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Blue Carbon stocks and accumulation analysis for Secretary of State (SoS) region:

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V1	Parker et al.	22/10/2020	Initial draft for Cefas Review
V2	Parker et al.	22/10/2020	Final version to Defra for comment
V3	Parker et al.	05/11/2020	Final version to Defra for finalising comments
V4	Parker et al.,	16/12/2020	Final draft to Defra
V5	Parker et al.,	16/03/2021	Response to Defra comments
V6	Parker et al.,	24/05/2021	Response to final Defra comments

Introduction:

The ocean and climate are closely linked through the global carbon cycle, with marine processes both removing and adding carbon dioxide (CO_2) and other greenhouse gases from or to the atmosphere. Safeguarding blue carbon uptake and storage therefore helps to mitigate global warming, ocean acidification and sea-level rise. Management, restoration and protection of marine blue carbon habitats are potential nature-based solutions to mitigate against climate change. An overview of carbon storage services provided by different habitats, and how different activities influence this process, is a fundamental requirement to the effective management of this component of the marine system. A significant evidence gap has been a baseline understanding of present stocks and fluxes[1] associated with blue carbon habitats in Secretary of State (SoS) waters (the waters for which the Secretary of State has responsibility: the English inshore and offshore and Northern Ireland offshore zones) and UK Exclusive Economic Zone (EEZ); a gap this report addresses through an extensive review of the relevant literature.

Which habitats are considered most important?

Habitats internationally considered most important in terms of their contribution to the formation and storage of blue carbon are ***saltmarshes, seagrass meadows and mangroves (though the latter not in the UK context)***. Coastal vegetation is very effective in sequestering carbon (taking it out of circulation from the atmosphere) by burying it in root systems and surrounding muddy sediments. This process is primarily driven by local plant growth but may also involve the trapping of organic material originating elsewhere. Recently though, ***macroalgae (including kelp), intertidal sediments, subtidal sediments and deep mud / slope (>200m) habitats*** have also received attention as having potential to act as key stocks/sources of organic material, carbon reservoirs, or habitats which actively store carbon long-term (Diesing *et al.*, 2017; Kröger *et al.*, 2018; Wilson *et al.*, 2018; Attwood *et al.*, 2020; Legge *et al.*, 2020; Turrell *et al.*, 2020).

Methodology:

A review of the published literature was undertaken to provide a meta-analysis of the evidence base and report carbon stock (carbon stored within the habitat) and accumulation rate[1] information of Particulate Organic Carbon (POC) for the key blue carbon habitats within SoS (and where possible UK EEZ) waters. The associated data were compiled into a database of over 500 records, extracted from 114 publications. The focus was on literature reporting measurements within the UK but also some global-scale reviews to enable comparison of contrasting CO_2 sequestration capacity for a given habitat where UK values were absent (namely seagrasses). Where raw data from the literature were available these were added into the database. Raw data includes where original measured values for carbon density,

[1] Carbon fluxes, in the context of accumulation of buried carbon in sediments of blue carbon habitats, are referred to throughout this report as "carbon accumulation rates", to clarify that blue carbon sediments provide long-term carbon storage. The carbon flux is therefore considered unidirectional: with carbon flowing into, but not out of, blue carbon sediments. In addition to providing long-term storage of carbon in marine sediments, these habitats exchange carbon (and other greenhouse gasses) with the atmosphere and ocean environments. Net carbon fluxes, in terms of CO_2 equivalence and climate mitigation, should consider both carbon accumulation and these other, shorter timescale, greenhouse gas exchange processes.

carbon stock, or carbon accumulation were reported for individual sediment samples, replicates, or in some cases aggregation of sites.

The stock and accumulation rate information were then examined and analysed within habitat categories to determine if the evidence base was sufficient; whether conservation; management or restoration measures affected the blue carbon status (condition) of the habitats and associated estimates of average stocks and accumulation rates.

The evidence summaries and literature list (see Annex 1) were reviewed by selected UK experts for each habitat to ensure that the evidence base had been captured accurately and that associated recommendations represented research community consensus.

Stocks and accumulation summary:

A summary of the compilation of carbon stocks and accumulation rates for the key blue carbon (BC) habitats and resulting ranges and average values are reported in Table 1 below for Secretary of State (SoS) waters (Annex 1 for UK EEZ). The stock and accumulation rate information provides a good initial assessment of the ranges in carbon stores and burial rates. The final average stock and accumulation rates provided (in Figures 1 and 2; Tables 1) provide the best available summary of evidence from observations within SoS waters. It should be noted that there is an inherent uncertainty associated with each measurement itself (black points in the figures) and the habitat averages will include geographical and site specific biases depending on the distribution of sampling locations at local and regional scales. As indicated by *n* values within Table 1, there are also differing numbers of samples underlying average values across each habitat. For example only 4 data points could be summarised to calculate an average for intertidal sand carbon stocks whereas 68 data points were available to be summarised for subtidal sands. For accumulation rates low sample numbers combined with varied results contribute to average accumulation rates with large error values, which it is important not to overlook when progressing to consider habitats across their whole extents (see footnote of Table 2). A fuller narrative of the evidence base, caveats and assumptions appear in the 'evidence review' sections by habitat in Annex 1. The literature from which the data are compiled appears in the 'references' section after each habitat review in Annex 1.

Carbon stocks (kg C m^{-2}) for the different ecosystems across SoS waters are given in Figure 1 and in Table 1.

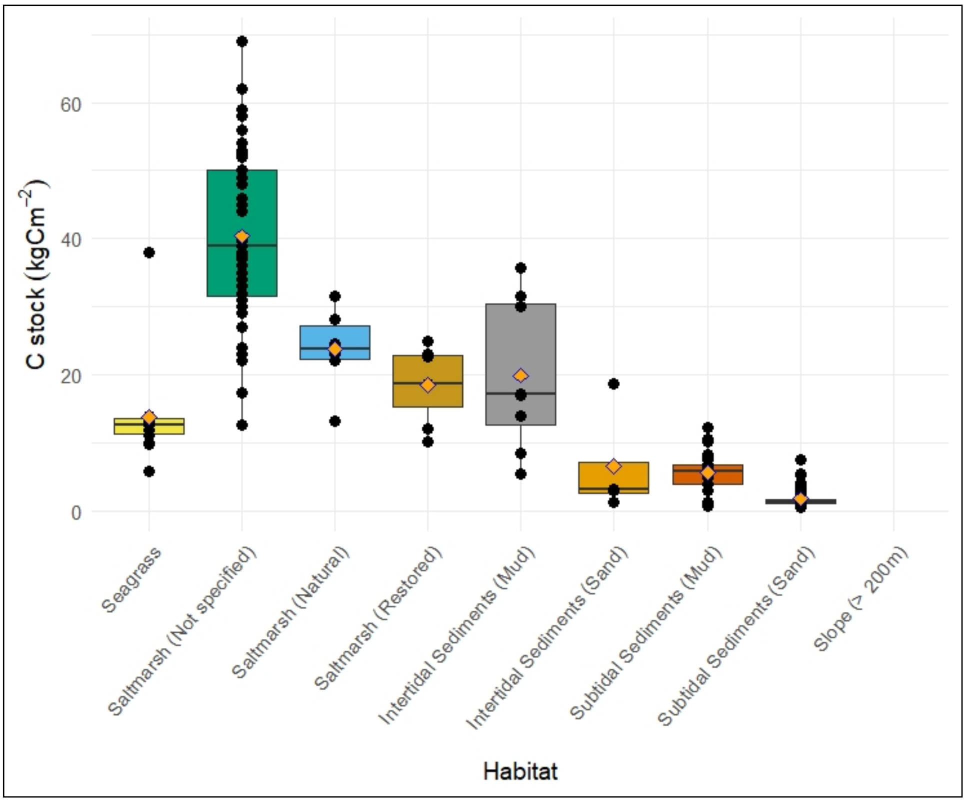

Figure 1: *Box plots showing the data distribution of sediment carbon stock values (C stock; kg C m^{-2}) for the SoS waters, to 1m depth, including the minimum, the maximum, the median, and the first and third quartiles of the data. The orange diamond shows the mean value. Gaps indicate a lack of available data for that habitat.*

The highest stocks are observed in the saltmarsh habitats (ranging from 10 to 70 kg C m^{-2} across natural and restored settings) and intertidal muds (ranging from 5 to 35 kg C m^{-2}). Both these habitats have high levels of variability associated with them. Seagrass values show much less variability with an average stock of 13.7 ± 0.2 kg C m^{-2}. Intertidal sands and subtidal sediments (muds and sands) all show a lower stock level of 6.5 (± 4.0); 6.4 (± 0.4) and 1.8 (± 0.2) kg C m^{-2} respectively as would be expected with increased sediment oxygenation due to seabed mobility, reduced supply of POC and increased depth of substrates offshore. The kelp standing stock biomass numbers are an order of magnitude smaller, with an average 0.31 ± 0.02 kg C m^{-2}, which is expected because these habitats do not include a stored stock in underlying sediments.

To achieve comparability across habitats, we chose to standardise to a sediment depth of 1 m below 1 m^2 (a total sediment volume of 1 m^3) as per IPCC Wetlands Guidance (IPCC, 2014). Overall, few studies measured or reported POC stocks to this depth (reported depths ranged from 1 cm to 50 cm and so standarisation to 1m assumes a uniform POC distribution with depth and hence may over or underestimate stocks depending on the actual POC distribution with depth). There is a developing convention for subtidal sediments to be reported to 10 cm but this includes the active processing layer of the sediment, not the full sediment depth. This is partly a reflection in differences between terrestrial and marine sampling conventions but especially for subtidal environments is largely a result of monitoring conventions for seasonal biogeochemical carbon cycling studies, resulting in the largest available datasets being focused on 0-10cm depth. Agreement on a convention for future measurements across the coastal-offshore continuum would be ideal.

Carbon accumulation rates (g C m^{-2} yr^{-1}) for the different ecosystems across the UK SoS are given in Figure 2 and in Table 1.

