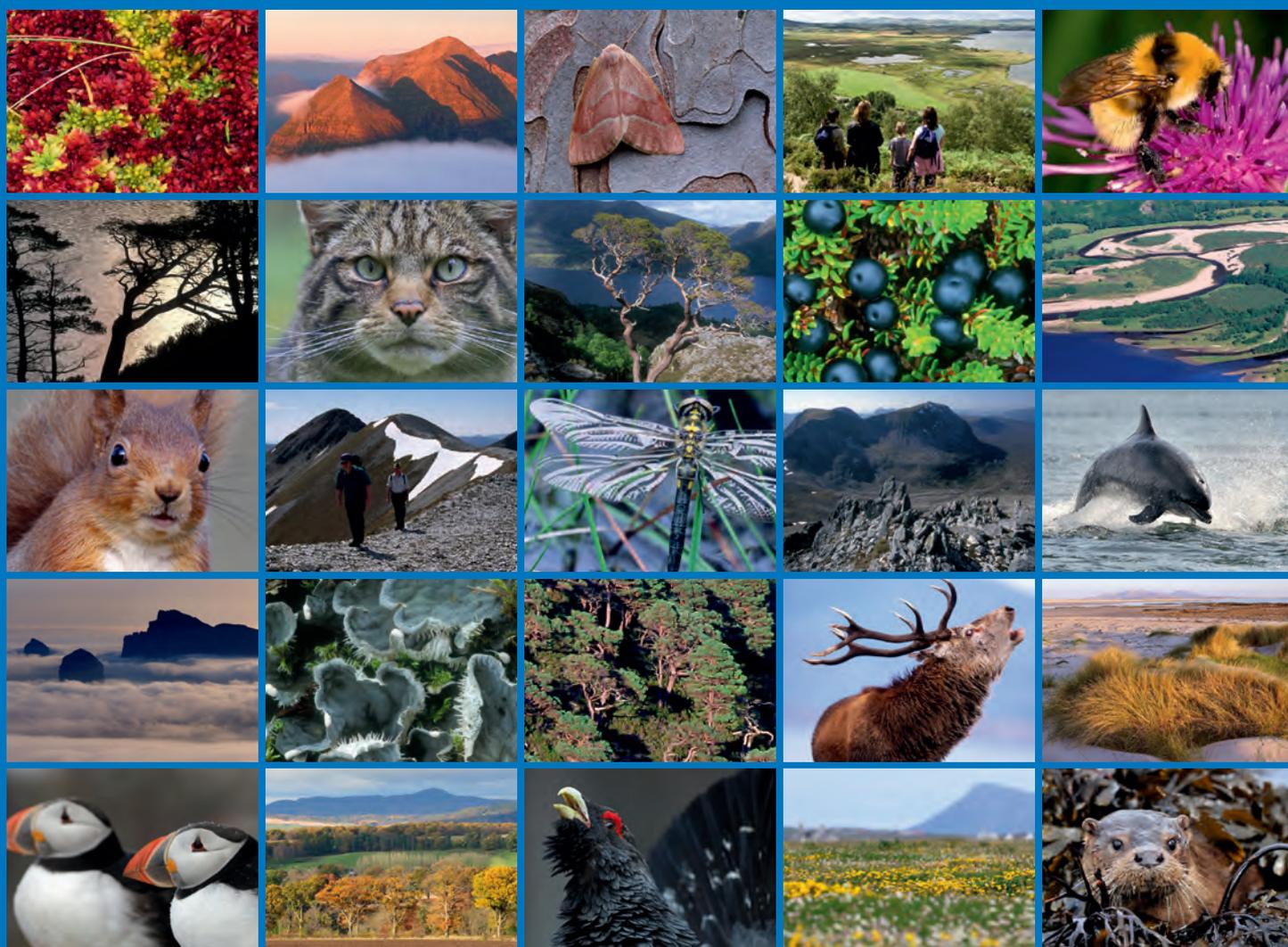


# Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment





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# COMMISSIONED REPORT

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**Commissioned Report No. 761**

## **Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment**

For further information on this report please contact:

Professor John M. Baxter  
Scottish Natural Heritage  
Silvan House  
231 Corstorphine Road  
EDINBURGH, EH12 7AT  
Telephone: 0131 3162610  
E-mail: [john.baxter@snh.gov.uk](mailto:john.baxter@snh.gov.uk)

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## COMMISSIONED REPORT

# Summary

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## Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment

**Commissioned Report No. 761**

**Project No: 13719**

**Contractor: Scottish Association for Marine Science**

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### **Keywords**

Blue carbon; sequestration; carbon sinks; fluxes; carbon stores.

### **Background**

A three-tiered approach has been adopted to assess Scotland's marine blue carbon stores. Information on habitat extent, or predicted habitat extent, has been collated into a GIS. The relevant scientific information on the primary habitats for carbon uptake and storage have been reviewed and quantitative rates of production and storage were obtained. Habitat-specific reviews also include a brief assessment of the main threats to each habitat. Finally, the collected information has been assembled into an ecosystem-scale inventory of the key rates and ultimate sequestration capacity of each habitat.

Habitats were reviewed by relevant experts (Michael Burrows, for kelp; Paul Tett, phytoplankton; David Hughes, benthic suspension feeders including reef-building species; Henrik Stahl, for fate of carbon in marine sediments; John Howe; postglacial geology of sediments; Nick Kamenos, maerl beds).

### **Main findings**

- Coastal and offshore sediments are the main repositories for carbon in Scotland's marine environment.
- An estimated 18 million tonnes (MtC) of organic carbon are stored in the top 10cm of sediments across the 470 000km<sup>2</sup> area of Scotland's seas.
- An estimated 1738 million tonnes (MtC) of inorganic carbon are similarly stored as non-living shell material.
- Deposition of organic carbon amounts to 7.2 MtC/yr and inorganic carbon 0.5 MtC/yr in Scotland's marine sediments.
- The main producer of carbon entering long-term storage in sediments is phytoplankton, 3.9 MtC/yr, with coastal plants (predominantly kelp) potentially contributing a further 1.8 MtC/yr.
- Habitat-forming species on the coast (seagrasses, saltmarsh, bivalve beds), are highly productive but their contribution to the overall carbon budget is very small because of the limited extent of each habitat.

- Maerl beds and cold water coral reefs contribute 0.5MtC of inorganic carbon to the standing stock. While their growth rates are relatively slow providing small annual sequestration capacity of inorganic carbon, their longevity (centuries) means that sequestered carbon is locked away at geological time scales.
- Sea lochs contain 0.33 MtC and have a sequestration capacity for sediment organic carbon of 0.07 MtC/yr

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*For further information on this project contact:*

Professor John M. Baxter, Scottish Natural Heritage, Silvan House, 231 Corstorphine Road,  
Edinburgh, EH12 7AT.

Tel: 0131 316 2610 or [john.baxter@snh.gov.uk](mailto:john.baxter@snh.gov.uk)

*For further information on the SNH Research & Technical Support Programme contact:*

Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.

Tel: 01463 725000 or [research@snh.gov.uk](mailto:research@snh.gov.uk)

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## **1. INTRODUCTION**

### **1.1 Reviewing and estimating Scotland's Marine Carbon sinks and sources**

The three aims for this report were to:

- (i) produce detailed reviews of the carbon budgets of a range of potential Scottish marine carbon stores (including saltmarsh, seagrass beds, kelp forest, maerl beds, biogenic reefs, cold water corals and soft sediments),
- (ii) estimate the extent of these different habitats in Scotland and their capacity to trap and store carbon in the short, medium or long term,
- (iii) review the main threats to these habitats and the implications for the carbon stores.

This was achieved by:

1. Collating all information on habitat extent, or predicted habitat extent, into a GIS.
2. Reviewing the ecology of the primary habitats identified in the project scope of work, focusing on extracting quantitative rates. These habitat-specific reviews also included an assessment of the main threats to each habitat where information was available.
3. The data from the specific habitat reviews and associated information was assembled into an ecosystem-scale inventory of the key rates and ultimate sequestration capacity of each habitat.

The outcomes of each of these tasks are described within this report.

## 2. APPROACH

Assessment of the carbon budget and sequestration potential for Scotland's marine habitats required a common approach to each habitat: gathering the appropriate data sources, literature values for rate processes underpinning sequestration and integrating this information into quantitative assessments of the carbon budgets of Scotland's seas and oceans. Estimates of the area of each habitat were combined with area-specific rates of production and loss of carbon, and thence area-specific rates of sequestration, to give area-integrated estimates of the total amount of carbon locked away by biological activity in the coastal zone.

Two existing reviews by Henrik Stahl informed the review: one dealing with the fate of terrestrial carbon in marine systems (Stahl, 2012b), and the other on carbon fixed in the marine environment (Stahl, 2012a). A recent review of sea loch sediments since glacial times gave sedimentation rates (McIntyre and Howe, 2010), a key long term store for carbon.

### 2.1 Assessment of extent and distribution of habitats

Primary information on the area (m<sup>2</sup>) and location of habitats were collated from existing maps: those produced by the JNCC UKSeaMap project and Scotland's Marine Atlas; and those provided directly to the project team by SNH (point records and habitats mapped as polygons in GeMS V2i10, the Geodatabase for Marine Habitats and Species in Scotland).

Where these maps do not give the extent of habitats directly, we estimated the likely area from the relationships between known records and data layers for physical and biological drivers of distribution. Kelp species, for example, have characteristic distributions across gradients of wave exposure and depth (Burrows, 2012), with the latter effect modified by light attenuation. Wave exposure on the scale of the total habitat for kelp has been modelled using wave fetch as a proxy for wave height (Burrows *et al.*, 2008). Ocean-colour-sensing satellites give estimates of euphotic depth at an appropriate scale for the prediction of the depth-penetration of primary producers (see Section 3.1.1).

We also considered more detailed sources that record the physical habitat, such as the British Geological Survey 1:250 000 scale offshore geological maps of seabed sediments (DigSBS250) and records of percentage biogenic carbonate in sediment samples (see Section 3.5.2), and bathymetry (from SeaZone, available for use by agreement). The sediment maps show the diversity of marine sediment features, mostly inshore sediment traps (fjords, estuarine, riverine deltas), that ensure trapping and storage of carbon in the coastal zone.

The extent of maerl and the depth of maerl deposits have been gleaned from a variety of sources, including contributions from JNCC, SNH, MCS and Seasearch surveys to the Marine Nature Conservation Review, JNCC SeaMap 2010, the British Phycological Society Seaweed data for Great Britain and Ireland, as well as contributions for scientific papers (Kamenos *et al.*, 2004a; Kamenos, 2010).

### 2.2 Carbon budgets and carbon stores

Estimates of the total carbon currently stored in different areas and habitats were derived from the best available information on habitat extent and biomass per unit area for that habitat (gC m<sup>-2</sup>). For kelp, categorical measures of abundance (SACFOR) from point survey data were converted into biomass equivalents by constructing statistical models for predicting the occurrence of areas where the plants were likely to be abundant, and using previously recorded values for biomass per unit area for abundant areas to estimate biomass totals.

The net sequestration rate ( $\text{gCm}^{-2}\text{yr}^{-1}$ ) of particular habitats depends on the balance of processes of net production (*cell level*: photosynthesis, respiration, calcium carbonate growth and dissolution; *organism level*: growth in size, death; *population/habitat level processes*). This report has not attempted to estimate these balances, but used the most relevant and appropriate values reported in the scientific literature for calculating rates. **Rates given are generally given as net values, after accounting for losses due to respiration and other processes.**

For sediments, rates of sequestration were obtained simply from sedimentation rates for particulate inorganic or organic carbon. We consider that the long-term fate of carbon fixed by primary production in the plankton and by macroalgae on hard substrata depends on transport to and incorporation into sediment in depositional environments.

### **2.3 Threats to carbon stores**

Threats to carbon stores can be considered mostly habitat specific. Kelp beds and biogenic reefs face particular problems from physical disturbance, either naturally from increased storminess related to climate change, or by direct human-related impacts from trawling. Seagrasses and saltmarsh may be affected by coastal erosion and coastal development, and efforts to protect coasts by building seawalls ('coastal squeeze'). Ocean acidification poses a particular problem for calcifying species and may bring about increased erosion of already calcified but dead material. Finally, climate change may pose threats to particular species near edges of their thermally limited geographical range edges.

### 3. CARBON BUDGETS BY HABITAT

Each review presented here uses estimates of extent ( $m^2$ ) and distribution and the carbon content by area or volume, to calculate the mass of carbon currently stored (gC) in each habitat. Sequestration rates ( $gCm^{-2}yr^{-1}$ ) are derived from literature values and sequestration capacity ( $gCyr^{-1}$ ) as the product of rates and extents of habitats, or sub-habitats (such as different sediment types) where different rates apply.

#### 3.1 Kelp forest

Total primary production from kelp beds around has been considered in a recent review (Smale *et al.*, 2013). Detailed *in-situ* surveys of the coastline using aerial photography and quadrat sampling between 1946-1955 (Walker and Richardson, 1955, 1956) estimated that there were 10 million tons total biomass of subtidal kelp around Scotland (mostly *Laminaria hyperborea*) over about 2900km<sup>2</sup> of kelp habitat spread across a total sublittoral (<19m depth) area of 8000km<sup>2</sup> (Walker, 1954). Primary production from kelp can be in excess of 1000  $gCm^{-2}yr^{-1}$ , and that from *Laminaria* has been estimated as between 110 and 1780  $gCm^{-2}yr^{-1}$ , while primary production from phytoplankton in coastal temperate regions is typically between 100 and 300  $gCm^{-2}yr^{-1}$  (Mann, 2000). The contribution from intertidal macroalgae is smaller, typically 10-20% of macroalgal primary production (Mann, 1973).

Here we reassess this contribution to coastal production and carbon uptake by kelp, and consider it in terms of its longer-term sequestration. Most subtidal and intertidal production (>80%) ends up as detritus and as dissolved organic matter, since little is directly grazed by herbivores, and enters the detrital food web. Much of the carbon originating from kelp is consumed by suspension feeders, detrital grazers and general consumers of organic material in soft sediments, but the general contribution of this carbon to long term stores is not well understood. The ultimate influence is likely to depend on the refractory nature of kelp detritus and its incorporation into sediments.

##### 3.1.1 Extent of Scottish kelp beds

No newer estimate of the extent of kelp beds in Scotland exists than that given by Walker (1954). Yet much effort was made from the 1980s onwards to describe the sublittoral of the UK by the JNCC's Marine Nature Conservation Review (MNCR) using experienced survey divers. Data were recorded systematically using categorical abundance scales (SACFOR, (Hiscock, 1996)), from over 5000 dives at nearly 3500 sites, generally in less than 20m of water. Over 3200 of these dives took place in Scotland. MNCR surveys were well spaced around the coastline, and extended into sea lochs such as Loch Ewe and Gairloch (Figure 1), and captured the shifts in dominant kelp species from *Laminaria hyperborea* in wave-exposed conditions to *Saccharina latissima* in wave-sheltered areas.

Analysis of MNCR data in relation to geographical patterns of ocean colour (satellite estimates of chlorophyll a), tidal flow, and along gradients of wave exposure and depth showed that spatial trends could be captured by statistical relationships (Figure 2 and (Burrows, 2012)). The main components of these trends were the decreasing depth penetration of kelp with increasing concentration of water column chlorophyll (Figure 2a and d), and emergent specific habitat requirements for each of the major kelps. *Laminaria hyperborea* and *Alaria esculenta* were most abundant in extreme wave exposure on open coasts. *Saccharina latissima* was most abundant in wave shelter, and *Laminaria digitata* only in the most-shallow depths.

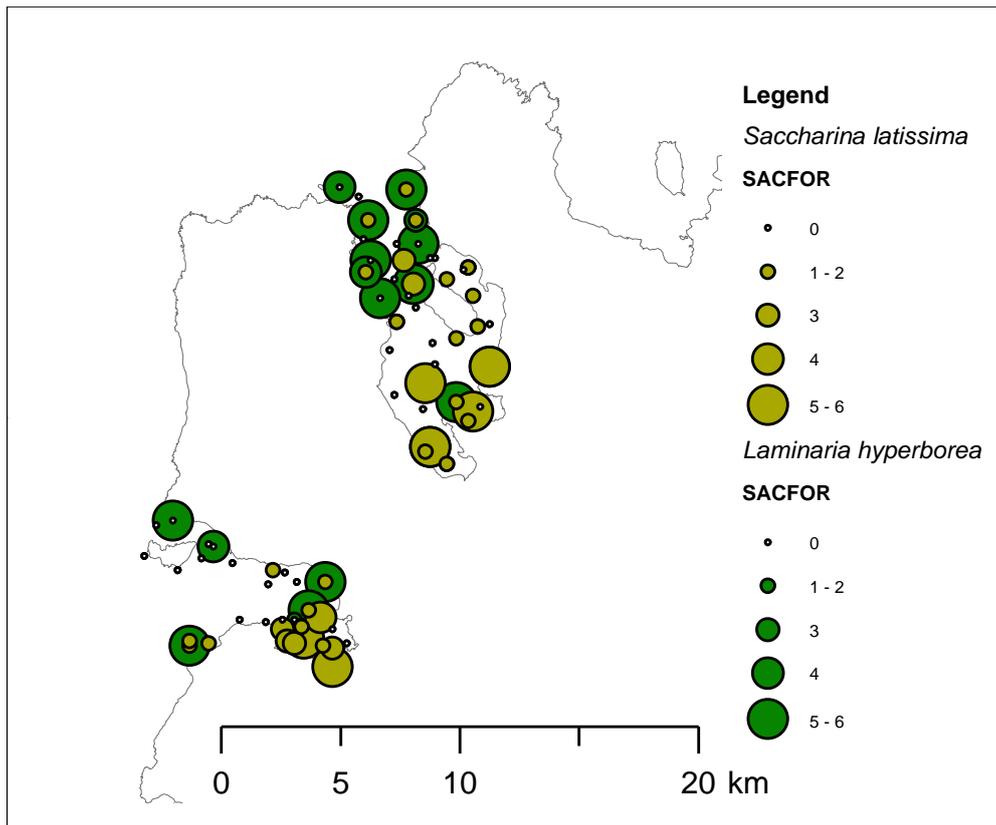


Figure 1: Categorical abundance data for kelp species *Laminaria hyperborea* and *Saccharina latissima* in Loch Ewe and Gairloch surveyed by MNCR divers in June 1990. SACFOR abundance is shown as corresponding numerical values from 0 for N (absent) to 6 for S (super abundant).

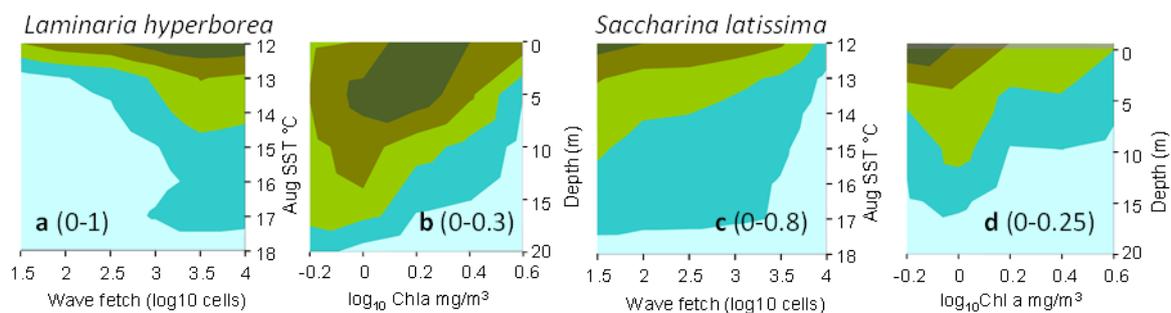


Figure 2: Likelihood of >20% cover of the kelp *Laminaria hyperborea* and *Saccharina latissima* as a function of depth, wave fetch and satellite-derived chlorophyll a concentrations ( $\text{mg}/\text{m}^3$ ) from statistical models fitted to MNCR data by Burrows (2012).

We modified this approach to estimate the extent of kelp habitat in Scotland. Species abundance data in the MNCR data were reclassified to give a single value for kelp abundance by taking the maximum SACFOR category across all the kelp species recorded in each dive. Thus, if *Laminaria hyperborea* were recorded as 'abundant' and *Saccharina latissima* were recorded as 'common', the kelp abundance record was set as 'abundant' for that survey.

A statistical (ordinal logistic regression) model was then fitted to the kelp abundance data for Scotland (Appendix A). The model used environmental data on local (<10km) and regional

scales (>10km to 100s km, Figure 3) to evaluate where kelp should be found, and expressed this as the likelihood that abundance exceeds a particular abundance category, and thereby the most likely abundance category of kelp given the prevailing environmental conditions. Since these categories are defined on the basis of percentage cover of kelp (R <1%, O 1-5%, F 5-9%, C 10-19%, A 20-40%, S >40%, ), this method gives the likely extent of dense stands of kelp (A and S, >20% cover, kelp forest) as well as the extent of less dense beds (5-20% cover, F and C), as well as the most likely abundance category for each location.

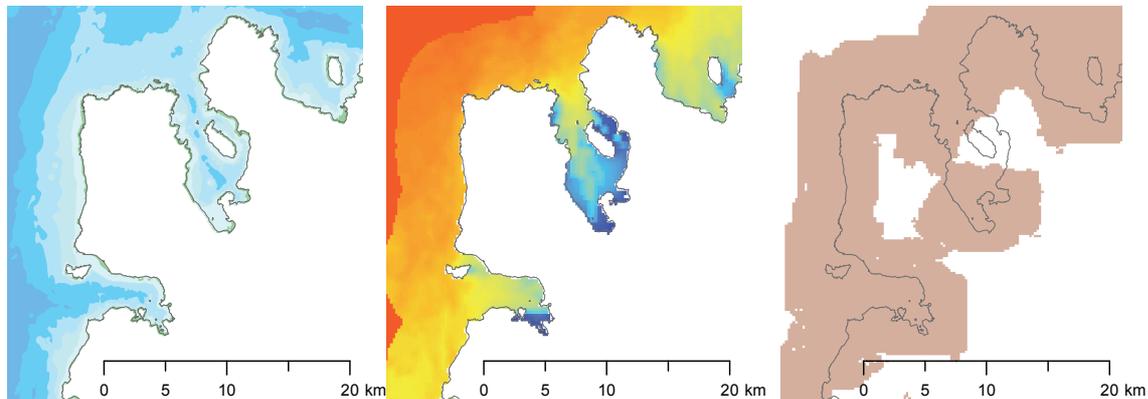


Figure 3: Local-scale habitat layers for predicting kelp habitat extent: (left) depth from Seazone bathymetry, (middle) wave fetch from Burrows (2012), and (right) likely presence of suitable subtidal rock habitat (shaded area <3km from intertidal rock substrata, in the Defra Intertidal Substrate dataset)

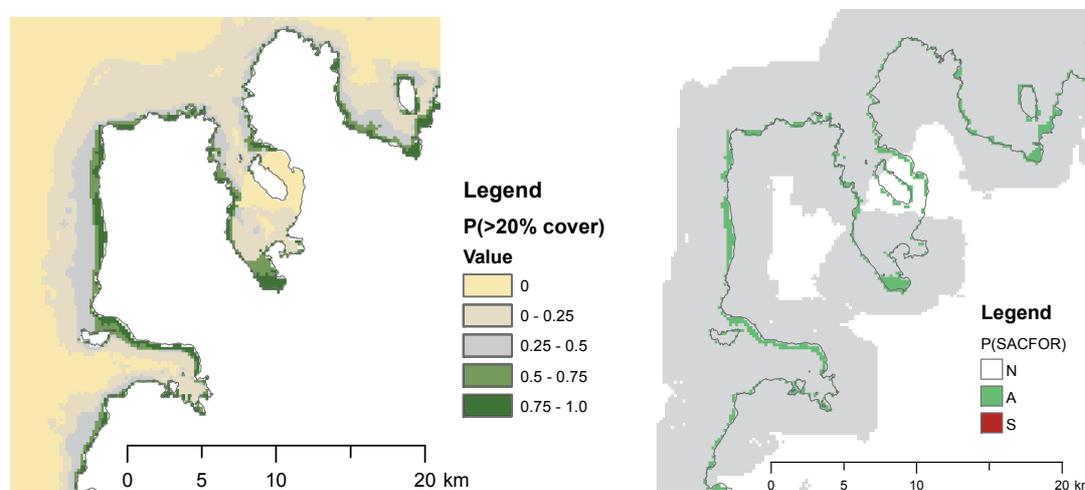
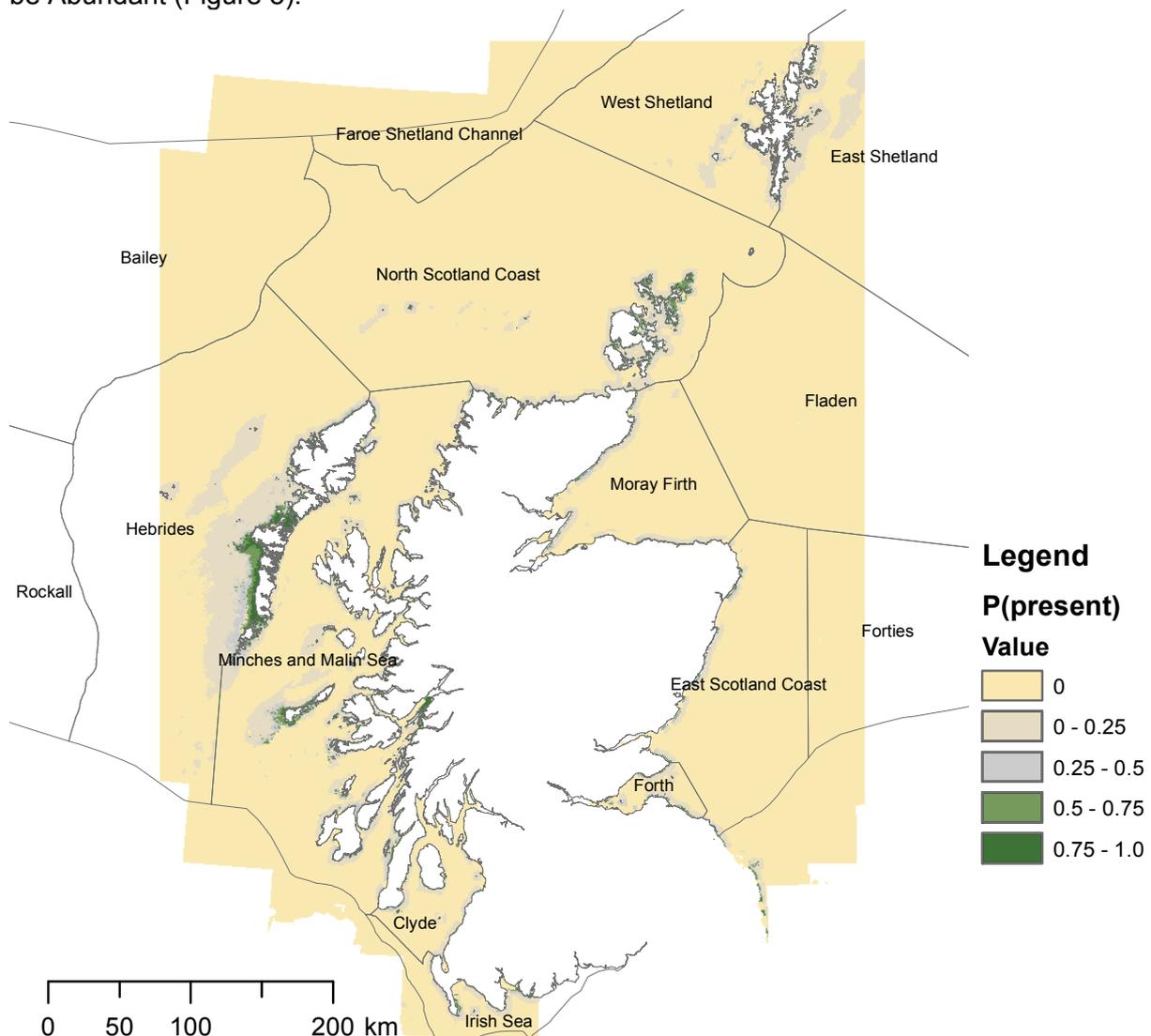


Figure 4: Predicted kelp habitat in Loch Ewe and Gairloch, based on relationships between MNCR kelp abundance data and underlying habitat predictors, as shown in Figure 1. The left hand plot shows the likelihood of kelp exceeding a threshold percentage cover of the sea bed, while the right hand plot shows the most likely abundance category for each grid cell, overlaid on areas where habitat is likely to comprise bedrock based on proximity to intertidal substratum, shown in grey.

