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Scottish Marine and Freshwater Science Vol 11 No 2

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Published by Marine Scotland Science

ISSN: 2043-722

DOI: 10.7489/12267-1

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# Re-Evaluating Scotland's Sedimentary Carbon Stocks

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## 1. Summary

This report sets out to provide an improved estimate of the carbon (C) held within Scotland's marine sedimentary environments across Scotland's mapped extended Exclusive Economic Zone (i.e. 554,755 km<sup>2</sup>). Marine sediments accumulating on the ocean floor hold large quantities of carbon (C); these environments can also act to trap and store C over long periods of time (> 10<sup>3</sup> yrs). The surficial sediments (top 10 cm) of the mapped extended Scottish EEZ holds an estimated 1,515 ± 252 Mt C. The majority of this C is in the form of calcium carbonate (CaCO<sub>3</sub>), with an estimated 1,294 ± 161 Mt IC being held within the surficial sediments. A significantly lower quantity of C in these surface sediments is stored in the organic form, with an estimated 221 ± 92 Mt OC currently held within the top 10 cm of sediment within Scotland's mapped extended EEZ.

## 2. Introduction

Marine sediments accumulating on the ocean floor are generally well known to hold large quantities of carbon (C); these environments can also act to trap and store C over long periods of time (> 10<sup>3</sup> yrs) (Hedges et al., 1997). Currently, however, there is no global estimate of the quantity of C stored in marine sediments. Recent estimates by Diesing et al. (2017), for example, calculated that the top 10 cm of sediment across the North-West European continental shelf holds 250 Mt of organic carbon (OC). Furthermore, the sea lochs (fjords) of Scotland alone are estimated to store a further 252.4 ± 62 Mt OC and 214.7 ± 85 Mt of inorganic carbon (IC) in their postglacial sediments (Smeaton et al., 2017).

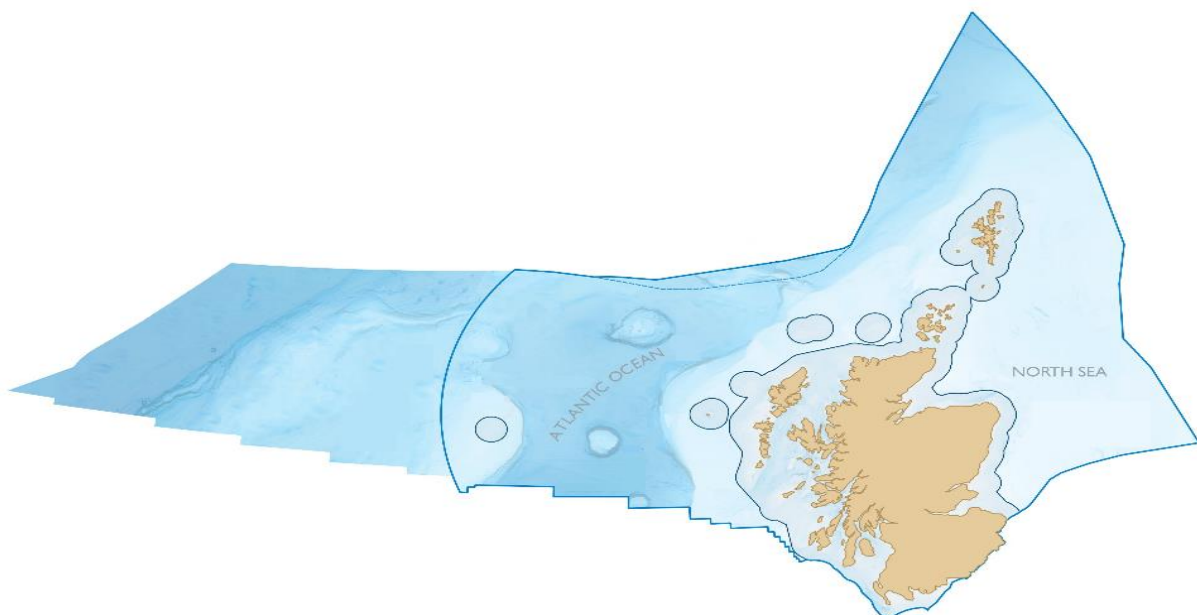
Whilst these marine sedimentary environments do not directly sequester carbon dioxide (CO<sub>2</sub>) from the atmosphere, they are recipients of C from *in situ* biological processes and they often receive large C subsidies from other environments. These

C subsidies can derive from marine biological (Santschi et al., 1990; Glud, 2008, Krause-Jensen and Duarte, 2016), terrestrial biological (Bianchi, 2011, Bauer et al., 2013, Cui et al., 2016, Smeaton and Austin, 2017) and geological sources (Dicken et al., 2014, Galy et al., 2015). Globally, it is estimated that marine sediments bury approximately 160 Mt OC yr<sup>-1</sup> (Hedges et al., 1997, Smith et al., 2014) with 42% of this total captured by non-deltaic shelf sea sediments. The global annual IC burial in marine sediments remains poorly constrained.

