# The Blue Carbon Potential of the Marine Protected Area Network in the Welsh Marine Environment

Report No: 631

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| | |
|---|---|
| Report series: | NRW Evidence Report |
| Report number: | 631 |
| Publication date: | May 2022 |

| | |
|---|---|
| Contract number: | 631 |
| Contractor: | ABPmer |
| Contract Manager: | Hatton-Ellis, M. A. |
| Title: | **The Blue Carbon Potential of the Marine Protected Area Network in the Welsh Marine Environment** |
| Author(s): | Robbins, K., Armstrong, S., Williamson, D., Frost, N., Hull, S. |
| Technical Editor: | Frost, N. |
| Quality assurance: | Tier 2 |
| Peer Reviewer(s): | M. A. Hatton-Ellis, K. Robinson & J. Sharp |
| Approved By: | M. Lewis |
| Restrictions: | None |

# Distribution List (core)

| | |
|---|---|
| NRW Library, Bangor | 2 |
| National Library of Wales | 1 |
| British Library | 1 |
| Welsh Government Library | 1 |
| Scottish Natural Heritage Library | 1 |
| Natural England Library (Electronic Only) | 1 |

# Recommended citation for this volume:

Robbins, K., Armstrong, S., Williamson, D., Frost, N., Hull, S. 2021. The Blue Carbon Potential of the Marine Protected Area Network in the Welsh Marine Environment. NRW Evidence Report No: 631, 55pp, Natural Resources Wales, Bangor.

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# Crynodeb Gweithredol

Mae'r cefnforoedd yn chwarae rhan hanfodol yn y cylch carbon byd-eang ac mae cynefinoedd arfordirol yn gweithredu fel un o'r dalfeydd carbon naturiol mwyaf ar lefel fyd-eang. Cydnabyddir mai'r gwaith o gyfrif faint o garbon sy'n cael ei storio a'i atafaelu yn y cynefinoedd hyn yw'r cam cyntaf wrth ddeall beth yw eu cyfraniad tuag at liniaru newid hinsawdd.

Mae Ardaloedd Morol Gwarchodedig (AGAau) yn rhoi amddiffyniad gwerthfawr i gynefinoedd morol, gan gynnwys cynefinoedd carbon glas sy'n amrywio o elfennau biolegol a daearegol, megis morfeydd heli a gwelyau morwellt, riffiau biogenig, a gwaddodion morol. Gallai amcangyfrif cyfraniad AGAau i garbon glas wrth wneud penderfyniadau rheoli helpu i ddiogelu'r cynefinoedd hyn yn well. Gallai hyn yn ei dro wella eu gallu i ddarparu dalfa garbon a hyrwyddo storio carbon yn yr amgylchedd morol.

Yn 2020, cyhoeddodd CNC adroddiad tystiolaeth 428 (Armstrong *et al*., 2020) a oedd yn datgelu potensial carbon glas cynefinoedd gwaddodol a biogenig morol Cymru. Er bo'r adroddiad hwn yn datgelu rôl bwysig moroedd arfordirol Cymru fel dalfa garbon, nid yw pwysigrwydd y rôl a chwaraeir gan rwydwaith AMGau o ran storio ac atafaelu carbon wedi cael ei asesu. Nod yr astudiaeth hon felly oedd cynyddu'r ddealltwriaeth o'r adnodd carbon glas yn rhwydwaith ACAau Cymru drwy fesur cyfraniad y rhwydwaith i storio ac atafaelu carbon.

Drwy ddefnyddio'r gwerthoedd llenyddiaeth mwyaf perthnasol ar gyfer storio ac atafaelu carbon gyda golwg ar gynefinoedd Cymru a chyfrifo meintiau'r cynefinoedd o fewn pob nodwedd Atodiad 1 pob ACA, gellid amcangyfrif potensial carbon glas nodweddion Atodiad I. Amcangyfrifwyd bod cyfanswm cyfraniad nodweddion Atodiad I ACA Cymru i storio carbon tua 11 Mt o garbon yn y 10 cm uchaf o waddod. Mae hyn yn cyfrif am oddeutu 10% o'r holl garbon sy'n cael ei storio ar draws holl gynefinoedd ardal Cynllun Morol Cenedlaethol Cymru. Roedd cyfradd atafaelu tua 12,300 t o garbon bob blwyddyn ar draws rhwydwaith yr ACAau, sy'n cyfrif am 47% o'r holl garbon sy'n cael ei atafaelu o fewn cynefinoedd Cymru (Armstrong *et al*., 2020). Y nodweddion Atodiad I a oedd yn cynrychioli ardaloedd gofodol eang megis aberoedd a chilfachau a baeau bas mawr oedd yn cyfrannu fwyaf tuag at storio ac atafaelu carbon ar draws y rhwydwaith, fodd bynnag nodweddion morfa heli dynodedig oedd yn cyfrannu fwyaf tuag at y carbon glas fesul uned arwynebedd.

Ar y cyfan, roedd yr astudiaeth hon yn amlygu fod ACAau yn gwneud cyfraniad pwysig i garbon glas yn nyfroedd Cymru, yn arbennig o ran atafaelu carbon, ac o'r herwydd mae'r ffaith bod cynefinoedd carbon glas a gysylltir â nodweddion dynodedig yn parhau i gael eu hamddiffyn yn hynod o bwysig. Dylai casglu data safle benodol a'u hymgorffori i amcangyfrifon o botensial carbon glas yn y dyfodol fod yn flaenoriaeth er mwyn asesu amrywioldeb storio ac atafaelu carbon ar draws rhwydwaith yr ACAau.

# Executive Summary

The oceans play a vital role in the global carbon cycle with coastal habitats acting as one of the largest natural sinks of carbon globally. It is recognised that quantifying the carbon stored and sequestered in these habitats is the first step in understanding their contribution towards mitigating climate change.

MPAs provide valuable protection to marine habitats, including blue carbon habitats ranging from biological and geological components, such as saltmarshes and seagrass beds, biogenic reefs, and marine sediments. Estimating the contribution MPAs make toward blue carbon when making management decisions could help to better protect these habitats. In turn this could further enhance their capacity to provide a carbon sink and promote the storage of carbon in the marine environment.

In 2020, NRW published evidence report 428 (Armstrong *et al*., 2020), which revealed the blue carbon potential for Welsh marine sedimentary and biogenic habitats. Whilst this report revealed the important role of Wales' coastal seas as a carbon sink, the importance that the MPA network plays towards carbon storage and sequestration has not been assessed. The aim of this study was therefore to increase understanding of the blue carbon resource in Wales' SAC network by quantifying the contribution of the network to carbon storage and sequestration.

From using the most relevant literature values for carbon storage and sequestration for Welsh habitats and calculating the habitat extents within each SAC Annex I feature, the blue carbon potential of Annex I features could be estimated. The total contribution of Welsh SAC Annex I features to carbon storage was estimated to be approximately 11 Mt of carbon in the top 10 cm of sediment. This accounts for almost 10% of the total carbon storage across all habitats in the Welsh National Marine Plan area. The rate of sequestration was approximately 12,300 t of carbon per year across the SAC network, which accounts for 47% of the total carbon sequestered within Welsh habitats (Armstrong *et al*., 2020). Annex I features which covered large spatial extents such as estuaries and large shallow inlets and bays contributed the most towards carbon storage and sequestration across the network, however designated saltmarsh features contributed the most towards blue carbon per unit area.

Overall, this study highlighted that SACs make an important contribution towards blue carbon in Welsh waters, particularly in terms of carbon sequestration, and therefore the continued protection of the blue carbon habitats associated with designated features is of high importance. The collection and incorporation of site-specific data into future estimates of blue carbon potential should be a priority in order to assess the variability of carbon storage and sequestration across the SAC network.

# 1. Introduction

The oceans play a vital role in the global carbon cycle, and the importance of the oceans in mitigating against climate change is now widely recognised. Coastal marine habitats are one of the largest natural sinks for carbon and sequester (the process of capture and addition of carbon to the standing stock) a significant proportion of the carbon emitted by human activities each year. The carbon sequestered and stored in marine ecosystems is termed ‘blue carbon’. Blue carbon occurs within a range of habitat types covering biological and geological components, such as saltmarshes and seagrass beds, biogenic reefs, and marine sediments over short to long timescales. With ever increasing carbon dioxide and other greenhouse gas concentrations driving global climate change, there is a growing need to understand how these marine habitats can facilitate climate change mitigation.

The estimation of carbon stocks and sequestration in marine habitats has received increasing attention over recent years. The first national scale assessment of its kind was undertaken by Burrows *et al*. (2014), who estimated Scotland’s blue carbon stocks. This audit remains a primary source of information for habitat-specific estimates. Since then, several studies have used similar approaches to estimate blue carbon across large spatial scales in the UK. These include estimates for Secretary of State waters (Parker *et al*., 2021), Scotland (Burrows *et al*., 2017, 2021; Porter *et al*., 2020), Northern Ireland (Strong *et al*., 2021) and Wales (Armstrong *et al*., 2020). In addition, attention has been paid specifically to carbon storage in UK shelf sea sediments (Diesing *et al*., 2017; Smeaton *et al*., 2021). Several of these studies have also estimated blue carbon within Marine Protected Area (MPA) networks, in order to understand the role MPAs have in protecting the capacity for coastal seas to sequester carbon (Burrows *et al*., 2017, 2021; Strong *et al*., 2021).

MPAs provide valuable protection to marine habitats and species. Understanding the contribution MPAs make toward blue carbon when making management decisions could help to better protect these habitats (Burrows *et al*., 2017). In turn this could further enhance their capacity to provide a carbon sink and promote the storage of carbon in the marine environment. In Wales, MPAs cover approximately 69% of the Welsh inshore waters. There are 139 MPAs in Welsh waters, and this network is made up of:

- 15 Special Areas of Conservation (SACs);
- 13 Special Protection Areas (SPAs);
- 1 Marine Conservation Zone (MCZ);
- 107 Sites of Special Scientific Interest (SSSIs); and
- 3 Ramsar sites.

It has been estimated that more than 99 km² of blue carbon habitat is located within the MPA network in Wales (Stewart and Williams, 2019). Further, over 77 km² of these blue carbon habitats occur within Wales’ 15 SACs (Stewart and Williams, 2019). Marine SACs are designated in order to protect one or more Annex I feature under the Habitats Regulations 2017. Most of these Annex I features contain sedimentary and / or biogenic habitats which are known to sequester and store carbon.

In 2020, NRW published evidence report 428 (Armstrong *et al*., 2020), which revealed the blue carbon potential for Welsh marine sedimentary and biogenic habitats. This report found that at least 113 Mt of carbon are stored in the top 10 cm of the Welsh marine sediments and an estimated 26,100 tonnes of carbon (0.03 Mt C) are sequestered each year. Whilst this report revealed the role of Wales' coastal seas as a carbon sink, the importance that the MPA network plays towards carbon storage and sequestration has not been assessed.

The aim of this study was to increase understanding of the blue carbon resource in Wales' SAC network by quantifying the contribution of the network to carbon storage and sequestration. The key objectives for this study were:

- To review the most recent literature on carbon storage and sequestration for different marine habitats present in Wales;
- To determine the spatial extent of Annex I features in the Welsh marine SAC network; and
- To estimate carbon storage and sequestration potential of Annex I features in the SAC network.