The maps were constructed using 200-m grid cells, following the resolution of the wave-fetch model in Burrows (2012). The total extent of kelp habitat in each of Scotland's Marine Atlas regions Table 1 was estimated in two ways (1) by adding up the total number of 200-m cells where the predicted probability of finding kelp above a particular % cover exceeded a

threshold probability, and (2) by adding up the number of cells where kelp was predicted to be Abundant (Figure 5).



*Figure 5: Predicted kelp habitat in Scotland Marine Atlas regions, based on relationships between MNCR kelp abundance data and underlying habitat predictors, as shown in Figure 1.*

Environmental data such as Seazone bathymetry and satellite estimates of chlorophyll concentrations are not available for many sea lochs. The kelp model may underestimate the area of potential habitat as a consequence. The Scottish Sea Lochs Catalogue (Edwards and Sharples, 1986) reports the area of 110 sea lochs, 72 in the Minches and Malin Sea area. The Sea Lochs Catalogue presents areas within depth contours, of which the 10m depth contour probably encompasses most of the probable kelp habitat. Table 1 therefore includes this area for consideration in the assessment of the total extent of kelp habitat.

The overlap between the extent of sea lochs in Edwards and Sharples (1986) and the Seazone bathymetry data is not quantified here. The overlap area is likely to inflate the kelp habitat total area if sea loch areas <10m (374km<sup>2</sup>) are included. Seazone bathymetry does not record bathymetry accurately in some areas. One such area is the southern portion of Loch Linnhe, where a depth of less than 10m is reported for the entire breadth of the loch.

This area is predicted to be kelp habitat by the model and increases the total area of kelp habitat in Scotland and in the Minches and Malin Sea by around 150km<sup>2</sup>

Table 1: Predicted extent of kelp in Scotland's Marine Atlas regions.

Region	Area km <sup>2</sup>	Area ≥50m depth	Area <50m depth	Area where pKelp > 0.25	Area where pKelp > 0.5	Area where pKelp =(A)	Area of Sea lochs <10m deep
Minches and Malin Sea	30028	21253	8776	2215	1334	856	258
Hebrides	41239	40856	383	1607	976	576	4
Moray Firth	10127	9762	365	245	103	55	0
Forties	24668	24668	0	0	0	0	0
North Scotland Coast	46047	45747	300	894	596	352	7
West Shetland	34790	34730	60	192	131	85	26
East Shetland	37955	37909	47	195	136	77	9
Clyde	4088	3885	203	161	93	50	71
Bailey	74920	74920	0	0	0	0	0
Irish Sea	3920	3745	175	165	78	40	0
Forth	1527	1399	129	121	58	29	0
East Scotland Coast	14970	14626	344	138	70	36	0
Rockall	65814	65814	0	0	0	0	0
Fladen	37168	37168	0	0	0	0	0
Faroe Shetland Channel	42696	42696	0	0	0	0	0
Total	469960	459178	10782	5933	3575	2155	374
		97.7%	2.3%	1.3%	0.8%	0.5%	0.1%

As can be seen in Table 1 above, different criteria give different estimates for the extent of kelp habitat. The most generous criterion, a 25% chance of finding any kelp (Rare or above, <1% cover or greater) in a particular cell, gives the largest estimate of kelp habitat nearly 6000 km<sup>2</sup>. A somewhat more stringent criterion, predicting where there is a more than 50% chance of finding kelp, gives a more modest area of 3600 km<sup>2</sup>.

The most robust criterion, predicting those areas where kelp is most likely to be Abundant or >20% cover, gives a total area of 2155 km<sup>2</sup>. We recommend that this latter value should be that used in estimating kelp production and biomass in Scotland.

The 2155 km<sup>2</sup> estimate of the extent of Scotland's kelp habitats is only 25% smaller than the 2860 km<sup>2</sup> made by Walker (1954). His estimate was based on surveys of 1115 km<sup>2</sup> of sublittoral rock, considered to contain 39% of the total kelp biomass, and by extrapolation assuming a similar biomass per unit area in unsurveyed areas, gives an estimate of 2860 km<sup>2</sup>. This is a very satisfying level of agreement, particularly given the uncertainties in the underlying data.

### 3.1.2 Standing stock of kelp carbon

Marine Nature Conservation Review data on abundance of kelp in Scotland report only percentage cover of the substratum, not the biomass of living plants or their carbon equivalent. Quantitative estimates of standing stock must be obtained from elsewhere. Kain (1979) reviewed reports of standing stock (fresh weight per  $m^2$ ) of *Laminaria hyperborea* for shallow water areas around the UK, and including only those samples collected by divers by hand. Values ranged from 12 to 20  $kg/m^2$ , equivalent to 1.8 to 3  $kg/m^2$  dry weight and 540 to 900  $gC/m^2$ , assuming that dry weight is 15% of fresh weight, and a 30% carbon content of dry matter (from Krumhansl and Scheibling, 2011). The highest value (900  $gC/m^2$ ) was in western Scotland and the lowest (540  $gC/m^2$ ) was in the Outer Hebrides. Taking an average of the four values (12, 12, 14 and 20  $kg/m^2$ ) gives a value of 14.5  $kg/m^2$  fresh weight, equivalent to 2.2  $kg/m^2$  dry weight, and 652  $gC/m^2$ .

Kain's (1979) standing stock estimates apply only to the depth of maximum abundance, generally the shallowest depth for *Laminaria hyperborea*. Standing stock diminishes rapidly with depth (Figure 6), reaching only 10% of the surface values by 12-25m depth. The rate of decline with depth is site dependent: faster where light attenuation is more rapid and least in clearer water. This relationship has not yet been described statistically, and cannot be used immediately to extrapolate to kelp habitats around Scotland as has been done here for the MNCR categorical abundance data. Instead, estimates of standing crop for the 'Abundant' (>20% cover) are used here to convert estimated habitat extent to areal estimates.

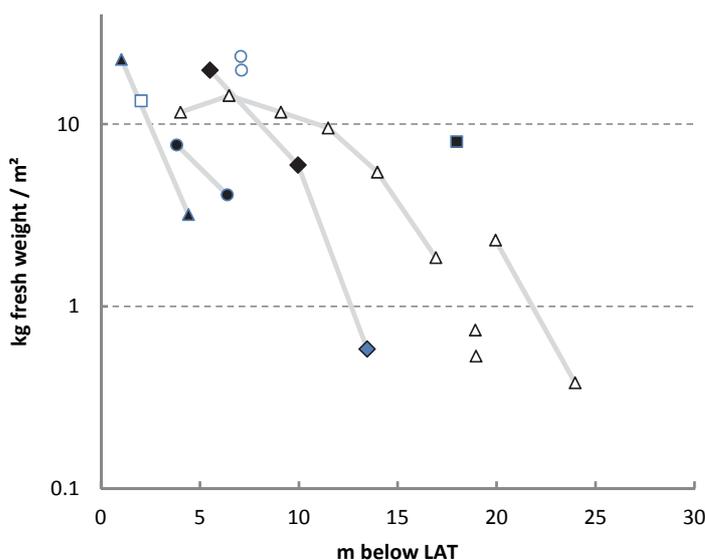


Figure 6: Standing crop of *Laminaria hyperborea* declining with depth, as fresh weight  $kg/m^2$ , at seven sites around northern UK (▲, Port Erin; ■, Grian Head; □, Kallow Point; ○, Cuan Sound; ●, Connel Sound; ◆, Spanish Head; △, SE Muldoanich). From Kain (1977).

Walker and Richardson (1955) gave values from 65 to 75% cover with corresponding standing crop of 3.0 to 4.5  $kg/m^2$  fresh weight for depths down to 9m (5 fathoms, 1 fathom = 1.8288 metres) off Bennane Head, near Girvan over three dates (July 1950, May 1952, and October 1952). Estimates of 3.0 to 4.5  $kg/m^2$  for standing crop as fresh weight (135 - 200  $gC/m^2$ ) are likely only to be achieved for the highest percentage cover areas, and the average for all areas >20% cover is likely to be less. Proportionately, for a cover value of 40% to represent all habitats where kelp is 'Abundant', this produces a standing crop estimate of **94  $gC/m^2$**  (40/70ths of the average 164 $gC/m^2$ ). As Kain (1979) pointed out, these values along with the rest of the surveys done by the Scottish Seaweed Research

Association were made with spring grabs operated from small boats and are likely to be less representative than those collected by divers, most likely underestimating biomass if the grabs were <100% efficient. Kain's (1979) average estimates of standing crop were over 10 kg/m<sup>2</sup> fresh weight (14.5 kg/m<sup>2</sup> on average), giving estimates of carbon per unit area (652 gC/m<sup>2</sup>) that are four times greater than Walker and Richardson's (1955) values, but her values were restricted to the shallowest depths rather than the whole 0 to 9m range. These maximal values of fresh weight >10 kg/m<sup>2</sup> are also evident in Kain's (1977) plot of changing fresh weight per unit area with depth for *Laminaria hyperborea*, and do extend down to 5 to 10m depth, especially at clear water sites in the Outer Hebrides. The estimate of **94 gC/m<sup>2</sup>** based on Walker and Richardson's (1955) data may therefore be too low, and a revised value may be up to twice this figure (**187 gC/m<sup>2</sup>**)

Using these two values of standing crop (**94 gC/m<sup>2</sup>** based on SSRA data and **187 gC/m<sup>2</sup>** based on Kain's studies) for areas where kelp is 'Abundant' (>20% cover), this produces total estimates of standing stock of kelp around Scotland of **202 000t** and **404 000t C**, over a total area of 2155km<sup>2</sup>. This corresponds to fresh weight equivalents of 4.5 and 9.0Mt.

Standing crop of kelp will change from year to year. Over ten years of similar surveys all around Scotland using the same spring grab methods (1946-1955), Walker (1956) found variation in annual average fresh weight per unit area from a minimum of 1.5kg/m<sup>2</sup> to a maximum of 7.2 kg/m<sup>2</sup>, equivalent to 70 to 325 gC/m<sup>2</sup>. The average of these yearly values is equivalent to 167 gC/m<sup>2</sup>, very similar to the Bennane Head estimates given above, and giving a range of yearly variation in standing stock of 40% to 200%.

### 3.1.3 Production from kelp

Production rates by kelp species found in the UK (Table 2) have been recently reviewed by Krumhansl and Scheibling (2012). Growth rates and the rates of loss and erosion of plants are usually measured by divers, monitoring changes in plant sizes using punched holes in tagged plants revisited over a number of dates throughout the year (Krumhansl and Scheibling 2011). Another approach involves the assumption that the maximal dry weight of the frond in June and July at the end of tissue growth gives the year's production, but it is acknowledged that this may underestimate the total annual production (Kain 1977).

Production rates vary enormously and generally by more than an order of magnitude. Estimates of production from *Laminaria* species range from 110 and 1780 gCm<sup>-2</sup>yr<sup>-1</sup> (Mann, 2000), with 1225 gCm<sup>-2</sup>yr<sup>-1</sup> for *Laminaria* at its most favourable depth in south-west England (Bellamy *et al.*, 1968, cited in Mann, 1982), and between 400 and 1900 gCm<sup>-2</sup>yr<sup>-1</sup> in earlier studies (Westlake, 1963). The lowest value for productivity is for *Saccharina latissima* in Loch Creran at only 120 gCm<sup>-2</sup>yr<sup>-1</sup>, attributed by Mann (1982) to nutrient limitation in a low-flow site.

Production rates shown in Table 2 are net rates and give the balance between photosynthesis and respiration for the species and location of measurements.

Table 2. Estimates of rates of production for UK kelp species, modified from Krumhansl and Scheibling (2011) as production of dry matter ( $\text{g m}^{-2}\text{yr}^{-1}$ ) and carbon ( $\text{g C m}^{-2}\text{yr}^{-1}$ ). Carbon production rates are shown in **bold**. Carbon content of dry matter is assumed to be 30%.

Location	Species	Productivity ( $\text{g m}^{-2}\text{yr}^{-1}$ ) ( <b><math>\text{g C m}^{-2}\text{yr}^{-1}</math></b> )	Erosion ( $\text{g m}^{-2}\text{yr}^{-1}$ ) ( <b><math>\text{g C m}^{-2}\text{yr}^{-1}</math></b> )	% Eroded	Dislodgement ( $\text{g m}^{-2}\text{yr}^{-1}$ ) ( <b><math>\text{g C m}^{-2}\text{yr}^{-1}</math></b> )	% Dis- lodged	Source
Nova Scotia, Canada	<i>Laminaria digitata</i> , <i>Saccharina latissima</i>	951 <b>289</b>	1058 <b>322</b>	111	–    –		Krumhansl and Scheibling (2011)
Nova Scotia, Canada	<i>Laminaria digitata</i> , <i>Saccharina latissima</i>	–    –	–    –		74 <b>22</b>		Chapman (1984)
Rhode Island, USA	<i>Laminaria digitata</i> , <i>Saccharina latissima</i>	6152 <b>1938</b>	–    –		2798 <b>839</b>	46	Brady- Campbell <i>et al.</i> (1984)
Loch Creran, Scotland	<i>Saccharina latissima</i>	395 <b>120</b>	160 <b>48</b>	40	–    –		Johnston <i>et al.</i> (1977)
Southwest England	<i>Laminaria hyperborea</i>	4083 <b>1225</b>	–    –	–	–    –	–	Bellamy <i>et al.</i> (1968) in Mann (1982)
W. Scotland	<i>Laminaria hyperborea</i>	1670 <b>501</b>	–    –	–	–    –	–	Jupp and Drew (1974)
Outer Hebrides	<i>Laminaria hyperborea</i>	1100 <b>330</b>	–    –	–	–    –	–	Kain (1979)
Isle of Man	<i>Laminaria hyperborea</i>	1300 <b>390</b>	–    –	–	–    –	–	Kain (1979)

Most of these rates apply to shallow water in optimum depths for growth, where standing crop is at a maximal rate. There is no equivalent model or set of observations for rates of annual production to describe changes with depth to that for changes in percentage cover or standing crop. Kain (1977) used a fixed ratio of production to biomass to estimate production, but this approach is unverified by observational and experimental data on growth rates over time. It seems likely that the production to biomass ratio will decline with depth, as photosynthesis declines with available light, and that the rate of production will decline faster with depth than does standing crop.

The average rate of production reported in Table 2 is **685 gC/m<sup>2</sup>/yr**, with a large standard deviation of 656 gC/m<sup>2</sup>/yr. Applying this value across all kelp habitat in Scotland to produce an estimate of production carries a *high degree of uncertainty*, due to (i) variability in rates across different methods of estimation of production, (ii) habitat- and depth-specific rates, varying with biomass, production rates and dominant kelp species, and most likely related to availability of light, nutrients (including flow limitations) and temperature. The value is likely to be at the high end of the actual range, given that it is based on shallow water estimates.

Combined with the estimate for kelp habitat extent of 2155km<sup>2</sup>, defined as the area where kelp is predicted to exceed 20% cover, this gives estimated production from kelp in Scottish waters as **1 732 000 tC/yr (or 1.73 MtC/yr)**.

### 3.1.4 Fate of kelp detritus and potential for carbon sequestration

Kelp production is not stored within kelp beds, and therefore kelp beds alone offer no potential for carbon sequestration. Instead dead material is exported from kelp beds into other habitats, as dislodged whole plants or fragments of plants eroded from the end of fronds. This detritus supports coastal food webs, particularly for benthic suspension feeding organisms in rocky areas such as mussels and barnacles (Duggins *et al.*, 1989), and grazers such as limpets (Bustamante and Branch, 1996). Kelp detritus is an important source of food in soft sediment areas too (see Krumhansl and Scheibling, 2012 for the most recent review), as food for small detritivores. The incorporation of kelp detritus into sediments may ultimately be the major route for a fraction of the **1.73 MtC/yr** produced from kelp around Scotland to be sequestered for the long term.

Little is known of the rate of short or long term incorporation of kelp detritus into coastal sediments. The distance over which this detritus could be dispersed may be limited to a few km from the kelp beds themselves. A stable isotope study in South Africa (Hill *et al.*, 2006) found that mussels and detritus in nearshore areas (<5km) showed a signal consistent with kelp as a major source, while further offshore the signal was dominated by production from phytoplankton. This suggests that the kelp influence may not extend very far offshore.

More is known of the deposition of kelp ('wrack') on sandy intertidal coastlines (see Orr, 2013 for review). Beach cast kelp can be found at up to 150kg/m<sup>2</sup> at high wrack beaches in the Outer Hebrides after winter storms (Orr, 2013), and typically 20-30kg/m<sup>2</sup> during the rest of the year at these sites. Here the cast weed supports a large biomass of invertebrates that, in turn, are important food for resident and migrating birds. Traditionally, this beach cast material has been harvested by coastal farmers who have used it to fertilise their land.

Losses of kelp following storms may comprise 50% of the local biomass (Chapman, 1948), but the fraction of this biomass that accumulates on beaches depends on local currents and wind directions. The Scottish Seaweed Research Association's (SSRA) surveys of Tiree, Barra, North Uist, Lewis, Sanday and Orkney gave total estimates of beach cast kelp in these areas of 15 000t and 37 000t (fresh weight) in 1945/6 and 1946/7 respectively (SSRA, 1947a, b). The latter value represents just 0.4% of the estimated 9.0Mt standing crop across Scotland, albeit a higher percentage locally, suggesting that only a few percent of kelp standing crop are cast on beaches each year. The long term fate of beach cast kelp-derived carbon is little understood, but food web models suggest (Orr, 2013, Table 5.5 p 156) that most is either re-exported as detritus, respired or consumed by higher trophic levels.

The proportion of annual kelp production that is incorporated into long-term stores is unknown, but given the readiness with which kelp-derived detrital material is consumed by detritivores and broken down by microbial activity, it seems likely to be only a few percent or less. This is a *highly uncertain* area, potentially important given the total quantity of carbon incorporated into kelp production.

### 3.1.5 Threats to kelp forests

Threats to kelp forests around Scotland have been recently reviewed by Smale *et al.* (2013). These authors saw the main threats to kelp habitats as being from climate change, increased turbidity and nutrient loading from coastal runoff, effects of the removal of top predators by fishing or other human activities, and harvesting and cultivation. The different threats may combine to affect kelp populations in synergistic and even surprising ways. Kelp species like *Laminaria digitata* and *Alaria esculenta* approach their southernmost geographical range limits in the UK, and recent range contractions of other UK species, *Saccorhiza polyschides*, further south in Northern Spain may be associated with increased seawater temperatures (Fernández, 2011). Increased storminess may also negatively

impact kelp forests (see Smale *et al.*, 2013 for review), damaging plants and changing the dynamics of whole beds. Current evidence suggests that ocean acidification and increased dissolved CO<sub>2</sub> may have a positive effect on production by macroalgae (Kroeker *et al.*, 2013). Increased coastal runoff of sediment and nutrients is likely to have a negative impact on kelps. Kelp abundance is reduced in areas of reduced light penetration (Burrows, 2012), so changes that negatively influence water clarity will have a negative impact on kelp and kelp production. Kelp 'barrens', areas where kelp would be expected to grow but are not present, are thought to be caused by overgrazing by herbivores, usually sea urchins (reviewed in Steneck *et al.*, 2002). While such barrens are not common around the UK, removal of the predators that control urchin numbers may cause a consequential decline in kelp through an increase in herbivore pressure. Currently there is increased interest in cultivation and harvesting of kelp for biofuel, food and other products. Norway and Chile both currently harvest between 130,000 and 200,000t of kelp annually. While a limited harvest may be sustainable, the immediate impacts on the local environment in terms, for example, of habitat use by fishes and seabirds can be appreciable (Lorentsen *et al.*, 2010). Environmental impacts of increased kelp mariculture are not well understood, with potential benefits and impacts on the local environment. Finally, the construction of offshore renewable energy devices, mostly wave-energy extraction devices and tidal turbines, may have a limited effect on kelp habitats (MacLeod *et al.*, 2014). The area covered by planned wave energy arrays covers between 1% and 13% of Scotland's kelp habitats, but the footprint of individual devices is considerably less than that amount. These figures should be considered alongside annual losses of up to 34% of biomass during winter storms each year.

### 3.2 Saltmarshes and seagrass beds

The contribution of saltmarshes and seagrass beds to Scotland's carbon budget has been recently reviewed by Stahl (2012a), and this review forms the basis for our assessment.

#### 3.2.1 Saltmarshes

Saltmarshes are intertidal ecosystems that are dominated by vascular plants. They occur on sheltered marine and estuarine coastlines from the arctic to the tropics, but are most common in temperate regions. It has recently been suggested that saltmarshes are one of the most efficient habitats on earth for sequestering and storing carbon in their soils with an average sequestration rate of 210 g C /m<sup>2</sup>/yr which is the equivalent of 770 g CO<sub>2</sub> m<sup>-2</sup>yr<sup>-1</sup> (Chmura *et al.*, 2003). In addition to this, each molecule of CO<sub>2</sub> sequestered in saltmarsh soils is more valuable from a 'Greenhouse gas perspective' than CO<sub>2</sub> molecule sequestered in freshwater wetland soils which tend to produce and release methane gas (CH<sub>4</sub>) associated with carbon accumulation. The high concentrations of sulphates and associated microbes in coastal and marine soils and sediments mitigate against CH<sub>4</sub> formation and escape to the atmosphere, where it otherwise would act as a considerably more potent greenhouse gas than CO<sub>2</sub>.

In Scotland the extent of saltmarshes has been estimated to 6,747 ha (hectares) which is about 15% of the total extent of saltmarshes in the UK (Burd, 1995). Scottish saltmarshes are mainly concentrated to the low lying firths of eastern and south-west of Scotland, whereas a large number of very small saltmarsh sites are located at the head of sea lochs, in embayments and on beaches in the north-west of Scotland. Approximately, 3% of the Scottish coastline is covered by saltmarsh vegetation.

Given the average sequestration capacity of 210 g C/m <sup>2</sup> /yr according to Chmura <i>et al.</i> (2003), Scottish saltmarshes may have an average sequestration potential of <b>14200 t C/yr (0.014 Mt C yr<sup>-1</sup>)</b> .
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About 80% of UK's saltmarsh areas are today designated SSSIs (including SACs and SPAs), except in the north-west of Scotland where about 50% are notified as SSSIs ([www.ukbap.org.uk/PriorityHabitats.aspx](http://www.ukbap.org.uk/PriorityHabitats.aspx)). Other management actions for the restoration of lost saltmarsh areas include soft engineering measures such as managed realignment (e.g. Nigg Bay in Cromarty Firth) and transplanted saltmarsh plants (Maynard *et al.*, 2011). A recent study showed that significant managed realignment of the Humber estuary could significantly enhance the carbon sequestration (150%) and reduce concentrations of nutrients (83-50%) and contaminant metals in the estuary (Andrews *et al.*, 2006). Restoration of an eroding fringe saltmarsh has also been successfully carried out (Eden Estuary, St Andrews) using vegetative transplants that enhanced the sedimentation in the marsh (Maynard *et al.*, 2011).

### 3.2.2 Seagrass beds

Seagrass is a globally distributed group of marine flowering plants (~60 different species) that form extensive meadows in shallow waters of all continents except the Antarctic. In Scotland they typically occur from the lower saltmarsh limit (*Zostera noltii*) into the sublittoral zone (*Zostera marina*) at approximately 10m below the surface. It has recently been suggested that although these plants 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 (Laffoley and Grimsditch, 2009). 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<sup>-2</sup> yr<sup>-1</sup>**, which translates to global storage of 27-40 Tg C yr<sup>-1</sup> (Laffoley and Grimsditch, 2009). As with saltmarsh sediments, carbon accumulation in seagrass beds is more efficient from a 'greenhouse gas perspective' since, while both release CO<sub>2</sub> through respiration, seagrass beds do not release as much of the more potent greenhouse gases (e.g. CH<sub>4</sub>) as their terrestrial counterparts can do.

There are no complete estimates for the total coverage of seagrass beds in Scottish territorial waters and hence it is difficult to directly translate their local importance as blue carbon sinks. However, according to the Geodatabase of Marine Habitats and Species in Scotland, 355 records of seagrass beds have been recorded all around the coast of Scotland (Figure 7).