This report sets out to provide an improved estimate of the C held within Scotland's marine sedimentary environments. Using a standardised framework, first-order estimates of Scotland's surficial (top 10 cm) marine sedimentary C stock were undertaken using open-access data sources. Currently, reliable estimates of the rates at which C is being trapped and buried cannot be made for Scottish waters because of the lack of data available to constrain these burial rate estimates across large areas of the shelf. However, the adoption of a standardised framework to establish the best current estimates of marine sedimentary C stocks does allow for these estimates to be updated as more burial rate data become available.

### 3. Study Area

This report focuses on an assessment of sedimentary C stores across Scotland's Exclusive Economic Zone (EEZ), which covers an area approximately six times larger than Scotland's land area (MS, 2019). In addition to the EEZ, the C stores in the surficial sediments west of Rockall are also quantified (EEZ Extension; Figure 1).

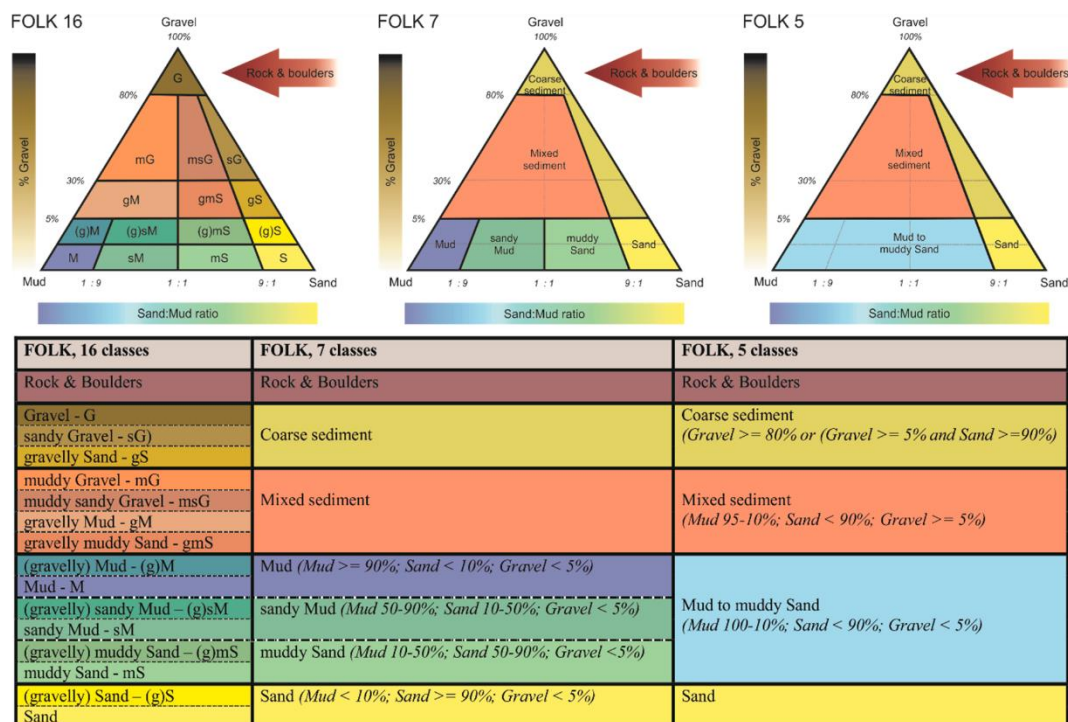


**Figure 1:** Areal extent of the study with the 12nm limit, Exclusive Economic Zone (EEZ) and the area west of Rockall highlighted (EEZ Extension) shown.

## 4. Methodological Approach

### 4.1. Substrate Classification

The Folk classification scheme (Folk, 1954) was chosen to classify seafloor sediment type as it is internationally recognized and widely applied in sedimentological studies; this audit therefore benefits from existing sedimentological and OC data, such as those generated by the British Geological Survey in their offshore sediment mapping programme (BGS offshore index; e.g. Skinner, 1998). Furthermore, the Folk classification scheme allows outputs from this study to be readily integrated and compared with other such studies (e.g. Diesing et al., 2017). The Folk sediment classification scheme itself can be used at three resolutions, containing 16, 7 and 5 classes (Figure 2), with a simple hierarchy enabling the straightforward union of 16 classes into 7 or 5 classes (Kaskela et al., 2019). Wherever possible, the most detailed Folk classification was used.