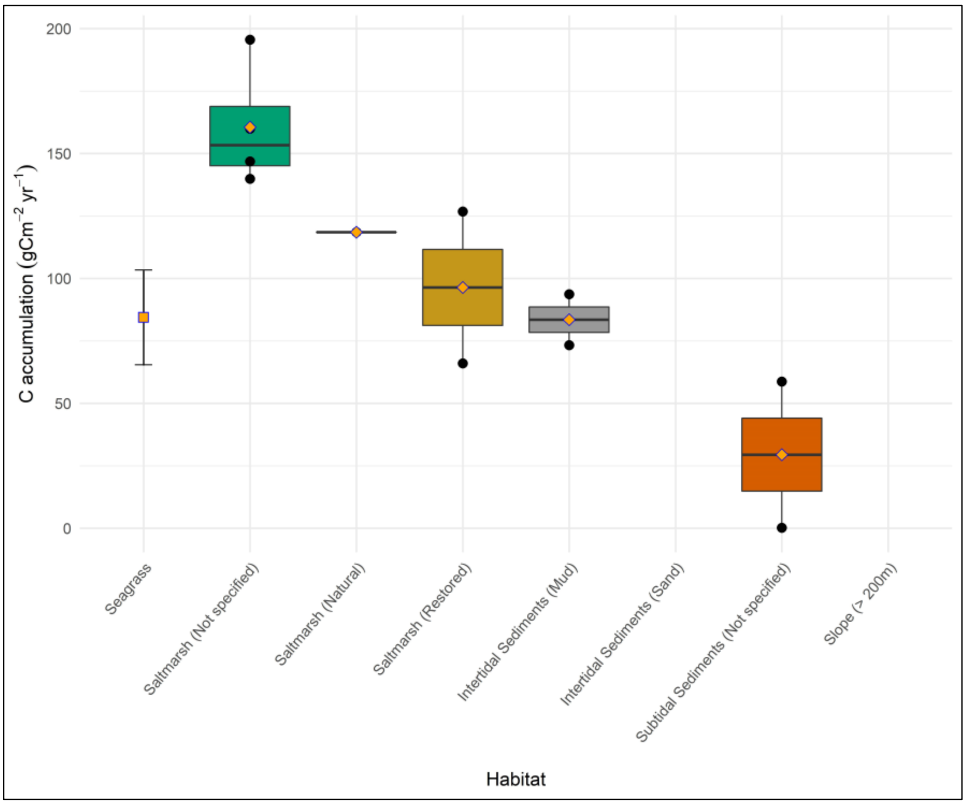

Figure 2: *Box plots showing the data distribution of carbon accumulation rates (gCm^{-2}yr^{-1}) in SoS waters, to 1 m depth including the minimum, the maximum, the median, and the first and third quartiles of the data. There are no available seagrass accumulation data for the UK. Data represented for seagrass here are the mean (orange square) and standard error values reported by Novak et al. (2020) for the Northwest Atlantic. The orange diamond shows the mean value. Gaps indicate a lack of available data for that habitat.*

The evidence base for carbon accumulation rates in SoS water habitats is poor overall. There is no information for seagrasses, intertidal sands or slope areas.

For seagrass beds in particular, no values were found that had been measured within the SoS or UK EEZ. UK studies that included values for accumulation rates cited a global average value based on limited observations in regions not representative of UK habitats (e.g. n=5 studies; non-temperate; Mediterranean; Duarte *et al.*, 2005). In the absence of measurements in the UK, the most relevant observations are likely to be those of UK seagrass species (*Zostera sp.*) within temperate settings, cite in reviews including multiple measurement sites (e.g. Novak et al., 2020; *Z. marina* in North Western Atlantic; Prentice et al., 2020). We propose that currently, the estimate of Novak et al., of 86 ± 19 g C m^{-2} yr^{-1} is the most appropriate estimate. However, the ranges of values, indicates that the average of even a large number of observations is unlikely to describe any particular site, so filling this UK evidence gap should be a priority.

Looking at carbon accumulation rates for the remaining habitats, (Figure 2), saltmarshes yielded by far the highest values, but also display the biggest range of accumulation rates across the differing habitat histories (66 to 196 g C m^{-2} yr^{-1}). Intertidal muds and subtidal sediments showed lower reported accumulation rates (averages of 83.5 and 29.5 g C m^{-2} yr^{-1} respectively) but the evidence base is very poor with <5 reported measurements per habitat.

Literature constraints: there is an issue both in the saltmarsh and seagrass literature that some reports (e.g. Burrows *et al.*, 2014; 2017) have had to use the best available alternative data where no UK measurements were available but the limitations of doing so are not clear. These may not reflect the BC storage and accumulation rates of UK habitats. Subsequent studies have gone on to cite these values as if they represent measurements of UK habitats, resulting in a growing distance between the cited references in reports and the studies where the measurements were originally reported, which complicates identification of the primary evidence base. This potential error can then propagate up to economic valuation studies (e.g. Watson *et al.*, 2020) without maintaining the original assumptions and caveats.

Early studies, which pre-date the research focus on 'blue carbon', made measurements which can be used to derive stocks and accumulation rates, but often did not publish the information on all parameters required to derive these values. We expect that more UK data may be available if unpublished supplemental data could be obtained, and from other older unpublished datasets. In some cases, reasonable estimates can be made by deriving estimated sediment bulk density for example, but these calculations introduce additional sources of uncertainty and have not been considered for this data aggregation. There are instances (e.g. Atwood *et al.*, 2020) where publications have manipulated data from earlier studies without clearly identifying methodology, the assumptions made or their implications on uncertainty.

Habitat status and timescales of change:

<u>Habitat state:</u> For most habitats (seagrasses, intertidal sediments, macroalgae (kelp), subtidal sediments and slope) there were not sufficient data (not enough measurements) to allow any statistical assessment of status variability driven by habitat management, history or impact/degradation. Similarly, for saltmarshes specifically, the habitat state information (for example; natural/mature, restored, created, management regime) was often not recorded during all measurements (appears as 'not specified' in the figures/tables), so it was not possible to assign an overall condition level.

The evidence base for saltmarshes does show some difference between restored and natural sites with both stocks and accumulation rates being lower in the restored sites. However, the number of measurements of accumulation rates is low ($n < 5$). The bulk of saltmarsh values sit in the 'not specified' category but it is clear from the distribution that the literature cover both natural/mature and restored sites.

Similarly, a comparison of natural saltmarsh and managed realignment sites in the Blackwater estuary (Adam *et al.*, 2012) found that less vegetationally developed (younger) sites had lower carbon densities and stocks then natural saltmarshes, while those with better developed vegetation were equal or even higher than their natural counterparts. The factors influencing vegetation development were not explored in this study but are likely to be complex and changeable with time, involving for example climate, pressures from uses and state of adjacent sites, as well as inherent sediment characteristics. A study by Kellaway *et al.* (2016) in Australian saltmarshes found that sediment factors were key.

Additionally, UK studies investigating the impacts of grazing intensity across 22 saltmarshes showed no difference in soil organic carbon content (see saltmarsh review in Annex 1 for more info).

Timescales of change: The timescale associated with habitat age/condition/history was only reported for saltmarshes. In one study (Burden *et al.*, 2019; see saltmarsh review) evaluating the length of time a recreated marsh will take to become functionally equivalent to a natural system, the authors conclude that carbon accumulation was initially rapid then slowed to a steady rate and that it would take approximately 100 years for a restored saltmarsh to reach the same carbon stock as a natural site.

A study exploring the effect of returning some 26 km^2 of reclaimed land in the Humber estuary to intertidal habitats such as mudflats and saltmarshes (Andrew *et al.*, 2008), through managed realignment, suggests it could result in extra storage of about 800 t of carbon per year, along with extra storage of nitrogen, phosphorus and heavy metals. The authors state, that over the last 50 years almost 14,000 tonnes of organic carbon were stored in Welwick Marsh. Furthermore, historic reclamation between 1744 and 1965 of about 35 km^2 of saltmarsh in the same area has probably prevented burial of some 200,000 tonnes of organic carbon and 11,000 tonnes of organic nitrogen . While the authors do not specifically discuss future restoration timescales, they do suggest based on their previous work that managed realignment schemes are likely to be cost effective on a 50-year time frame. Generally, time-scale analysis of land reclamation or habitat restoration and their effect on carbon accumulation and long-term storage are sparse and should be considered as a next step.

SoS total POC stock and accumulation rates:

Linking the stock and accumulation rate information together with the habitat extent (JNCC, 2020) allows an initial understanding of the total carbon stock or carbon sequestration rates associated across the SoS. The extents, total stock and accumulation, and CO_2 equivalents across the SoS are shown in Table 2 and Figure 3a (stock) and b (accumulation) below.

Table 1: *A summary of SoS blue carbon habitat sediment organic carbon stocks and accumulation rates. 'nd' = not determined*

Habitat	Granularity	Range of sediment organic carbon stock (kg C m^{-2})	Average organic carbon sediment stock (kg C m^{-2}) (± SE)	Range of organic carbon accumulation rate (gC m^{-2} yr^{-1})	Average organic carbon accumulation rate (gC m^{-2} yr^{-1}) (± SE)	Number of studies / references
Seagrass		5.9 - 38.0	13.7 (± 0.2) (n = 14)	nd	*[86 ± 19]* *	Sediment carbon stocks = 2 studies (Green *et al.*, 2018; Röhr *et al.*, 2018); *Sediment C accumulation rates – Novak et al., 2020 (non-UK - summary estimate temperate, N. W. Atlantic sites)*
Saltmarsh	Not specified	12.7 - 69.0	40.3 (± 0.4) (n = 59)	139.9 - 195.5	160.6 (± 12.4) (n = 4)	Sediment C stocks = 7 studies; (Adams *et al*., 2012; Beaumont *et al*., 2014; Burden *et al*., 2019; Burrows *et al*., 2014; Cannell *et al*., 1999; Chmura *et al*., 2003a; Ford *et al*., 2019) Sediment C Accumulation = 2 studies (Callaway *et al*., 1996; Adams *et al*., 2012)
	Natural	13.2 - 31.6	23.8 (± 0.2) (n = 16)	NA	118.5 (n = 1)	
	Restored	10.1 - 25.0	18.6 (± 0.4) (n = 7)	66.0 - 126.8	96.4 (± 30.4) (n = 2)	
Intertidal Sediments	Mud	5.4 - 35.6	19.9 (± 4.0) (n = 8)	73.3 - 93.7	83.5 (± 10.2) (n = 2)	Sediment carbon stocks = 3 studies (Trimmer *et al.*, 1998; Thornton *et al.*, 2002; Adams *et al.*, 2012) Sediment carbon accumulation rates = 1 study (Adams *et al.*, 2012)
	Sand	1.3 - 18.6	6.5 (± 4.0) (n = 4)	nd	Nd	
Subtidal Sediments	Mud	3.1 - 12.3	6.4 (± 0.4) (n = 23)	0.2 – 58.7	29.5 (± 29.3) (n = 2)	Sediment carbon stocks - Multiple Cefas surveys Sediment C accumulation rates = 2 studies (De Haas *et al.*, 1997; Queirós *et al.*, 2019)
	Sand	0.4 - 7.6	1.8 (± 0.2) (n = 68)			
Slope (>200m)		nd	nd	nd	nd	NA
			Average biomass standing stock (kgCm^{-2})			
Kelp		nd	0.309 (± 0.017) (n = 4)	NA	NA	Pessarrodona *et al.*, 2018

Table 2: *a summary table of SoS blue carbon Habitat extents, average habitat carbon stocks and accumulation rates, total stock and total accumulation rates, and CO_2 equivalents. 'nd' indicates not determined.*