Eelgrass beds (*Zostera* spp.) are especially well developed in Scotland compared to other parts of UK, which is probably due to the presence of extensive suitable habitats and uncontaminated waters (Hiscock *et al.*, 2004). For example, Cromarty Firth alone supports probably the largest total area of dwarf eelgrass and narrow-leaved eelgrass in UK (~1200ha). Distribution maps of seagrass (Green and Short, 2003), indicate that Scotland has larger numbers of seagrass beds than much of the Western European coastline. Since only 31ha of seagrass beds in Scotland have been mapped to date (October 2013), and less than 10% of records lie within the mapped areas, this suggests that the actual area is at least 10 times the mapped area. This gives an estimate of **the total extent of seagrass beds in Scotland of 15.9km<sup>2</sup>** when the 1200ha in the Cromarty Firth is added in.

Combined with the global average sequestration rate for seagrass beds (**83 g C m<sup>-2</sup> yr<sup>-1</sup>**), the estimated total extent gives an estimate of sequestration capacity for seagrasses in Scotland of **1321 t C/yr**.

In order to sustain and promote the role of seagrass beds as significant carbon sinks and providers of important ecosystem goods and services, it is vital to maintain a high water quality with low mean turbidity and low levels of eutrophication, ensuring sufficient light penetration for the seagrass to thrive. Today, about 64% of the known records of

seagrass beds in Scotland are in protected areas or fisheries areas (SNH, 2012 – <http://www.snh.gov.uk/docs/B1000612.pdf>). Furthermore, synergistic effects of proper management of coastal wetlands and saltmarshes may include enhanced water quality in many estuaries and coastal embayments which often include seagrass beds.

### 3.2.3 Threats to saltmarshes and seagrass beds

Current and potential threats for saltmarsh habitats come from both human and natural activities including land claim, coastal erosion, 'coastal squeeze' and climate change ([www.ukbap.org.uk/PriorityHabitats.aspx](http://www.ukbap.org.uk/PriorityHabitats.aspx)). Although large scale land claim schemes for agriculture are now rare, smaller land claims of marsh area associated with development of industry, port facilities, small marinas and waste disposal sites frequently occur. Erosion of the seaward edge of saltmarshes occurs widely in the high energy locations of the larger estuaries as a result of coastal processes and many saltmarshes are being 'squeezed' between an eroding seaward edge and fixed flood defence walls that prevent the vegetation to naturally progress landwards with the rising sea level. Climate change, associated sea-level rise and increased frequency of severe storms is predicted to worsen this effect (Laffoley and Grimsditch, 2009). Sediment transport and dynamics in saltmarshes may also be affected negatively by coastal protection works, changes in estuary morphology from land reclamation, dredging for shipping channels and marina construction as a few examples. Other pressures from human activities include introduction of non-native species of certain types of cord grass (*Spartina* sp.), pollution, high nutrient loads from agricultural activities, and waste disposal, etc. All these activities have caused extensive loss of saltmarsh areas in the UK and best estimates show that the current rate of saltmarsh habitat loss can be up to 100ha per year in the UK.

The greatest threats to saltmarshes globally are sea-level rise, invasive species and effects of overgrazing according to a review by Gedan *et al.* (2009) whose findings are summarised here. Saltmarshes appear fairly resilient to grazing by livestock, a primary use of the habitat. In the past, conversion of low lying areas to agricultural land by drainage schemes may have reduced the area of saltmarshes. But increases in geese populations in other parts of the world, particularly sub-Arctic Canada, produced denudation of Arctic marshes and collapse of the saltmarshes. It is not known whether a similar increase in grazing by increasing geese numbers poses a threat to Scotland's saltmarshes. Managed retreat (or realignment) by breaching coastal defence structures, as a method of adapting to sea-level rise, may increase the area of saltmarshes. Where this has been attempted in Scotland, in Nigg Bay in the early 2000s, the result was to increase the area of saltmarsh vegetation and encourage habitat use by coastal birds (SNH, 2014). Sea-level rise produces landward migration of vegetation types and drowning of existing marshes. While saltmarshes can expand landwards to compensate for rising sea levels, existing coastal flood protection structures may prevent this landward migration, producing 'coastal squeeze' (Doody, 2004). This produces loss of marsh seaward of flood defences, and has important consequences for the capacity of saltmarsh vegetation to attenuate waves and thereby offer protection from coastal erosion (Möller, 2006). Increased atmospheric CO<sub>2</sub> concentration may have a positive effect on production by saltmarsh plants (Gedan *et al.*, 2009) and may favour a shift from C<sub>4</sub> to C<sub>3</sub> plants like grasses. Increased storminess associated with climate changes may cause decreases through erosion or increases through increased sediment supply.

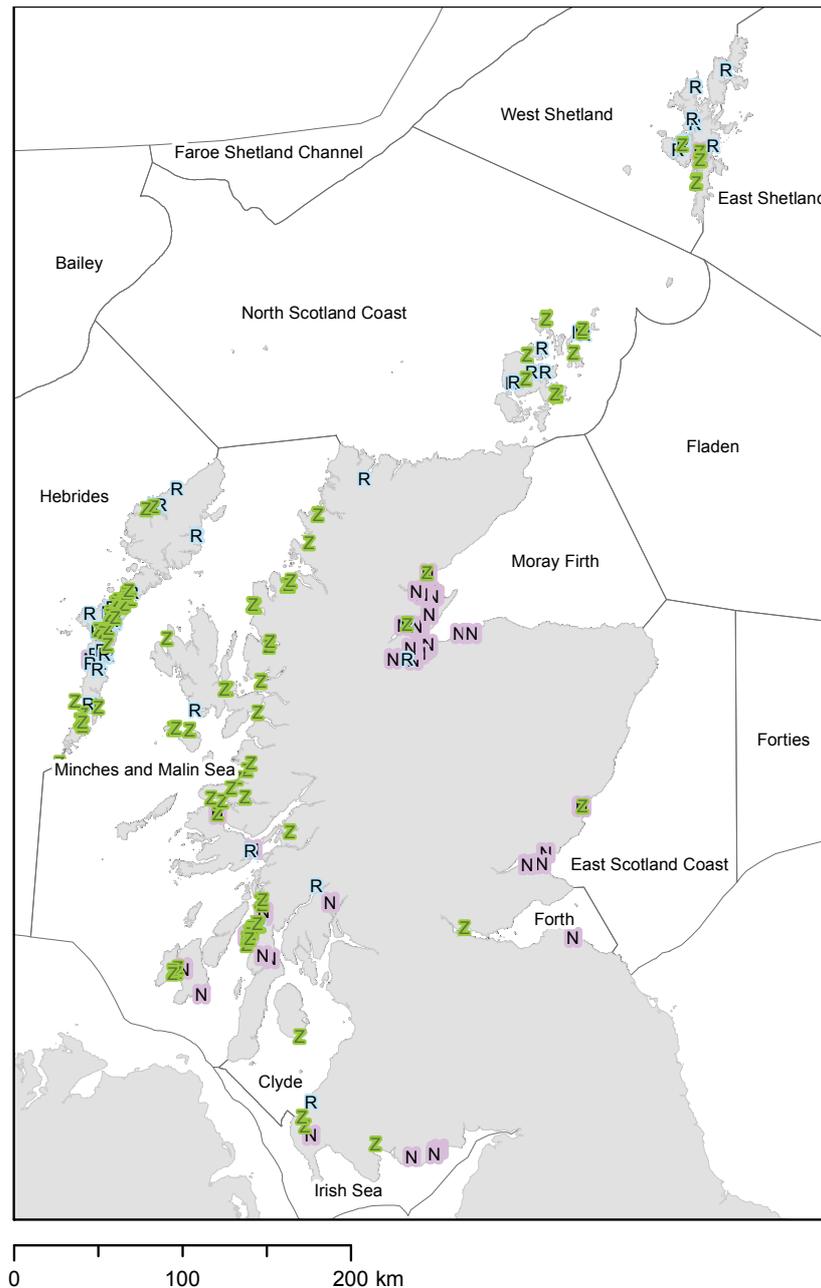


Figure 7: Seagrass records around Scotland *Zostera marina* (Z, 169 records), *Zostera noltii* (N, 93 records) and *Ruppia* (R, 112 records in the Geodatabase for Marine Habitats and Species in Scotland, GeMS V2i10).

A wasting disease was responsible for the die-back of large areas of seagrass in the UK in the 1930s, and has recently reappeared in seagrass beds around the Isles of Scilly (UK). Other current and potential threats to seagrass communities include natural factors such as storms, exposure to air and fresh water pulses, as well as heavy grazing by wildfowl that can have a negative impact on seagrass coverage. Recent studies have shown that ~1/3 of the global seagrass distribution has now been lost through human activities associated with coastal development, which includes increased turbidity and eutrophication (nutrient enrichment) which affects seagrass photosynthesis and growth

### 3.3 Maerl

Unlike fleshy macroalgae, maerl does not break down quickly due to its calcium carbonate skeleton and thus forms long lasting maerl beds or deposits that are populated by invertebrate and vertebrate biota (Kamenos *et al.*, 2004a, b). These deposits act as a longer term store for organic and inorganic carbon and also lock up associated calcifying biota in their matrix-like structure. While the rate of deposit accretion is slow (0.25mm/yr) the beds are extensive and area/volume is great with Scottish species-specific accretion rates varying from 420 to 1432 g CaCO<sub>3</sub> m<sup>-2</sup>yr<sup>-1</sup> (Freiwald and Henrich, 1994). Live maerl deposits on the west coast of Scotland can reach at least 60cm depth with some dead deposits being significantly deeper (Kamenos, 2010). Primary productivity from maerl deposits can reach 407 g C m<sup>-2</sup> yr<sup>-1</sup> which then becomes locked within each deposit. Based on current knowledge of maerl bed position, extent, live / dead status, accretion rate, deposit depth and primary productivity we can determine their carbon budgets, capacity to trap and store carbon at short- to long-term temporal scales and determine the main threats to their storage capacity (e.g. trawling, Kamenos *et al.*, 2003). Our assessment includes the relative importance of live and dead deposits.

Table 3. Carbon sequestration (as CaCO<sub>3</sub>) by coralline algae in Scotland (m=depth in metres)

Species	Max g CaCO <sub>3</sub> yr <sup>-1</sup> m <sup>-2</sup>	Min g CaCO <sub>3</sub> yr <sup>-1</sup> m <sup>-2</sup>	Max g C yr <sup>-1</sup> m <sup>-2</sup>	Min g C yr <sup>-1</sup> m <sup>-2</sup>
<i>Lithothamnion glaciale</i> (7m)	1432	895	171.8	107.4
<i>Lithothamnion glaciale</i> (18m)	630	420	75.6	50.4
<i>Phymatolithon calcareum</i>	244	79	29.3	9.5

#### 3.3.1 Extent of Scottish maerl beds

There are 353 records of maerl “beds” in Scotland with little extent or live/dead status information. Taking four beds (Stravanan Bay and Lamlash Bay Clyde, Caol Scotnish, Loch Sween and Inner Loch Torridon) for which a good approximation of extent is known gives a total Scottish maerl bed area of 7.06 km<sup>2</sup> (i.e. 353 sites multiplied by 20000 m<sup>2</sup>), assuming that these four beds are representative of the ‘average’ Scottish maerl bed. This estimated total area of maerl may, however, be an under- or over-estimate since some beds may remain to be discovered and the average extent may be greater or smaller.

#### 3.3.2 Volume of Scottish maerl beds

Very little information is available on maerl bed thickness. The Caol Scotnish bed is at least 60cm thick (Kamenos 2010) while other beds are much thicker (e.g. Wyre Sound, unpublished data; Loch Ailort, Kamenos pers. obs) and others are thinner (Ardlamont Point, Clyde, Kamenos, pers. obs.). Taking 60cm as the average, this suggests the volume of Scottish maerl (alive or dead) is 4.23 km<sup>3</sup> (7.06 km<sup>2</sup> (area) \* 60 cm (thickness)). Again this is likely an underestimate as there are undiscovered maerl beds, but also because a significant volume of dead maerl makes up beach sediment and is not classified as a maerl bed *per se* (e.g. Plockton, Isle of Skye, Outer Hebrides).

#### 3.3.3 Standing stock of maerl carbon

As the beds are long-lived this is a continuous standing stock of organic and inorganic C which has likely been accreted since the Holocene deglaciation. Based on the estimated volume of Scottish maerl beds and mass of maerl (866.7 kg m<sup>-3</sup> Kamenos *et al.*, in prep) we estimate **440561 t C are locked within maerl deposits.** (4.23 km<sup>3</sup> × 0.8667 Tons m<sup>-3</sup> ×

12%. The last figure is the proportion of C in maerl skeletal calcite and also the proportion of organic C making up the skeletal mass, such as in starch). Again we suspect this is an underestimate as there are undiscovered maerl beds but also because a significant volume of dead maerl makes up beach sediment and is not classified as a maerl bed *per se* (e.g. Plockton, Isle of Skye, Outer Hebrides).

### 3.3.4 Sequestration from maerl

There are no extensive quantitative data on the proportion of live and dead beds present in Scotland. The surface layer (not the entire thickness) of some beds ranges from 100% live (e.g. Caol Scotnish, Kamenos, pers. obs.), through 50% live (Loch Torridon, Kamenos, pers. Obs), down to <5% live (Tany Buoy, Clyde, Kamenos, pers. obs). In general, beds in the Clyde sea are <100% live (BIOMAERL team 1999). We have thus used a blanket average of 50% live generating an annual carbon sequestration added to the standing stock of between **33.5-607- tC/yr** for all Scottish beds.

### 3.3.5 Missing data summary

Several organic C components are not included in the calculations due to the limited information available. Some components affect all calculations, others just some as indicated here.

Carbon standing stock may be underestimated through non-inclusion of organic and inorganic carbon in other elements of maerl beds:

- (1) Sediment locked within the maerl thalli.
- (2) In maerl-associated organisms, such as bivalves and foraminifera

The total volume of maerl and habitat extent, and hence standing stock, may be underestimated by omission of:

- (3) Unmapped maerl beds.
- (4) Dead maerl in beach sediment, particularly on the West coast of Scotland. This is not classified as a maerl bed *per se* (e.g. Plockton, Isle of Skye, Outer Hebrides) and not included in calculations. This component will be composed of a terrestrial and marine beach component (e.g Plockton, Isle of Skye) and will likely have different geological storage times due to different environmental exposure.

Volume, extent and rates of carbon sequestration depend on data on:

- (5) Extent and percentage live / dead composition of all Scottish beds. Some extent data are available in impact assessment reports conducted as part of the programme of installation of sewage processing plants to fulfil the requirements of the Water Framework Directive, but our understanding is that many of these are held by private contractors who conducted the impact assessments before building commenced.

### 3.3.6 Threats to maerl beds

The main threats to maerl sequestering carbon occur at different time scales; 1) years-decades: trawling, sedimentation and other physical impacts. 2) Decades to centuries: ocean acidification (OA). Physical impacts and sedimentation will kill live maerl thalli involved in accreting maerl deposits. While this is likely to have a small effect on the geological C standing stock held (some organic C may be released by physical disturbance) it will prevent

further growth of maerl deposits, halting the growth of the geological C reservoir. In addition to killing the maerl thalli, at longer time scales OA may also lead to the chemical and physical breakdown of maerl deposits releasing the organic and inorganic carbon they hold.

The following is needed to understand the system better:

1. Production of a complete carbon budget for maerl beds.
2. Obtain extent / volume information for more Scottish maerl beds to give a more accurate Scottish maerl C sequestration figure and Scottish maerl C standing stock. This includes the % live and dead thalli on maerl beds.
3. Assess the importance of non-marine maerl beds in C storage.
4. Define the C standing stock in maerl at geological and modern time scales.

### 3.4 Biogenic reefs

The question of what constitutes a biogenic “reef” has been discussed at considerable length in the scientific literature (e.g. Riding, 2002; Hendrick and Foster-Smith, 2006; Rabaut *et al.*, 2009). In the context of UK marine habitat mapping and nature conservation, Holt *et al.* (1998) provided a working definition that summarises the essential characteristics of these features:

*“Solid, massive structures which are created by accumulations of organisms, usually rising from the sea bed, or at least clearly forming a substantial, discrete community or habitat which is very different from the surrounding sea bed. The structure of the reef may be composed almost entirely of the reef building organism and its tubes or shells, or it may to some degree be composed of sediments, stones and shells bound together by the organisms”.*

With respect to the potential for carbon storage in Scottish waters, the following benthic communities can be considered to fall within Holt *et al.*'s (1998) broad definition and will be discussed in this report section:

- Cold-water coral (*Lophelia pertusa*) reefs
- Tubeworm (*Serpula vermicularis*) reefs
- Flame shell (*Limaria hians*) beds
- Horse mussel (*Modiolus modiolus*) beds
- Blue mussel (*Mytilus edulis*) beds

An additional benthic community – subtidal brittlestar beds (usually *Ophiothrix fragilis*, but in some cases supplemented or replaced by *Ophiocolina nigra* or *Ophiopholis aculeata*) - will also be mentioned briefly. Brittlestar beds are not “reefs” under the terms defined above, but they do represent substantial concentrations of benthic biomass that are abundant and widespread in Scottish waters (Hughes, 1998). Dense populations of brittlestars and other echinoderms may play a significant (and until recently, under-appreciated) role in marine carbon cycling (Lebrato *et al.*, 2010), so that some consideration of them here is justified.

All of these communities share important structural and functional characteristics: they are characterised by animals that are either sessile (cold-water corals and serpulid tubeworms) or sedentary with very limited mobility (bed-forming bivalves). Brittlestars are freely mobile but probably largely sedentary when aggregated in dense populations (Broom, 1975). The characterising species are all suspension-feeders on phytoplankton, zooplankton or suspended detritus. The collective suspension-feeding activity of dense benthic populations constitutes a potentially important pathway for the accelerated flux of organic carbon from the water column to the sea floor (Hily, 1991). These reef- and bed-forming animals all build tubes, shells or skeletons of calcium carbonate (CaCO<sub>3</sub>), which may persist on the sea floor

or become incorporated into bottom sediments after the death of the animal. The focus of this report section will be the potential of calcareous skeletal material to act as a carbon store, with carbon assumed to make up 12.0% of the molar mass of CaCO<sub>3</sub> (Windholz *et al.*, 1983). Organic carbon contained in soft tissues will be rapidly consumed or degraded by heterotrophic organisms and recycled back into the food web.

Data required to estimate the carbon storage capacity of Scottish biogenic reefs and similar benthic communities are patchy and of varying quality. For some coastal systems (e.g. serpulid reefs), spatial location and extent are relatively easy to determine and good information is available from recent monitoring surveys. In contrast, cold-water corals inhabit much deeper, mainly offshore waters and our knowledge of their occurrence in Scottish seas is still highly incomplete. Published measurements of carbonate production and degradation rates (required for mass-balance estimates of net carbon sequestration) are also rare or non-existent for several of these systems. In some of the following cases, simplifying assumptions and improvised measurements using archived specimens have been made to allow tentative estimation of carbonate standing stock. Where such procedures have been necessary, the steps involved in calculation are clearly explained so that the resultant estimates can be revised if better information becomes available.

### 3.4.1 Cold-water coral (*Lophelia pertusa*) reefs

#### 3.4.1.1 Current extent and distribution

*Lophelia pertusa*, the most important reef-building cold-water coral species, is widely distributed around the north-east Atlantic margin in the approximate depth range 100-1500m (Roberts *et al.*, 2003). In Scottish waters there are many historical records from the offshore banks, ridges and seamounts which form the northern rim of the Rockall Trough, but it is only within the past 10-15 years that accurate information on the current distribution of the species has started to become available. There are currently two localised and well-defined coral “hotspots” known in Scottish waters – the Darwin Mounds and the Mingulay Reef Complex – both designated as Marine Special Areas of Conservation (SACs). In addition, offshore surveys are continuing to update our knowledge of *L. pertusa* occurrence on the continental slope, seamounts and banks of the Rockall Trough. However, due to the vast spatial extent of these offshore topographic features and the limited resources available for deep-sea habitat mapping, a comprehensive assessment of cold-water coral distribution in Scotland’s deep sea is not yet possible.

The Darwin Mounds province (discovered 1998) is a concentration of small, coral-topped sediment mounds at ~1000 m water depth at the northern edge of the Rockall Trough, just south of the Wyville Thomson Ridge (Masson *et al.*, 2003). The individual mounds are subcircular, 75-100 m in diameter and ~5 m high. *Lophelia pertusa* colonies occur scattered across the mound surfaces (Masson *et al.*, 2003). The Darwin Mounds SAC covers an area of ~1400 km<sup>2</sup> and includes two main concentrations of mounds (eastern and western) with additional mounds outside these high-density areas (De Santo, 2013). The total number of mounds does not appear to have been determined, but is in the order of several hundred (De Santo, 2013).

The presence of *Lophelia pertusa* to the east of the island of Mingulay (Outer Hebrides) was known from historical records but scientific confirmation in 2001, followed by initial mapping in 2003, revealed the existence of the only currently-known cold-water coral reefs on the Scottish continental shelf (Roberts *et al.*, 2005). The reef complex consists of a series of bedrock ridges at 120-190 m depth, five of which support a dense cover of *Lophelia pertusa* colonies growing on mounds of accumulated coral rubble and trapped sediment (Roberts *et al.*, 2009; Douarin *et al.*, 2013). A recent (January 2011) document on the Scottish Natural Heritage website ([www.snh.gov.uk/docs/B749424.pdf](http://www.snh.gov.uk/docs/B749424.pdf)) gives an estimate of 5.4 km<sup>2</sup> for the total area of cold-water coral reef east of Mingulay.

Elsewhere on the Scottish shelf, *Lophelia pertusa* occurs as a fouling organism on some oil/gas platforms in the northern North Sea (Gass and Roberts, 2006). Of greater importance in the present context are deep-water populations in the Rockall Trough area. There are many historical records from the Rockall and Hatton Banks (Roberts *et al.*, 2003) but surveys of current status using modern deep-sea habitat-mapping techniques (multibeam bathymetry, ground-truthed by ROV or drop-down video) have only begun over the last decade or so. Cold-water coral reef frameworks, with evidence of carbonate mound formation, have been recorded from stations on Hatton Bank (Roberts *et al.*, 2008). *Lophelia pertusa* also occurs on the slopes of the Anton Dohrn Seamount (Stewart *et al.*, 2009). A recent survey of East Rockall Bank found no extensive biogenic reef structures, although clumps of *L. pertusa* were observed in the north-west and western summit areas and on the eastern flanks (Howell *et al.*, 2009). The information from these surveys is localised and incomplete, but is sufficient to show that cold-water corals are still widely distributed across the elevated topography of the Rockall Trough. Reef development appears to be very localised but may be extensive in some areas of the Hatton Bank. Given the areal extent of these submarine banks, even scattered coral growth could potentially amount to a substantial repository of biogenic carbonate, but in the present state of knowledge quantitative estimates are not possible. This report section will therefore focus on the two best-defined and mapped cold-water coral reef systems in Scottish waters, the Darwin Mounds and the Mingulay Reef Complex.

#### 3.4.1.2 Quantity of carbon currently stored

Estimation of carbon storage by cold-water corals requires a figure for the mass per unit volume of *Lophelia pertusa*. There appear to be no published data for this, so a value was calculated using cleaned and dried colonies of *L. pertusa* collected west of Shetland and held at SAMS. Thirteen blocks of *L. pertusa* with a total weight of 53 kg occupied a planar area measuring 85 x 100 cm when placed in close contact (Figure 8). The coral blocks were ~20 cm tall, so 53 kg can be considered to occupy a volume of approximately (85 x 100 x 20) cm, or 170,000 cm<sup>3</sup> (0.17 m<sup>3</sup>). The coral specimens used in this estimation belong to the domed, high-density morphotype formed when *L. pertusa* grows as a fouling organism (Gass and Roberts, 2006, 2011). They may therefore not be entirely representative of the more diffusely-branching colony morphs found in some other environmental settings, but in the absence of any other information a mass-volume relationship of 53 kg 0.17 m<sup>-3</sup>, equivalent to 312 kg m<sup>-3</sup>, will be used in the calculations to follow. Note that this figure includes void spaces within and between the coral blocks and does not treat the unit volume as a solid mass of calcium carbonate.



Figure 8: Cleaned and dried blocks of *Lophelia pertusa* used to obtain an estimate for the mass per unit volume of cold-water coral. Plastic ruler = 45 cm.

*Darwin Mounds*: The western group within the Darwin Mounds province contains ~75 mounds, with ~150 mounds in the eastern group (JNCC, 2008). Figure 2 in Masson *et al.* (2003) shows ~100 additional mounds outside the two high-density areas, giving an estimated total of 325 mounds. If mounds are assumed to be approximately circular with a diameter of 75 m, each will occupy ~4420 m<sup>2</sup> of sea floor (ignoring the added contribution due to surface convexity). Coral colonies are patchily distributed across the mound surfaces, with Bett (2001, cited in Masson *et al.*, 2003) giving a figure of one colony per 4 m<sup>2</sup> for a single mound. At this density, a 75 m-diameter mound would support 1105 coral colonies, which is broadly consistent with Masson *et al.*'s description of "...many hundreds to some 1000 colonies". Coral colonies on the Darwin Mounds have been described as "thickets...between one and several metres wide and high" (JNCC, 2008). This indicates considerable variability in size and shape, but for the present purposes, a conservative volume estimate of 1 m<sup>3</sup> per colony will be applied. Using these figures, a rough estimate of the standing stock of coral carbonate and stored carbon in the Darwin Mounds province can be derived as follows:

$$\begin{array}{rclcl}
 (\text{Number of mounds}) \times (\text{Coral colonies mound}^{-1}) & = & \text{Total number of coral colonies} \\
 325 & \times & 1105 & = & 359125
 \end{array}$$

Assuming coral colony volume = 1 m<sup>3</sup>,

$$\begin{array}{rclcl}
 (\text{Total coral colonies}) \times (\text{Coral mass m}^{-3}) & = & \text{Total mass of coral CaCO}_3 \\
 359125 & \times & 312 & = & 112047000 \text{ kg} = 112047 \text{ t CaCO}_3
 \end{array}$$

Carbon = 12% molar mass of CaCO<sub>3</sub>,

$$\text{Standing stock of stored carbon} = 0.12 \times 112047 = 13445.64 \text{ t}$$

There are many simplifying assumptions involved here, but the standing stock of stored carbon in the Darwin Mounds cold-water corals can be tentatively estimated as **~13500 t**.