# 2. Methodology

## 2.1. Review of carbon values

As part of the Armstrong *et al*. (2020) study, a literature review was undertaken to estimate carbon biomass stock, soil stock and sequestration rates for key habitats known to be present in the Welsh marine environment. The habitats reviewed included:

- Intertidal habitats:
    - Mud and sand flats;
    - Saltmarshes;
    - Intertidal macroalgae (vegetated rocky shores);
- Subtidal habitats with an intertidal element:
    - Seagrass beds;
- Subtidal habitats:
    - Shellfish beds (horse mussel, blue mussel and oyster beds);
    - Subtidal macroalgae (kelp and maerl);
    - Brittlestar beds;
    - Faunal turf; and
- Subtidal muds, sands and gravels.

As part of this MPA report, a review of the most recent scientific literature was undertaken to evaluate the estimates of carbon storage and sequestration used in Armstrong *et al.* (2020) and update the estimates, where appropriate. The review focussed on literature published since the start of 2020 to November 2021. Values from the literature have been converted to kg C $m^{-2}$ and scaled to reflect the top 10 cm of soil where necessary in order to directly compare with values from Armstrong *et al*. (2020).

## 2.2. Quantifying blue carbon in Annex I features

### Mapping of SAC Annex I features

A spatial layer for Welsh marine SACs was obtained from the Lle Geo-Portal. There are 15 marine SACs in Welsh waters, 10 of which were considered in this study, including:

- Y Fenai a Bae Conwy / Menai Strait and Conwy Bay;
- Dee Estuary / Aber Dyfrdwy;
- Pen Llŷn a'r Sarnau / Lleyn Peninsula and the Sarnau;
- Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd;
- Pembrokeshire Marine / Sir Benfro Forol;
- Cardigan Bay / Bae Ceredigion;
- Severn Estuary / Môr Hafren;
- Kenfig / Cynffig;
- Glannau Môn: Cors heli / Anglesey Coast: Saltmarsh; and
- Bae Cemlyn / Cemlyn Bay.

Three SACs within the network (North Anglesey Marine/Gogledd Môn Forol, West Wales Marine/Gorllewin Cymru Forol and Bristol Channel Approaches/Dynesfeydd Môr Hafren) have been removed from the study as they are designated for harbour porpoise (*Phocoena phocoena*) only. In addition, Croker Carbonate Slabs SAC was removed as it is designated for submarine structures made by leaking gases.

The spatial layers of Annex I habitats were obtained from the Habitats Directive Article 17 reporting maps on the Lle Geo-Portal. These maps represent the current known extent and location of Annex I habitats both inside and outside of SACs. These Annex I habitat spatial layers were overlapped with the SAC layers and clipped to the SAC boundaries. Annex I habitats for which the marine SACs are designated were used in this assessment. These included:

- Estuaries;
- Large shallow inlets and bays;
- Mudflats and sandflats not covered by seawater at low tide;
- Reefs;
    - Intertidal;
    - Subtidal;
- Saline lagoons;
- Sandbanks which are slightly covered by sea water all the time; and
- Saltmarsh (Atlantic salt meadows (*Glauco-Puccinellietalia maritimae)* and/or Salicornia and other annuals colonising mud and sand).

The spatial extents of Annex I features contained within each SAC are shown below in **Figure 1**.

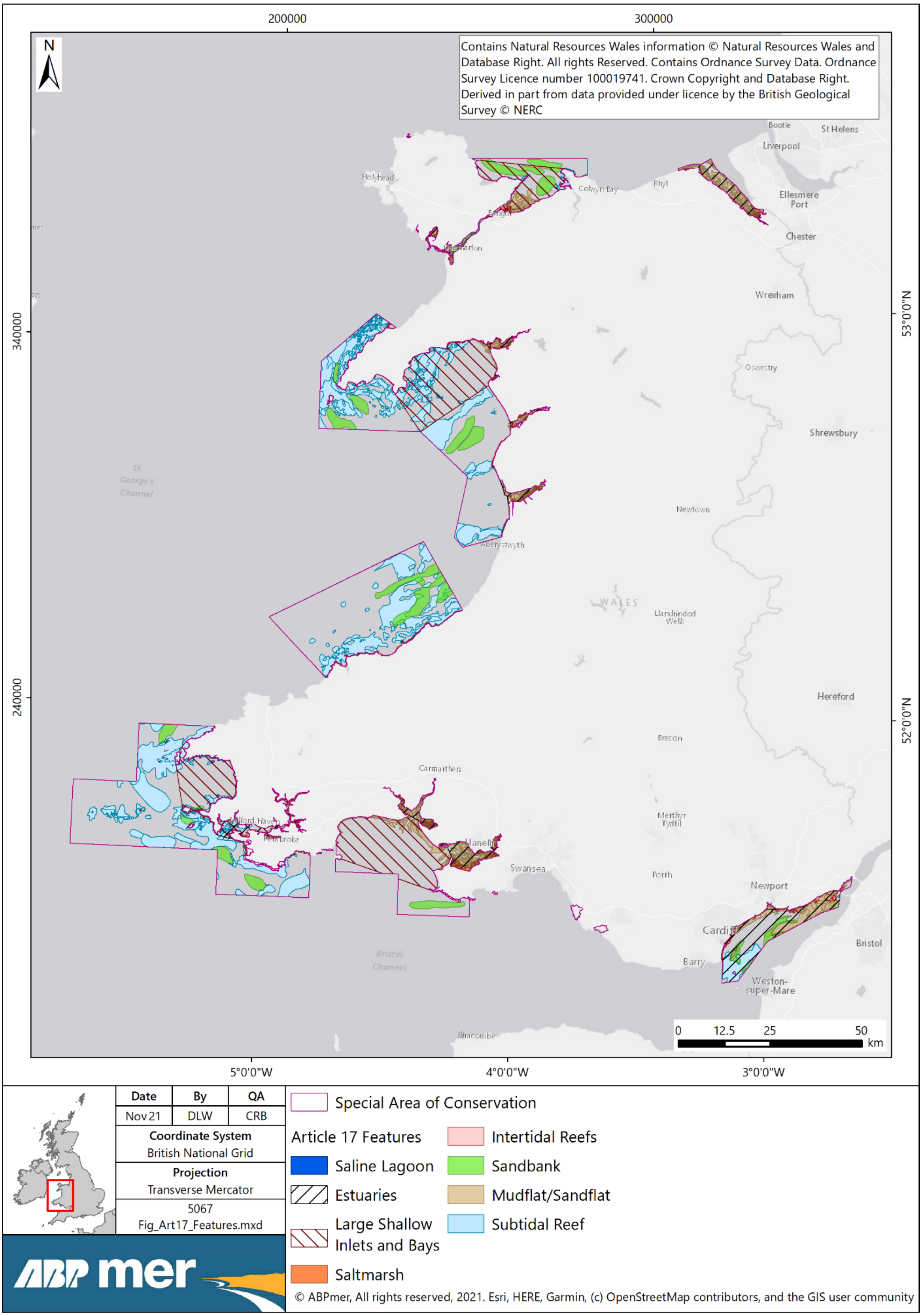



**Figure 1** The location of Welsh SACs and the Annex I features for which they are designated

## Component blue carbon habitats

Based on the blue carbon sediment and biogenic habitats reviewed in Armstrong *et al*. (2020) and Section 2.1, a combined map was made for Welsh waters in order to facilitate the calculation of carbon storage and sequestration in Annex I features in the SAC network (Figure 2). The Joint Nature Conservation Committee (JNCC) 'combined' habitat map (JNCC, 2019) was used as the main layer for biogenic habitats and was supplemented with data supplied by Welsh government bodies (**Table 1**). For habitats where more recent or refined data were available, separate data layers have been used and given priority. The 'HabMap' sediment data layer was used as the main spatial layer for sedimentary habitats, with offshore gaps filled using the JNCC layer. The data layers used to create the sediment and habitat map are listed in Table 1. Key layer for biogenic habitats; also used to fill offshore gaps in HabMap layer; and re-classified according to Folk system. The Folk (1954) sediment classification system is the most commonly used system for describing the grain/size range of gravel, sand, silt, and clay classes. In this system, 15 sediment texture classes are defined according to the relative proportions of mud (clay and silt particles), sand (very fine to very coarse sand grains) and gravel (granule to boulder).

**Table 1** Spatial layers used to create combined carbon storage / sequestration habitat maps from Armstrong *et al*. (2020). *This table is in two sections, base layers and habitat layers.*

**Base layers:**

| Data layer origin / name | Processing detail |
|---|---|
| JNCC - EUNIS Combined Map (available on JNCC website) | Key layer for biogenic habitats; also used to fill offshore gaps in HabMap layer; and re-classified according to Folk system. |
| NRW - HabMap Sediment layer (not publicly available) | Key layer for sedimentary habitats. Where not already classed according to the Folk system, some polygons were re-classified (Appendix A for further detail). |

**Habitat Layers Used to Supplement that Base Layers:**

| Habitats; in priority order | Data layer origin / name | Processing detail |
|---|---|---|
| Saltmarshes | Lle Geo-Portal - Saltmarsh Extents | No processing detail |
| Seagrass Beds | Lle Geo-Portal - Priority Marine Habitats of Wales: Seagrass Beds | No processing detail |
| Intertidal Macroalgae | Lle Geo-Portal - NRW Intertidal Phase 1 Habitat Survey | Only macroalgae polygons extracted |
| Intertidal mudflat and sandflats | Lle Geo-Portal - Marine Article 17 Reporting Habitat Features | Each polygon categorised according to Folk system |

| Habitats; in priority order | Data layer origin / name | Processing detail |
|---|---|---|
| Maerl | Lle Geo-Portal - Environment (Wales) Act Section 7 and OSPAR: Marine Habitats | No processing detail |
| Shellfish Beds - Oyster | Section 7 / OSPAR Oyster Bed layers (not publicly available) | Point file buffered and merged with polygon file |
| Shellfish Beds – Blue mussel | Lle Geo-Portal - Priority Marine Habitats of Wales: Blue Mussel Beds | No processing detail |
| Shellfish Beds – Horse Mussel | Lle Geo-Portal - Priority Marine Habitats of Wales: Horse Mussel Beds | No processing detail |
| Shellfish Beds - *Musculus discors* | Lle Geo-Portal - Section 7 *Musculus Discors Green crenella* Beds | No processing detail |
| Subtidal Macroalgae | JNCC EUNIS Combined Map | Extracted higher EUNIS class information from ‘habitat type’ column, where available. |
| Subtidal Brittlestar beds | JNCC EUNIS Combined Map | Extracted higher EUNIS class information from ‘habitat type’ column, where available. |
| Surficial Sediments | NRW - HabMap Sediment layer | No processing detail |