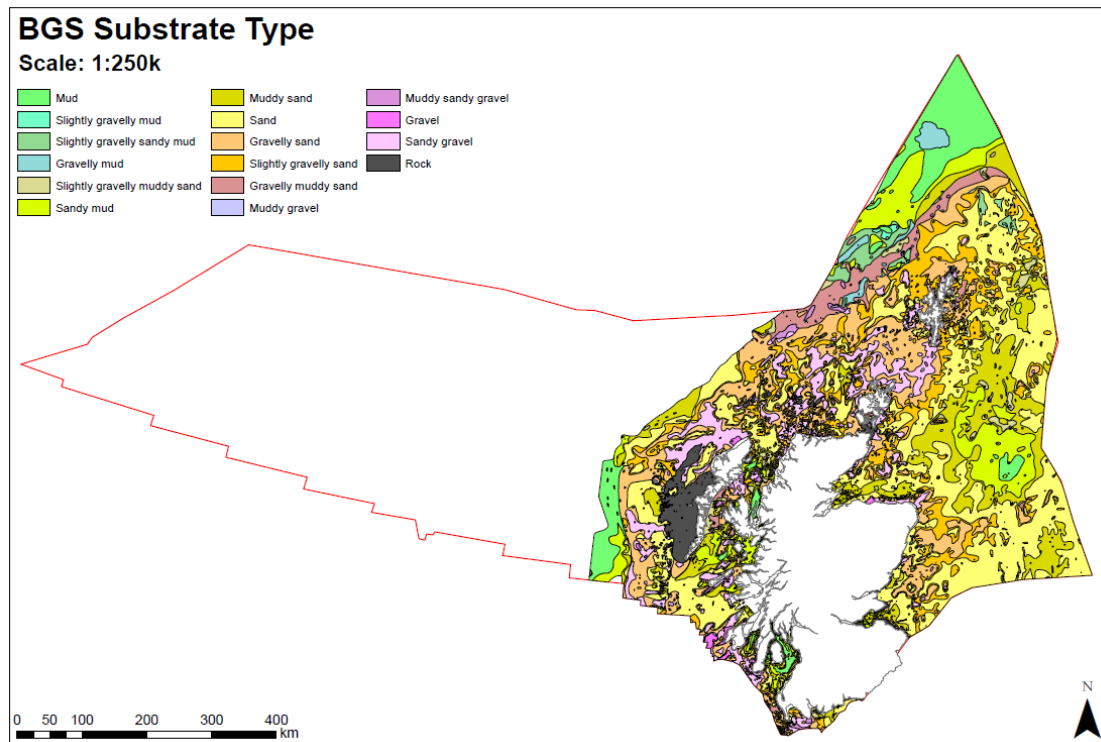


**Figure 2:** The Folk sediment triangle and the hierarchy of Folk classification, with the rock and boulders class indicated by the arrow as used in the EMODnet Geology project (Kaskela et al., 2019).

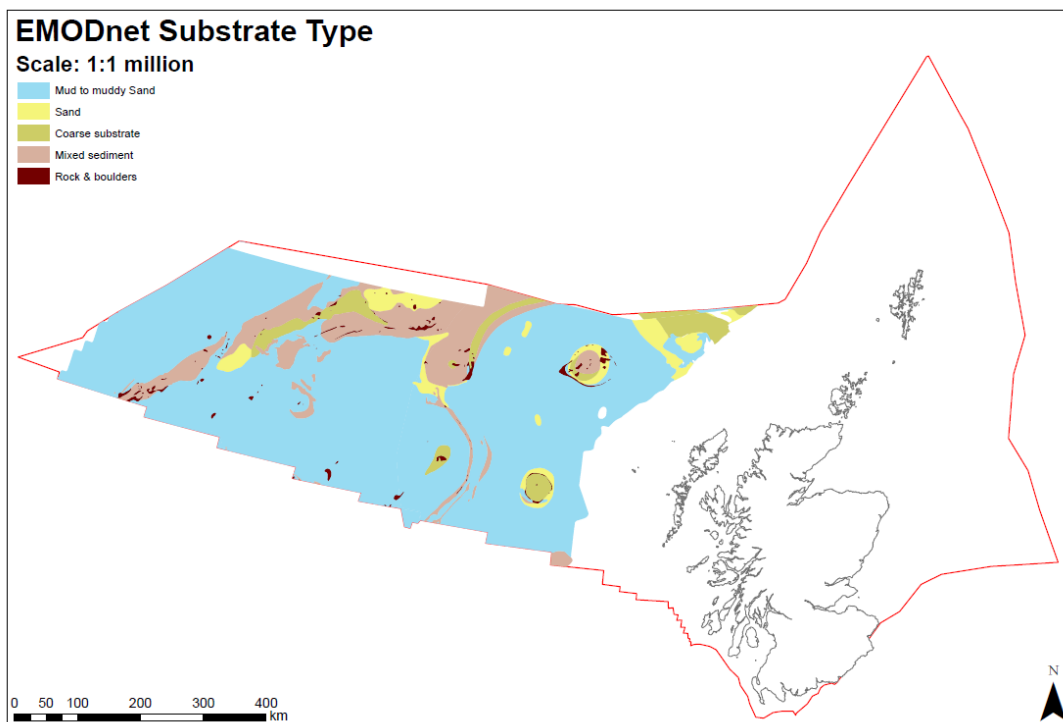
### 4.2. Areal Extent of Sediment Types

The sediment type data was extracted from the 250 k BGS SeaBed Sediment map (BGS: Geology, 2019. Figure 3) for the sediments in Scotland's EEZ and from the

EMODnet Multiscale substrate map (EMODNet: Geology, 2019. Figure 4) for the western portion of Scotland's seas.



**Figure 3:** Spatial distribution of the different sediment types extracted from the 250 k BGS SeaBed Sediment Map (Accessed from: *Digimap: Geology, 2019*).



**Figure 4.** Spatial distribution of the different sediment types extracted from the 5 Folk Class EMODnet multiscale substrate Map (Accessed from: *EMODnet Geology, 2019*).

In total, the BGS data covers an area of 422,083 km<sup>2</sup> leaving an area of 40,180 km<sup>2</sup> of the EEZ currently unmapped. The sea lochs situated along Scotland's West coast and islands account for 2,052 km<sup>2</sup> of this unmapped area; sea loch sediments (top 10cm) are estimated to store 4.16 ± 0.5 Mt OC (Smeaton and Austin, 2019). Table 1 summarises the area values and terminology used in this study.