*Mingulay Reef Complex*: On the Mingulay Reef Complex the crests of five bedrock ridges support a dense cover of *Lophelia pertusa* growing as elevated mounds up to 5 m high and 15 m in diameter (Roberts *et al.*, 2005; Douarin *et al.*, 2013). Unlike the Darwin Mounds, which are composed largely of sand (Masson *et al.*, 2003), the coral mounds off Mingulay are formed by accumulations of coral rubble infilled with sediment and shelly hash (Douarin *et al.*, 2013). The total volume of the Mingulay mounds must therefore be included in estimates of carbonate standing stock. For simplicity of calculation, mounds will be considered to be regular cones of 15 m diameter. A cone of this size will cover a basal area of 176.8 m<sup>2</sup> and have a volume of ~295 m<sup>3</sup>. Scottish Natural Heritage (undated) give a figure of ~5.4 km<sup>2</sup> for the “area considered to qualify as cold-water coral reefs” off Mingulay. It is not entirely clear whether this refers only to the mounded reef growth on the ridge crests, or whether it also includes areas of less dense coral cover on the ridge slopes. For present purposes it will be considered to represent the total area of mounded reef growth on the five coral-covered ridges *Mingulay 1*, *Mingulay 5 North*, *Mingulay 5 South*, *Banana Reef* and *4 Mounds* (Roberts *et al.*, 2009). The five ridges do show some differences in coral coverage (Roberts *et al.*, 2009) but with the information available there is no way to factor this variation into the calculations, and uniform cover will be assumed from here on.

An area of 5.4 km<sup>2</sup> covered by mounds of basal area 176.8 m<sup>2</sup> will contain 30543 individual mounds. At a volume of 295 m<sup>3</sup> mound<sup>-1</sup> this represents a total mound volume of ~9 x 10<sup>6</sup> m<sup>3</sup>. Core samples show that the Mingulay reef mounds have a complex internal stratigraphy (Douarin *et al.*, 2013). Layers rich in large pieces (clasts) of coral rubble are interspersed with layers of finer coral fragments and shelly hash, and layers of sediment containing little or no calcareous material. Translating this information into an estimate of coral content is difficult, but if we assume conservatively that coral accounts for 33% of mound volume, the standing stock of stored carbonate can be calculated as follows:

Assuming coral volume = 33% of mound volume,

$$\text{Total coral volume} = 0.33 \times (9 \times 10^6) = \sim 3 \times 10^6 \text{ m}^3$$

Assuming volume-specific coral mass = 312 kg m<sup>-3</sup>,

$$\text{Total mass of coral carbonate} = 312 \times (3 \times 10^6) = 936 \times 10^6 \text{ kg} = 936,000 \text{ t}$$

Carbon = 12% molar mass of CaCO<sub>3</sub>,

$$\text{Standing stock of stored carbon} = 112,320 \text{ t}$$

The reasoning here again involves a number of simplifying assumptions, and changes to any of the assigned values will affect the final result. For example, if coral is assumed to account for 50% of mound volume rather than 33%, the estimate for standing stock of stored carbon would increase to 168,480 t. Treating the mounds as regular cones is also conservative, as in reality they are likely to be irregular domes (as shown in Figure 9 of Douarin *et al.*, 2013), with correspondingly greater volume per unit basal area than a cone.

Greater accuracy is impossible at this stage, but these simple calculations are sufficient to indicate that the Mingulay Reef Complex is likely to be a much larger repository of stored carbon than the Darwin Mounds, and is conservatively estimated here as **~112,000 t**.

#### 3.4.1.3 Net carbon sequestration capacity

On North Sea oil/gas platforms, *Lophelia pertusa* grows at a rate of ~27 mm yr<sup>-1</sup>, equivalent to the addition of one polyp to a growing branch each year (Gass and Roberts, 2011).

Comparable extension rates have been estimated for *L. pertusa* on Norwegian reefs (data cited in Gass and Roberts, 2006). However, these relatively rapid growth rates may not be typical of colonies growing in deeper, less productive environments (such as the Darwin Mounds). Radiometric dating of samples from Mingulay indicates reef growth rates of up to 12 mm yr<sup>-1</sup>, with a mean rate of 3-4 mm yr<sup>-1</sup> (Douarin *et al.*, 2013). Reef expansion has not been constant throughout the Holocene, with at least two extended periods of reduced growth rates recorded at 1.75-2.8 ka and 3.2-3.6 ka (Douarin *et al.*, 2013).

The mean linear extension rate for mounds given by Douarin *et al.* (2013) can be converted into an area-specific carbonate accretion rate (g CaCO<sub>3</sub> m<sup>-2</sup> yr<sup>-1</sup>) by simple geometry (and the usual simplifying assumptions). Assuming a conical coral-covered mound (diameter 15m, height 5m) adds 3 mm of new coral growth yr<sup>-1</sup> across its entire surface, this represents a volumetric increase from 294.52 m<sup>3</sup> to 294.71 m<sup>3</sup>, a 0.2 m<sup>3</sup> increase equivalent to 62.4 kg CaCO<sub>3</sub>, using the volume-mass relationship for *L. pertusa*. A cone of diameter 15 m and height 5 m has a surface area (excluding the base) of 212.38 m<sup>2</sup>, giving an area-specific accretion rate of ~294 g CaCO<sub>3</sub> m<sup>-2</sup> yr<sup>-1</sup>.

This would represent a net carbon sequestration rate of ~35 g C m<sup>-2</sup> yr<sup>-1</sup>. Gross sequestration must be somewhat higher, as this net figure based on mound growth must incorporate loss of coral carbonate by bioerosion (Beuck and Freiwald, 2005) and chemical dissolution.

Cores from the Darwin Mounds did not contain carbonate mud or concentrated accumulations of dead coral, indicating that coral debris is not a major component of the mound sediment (Masson *et al.*, 2003). The carbon storage capacity of the Darwin Mounds SAC therefore appears to be represented solely by the living coral colonies themselves. In contrast, the coral-topped mounds of the Mingulay Reef Complex have been formed by build-ups of coral rubble infilled with sediment and calcareous debris produced by other organisms (Douarin *et al.*, 2013). The oldest coral fragment so far revealed by radiometric dating, has an age of 7.7 ka, and many dates in the 3-4 ka range have been recorded (Douarin *et al.*, 2013). The Mingulay Reef Complex has therefore been in existence for much of the later Holocene, and has acted as a repository of stored carbon over a timescale of several millennia.

### 3.4.2 Tubeworm (*Serpula vermicularis*) reefs

#### 3.4.2.1 Current extent and distribution

The serpulid polychaete *Serpula vermicularis* is common and widespread in Scottish waters but the formation of reefs composed of masses of aggregated tubes is a very localised phenomenon. Serpulid reefs are currently known to exist only in Loch Creran, Argyll (Moore *et al.*, 1998) and in Loch Teacuis, a small inlet of Loch Sunart on the Morvern Peninsula (Dodd *et al.*, 2009). Reefs were also recorded in the Linne Mhuirich arm of Loch Sween (mid-Argyll) during the 1980s but they have since disappeared from this locality (Hughes *et al.*, 2008).

In Loch Creran, serpulid reefs occur in a narrow depth band (1-13 m) around the periphery of the loch (Moore *et al.*, 1998). Distribution along this band is patchy, with stretches of lower and higher reef density, and local variation in the size distribution of the individual reefs. In the most recent published survey (conducted July 2005) of the status of the biotope in Loch Creran, the total areal extent of the reef band was estimated as 108 ha (1.08 km<sup>2</sup>) (Moore *et al.*, 2009). Percentage cover of serpulid reefs ranged from 4.86-16.88% along four transects surveyed by divers. Applying the mean value from these transects (11.23%) to the total areal extent of the reef band gives an estimate of 0.121 km<sup>2</sup> of Loch Creran's sea bed occupied by serpulid reefs.

The serpulid reefs of Loch Teacuis also occur in a narrow peripheral band, estimated in July 2006 as occupying 0.2 km<sup>2</sup> (Dodd *et al.*, 2009). Sea bed percentage cover within this band was estimated as 4.21%, giving a total serpulid coverage of 0.008 km<sup>2</sup>. When first recorded in 2006, the reefs in Loch Teacuis consisted of small clusters of tubes up to 26 cm in height and 19 cm diameter (Dodd *et al.*, 2009). The reefs were considered to be in an incipient stage of development and might therefore now be more extensive, but there appears to be no more recent published information on their status.

Combining the data from these two sea lochs gives an estimate of 1.28 km<sup>2</sup> for the total extent of the Scottish serpulid reef biotope in 2005-06, of which an estimated 0.129 km<sup>2</sup> represents the total area occupied by the tubeworms themselves.

#### 3.4.2.2 Quantity of carbon currently stored

Serpulid reefs consist of dense, irregularly-shaped masses of intertwined tubes. A wide range of tube sizes can be found within a cluster, formed as successive cohorts of recruits settle on established tubes and grow among them. This complexity effectively rules out calculation of reef mass by simple multiplication of the value for an individual tube. As an alternative approach, dried clusters of *Serpula vermicularis* tubes collected from Loch Creran in previous studies were used to determine the weight of an improvised artificial "reef" of known area. Tube clusters of varying size were placed upright in a rectangular cardboard box of basal area 31 x 22 cm (682 cm<sup>2</sup>) (Figure 9). The total mass of serpulid fragments needed to approximately fill the box was 1953.54 g, a figure that equates to 28644 g m<sup>-2</sup>. The tube clusters used in this estimation were mostly 20-30 cm tall, which is approximately the same as the maximum dimensions recorded for serpulid reefs in Loch Teacuis in 2006 (Dodd *et al.*, 2009). A value of 28644 g CaCO<sub>3</sub> m<sup>-2</sup> may therefore be a reasonable estimate for the standing stock of serpulid tube carbonate in this sea loch.

Serpulid reefs in Loch Creran reach a considerably larger size than those recorded in Loch Teacuis in 2006. Well-formed reefs may reach a height of ~100 cm, although they tend to fragment and collapse above a height of ~60 cm (Moore *et al.*, 2009). To allow for the greater reef height in Loch Creran, a doubling of the experimentally-measured value given above (to 57288 g CaCO<sub>3</sub> m<sup>-2</sup>) gives a conservative estimate for area-specific serpulid carbonate mass.



Figure 9: Improved serpulid “reef” used to estimate area-specific mass of tube material in Lochs Creran and Teacuis. Plastic ruler = 45 cm.

Table 4. The standing stock of carbon stored in serpulid reefs in Lochs Creran and Teacuis can now be estimated as follows:

	Total serpulid reef area (m <sup>2</sup> )	Estimated area-specific serpulid mass (g m <sup>-2</sup> )	CaCO <sub>3</sub> standing stock (t)	Stored carbon standing stock (=12% CaCO <sub>3</sub> ) (t)
Loch Creran	121,000	57288	6931.85	831.82
Loch Teacuis	8000	28644	229.15	27.50
<b>Total</b>				<b>859.32</b>

The methodology used here is heavily reliant on the mass of the improvised serpulid “reef” and on the multiplication factor applied for reef height in Loch Creran. A trebling of the area-specific mass estimate for Loch Creran (if reef height is assumed to be ~60-90 cm rather than the ~40-60 cm used in Table 4) would result in a higher figure of 1247.73 metric tonnes (t) for stored carbon in this sea loch. The much less extensive reefs of Loch Teacuis clearly add only a very small contribution to the total.

Given the approximations and uncertainties involved in generating these figures, an order-of-magnitude estimate for standing stock of stored carbon in Scotland’s tubeworm reefs would be **~1000 t**.

### 3.4.2.3 Net carbon sequestration capacity

In Loch Creran, mean individual tube extension rate was measured as 33 mm yr<sup>-1</sup> (Hughes *et al.*, 2008). For tubes in the size range studied, this corresponds to ~0.56 g CaCO<sub>3</sub> tube<sup>-1</sup> yr<sup>-1</sup> (personal observation, based on tube sections weighed in the laboratory). In theory, this figure could be extrapolated to an area-specific estimate of carbonate production, but this is hard to achieve in practice since the complexity and irregular shape of the reefs makes it difficult to count the number of individual tubes per unit area. Smith *et al.* (2005) estimated carbonate production by the reef-building serpulid *Galeolaria hystrix* in temperate southern New Zealand as ~11 kg CaCO<sub>3</sub> m<sup>-2</sup> yr<sup>-1</sup>. The individual calcification rate for *G. hystrix* of 1.5 g CaCO<sub>3</sub> tube<sup>-1</sup> yr<sup>-1</sup> (Reidi, 2012; Smith *et al.*, 2013) is rather higher than the measured rate for *Serpula vermicularis* in Loch Creran. Assuming similar reef morphology in the two serpulid species, this would suggest a carbonate production rate of ~3.5 kg m<sup>-2</sup> yr<sup>-1</sup> for the Loch Creran reefs, equivalent to ~420 g C m<sup>-2</sup> yr<sup>-1</sup>.

Hughes (2011) found that *Serpula vermicularis* tube clusters experimentally deployed on the Loch Creran sea bed showed very little net weight change over a 5-year period. It was also noted that relict tube debris was still conspicuously present in the surface sediments of Linne Mhuirich, Loch Sween, at least 15 years after the disappearance of living tubeworm reefs in this locality. However, the absence of large-scale accumulations of relict tube material in Loch Creran is evidence that taphonomic processes (chemical dissolution and/or bioerosion) do ultimately lead to the degradation and disappearance of serpulid skeletal carbonate. Chemical dissolution of calcium carbonate is expected to be most rapid in bioturbated terrigenous muds, as typically found in sea lochs (Aller, 1982). The taphonomic sequence for relict carbonates may include an initial phase of net weight increase by encrustation, followed by a longer-term degradation and weight loss as a result of bioerosion and chemical dissolution (Smith and Nelson, 2003). In New Zealand, terrigenous muds surrounding reefs of *Galeolaria hystrix* contained only 2% by weight of skeletal carbonate fragments, while a radiocarbon-dated basal section of the serpulid reef was <50 years old (Smith *et al.*, 2005). Surface-volume ratio of carbonate skeletons is believed to be a key factor determining susceptibility to chemical dissolution (Smith and Nelson, 2003), and for this reason serpulid tubes would be expected to degrade rapidly in chemical environments favouring dissolution.

The evidence from Scotland and New Zealand together suggests that serpulid skeletal carbonate can persist in coastal terrigenous muds for one to several decades, but is unlikely to be preserved over longer periods. Carbon sequestration in these biogenic reefs can therefore be considered to operate over a timescale of <100 years.

### 3.4.3 Flame shell (*Limaria hians*) beds

#### 3.4.3.1 Current extent and distribution

The flame shell *Limaria hians* is an epifaunal bivalve that constructs a “nest” of byssal threads interwoven with shell and algal fragments and partially infilled with trapped sediment (Hall-Spencer and Moore, 2000b). In dense populations these nests can form continuous reef-like structures 10-20 cm thick and several hectares in extent. *Limaria hians* can occur at densities of several hundred individuals m<sup>-2</sup>, with >700 m<sup>-2</sup> recorded from a bed at Creag Gobhainn, Loch Fyne (Hall-Spencer and Moore, 2000b). Historical records are widespread around the western and northern Scottish coasts, particularly on muddy gravels and sands in tidal channels and other areas with moderate-to-strong tidal streams. The species is also often associated with maerl beds (Hall-Spencer and Moore, 2000a). *Limaria hians* is believed to have suffered a severe decline in abundance in Scotland (and elsewhere in the UK) and until very recently few extensive beds were known to exist. However, over the last few years surveys mounted by Scottish Natural Heritage have located (or re-located) several dense populations in west coast sea lochs, with the largest-known covering an estimated 75 ha near Kyle Akin, Loch Alsh (Moore *et al.*, 2013). Moore *et al.* (2013) provide a summary

list of condition measures for Scottish *L. hians* beds. Where data for bed extent and *L. hians* density were included, these have been reproduced in Table 5, along with estimates for total carbonate standing stock for each bed. Two beds in Loch Carron with no data for spatial extent have been excluded from Table 5.

Table 5. Location and extent of known *Limaria hians* beds in Scotland. (Modified from Table 4 in Moore et al., 2013)

Location	Year	Bed extent (with >50% cover) (m <sup>2</sup> )	<i>L. hians</i> density (ind. m <sup>-2</sup> )	Total number of <i>L. hians</i>	Standing stock CaCO <sub>3</sub> (t)
Loch Broom	2010	~70,000	97	679 x 10 <sup>4</sup>	11.54
Loch Alsh	2012	700,000	275	1925 x 10 <sup>5</sup>	327.25
Laudale Narrows, Loch Sunart	2006	200,000 (July 2000 data)	229	458 x 10 <sup>5</sup>	77.86
Port Appin, Loch Linnhe	See below*	~30,000	343	1029 x 10 <sup>4</sup>	17.49
Shian, Loch Creran	2012	140,000	612	8568 x 10 <sup>4</sup>	145.66
Creagan, Loch Creran	2012	1000	31	31,000	0.05
Otter Spit, Loch Fyne	2012	270,000	367	9909 x 10 <sup>4</sup>	168.45
<b>Total</b>		<b>1411 x 10<sup>3</sup></b>			<b>748.30</b>

\*Bed extent for Port Appin was measured in August 2011 (*L. hians* density not recorded). The value for *L. hians* density is the most recent measurement (February 2007).

### 3.4.3.2 Quantity of carbon currently stored

*Limaria hians* has a thin, delicately-ribbed shell up to 4 cm in length (Hall-Spencer and Moore, 2000b). There appears to be no published data for shell weight, and no specimens were available for direct measurement. Baldwin and Lee (1979) stated that the shell accounted for 14.7% of total weight in the Australian *Limaria fragilis* (a species of similar size to *L. hians*), and that wet weight of tissue minus shell was in the range 5-15 g. Using these figures, it is possible to calculate a shell weight of 1.72 g for a *Limaria* individual of 10 g tissue weight, and this value will be used to estimate standing stock of Scottish flame shell beds.

The distribution of nests in a flame shell bed can be extremely patchy, with areas of lower and higher percentage cover (Trigg and Moore, 2009). Moore et al.'s (2013) figures for areas with >50% nest cover are used to represent bed extent. Mollusc shells typically contain 1-5% organic material by weight (Kawaguchi and Watabe, 1993), and 1.7 g is therefore used as the value for carbonate content of a *L. hians* shell.

The summed estimate of 748.3 t CaCO<sub>3</sub> in these seven flame shell beds represents ~90 t of stored carbon. Carbonate fragments incorporated into the byssal nests will make an additional contribution, but even if this equalled the contribution of the flame shells themselves, the overall total would still be very small.

#### 3.4.3.3 Net carbon sequestration capacity

There appear to be no published data on individual growth or settlement rates for *Limaria hians*. As a medium-sized, thin-shelled bivalve, a relatively rapid rate of individual growth might be expected (in comparison with larger, more robustly-shelled bivalves such as *Modiolus modiolus*). Trigg and Moore (2009) reported that nest regrowth over experimentally-cleared areas was slow, averaging ~3.2 cm yr<sup>-1</sup>. Over the experimental timescale, bed expansion was considered to result from the spread of established flame shells from undisturbed areas rather than spatfall and growth of recruits. The slow rate of regrowth highlights the vulnerability of flame shell beds to physical disturbance (e.g. by dredging), which is believed to be the main factor responsible for the decline of the species in UK waters (Hall-Spencer and Moore, 2000a, b).

There are no published data on the taphonomy of *Limaria hians* shells, but given their thin, delicate structure they would not be expected to persist for very long after death. It is therefore likely that flame shell beds will act as a carbon store (on a very modest scale, as estimated above) only when occupied by dense and healthy populations. Destruction or severe disturbance of the bed will probably result in the remobilisation of stored carbon on a timescale of years to decades.

#### 3.4.4 Horse mussel (*Modiolus modiolus*) beds

##### 3.4.4.1 Current extent and distribution

The horse mussel *Modiolus modiolus* is widely distributed in the shallow subtidal around Scotland, particularly on western and northern coasts, including Orkney and Shetland (Mair *et al.* 2000). Many records are of isolated individuals or of sparse, low-density populations, but beds dense enough to be regarded as biogenic reefs are formed in some localities. As with *Limaria hians*, records of horse mussel beds have increased recently as MPA search feature surveys have applied modern habitat mapping methods to poorly-known regions of the Scottish seas. The horse mussel bed off Noss Head, Caithness, is by far the largest currently known from Scottish waters. The Noss Head bed lies at 37-47 m depth with an estimated extent of ~3.85 km<sup>2</sup> (Hirst *et al.*, 2012). Density of living *M. modiolus* within the bed is patchy but the SACFOR category of Superabundant (10-90 individuals m<sup>-2</sup>) was recorded at several stations (Hirst *et al.*, 2012). The mussel bed has an undulating surface similar to that described from a large (3.54 km<sup>2</sup>) bed off Pen Llŷn, North Wales (Lindenbaum *et al.*, 2008).

Table 6 lists the spatial extent and mussel density (where known) of Scottish *Modiolus modiolus* beds, using information from recent Scottish Natural Heritage reports. Recorded beds without extent/density data have been excluded. The data show that with the exception of Noss Head, Scottish horse mussel beds, mostly located in west coast sea lochs, are typically much <1 km<sup>2</sup> in extent. At 3.85 km<sup>2</sup>, the Noss Head bed is ~5 x larger than all other recorded sites combined, and it will therefore be the main focus of the following section.

Table 6. Summary of published spatial extent and mussel density data for Scottish *Modiolus modiolus* beds. Mussel density was not recorded in all cases.

Location	Bed area (km <sup>2</sup> )	Mussel density or % cover	Source
Copinsay, Orkney	0.42		Hirst <i>et al.</i> (2012)
Noss Head, Caithness	3.85	Up to 10-90 m <sup>-2</sup> Surface sediment ~90% dead shell	Hirst <i>et al.</i> (2012)
String Rock, Loch Alsh	0.06	6.83%	Moore <i>et al.</i> (2013)
Kyle Akin, Loch Alsh	0.12		Moore <i>et al.</i> (2013)
An Dunan, Loch Leven	0.004		Moore <i>et al.</i> (2012)
Ballachulish, Loch Leven	0.01		Moore <i>et al.</i> (2012)
Annat Narrows, Loch Linnhe	0.04		Moore <i>et al.</i> (2012)
Port Appin, Loch Linnhe	0.02	Surface sediment ~60% dead shell	Moore <i>et al.</i> (2012)
Creagan Narrows, Loch Creran	Not recorded, but very small	34%	Moore <i>et al.</i> (2006)
Upper Basin, Loch Creran	~0.05	10-20 m <sup>-2</sup>	Mair <i>et al.</i> (2000), Moore <i>et al.</i> (2006)

#### 3.4.4.2 Quantity of carbon currently stored

Density of living horse mussels in the Noss Head bed varied from Frequent (1-9 10 m<sup>-2</sup>) to Superabundant (10-90 m<sup>-2</sup>) (Hirst *et al.*, 2012). Surface sediment was estimated to consist of ~90% dead shell, and still photographs (Figure 18 in Hirst *et al.*, 2012) show an almost complete coverage of the sea floor by shelly material. Noss Head sea bed grab samples were described as “*hard packed shelly sediments*” which were difficult to penetrate. The *Modiolus modiolus* bed off Pen Llŷn, North Wales, covers about the same area as the Noss Head example, and has a characteristic undulating bedform of ridges and troughs which also appear to be present at Noss Head (Lindenbaum *et al.*, 2008; Hirst *et al.*, 2012). At Pen Llŷn, a sea bed of cobble and lag gravel is overlain by shelly reef deposits 0.5-1.0 m deep depending on the amplitude of the surface undulations (Lindenbaum *et al.*, 2008). It is therefore quite possible that comparable accumulations of shelly material may exist off Noss Head.

Collins (1986) studied a horse mussel bed at ~160-190 m depth in the Firth of Lorn (between Mull and Kerrera). *Modiolus modiolus* density was estimated as 125 ind. m<sup>-2</sup>, indicating a dense population. Grab samples gave a standing stock (“calcimass”) attributable to *M. modiolus* of 2219 g CaCO<sub>3</sub> m<sup>-2</sup>. The grabs penetrated to a depth of 5-7 cm, so that this figure represents standing stock in the near-surface layer of the sea bed. Applying Collins’ (1986) figure to Noss Head (area 385 x 10<sup>4</sup> m<sup>2</sup>) gives an estimated standing stock of ~8543 t CaCO<sub>3</sub> in the ~5 cm of superficial sediments, representing ~1025 t stored carbon. If Noss Head supports shelly deposits of similar depth to those at Pen Llŷn (assume mean depth 75 cm), the carbonate standing stock estimate would increase to ~128,145 t, representing ~15377 t stored carbon. In reality these would probably be maximum values, as horse mussel density is not uniform across the extent of the bed, and relict shells will lose mass as a result of chemical dissolution and bioerosion (Akpan and Farrow, 1985; Powell *et al.*, 2006). Nevertheless, Collins’ (1986) data provide an insight into the potential standing stock of stored carbon in the Noss Head horse mussel bed.

### 3.4.4.3 Net carbon sequestration capacity

In the Firth of Lorn, *Modiolus modiolus* accounted for ~94% of carbonate standing stock in the mussel bed community, but only ~38% of the estimated carbonate production (Collins, 1986). Brachiopods, brittlestars and smaller bivalve species accounted for the remaining community production. The very low production/biomass (P/B) ratio of *M. modiolus* (0.05) was attributed to a long lifespan (~40 years) and slow growth rate. Studies in other localities support a lifespan of at least 20-35 years for *M. modiolus* (Comely, 1978; Seed and Brown, 1978; Anwar *et al.*, 1990). Size-frequency distributions in three Scottish west coast populations studied by Mair *et al.* (2000) showed no evidence for recruitment in the preceding 5-10 years. Comely (1978) reported very low recruitment rates in two horse mussel beds at low-energy sites, but a higher frequency of juveniles in more energetic conditions. Overall, *M. modiolus* appears to be a long-lived, relatively slow-growing bivalve with very sporadic recruitment, and in consequence has a low area-specific carbonate production rate, estimated as 330 g CaCO<sub>3</sub> m<sup>-2</sup> yr<sup>-1</sup> in the Firth of Lorn (Collins, 1986), equivalent to ~40 g C m<sup>-2</sup> yr<sup>-1</sup>.