Habitat	Extent (km^2) (Flavell *et al.*, 2020)	Average carbon stock ($kgCm^{-2}$)	Average carbon accumulation ($gC\ m^{-2}yr^{-1}$)	Total stock (million tonnes C)	Total accumulation (tonnes C yr^{-1})	CO_2 equivalent stock (million tonnes CO_2)	CO_2 equivalent accumulation (tonnes CO_2 yr^{-1})
Seagrass	48	13.7 (± 0.2)	*[86 ± 19] **	0.66 (± 0.01)	*4080* (± 912)	2.4 (± 0.03)	*15,000* (± 3,300)
Saltmarsh	110	36.8 (± 0.5)	136.2 (± 15.1)	4.05 (± 0.06)	15,000 (± 1,700)	14.8 (± 0.2)	55,000 (± 6,000)
Intertidal (mud) sediments	431	19.9 (± 4.0)	83.5 (± 10.2)	8.6 (± 1.7)	36,000 (± 4,000)	31.4 (± 6.3)	132,000 (± 16,000)
Subtidal (mud) sediments	3732	6.4 (± 0.4)	29.5 (± 29.3)	23.9 (± 1.4)	110,000 (± 109,000)	87.5 (± 5.07)	403,000 (± 400,000)
	15,440			98.8 (± 5.7)	455,000 (± 452,000)	362.1 (± 21)	1,667,000 (± 1,656,000)
Slope	131	nd	nd	nd	nd	nd	nd
		Average biomass standing stock ($kgCm^{-2}$)		Total biomass standing stock (million tonnes)		CO_2 equivalent total biomass standing stock (million tonnes)	
Kelp	239	0.31 (± 0.017)	na	0.074 (± 0.004)	na	0.271 (± 0.015)	na

NB: For both tables - saltmarsh in this case includes saline reedbeds; intertidal sediments includes mud and sand (extent is "littoral mud"), subtidal sediments includes mud and sand (extent is "sublittoral mud') and kelp/macroalgae is only kelp biomass. The subtidal sediment (mud) extents and stock and accumulation levels are reported using the 50% and 10% mud/sand boundaries respectively as described below. All habitat organic carbon (OC) stocks are reported to a sediment depth of 1 m as per IPCC guidance. The standard error (±) provided for total stock and accumulation rates is based *only* on the reported standard error of the average stock and accumulation rate derived in this report and does not take into account the unquantified uncertainty of the habitat extent values of Flavel *et al*., 2020 which were reported with a confidence rating but not an uncertainty range. Any uncertainty in the habitat extent would need to be propagated through the calculation of total stock and accumulation rate values. In sum, the 'total' values presented here are therefore minimum potential variances rather then complete. The SoS stock and accumulation rate averages include data from Wales as well (mainly saltmarshes) to improve the confidence level of this average and in light of the little variance between geographic areas across England and Wales. The burial rates for seagrasses use a Northwest Atlantic average (Novak et al., 2020) in the absence of UK information.

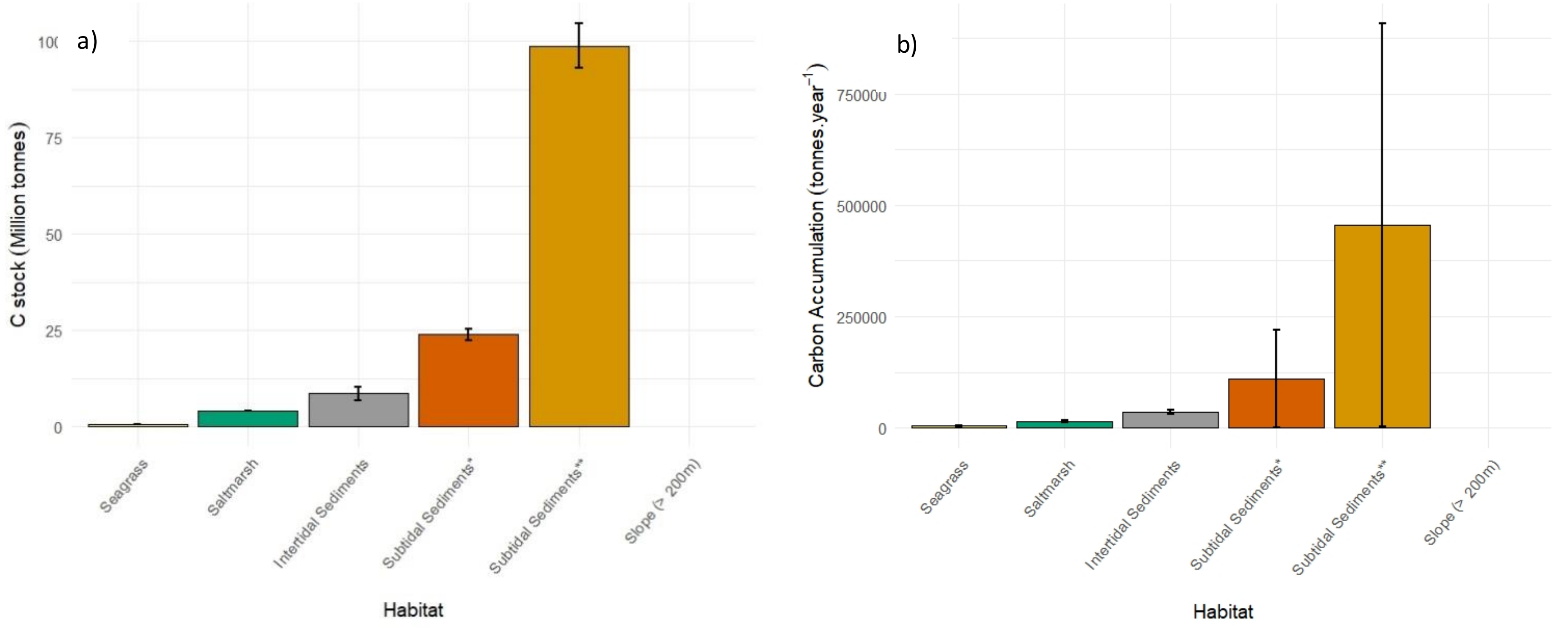

Figure 3: *Box plots showing the total carbon stock a) and annual accumulation b) for the SoS waters, to 1 m depth as listed in Table 2. The error bars are the +/- as standard errors. The gap in slope data indicates where totals have not been determined due to gaps in stock and burial evidence. The subtidal sediment (mud) totals for stock and accumulation are reported using the 50%* and 10%* mud/sand boundaries respectively.*

Overall, the POC stock held in the non-conventional blue carbon habitats, intertidal and seabed sediments (8.6 and 23.9 million tonnes respectively) is nearly an order of magnitude bigger than the other coastal habitats (0.7 and 4.1 million tonnes for seagrasses and saltmarsh respectively). This is consistent with findings in Legge *et al.* (2020) and Kröger *et al.* (2018) for the UK Shelf and North–West European Shelf regions. The seabed sediments (sublittoral muds) have the largest potential accumulation total, compared to other habitats, at ~ 0.1 to 0.5 million tonnes C per annum, although this is based on very few rate measurements, so has significant uncertainties and is produced largely by the large extents of this habitat. This gives some context in the comparative reservoirs of carbon residing within these habitats and their role in sequestering atmospheric CO_2 long-term.

Habitat boundaries: EUNIS (European Nature Information System) habitat classification carbon processing - The extents used here are derived from the JNCC report (2020) on SoS habitat extents based on EUNIS habitat classification. It should be noted that EUNIS is based on Folk classification sediment types (mud and sandy-mud for littoral, sublittoral and deep-sea muds defined as approximately 50% fines/sand). This does not account directly for sediment permeability transitions which drive POC storage and fate which occur at ~ 10% fines alone (Parker *et al.*, 2012; Silburn *et al.*, 2018). This means that the area extents for these habitats relevant to areas of POC storage are very likely significant underestimates. The stock and accumulation values (Table 2 and Figures 1 and 2) for the subtidal sediment take the ~10% fines boundaries into account. When scaled to total stock and accumulation rates the extents of both the 50% and 10% fines boundaries are reported for the sub-tidal sediments.

CO_2 equivalents: the total carbon stored as CO_2 equivalents, held in SoS blue carbon habitats (excluding a small slope extent which has no measurements) is ~136 million tonnes, with shelf and intertidal sediment stocks accounting for ~64% and 23% of this stock respectively. The total stock is equivalent to about 37% of the UK total annual emissions in 2019. Combining the stock and accumulation rate CO_2 equivalents for each habitat allows some estimation of the potential achievable impact on CO_2 sinks of different policies on habitat management creation, restoration or protection. For example: if 15% of saltmarsh extent is re-established/created it will allow an additional storage of 2.25 million tonnes once the habitat is fully established (~100yrs; Burden et al., 2019) and increases the annual accumulation by 8250 tonnes of CO_2. The trajectories of carbon burial and green house gas emissions (and hence net C sequestration) can be complex and non-linear over time (Adams et al., 2012).

Considering the timescales of this service delivery (under habitat creation or restoration), change under impact / recovery and also future change (under climate change) of carbon and CO_2 stock/accumulation rate, it is important to understand the future benefits these habitats can offer in terms of climate mitigation. Similarly, protection of seabed stocks or coastal habitats have the potential to avoid emissions in future, although the evidence base to understand changes of this type needs improvement. While it is apparent that GHG emissions occur if coastal habitats (seagrasses, saltmarshes) are disturbed, eroded or destroyed, the understanding of the net effects of disturbance on intertidal, subtidal and slope sediments on GHG release is still unclear (Legge *et al.*, 2020). Similarly, the dynamics of irrecoverability (i.e. what proportion of carbon loss is permanent or can be recovered under protection/restoration) and the associated timescales of the achievable benefits needs systematic understanding (Goldstein *et al.*, 2020).

Status of the SoS waters evidence base:

Below is a summary of the confidence level of the evidence base for stocks/accumulation rates associated with each blue carbon habitat across the SoS waters. The confidence rating used is the Marine Climate Change Impacts PartnershipPartnership approach (MCCIP 2011) based upon level of evidence and consensus across the literature relevant to SoS waters.

Seagrasses: LOW/LOW Existing information indicates that seagrass stock per unit area is significant at 13.7 (± 0.2) Kg C m^{-2} which scales to a total SoS stock of 0.7 million tonnes. Linking to the temperate storage rates (86 +/- 19 g C m^{-2} yr^{-1}) gives considerable SoS total accumulation of 4080 g C per annum. While this ecosystem has by far the smallest extent, and thus very likely plays only a minor role in the total carbon accumulation and storage budget in SoS waters, it is evident that very little is known about POC stocks across the SoS waters and particularly about region-specific accumulation rates.

Saltmarshes: MEDIUM/LOW these ecosystems are hugely important both in terms of total stocks and annual carbon accumulation rates and the evidence base is the most robust across the coastal habitats. However, existing observations are focused on Welsh and Essex estuaries (see Figure A1). A better geographical spread of observations is required to reduce the uncertainty in the SoS-wide or UK-wide average. A significant dataset of stocks and some accumulation rate measurements will be coming on-line in mid-2021 as part of the NERC CSide (Carbon Storage in Intertidal Environments) project[2].

Intertidal mud and sandflats: LOW/LOW These ecosystems have not yet received the attention they deserve in the blue carbon context as the literature base has largely focused on establishing the seasonal variability in the processing of carbon. However, as the numbers in Table 1 illustrate, they are likely to contain significant total carbon stores and with their high annual accumulation rates contribute to capturing large amounts of carbon. The evidence base is focused on a few locations on the east coast (Colne, Ouse, Blackwater and Humber) so further measurements with a more even geographical distribution are advisable.

