F: Cromarty Firth, G: Dornoch Firth). Reproduced from Potouroglou (2017).

We went down to 50 cm, and on the table below which summarises my results, you can see both organic carbon stocks for 50 cm and 100 cm for seagrass and control plots. Total C_{org} stored in the top 50 cm of the sediments of intertidal seagrasses in Scotland ranged from a minimum of 23 Mg C ha^{-1} at Moray Firth to a maximum of 108 Mg C ha^{-1} at the Firth of Forth. Mean organic carbon stock across the 7 sites sampled was 57 Mg C ha^{-1} (for the top 50 cm), or 114 Mg C ha^{-1} as projected for the top meter of the sediment.

Table B1 Summary of study sites and sediment C$_{org}$ stocks (Mg ha^{-1}) over 50 cm and 100 cm horizons for vegetated and [unvegetated] plots. Zn: *Zostera noltii*, Zm: *Zostera marina*. Reproduced from Potouroglou (2017).

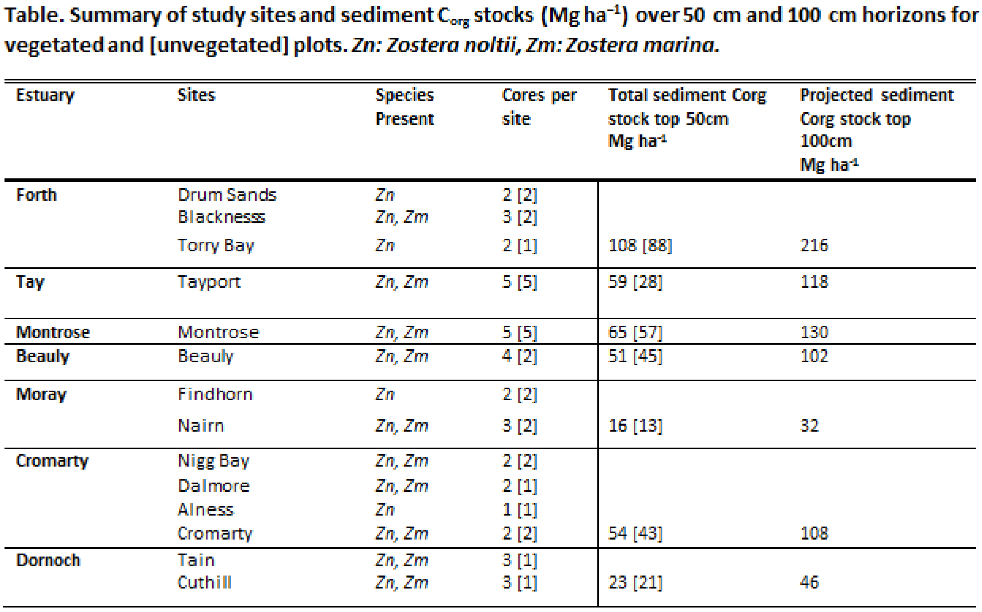
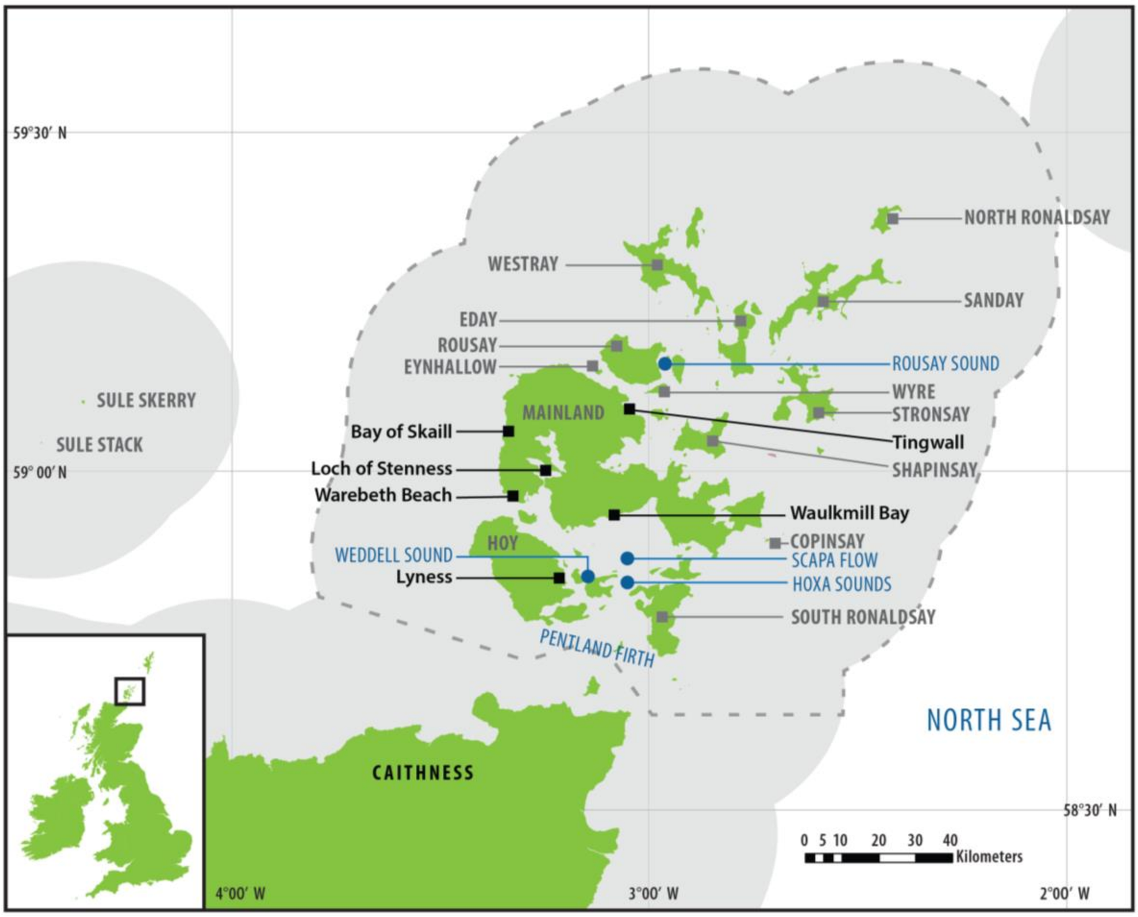