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

### 3.4.5 Subtidal brittlestar beds

#### 3.4.5.1 Current extent and distribution

Dense beds of brittlestars are common in Scottish inshore waters, particularly around the west coast but also including localities in Orkney, Shetland and the North Sea (Hughes, 1998). The main bed-forming species, *Ophiothrix fragilis* and *Ophiocomina nigra*, may occur together or in monospecific aggregations (Aronson, 1989). In a few localities, particularly in Lochs Duich and Alsh, beds are formed by a third species, *Ophiopholis aculeata* (Emu Ltd, 2006). Brittlestar beds have been recorded from many recent surveys in Scottish waters (e.g. Hirst *et al.*, 2012; Moore and Atkinson, 2013; Moore *et al.*, 2013). However, lacking Priority Marine Feature or MPA Search Feature status they are not generally the focus of attention and there are very few measurements of bed extent or density in Scotland. Off Keppel Pier, Great Cumbrae, Aronson (1989) recorded densities of *Ophiocomina nigra* >2000 ind. m<sup>-2</sup>. Similar densities can be found in *Ophiothrix fragilis* beds off southern England (Warner, 1971; Davoult, 1990). In the Dover Strait and eastern English Channel, *O. fragilis* populations have been estimated to cover 600 km<sup>2</sup> and 5400 km<sup>2</sup> respectively (Migné *et al.*, 1998). On this scale, brittlestar beds represent very substantial concentrations of benthic biomass. As echinoderms, brittlestars have an endoskeleton of calcareous plates, and due to their abundance in virtually all benthic environments they may play an important (and largely overlooked) role in the marine carbon cycle (Lebrato *et al.*, 2010).

#### 3.4.5.2 Quantity of carbon currently stored

The lack of information on number and spatial extent of Scottish brittlestar beds means that it is not possible to estimate the size of the habitat or the total quantity of carbon stored. However, published data from the English Channel show the potential scale of carbon storage per unit area and are likely to be broadly applicable to Scotland. A Dover Strait *Ophiothrix fragilis* bed averaged 1229 ind. m<sup>-2</sup> between February 1987 and February 1988 (Migné *et al.*, 1998), representing 555 g CaCO<sub>3</sub> m<sup>-2</sup>, equivalent to 66.2 g C m<sup>-2</sup>. If this density was found across the entire 600 km<sup>2</sup> estimated for the population, this would equate to 39,720 t of carbon stored in the skeletons of living brittlestars.

Offshore, a dense population of the small brittlestar *Ophiocten gracilis* exists on the Hebridean Slope in the depth range around 600-1000 m (Lamont and Gage, 1998). Brittlestar density peaks at depths of 750-860 m, reaching 792 individuals per m<sup>2</sup>. The population occupies a ribbon-like band along the depth contours and appears to extend along the entire Scottish sector of the continental slope from the Barra Fan in the south to north-west of the Isle of Lewis (Hughes, unpublished data). *Ophiocten gracilis* is a small species (adult disc diameter around 5 mm), and carbon content per individual will be very low, but over such a huge stretch of continental slope the collective mass of the population may represent a substantial deep-water carbon store.

#### 3.4.5.3 Net carbon sequestration capacity

Migné *et al.* (1998) estimated a carbonate production rate of the Dover Strait *Ophiothrix fragilis* bed as 682 g m<sup>-2</sup> yr<sup>-1</sup>. This is equivalent to a carbon sequestration rate of ~82 g C m<sup>-2</sup> yr<sup>-1</sup>.

After death, brittlestar skeletons will disaggregate and individual calcareous plates will become incorporated into the bottom sediments (Lebrato *et al.*, 2010). "Echinoderm sands" containing a high proportion of echinoderm skeletal particles, along with fragments of other shell-forming organisms, have been described from the coastal zone of Australia (Brunskill *et al.*, 2002). Brittlestar skeletal fragments will be subject to the same processes of bioerosion and chemical dissolution as carbonates produced by corals, serpulids or bivalves, and the timescale of their persistence in sediments will depend on the local environment and the potential for burial below the Taphonomically Active Zone (Walker and Goldstein, 1999).

#### 3.4.6 Biogenic reef summary

Table 7 summarises the estimated spatial extent, carbon storage and carbon sequestration rate for the different biogenic forms of biogenic reef (and reef-like communities) discussed above.

It can be seen that the fast-growing *Serpula vermicularis* has by far the highest estimated sequestration rate, but owing to the very limited spatial extent of the tubeworm reef habitat the total carbon store is very small. The accumulated rubble of the Mingulay Reef Complex constitutes the largest estimated carbon repository. The Noss Head horse mussel bed may contain a similar quantity of stored carbon to the Darwin Mounds if its shell deposits are equal in depth to those recorded at Pen Llŷn. The extent and density of brittlestar beds are a large unknown quantity in the assessment of benthic carbon storage in Scottish seas.

#### 3.4.7 Threats to biogenic reefs

The main threats to calcifying biogenic reefs in Scotland and elsewhere in the UK and beyond have been extensively reviewed. Threats to cold-water coral (*Lophelia pertusa*)

Table 7. Biogenic reefs in Scottish waters: summary of estimated extent, standing stock and sequestration rate.

	Total extent in Scotland (km <sup>2</sup> )	Estimated standing stock of skeletal carbon (t)	Estimated carbon sequestration rate (g C m <sup>-2</sup> yr <sup>-1</sup> )
<i>Lophelia pertusa</i> reef (Darwin Mounds)	1.44 (mound area)	~13,500	Unknown, but probably lower than Mingulay
<i>Lophelia pertusa</i> reef (Mingulay)	5.40 (biogenic reef area)	~112,000	~35
<i>Serpula vermicularis</i> reefs	1.28 (habitat area) 0.13 (biogenic reef area)	~1000	~420
<i>Limaria hians</i> beds	1.41	~90	Unknown
<i>Modiolus modiolus</i> bed (Noss Head)	3.85	~15,400	~40
Brittlestar beds (shelf seas)	Unknown	Unknown	~82
Total		141,990	

reefs, for example, were summarized by Hall-Spencer and Stehfest (2009). The main threats are from (a) physical damage and loss of reefs mainly caused by mobile fishing gear and to a much lesser extent by diving and recreation, (b) contamination through oil and gas exploration and runoff from land-based activities (nutrients, heavy metals and other hazardous substances), and (c) siltation from dumping of solid waste and dredged material. It has been estimated that 30-50% of the 1500 - 2000km<sup>2</sup> of *Lophelia pertusa* reefs in the Norwegian EEZ, for example, has been damaged by fishing (Hall-Spencer and Stehfest, 2009).

Similar threats to those for cold water corals exist for shallow water reef building species. Physical damage by fishing and other activities are most often cited as threats (see, for example, the assessments produced for the UK Marine SACs project in 1998). Tube worm (*Serpula vermicularis*) reefs in Loch Creran have been threatened by scallop dredging and anchoring and mooring of boats (Moore *et al.*, 1998) but the designation of the loch as a Special Area of Conservation provides a mechanism to protect these structures. Previous discharge of effluent from a local alginate factory may also have negatively impacted the reefs.

Flame shells (*Limaria hians*) are thought to be in decline around the UK (Trigg, 2009), mainly due to scallop dredging (Hall-Spencer and Moore, 2000b). The thin-shelled animal is particularly vulnerable to physical damage and this vulnerability and the potential for impact by dredging activities has led to flame shell beds being identified as a priority habitat for conservation action through its recognition as a Priority Marine Feature and MPA search feature. Horse mussel (*Modiolus modiolus*) beds are similarly sensitive to physical damage, and are therefore also most threatened by the effects of mobile fishing gear (Rees, 2009),

with other effects such as coastal development and discharges thought to be of more minor importance.

Globally, ocean acidification is an important threat to calcifying organisms (Orr *et al.*, 2005), including cold-water corals (Davies *et al.*, 2007). The effects are specific to the particular organisms in question but are often modified by temperature (Kroeker *et al.*, 2013). This threat is much more likely to impact on carbon sequestration by coastal biogenic-reef-building species in the much longer term, by which time other human-induced effects and the policy making framework itself may have changed beyond recognition.

### 3.5 Sediment

Marine sediments, and particularly deep sea sediments, are the primary store of biologically derived carbon (mostly inorganic carbon), while sea loch sediments are an important store for organic carbon from terrestrial sources (Ansell, 1974; Loh *et al.*, 2010). Carbon may be sequestered as precipitated carbonates (PCO) or as particulate organic carbon (POC). These materials accumulate in soft sediments in 'shelf deeps', accumulation basins on the continental shelf and in basins of sea lochs. There tend to be faster sediment accumulation rates nearer to land (e.g. in sea lochs), but areas of these faster rates are limited. It is unclear what processes maintain the accumulation basins on the shelf, or whether any of the rich supply of organic material from phytoplankton in productive shelf waters (see Section 3.6) becomes refractory and remains there. A missing sink that may be important is that of the shelf edge; POC and PCO may be transported in near-bed layers to deep water in the Rockall Trough or Norwegian Trough. Export of dissolved organic carbon (DOC) may occur in slope cascades. We also do not know whether shallow water soft-sediment ecosystems such as saltmarshes and seagrass beds, are permanent accumulation regions. Such regions may be more dynamic, subject to die-back and physical remobilization at intervals of decades or centuries (as in the seagrass dieback of the 20th century).

The following provides a summary narrative and assessment on the distribution of sedimentary carbon (C) repositories, and an estimate of the carbon (organic and inorganic) held in these sediments. The estimates in this report were provided with reference to the British Geological Survey's (BGS) offshore 1:250 000 sediment maps, based on a Folk (1954) sediment classification scheme and derived from grab and geophysical surveys (Figure 10). These data were mostly available as Geographical Information Software (GIS), with additional information also gathered from Marine Science Scotland (MSS) Interactive website and the Joint Nature Conservation Committee (JNCC) UK Seemap website. Detailed information on sediment type and distribution, especially for the west coast of Scotland was collected from NERC's MAREMAP (Marine Environmental Mapping Program) website, also hosted by the BGS. Further information was found in the BGS Offshore Regional Reports; Andrews *et al.* (1990), Pantin and Crosby (1991), Stoker *et al.* (1993), and Fyfe *et al.* (1993), all providing useful overviews on UK EEZ sediment type and distribution.

Although this report will provide an overview of Scotland's sedimentary C-storage, the majority of reliable information is obtained from studies around Scotland's inshore areas, on the continental shelf. Whilst some information is available further offshore from deep-water areas (e.g. Rockall Trough) assessing the C-content in these sediments is very difficult. Also difficult to assess are the offshore, deep water deposits of methane and hydrocarbons which potentially could increase the quantity of carbon considerably.

The fine-grained sediments of Scotland are described, followed by descriptions of carbonate-rich sands and gravels.

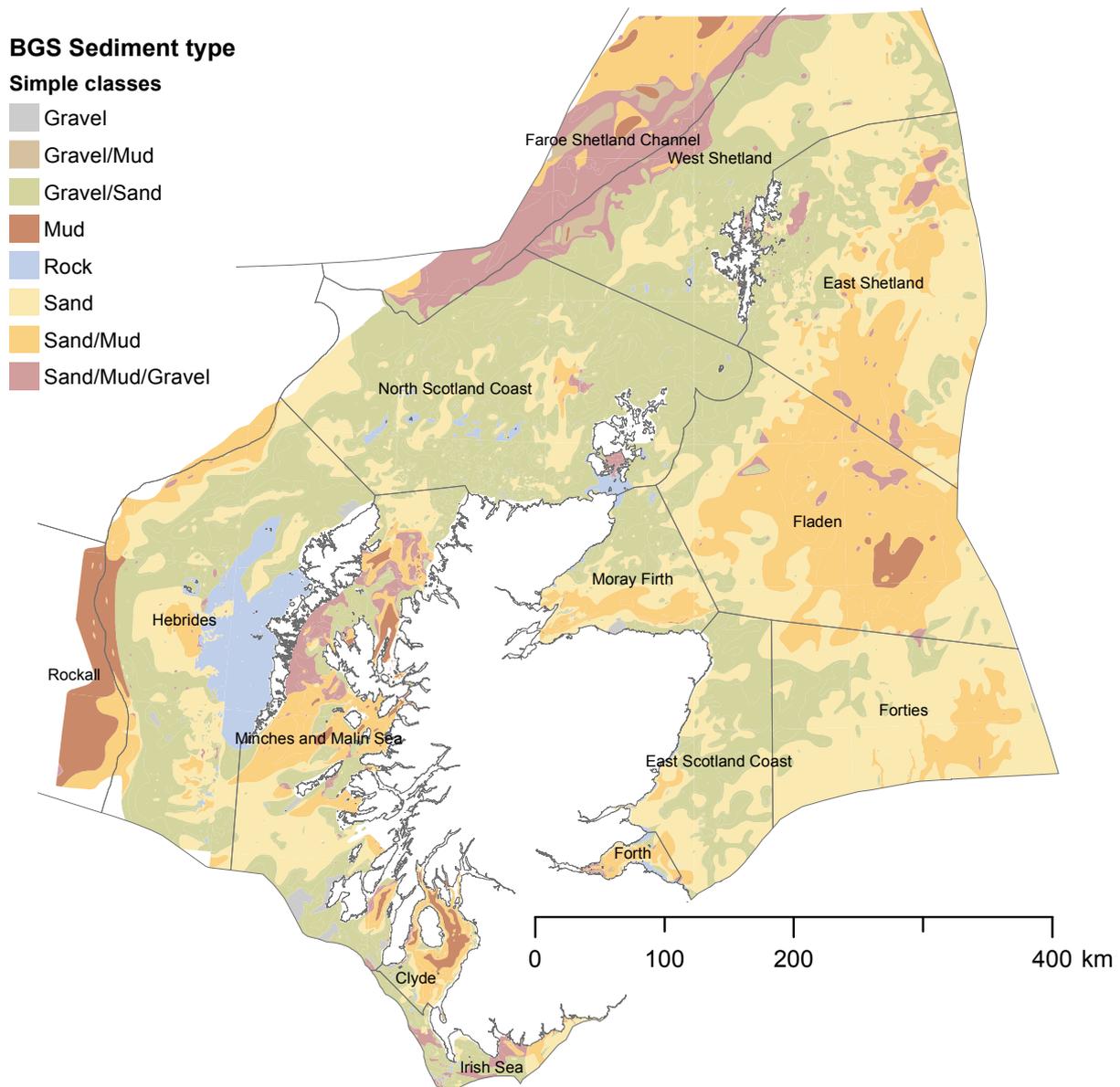


Figure 10: British Geological Survey superficial sediments in Scotland's Marine Atlas regions. Data copyright BGS.

### 3.5.1 Fine-grained sediments (muds, sandy-mud and muddy-sands)

Fine-grained sediments are generally associated with depositional areas, typically deeper-water depressions on the shelf (e.g. glacial incisions of western Scotland and the North Sea depressions) or inshore (e.g. sea lochs of western Scotland). Around Scotland generally, these sediments tend to dominate the western coast and margin, the naturally indented fjordic coastline and highly variable bathymetry further offshore producing traps for these sediments. The origin of the muds and sandy-muds varies from near shore estuarine transport, driven by riverine input and direct terrestrial run-off to reworking of glacial and post-glacial sediments. Sediment thickness is also highly variable depending on location, from <10m across some of the bathymetric highs to >100m in the depositional basins. Sedimentation rates in the inshore sea lochs can be as high as  $0.06 \text{ g cm}^{-3} \text{ yr}^{-1}$  (Howe *et al.*, 2002; Loh *et al.*, 2010). Offshore muds accumulate more slowly, being in an open more dynamic environment where the mobility of sediment is higher, driven by currents on the continental shelf.

Table 8. Sediment distribution and extent (derived from BGS GIS database, showing parts of Marine Atlas regions not covered by BGS data). Values given show areas in km<sup>2</sup>.

Region	Coarse sediment			Fine sediment					BGS area	Unmapped Sand/Mud	Total Area
	Rock	Gravel	Gravel/Mud	Gravel/Sand	Sand	Sand/Mud	Sand/Mud/Gravel	Mud			
Irish Sea	36	16	0	1652	536	288	656	0	3184	736	3920
Clyde Minches and Malin Sea	8	44	4	640	524	1368	80	708	3376	712	4088
Hebrides	56	684	32	7928	5784	6316	2896	872	24568	5460	30028
Rockall	6856	208	36	18316	9320	3552	192	1096	39576	1663	41239
North Scotland Coast	0	0	0	0	20	1216	36	4052	5324	60490	65814
Faroe Shetland Channel	932	168	0	34104	6860	404	816	0	43284	2763	46047
West Shetland	0	0	1236	564	0	5536	9556	768	17660	25036	42696
Bailey	92	44	568	17332	10424	304	3364	44	32172	2618	34790
East Shetland	0	0	0	0	0	864	0	0	864	74056	74920
Fladen	0	24	0	9860	16696	9696	1392	0	37668	287	37955
Moray Firth	0	0	0	4324	10788	20080	804	1148	37144	24	37168
East Scotland Coast	196	128	4	4124	3060	2196	12	16	9736	391	10127
Forth	108	16	4	8492	5532	508	16	0	14676	294	14970
Forties	160	4	32	116	236	756	72	0	1376	151	1527
Grand Total	0	0	0	4300	15960	4184	56	0	24500	168	24668
	<b>8444</b>	1336	1916	111752	85740	57268	19948	8704	295108	174852	469960
		<b>Coarse total:</b>		<b>115004</b>	<b>Fine total:</b>		<b>171660</b>				

An early study by Farrow and Fyfe (1988) suggests carbonate content in fine-grained sediments of the Clyde, Sea of the Hebrides and the Minch as >20% (from Fyfe *et al.*, 1993). Pantin and Crosby (1991) provide a useful summary of these regions; suggesting that most of these areas are dominated by muds with muddy-sand and sandy-mud. Fine-grained sediments are mostly confined to the deeper regions of the Sea of the Hebrides (e.g. Muck Deep & Inner Sound of Raasay). Most carbonate content in these muds is the result of mechanical breakdown of benthic organisms, either by physical erosion (maceration of foraminifera) or by bioerosion (boring by animals). The greatest contribution of carbonate in the muds is through maceration of foraminifera, this being confined to the deeper water regions of the shelf, whilst inshore the process is dominated by bioerosion. These processes lead to two zones of carbonate mud, one inshore and one offshore. In the North Sea this distribution is not so clear, with carbonate-rich muds being more associated with regions of active pockmarks, focused depressions of hydrocarbon seepage from the sea floor.

**Table 9. Studies of the characteristics of organic carbon in sediment in northern European seas, including percentage by weight and rates of burial.**

Study	Type	Location	Sediment type	Solid phase C <sub>org</sub> (%)	Depth range (m)	Sediment accumulation rates (cm yr <sup>-1</sup> )	Burial rates (g C <sub>org</sub> m <sup>-2</sup> yr <sup>-1</sup> )	Average burial rate (g C <sub>org</sub> m <sup>-2</sup> yr <sup>-1</sup> )	SD
Stahl <i>et al.</i> (2004b)	Shelf	Skagerrak / Kattegat	Sandy mud/mud	2-4% (0-10cm) 1-2% (>10cm)	112-562	0.12-0.63	26.3-119.7	53.6	36.6
de Haas & van Weering (1997)	Shelf	Skagerrak / northern Kattegat	Sandy mud	1.5-3.3% (0-10cm) 1.8% (>10cm)	100-500		35		
Van Weering <i>et al.</i> (1987)	Shelf	Skagerrak	Silty clay/sand	1.5-2.5% (>10cm)	47-677	0.12-0.4	2.8-65.6	29.3	27.0
Meyenburg & Liebezeit (1993)	Shelf	Skagerrak	Sandy mud		100-500		45		
Anton <i>et al.</i> (1993)	Shelf	Skagerrak	Mud	8% (surface) 2% (at depth)	100-500	0.38-0.93	31-150	77.3	52.6
Jørgensen <i>et al.</i> (1990)	Shelf	Skagerrak	Mud		500		130		
de Haas <i>et al.</i> (1997)	Shelf	North Sea	Sand	0.02-1.88% (0-10cm) 0.05-1% (>10cm)	<200m	0.05-0.35	0.2		
Loh <i>et al.</i> (2010)	Fjord	Loch Creran	Mud	1.1-4.8% (surface sediments)	<50m	0.2-0.5	91.3		
Overnell and Young (1995)	Fjord	Loch Linnhe	Mud		110-120m	0.5-2.7	146		
St-Onge and Hillaire-Marcel (2001)	Fjord	Saguenay Fjord Quebec	Mud	2% (surface) 1% at depth	85-242	0.2-1.5	18.7-291.6	92.4	133
Glud <i>et al.</i> (2000)	Fjord	Young Sound, Greenland	n/a	1.2-1.4% (0-10cm)	36-163	0.14-0.23	11.6-25.3	18.5	9.7
Glud <i>et al.</i> (1998)	Shelf	Malangen, Noway	silt, cohesive, stones	0.6%	329		7.0		
Glud <i>et al.</i> (1998)	Fjord	Svalbard	silt, cohesive, stones	1.5-2.4% (>10cm)			33.8-70.6	43.2	18.3
Van Weering <i>et al.</i> (1998)	Slope	Goban Spur	n/a	0.15-0.65% (0-10cm) 0.15-0.55% (>10cm)	200-4500		0.03-0.16	0.09	0.03
Stahl <i>et al.</i> (2004a)	Abyssal	Porcupine Abyssal Plain	Mud/silt	0.25% (>10cm)	4800	0.0061			
Turley and Dixon (2002)	Deep	Rockall Trough/ Basin	n/a	0.22-0.61% (>10cm)	1100-3580				
Mitchell <i>et al.</i> (1997)	Slope	Hebridean Shelf edge	n/a	0.2-0.7% (>10cm)	700-2000				
Thomson <i>et al.</i> (2006)	Deep	Rockall trough	n/a		1100-2500	0.004 - 0.023			
Thomson <i>et al.</i> (2006)	Abyssal	Abyssal Plain south			3300-4500	0.003 - 0.007			

### 3.5.1.1 Organic carbon: stores and rates of deposition

Sediment accumulation rates give the rate of incorporation of organic carbon into sediment, and the quantity of organic carbon gives the standing stock. A review of such rates in northern Europe (Table 9) shows that the burial rates for organic carbon are strongly dependent on sediment type. Summarising these rates by sediment types gives rates for calculating sequestration capacity across Scotland's Marine Atlas areas (Table 10). Burial rates for organic carbon into coarse sediment are considered to be negligible. These rates and organic carbon content values were combined with estimates of extent for each sediment type (Table 8) to give sequestration capacity and standing stocks (summarised in Table 15, p53).

Scotland's sea lochs have a total area of 847km<sup>2</sup> below 10m depth. Assuming that the sea bed in these lochs comprises entirely mud, this gives a **standing stock of organic carbon in the top 10cm of sea loch sediment of 338 000 tC or 0.34 MtC, and a sequestration capacity of sea lochs of 0.18 MtC/yr.**

Total **standing stock of organic carbon in Scotland's marine sediments was estimated as 18.1 MtC**, and total **sequestration capacity of Scottish seas as 7.2 MtC/yr**. Patterns of standing stocks and sequestration capacity of organic carbon follow the distribution of mud and mud-sand-gravel combinations. Most organic carbon and the largest capacity for sequestration of organic carbon appears to be in deep mud off the continental shelf.

*Table 10. Burial rates, percentage organic carbon and organic carbon content of sediments summarised from reviewed literature values.*

Sediment type	Burial rates (g org C m <sup>-2</sup> yr <sup>-1</sup> )			wt % organic C (0-10cm)		Organic C content (kg C/m <sup>3</sup> )		
	Average	Min	Max	low	high	low	high	
Shelf	Rock	0.0	0.0	0.0	0	0	0	0
	Gravel	0.0	0.0	0.0	0	0	0	0
	Gravel/ Mud	7.0	7.0	0.0	1.5	4	39	104
	Gravel/ Sand	0.1	0.1	0.2	0	0	0	0
	Sand	0.2	0.1	0.3	0.02	0.1	0.52	2.6
	Sand/ Mud	50.6	46.0	150.0	1.5	4	39	104
	Sand/ Mud/ Gravel	7.0	7.0	0.0	0.0	0.0	0	0
	Mud	155.2	18.7	291.6	1.5	8	39	208
Fjord	All	155.15	18.70	291.60	1.55	4.80	40.3	124.8
Slope	Unmapped Sand/ Mud	0.13	0.03	0.24	0.15	0.68	3.9	17.8

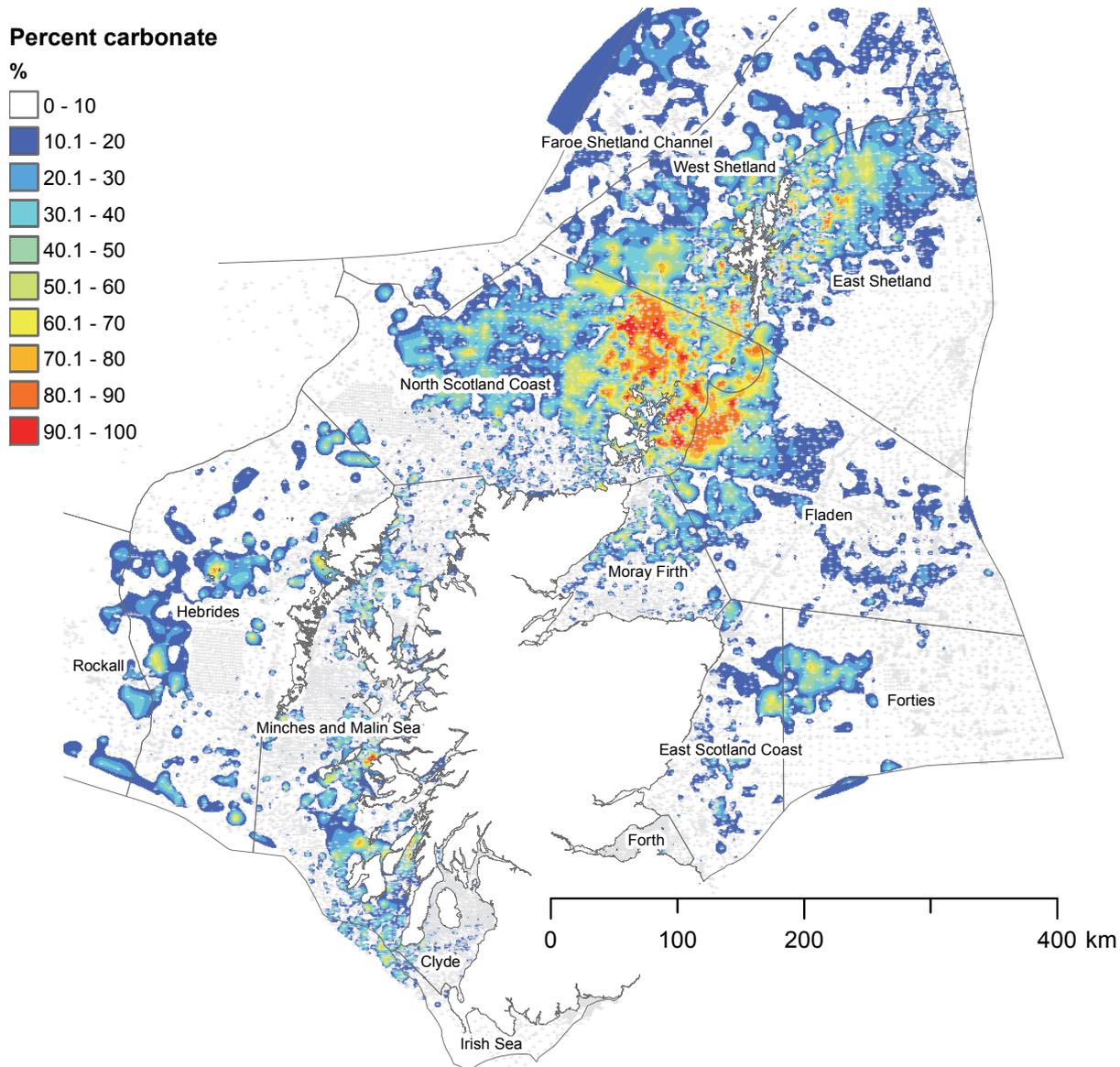
### 3.5.2 Coarse-grained sediments (sands and gravels)

Sediments around Scotland can be described as being relict, representing deposition in a different environment from the present-day. The origin of the majority of coarser-grained sediments in Scotland's seas is highly variable, most being reworked from older glacial deposits, but also seeing contributions from physically eroding bedrock. Around Scotland this contribution can be from a vast range of igneous, metamorphic and sedimentary rocks. Hence the composition of the offshore sand and gravel to some extent reflects this diversity of origin and processes. Scotland's offshore sands and gravel are different to the rest of the

UK in that the biogenic carbonate content is higher. In particular regions of the Malin Shelf, Inner Hebrides, Hebridean Shelf, Orkney, Shetland and Moray Firth contain biogenic carbonate sands consisting of mollusc, echinoderm, worm tube and foraminifera debris (Pantin and Crosby, 1991). The source of this biogenic carbonate appears to be predominantly local, since the composition of shell fragments reflects the local community of shell-building organisms (Wilson, 1979). Carbonate-rich sands around rocky areas comprise rock-dwelling species such as barnacles, while sands further away are dominated by soft-sediment benthos such as bivalves and the sediment-living serpulid worm *Ditrupa* sp. (Wilson, 1979). Radiocarbon aging of the shell material gives an average age of 2000-3000BP (Wilson, 1979). BGS sediment samples, taken using surface sediment grabs since the early 1970s and analysed for carbonate content, show that the surface sandy sediments around Scotland comprises 30-90% carbonate (Figure 11). The region between Orkney and Shetland is especially rich in carbonate sand, reflecting the presence of active Holocene-age sand waves and sand banks in the area. Andrews *et al.* (1990), Fyfe *et al.* (1993) and Stoker *et al.* (1993) discuss the economic potential for extraction suggesting uses for fertiliser and cement industries and summarise the deposits around Scotland.