Shelf seabed: MEDIUM/LOW This review highlights the dominance of the shelf seabed as a carbon reservoir and its potential capacity to annually sequester carbon and store it long-term. However, despite good stock information (for the upper 10 cm of sediment) the evidence base for sequestration rates is very poor and biased, to an unknown degree, across the UK EEZ towards measurements in high sequestration environments (namely, sea lochs). Deeper measurements (ideally to 1 m sediment depth) would shed light on long-term carbon fate and enable extrapolation to an equivalent depth as used for other habitats. For more accurate assessments of total seabed stocks and accumulation, some refinement of the extents (beyond mud/sandy-mud) would be useful to represent all substrates which can store POC.

Slopes: LOW/LOW These are sea areas where carbon parameters are particularly underrepresented in terms of measurements, with no measurements within the SoS waters, which is understandable given their inaccessible nature. Nevertheless, a dedicated

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[2] NERC CSide (Carbon Storage in Intertidal Environments) project information will be available via https://www.c-side.org/

programme to evaluate their role in carbon storage is desirable, given the large sequestration potential due to the deep, cold nature of these substrates.

Kelp: MEDIUM/LOW This review has shown that the macroalgal (kelp) biomass carbon storage is potentially significant per unit area (0.31 Kg C m^{-2}). Across the UK SoS waters these data scale to a biomass reservoir of 0.074 million tonnes C. However, this only contributes to long-term carbon storage if the biomass is buried long-term in a receiving habitat area (intertidal or shelf seabed). The evidence base on the fate of macroalgal / kelp carbon is very poorly constrained (with ranges from 4 to 9% of biomass being stored in sediments; Querios *et al.*, 2019) and remains a key gap.

Linking gaps in the evidence base and recommendations for priorities, next steps:

This review provides a good but snap-shot understanding of the status of the evidence base for SoS blue carbon habitats. There are significant gaps in the evidence base, perhaps not initially apparent from the literature due to the large number of reviews and global measurements used in publications relating to the UK. This work has led to a number of recommendations;

1. **Targeted observations of carbon stocks and accumulation rates** are required across the main blue carbon habitats to improve the evidence base overall and gap-fill in certain geographical locations to understand regional variability and ensure aggregated values are representative of any spatial variability or site specific controlling mechanisms (salinity, temperature, context). This is true especially for seagrasses (where the carbon evidence base for both stocks and accumulation rates is poor), intertidal and shelf sediments as well as slope sediments, due to the very low numbers of measurements of accumulation rates and the potential overall stock significance of these habitats due to their significant extents.

   Furthermore, it must be stressed that a SoS or UK EEZ wide stock or accumulation average (even if well constrained by numerous geographically dispersed measurements) may not be representative of actual stock or accumulation rates for any given site. The spread of available measurements within the UK to date represent, not uncertainty in those values for the sites studied, but uncertainty in an appropriate average over the extent of any habitat in the UK. As observations increase in both number and geographical spread, these should include the information needed to parameterise the between-site variability so that future SoS and UK-wide estimates can account for differences of relevant habitat condition and context controlling factors for blue carbon.

2. **Provenance of the shelf Particulate Organic Carbon (POC) stock** is also key (terrestrial vs marine, POC source such as from coastal habitats, macroalgae (kelp) or other sources) to aid management decisions. Particular habitats such as macroalgae (kelp) act as carbon donors rather than burying *in situ* and understanding supply amounts and pathways from these carbon capture habitats to receiver areas on the shelf are key, both to understand fate/sink but also in terms of management and protection of stocks from disturbance. While focus on the fate of macroalgal carbon is increasing, the broader evidence base around shelf carbon provenance remains poor.

3. **Inclusion in monitoring:** The sampling protocols required for determining POC stocks and accumulation rates are relatively low cost and routine (core sampling, POC concentration determination). The only higher costs element is isotopic analysis for sediment accumulation rates, but again these are standard geochemical techniques. Given this fact and that the evidence base is generally so poor there is scope for urgent inclusion of key blue carbon parameters in existing monitoring of the main blue carbon habitats to rapidly raise the confidence of the evidence base. There is an urgent need to link up monitoring in a systematic way to allow reporting of robust stocks/accumulation rate assessments across SoS / UK EEZ and also to consider how

IPCC/UNFCCC or other requirements can be included. For coastal wetland habitats (i.e. saltmarsh and seagrass) to meet the IPCC reporting standards for UK GHG emission accounting, there are several data gaps to resolve, such as the collection of accurate spatial data of habitats, including changes and loss due to specific activities and the establishment of consistent baseline time series. UK-based measurements of carbon stock and accumulation rates would also be required to provide accurate emission or removal totals. There are considerable present opportunities across coastal biodiversity sampling programmes such as the Natural England ReMEDIES (Seagrasses) and Environment Agency ReMeMaRe (Restoring Meadows, Marshes and Reefs) initiatives as well as various intertidal and offshore sampling opportunities, including in Scotland and other Devolved Administrations, and they provide integrated sampling opportunities for various requirements which will add considerable value to these programmes. Understanding the requirements for differing policy drivers across climate mitigation/blue carbon (including requirements for future Greenhouse Gas Inventory reporting), Natural Capital accounts and valuation, in support for Nature-based Solutions and Marine Protected Area/Highly Protected Marine Area (MPA/HPMA) objectives offshore, may allow full integration of carbon sequestration alongside assessments and observations of other habitat functions and services.

4. **Status, irrecoverability and management:** Improved understanding of the effects of management, including protection and restoration, and pressures on the carbon storage of all the habitats is urgently needed as this will allow insights into the gains possible through habitat restoration, management or protection and the timescales upon which they can be delivered. Key questions are: what mechanisms produce and maintain carbon stocks and accumulation; are existing degraded stocks recoverable or irrecoverable once pressures are removed and over what timescales?

   Assessing the impacts of management on habitat condition (grazing, impact levels) and timescales of recovery/change was outside the scope of this review. However, applying the existing baseline stock and accumulation levels provided in this review to future management or climate pressure considerations would be of merit in future. In particular, improved understanding of the impacts of trawling (Parker *et al.*, 2012) and other activities, could give useful insights to stock or accumulation degradation, timescales of change (including irrecoverability) and help inform management actions (including HPMAs or other Nature-based Solutions) to preserve, protect or restore the considerable carbon stocks offshore.

5. **Predicting future habitat carbon stocks and accumulation:** Linking all the recommendations (1-4) above is the need to test and develop tools (models) which can be used to investigate habitat specific carbon cycles (including carbon stocks and accumulation), their sensitivity to various impacts or associated policy and management decisions (including climate forcing itself) and timescales of response.

6. **Formation of a UK blue carbon technical group:** To build on the baseline information (across SoS and UK EEZ) collated in this project, to collate any unpublished data and support the Defra and other policy makers with state-of-the-art information and identified evidence gaps. This group could also facilitate legacy for a 'live' stocks and

accumulation rates portal across the UK EEZ. This could be based on the reviewers group here with links to key Defra Arm's Length Bodies (ALBs) and Devolved Administrations (DAs). This group could draw together and update the evidence base required to support policy objectives relating to Blue Carbon.

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Annex 1: Summaries of reviews of the existing evidence base, uncertainties, and gaps for each of the main blue carbon habitats within UK EEZ / SoS waters.

An overview of the evidence base for SoS/UK EEZ waters (as of October 2020) is illustrated in the map below.

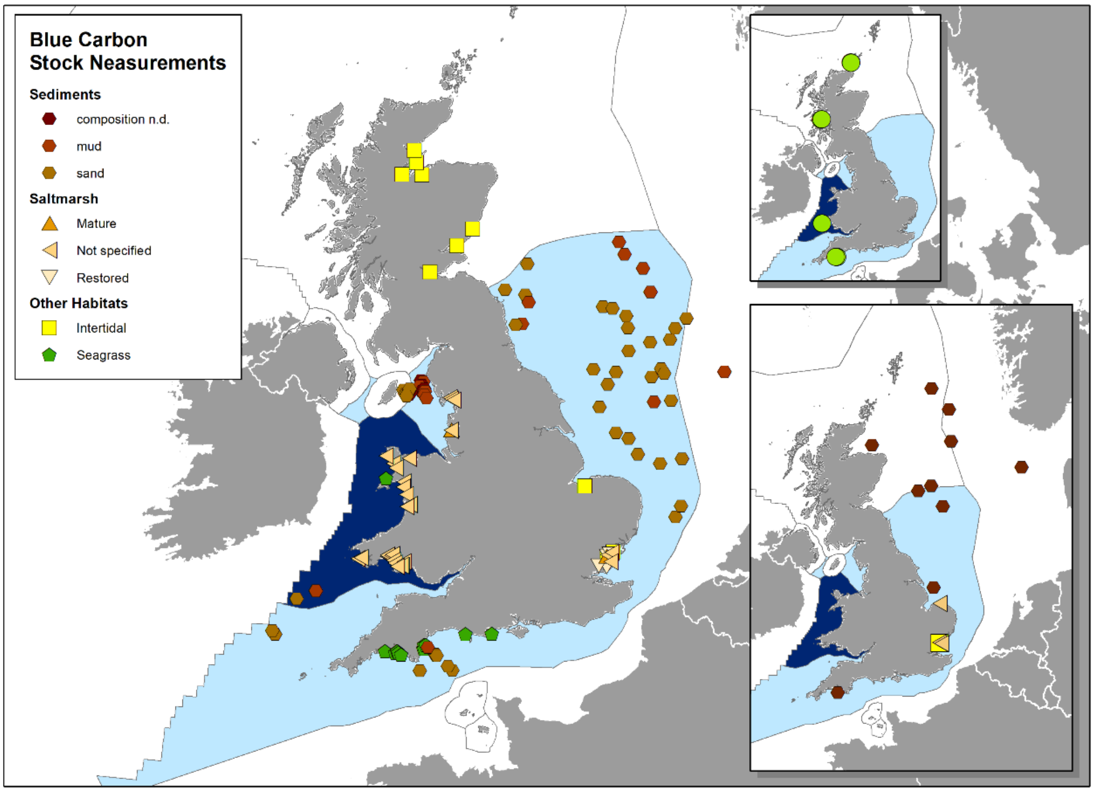

Figure A1: Locations of measurements of blue carbon habitat carbon stocks (large map), kelp biomass (small inset map) and carbon accumulation rates (upper right-hand inset). Sea areas delineated by the light grey lines are Devolved Administration Boundaries from the ADMIRALTY Marine Data Portal (UK Hydrographic Office). Discrepancies were found in the original data and while those were addressed, these amendments were not agreed upon by the DAs. English and Northern Irish Offshore waters (together making up the SoS) are shaded in light blue, Welsh waters dark blue. Data for both areas have been used to determine the average stock/accumulation levels but SoS water habitat extents only for scaling.

Methodology:

A total of 116 sources of data (reports, peer-reviewed publications, datasets, etc.) were reviewed during this exercise and, where available, the following key information was extracted:

- Habitat type
- Habitat condition (e.g. degraded/pristine and/or natural/restored)
- Sediment type (e.g. mud/sand)
- Location information/geographic coordinates of specific sites sampled
- Sediment organic carbon (%), or organic matter (%)
- Sediment dry bulk density (DBD)
- Carbon stock
- Sediment depth to which carbon stock data were measured and reported
- Carbon accumulation rate

Additional information also recorded where available, e.g. organic matter content, vegetation biomass and sediment accumulation rates in case of future usefulness.