**Table 1**

Summary of the various areas used in this report, their values and terminology used.

Name	Acronym	Value	Comment
Mapped EEZ	M-EEZ	422,083 km <sup>2</sup>	Covered by BGS 250k data
Unmapped EEZ	UM-EEZ	40,180 km <sup>2</sup>	In a strip around Scotland's coastline
Total EEZ	EEZ	462,263 km <sup>2</sup>	M-EEZ+UM-EEZ
EEZ Extension	EEZ-E	132,672 km <sup>2</sup>	Area west of EEZ. Mapped by EMODnet data.
Extended EEZ	Ex-EEZ	594,935 km <sup>2</sup>	EEZ + EEZ-E
Mapped Extended EEZ	MEx-EEZ	554,755 km <sup>2</sup>	UM-EEZ + EEZ-E

The sediments around Scotland's EEZ were classified into 15 separate sediment types (Table 2) in accordance with the Folk classification scheme (Folk, 1954)(Figure 2). The area around and to the west of Rockall (Figure 4) was classified into five different substrate types (Table 2) covering an area of 132,672 km<sup>2</sup>.



**Table 2**

Areal extent of the different sediment types found within the Scottish EEZ and Scottish EEZ Extension.

	<b>Substrate Type</b>	<b>Area (km<sup>2</sup>)</b>
<b>M-EEZ - BGS Seabed Substrate 250k</b>		
1	Mud	22815.73
2	Sandy Mud	24140.93
3	Muddy Sand	43405.29
4	Sand	170988.55
5	Slightly Gravelly Sand Mud	4597.71
6	Slightly Gravelly Muddy Sand	5486.6
7	Slightly Gravelly Sand	39483.51
8	Gravelly Mud	3157.21
9	Gravelly Muddy Sand	12869.24
10	Gravelly Sand	55382.74
11	Muddy Gravel	85.73
12	Muddy Sandy Gravel	1788.72
13	Sandy Gravel	28205.78
14	Gravel	1594.29
15	Rock	8081.44
	<i>EEZ - Mapped</i>	<i>422083.47</i>
<b>EEZ Extension - EMODnet 5 Folk</b>		
1	Mud to Muddy Sand	56458.7
2	Sand	1281.04
3	Coarse Sediment	2546.53
4	Mixed Sediment	5679.19
5	Rock Boulders	66706.98
	<i>EEZ Extension (EEZ-E)</i>	<i>132672.44</i>
	<i>M-EEZ+ EEZ-E</i>	<i>594,936</i>

### 4.3. Sediment Thickness

In this audit a conservative approach has been taken, with only the top 10 cm of sediment included in the calculations of sediment C stocks as there is generally only very limited data available on sediment thickness, dry bulk density and OC content below the surficial sediments. Additionally, this approach follows earlier attempts to map sedimentary C stores by Burrows et al. (2014, 2017), allowing for comparisons across Scotland and the extensive Marine Protected Area (MPA) network.

Examination of the BGS Quaternary Deposits maps, for example, suggest that much of the EEZ has Quaternary-age sediments >50 m thick. The stocks reported here, therefore, represent only a small fraction of full-thickness sedimentary carbon stocks

and may not represent age-equivalent deposits. It should also be highlighted that the organic matter at these shallow depths (<10 cm) is still actively remineralizing (Middleburg, 2018).

#### 4.4. Physical Properties and Carbon Content of Marine Sediment Types.

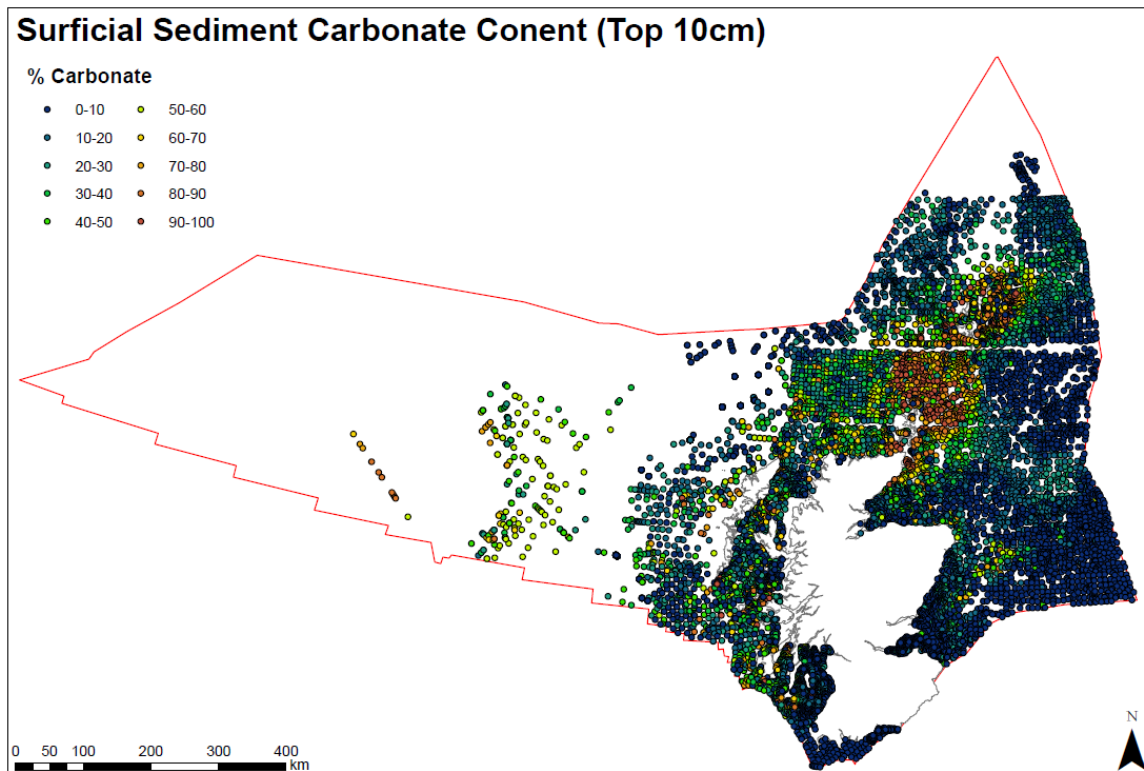
Within the continental shelf limits of the study there is limited physical property (i.e. dry bulk density) or C data available that is representative of the wider area; we have therefore resorted to using dry bulk density and %OC values from the eastern and southern North Sea compiled by Diesing et al. (2017) (Table 3).