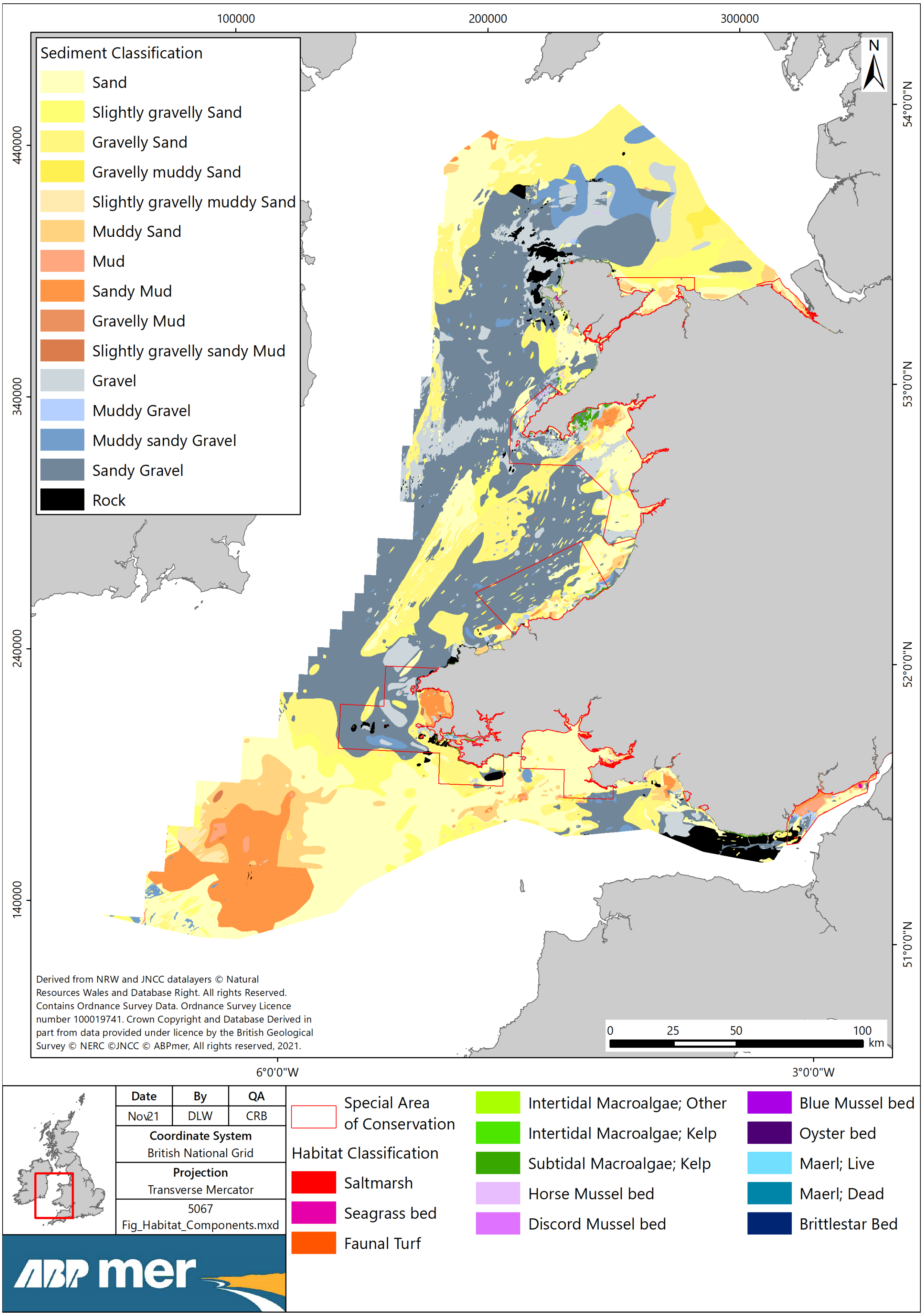



Figure 2 Habitat areas in Welsh waters used to calculate blue carbon potential of Annex I features

## Carbon estimates of Annex I features

To estimate carbon storage and sequestration in SAC Annex I features, the component blue carbon habitat layers were firstly overlapped with the SAC Annex I feature layers and clipped to the feature boundaries. The spatial extents of blue carbon habitats within each of the Annex I features were then extracted (in $m^2$). These spatial extents were multiplied by the estimates for carbon storage (in kg $m^{-2}$) and carbon sequestration (in kg $m^{-2}$ $yr^{-1}$) for each of the blue carbon habitats (see Appendix A). The total carbon storage and sequestration within each Annex I feature was then determined as the sum of its component blue carbon habitats. Values for each Annex I feature were converted to tonnes or tonnes per year for carbon storage and sequestration, respectively.

For the purposes of this study, carbon storage values and sequestration rates for each component blue carbon habitat were assumed to be the same across Welsh waters, as limited site-specific information was available.

Carbon storage and sequestration estimates could not be made for the majority of the designated saline lagoons features in the Cemlyn Bay SAC, Lleyn Peninsula and the Sarnau SAC, and Pembrokeshire Marine SAC, as the habitat components layers did not overlap with the features at these sites. Therefore, saline lagoon features were excluded from this study. As saline lagoons cover a relatively small spatial extent of 0.4 $km^2$ across the SAC network, their contribution to carbon storage and sequestration is likely small and unlikely to make a substantial difference to the contribution Annex I features make towards blue carbon.

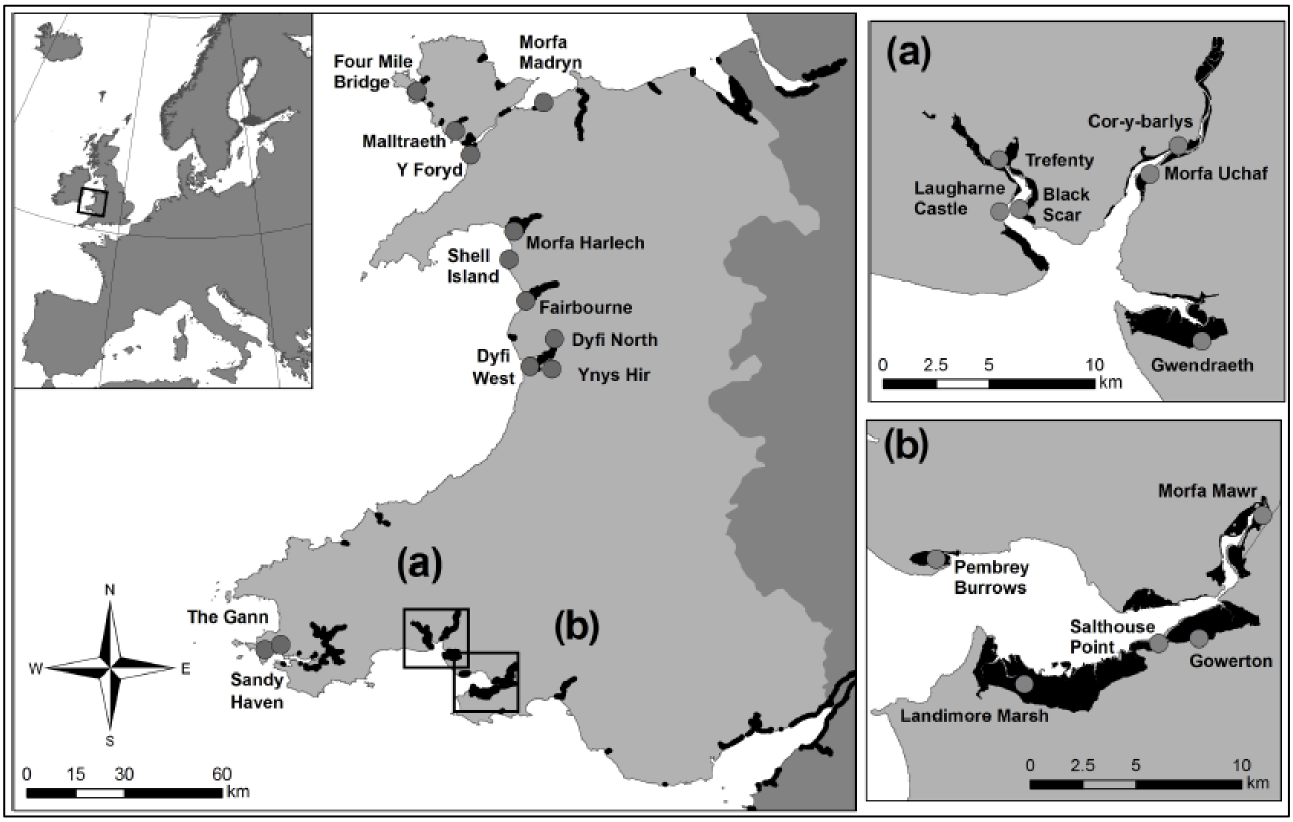
It is important to note that there is often overlap between Annex I features. This is particularly the case where larger features, such as Estuaries and Large Shallow Inlets and Bays, have smaller features contained within them. As part of this study, where Annex I features are evaluated individually, the overlap between the features was not taken into account in order to estimate the total carbon storage and sequestration for the feature. For calculations of total carbon storage and sequestration across the entire network the overlaps between the features were identified in order to avoid double counting.

Carbon storage and sequestration of areas outside of Annex I features were not quantified as part of this study. Therefore, it is acknowledged that the blue carbon potential within Welsh SACs is likely to be higher when taking into account habitats within and outside Annex I designated features.

# 2.3. Site-specific variability in saltmarsh carbon stock

The approach above uses the best available literature from the UK to estimate carbon storage and sequestration in blue carbon habitats, however it is important to acknowledge that carbon storage and sequestration vary naturally depending on location. Site-specific carbon data on Welsh habitats are scarce in the literature, however, carbon stock values in the surface soils (0-10 cm) for saltmarsh have been estimated by Ford *et al*. (2019) across 23 sites in Wales in 2015 (Figure 3). Ford *et al*. (2019) found that carbon stocks varied between sites depending on both soil type and plant community type. Sandy soils were found to store less carbon (average 29 t C $ha^{-1}$) than non-sandy soils (43 t C $ha^{-1}$). Stored carbon varied from 32 t $ha^{-1}$ (or 3.2 kg $m^{-2}$) for the *Atriplex portulacoides* vegetation class to 50 t $ha^{-1}$ (or 5.0 kg $m^{-2}$) for the *Juncus gerardii* vegetation class.

In order to assess the importance of incorporating natural variability into the estimates of carbon storage, the carbon stock values from Ford *et al*. (2019) were grouped together based on the SAC they overlapped with and the mean stock values for each SAC were calculated. These site-specific carbon stock values were then also used in place of the carbon stock values for saltmarsh component habitats (used in Section 2.2) for the relevant SACs. The total carbon storage and sequestration within each Annex I saltmarsh feature was then determined as the sum of its component blue carbon habitats and briefly compared to the estimates based on the assessment described in Section 2.2.




Source: Ford *et al*., 2019

Figure 3 Location of carbon stock estimates in 23 Welsh saltmarshes by Ford *et al*. (2019)

# 3. Results

## 3.1. Review of carbon values in Wales

Since early 2020, there have been relatively few new UK-based studies which have quantified carbon storage and sequestration in marine habitats around the UK. New estimates of carbon sequestration and/or storage identified from the literature review have been summarised below and compared to values used in Armstrong *et al*. (2020) with justification for the most appropriate values to use in the present study. Overall, the majority of new values in the literature have been consistent with values used in Armstrong *et al*. (2020) (see Appendix B for a summary table of the review).

## Sedimentary habitats

Values for particulate organic carbon (POC) stock for subtidal sediments in Armstrong *et al*. (2020) were derived from Diesing *et al*. (2017). Diesing *et al*. (2017) modelled POC concentration and dry-bulk density for the top 10 cm of a range of subtidal mud, sand and gravel sediments across the northwest European continental shelf, predominately around England and Wales. A database of 849 sediment samples processed for grain size and POC concentration was used for the analysis, which was collected between 1996 and 2015 for the Centre for Environment Fisheries and Aquaculture (Cefas) (Mason *et al*., 2017).

A recent review undertaken by Cefas estimated blue carbon stocks and sequestration for subtidal sediments in the Secretary of State region (Parker *et al*., 2021). Similar to Diesing *et al*. (2017), estimates were derived from the sediment samples from Mason *et al*. (2017), however only two general sediment types were estimated – subtidal mud and sand. The range of carbon stock in subtidal mud and sand were comparable with the range of estimates used in Armstrong *et al*. (2020) for a wide range of sediment types (Appendix B). Therefore, the values from Armstrong *et al*. (2020) were used for the present study.

Diesing *et al*. (2021) recently calculated the POC stock in subtidal sediments in the North Sea and Skagerrak which accounts for 50% of the northwest European continental shelf. New modelled POC stock in this region was estimated to be 230.51 teragrams (Tg) of carbon. This value was comparable to the estimates in Diesing *et al*. (2017) of 230 – 882 Tg of carbon in the top 10 cm of sediments across the entire northwest European continental shelf.