The gridded map of percentage carbonate in sediments allows a breakdown of percentage carbonate by sediment types and among Scotland's Marine Atlas regions (*Table 11*). Combining these percentages of carbonate with the areal extent of sediment types in each region allows an estimate of the standing stock of carbon stored as biogenic carbonate in each sediment type and region. If only the top 10cm of sediment are considered, as measured in the BGS sediment samples, multiplying the average percentage carbonate by the area of each sediment-type/region parcel (km<sup>2</sup>) and depth (0.1m) gives an approximate volume of sediment biogenic carbonate for Scotland's waters. The density of calcite is around 2800kg/m<sup>3</sup>, of which 12% is carbon. Further multiplying the total volume of carbonate by density and percentage carbon in calcite gives an estimate of carbon mass as standing stock.

<p>The standing stock of carbon as biogenic carbonate in sediment around Scotland is estimated as <b>1739 Mt</b> (1285 Mt in BGS mapped area in Table 12 plus 472 Mt on unmapped offshore sediments). <b>46%</b> of this is in <b>gravel/sand deposits</b> in mapped areas, with 26% of these deposits in the North Scotland Coast region.</p>
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*Figure 11: Percentage carbonate in the top 10cm of superficial sediments, interpolated from BGS sediment records (locations shown as grey crosses). Values were interpolated onto a 2-km grid using distance-weighted averaging of nearest neighbours, to a maximum radius of 32km.*

Table 11. Percentage carbonate in the top 10cm of superficial sediments from BGS core data. Values shown average percentages by region and sediment type. Areas beyond the BGS mapped area are excluded, but are assumed to have a percentage carbonate corresponding to the area-weighted average value for sand/mud on the shelf (8.0%).

Region	Coarse sediment			Fine sediment				Average	
	Rock	Gravel	Gravel/ Mud	Gravel/ Sand	Sand	Sand/ Mud	Sand/ Mud/ Gravel		
Irish Sea	1.0	0.0		2.4	0.6	0.1	0.1	0.7	
Clyde	6.0	27.2	0.0	15.8	5.2	5.7	13.2	8.1	10.1
Minches and Malin Sea	3.6	6.8	27.4	16.3	9.6	8.6	8.8	10.7	11.5
Hebrides	6.1	1.1	10.1	8.8	6.7	3.0	10.0	8.4	6.8
Rockall					14.2	14.0	6.9	6.8	10.5
North Scotland Coast	11.1	20.1		29.1	17.5	50.4	17.7		<b>24.3</b>
Faroe Shetland Channel			7.1	6.0		10.9	6.3	8.0	7.7
West Shetland	34.1	16.6	10.9	21.7	12.6	12.4	8.7	13.7	16.3
Bailey						0.2			0.2
East Shetland		22.9		25.1	8.7	7.1	11.9		15.1
Fladen				38.3	8.8	9.5	9.7	5.9	14.4
Moray Firth	8.7	3.4	17.6	18.1	9.0	5.2	19.3	5.8	10.9
East Scotland Coast	2.9	0.8	1.2	12.0	4.0	3.6	2.8		3.9
Forth	4.7	2.2	9.9	3.4	2.7	1.8	4.1		4.1
Forties				18.3	2.9	2.9	3.8		7.0
<b>Average value</b>	<b>8.7</b>	<b>10.1</b>	<b>10.5</b>	<b>16.6</b>	<b>7.9</b>	<b>9.0</b>	<b>8.8</b>	<b>8.4</b>	<b>10.1</b>

Table 12. Carbon content of carbonate resources in the top 10cm of superficial sediments, estimated from the proportion of carbonate in sediments, assuming a density of carbonate material of 2800kg/m<sup>3</sup> and a stoichiometric estimate of the proportion of carbon in calcium carbonate of 12% by weight. Values shown are Mt (millions of metric tonnes). Areas beyond the BGS mapped area are excluded, but given a percentage carbonate similar to the average value for sand/mud on the shelf (8.0%), would comprise 472 Mt C as carbonate in the top 10cm.

Region	Coarse sediment				Fine sediment				Grand Total
	Rock	Gravel	Gravel/ Mud	Gravel/ Sand	Sand	Sand/ Mud	Sand/ Mud/ Gravel	Mud	
Irish Sea	0	0	0	1	0	0	0	0	1
Clyde	0	0	0	3	1	3	0	2	9
Minches and Malin Sea	0	2	0	43	19	18	9	3	94
Hebrides	14	0	0	54	21	4	1	3	97
Rockall	0	0	0	0	0	6	0	9	15
North Scotland Coast	3	1	0	333	40	7	5	0	389
Faroe Shetland Channel	0	0	3	1	0	20	20	2	46
West Shetland	1	0	2	126	44	1	10	0	184
Bailey	0	0	0	0	0	0	0	0	0
East Shetland	0	0	0	83	49	23	6	0	161
Fladen	0	0	0	56	32	64	3	2	157
Moray Firth	1	0	0	25	9	4	0	0	39
East Scotland Coast	0	0	0	34	7	1	0	0	42
Forth	0	0	0	0	0	0	0	0	0
Forties	0	0	0	26	16	4	0	0	46
Grand Total	19	3	5	785	238	155	54	21	1280
	19	Coarse total:		793	Fine sediment total:			468	

### 3.5.2.1 Sequestration rate of sediment biogenic carbonate

The rate of sequestration of carbon as sediment biogenic carbonate can be estimated from the rate of accumulation of sediments in the major deposits to the north-east of the Scottish mainland between Orkney and Shetland. Andrews *et al.* (1990) describe sediment accumulation rates of the carbonate sands around Orkney and the Pentland Firth as between 123-581 g m<sup>-2</sup> yr<sup>-1</sup>, the higher value being from the highly mobile sand wave zone of the Sandy Riddle, east of the Pentland Firth.

Assuming that 80% of this deposited material is calcium carbonate, as suggested by the local percentage carbonate in sediments (Figure 11), then multiplying sediment accumulation rate by percentage carbon in calcium carbonate (12%) and percentage carbonate in sediment (80%) gives sequestration rates of **11.8 gC/m<sup>2</sup>/yr** for the lower accumulation rate (123 g/m<sup>2</sup>/yr) and **55.8 gC/m<sup>2</sup>/yr** for the higher rate (581 g/m<sup>2</sup>/yr).

Applying these rates across the entire Scotland region is problematic, since most of the shell material in the carbonate-rich areas appears to reflect the local fauna (Wilson 1979) and not to have been transported in from other areas. The fate of shell material in other sediment types is not known, but since finer sediments support a rich community of benthic organisms it would seem reasonable to infer that similar amounts of shell material are produced elsewhere. In the areas of fast tidal flow the smaller sediment particles are winnowed away, leaving only the denser, larger fragments of shell, while shell material may be buried in finer sediments in areas of slower flows.

The highest area-integrated sequestration rates result from the assumption that the above area-specific rates apply to all sediment types across the whole region. This is probably unrealistic. A better estimate may be obtained by weighting these sequestration rates by the percentage carbonate in sediments (Figure 11). This gives total amounts of 0.45 to 2.13 Mt C/yr over the BGS mapped area.

Assuming that the percentage carbonate in sediments is the same in the larger Scotland's Marine Atlas area as in the BGS-mapped area (13%), this approach gives estimates of **0.72 to 3.40 Mt C/yr** for carbon sequestered as biogenic carbonate in sediments (Table 13). There is a considerable range of uncertainty in these estimates, but measurement of sediment accumulation rates across a larger region would reduce this uncertainty.

Table 13. Estimated area-integrated rates of sequestration of carbon into sediment biogenic carbonate.

		Sediment accumulation rate gC/m <sup>2</sup> /yr	low <sup>1</sup>	high <sup>2</sup>
		Area	11.8	55.8
		km <sup>2</sup>	Mt C/yr	Mt C/yr
BGS mapped	All sediments	295108	<b>3.48*</b>	<b>16.46*</b>
	Weighted by percentage carbonate	38252	<b>0.45</b>	<b>2.13</b>
Total Area	All sediments	469960	<b>5.55*</b>	<b>26.21*</b>
	Extrapolated from percentage carbonate in BGS mapped area	13%	<b>0.72</b>	<b>3.40</b>

Notes: based on low<sup>1</sup> accumulation rates of 123 g/m<sup>2</sup>/yr and high<sup>2</sup> rates of 581 g/m<sup>2</sup>/yr given by Andrews *et al.* (1990). \* total if all sediment deposited were 80% carbonate.

### 3.5.3 Threats to carbon stores in sediment

Scotland's long-term sediment stores of carbon have accumulated as sediments that have been deposited over the recent geological past. Threats to these stores can be considered in terms of the likelihood that carbon within the stores is released. Given the depth of sediment, the prospect of remobilisation of deeply buried carbon stores seems remote. Ocean acidification may increase dissolution of carbonate from sediments (Doney *et al.*, 2009), but is also likely to impact upon the rate at which carbon is added to sediment as organic material (see section 3.6.6) or as inorganic carbon, as carbonate skeletal material. However, elevated pCO<sub>2</sub> does not have a simple negative effect on the calcification rate of

coccolithophores, for example (Doney *et al.*, 2009). Some studies report increased rates of calcification at higher pCO<sub>2</sub>, some report no change, while others show a decrease calcification at CO<sub>2</sub> levels above present day. Counter-intuitively, increased dissolution of carbonate store in the ocean will actually increase the capacity of the ocean to absorb atmospheric CO<sub>2</sub>. Doney *et al.* (2009) state: “Because ocean acidification is expected to decrease CaCO<sub>3</sub> saturation states and increase dissolution rates, ocean alkalinity and the ocean’s capacity to take up more CO<sub>2</sub> from the atmosphere will presumably increase. If all carbonate production were shut down by ocean acidification, the atmospheric CO<sub>2</sub> would decline by approximately 10–20 ppmv. In the near-term this may be observed first in coastal regions where coral reef calcification rates could decrease by as much as 40% by the end of this century. However, over the same timeframe, the uptake rate of anthropogenic carbon dioxide from the atmosphere could completely overwhelm these natural buffering mechanisms so the ocean’s efficiency for taking up carbon will probably decline with time over the next two centuries.”

The global scale of the ocean acidification problem sets the scale on which effective action must be taken to mitigate such effects.

### **3.6 Phytoplankton: Carbon Fixation and Sedimentation in the Pelagic Zone of Scottish Seas**

#### *3.6.1 Introduction*

Two main pelagic biogeochemical processes (Figure 12) contribute to sinks of carbon in Scottish seas. (1) Photosynthetic micro-organisms (algae and cyanobacteria) convert dissolved inorganic into organic forms of carbon. Much of this organic matter is recycled in the upper waters of the sea, but some particulate organic carbon (POC) sinks into deeper water or onto the sea bed. (2) Some plankters armour themselves with calcareous scales or shells, which subsequently sink: this is particulate inorganic carbon (PIC). Sinking material that reaches the sea bed on the continental shelf is withdrawn from the atmosphere-ocean carbon cycle only if it is permanently incorporated into the sediment. Material sinking into the permanent thermocline of the ocean, however, is effectively sequestered for hundreds of years. The aim of this section is to provide estimates of POC and PIC sinking into either the permanent thermocline in oceanic regions, or into the bottom boundary layer (BBL) in waters on the continental shelf. The glossary (Annex F) explains technical terms used here.

#### *3.6.2 Methods*

There are many methods for estimating marine pelagic primary production (Holligan, 1989; Williams *et al.*, 2008). They can be loosely characterized as (i) measuring changes associated with small amounts of phytoplankton incubated in bottles; (ii) budgets calculated from changes observed in larger volumes of water; (iii) calculation methods using *in situ* observed or remotely sensed phytoplankton biomass and light; and (iv) mechanistic models. Annex B discusses these methods in relation to the range of annual productions that have been estimated for the northern North Sea. For present purposes results have been taken from two ‘microplankton’ models (Lee *et al.*, 2002; Proctor *et al.*, 2003; Tett and Lee, 2005), in some cases correcting them for the amount of production-limiting nutrient available. Annex C gives details. Measurements of particulate sedimentation are unreliable on the continental shelf, but results are available from sediment traps moored in the more tranquil waters of the permanent thermocline in the Rockall Trough during the NERC ‘Shelf-Edge-Study’ in 1995-6 (Perez-Castillo, 1999; Annex D). The trap data included some information about sinking PIC, which have been supplemented by theory and by model results (Annex E).

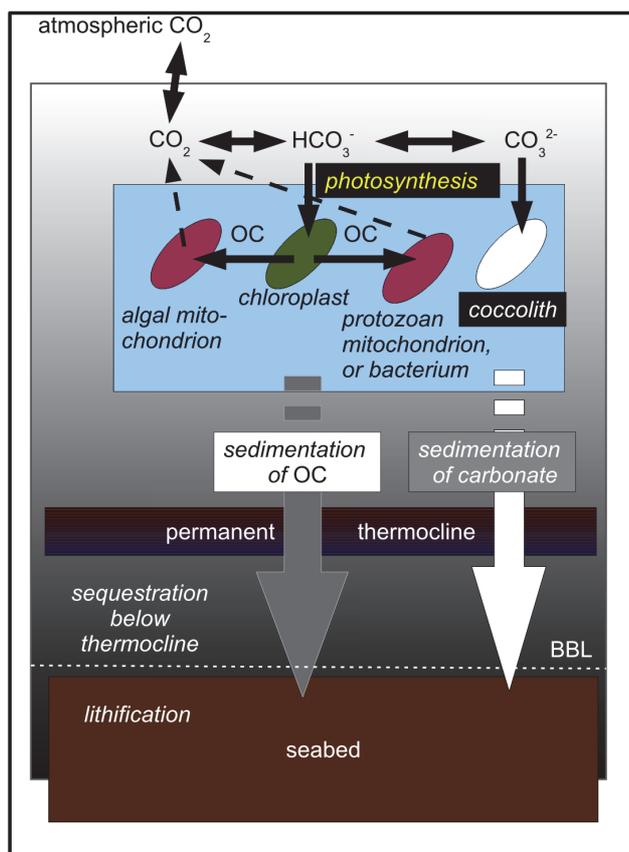


Figure 12. Main processes relevant to the sinking of particulate carbon

### 3.6.3 Scottish sea-areas

Scotland's Marine Atlas ((Baxter *et al.*, 2011)) divides Scottish salt waters into 15 sea-areas, as listed in Table 14. Of these regions, three are oceanic in nature, encompassing waters in the Rockall Trough and Faroes-Shetland Channel, lying beyond the edge of the Scottish continental shelf and overlying sea beds at depths of up to 2 km. In these waters a mixed surface layer extends in winter to depths of a few hundred metres; below this lies a permanent thermocline. A seasonal thermocline forms, nearer the sea surface, during spring of each year. Any particulate carbon sinking into the permanent thermocline may be considered sequestered in the medium term (i.e. on a century time-scale), even if the fraction subject to lithification, and hence near-permanent removal from the atmosphere-ocean carbon cycle, is small.

Another eight regions overlie the continental shelf, with sea beds at depths to about 120 metres; the offshore waters develop a seasonal thermocline, but waters closer to shore may be mixed throughout the year by tidal streams.

The remaining four regions are partly enclosed by land: the Solway Firth, the Clyde Sea, the Minches, and the Forth, and are all impacted by freshwater runoff [and in some cases the nutrients this contains]. The Clyde and the Minches have thermohaline stratification during much of the year; the others are shallow, estuarine and turbid in their inner parts, and include 'Regions of Freshwater Influence' (ROFI, see (Simpson, 1997)). Such regions, alternating mixed conditions with stratification on timescales of a few days or weeks, are liable to primary production enhanced by anthropogenic nutrients in the freshwater.

Included in the Clyde, Minches and North Scotland areas are the fjordic sea lochs of the highland coast and the islands; in Shetland similar inlets are called voes, although many of these lack inlet sills and hence are not fjords.

The fjordic inlets in particular are likely to be basins that accumulate organic carbon, but rates are probably best estimated directly (i.e. by rates of sediment accumulation and measurements of its POC and dissolved inorganic carbon (DIC) content) rather than by methods used here. Most other coastal waters are tidally stirred and hence not environments in which particulate carbon can accumulate; furthermore, seaweeds compete with pelagic micro-algae for nutrients in these regions. Thus, the estimates in Table 14, discounts production and sedimentation inshore of the 40 m sea bed depth contour. So far as sea-areas on the continental shelf are concerned, the estimates in this section consider fluxes into the bottom boundary layer, which are stirred mainly by tidal flows. Other sections (organic carbon in section 3.5.1.1, inorganic carbon in section 3.5.2.1) consider what fraction of these fluxes is converted into POC stored in the sediments. However, it is likely that the outer regions of the Scottish continental shelf export POC over the edge of the shelf, and hence to carbon sinks in ocean waters. Estimates of this flux are provided by a model (Proctor *et al.*, 2003).

#### 3.6.4 Estimates of carbon fluxes

In the best-fit simulation with PROWQM, 'Net Microplankton Production' (NMP) was  $77 \text{ g C m}^{-2} \text{ yr}^{-1}$  at  $59^\circ\text{N } 1^\circ\text{E}$  (northern North Sea, 210km due east of Orkney). As explained in Annex B, NMP is less than 'net primary production', because it takes account of consumption within the euphotic zone by pelagic micro-heterotrophs, and is intended as a measure of organic matter available for export from this zone. Some of the exportable POC is consumed by zooplankters, although a part of what is eaten is defaecated. This part joins sinking live and dead microplankters, and the total flux into the bottom boundary layer was estimated to be up to  $50 \text{ g C m}^{-2} \text{ yr}^{-1}$ . However, much of this is likely to be mineralized through biological activity either in this part of the water column, or by the micro- and macro-benthos. The part most likely to be available for longer term export is that associated with rapid intense settlement of the spring bloom (in part associated with aggregation of diatoms cells and chains). The PROWQM model simulations show that this pulse of about  $10 \text{ g C m}^{-2}$ , remains within the benthic boundary layer (BBL) for at least 100 days, and observations during the SES project, both on and off the shelf, showed large amounts of phytodetrital 'fluff' on the sea bed towards the end of the bloom period. For purposes of further calculation, this flux is taken as 10% of annual NMP.

The PROWQM simulation (described in more detail in Annex C) was initialized with  $10 \mu\text{M}$  DIN. In Table 14, the values for NMP and sedimenting POC have, in on-shelf sea-areas, been adjusted by the ratio of observed winter maximum DIN to this  $10\mu\text{M}$ . on the grounds that exportable production is likely to be N-limited in these waters.

Observations in the northern North Sea during the PROVESS project ((Jago *et al.* 2002)) suggest that very little of this sedimenting material is retained within the sediments, but is continuously reworked by resuspension during spring tides; that which is not locally remineralized may be transported in near-bed flows to the shelf edge or into the Norwegian trough. There seems to be no reliable estimate of such transport within Scottish waters of the North Sea. On the west coast, it is possible that POC collects in some of the depressions and glacially-dredged deeps on the continental shelf. Estimates of such sequestration will need measurements of sediment accumulation rates, and percentage organic content, in these basins.

Proctor *et al.* (2003) used a microplankton-detritus model to simulate POC flux across the shelf break of the outer Malin Sea (i.e. into the Rockall sea-area); at 300 m depth on the

continental slope, the annual amount was 480 kg C for each linear metre of the shelf edge, or 480 Kt C yr<sup>-1</sup> over the roughly 1000 km of shelf edge.

During the SES project, in 1995-1996, a pair of sediment traps were maintained at station N1500 in the Rockall trough (Perez-Castillo, 1999; Annex C). The trap at 1000 m depth below the sea-surface (and 480 m above the sea bed) lay within the permanent thermocline and likely trapped only locally sinking material, whereas the deeper trap, at 1400 m, caught more material that might have included either that re-suspended from the sea bed by local currents, or that in transport down the continental slope. At 1000 m, the annual POC flux was 2.3 g C m<sup>-2</sup> y<sup>-1</sup>, with a PIC flux of 2.8 g C m<sup>-2</sup> y<sup>-1</sup>.

The POC flux scales to 460 Kt C yr<sup>-1</sup> for a region 1000 km x 200 km (corresponding to Scottish sea-areas Rockall, Bailey and Faroes-Shetland). Adding the PIC flux suggests a total in excess of one Mt C yr<sup>-1</sup>.

Coccolithophorid blooms, the main source of sinking PIC in Scottish waters, are thought to be mainly an oceanic phenomenon, but extend onto the shelf in flows of Atlantic water ((Houghton, 1991); Annex E). A rough estimate for the outer shelf region suggests a DIC downflux of 0.5 Mt C yr<sup>-1</sup>, based on mean DIC flux of 2.8 g C m<sup>-2</sup>yr<sup>-1</sup> over 1.85 x 10<sup>5</sup> km<sup>2</sup>. It seems likely that much of this material accumulates in basins on the shelf, or is exported across the shelf break into the deep ocean.

### 3.6.5 Discussion

The data reported here (i.e. directly sedimenting PIC and POC fluxes, plus transport from the shelf onto the slope and some accumulation in shelf basins) suggest overall C sequestration of **c.2 x Mt C/yr** into the ocean depths west and north-west of Scotland, and onto the outer continental shelf. UK C emissions are limited by law to 2,782 MtCO<sub>2</sub> equivalent over the second carbon budget period (2013 to 2017) - i.e. 174 Mt C per year, so this suggests that the Scottish oceanic sink can account for about 1% of the UK emissions (or perhaps as much as 10% of Scottish emissions if they are scaled per head).

In essence, this has been a scoping study. To fully understand the carbon cycle in Scottish coastal waters will require further development of appropriate mechanistic models, perhaps coupled to near-real-time remote sensing, and verified against historical and occasional new direct measurements of production and sedimentation. Given the range of estimated values for the pelagic production of the northern North Sea (Annex B), and the issues about models raised in Annex C, it was decided to use the production and sedimentation values output by a model (PROWQM) that was designed for this purpose rather than as a more general ecosystem model.

### 3.6.6 Threats to phytoplankton production

Climate change and associated ocean acidification may decrease the sinking of carbon from the euphotic zone. Recent studies have shown falling nutrient concentrations in the upper waters of the north-East Atlantic (Johnson *et al.*, 2013). These waters are the main supplier of nutrient to the shelf seas around Scotland, and so, all other things remaining the same and the trend continuing, a decrease in primary production and sedimentation of POC may be expected. Ocean acidification (a consequence of increasing atmospheric CO<sub>2</sub>) is thought likely (Doney *et al.*, 2009) to suppress coccolithophore production, and hence the sinking of DIC. However, both changes involve complex sets of physical, chemical and biological processes, and further study is needed.

Table 14: Pelagic production rates and totals by regions in Scotland's Marine Atlas, listing sea-area names and details, and estimates of their production and sedimentation.