**Table 3**

Dry bulk density (kg m<sup>-3</sup>) and OC (%) values for each of the folk classes derived from North Sea samples (Diesing et al., 2017).

Substrate Type	Dry Bulk Density (kg m <sup>-3</sup> )				OC (%)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
	<b>BGS Seabed Substrate 250k</b>							
Mud	580	29	536	624	0.88	0.2	0.59	1.11
Sandy Mud	828	120	646	1011	0.78	0.21	0.54	1.11
Muddy Sand	1323	99	1111	1429	0.54	0.22	0.27	0.92
Sand	1511	25	1454	1535	0.24	0.12	0.1	0.5
Slightly Gravelly Sand Mud	945	73	789	1030	0.67	0.16	0.55	0.93
Slightly Gravelly Muddy Sand	1357	80	1192	1433	0.54	0.22	0.32	0.82
Slightly Gravelly Sand	1512	21	1467	1534	0.22	0.11	0.07	0.43
Gravelly Mud	1011	102	845	1080	0.91	0.51	0.7	1.69
Gravelly Muddy Sand	1397	51	1287	1447	0.49	0.23	0.3	0.77
Gravelly Sand	1515	16	1486	1534	0.23	0.1	0.12	0.44
Muddy Gravel	1314	125	1234	1394	0.62	0.01	0.62	0.62
Muddy Sandy Gravel	1482	25	1438	1510	0.16	0.1	0.16	0.45
Sandy Gravel	1521	13	1492	1534	0.12	0.09	0.12	0.35
Gravel	1529	8	1511	1535	0.13	0.05	0.13	0.25
Rock	0	0	0	0	0	0	0	1.11
	<b>EMODnet 5 Folk</b>							
Mud to Muddy Sand	1015	74	874	1108	0.67	0.20	0.45	0.97
Sand	1512	23	1461	1535	0.23	0.12	0.09	0.47
Coarse Sediment	1522	12	1496	1534	0.16	0.08	0.12	0.35
Mixed Sediment	1291	83	1177	1354	0.56	0.21	0.45	0.90
Rock Boulders	0	0	0	0	0	0	0	0

The BGS collected significant numbers of surficial sediment samples during the 1970s and 80s and as part of an extended mapping programme of the UK shelf and carbonate content of the sediments were routinely analysed by coulometry. All carbonate data for the Scottish EEZ Extension were extracted from the BGS Offshore Geoindex and are presented in Figure 6.



**Figure 6:** Carbonate content of surficial sediment (data accessed from: *BGS Offshore Geindex, 2019*).

The carbonate data extracted from the BGS Offshore Geindex was initially corrected to %IC (12% of CaCO<sub>3</sub> is C). The carbonate data were accompanied by sediment descriptions allowing the range of IC to be calculated for different sediment types (Table 4).

**Table 4**

Inorganic Carbon (IC) percentage values for each of the sediment types derived from the BGS carbonate point data (*data available at: BGS offshore index*) (Fig. 6).

Substrate Type	IC (%)			
	Mean	SD	Min	Max
<b>BGS Seabed Substrate 250k</b>				
Mud	1.51	1.03	0.01	5.89
Sandy Mud	1.77	1.27	0.00	7.16
Muddy Sand	1.26	1.11	0.05	6.66
Sand	1.48	1.71	0.00	8.26
Slightly Gravelly Sand Mud	1.19	0.36	0.10	1.99
Slightly Gravelly Muddy Sand	2.95	2.20	0.10	8.20
Slightly Gravelly Sand	1.67	1.42	0.05	6.49
Gravelly Mud	1.47	0.96	0.14	4.80
Gravelly Muddy Sand	2.05	1.57	0.21	6.44
Gravelly Sand	3.99	2.41	0.14	8.29
Muddy Gravel	1.21	1.06	0.20	5.68
Muddy Sandy Gravel	2.22	1.91	0.22	8.13
Sandy Gravel	3.57	2.45	0.01	8.27
Gravel	1.61	2.23	0.00	8.25
Rock	0	0	0	0
<b>EMODnet 5 Folk</b>				
Mud to Muddy Sand	1.56	1.20	0.07	5.63
Sand	1.57	1.12	0.02	7.38
Coarse Sediment	3.05	0.80	0.05	8.27
Mixed Sediment	1.96	1.21	0.16	6.70
Rock Boulders	0	0	0	0