Where papers conducted a review or used carbon stock or accumulation rate values from other sources (not original measurements) the original data source was reviewed and cited directly in the data summary. This avoided potential "double counting" of observations which had been re-reported in multiple studies. Of all data sources reviewed 12 contained original measurements of carbon stock and/or carbon accumulation rates within the SoS region. There were three more sources that reported original measurements for stocks and/or accumulation rates within the UK as a whole.

Where carbon stocks were not reported, but sediment carbon content was presented as either organic matter (%OM) or organic carbon (%OC) content, carbon stock was calculated as follows. Where organic matter content (often as "loss on ignition") was reported and organic carbon measurements were not available, the equation of Howard *et al.* (2017) was used to convert organic matter (OM) to organic carbon (OC) (Equation 1). Carbon stock was calculated from dry bulk density (DBD) and organic carbon content using Equation 2.

$$OC(\%) = 0.40 * OM(\%) + 0.0025 * [OM(\%)]^2 \qquad \text{(Equation 1)}$$

$$\text{Carbon Stock } (g\ C\ cm^{-3}) = OC(\%)/100 * DBD(g\ cm^{-3}) \qquad \text{(Equation 2)}$$

Where possible, data for individual samples was extracted from the evidence base. However, many data sources presented measurements as means (with variance) of replicates or averaged over several sites. These were recorded along with the sample size information. Where sample size (e.g. number of replicates) was not reported, the corresponding mean values could not be included in the data summaries due to the inability to calculate the resulting variances. Including these data would have made it impossible to estimate uncertainty in the SoS averages presented, or more importantly, represent the observed variability of carbon stocks and accumulation rates across the SoS.

For subtidal and intertidal sediment carbon stocks, all data sources reported singular original observations (not averages) therefore, mean and standard errors for SoS and UK EEZ were calculated directly.

Conversely, all saltmarsh and seagrass observations were presented in data sources as mean values. The following procedure was followed in order to summarise these data while preserving a quantification of variability (uncertainty):

1. Each reported measure of variation, from the original data source, was converted into a standard error for its accompanying carbon flux or accumulation rate value.
2. A "mean of means" (MOM) was calculated for each habitat. Note that it was deemed not appropriate to weight the values (e.g. by their standard error) for the calculation of the mean, since the standard error reflects the natural variability within the measured samples. The assumption was made that surveys within a habitat were representative and approximately unbiased.
3. Assuming independence between surveys (data sources), the variance (var) of the MOM was calculated as sum of the variances of each survey's mean value (m_i), all divided by N^2, where N is the total number of surveys for that habitat:

   $$var(MOM) = [var(m_1) + var(m_2) + \dots + var(m_N)] / N^2$$

   The variance of each survey's mean value is the square of the standard error associated with that mean.
4. The standard error of the MOM was calculated as the square root of var(MOM).

Seagrasses *- Carolyn Graves*
Reviewed by H. Kennedy, Bangor University

Stocks:

To date, there are only two published records of UK seagrass sediment carbon stocks. These report on 13 sites from the western Channel (subtidal; Green *et al.*, 2018), and one site from north–west Wales (inter/subtidal not reported; Röhr *et al.*, 2018). A PhD thesis (Potouroglou, 2017) reports carbon stocks for seven intertidal sites along the west coast of Scotland. Based on these limited measurements, the SoS seagrass carbon stock, to 1 m sediment depth, is: 13.7 ± 0.2, and the UK stock is: 13.0 ± 0.1 kg C m^{-2}.

From the few UK sites which have been surveyed, seagrass carbon stocks are highly variable. In the western Channel, most 13 of 14 sites reported had between 9.6 and 15.0 kg C m^{-2}, while one had 38.0 ± 7.2 kg C m^{-2} (Green *et al.*, 2018). This clearly demonstrates the risk (inappropriateness) of extrapolating the average of a heterogenous property across the habitat extent for the whole SoS or UK EEZ. More measurements are needed to determine the spatial variability of stocks and improve the validity of a UK or SoS-wide stock estimate.

Published measurements of seagrass-associated carbon stocks, reported in global scaled reviews, were initially biased towards the species *Posidonia oceanica* in the Mediterranean Sea. However, now clear differences between species have been established (e.g. Lavery *et al.*, 2013). It is widely accepted that *Posidonia oceanica* store more carbon than other species, however between other seagrasses species site specific factors (sediment type, proximity sources of allochthonous carbon) are expected to be a more significant driver of carbon storage variability (Kennedy *et al.*, 2010).

All seagrass in the UK (also called eelgrass) is *Zostera spp*. (Wilding *et al.*, 2009). Applying average carbon stocks from global reviews based on other species to UK seagrass (e.g. Burrows *et al.*, 2014) is therefore not appropriate. All SoS measurements to date are for *Z. marina*, while in Scotland both *Z. marina* and *Z. noltii* meadows were sampled and the latter found to have higher carbon stocks (Potouroglou, 2017).

On average the available UK data are at the upper end of the reported range of European *Zostera marina* stocks (0.15 ± 0.9 to 4.3 ± 1.2 kg C m^{-2}; Green *et al.*, 2018). For comparison, *Posidonia oceania* stocks have been reported as up to 40 - 410 kg C m^{-2} (e.g. Lavery *et al.*, 2013), while *Z. marina* stocks are 2.3-35.2 kg C m^{-2} (Röhr *et al.*, 2018).

Accumulation rates:

For English, Northern Irish, and Welsh waters there are no reported observations of seagrass carbon sequestration. For Scotland, a carbon sequestration capacity of 1321 t C/yr has been reported (Burrows *et al.*, 2014; 2017; Turrell, 2020). This flux is based on the roughly estimated Scottish habitat area of Burrows *et al.* (2014), combined with a seagrass carbon sequestration value of 83 g C m^{-2} yr^{-1} which is the average of a limited number of observations (range: 10-350 g C m^{-2} yr^{-1}; n=5, geographically limited to the Mediterranean) reported in the global review of Duarte *et al.* (2005a). McLeod et al (2011) presented an updated higher global estimate of 138 ± 38 g C m^{-2} yr^{-1} (range 45-190, n=123 sites). This is much smaller than the more recent global, all species, accumulation rate of Forqurean et al. 2012 (251 ± 49 g C m^{-2} yr^{-1}), However a recently reported *Z. marina* specific value of 85 ± 19 g C m^{-2} yr^{-1} based on seven sites in the north-western Atlantic (Novak *et al.* 2020), is close to the mediterranean estimate used in the Scottish reports, and is currently the most appropriate estimate for UK waters in the absence of observations or more comprehensive relevant reviews.

Summary:

The evidence base for seagrasses is limited, and more measurements are required for both UK seagrass carbon stocks and fluxes (for which there are currently no measurements) across the SoS and UK EEZ.

<u>*Seagrass references:*</u>

SoS data:

Green, A., Chadwick, M. A., and Jones, P. J. S. (2018). Variability of UK seagrass sediment carbon: Implications for blue carbon estimates and marine conservation management. *PLoS ONE*, 13(9), 1–18. doi: 10.1371/journal.pone.0204431.

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Turrell, W. R. (2020). A Compendium of Marine Related Carbon Stores, Sequestrations and Emissions. Scottish Marine and Freshwater Science 11(1) Marine Scotland Science. doi: 10.7489/12261-1

Saltmarshes *- Silke Kröger*
Reviewed by Julian Andrews (UEA) and Natalie Hicks (University of Essex)

Stocks:

So far, we have reviewed 27 published papers reporting on saltmarshes in the UK. The largest number of the UK measurements are focused on the west coast, where Ford and co-workers (2019) made field observations of vegetation (species), sediment bulk density, percentage of organic matter and sediment stock ($tCha^{-1}$) in 23 saltmarshes in Wales. They also developed large-scale predictions of carbon stock in these habitats based on plant community and soil type, parameters that were found to explain 44% of variation in carbon stock. Across the SoS and the UK, organic **carbon content** expressed as a percent of the sediment varies from site to site, but typical values range between **1-6 %** (Andrews *et al.*, 2008; Beaumont *et al.*, 2014; Burden *et al.*, 2019). Variable carbon stocks of **12.7-69 kg C m^{-2}** (Adams *et al.*, 2012; Beaumont *et al.*, 2014; Burden *et al.*, 2019; Chmura *et al.*, 2003; Ford *et al.*, 2019) have been reported. To aid comparability and following IPCC coastal wetlands guidance, the reported carbon stock values were standardised to be integrated over a sample depth of 1 m below an area of 1 m^2 (some literature values had been reported to 30 cm depth below a 1m^2 area, others reported per cm^3). When differentiating between natural and restored saltmarshes, the average carbon stock of natural ecosystems is higher (range 12.7-69 kgCm^{-2}; n=85; average **40.3 kg C m^{-2}**) than that of restored saltmarshes (10.1-25 kgCm^{-2}; n=12; average **18.6 kg C m^{-2}**), but clearly this depends on the time elapsed since restoration (see section below).

Accumulation rates:

Carbon accumulation rates have been estimated as ranges of **66-196 gC m^{-2} yr^{-1}** (Adams *et al.*, 2012; Burrows *et al.*, 2014; Cannell *et al.*, 1999; Chmura *et al.*, 2003), which broadly agrees with the global value of **151 gC m^{-2} yr^{-1}** from Duarte *et al.* (2005). The value for a natural saltmarsh found was 118 gC m^{-2} yr^{-1}, for restored salt marshes 66-127 gC m^{-2}yr^{-1}and for those where the status was not specified it ranged from 140-196 gC m^{-2} yr^{-1}, which in sum did not allow firm conclusions about the effect of saltmarsh restoration on carbon fluxes. Overall, having just four studies, two of which are reviews, is a very limited evidence base, particularly as Burrows *et al.* (2014) cites Chmura *et al.* (2003) for carbon accumulation, but the values given are different. Chmura *et al.* (2003) in turn cite Callaway *et al.* (1996) for Dengie Marsh and French and Spencer (1993) for Hut Marsh and Scolt Island, but when reviewing these source papers we found that the cited carbon accumulation values are not actually detailed, leaving the evidence base even less certain. It is concluded that more measurements are needed, though the relative agreement between the ranges and with global values is good.

Temporal changes from restoration:

A comparison of natural and regenerated saltmarshes in New South Wales, Australia (Santini *et al.*, 2019) found little difference in soil organic carbon stocks and below ground biomass after 20 years, though above ground biomass was higher in the natural habitat. In contrast, comparison between a disturbed and undisturbed saltmarsh at another Australian site (Howe *et al.*, 2009) noted a 60 % lower carbon stock in the disturbed site, but a 55% higher carbon sequestration rate, showing how the recently disturbed site was on a trajectory to rebuilding its carbon stock. Within England, a comparison of natural saltmarsh vs managed realignment sites in the Blackwater estuary (Adams *et al.*, 2012) found that less vegetationally developed sites had lower carbon densities then natural saltmarshes, while those with better developed vegetation were equal or even higher than their natural counterparts. It was noted though that net carbon sequestration in managed realignment sites was reduced compared to natural sites due to increased methane and nitrous oxide outgassing, but that significant biogeochemical value in terms of carbon storage remained. In another study (Burden *et al.*, 2019) evaluating the length of time a recreated marsh will take to become functionally equivalent to a natural system, the authors conclude that carbon accumulation was initially rapid then slowed to a steady rate and that it takes approximately 100 years for a restored saltmarsh to obtain the same carbon stock as a natural site. When investigating the influence of grazing on greenhouse gas fluxes from a temperate salt marsh (Ford *et al.*, 2012), it was concluded that grazing did not significantly affect the global warming potential and a comparison of 22 UK saltmarshes found no detectable relationship between grazing intensity and soil organic carbon (Harvey *et al.*, 2019).