Intertidal sediment estimates in Armstrong *et al*. (2020) were derived by multiplying subtidal sediment values from Diesing *et al*. (2017) by a factor of 2 under the assumption that nearshore sediments hold more carbon. Parker *et al*. (2021) based estimates of intertidal mud and sand on three UK studies which led to a range of carbon stock values being applied, as shown in Appendix B. The range of values used in Armstrong *et al*. (2020) were within the range of values identified by Parker *et al*. (2021). This provided further validation of the estimation used in Armstrong *et al*. (2020) and thus these values were used in the present study for consistency.

## Saltmarsh

There have been three new estimates of carbon stock in UK saltmarshes since early 2020. These values range from between 5.11 kg $m^{-2}$ and 5.64 kg $m^{-2}$ in Scotland (Porter *et al*., 2020; Austin *et al*. 2021) to an average value of 3.6 kg $m^{-2}$ in a review by Parker *et al*. (2020) of 7 UK studies. A saltmarsh carbon stock value of 4.2 kg $m^{-2}$ was used in Armstrong *et al*. (2020), which was based on the average carbon stock value of analysed plant and soil characteristics across 23 saltmarshes in Wales from Ford *et al*. (2019). Due the relevance of the Welsh data from Ford *et al*. (2019) to this study, and the identification of comparable values in the literature, the value used in Armstrong *et al*. (2020) was used for the main assessment of carbon storage in this study (see Section 2.2).

The saltmarsh carbon sequestration value in Armstrong *et al*. (2020) of 0.084 kg $m^{-2}$ $yr^{-1}$ was calculated as a 2 mm proportion of the soil stock value, assuming an accretion rate of 2 mm $yr^{-1}$. Parker *et al*. (2021) found a similar range of values from 0.066 – 0.195 kg $m^{-2}$ $yr^{-1}$ from the literature. Armstrong *et al*. (2020) noted that whilst higher values have been found in the literature, applying a proportion of the standing stock was both consistent with the methodology adopted for other habitats (such as seagrass) and was likely to be more applicable to Welsh conditions as the stock value was derived from Welsh saltmarshes. Thus, the value from Armstrong *et al*. (2020) was used in the present study. It should be acknowledged that the 2 mm assumption likely represents a conservative approach for Welsh saltmarshes.

## Seagrass

There have been 2 recent studies on seagrass carbon stocks by Potouroglou *et al*. (2021) and Lima *et al*. (2020). They estimated 1.1 kg $m^{-2}$ of carbon across Scotland and 0.8 kg $m^{-2}$ of carbon in the Solent, England, respectively in the top 10 cm of sediment. In addition, two recent literature reviews of UK and European estimated seagrass carbon stock values of 2 – 5 kg $m^{-2}$ and 1.37 kg $m^{-2}$ (Hendricks *et al*., 2020; Parker *et al*., 2021).

The seagrass carbon stock estimate in the top 10 cm of sediment in Armstrong *et al*. (2020) was 1.35 kg $m^{-2}$, based on the average value of carbon stock at 13 southwest England meadows by Green *et al*. (2018). Due to the closer proximity of the sites in Green *et al*. (2018) to Wales, and the comparable values in the new literature, values from Armstrong *et al*. (2020) are used in the present study.

A review of carbon sequestration rates in Parker *et al*. (2021) found a value of 0.086 kg $m^{-2}$ $yr^{-1}$ based on a non-UK study in the northwest Atlantic. Carbon sequestration in seagrass was therefore kept consistent with the value in Armstrong *et al*. (2020) of 0.027 kg $m^{-2}$ $yr^{-1}$ (assumed at 2 mm $yr^{-1}$ as proportion of soil standing stock value) as it was based off the values for carbon stock from Green *et al*. (2018).

## Kelp

Armstrong *et al*. (2020) used a value of 0.465 kg $m^{-2}$ for the carbon stock of kelp. This value was based on the average carbon stock of Welsh and southwest England sites studied in Smale *et al*. (2016). Recent UK and European reviews found similar values for kelp carbon stock of 0.31 kg $m^{-2}$ and 0.5 – 0.9 kg $m^{-2}$ (Hendricks *et al*., 2020; Parker *et al*., 2021). Porter *et al*. (2020) also estimated a comparable value of 0.21 kg $m^{-2}$ for kelp around Orkney, Scotland. Due to the relevance of the data from Smale *et al*. (2016) to the study area, values in this study were kept consistent with Armstrong *et al*. (2020). In line with Armstrong *et al*. (2020) and recent literature, it was assumed that no carbon sequestration occurs in kelp habitats.

## Maerl

New estimates of 68.8 kg $m^{-2}$ of carbon stock in live maerl were made by Porter *et al*. (2020) for maerl beds around Orkney. This is comparable to values estimated by Burrows *et al* (2014) of 62.1 kg $m^{-2}$. Armstrong *et al*. (2020) based estimates off Burrows *et al*. (2014), however they only used one fifth of the value (12.4 kg $m^{-2}$). This was due to Welsh beds being dominated by *Phymatolithon calcareum* species, which sequesters approximately one fifth of the amount compared to *Lithothamnion glaciale* (Burrows *et al*., 2014), and also as Welsh beds are considered degraded (Armstrong *et al*., 2020, NRW *pers comms*). The values used in the present study were therefore from Armstrong *et al*. (2020).

## 3.2. Habitat carbon values

Table 2a-2c summarises the carbon storage and sequestration values used in this study. After the review of recent literature in Section 3.1, all carbon values were kept consistent with those used in Armstrong *et al*. (2020). A table providing an extensive breakdown of the carbon values used in the present study is presented in Appendix A.

**Table 2a** Summary of carbon sequestration and storage values per studied habitat from Armstrong *et al*. (2020) for Intertidal (Organic Carbon) (* refers to Top 10 cm, ∆ refers to top 60 cm)

| Sedimentary Area / Habitat | Carbon Rate | Parameter (Unit) | Source / Justification |
|---|---|---|---|
| Saltmarsh | 0.21 | Biomass standing stock (kg $m^{-2}$) | Taken from Burrows *et al.*, 2014 |
| Saltmarsh | 4.20 | Soil standing stock (kg $m^{-2}$*) | Average of 51 Welsh samples (Ford *et al.*, 2019). |
| Saltmarsh | 0.084 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Proportion of soil stock value (2 mm $yr^{-1}$ accretion) |
| Intertidal macroalgae | 0.0465 | Biomass standing stock (kg $m^{-2}$) | 10% of subtidal value (as per Smale *et al.*, 2013) |
| Intertidal Muds, gravels and sand (POC) | 0.55 - 1.84 | Soil standing stock (kg $m^{-2}$*) | Subtidal values from Diesing *et al.*, 2017, multiplied by 2 |
| Intertidal Muds, gravels and sand (POC) | 0.011- 0.037 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Proportion of stock value (2 mm $yr^{-1}$ accretion) |

**Table 3b** Summary of carbon sequestration and storage values per studied habitat from Armstrong *et al*. (2020) for Shellfish beds (incl. intertidal) (organic and inorganic carbon) (* refers to Top 10 cm, ∆ refers to top 60 cm)

| Sedimentary Area / Habitat | Carbon Rate | Parameter (Unit) | Source / Justification |
|---|---|---|---|
| Oysters (*Ostrea*) (may have intertidal element) | 0.13 | Soil standing stock (kg $m^{-2}$*) | Proportion of sequestration (relationship as per Burrows *et al.*, 2014) |
| Oysters (*Ostrea*) (may have intertidal element) | 0.001 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 1% of US value in Fodrie *et al.* (2017). |
| Horse mussel (*Modiolus*) | 4.00 | Soil standing stock (kg $m^{-2}$*) | Burrows *et al.* 2014 values (10 cm depth inferred) |
| Horse mussel (*Modiolus*) | 0.040 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Burrows *et al.* 2014 values (10 cm depth inferred) |
| Other mussels (*Mytilus*, *M. discord*, etc.) | 0.40 | Soil standing stock (kg $m^{-2}$*) | 10% of horse mussel values, as lower biomass assumed |
| Other mussels (*Mytilus*, *M. discord*, etc.) | 0.004 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 10% of horse mussel values, as lower biomass assumed |

**Table 4c** Summary of carbon sequestration and storage values per studied habitat from Armstrong *et al*. (2020) for Subtidal (organic and inorganic carbon) (* refers to Top 10 cm, ∆ refers to top 60 cm)

| Sedimentary Area / Habitat | Carbon Rate | Parameter (Unit) | Source / Justification |
|---|---|---|---|
| Seagrass (may have intertidal element) | 0.26 | Biomass standing stock (kg $m^{-2}$) | Taken from Burrows *et al*., 2014 |
| Seagrass (may have intertidal element) | 1.35 | Soil standing stock (kg $m^{-2*}$) | Average of 13 SW England meadows quoted in Green *et al.* 2018, adjusted to top 10 cm |
| Seagrass (may have intertidal element) | 0.027 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Proportion of soil stock value (2 mm $yr^{-1}$ accretion) |
| Macroalgae - kelp | 0.47 | Biomass standing stock (kg $m^{-2}$) | Average of six sites (Smale *et al.,* 2016) |
| Macroalgae - maerl | 0.10 | Biomass standing stock (kg $m^{-2}$) | 10 times sequestration (same relationship as applied by Burrows *et al*., 2014) |
| Macroalgae - maerl | 12.41 | Soil standing stock (kg $m^{-2\Delta}$) | 20 % of value applied by Burrows *et al*., 2014 for kelp (as Welsh beds contain much less carbon) |
| Macroalgae - maerl | 0.010 | Sequestration | From Table 3 of Burrows *et al*., 2014 |
| Brittlestar Beds | unknown | Biomass standing stock | No values found in literature |
| Brittlestar Beds | 0.29 | Soil standing stock | Applied same value as subtidal sandy gravel, as brittlestars normally found on coarse sediment. |
| Brittlestar Beds | 0.082 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Taken from Burrows *et al*., 2014 |
| Faunal Turf | 0.014 | Biomass standing stock (kg $m^{-2}$) | Calculated for this study using weight values quoted by Taylor (1998) for New Zealand, and assuming 40% carbon. |
| Subtidal Muds, gravels and sand (POC) | 0.28- 0.92 | Soil standing stock (kg $m^{-2*}$) | Derived from Diesing *et al*., 2017 |
| Subtidal Muds, gravels and sand (POC | 0.0003 - 0.0009 | Sequestration (kg $m^{-2}$ $yr^{-1}$) | Proportion of stock value (0.1 mm $yr^{-1}$ accretion) |

| Sedimentary Area / Habitat | Carbon Rate | Parameter (Unit) | Source / Justification |
|---|---|---|---|
| Sediments (carbonate) | 3.36 | Soil standing stock (kg $m^{-2}$*) | Calculated based on relationships in Burrows *et al.*, 2014, and conservative assumption of 10% carbonate across all sediments. |
| Sediments (carbonate) | 0 | Sequestration | n/a (or see shellfish beds) |

## 3.3. Blue carbon in SAC habitat features

### Carbon storage across the SAC network

The SACs assessed for carbon storage and sequestration covered approximately 5,100 km², which accounted for around 16% of the Welsh National Marine Plan Area. Within the SACs, Annex I features covered approximately 75% of the total area. The total contribution of the Welsh SAC Annex I features to carbon storage was estimated to be approximately 11 Mt of carbon in the top 10 cm of sediment (based on soil and carbonate standing stock and is estimated considering overlaps between features, see Section 2.2). This accounts for almost 10% of the total carbon storage across all blue carbon sediment and habitat types across the entire the Welsh National Marine Plan area as estimated in Armstrong *et al*. (2020) (excluding the water column estimates). The rate of sequestration was approximately 12,300 t of carbon per year across the SAC network (Figure 4), which accounts for 47% of the total carbon sequestered across all Welsh blue carbon habitats from Armstrong *et al*. (2020).