#### 4.5. Carbon Stock Quantification

A series of standard calculations were carried out with the compiled data to estimate both the OC and IC stock of the surficial sediments (top 10cm). Alongside the C stock calculations, OC and IC densities were also calculated (Tables 5 and 6); the latter provide an area normalized value to allow the results from this study to be compared to other sedimentary and Blue Carbon studies.

$$\text{Sediment Volume (m}^3\text{)} = \text{Areal Extent of Substrate Type (m}^2\text{)} \times \text{Sediment Thickness (m)}$$

$$\text{Sediment Mass (kg)} = \text{Sediment Volume (m}^3\text{)} \times \text{Dry Bulk Density (kg m}^{-3}\text{)}$$

$$\text{Carbon Mass (kg)} = \text{Sediment Mass (kg)} \times \text{Carbon Content (\%)}$$

$$\text{Carbon Stock (tonnes)} = \text{Carbon Mass (kg)} / 1,000$$

$$\text{Carbon Stock (Mt)} = \text{Carbon Stock (tonnes)} / 1,000,000$$

$$\text{Carbon Density (tonnes ha}^{-1}\text{)} = \text{Carbon Stock (tonnes)} / (\text{Area (m}^2\text{)}/10,000)$$

The uncertainties within the data are expressed as standard deviations ( $\sigma$ ); these uncertainties were propagated through the different calculations steps. To

propagate these uncertainties it was assumed that errors in the measurements are governed by normal (or Gaussian) distributions and that measured quantities are independent of each other. This report utilises the *adding in quadrature* method to propagate errors (UKAS, 1997).

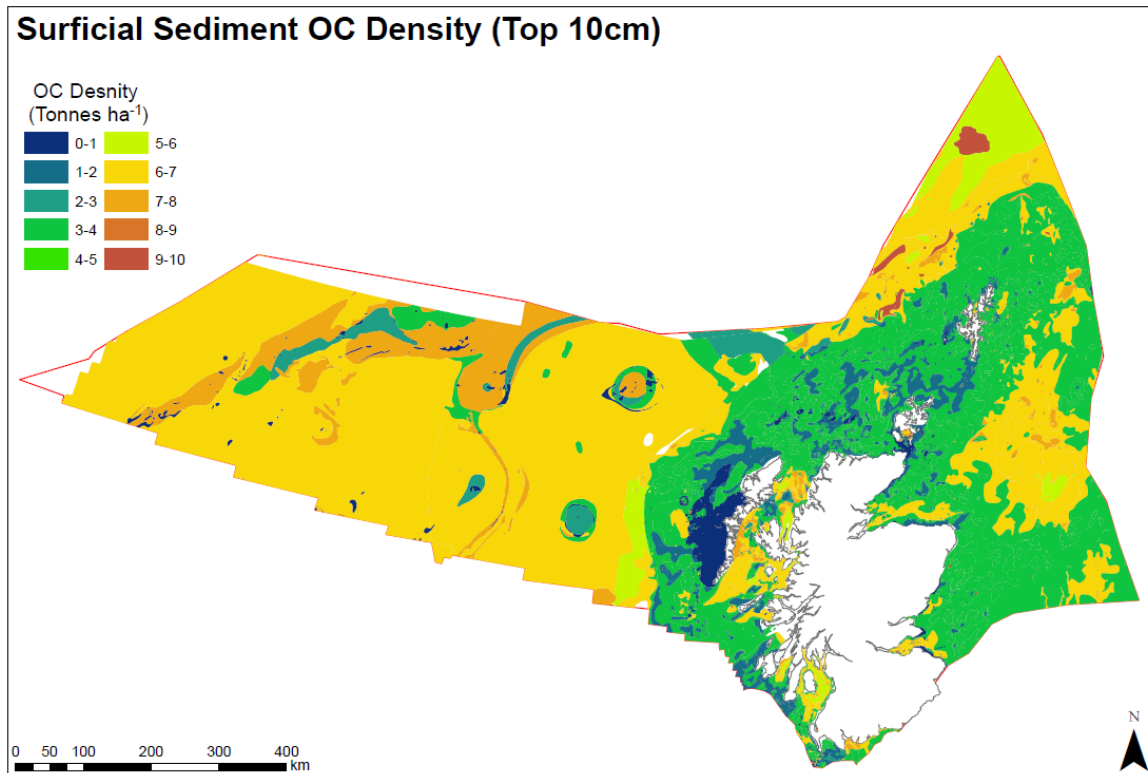
## 5. Continental Shelf Sedimentary Carbon Stocks

### 5.1. Sedimentary Organic Carbon Stocks

**Table 5**

Sedimentary organic stocks (Mt) and OC density (tonnes ha<sup>-1</sup>) for the Scottish continental shelf derived from the BGS seabed substrate and EMODnet data.