Geographically, the gaps in locations of carbon stock measurements are along the south coast and in northern England for analysis of specific stocks and fluxes, while Wales is well covered, and detailed work has been conducted in the East of England. It is expected that there will be a significant pool of stock information, with a limited amount of flux data becoming available from the NERC C Side project in summer 2021 and we have been told that restoration efforts by Essex Wildlife Trust and the Environment Agency, supported by the University of Essex, are resulting in more research on the topic in the East of England, though to date not involving information on fluxes.

Saltmarsh references:

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Intertidal mud/sand flats *- Silke Kröger*
Reviewed by Julian Andrews (UEA) and Natalie Hicks (University of Essex)

Intertidal mud and sandflats are habitats not usually included in blue carbon literature as they do not represent vegetated systems, but they do contain significant organic carbon stores. It is important to understand that the carbon in intertidal mud- and sandflats (and indeed subtidal sediments) is not well identified in terms of its age and origin and can be young or recycled or already have been stored for many thousand years. If the latter, then its presence now may not be telling us much about storage in the future. Rivers and run-off from land deliver both very refractory carbon (i.e. carbon that is largely protected from being broken down due to being highly inert or already very degraded), which could be stored for many years, but also rather labile carbon (fresh carbon or carbon which is easily broken down) . The labile carbon is probably dominant, having a short sediment lifetime measured in months rather than years. Bioturbation and erosion all cause net loss. Carbon in intertidal areas and sediments is different to that in saltmarshes where the main burial component is root carbon and not much is being recycled after the first phase of oxidation near the surface. In terms of location, mudflats are typically found where saltmarshes are, they can be coupled in their carbon storage ability, for example with carbon flowing out of a saltmarsh may end up in the mudflats.

For carbon concentration in mud- and sandflats, sediment type is very likely a determinant, along with location and parameters such as the carbon loading of any river feeding into the estuarine intertidal areas and the productivity of adjacent sea areas. In our selection of literature, we followed where authors characterised their study area as an intertidal mud or sandflat or estuarine intertidal sediment. As mentioned above, mudflats are unvegetated in terms of macro-fauna, but they can support microphytobenthos biofilms for example consisting of diatoms. A narrower habitat description – maybe including salinity range, might be beneficial in future iterations.

Stocks:

A review of literature yielded a range of **organic carbon concentration** between **0.1 and 2.23 %** (Andrews *et al.*, 2000; Andrews *et al.*, 2008; Trimmer *et al.*, 2000). **Carbon stocks** (when integrating over a depth of 1 m) ranged from **1.3-35.6 kgCm^{-2}** (Adams *et al.*, 2012; Potouroglou, 2017; Thornton *et al.*, 2002; Trimmer *et al.*, 1998). When differentiating between mud and sand, mudflats had an average stock of **19.9 kgCm^{-2}** (n=8) while sandy sites only contained **6.5 kgCm^{-2}** (n=4). A recent study in Korea (Byun *et al.*, 2019) compared mean carbon storage in two saltmarshes and three tidal mudflats and found ranges of 14.6 – 25.5 kgCm^{-2} for the former and 18.2-28.6 kgCm^{-2} for the later, illustrating how significant carbon stocks in intertidal mudflats can be.

Accumulation rates:

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

While the literature search for this topic has not yet been as extensive as for some of the other habitats to date, it is likely that significant gaps in both coverage and carbon stocks and flux numbers exist.

Important aspects to consider would be the status of the intertidal flats, i.e. whether they are stable or eroding and what the age profile and origin (terrestrial or marine) of the organic carbon content is. Even less is known about sandflats than mudflats and both systems require additional observations.

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***Macroalgae (Kelp)** – Carolyn Graves*
Reviewed by Ana Querios (PML); Mike Burrows (SAMs)

Stocks:

Macroalgae, including kelp, are the dominant primary producers in the coastal zone, but the lack of carbon burial within their typically rocky habitats makes their carbon sequestration potential difficult to include in carbon accounting where 'stock' is reported as the carbon in the sediments underlying the habitat. They can be conceptualised as a "carbon donor" to "receiver sites" (Hill *et al.*, 2015). Their stock cannot be quantified analogously to the other habitats considered in this report, since the long-term storage occurs elsewhere (Krause-Jensen *et al.,* 2018). The role of macroalgae in carbon storage globally was reviewed by Krause-Jensen & Duarte (2016) who found its global contribution to deep-sea carbon sequestration to be 173 (61-268) Tg C/yr. The only UK data included in that synthesis were from Scotland (Zetsche *et al.,* 2011).

The average carbon stock in **UK kelp biomass carbon** has most recently been estimated at between **0.31 kg C m^{-2}** (warm water, England and Wales) **and 0.98 kg C m^{-2}** (cold water, Scotland) (Pessarrodona *et al.*, 2018), extending the range of previous estimates for the UK (at the same four sites) of **0.594-0.862 kg C m^{-2}** (Smale *et al.,* 2016), and above the estimates of **94 - 187 kg C m^{-2}** for Scottish areas of abundant (above 20 %) kelp coverage (Burrows *et al.,* 2014).

Accumulation Rates:

Because long-term storage of macroalgal storage occurs outside the habitat, blue carbon studies focus on tracking the fate of macroalgal biomass (Wantanabe *et al*., 2020; Ortega *et al*., 2019; Kokubu *et al*., 2019), including as detritus of animals feeding on it (Wernberg *et al*., 2018; Filbee-Dexter *et al*., 2020), specifically transport of particulate and dissolved organic carbon off-shelf where carbon is stored on longer timescales. Emerging molecular techniques for tracing carbon across marine habitats are increasingly being used (e.g. Ortega *et al*., 2019), and further work is needed to understand the variability of carbon fate between methodologies and regions. A recent global synthesis of **detritus production from different habitats, in kg C m^{-2} yr^{-1}** with standard deviation in brackets, found **0.486 (0.412) for kelp** compared to 0.263 (0.250) for non-kelp seaweeds, 0.411 (0.354) for seagrasses and 0.504 (0.325) for mangroves (Pedersen, 2020).

In the UK macroalgae-related carbon fluxes have recently been studied at sites in the English Channel, western Wales, and around Scotland (Queirós *et al*., 2019; Pessarrodona *et al.*, 2018). Extrapolating measurements off Plymouth, where macroalgae on hard substrates were found to be a donor of organic carbon sequestered in circalittoral fine sand and muddy sand (at **8.77 ± 9.85 gC m^2 yr^{-1}**) such that UK-wide these habitats accumulate 0.7 Tg C yr^{-1} from macroalgae (Queirós *et al*., 2019). In these habitats, any kelp contribution to carbon stocks and accumulation would already be accounted for.

The percentage transfer calculated from biomass stocks/donor sites to long-term burial within the SoS waters and UK overall is estimated at between 4-9%. These values are based on the measurements of Querios *et al.*, 2019 at the L4 offshore site, near Plymouth. A higher level of ~20% can be calculated from from Legge et al., 2020, based on Krause-Jensen *et al.*, 2016 and Krause-Jensen for sites in the North-Western European Shelf. These numbers globally are highly variable and depend largely on shelf conditions, hydrography, kelp or algal species and connectivity between donor and receiver sites.

<u>*Macroalgae/kelp references:*</u>

England & UK

Burrows, M. T., Kamenos, N. A., Hughes, D. J., Stahl, H., Howe, J. A. and Tett, P. (2014). Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment. Project Report. Scottish Natural Heritage Commissioned Report No. 761. 7, 90 pp.

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Pedersen MF, Filbee-Dexter K, Norderhaug KM, *et al.* (2020) Detrital carbon production and export in high latitude kelp forests. *Oecologia* 192(1):227-239. doi:10.1007/s00442-019-04573-z

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Shelf sediments – *Silke Kröger*
Reviewed by Natalie Hicks (University of Essex), and Craig Smeaton (University of St. Andrews)

In the below section, we differentiated between organic carbon stock values found in published literature and those we were able to derive directly from data held at Cefas.

<u>Stock values from literature:</u>

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

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

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

<u>Stock values (to depth of 1 m) based on Cefas data alone:</u>

A large data collection exercise undertaken at Cefas has brought together in excess of 1000 carbon concentration measurements in sediments. A map showing the locations of the collected samples is shown in Figure A2 and the modelled carbon stock distribution derived from these observations by Diesing *et al.* (2017) is shown in Figure A3.

When using only the data collected by Cefas, sediment density data was derived in a number of ways: where concurrent measurements were made of total organic carbon (TOC) and sediment porosity (n=87), carbon density could be calculated directly (assuming a grain density of 2650 g/m^3 as in Diesing *et al.* (2017)) using:

1. Dry bulk density = (1-porosity)*grain density
2. Carbon density= dry bulk density *TOC%

Where porosity was not determined, but % mud and TOC were, a formula from Jenkins (2005):

3. Por = 0.4 * mud + 43

This equation has only been derived for mud% > 7%, so any samples with a lower mud content had to be excluded (resulting in n=851), somewhat biasing the results towards finer sediments. The expected effect of limiting the analysis to samples with > 7 % mud is an increase in the derived carbon density value, as finer sediments tend to have higher carbon concentrations.

The results from these calculations are summarised in Table A1. Surprisingly, the carbon values from the deeper sediment slice (5-10 cm) resulted in higher carbon densities, with even higher values found when using the larger sample size and derived porosity, which might be a reflection of the much wider range of locations and sediment carbon concentrations included. Overall, the values derived from Cefas data are very similar to the carbon stock values found in the literature and reviewed above.

Table A1: *Carbon density values derived from Cefas data. Integration depth 100 cm, assuming even carbon concentration and grain density of 2650 g/m3).*

Data source	Average carbon density ($kgCm^{-2}$ to 100 cm depth)	Standard deviation (gCm^{-2})	Median	Range
Data with TOC and Porosity (0-5 cm)	3.8	2.8	3.2	0.4-12.3
Data with TOC and Porosity (5-10 cm)	4.3	2.6	3.9	0.4-11.1
Data with TOC and %mud (only>7% mud)	8.6	9.1	6.7	0.2-173.2

Stocks: To refine the review of sedimentary carbon stocks, samples were divided into "mud" and "sand" using a cut-off of 10% fines (particles <64 μm). For muds, a sediment organic carbon stock range of **0.6-12.3 $kgCm^{-2}$** with an average of **5.5 $kgCm^{-2}$** (n=33) was found, and for sands a range of **0.4-7.6 $kgCm^{-2}$** with an average of **1.8 $kgCm^{-2}$** (n=90), illustrating the significant correlation between grain size and carbon content.