Table. Summary of study sites and sediment C$_{org}$ stocks (Mg ha^{-1}) over 50 cm and 100 cm horizons for vegetated and [unvegetated] plots. *Zn: Zostera noltii, Zm: Zostera marina.*

Estuary	Sites	Species Present	Cores per site	Total sediment Corg stock top 50cm Mg ha^{-1}	Projected sediment Corg stock top 100cm Mg ha^{-1}
Forth	Drum Sands	*Zn*	2 [2]		
	Blacknesss	*Zn, Zm*	3 [2]		
	Torry Bay	*Zn*	2 [1]	108 [88]	216
Tay	Tayport	*Zn, Zm*	5 [5]	59 [28]	118
Montrose	Montrose	*Zn, Zm*	5 [5]	65 [57]	130
Beauly	Beauly	*Zn, Zm*	4 [2]	51 [45]	102
Moray	Findhorn	*Zn*	2 [2]		
	Nairn	*Zn, Zm*	3 [2]	16 [13]	32
Cromarty	Nigg Bay	*Zn, Zm*	2 [2]		
	Dalmore	*Zn, Zm*	2 [1]		
	Alness	*Zn*	1 [1]		
	Cromarty	*Zn, Zm*	2 [2]	54 [43]	108
Dornoch	Tain	*Zn, Zm*	3 [1]		
	Cuthill	*Zn, Zm*	3 [1]	23 [21]	46

Appendix C - Map of the study region with key place names



Appendix D - Unit conversion

The table below shows the conversion between some of the units commonly used in this report.

1 tonne (t)	=	1 Mg
	=	1,000 kg
	=	1 million g
1 Tg	=	1 million tonnes (1 Mt)
	=	10^{12} g
1 hectare (ha)	=	0.01 km^2
	=	10,000 m^2
1 Mg ha^{-1}	=	1 tonne ha^{-1}
	=	100 tonne km^{-2}
	=	10^6 g ha^{-1}
	=	10^8 g km^{-2}
	=	10^2 g m^{-2}

Marine Scotland Science
Marine Laboratory
375 Victoria Road
Aberdeen
AB11 9DB

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