Substrate Type	OC Stock (Mt)				OC Density (tonnes ha <sup>-1</sup> )			
	Mean	SD	Min	Max	Mean	SD	Min	Max
	<b>BGS Seabed</b>				<b>Substrate 250k</b>			
Mud	11.6	2.6	7.2	15.8	5.1	1.2	3.2	6.9
Sandy Mud	15.6	4.2	8.4	27.1	6.5	1.7	3.5	11.2
Muddy Sand	31.0	12.6	13.0	57.1	7.1	2.9	3.0	13.1
Sand	62.0	31.0	24.9	131.2	3.6	1.8	1.5	7.7
Slightly Gravelly Sand Mud	2.9	0.7	2.0	4.4	6.3	1.5	4.3	9.6
Slightly Gravelly Muddy Sand	4.0	1.6	2.1	6.4	7.3	3.0	3.8	11.8
Slightly Gravelly Sand	13.1	6.6	4.1	26.0	3.3	1.7	1.0	6.6
Gravelly Mud	2.9	1.6	1.9	5.8	9.2	5.2	5.9	18.3
Gravelly Muddy Sand	8.8	4.1	5.0	14.3	6.8	3.2	3.9	11.1
Gravelly Sand	19.3	8.4	9.9	37.4	3.5	1.5	1.8	6.7
Muddy Gravel	0.1	0.0	0.1	0.1	8.1	0.1	7.7	8.6
Muddy Sandy Gravel	0.4	0.3	0.4	1.2	2.4	1.5	2.3	6.8
Sandy Gravel	5.1	3.9	5.0	15.1	1.8	1.4	1.8	5.4
Gravel	0.3	0.1	0.3	0.6	2.0	0.8	2.0	3.8
Rock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Sub-Total</b>	<b>177.3</b>	<b>77.8</b>	<b>84.2</b>	<b>342.6</b>	<b>4.2</b>	<b>1.8</b>	<b>2.0</b>	<b>8.1</b>
	<b>EMODnet 5 Folk</b>							
Mud to Muddy Sand	38.5	11.7	22.2	60.6	6.8	2.1	3.9	6.8
Sand	0.4	0.2	0.2	0.9	3.5	1.7	1.2	3.5
Coarse Sediment	0.6	0.3	0.5	1.4	2.4	1.2	1.8	2.4
Mixed Sediment	4.1	1.5	3.0	6.9	7.2	2.7	5.3	7.2
Rock Boulders	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Sub-Total</b>	<b>43.6</b>	<b>13.8</b>	<b>25.8</b>	<b>69.7</b>	<b>3.3</b>	<b>1.0</b>	<b>1.9</b>	<b>5.3</b>
<b>Total</b>	<b>220.9</b>	<b>91.5</b>	<b>110.1</b>	<b>412.3</b>	<b>4.0</b>	<b>1.7</b>	<b>2.0</b>	<b>7.4</b>



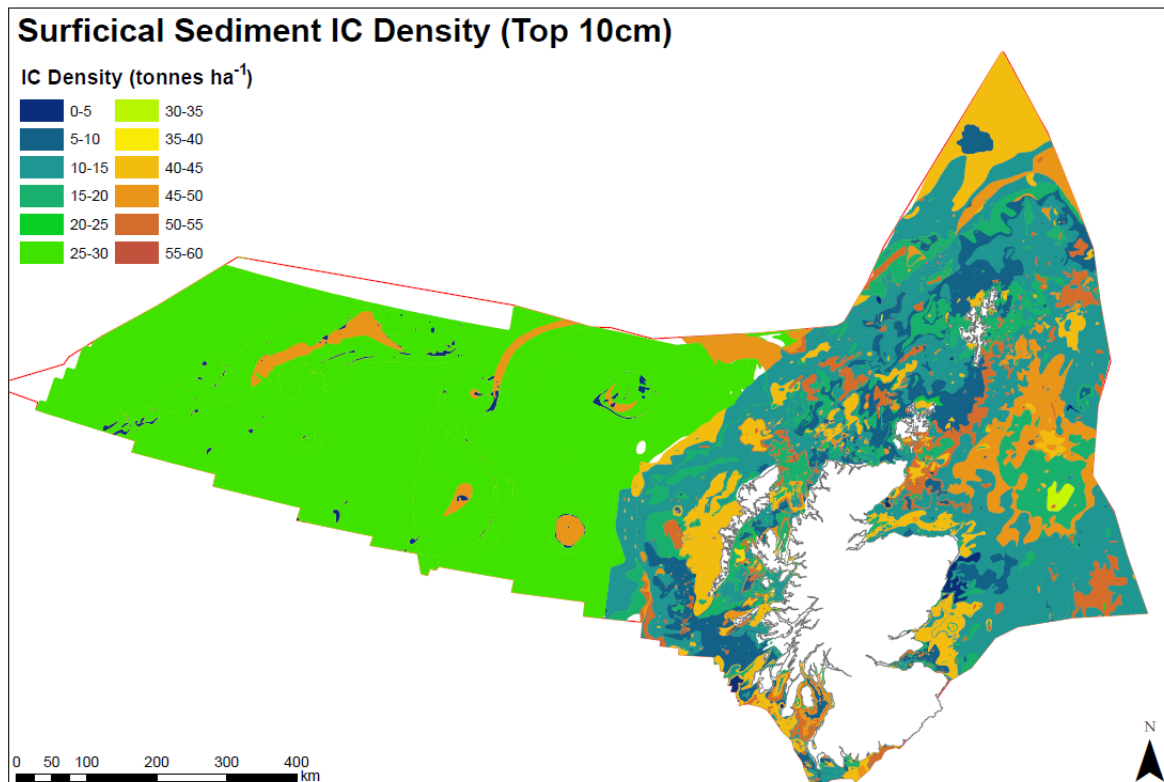
**Figure 7:** Spatial distribution of OC across Scotland's continental shelf sediments.