<u>Accumulation rates:</u>

Very few published works cite carbon flux measurements within the SoS/UK EEZ waters. One study in the North Sea (De Haas *et al.*, 1997) gives estimate of **0.2 $gC\,m^{-2}\,yr^{-1}$**, another **~ 59 $gC\,m^{-2}\,yr^{-1}$** (Queirós *et al.*, 2019). Carbon burial rates are often limited due to the lack of deeper carbon concentration measurements and sedimentation rates derived from Pb^{210} or another dating technique. The evidence base of carbon burial (relating to stocks) in the offshore therefore remains poor and additional observations are required across much of the shelf area. It should be noted, that in some instances where dating techniques have been applied, no clear profiles were obtained. This was likely due to the widespread impact of trawling which mixes sediment layers. It is possible in future work that 'refuge areas' that can't be trawled (e.g. around infrastructure or in protected areas) may provide data for 'background carbon stocks' removing the impact of trawling, thus allowing a more accurate dating procedure to estimate accumulation rates.

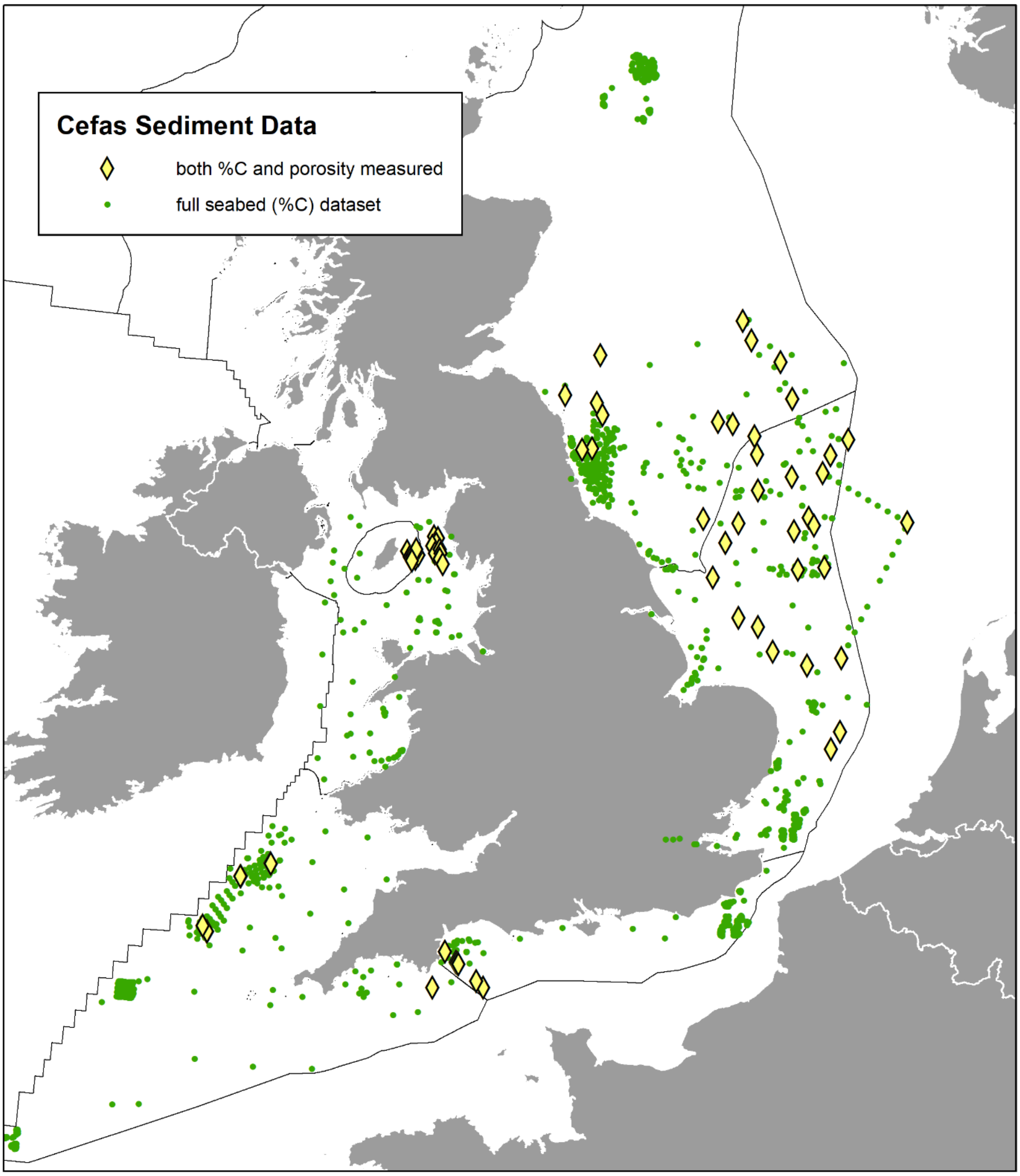

Figure A2: Map showing the locations of Cefas carbon (%) samples. The yellow diamonds denote sites where porosity was measured alongside carbon concentrations, allowing a more direct calculation of carbon density vales (see Table A1).

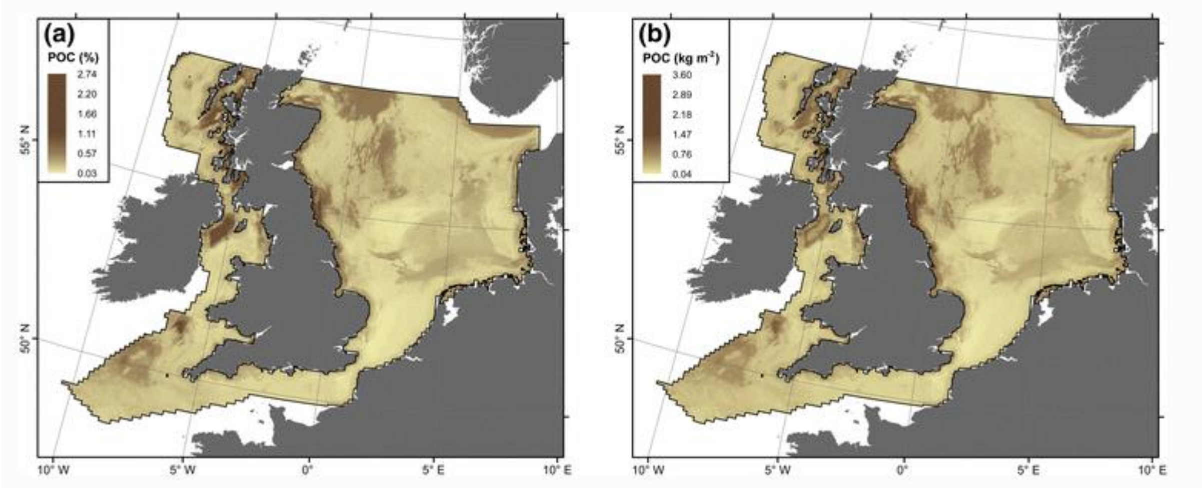

***Figure A3**: Map showing predicted organic carbon concentrations in surficial shelf sediments (top 10 cm) according to (Diesing et al., 2017).*

<u>*Shelf sediments references:*</u>

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UK continental slope *– Rui Vieira:*
Reviewed by Craig Smeaton (St Andrews)

While the UK EEZ has a significant area of slope, there is only a very small area within the SoS waters (off the Celtic Sea) and there are no known measurements of either carbon stocks or fluxes within this habitat to date.

Continental slopes make up around 5.4% of the global ocean floor (Harris *et al.*, 2014) and are potential vectors of carbon transfer from the shelf to the deep ocean. Although few measurements are available in the literature, the UK's offshore sediments are known to accumulate large quantities of carbon, with **seasonal variability** in POC transport and deposition along continental slopes (Hartman *et al.*, 2010; Mitchell *et al.*, 1997; Rice *et al.*, 1986). Recent estimates across the extended Scottish Exclusive Economic Zone, which is largely continental shelf but includes a small region of continental slope at its western end, yield 1,515 ± 252 Mt C stored in the sediments, of which **organic carbon contributes to 221 ± 92 Mt** within the top 10 cm (Smeaton *et al.*, 2020). These are estimated using sediment bulk densities and organic carbon contents from the eastern and southern North Sea, because of limited data availability within this continental shelf area (Smeaton *et al.*, 2020; Diesing *et al.*, 2017). Along the Hebrides margin, within the UK EEZ and between 200 and 2000 m water depth, an even deposition of exported POC to the seabed could contribute with an average **flux of 88±65 g C m^{-2} yr^{-1}** (Painter *et al.*, 2016). Along the southern Celtic Sea continental slope near, but outside the UK EEZ, organic carbon burial fluxes range from 1–4% of the total particle flux arriving on the seabed, equating to between **0.05 g C m^{-2} yr^{-1} and 0.41 g C m^{-2} yr^{-1}** (van Weering *et al.*, 1998).

<u>*Slope references:*</u>

Diesing, M., Kröger, S., Parker, R., Jenkins, C., Mason, C., and Weston, K. (2017). Predicting the standing stock of organic carbon in surface sediments of the North–West European continental shelf. *Biogeochemistry* 135, 183–200. doi: 10.1007/s10533-017-0310-4

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Table A2: ***A summary of available UK EEZ blue carbon habitat sediment organic carbon stocks and accumulation rates***. All habitat OC stocks are reported to 1m as per IPCC guidance.

Habitat	Granularity	Range of sediment organic carbon stock (kg C m^{-2})	Average organic carbon sediment stock (kg C m^{-2}) (± SE)	Range of organic carbon accumulation rate (gC m^{-2} yr^{-1})	Average organic carbon accumulation rate (gC m^{-2} yr^{-1}) (± SE)	Number of studies / references
Seagrass		4.6 - 38.0	13.0 (± 0.1) (n = 21)	nd	*[86 ± 19] **	Sediment carbon stocks = 3 studies (Potouroglou, 2017; Green et al., 2018; Röhr et al., 2018) *Sediment C accumulation rates – Novak et al., 2020 (non-UK - summary estimate temperate, N. W. Atlantic sites)*
Saltmarsh	Not specified	12.7 - 69.0	40.3 (± 0.6) (n = 59)	139.9 - 195.5	160.6 (± 12.4) (n = 4)	Sediment C stocks = 7 studies; (Adams et al., 2012; Beaumont et al., 2014; Burden et al., 2019; Burrows et al., 2014; Cannell et al., 1999; Chmura et al., 2003; Ford et al., 2019) Sediment C Accumulation = 2 studies (Callaway et al., 1996; Adams et al., 2012)
	Natural	13.2 - 31.6	40.3 (± 0.3) (n = 6)	118.5	118.5 (n = 1)	
	Restored	10.1 - 25.0	18.6 (± 0.7) (n = 7)	66.0 - 126.8	96.4 (± 30.4) (n = 2)	
Intertidal Sediments	Not Specified	4.0 - 17.8	9.3 (± 1.8) (n = 7)	nd	nd	Sediment carbon stocks = 4 studies (Trimmer et al., 1998; Thornton et al., 2002; Adams et al., 2012; Potouroglou, 2017) Sediment carbon accumulation rates = 1 study (Adams et al., 2012)
	Mud	5.4 - 35.6	19.9 (± 4.0) (n = 8)	73.3 - 93.7	83.5 (± 10.2) (n = 2)	
	Sand	1.3 - 18.6	6.5 (± 4.0) (n = 4)	nd	nd	
Subtidal Sediments	Mud	0.6 - 12.3	5.5 (± 1.8) (n = 33)	0.2 - 58.7	29.5 (± 29.3) (n = 2)	Sediment carbon stocks - Multiple Cefas surveys Sediment C accumulation rates = 2 studies (De Haas et al., 1997; Queiros et al., 2019)
	Sand	0.4 - 7.6	1.7 (± 0.5) (n = 90)			
Slope (>200m)		nd	nd	nd	nd	NA
			Average biomass standing stock (kgCm^{-2})			
Kelp		nd	0.641 (± 0.022) (n = 8)	NA	NA	(Pessarrodona et al., 2018)