Area (clockwise, spiralling from outside) - Scottish Sea areas		CP2	Regime (PT)	area (km <sup>2</sup> )	area > 50 m depth	Estimate of NMP (g C/m <sup>2</sup> /yr)	Estimate of SPS (g prod/[PO]C/m <sup>2</sup> . sed yr)	Annual deep flux (g [PO]C/m <sup>2</sup> /yr)	Annual deep flux source	max Winter DIN, $\mu$ M	DIN source	Estimate of sou sed PIC (g C/m <sup>2</sup> /yr)	Estimate of NMP (Mt C/yr)	Estimate of SPS (Mt C/yr)	Estimate of PIC (Mt C/yr)
Rockall	Rockall Trough, Anton Dohrn seamount, Rockall	8	oceanic	65814	65814	100	10	2.3 (x)		13	a	2.8	6.59	0.66	0.18
Bailey	Rockall Trough, Rosemary Banks, Darwin Mounds	8	oceanic	74920	74920	100	10			13	a	2.8	7.50	0.75	0.21
Faroe Shetland Channel	slope beyond the Wyville-Thomson ridge	8	oceanic	42696	42696	100	10			13	a	2.8	4.27	0.43	0.12
West Shetland	outer shelf, inshore and voes of W. Shetlands	7	ST	34790	34730	81	8			10.5	a	2.3	2.81	0.28	0.08
East Shetland	northern North Sea	1	ST	37955	37909	69	7			9	b	1.9	2.63	0.26	0.07
Fladen	northern North Sea	1	ST	37168	37168	62	6			8	b	1.7	2.29	0.23	0.06
Forties	northern North Sea	1	ST	24668	24668	54	5			7	b	1.5	1.33	0.13	0.04
Hebrides	outer shelf, St Kilda, Stanton banks, to long island	7	ST/M	41239	40856	81	8			10.5	a	2.3	3.33	0.33	0.09
North Scotland coast	outer shelf, stacks, Orkneys, Pentland Firth, sea-lochs	7	ST/M	46047	45747	81	8			10.5	a	2.3	3.72	0.37	0.10
Moray Firth	northern North Sea, the Dingwall and Inverness firths	1	ST (R?)	10127	9762	81	8					n.a.	0.82	0.08	
East Scotland Coast	northern North Sea, inshore, and Firth of Tay	1	ST/M	14970	14626	81	8					n.a.	1.21	0.12	
Irish Sea	northern part of Solway and eastern part of Chanel	5	M (R?)	3920	3745	92	9					n.a.	0.36	0.04	
Minches and Malin Sea	from Mull of Kintyre to Cape Wrath, within the outer isles; all the sea-lochs of the west coast, inner Hebrides, and eastern Long Isle	6	TH/M	30028	21253	54	5		(i)	7	a	n.a.	1.62	0.16	
Clyde	The Firth and Estuary of Clyde and the sea-lochs	5	TH	4088	3885	92	9		(ii)	12	a	n.a.	0.38	0.04	
Forth	northern North Sea, the firth and estuary of Forth	1	M/R?	1527	1399	92	9					n.a.	0.14	0.01	
Total												<b>39.0</b>	<b>3.9</b>	<b>1.1</b>	

Notes:

1. *Regime*: oceanic = permanent thermocline, plus seasonal stratification; ST = seasonal thermal stratification (May - Sep +); M = mixed R = ROFI; TH = persistent haline or thermohaline stratification.
2. *SPS* = 'spring pulse sedimentation' from SML
3. *Production estimate*: (i) NMP from PROWQM simulations, multiplied by (max DIN)/10. SPS is taken as 10% of this; (ii) NMP from model in Lee (thesis).
4. Deep flux is that into permanent thermocline. Source (x) Perez-Castillo (1999), trap data.
5. a = Portilla and Tett (2008), and Tett *et al.* (2011b); b = Patsch and Radach (1997) (observations)
6. 0.028 PIC sediment fraction of NMP, see Annex D

#### 4. ECOSYSTEM-SCALE ESTIMATION

Habitat-specific information on rates of carbon production and sequestration are here integrated with habitat extent to produce a carbon budget for the whole of Scotland's waters, including the extent of the UK EEZ. This takes the form of a tabulated inventory of the areas, standing stocks and biomass as well as non-living material, and including rates of accretion and breakdown. A summary by all marine habitats is presented in Table 15 (p53) and more detailed information in mostly coastal biogenic habitats is given in Table 16 (p54).

##### 4.1 Stocks and rates of storage of Scotland's marine carbon

Most of Scotland's marine carbon is stored in sediments. Consideration of the amount of carbon in sediments has been limited to the top 10cm depth of the sediment, reflecting the depths for which there is most information and the location of most of the deposited material entering long-term storage. Organic carbon stored in the top 10cm of offshore and coastal sediments (**18 Mt**) far exceeds that present in living material, the latter comprising only 2% of the total (**0.4Mt**, Table 15). This **18 Mt of organic carbon** is spread across the total area of 470 000km<sup>2</sup>, with 95% located in fine sediments on the continental shelf. **1738 Mt of inorganic carbon** is stored as shell material, with a large proportion (46%) in sand and gravel deposits in the tide swept regions around and between Orkney and Shetland. While this shell material is in shallow sediment, it is relatively old with an average age of more than 2000 years. The pattern of sequestration rates is reversed: organic carbon is sequestered at a rate of 20-40 gC/m<sup>2</sup>/yr in fine sediments (mud and sandy mud), but inorganic carbon is added to the sediment store at a much lower rate of 0.8-1.1 gC/m<sup>2</sup>/yr. The difference in sequestration rates between organic and inorganic carbon results in a larger quantity of **organic carbon, 7.2 Mt/yr** (94% of the total sequestered), being stored in sediments than **inorganic carbon, 0.44 Mt/yr** (6%).

The primary source of organic carbon in sediments is phytoplankton, estimated as **3.9MtC/yr**, but carbon fixed by marine seaweeds, primarily kelp, may contribute up to a further **1.8MtC/yr** (Table 15). Other coastal marine plants including maerl, seagrasses and saltmarsh plants contribute a much smaller quantity (18 000 tC/yr). Organic carbon supply comes from living material when phytoplankton cells or whole plants die, or fragments break off, and become detritus. For phytoplankton, only 10% of surface production reaches the sediment as organic carbon. The rest is respired back as CO<sub>2</sub>. For attached plants (primarily kelp) the proportion of total production that becomes detritus and is subsequently incorporated into the sediment is unknown, but the amount of plant-derived organic carbon sequestered is likely to be less than the 1.8MtC/yr through consumption and respiration by other organisms.

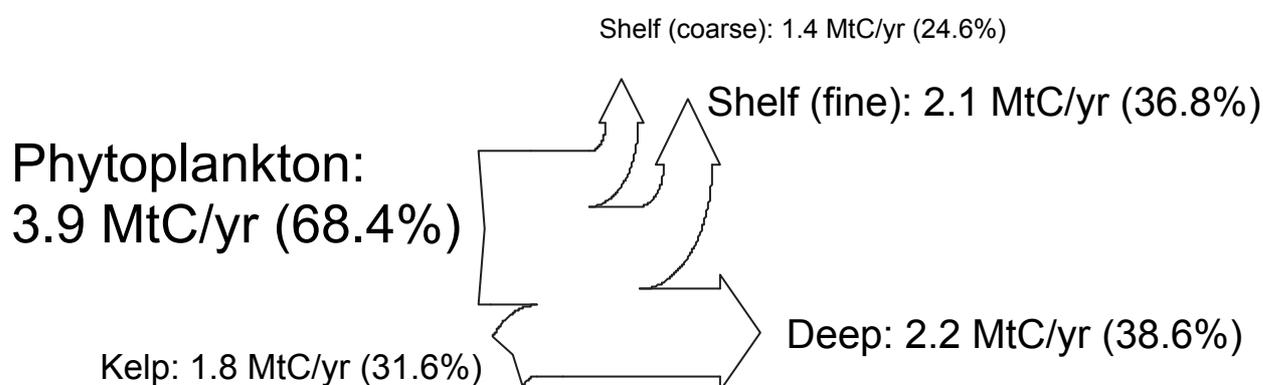


Figure 13: Primary sources of organic carbon supplied to Scotland's marine sediment, apportioned by area. Sea lochs receive 0.01MtC/yr (0.2%).

Once organic carbon reaches the sediment, the material is buried as fresh sediment accumulates. Sediment accumulation rates used here come partly from studies outside Scotland (Table 9). This could be one explanation for the mismatch between the estimated organic carbon inputs to sediments as detritus, and the rates of accumulation calculated from sedimentation rates. Another possibility is that the accumulation rate of organic carbon in deeper sediments (>1000m) is less than that on the continental shelf. It is worth noting, however, that the production and supply rates are derived from entirely separate information sources from those for sediment accumulation rates, and the relatively close agreement between these figures is comforting.

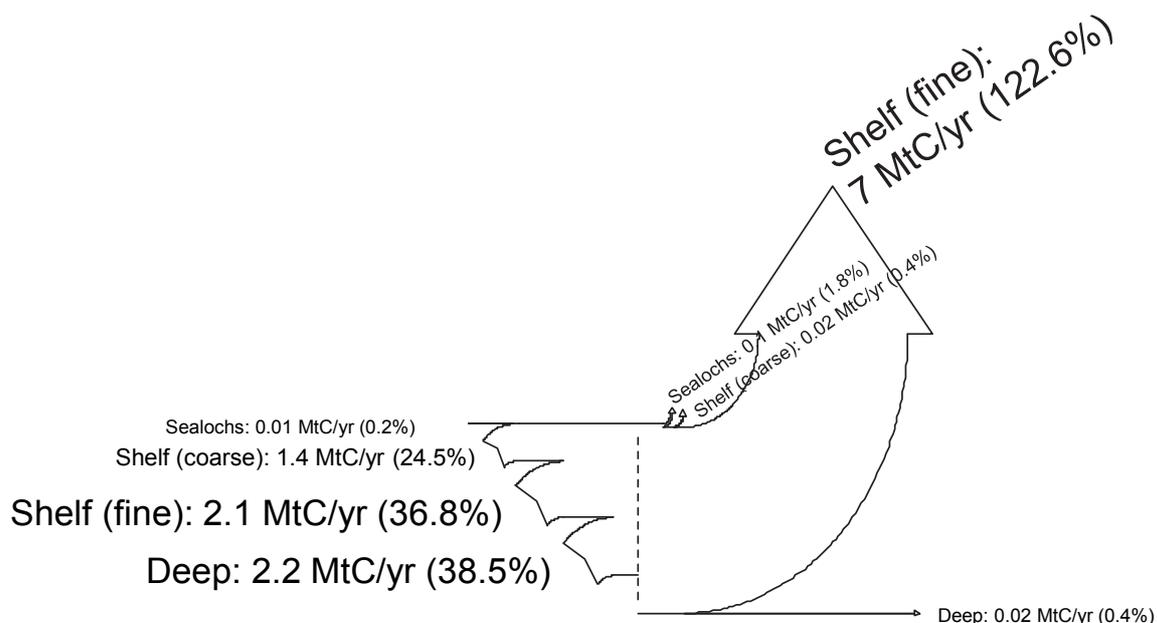


Figure 14: Estimated inputs of sediment organic carbon and estimated rates of accumulation of organic carbon in sediment in the Scotland's Marine Atlas area. There is a mismatch between inputs and estimated accumulation rates.

#### 4.2 Biogenic habitats in coastal and deeper waters

Scotland's biogenic marine habitats are highly productive places, with a very high rate of assimilation of carbon into plant material (**662 gC/m<sup>2</sup>/yr**), mostly in coastal areas. Yet their overall contribution to the carbon budget is relatively small. This primarily reflects the vastly smaller area of these habitats: only 0.5% of the total area considered (2 300 km<sup>2</sup> of a total of 470 000 km<sup>2</sup>). The actual extent of biogenic habitat is relatively poorly known. Many point records exist for the presence of seagrasses, for example, but relatively few beds have been adequately mapped. In deeper water, the cold water coral *Lophelia pertusa* forms large reefs, but even though these reefs comprise significant aggregations of calcium carbonate and the reefs are present in large numbers across the continental shelf and in deeper waters, the known extent of these structures is relatively small. The small area results in a relatively modest standing stock of 125 000t of inorganic carbon stored as biogenic carbonate in *Lophelia* reefs. Even when the true extent of these structures and habitats are better known, it is unlikely that their relative contribution to the carbon budget of Scotland's seas will increase dramatically.

How the carbon assimilated by coastal marine plants enters long-term stores is not well known. The fate of kelp detritus, for example, is poorly understood.

### 4.3 Comparison with annual Scottish atmospheric CO<sub>2</sub> emissions

According to the UK National Atmospheric Emissions Inventory (<http://naei.defra.gov.uk/>), Scotland's production of greenhouse gases (GHGs) in 2011 was 49Mt CO<sub>2</sub>e (+29%) with 35% (17Mt to the nearest Mt) from energy supply, 21% (10Mt) from transport, 18% (9Mt) from business, 16% (8Mt) from agriculture and 13% (7Mt) from residential energy use (Salisbury *et al.*, 2013). This value includes a negative contribution of 5Mt for land use, land use change and forestry (LULUCF), giving gross GHG emissions of 54Mt CO<sub>2</sub>e. The UK as a whole produced 556Mt in 2011 (Webb *et al.*, 2013).

**The estimated carbon storage of 7.2 MtC/yr organic carbon and 0.44 MtC/yr inorganic carbon in Scotland's marine sediments is equivalent to 28.2 MtCO<sub>2</sub>e/yr and accounts for 52% of Scotland's emissions in 2011 (Figure 15).**

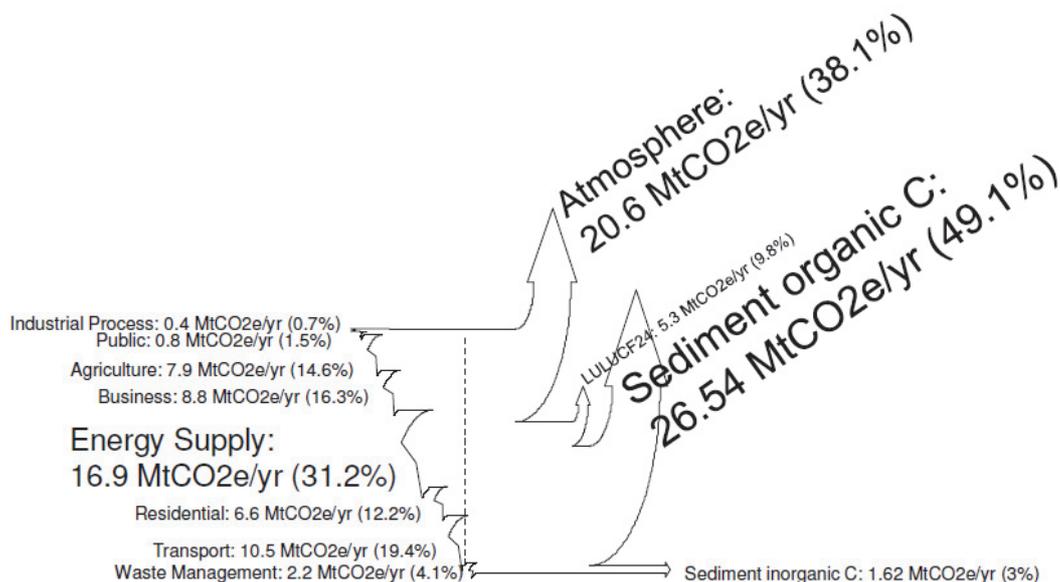


Figure 15: Scotland's production of atmospheric greenhouse gases and sequestration capacity of Scotland's marine environment. Land use, land use change and forestry (LULUCF) and the remaining CO<sub>2</sub> emissions ('Atmosphere') are shown for comparison with the sequestration capacity of marine sediments.

### 4.4 Threats to carbon sequestration and carbon stores in Scotland's marine ecosystem

Threats to habitats where carbon is sequestered are important on a local scale for Scotland's marine habitats (summarised for each habitat in Section 3). For the delicate organisms forming biogenic reefs, the main threat is due to physical disturbance from mobile fishing gear. Kelp beds may be threatened by increased occurrence of severe storms associated with climate change, with increased turbidity due to nutrient and sediment runoff from land as another potential threat.

Ocean acidification may be the biggest threat to sequestration of inorganic carbon being deposited into the sediment as fresh shell material, through influences on calcifying organisms (Orr *et al.*, 2005). Some planktonic organisms may find it difficult to maintain the

integrity of their shells (Bednaršek *et al.*, 2012), and the consequent reduction in delivery of dead shells to the sediment will reduce inorganic carbon sequestration rates. The threat to the large stores of carbon in the form of potential dissolution of carbonate sands is not known, but changes in the saturation states of the biominerals aragonite and calcite, the two main forms of calcium carbonate skeletons, in the seas around Scotland will determine whether this skeletal material persists (Feely *et al.*, 2009). The depth below which the water is undersaturated with calcium carbonate in its most sensitive form (and thereby likely to dissolve or be hard to lay down) is termed the 'aragonite saturation horizon'. In the North Atlantic in the 21st century, global climate models suggest that this depth will become much shallower (Orr *et al.*, 2005). Organisms that do not use aragonite to build shell and skeletons, and use calcite instead, are less immediately threatened, but, as Orr *et al.* (2005) point out, the changes in calcite saturation lag only 50 to 100 years behind those for aragonite. Undersaturation in calcite threatens the biogenic-reef-forming organisms around Scotland considered here on this much longer timescale

Table 15: Scotland's Marine Carbon budget summarised by habitats. Values compiled from habitat reviews in Section 3. Shaded cells indicate assumed zero values (e.g. production of carbon in sediments is negligible since most marine sediments are too deep for production from photosynthesis).

Habitat	Extent (km <sup>2</sup> )	Organic carbon							Inorganic carbon						
		Standing stock (Mt)	Production rate (g C/m <sup>2</sup> /yr)	Total production (Mt C/yr)	Outflux (Mt C/yr)	Influx (Mt C/yr)	Sequestration rate (g C/m <sup>2</sup> /yr)	Sequestration capacity (Mt C/yr)	Sequestration timescale (half life)	Standing stock (Mt)	Sequestration rate (g C/m <sup>2</sup> /yr)	Sequestration capacity (Mt C/yr)	Outflux (Mt C/yr)	Influx (Mt C/yr)	Sequestration timescale (half life)
Phytoplankton	469960		81	39.0	3.9	0						1.09	0.00		
Shelf Sediment: Coarse (top 10cm)	115004	0.0				1.4	0.2	0.0	1000	798	1.05	0.12		0.27	2000
Shelf Sediment: Fine (top 10cm)	171660	17.6				2.1	41.1	7.0	1000	468	0.84	0.14		0.40	500
Offshore Sediment (shelf/deep)	183296	0.1				2.2	0.1	0.02	1000	472	0.95	0.17		0.42	
Sea lochs: Mud	847	0.3				0.01	155.2	0.1	1000						
Biogenic habitats	2283	0.4	662	1.8	1.8	0.0		0.015		0.58	109	0.00093			
Total	473089	18.5	84	40.8	5.7	5.7		7.2		1739		0.44	1.09	1.09	

Table 16: Contributions of biogenic habitats to Scotland's Marine Carbon budget. Values compiled from habitat reviews in Section 3. Shaded cells indicate assumed zero values, either known (e.g. beds of intertidal algae are not long-term carbon stores) or unknown (e.g. fluxes of organic carbon into and out of saltmarshes and seagrass beds).

Habitat	Extent (km <sup>2</sup> )	Organic carbon								Inorganic carbon					Refractory period
		Standing stock (1000t C)	Production rate (g C/m <sup>2</sup> /yr)	Total production (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	Sequestration rate (g C/m <sup>2</sup> /yr)	Sequestration capacity (1000t C/yr)	Sequestration timescale (half life)	Standing stock (1000t C)	Sequestration rate (g C/m <sup>2</sup> /yr)	Sequestration capacity (1000t C/yr)	Outflux (1000t C/yr)	Influx (1000t C/yr)	
Biogenic habitats															
Kelp beds	2155	404	685	1732.4	1732.4					0					
Intertidal macroalgae	24.1	11.8	685	19.3	19.3					0					
Maerl beds	7.1									440.6	74	0.5			
Seagrass beds	15.9		261	4.2		83	1.3			0					
Saltmarshes	67.5	8.6	210	14.2		210	14.2			0					
<i>Biogenic reefs</i>															
<i>Modiolus modiolus</i> bed (Noss Head)	3.9									15.4	40	0.1540			
<i>Limaria</i>	1.4									0.1					
<i>Lophelia pertusa</i> reef (Darwin Mounds)	1.4									13.5	5	0.0072			
<i>Lophelia pertusa</i> reef (Mingulay)	5.4									112.0	35	0.1890	0	0	1000
<i>Serpula vermicularis</i> reefs	1.3									1.0	420	0.0546	0	0	10
Brittlestar beds (shelf seas)											82				

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## ANNEX A: STATISTICAL MODEL TO ESTIMATE KELP EXTENT

A statistical model fitted to Marine Nature Conservation Review data collected in Scotland between 1980 and 2005. The model is an ordinal logistic regression. Predicted values give the logit probability of abundance exceeding a particular threshold as a combination of the values of the three predictors: depth, chlorophyll a concentration and wave fetch. Data from 3234 separate surveys were used to estimate the model.

Table A1. Regression coefficients from the kelp habitat model.

Coefficients:		Variable name	Value	Std. Error	t value
Average depth (m)		avgd	0.202	0.027	7.498
Chlorophyll a (log10(mg/m <sup>3</sup> ))		lchla	2.632	0.496	5.307
Wave fetch (log10(km))		wf2	0.503	0.108	4.666
Depth by Chlorophyll		avgd:lchla	0.107	0.021	4.986
Depth by Wave fetch		avgd:wf2	-0.019	0.008	-2.586
Chlorophyll by Wave fetch		lchla:wf2	-1.077	0.168	-6.407
Intercepts:					
Abundance category	% cover	Boundary	Value	Std. Error	t value
R	< 1%	0 1	-0.629	0.335	-1.879
O	1 - 4%	1 2	-0.370	0.334	-1.106
F	5 – 9%	2 3	0.082	0.334	0.247
C	10 – 19%	3 4	0.516	0.334	1.543
A	20 – 39%	4 5	1.115	0.336	3.323
S	> 40%	5 6	3.182	0.350	9.097

Table A2. Percentage success at predicting kelp abundance from MNCR data.

	Less than Frequent	More than Occasional
	<=O	>=F
Correct	1839	480
Not correct	633	282
	2472	762
% success	74%	63%

## ANNEX B: PRIMARY PRODUCTION - METHODS AND NORTH SEA MEASUREMENTS

Methods of measuring or estimating marine pelagic primary production have been reviewed by Holligan (1989), Williams *et al.* (2002) and others. They are summarized in Table B1.

*Table B1. References, where cited, are typically, an early account of the method, a recent specific review if available, and an example from the North Sea. p is photosynthesis rate, often calculated from PI curves measured in 'light-gradient incubators'; P is production (possibly net of respiration) rate*

<b>Changes associated with phytoplankton in bottles</b> , which may be deployed in the sea ( <i>in situ</i> ) or on land or on a ship's deck exposed to partly obscured daylight (simulated <i>in situ</i> )		
	<i>C:14 method</i> : phytoplankton incubated in transparent bottles with radio-labelled bicarbonate; particulate matter concentrated on filter, and radioactivity measured; very sensitive, measures (gross) photosynthetic production with short incubations and bright light, otherwise unknown respiratory loss of labelled C complicates interpretation	Steeman Nielsen (1952)
	<i>L&amp;DBO2 method</i> : change in dissolved oxygen measured in transparent and some opaque bottles containing phytoplankton; less sensitive than C14 method, but can measure photosynthesis, respiration and NMP	Gaarder and Gran (1927)
<b>Budget methods</b> , based on observing: changes in dissolved O <sub>2</sub> or DIC or in POC, and correcting for gains and losses other than those due to photosynthesis and respiration; drawdown of nutrient converted to biomass change		
	free-water diel cycle methods	
	changes in semi-enclosed water bodies	Tett <i>et al.</i> (1988)
	drawdown of winter nutrients	Heath and Beare (2008)
<b>Calculation methods</b>		
	calculation of column production from observations of chlorophyll and light penetration and knowledge of respiration and of p from PI curves	
	calculation of wide-area production from observations of chlorophyll (X) and P = f(X) empirically determined (by other methods)	Joint and Pomroy (1993)
	use of remotely sensed data, notionally to estimate of chlorophyll and transparency, but, increasingly, directly calibrated against P measured by other methods	
<b>Mechanistic models</b> , involving descriptions of a physical-biological system in terms of its constituent parts, with each process described as far as possible on the basis of theoretical understanding. For present purposes all models must at least include descriptions of <i>PI curves</i> , respiration, vertical mixing of the water-column and light penetration		
	Physical processes - hydrodynamics -- mixed layer and depth-time 'vertical process' models -- OR 2D or 3D circulation models	
	Biological (production and consumption) processes -- simple NPZ (nutrient-phytoplankton-zooplankton) models -- OR more detailed submodels for plankton (e.g. several kinds of algae) and their consumers - i.e. an ecosystem model	

The L&DB02 method, introduced by Gaarder and Gran (1927) and Marshall and Orr (1928), is in most cases insufficiently sensitive for reliable measurements of production in offshore waters. The first systematic studies in the northern North Sea, those of seasonal cycles on the Fladen Ground in the 1950s, estimated 55-81 g C m<sup>-2</sup> yr<sup>-1</sup> from the draw-down of phosphate in 1951-1953 (Steele, 1959). More recently, Heath and Beare (2008) calculated new production from the observed Spring draw-down in nitrate, 1960-2003. Their central value for waters north of 57.5°N (ICES region IVa) was 70 (90% range 52-95) g C m<sup>-2</sup> yr<sup>-1</sup>.

The C14 method of Steeman Nielsen (1952) was applied by Gieskes and Kraay (1980) during the Fladden Ground Experiment in 1976 (FLEX'76), and these and other observational data were aggregated by Pätsch and Radach (1997) to suggest that annual (net) primary production over the northern North Sea was 100 - 125 g C m<sup>-2</sup> yr<sup>-1</sup>. Most subsequent estimates have been based on numerical simulations using mechanistic models, with little use made of empirical-calculation methods and remote sensing.

Model estimates for the northern North Sea include: 100 - 125 g C m<sup>-2</sup> yr<sup>-1</sup> from simulations with ECOHAM (Moll, 1998; Skogen and Moll, 2000); 50 - 100 g C m<sup>-2</sup> yr<sup>-1</sup> from simulations with ERSEM Pätsch and Radach (1997); and 100-200 g C m<sup>-2</sup> yr<sup>-1</sup> from NORWECOM (Skogen *et al.*, 1995). However, the simulated values are sensitive to the physical model used as well as the biological parameterization. A recent comparative study (Lenhart *et al.*, 2010) used two recent versions of ERSEM and two physical models: the POLCOMS physical model with POL version of ERSEM and the GETM physical model with the Cefas version of ERSEM. Although both simulated net production between 75 and 125 g C m<sup>-2</sup> yr<sup>-1</sup>, distributions of regions of higher and lower production differed strongly.