## 5.2. Sedimentary Inorganic Carbon Stocks

**Table 6**

Sedimentary inorganic stocks (Mt) and IC density (tonnes ha<sup>-1</sup>) for the Scottish continental shelf derived from the BGS seabed substrate and EMODnet data.

Substrate Type	IC Stock (Mt)				IC Density (tonnes ha <sup>-1</sup> )			
	Mean	SD	Min	Max	Mean	SD	Min	Max
	<b>BGS Seabed Substrate 250k</b>							
Mud	20.0	2.6	0.2	83.9	8.7	6.0	0.1	36.8
Sandy Mud	35.5	4.2	0.1	174.6	14.7	10.5	0.0	72.3
Muddy Sand	72.6	12.6	2.2	413.4	16.7	14.7	0.5	95.2
Sand	381.1	31.0	0.6	2167.8	22.3	25.8	0.0	126.8
Slightly Gravelly Sand Mud	5.2	0.7	0.4	9.4	11.3	3.4	0.8	20.5
Slightly Gravelly Muddy Sand	22.0	1.6	0.7	64.5	40.1	29.9	1.2	117.5
Slightly Gravelly Sand	99.8	6.6	2.7	393.3	25.3	21.5	0.7	99.6
Gravelly Mud	4.7	1.6	0.4	16.4	14.9	9.7	1.2	51.9
Gravelly Muddy Sand	36.8	4.1	3.5	119.8	28.6	21.9	2.7	93.1
Gravelly Sand	334.6	8.4	11.3	704.0	60.4	36.4	2.0	127.1
Muddy Gravel	0.1	0.0	0.0	0.7	15.9	13.9	2.4	79.2
Muddy Sandy Gravel	5.9	0.3	0.6	22.0	33.0	28.4	3.1	122.7
Sandy Gravel	153.0	3.9	0.2	357.9	54.2	37.2	0.1	126.9
Gravel	3.9	0.1	0.0	20.2	24.6	34.1	0.0	126.6
Rock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Sub-Total</b>	<b>1175.2</b>	<b>77.8</b>	<b>22.6</b>	<b>4547.8</b>	<b>27.8</b>	<b>23.6</b>	<b>0.5</b>	<b>107.7</b>
	<b>EMODnet 5 Folk</b>							
Mud to Muddy Sand	89.2	68.7	3.6	352.1	15.8	12.2	0.6	15.8
Sand	3.0	2.2	0.0	14.5	23.8	16.9	0.4	23.8
Coarse Sediment	11.8	3.1	0.2	32.3	46.5	12.2	0.7	46.5
Mixed Sediment	14.4	8.9	1.1	51.6	25.4	15.6	1.9	25.4
Rock Boulders	0.0	0.0	0.0	0.0	15.8	12.2	0.6	15.8
<b>Sub-Total</b>	<b>118.5</b>	<b>82.9</b>	<b>5.0</b>	<b>450.5</b>	<b>8.9</b>	<b>6.2</b>	<b>0.4</b>	<b>34.0</b>
<b>Total</b>	<b>1293.7</b>	<b>160.7</b>	<b>27.6</b>	<b>4998.2</b>	<b>23.3</b>	<b>19.4</b>	<b>0.5</b>	<b>90.1</b>



**Figure 8:** Spatial distribution of IC across Scotland's continental shelf sediments.

## 7. Conclusions

The surficial sediments (top 10cm) of the Mapped Extended Scottish EEZ (i.e. area = 554,755 km<sup>2</sup>) holds an estimated 1,515 ± 252 Mt C. The majority of this C is in the form of calcium carbonate, with an estimated 1,294 ± 161 Mt IC being held within the surficial sediments. A significantly lower quantity of C in these surface sediments is stored in the organic form, with an estimated 221 ± 92 Mt OC currently held within the top 10 cm of sediment within Scotland's Mapped Extended EEZ. A partial study of the North-west European shelf by Diesing et al. (2017), including some of the Scottish EEZ, yielded a comparable first-order estimate of 250 Mt OC in marine sediments covering an area of 633,000 km<sup>2</sup>. A further 4.16 ± 0.5 Mt OC is stored in the surficial sediment of Scotland's sea lochs (Smeaton and Austin, 2019). These sea loch sediments cover a significantly smaller area (2052 km<sup>2</sup>) than their shelf counterparts, yet their carbon density (20.27 ± 3.67 tonnes OC ha<sup>-1</sup>) far exceeds that found on Scotland's continental shelf (4.2 ± 1.8 tonnes OC ha<sup>-1</sup>). Currently there is no estimate for the quantity of IC held within these sediments.



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UKAS publication M 3003 The Expression of Uncertainty and Confidence in Measurement Edition 1, December 1997.

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