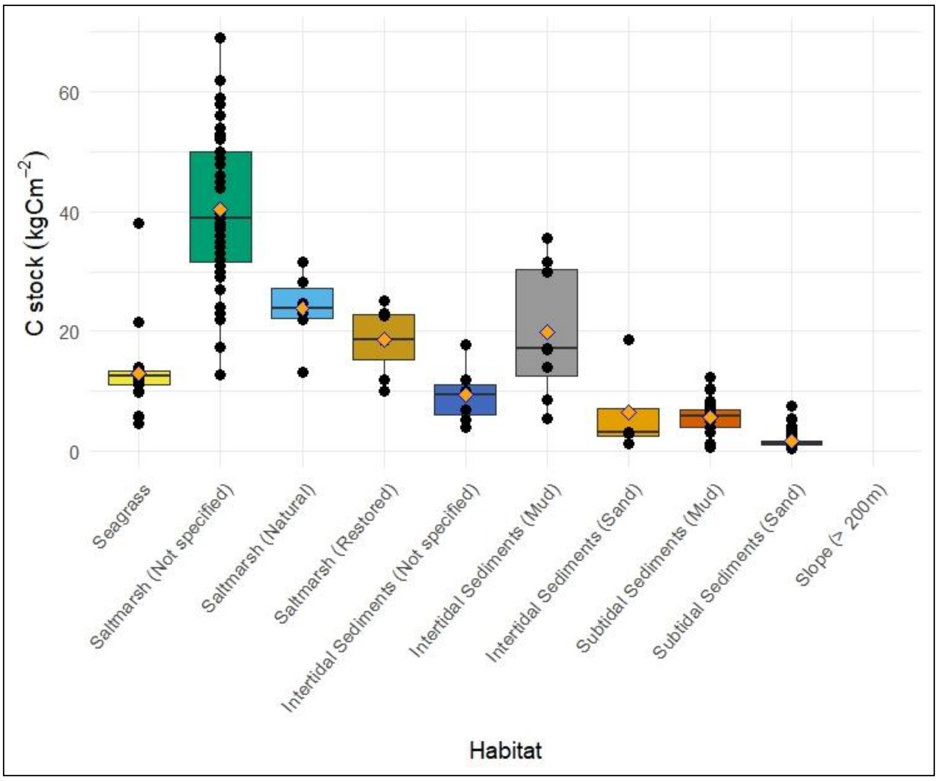

Figure A4: *Box plots showing the data distribution of sediment carbon stock values (carbon stock; kgCm^{-2}) for the UK EEZ waters, to 1m sediment depth. The minimum, the maximum, the median, and the first and third quartiles of the data are show. The orange diamond shows the mean value.*

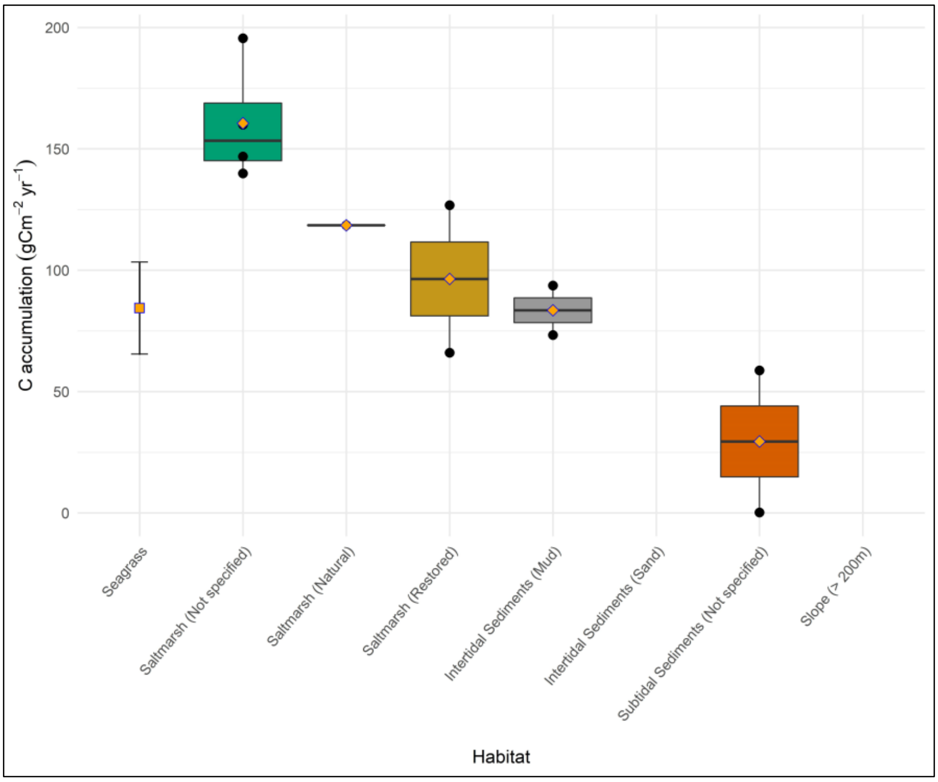

Figure A5: *Box plots showing the data distribution of carbon accumulation rates (gCm^{-2}yr^{-1}) in the UK EEZ, to 1 m depth including the minimum, the maximum, the median, and the first and third quartiles of the data. There are no available seagrass accumulation data for the UK. Data represented for seagrass here are the mean(orange square) and standard error values reported by Novak et al. (2020) for the Northwest Atlantic. The orange diamond shows the mean value. Gaps indicate a lack of available data for that habitat.*

Table A2: Habitat extents, average habitat carbon stocks (to 1m sediment depth) and accumulation rates, total UK EEZ stock and accumulation rates, and CO_2 equivalents

Habitat	**Extent (km^2)**	**Average Carbon Stock ($kgCm^{-2}$)**	**Average carbon accumulation ($gCm^{-2}yr^{-1}$)**	**Total stock (million tonnes)**	**Total accumulation (thousand tonnes yr^{-1})**	**CO_2 equivalent stock (million tonnes)**	**CO_2 equivalent Accumulation (thousands tonnes)**
Seagrass	70	13.0 (± 0.1)	*[86 ± 19] **	0.91 (± 0.01)	6.0 (± 1.3)	3.33 (± 0.03)	22 (± 5)
Saltmarsh	480	36.8 (± 0.5)	136.2 (± 15.1)	17.7 (± 0.3)	654 (± 7.2)	64.7 (± 0.9)	240 (± 27)
Intertidal sediments	2700	9.3 (± 4.0)	83.5 (± 10.2)	53.7 (± 10.7)	225 (± 28)	197 (± 39)	826 (± 101)
Subtidal sediments	88055	5.5 (± 1.8)	29.5 (± 29.3)	484 (± 48.0)	2,600 (± 2,580)	1,775 (± 176)	9,528 (± 9,400)
Slope	451000	nd	nd	nd	nd	nd	nd
		Average Biomass standing stock ($kgCm^{-2}$)		Biomass total stock (million tonnes)		CO2 equivalent Biomass total standing stock (million tonnes)	
Kelp/macroalgae	6000	0.641 (± 0.022)	na	3.846 (± 0.134)	na	14.092 (± 0.490)	na

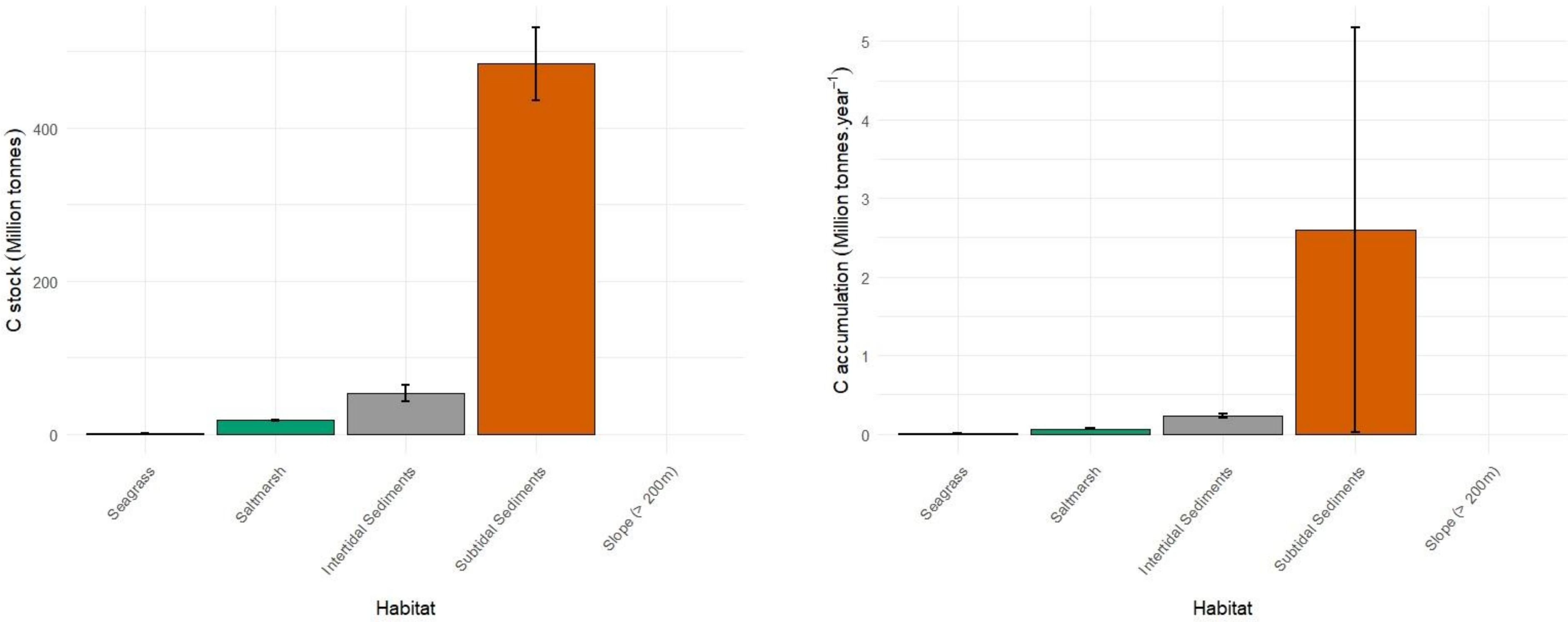

Figure A6: *Box plots showing the a) total carbon stock and b) annual accumulation for the UK EEZ, to 1 m depth as listed in Table A2. The error bars represent standard errors. The gap in slope data indicates where the total has not been determined due to gaps in stock and burial evidence*