Large shallow inlets and bays held the highest proportion of soil carbon stock with 4.6 Mt of carbon in the top 10 cm of sediment (Table 5), which was largely attributed to the large spatial extent they cover across the SAC network. The largest biomass standing stock of carbon was stored within the subtidal reef feature, likely due to the large spatial extent of kelp, faunal turf, and other macroalgae habitats (which store large amounts of carbon in biomass) in comparison to other Annex I features.

Estuaries sequestered the largest amount of carbon per year out of all the features at over 9,500 t $yr^{-1}$. Estuaries are a large feature which contain a range of smaller features (such as mudflats and sandflats, saltmarsh and reefs) which likely contributed greatly towards the high sequestration rate (Table 5). Mudflats and sandflats not covered by seawater at low tide had the second largest sequestration rate at over 6,500 t $yr^{-1}$.

Designated saltmarsh features contributed one of the largest amounts of carbon storage and sequestration per unit area within the SAC network. This was expected due to saltmarsh habitats having one of the highest carbon storage and sequestration values of all the habitat components included in the study (see **Table 2**).

Any habitats associated with rock were considered not to sequester carbon, therefore as expected, intertidal and subtidal reefs contributed the smallest proportion of carbon stock and sequestration per unit area within the SAC network (Table 5).

An example of the differences in the contribution of Annex I features to carbon sequestration, soil and biomass stock, are shown in Annex C for the Lleyn Peninsula and the Sarnau SAC (**Figure C1**).

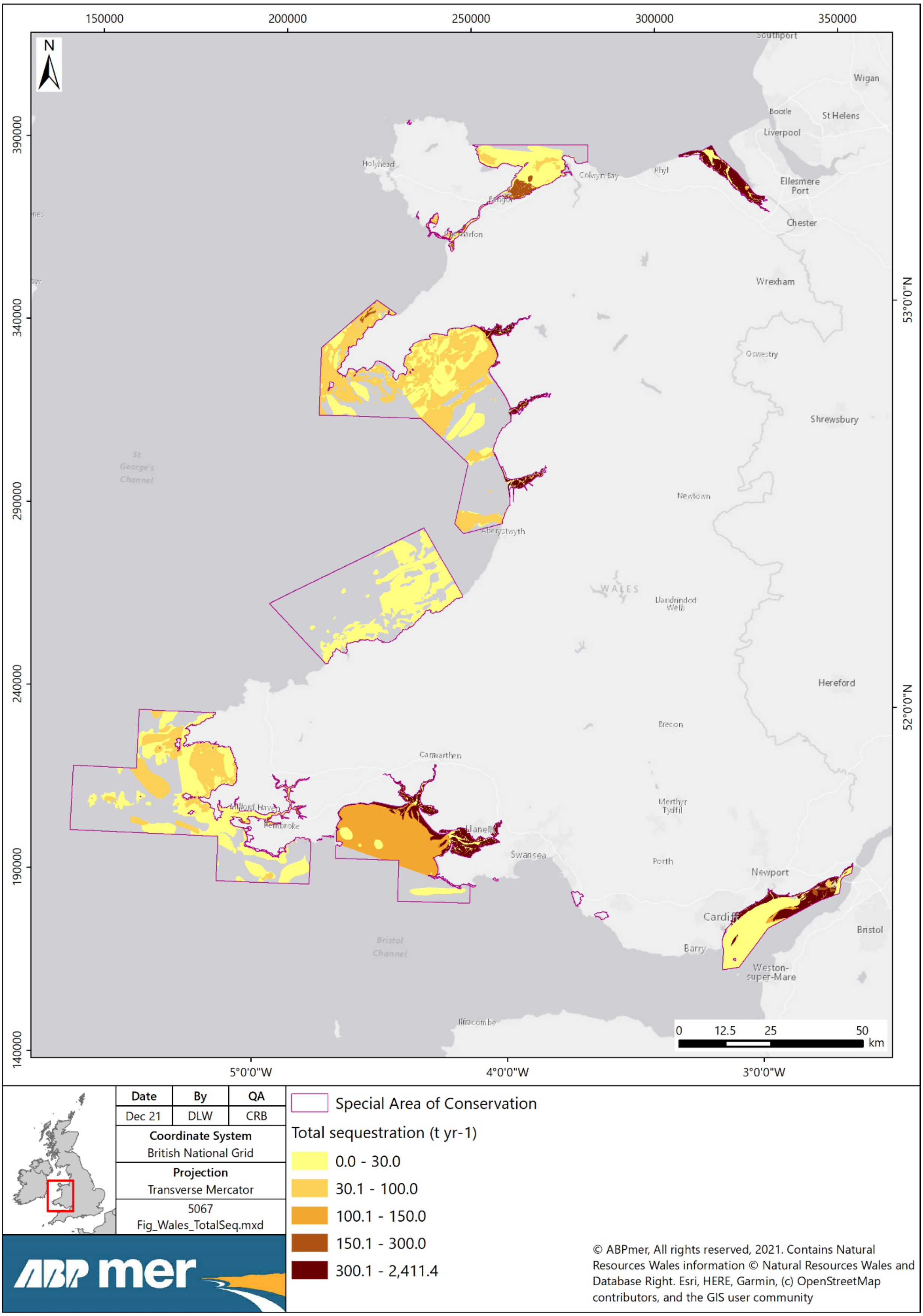



Figure 4 Carbon sequestration of Annex I features across the SAC network

Table 5 Carbon stored and sequestered in Welsh Annex I features for which SACs are designated

| Feature | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (top 10 cm)) | Carbonate Stock (t (top 10 cm)) | Sequestration ($t\ yr^{-1}$) |
|---|---|---|---|---|---|
| Estuaries | 524 | 16,545 | 586,047 | 1,619,550 | 9,584 |
| Intertidal Reef | 15 | 1,533 | 2,596 | 3,443 | 41 |
| Subtidal Reef | 1,264 | 22,366 | 388,963 | 3,773,050 | 533 |
| Large Shallow Inlets and Bays | 1,249 | 21,721 | 579,165 | 3,993,311 | 2,005 |
| Mudflats and sandflats not covered by seawater at low tide | 322 | 2,218 | 326,422 | 1,053,991 | 6,505 |
| Saltmarsh | 49 | 9,663 | 197,176 | 165,290 | 3,942 |
| Sandbanks which are slightly covered by seawater all the time | 366 | 121 | 142,986 | 1,223,560 | 241 |

*Values do not consider overlapping features and should not be summed to avoid double counting (see Section 2.2)*

## Estuaries

The Severn Estuary SAC contained the largest store of carbon in the top 10 cm of sediment in estuary features across the SAC network, accounting for approximately 44% of the total carbon stored in estuaries. This is due to the large spatial extent of the estuary, covering an estimated 261 km² (Table 12,Figure C2).

However, per unit area, Carmarthen Bay and Estuaries SAC stored the most carbon at over 5,200 t $km^{-2}$ (soil and carbonate stock). Carmarthen Bay and Estuaries SAC also had the highest sequestration rate per unit area at 38 t $km^{-2}$ $yr^{-1}$ (Figure 5). The high values associated with this SAC were likely due to the large spatial extent of saltmarsh habitat (almost 29 km²) within the SAC.

The highest biomass standing stock and sequestration rates of carbon in estuary features were from the Carmarthen Bay and Estuaries SAC. However, the highest biomass standing stock per unit area of the feature was in the Pembrokeshire Marine SAC at 76 t $km^{-2}$, likely due to the large extent of intertidal and subtidal kelp (6.5 km²) and other intertidal macroalgae (3.3 km²) in comparison to other SACs.

Table 6 Carbon stored and sequestered in designated estuary features in the SAC network

| SAC | Area (km²) | Biomass Standing Stock (t) | Soil Standing Stock (t (top 10 cm)) | Carbonate Stock (t (top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 91 | 6,074 | 179,336 | 298,580 | 3,484 |
| Dee Estuary / Aber Dyfrdwy (Wales) | 67 | 1,707 | 90,753 | 226,243 | 1,731 |
| Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh | 5 | 201 | 8,151 | 16,690 | 162 |
| Pembrokeshire Marine / Sir Benfro Forol | 57 | 4,292 | 57,698 | 138,398 | 597 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 42 | 2,694 | 80,388 | 139,530 | 1,575 |
| Severn Estuary / Môr Hafren (Wales) | 261 | 1,577 | 169,721 | 800,109 | 2,036 |

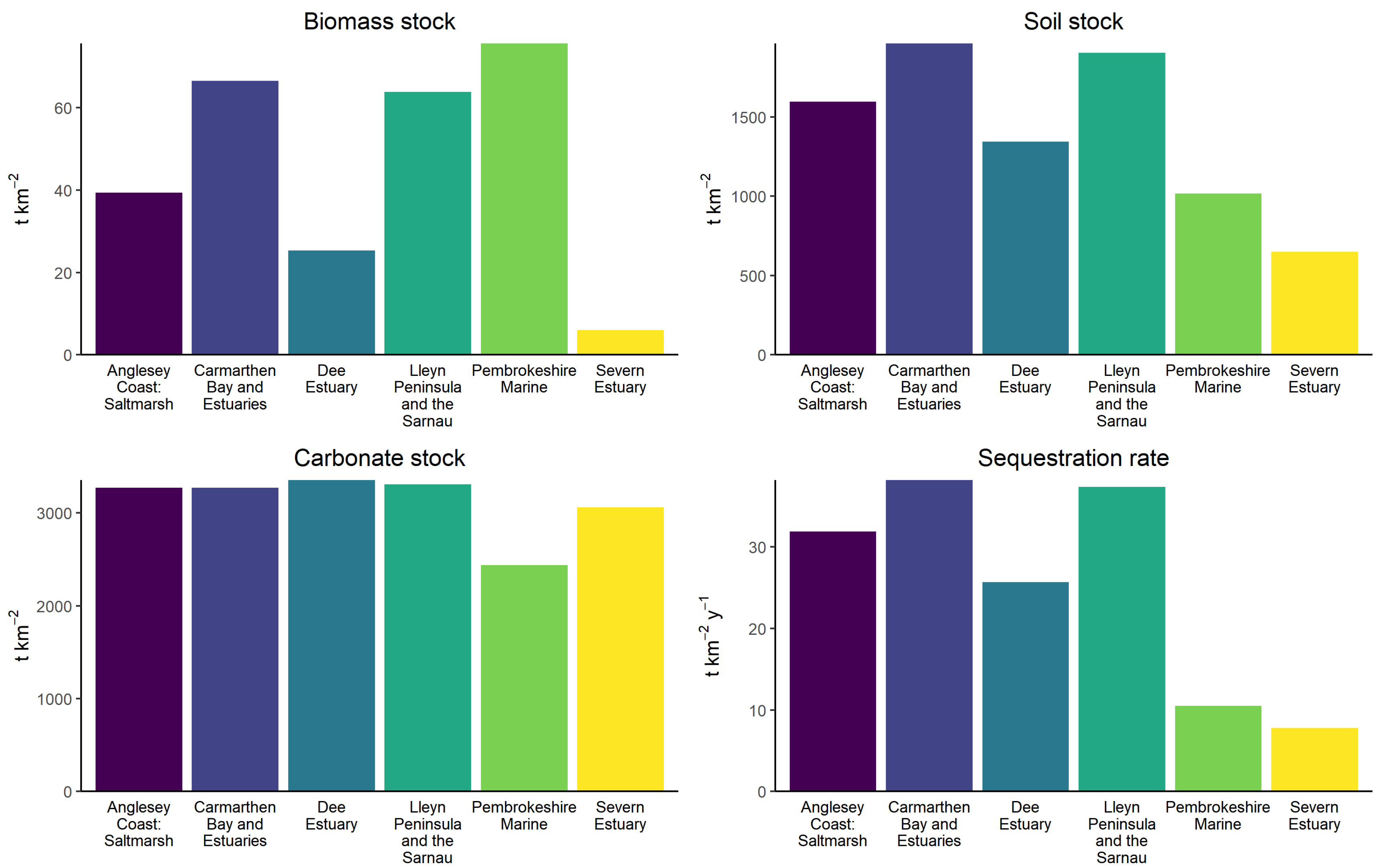



Figure 5 Carbon biomass, soil, carbonate stocks and sequestration rate per unit area for Annex I estuary features in Welsh SACs.