Net primary production refers to the (rate of) photosynthetic formation of organic carbon by the algae and cyanobacteria (in a water column of surface area 1 square meter) after subtracting the organic carbon respired by these phytoplankters. Some of this production uses nutrients that have been locally recycled, i.e. excreted by zooplankton or protozoans after eating micro-algal cells. Dugdale (1967) made the distinction between this recycled production, and what he called 'new production', resulting from the input of new nutrients into the euphotic zone. Excepting regions that import POC in lateral flows, the rate of sedimentation of POC (1) cannot exceed the rate of new production. Thus, estimates of production derived from nutrient drawdown are the most useful for the present purposes of estimating carbon sinks. Annex B considers 'microplankton' models that have been designed to provide better estimates of this exportable production.

*Notes:*

(1) strictly, export could also include mixing of DOC out of the euphotic zone

## ANNEX C: MICROPLANKTON MODELS

The microplankton, as defined by Tett (1987), comprises phytoplankton and associated pelagic heterotrophic micro-organisms: i.e., micro-algae, cyanobacteria, heterotrophic bacteria, protozoans and other protists. The concept arose from: (i) budgetting studies of production and consumption in an enclosed coastal water column (Tett *et al.*, 1988); (ii) ideas developing at that time about the 'microbial loop' (Azam, 1998; Pomeroy *et al.*, 2007); and (iii) the increasing understanding of the evolution of the protistan grade of eukaryotes through multiple symbioses (Margulis, 1981). Thus, from a functional viewpoint, the microplankton can be considered as a soup of chloroplasts (some within algae, some as cyanobacteria) and mitochondria (some within protists, some free-living as bacteria), synthesizing organic matter by photosynthesis and degrading it by respiration.

A series of microplankton models was developed from this concept, and combined with hydrodynamic models of various dimensionalities in a framework for simulating production, eutrophication, sedimentation and benthic-pelagic coupling (Table C1). The PROWQM ('PROCESS WATER QUALITY MODEL') was, biologically speaking, the most complex of these models, and was used to simulate seasonal cycles of production and sedimentation in the northern North Sea (Lee *et al.*, 2002). Coupled with state-of-the-art 'turbulence closure' algorithms for vertical mixing, it included 2 microplankton compartments (allowing simulation of seasonal succession from spring diatoms to summer flagellates), compartments for slow- and fast-sinking detritus, and benthic-pelagic interaction by way of a resuspendable fluff layer on the sea bed. The model outputs 'Net Microplankton Primary Production' (NMP), which is less than 'net primary production' because it also takes account of consumption of organic matter by pelagic micro-heterotrophs. NMP is what is available for export from the illuminated upper layers of the sea, by way of either grazing or sinking. Simulations show that much of the detritus thus produced, remains in suspension in the bottom mixed layer [Fig. C1]. Lee *et al.* (2002) report difficulties in parameterizing the physical model so as to give sufficient depth in the surface mixed layer; Tett and Lee (2005) increased wind drag, and their simulation that best fitted observed temperature and chlorophyll distributions was used as the source of the estimated NMP used in the main report.

Table C1: microplankton concepts and models

model name and reference	biology	physics	sedimentation and benthos
Tett (1987, 1990)	development of microplankton concept using data from Easdale Quarry study	light penetration and vertical mixing	sinking rate estimated by budget closure
L3VMP: Tett (1990), Tett <i>et al.</i> (1993), Tett and Grenz (1994), Tett and Walne (1995)	single, implicit-microplankton, compartment including cell-quota processes; zooplankton grazing treated as a closure term, giving rise to detritus	2-layer model (surface mixed and bottom tide-stirred), in some cases with simple advection between columns	single benthic layer of consolidated sediment where detritus undergoes (first-order) mineralization

<i>model name and reference</i>	biology	physics	sedimentation and benthos
<i>SEDBIOL</i> Smith and Tett (2000), <i>COHERENS</i> (Luyten <i>et al.</i> , 1999; Lee <i>et al.</i> , 2002); and model of Proctor <i>et al.</i> (2003)	single, explicit microplankton compartment including cell-quota processes and zooplankton closure	1D (vertical-process) and 3D models with turbulence closure for shelf process; 2D (shelf-slope section: Xing <i>et al.</i> 1999)	geophysical 'fluff layer' resuspension model of Jones <i>et al.</i> (1996) with slow- and fast-sinking particles
<i>CSTT</i> (CSTT, 1994, 1997), Tett <i>et al.</i> (2003), Laurent <i>et al.</i> (2006), Tett (2008)	simplified microplankton compartment using yield, parameterization subsequently made explicit	OD models - mostly 1 or 2 boxes with imposed exchange	either none, or imposed benthic boundary condition for nutrient input
<i>PROWQM</i> (Lee <i>et al.</i> , 2002, Tett and Lee, 2005)	double microplankton compartment (diatoms, flagellates) including cell-quota processes	1D vertical process, with turbulence closure (Luyten <i>et al.</i> , 2002)	consolidated sediment layer with biogeochemistry and bio-pumping, plus fluff layer and water column aggregation
<i>LESV</i> (Portilla <i>et al.</i> , 2009; Tett <i>et al.</i> , 2011a)	double microplankton compartment with dynamic <i>CSTT</i> (simplified yield) equations for nutrient	3-layer model for fjordic exchange (ACExr, Gillibrand <i>et al.</i> , 2013)	imposed background benthic boundary condition plus mineralization beneath fish-farms

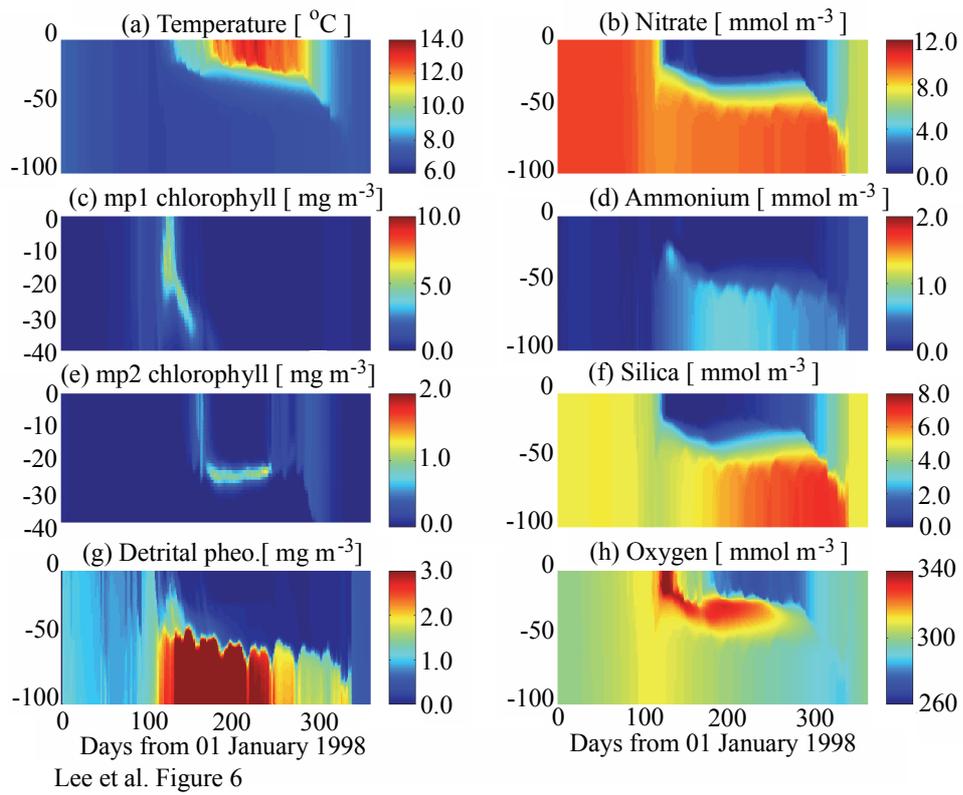


Figure C1: PROWQM simulation of a seasonal cycle in the northern North Sea, from Lee et al. (2002). Detrital pheo[pigment] shows the slow decay of the spring pulse of material into the BBL.

## ANNEX D: SEDIMENTATION

For the sea to act as a carbon sink, its surface waters must be under-saturated in CO<sub>2</sub> relative to the air (1). This can occur when DIC is removed from solution either by photosynthetic uptake or by the formation of carbonates. However, if the particulate carbon is returned to DIC in the same surface waters, there will be a reverse CO<sub>2</sub> flow, from ocean to atmosphere. Thus only when POC or PIC is removed from the upper layers by sinking can there be a continuing flux of atmospheric carbon into the ocean (2).

In shallow, tidally stirred, waters, micro-algae are kept in suspension by turbulent mixing. In estuaries and sea lochs, cells that sink may be returned by estuarine circulation. Otherwise, throughout the shelf seas and adjacent oceans of N-W Europe, phytoplankters are at risk of sinking from the euphotic zone during the growth season, because this is mainly contemporaneous with seasonal stratification. If micro-algae and cyanobacteria were not almost neutrally buoyant, they would rapidly be cleared from the surface mixed layer of the sea (3). Effective sedimentation occurs as a result of several processes. Grazing by zooplankton results in the production of faecal pellets, containing partly digested microplankton, that sink at tens or hundreds of metres a day. Protozoan grazing or parasitism of algal cells disables buoyancy control mechanisms, or in the ejected contents of food vacuoles, but these seem mainly to sink at only a few metres per day. Virus infection probably has a similar result. Probably the most effective process for generating fast-sedimenting material is that of aggregation of algal cells. As diatom populations, for example, grow dense, turbulence causes cell collisions, and entanglement of spines, or stickiness due to excreted organic matter on cell surfaces, clumps cells and chains. The result is fast-sinking 'phytodetritus' that may appear as 'marine snow' to deep-water cameras, or appear on the sea bed as a loose 'fluff layer' after sinking at hundreds of metres per day (Lampitt *et al.*, 2001).

Following theoretical work (e.g. Jackson, 1990) the aggregation processes are well understood, and have been included in models such as PROWQM (Lee *et al.*, 2002). The difficulty lies in measuring sedimentation fluxes. Sediment traps have been in use for many years, but it took some time to become clear that they did not measure all, and only, direct settlement. In turbulent waters, catches of particles might be augmented by capture them from lateral flows; or, with other designs of traps, trapped particles might be sucked out by such turbulence. Traps positioned near the sea bed can take locally resuspended material when this is disturbed by tidal or other flows. Even the deep ocean is now understood as a more dynamic environment than once thought.

Traps work best in tranquil environments. Results from shelf seas require careful analysis and special designs of traps, deployed for short periods only (Davies and Payne, 1984). The basin deep water of sea lochs is another environment wherein trap studies have been more successful (Overnell and Young, 1995). It is in the deep ocean that most trap studies have been carried out, often using funnels delivering their catch into preservative-filled jars held in a rotating turret, so that sedimentation can be assessed during periods of a few weeks within instrument deployments of months or years. Long term studies with such traps have been carried out in the Porcupine Sea-Bight, south-west of Ireland (Lampitt *et al.*, 2001; Lampitt *et al.*, 2010; Hartman *et al.*, 2012), but differences in topography and hydrodynamics suggest that results from this region should not be extrapolated to Scottish ocean waters.

During the NERC LOIS 'Shelf-Edge' study in 1995-96, a mooring was maintained for about a year at 56°43'N, 9°25'W in 1500m water depth in the Rockall Trough, a station on the lower slope called N1500. Rotating turret traps were attached at 1000 m and 1400 m below the surface (Perez-Castillo, 1999). Catches were analysed for POC, PIC and silica. If all material caught in a trap arrives from above, it is to be expected that deeper traps will catch less, because the sinking organic material is continuously subject to respiration by micro-

organisms and to predation by zooplankton. However, the N1500 bottom trap caught about twice as much as the trap at 1000 m, and so was assumed to be taking material locally resuspended by near-bed flows, or perhaps particles arriving in lateral (i.e. down-slope) flows. Therefore, the results from 1000 m were considered more reliable, although not without some interpretational problems. Most of the flux arrived during a few periods, but these did not relate in any simple way to events (such as the spring bloom) nearer to the sea surface, even when photographs of the sea bed, and data from fluorometers and transmissometers mounted on ship-lowered CTDs, showed a pulse of diatom-derived material arriving at the sea bed. Nevertheless, the estimates of sedimentation rates are similar to those obtained from more extensive studies on other, similar, continental slopes, such as those on the Atlantic coast of the US.

### Notes

(1) That is, the partial pressure of  $\text{CO}_2$  in the air next to the sea-surface must exceed that of  $\text{CO}_2$  in the water; the water pp is given by the water concentration multiplied by the Henry's law constant for this system.

(2) What is described here is the 'biological carbon pump', which may have other (probably minor) components in export of carbon by vertically migrating animals and as DOC in downwelling or downwards-mixing waters. In addition there is a 'chemical' or 'solubility' pump, the oceans in general absorbing  $\text{CO}_2$  as the oceanic DIC system tracks increasing atmospheric  $\text{CO}_2$  partial pressure. See Raven and Falkowski (1999).

(3) Explaining this is not as simple as might be thought. Consider a surface layer, mixed by night-time convection to a depth of 20 metres, but neglect day-time stirring by wind. Let cells sink at 1 m/d, so that during 24 hrs the entire column of cells subsides by 1 m. Night-time mixing redistributes most cells throughout the layer, except for the 5% in the bottom 1 m, which have departed the layer by falling into the un-mixed, or weakly-mixed thermocline below. So the daily population loss rate is 5%, which can be replaced by population increase given a supply of nutrients. In fact, trapping and budget studies in sheltered inshore waters (e.g. Tett *et al.*, 1988), suggests that 1 m/d is a fair estimate of overall microplankton sinking rate - possibly living cells sink more slowly and nutrient-depleted or parasitized cells more quickly.

## ANNEX E: COCCOLITHS AND CARBONATE SEDIMENTATION

In some satellite images of the North-East Atlantic Ocean, the most obvious features are the white swirls and streaks of myriads of coccoliths, produced by blooms of flagellated (Prymnesiophyte\Haptophyte) micro-algae called coccolithophorids. Such blooms seem to occur when upper ocean waters are enriched with nutrients from deeper water, which may explain why they are a common feature along the Scottish shelf break with its upwellings and enhanced mixing. The blooms often spread onto the shelf and into the northern North Sea; geologists report that coccoliths are rare in sediments underlying the tidally stirred southern North Sea (Houghton, 1991). They are common in the northern sediments, 90% of them originating from *Emiliana huxleyi*, and it is likely that much of the PIC collected in the SES sediment traps came from the same source.

Coccoliths are tiny calcareous plates grown as a covering by the flagellates during certain stages in their life-cycle, and sometimes shed into the water. Their biological function is unclear, but their contribution to the global carbon cycle has long been recognized (Honjo, 1976). They are made of the mineral calcite. The plates themselves are so small that their sinking rate is slow, less than 1 m/d; however, packaged into faecal pellets by zooplankters (which cannot use them), they sink much more rapidly. Possibly, processes leading to the formation of marine snow may also help package coccoliths, the falling 'snowflakes' sweeping up the little plates. Unlike POC, which is consumed and mineralized during its descent, neither free nor packaged coccoliths suffer decay, at least until they reach the 'calcite compensation depth' (CCD) at about 5 km in the Atlantic Ocean. Approaching this depth, pressure effects change the equilibrium between solid  $\text{CaCO}_3$  and DIC, so that the solid phase begins to dissolve. The CCD, however, is much greater than the 2 km maximum depth in the Rockall Trough. Hence, the export of coccoliths from surface waters either into deep water, whether or not followed by diagenesis and lithification in the sediments, is an effective route for carbon sequestration.

Compared with POC sedimentation, a much greater proportion of coccolithophorid PIC is liable to be sequestered. However, it is harder to estimate the annual production of these algae. Some measurements of biomass, coccolith abundance, and short-term primary production, are available from blooms that were fortuitously tracked by research vessels. In the PROWQM simulation of the northern North Sea, the 'flagellatey microplankton' fraction averaged only 16% of total total NMP. If half of this was coccolithophorid, that would be about 6 g POC  $\text{m}^{-2} \text{yr}^{-1}$ . Joassin *et al.* (2008) give 0.58 as the ratio of PIC to POC in *Emiliana*, and so an upper limit to coccolith flux would be about 4 g PIC  $\text{m}^{-2} \text{yr}^{-1}$ . This value is not far from the flux of 2.8 g C  $\text{m}^{-2} \text{yr}^{-1}$  measured by Perez-Castillo (1999) in the 1000m trap at N1500 during SES.

This suggests a calibration factor  $f$ , to be estimated by the ratio of the PIC sedimentation at N1500 to the PROWQM NMP (77 g POC  $\text{m}^{-2} \text{yr}^{-1}$ ) scaled to the peak winter nutrients (12  $\mu\text{M}$ ) observed at N1500. The value is 0.028, and this has been used to estimate PIC sedimentation in all the ocean and outer-shelf Scottish sea-areas in Table 14.

## ANNEX F: GLOSSARY

<i>Term</i>	<i>Definition/explanation</i>	<i>Reference</i>
alga	seaweeds and related micro-organisms; more precisely members of the Chlorophyta, Phaeophyta and Rhodophyta, and any protist containing chloroplasts - excepting those such as the ciliate <i>Myrionecta</i> (which contains symbiotic micro-algae) that are for historical reasons claimed by zoologists	
autotroph/ autotrophic/ autotrophy	autotrophs use an external source of energy (usually, sunlight) to synthesize organic compounds from inorganic substrates	
bottom boundary layer (BBL)	the part of the water column that is kept mixed by turbulence generated by water flows over the sea bed; especially prominent in tidal seas of continental shelves	
carbon cycle	the biogeochemical cycle involving the conversion of <i>inorganic carbon</i> (IC) compounds into <i>organic carbon</i> (OC) compounds, and back; in a steady-state the rate of formation of OC by photosynthesis would be balanced by the respiratory breakdown of these compounds to IC, and the dissolution of PIC in the Earth's crust would be balanced by the lithification of PIC (e.g. carbonates) formed by chemical and biological processes; the geological cycle however can be naturally perturbed by plate tectonics and anthropogenically by the burning of fossil OC	
carbon-14 (C14) method	method for estimating photosynthesis by measuring the incorporation into particulate matter (micro-algal cells) of bicarbonate labelled with the radio-isotope carbon-14	
cell-quota (model)	originating with Droop (1968, 1983), and distinguishing nutrient uptake processes from growth processes using nutrient stored within cells; uses 'law of the minimum' to identify limiting factor (nutrient or light)	
chloroplast	a cellular organelle (thought to be homologous with cyanobacterial cells) containing chlorophyll a and other pigments and able to carry out photosynthesis	
closure	method for returning nutrient and simulating mortality in a trophic model which does not include details of all higher trophic levels	
coccolith	scales or plates of calcite (a form of calcium carbonate) occurring on coccolithophorids	
coccolithophorid	Haptophyte micro-algae (unicellular photosynthetic flagellates with yellow-brown chloroplasts) bearing coccoliths	
continental shelf (sea)	around each continent is a region of submerged rock of the same type, at depths (of up to a few hundred metres) that are shallow compared with those in the ocean; around Scotland is a wide area of shelf reaching about 120 metres at its outer edge (deeper in a few glacier dredged troughs); the shelf seas, including the North and Malin Seas, are the waters over this shelf	
continental slope	the steeply sloping sea bed beyond the shelf break, leading down into the deep ocean	

<i>Term</i>	<i>Definition/explanation</i>	<i>Reference</i>
column primary production	estimated by integration of <i>production</i> (measured by <i>in situ</i> or <i>simulated in situ</i> methods, or calculated from <i>PI curves</i> and estimated light penetration) over depth	
cyanobacterium	a type of photosynthetic bacteria, formerly called 'blue-green algae'	
diagenesis	the changes (especially the [geo]chemical changes) undergone by sediments after their initial deposition on the seafloor, including those that are a part of <i>lithification</i>	
Diatom	a type of micro-alga with a silicified cell wall, flourishing especially during Spring in mid- and high- latitude seas; many species form long chains of cells	
DIC	Dissolved inorganic carbon	
DIN	Dissolved Inorganic Nitrogen: nitrate, nitrite and ammonium ions, plus dissolved ammonia	
DOC	Dissolved organic carbon	
dinoflagellate	a taxon of protists with two flagellae, typically one longitudinal and one transverse; often (but not characteristically) with a covering of cellulose plates; many are heterotrophic, others contain chloroplasts (and are probably myxotrophic); sometimes known to have a life-cycle than includes sexual reproduction and the formation of an encysted stage	
eukaryote	an organism in which most inheritable material (DNA) is contained within a nucleus, usually appearing as chromosomes during cell division, and with extra-nuclear cytoplasm containing organelles (especially mitochondria, and in some cases chloroplasts), thought to be derived from symbiotic bacteria	
euphotic zone	the upper layers of the sea, in which there is sufficient light for photosynthesis to exceed respiration	Tett (1990)
flagellate	a protist with a flagellum - which is a whip-like structure more complex than that of a bacterium	
haline stratification	water column layering due to lower salinity in the surface layers	
herotroph/ heterotrophic/ heterotrophy	a heterotroph obtains its energy by oxidation of organic compounds	
inorganic carbon	carbon dioxide(CO <sub>2</sub> ) gas, dissolved CO <sub>2</sub> and the ions bicarbonate (HCO <sub>3</sub> <sup>-</sup> ) and carbonate (CO <sub>3</sub> <sup>-</sup> ); particulate compounds of carbonate, e.g, calcium carbonate (Chalk, CaCO <sub>3</sub> )	
in situ incubation	bottles containing phytoplankton are suspended in the sea, usually for 24 hrs, for the estimation of photosynthesis by the C-14 or the L&DBO2 method; integration of photosynthesis over depth estimates column primary production	

<i>Term</i>	<i>Definition/explanation</i>	<i>Reference</i>
lithification	the process by which material is converted into rock (e.g. chalk, from sedimented carbonates or coal from sedimented organic matter) or metamorphosed compounds (e.g. oil) within rocks	
micro-alga	a protist containing chloroplasts	
microplankton	the ensemble of pelagic micro-organisms (including bacteria, protozoa and micro-algae), which reproduce mainly by cell division, as distinct from the animal zooplankton, which lay eggs	
microplankton production	the photosynthetic production of OC by the chloroplasts in microplankton organisms (and photosynthetic bacteria in their own right), less the respiration of that OC in the mitochondria of microplankton organisms (and in all bacteria); equivalent to net primary production (by phytoplankton) less contemporaneous respiration by heterotrophic pelagic micro-organisms	
myxotroph/ myxotrophic / myxotrophy	a myxotroph is an organism that primarily obtains energy by photosynthesis, like an autotroph, but can also ingest particulate or dissolved organic compounds as a secondary source of energy or of nutrients	
new production	exportable primary production, a part of <i>net production</i> , the other part resulting from locally recycled nutrients	
net production	primary production net of all contemporaneous respiration by the micro-algae and cyanobacteria concerned	
nitrate	the ion $\text{NO}_3^-$ , the most common oxidized form of dissolved nutrient-nitrogen in the sea	
nutrients	in the present context, compounds of nitrogen, phosphorus and in some cases silicon and iron, plus a few vitamins or their precursors, that algae and cyanobacteria need for the synthesis of organic compounds	
ocean/oceanic waters	waters that lie beyond the edge of continental shelves, i.e. with depths greater than 200 m, and typically exhibiting a permanent thermocline	
organic carbon (OC)	compounds of carbon and hydrogen and, in some cases, O, N, S ..., used by living organisms in the structure of their cells and as a reservoir of energy	
particulate inorganic carbon (PIC)	carbonates of several sorts, including calcite (in coccoliths) and aragonite.	
particulate organic carbon (POC)	OC in living or dead organisms	
pelagic	in or of the marine water column	
permanent thermocline	a region in the sea where temperature decreases significantly with increasing depth, whatever the season	
phosphate	a nutrient, the main form of dissolved inorganic phosphorus in the sea, the phosphate ion $\text{PO}_4^{3-}$	

<i>Term</i>	<i>Definition/explanation</i>	<i>Reference</i>
phytoflagellate	a 'plant flagellate', i.e. a flagellated micro-alga	
phytoplankton	photosynthetic plankton, containing the pigment chlorophyll a, which is often measured to quantify amounts of these pelagic algae and photosynthetic bacteria	
photosynthesis/ photosynthetic rate	the process in which (and rate at which) light energy is used by organisms containing photosynthetic pigments (especially, chlorophyll a) to convert DIC into OC and, usually, to release oxygen as a result of the splitting of water molecules	
plankter	an individual member of the plankton (sometimes, an individual species)	
plankton	the collective term for the drifting organisms found in the sea	
primary production (rate)	the (rate of) formation of organic matter from DIC, mainly, but not entirely, through oxygenic photosynthesis	
prokaryote	an organism in which inheritable material (DNA) is not separated from general cellular processes - i.e. there is no nucleus containing chloroplasts; cf: <i>eukaryote</i>	
protist	simple eukaryotes, characteristically small and single-celled (although some capable of forming simple chains or colonies) without elaborate reproductive structures and without an embryonic stage in their development; a grade (or level) of organization rather than a clade (taxon); includes protozoans, micro-algae, parasites and fungus-like organisms	
protozoan	a single celled heterotrophic eukaryote - with examples found in many phyla, including those of ciliates, dinoflagellates, amoebae and radiolarians; organisms with symbiotic algae or retained functional chloroplasts are for historical reasons still called protozoa even if they are functionally algae	
region of freshwater influence (ROFI)	a coastal region in which the hydrodynamics and biodynamics are strongly influenced by river discharge; interacting with wind and tide, this often leads to short periods of haline stratification, interrupted by periods of mixing	
seasonal thermocline	a thermocline found in mid-latitude waters during the part of the year when solar heating is sufficient to overcome heating	
shelf break	the edge of the continental shelf, beyond which is the continental slope	
silicate	a nutrient required by diatoms, and a few other micro-algae, that have cell walls or skeletons of silica	
simulated in situ incubation	bottles containing phytoplankton are exposed to filtered natural light, usually for 24 hrs, for the estimation of photosynthesis by the C-14 or the L&DBO2 method	
thermocline	a region in the sea where temperature decreases significantly with increasing depth	

<i>Term</i>	<i>Definition/explanation</i>	<i>Reference</i>
thermal stratification	water layering associated with the <i>seasonal thermocline</i>	
tidal (mixing) front	a topographically-linked boundary in the sea between (usually inshore) waters that are vertically mixed by tidal flows, and offshore waters that show thermal stratification in summer	
zooplankton	animal plankton, as distinct from phytoplankton and from nekton; the present context excludes pelagic protozoa, which are deemed to be part of the microplankton	

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Policy and Advice Directorate, Great Glen House,  
Leachkin Road, Inverness IV3 8NW  
T: 01463 725000

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