## Large shallow inlets and bays

The Carmarthen Bay and Estuaries SAC and Lleyn Peninsula and the Sarnau SAC have the largest stores of carbon within the top 10 cm of sediment within large shallow inlets and bays (Table 7). However, per unit area, all SACs for which large shallow inlets and bays are designated had similar stores of carbon, ranging from 3,456 to 3,883 t $km^{-2}$.

Large shallow inlets and bays in the Lleyn Peninsula and the Sarnau SAC had the largest biomass standing stock of carbon in terms of total volume and per unit area (42 t $km^{-2}$) (Figure 6). This was likely due to the large spatial extent of subtidal kelp habitat covering approximately 37 $km^2$ of the SAC.

Large shallow inlets and bays in the Carmarthen Bay and Estuaries SAC sequester the largest volume of carbon per year out of all the SACs; however, the Menai Strait and Conwy Bay SAC sequesters the largest volume of carbon per unit area at approximately 4 t $km^{-2}$ $yr^{-1}$.

Table 7 Carbon stored and sequestered in designated large shallow inlet and bays features in the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 406 | 27 | 163,048 | 1,361,854 | 736 |
| Pembrokeshire Marine / Sir Benfro Forol | 245 | 3,630 | 145,761 | 758,913 | 296 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 417 | 17,693 | 169,807 | 1,270,558 | 318 |
| Y Fenai a Bae Conwy / Menai Strait and Conwy Bay | 181 | 370 | 100,549 | 601,985 | 656 |

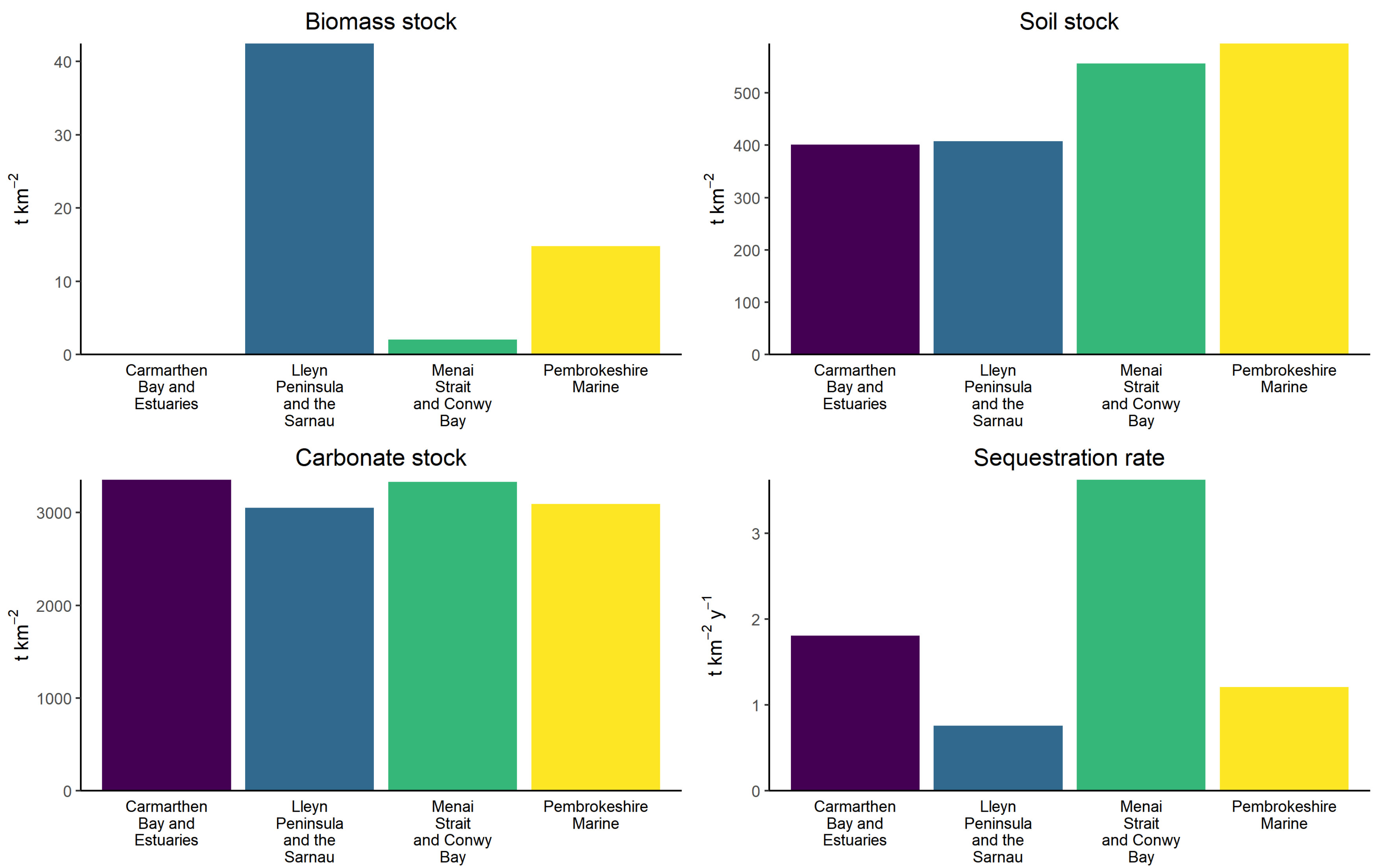



Figure 6 Carbon biomass, soil, carbonate stocks and sequestration rate per unit area for Annex I large shallow inlets and bays features in Welsh SACs.

## Mudflats and sandflats not covered by seawater at low tide

The largest stock of carbon in the top 10 cm of sediment in mudflats and sandflats features was in the Carmarthen Bay and Estuaries SAC, accounting for over 28% of the carbon storage across the feature. However, per unit area, all SACs stored similar amounts of carbon in the top 10 cm of sediment, ranging between 3,981 and 4,448 t $km^{-2}$.

Mudflats and sandflats designated in the Severn Estuary SAC had the largest volume of carbon stored in biomass, accounting for 34% of the total biomass standing stock of mudflat and sandflat features across the network (Table 8). However, the mudflat and sandflats feature at the Pembrokeshire Marine SAC had the largest volume of carbon stored in biomass, approximately 34 t $km^{-2}$.

Whilst mudflats and sandflats in the Carmarthen Bay and Estuaries SAC sequester the largest volume of carbon in the network per year, all SACs had similar rates per unit area (19 – 23 t $km^{-2}$ $yr^{-1}$).

Table 8 Carbon stored and sequestered in mudflats and sandflats not covered by seawater at low tide features designated within the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 91.2 | 399 | 91,095 | 298,474 | 1,810 |
| Dee Estuary / Aber Dyfrdwy (Wales) | 49 | 78 | 53,978 | 165,445 | 1,079 |
| Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh | 8 | 51 | 8,632 | 24,663 | 172 |
| Pembrokeshire Marine / Sir Benfro Forol | 17 | 583 | 18,886 | 49,912 | 375 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 36 | 199 | 37,364 | 119,069 | 744 |
| Severn Estuary / Môr Hafren (Wales) | 86 | 749 | 82,914 | 283,556 | 1,656 |
| Y Fenai a Bae Conwy / Menai Strait and Conwy Bay | 35 | 159 | 33,553 | 112,872 | 669 |

# Reefs

## Intertidal reefs

Intertidal reefs cover a relatively small proportion of the SAC network. Intertidal reefs within the Pembrokeshire Marine SAC accounted for 51% of the total carbon stored in the top 10 cm of sediments in intertidal reef features, the highest proportion across the Welsh SAC network. The Severn Estuary had the largest volume of carbon stored per unit area with approximately 690 t $km^{-2}$ of carbon. Sequestration was low in intertidal reefs; between 0 and 4 t $km^{-2}$ $yr^{-1}$ across all SACs.

The Pembrokeshire Marine SAC also had the largest total volume of carbon stored in biomass (Table 9), however Cardigan Bay and Estuaries SAC had the largest volume per unit area at 142 t $km^{-2}$.

Table 9 Carbon stored and sequestered in intertidal reefs designated within the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Cardigan Bay / Bae Ceredigion | 0.7 | 101 | 44 | 115 | 0.3 |
| Pembrokeshire Marine / Sir Benfro Forol | 6.3 | 715 | 1,398 | 1,716 | 23 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 3.0 | 285 | 298 | 166 | 4 |
| Severn Estuary / Môr Hafren (Wales) | 2.9 | 187 | 698 | 1,287 | 12 |
| Y Fenai a Bae Conwy / Menai Strait and Conwy Bay | 2.1 | 245 | 160 | 159 | 2 |

## Subtidal reefs

Subtidal reefs within the Pembrokeshire Marine SAC accounted for the largest total volume of carbon stored in the top 10 cm of sediment in subtidal reef features across the SAC network, at 32% (Table 10). However, all SACs stored similar amount of carbon per unit area ranging from 2,973 to 3,651 t $km^{-2}$. Sequestration rate of carbon was the largest in Lleyn Peninsula and the Sarnau SAC (**Figure C1**), however, per unit area, reef sequestration rates were low for all SACs (less than 1 t $km^{-2}$) (Figure 7).

Whilst the Pembrokeshire Marine SAC had the largest total volume of carbon stored in reef biomass, the Menai Strait and Conwy Bay SAC had the largest volume of carbon in biomass per unit area at approximately 68 t $km^{-2}$.

Table 10 Carbon stored and sequestered in subtidal reefs designated within the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Cardigan Bay / Bae Ceredigion | 279 | 2,550 | 101,748 | 917,106 | 102 |
| Pembrokeshire Marine / Sir Benfro Forol | 433 | 3,855 | 124,796 | 1,208,313 | 124 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 493 | 15,338 | 147,545 | 1,517,903 | 292 |
| Severn Estuary / Môr Hafren (Wales) | 51 | >0.01 | 12,420 | 104,960 | 12 |
| Y Fenai a Bae Conwy / Menai Strait and Conwy Bay | 9.2 | 623 | 2453 | 24,768 | 3 |

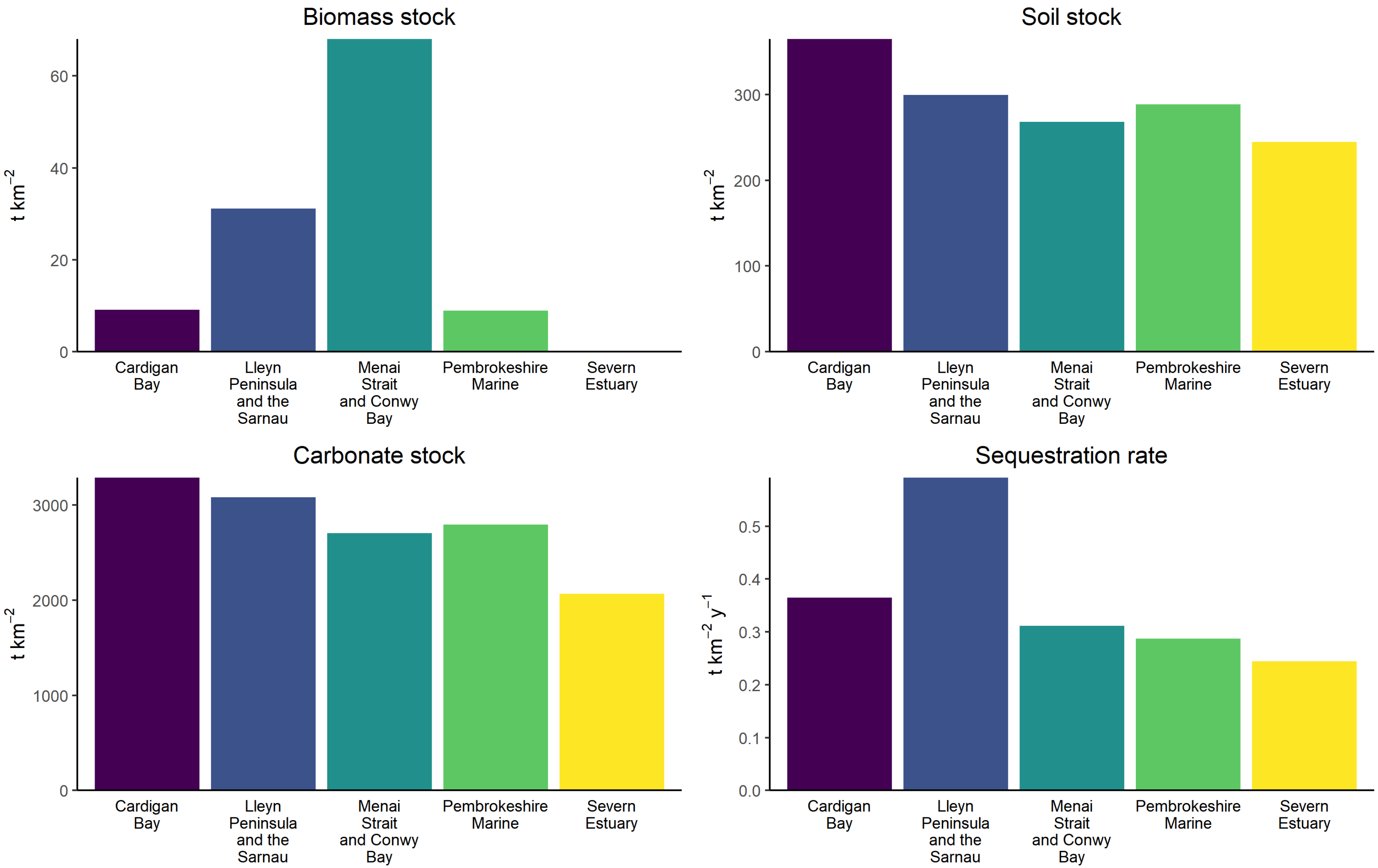



Figure 7 Carbon biomass, soil, carbonate stocks and sequestration rate per unit area for Annex I subtidal reef features in Welsh SACs.

## Saltmarsh

The saltmarsh feature within the Carmarthen Bay and Estuaries SAC accounted for 56% of the total volume of carbon in the 10 cm of sediment in saltmarsh features across the SAC network (Table 11). This SAC also had the largest total carbon stored in biomass (see Figure C3) and sequestration rate, likely due to the large spatial extent of the feature at this SAC.

However, all saltmarsh features across the SAC network store similar volumes of carbon per unit area, between 7,092 and 7,559 t $km^{-2}$. All saltmarshes designated within SACs also had similar volumes of carbon stored in biomass and sequestration rates per unit area, 181 to 209 t $km^{-2}$ and 76 to 84 t $km^{-2}$ $yr^{-1}$, respectively (Figure 8).

**Table 11** Carbon stored and sequestered in saltmarshes designated within the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 27.9 | 5,404 | 110,658 | 93,323 | 2212 |
| Dee Estuary / Aber Dyfrdwy (Wales) | 5.5 | 1,148 | 23,052 | 18,633 | 461 |
| Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh | 1.4 | 251 | 5,258 | 4,634 | 105 |
| Kenfig / Cynffig | 0.04 | 9 | 170 | 136 | 3 |
| Pembrokeshire Marine / Sir Benfro Forol | 2.6 | 499 | 10,115 | 8,522 | 202 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 11.5 | 2,270 | 46,228 | 38,639 | 924 |
| Severn Estuary / Môr Hafren (Wales) | 0.4 | 84 | 1,695 | 1,403 | 34 |

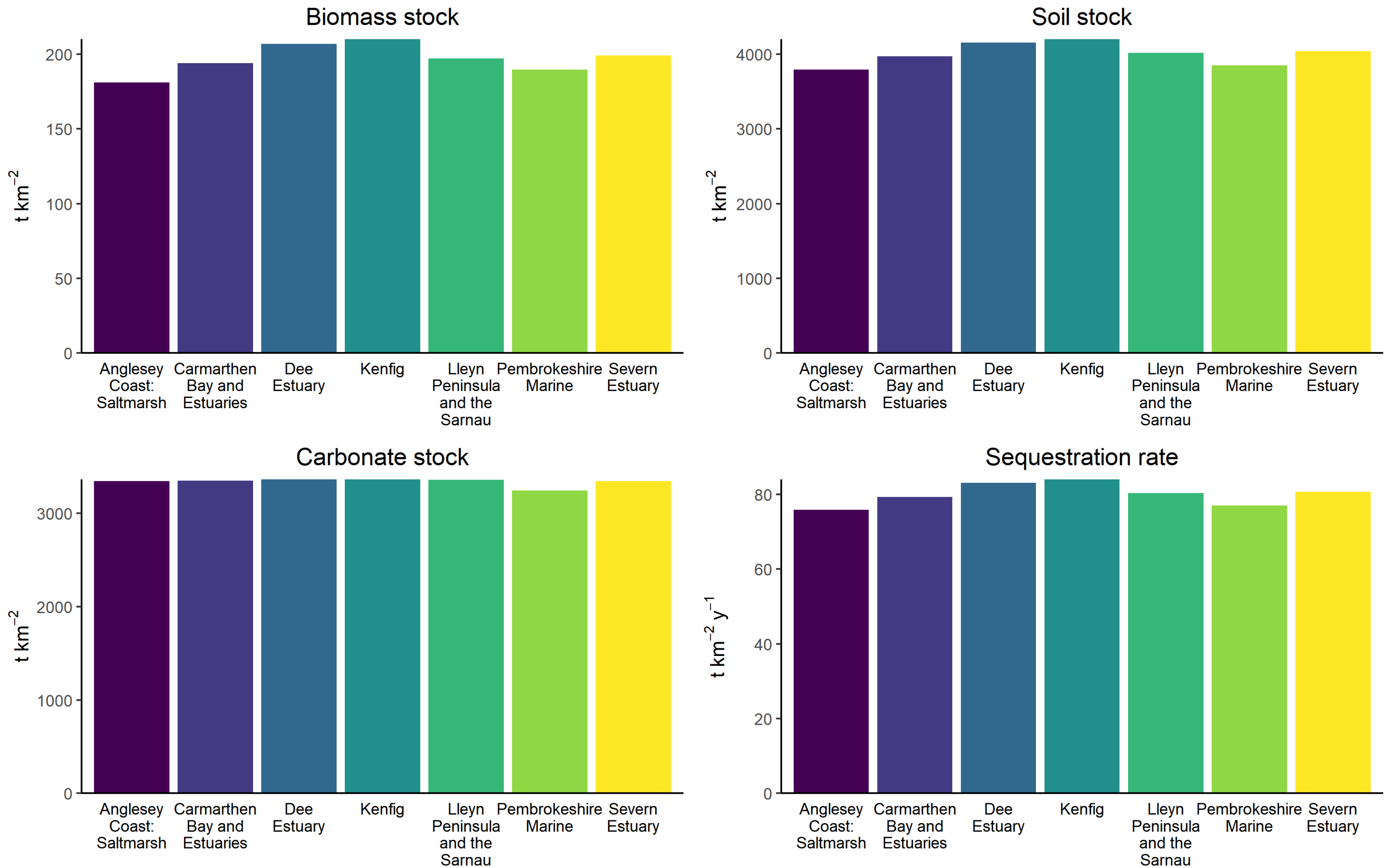



Figure 8 Carbon biomass, soil, carbonate stocks and sequestration rate per unit area for Annex I saltmarsh features in Welsh SACs.

## Site-specific estimates of carbon stored in Welsh saltmarshes

Estimates of carbon storage based on site-specific carbon stock data (see Section 2.3) found that carbon soil stock in Welsh saltmarshes ranged from 2.93 kg $m^{-2}$ in the Anglesey Coast: Saltmarsh SAC to 4.32 kg $m^{-2}$ in the Carmarthen Bay and Estuaries SAC (Table 12).

The total carbon storage in each SAC was similar to the results for saltmarsh above, which were based on a range of habitat component types in the Welsh SACs. However, low mean carbon per unit area for the saltmarsh at Anglesey Coast: Saltmarsh SAC led to a decrease of almost 30% in soil standing stock compared to results presented above. Site-specific data for Welsh habitats could therefore lead to substantial differences in the carbon stocks estimated in Welsh Annex I features.

Table 12. Carbon stock values estimated for saltmarshes which are designated under Welsh SACs, derived from Ford *et al*. (2019). The sample size (N) refers to the number of locations sampled within each SAC.

| Saltmarsh SAC | N | Carbon Soil Stock in Saltmarsh Habitat (kg $m^{-2}$) | Total Soil Standing Stock in Annex I Saltmarsh Feature (t) |
|---|---|---|---|
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 11 | 4.32 | 113,744 |
| Dee Estuary / Aber Dyfrdwy (Wales) | NA | NA | NA |
| Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh | 1 | 2.93 | 3,741 |
| Kenfig / Cynffig | NA | NA | NA |
| Pembrokeshire Marine / Sir Benfro Forol | 2 | 3.95 | 9,527 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 6 | 4.11 | 45,255 |
| Severn Estuary/ Môr Hafren | NA | NA | NA |

## Sandbanks which are slightly covered by seawater all the time

The largest total carbon stock in the top 10 cm of sediment in designated sandbanks which are slightly covered by seawater all the time features was in the Cardigan Bay SAC and Lleyn Peninsula and the Sarnau SAC (Table 13). These sites account for approximately 26% and 24% of the total carbon stock of sandbank features across the SAC network due to large spatial extents of the feature. Per unit area of sandbanks, all SACs had similar volumes of carbon stored, ranging from 3,674 – 3,845 t $km^{-2}$.

Total biomass stock was overall low across all SACs, with three of the SACs having no biomass stock (Table 13). Menai Strait and Conwy Bay SAC had the largest total biomass stock and biomass stock per unit area at approximately 1 t $km^{-2}$. This feature is characterised by sand and gravel sediments which store and sequester relatively small volumes of carbon (see Appendix A). Where values for biomass standing stock are high, this likely reflects the patchy presence of kelp which is not designated as part of the feature

Similarly, subtidal sandbank sequestration rates of carbon were low per unit area, with all SACs having less than 1 t $km^{-2}$ $yr^{-1}$ apart from in the Severn Estuary, which had rate of 4 t $km^{-2}$ $yr^{-1}$.

Table 13. Carbon stored and sequestered in sandbanks which are slightly covered by seawater all the time designated within the SAC network

| SAC | Area ($km^2$) | Biomass Standing Stock (t) | Soil Standing Stock (t (Top 10 cm)) | Carbonate Stock (t (Top 10 cm)) | Sequestration (t $yr^{-1}$) |
|---|---|---|---|---|---|
| Cardigan Bay / Bae Ceredigion | 94.1 | 45 | 33,720 | 315,872 | 34 |
| Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd | 24.6 | 0 | 9,052 | 82,696 | 9 |
| Pembrokeshire Marine / Sir Benfro Forol | 51.8 | 4 | 18,136 | 172,101 | 18 |
| Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau | 88.6 | 0 | 30,472 | 297,544 | 30 |
| Severn Estuary / Môr Hafren (Wales) | 31.7 | 0 | 16,416 | 105,458 | 114 |
| Y Fenai a Bae Conwy / Menai Strait and Conwy Bay | 75.0 | 72 | 35,189 | 249,888 | 35 |

# 4. Discussion, conclusions and limitations

## 4.1. Key findings

By combining existing knowledge of the carbon potential and spatial extents of sedimentary and biogenic habitats in Welsh waters, it has been possible to estimate quantities of blue carbon resources that lie within Annex I features in the Welsh SAC network. From the assessment undertaken in this study, it was highlighted that the Annex I features contribute a large amount of carbon storage and sequestration. It was estimated that approximately 11 Mt carbon is stored in the Annex I features, accounting for almost 10% of the total carbon stored in the top 10 cm of sediment blue carbon habitat types across the entire the Welsh National Marine Plan area (as estimated in Armstrong *et al*., 2020). The carbon stored in Annex I features is equivalent to 17% of the carbon held in Welsh forests. Please note that Welsh woodland stock value was estimated to be 64.7 Mt C. Calculated by extrapolating the stock value quoted in NRW (2018) (for the NRW estate only) and using total woodland values reported in National Assembly for Wales (2017) (306,000 ha in total).

The estimated carbon sequestration per year within Welsh Annex I features was estimated to be 47% (12,300 t) of the total carbon sequestered across the Welsh National Marine Plan area (Armstrong *et al*. 2020). The sequestration in Welsh Annex I features was equivalent to 3% of the sequestration of Welsh woodlands and equates to the sequestration of approximately 97 km² of woodland. This is based on woodland sequestration value of 1.42 Mt of CO2e quoted by National Assembly for Wales (2017) (and applying assumption that 3.67 t of CO2 contain 1 t of carbon) and using total woodland values reported in National Assembly for Wales (2017) (306,000 ha in total).

The spatial extent of the features was the main factor determining carbon storage and sequestration. However, examining carbon storage and the sequestration rate per unit area of the Annex I features highlighted that the habitat components making up the features played an important role in the density of carbon within the features. For example, the largest volume of carbon stored in biomass for estuary features was in the Carmarthen Bay and Estuaries SAC, however the highest biomass standing stock per unit area of an estuary feature was in the Pembrokeshire Marine SAC, due to the large extent of intertidal and subtidal kelp and intertidal macroalgae here, in comparison to other SACs.

Vegetated coastal habitats have been identified as some of the most important carbon sinks, sequestering and storing large amounts of carbon per year. Although vegetated coastal habitats have a relatively small spatial extent in Welsh waters, SACs often protect features which cover large areas of vegetated coastal habitats, such as saltmarshes (for which SACs are also designated), seagrasses, kelp and macroalgae. As such, SACs account for a high proportion of total carbon sequestered in Welsh marine habitats every year. This study also highlighted that saltmarsh Annex I features were one of the biggest stores of carbon per unit area across the SAC network.

Given the importance of blue carbon habitats as a mechanism for mitigating against climate change, the need to conserve these habitats is a priority. In particular, the protection and restoration of intertidal and shallow subtidal habitats which could substantially increase the blue carbon potential of Welsh MPAs.

## 4.2. Limitations and considerations

There are a number of limitations associated with the estimates of carbon storage and sequestration and some important considerations for future predictions of blue carbon potential in Wales. These relate to:

- Uncertainty of stock and sequestration values in intertidal and subtidal sediments;
- Potential overestimation of blue carbon contribution;
- Availability of Welsh-specific carbon storage and sequestration estimates;
- Uncertainty of blue carbon habitat extents; and
- Uncertainty associated with future environmental change.

As recognised by Armstrong *et al*. (2020), there was uncertainty regarding the rates of carbon sequestration in both intertidal and subtidal sediments. Estimates of annual carbon sequestration are scarce in the literature, but further research could increase the robustness of the values used in this study. There was also uncertainty relating to the amount of inorganic carbon (carbonate) stored in Welsh sediments, with Armstrong *et al*. (2020) using a conservative lower bound estimate. Other studies have estimated local to regional carbonate values based on British Geological Society (BGS) sediment records (Burrows *et al*., 2014; 2017; Porter *et al*., 2020). A similar approach could be used to obtain a more robust estimate of carbonate in Welsh waters, however, Burrows *et al*. (2017) acknowledged that BGS do not account for other forms of inorganic carbon, so estimates based on these values are likely still an underestimate.

Within a given SAC, not all blue carbon habitats are necessarily protected as part of an Annex I feature. For example, the mapped spatial extents for reef features covered a wide range of sediment types, such as sands, muds and gravels which are not designated as part of the Annex I feature. It is therefore likely that the contribution of reef features to blue carbon storage and sequestration in the SAC network has been overestimated.

The majority of data used in this study are based on blue carbon estimates from England, Scotland and the northwest European continental shelf. Whilst this has allowed for an initial assessment of blue carbon in Welsh MPAs, Welsh-specific data would allow for more robust estimates and comparisons across the SAC network. It is recognised in several carbon estimate studies that more location-specific data are needed to make confident estimates of carbon storage and sequestration (Burrows *et al*., 2017). For biogenic habitats, blue carbon storage and sequestration have been shown to vary depending on factors such as plant species composition of saltmarshes and seagrass beds (Duarte *et al*., 2010; Lavery *et al*., 2013; Ford *et al*., 2019), age of the habitat (Sousa *et al*., 2010; Greiner *et al*., 2013; Burden *et al*., 2019), sedimentation rates and anthropogenic threats (Serrano *et al*., 2016; Bulseco *et al*. 2019; Paradis *et al*., 2021), all of which contribute to uncertainty in local and global estimates. In addition, as shown for saltmarshes, there will be within-country variability, as demonstrated by the Ford *et al*. (2019).

Climate change is forecasted to alter the spatial distribution and extent of the fauna and flora which contribute towards blue carbon. Sea-level rise and extreme weather events also pose a serious threat to the carbon storage of different habitat types. In addition, increasing temperatures, ocean acidification, and hypoxia are expected to have negative effects on the carbon cycle and on biological stores such as fauna and flora which calcify (maerl, shelled organisms). With this in mind, carbon stocks and sequestration rates across Wales have the potential to change considerably over the next few decades.

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# Appendix A: Applied carbon sequestration and storage values per habitat

Table A1. Applied carbon sequestration and storage values per studied habitat from Armstrong *et al*. (2020).

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Subtidal Mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.51040 | Derived from Diesing *et al*., 2017 (contacted author to ensure calculations are correct, as no per area stock values supplied *per se*). |
| Subtidal Mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00051 | Assumed at 0.1 mm $yr^{-1}$ as proportion of soil standing stock value; compares with fine sediment annual sequestration value by Burrows *et al*., 2014 of 0.041 kg $m^{-2}$ $yr^{-1}$, and coarse of 0.0002 kg $m^{-2}$ $yr^{-1}$. Note that Thomas *et al.* 2005 state that shelf sequestration is negligible, and Nelleman *et al.* 2009 estimated shelf sequestration at 0.2 tC $ha^{-1}$, or 0.02 kg $m^{-2}$. |
| Subtidal Sandy mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.64584 | As Subtidal Mud |
| Subtidal Sandy mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00065 | As Subtidal Mud |
| Subtidal Muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.71442 | As Subtidal Mud |
| Subtidal Muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00071 | As Subtidal Mud |
| Subtidal Sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.36264 | As Subtidal Mud |
| Subtidal Sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00036 | As Subtidal Mud |
| Subtidal Slightly gravelly sandy mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.63315 | As Subtidal Mud |
| Subtidal Slightly gravelly sandy mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00063 | As Subtidal Mud |
| Subtidal Slightly gravelly muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.73278 | As Subtidal Mud |
| Subtidal Slightly gravelly muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00073 | As Subtidal Mud |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Subtidal Slightly gravelly sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.33264 | As Subtidal Mud |
| Subtidal Slightly gravelly sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00033 | As Subtidal Mud |
| Subtidal Gravelly mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.92001 | As Subtidal Mud |
| Subtidal Gravelly mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00092 | As Subtidal Mud |
| Subtidal Gravelly muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.68453 | As Subtidal Mud |
| Subtidal Gravelly muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00068 | As Subtidal Mud |
| Subtidal Gravelly sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.34845 | As Subtidal Mud |
| Subtidal Gravelly sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00035 | As Subtidal Mud |
| Subtidal Muddy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.81468 | As Subtidal Mud |
| Subtidal Muddy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00081 | As Subtidal Mud |
| Subtidal Muddy sandy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.42978 | As Subtidal Mud |
| Subtidal Muddy sandy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00043 | As Subtidal Mud |
| Subtidal Sandy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.28899 | As Subtidal Mud |
| Subtidal Sandy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00029 | As Subtidal Mud |
| Subtidal Gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.27522 | As Subtidal Mud |
| Subtidal Gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.00028 | As Subtidal Mud |
| Intertidal Mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.02080 | Subtidal values from Diesing *et al.*, 2017 multiplied by 2 - on the assumption that nearshore sediments hold more carbon (likely underestimates stock). |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Intertidal Mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02042 | Assumed at 2 mm $yr^{-1}$ as proportion of soil standing stock value (2 mm accretion per annum assumed for all intertidal areas). Compares to ABPmer carbon calculator value of 22 g C $m^{-2}$(so 0.0222 kg $m^{-2}$) for 2 mm of accretion, based on 5% carbon (at 2% carbon it would be 4 g C $m^{-2}$, so 0.004 kg $m^{-2}$). |
| Intertidal Sandy mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.29168 | As Intertidal Mud |
| Intertidal Sandy mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02583 | As Intertidal Mud |
| Intertidal Muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.42884 | As Intertidal Mud |
| Intertidal Muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02858 | As Intertidal Mud |
| Intertidal Sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.72528 | As Intertidal Mud |
| Intertidal Sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.01451 | As Intertidal Mud |
| Intertidal Slightly gravelly sandy mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.26630 | As Intertidal Mud |
| Intertidal Slightly gravelly sandy mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02533 | As Intertidal Mud |
| Intertidal Slightly gravelly muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.46556 | As Intertidal Mud |
| Intertidal Slightly gravelly muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02931 | As Intertidal Mud |
| Intertidal Slightly gravelly sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.66528 | As Intertidal Mud |
| Intertidal Slightly gravelly sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.01331 | As Intertidal Mud |
| Intertidal Gravelly mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.84002 | As Intertidal Mud |
| Intertidal Gravelly mud | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.03680 | As Intertidal Mud |
| Intertidal Gravelly muddy sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.3690 | As Intertidal Mud |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Intertidal Gravelly muddy sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.02738 | As Intertidal Mud |
| Intertidal Gravelly sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.69690 | As Intertidal Mud |
| Intertidal Gravelly sand | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.01394 | As Intertidal Mud |
| Intertidal Muddy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.62936 | As Intertidal Mud |
| Intertidal Muddy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.03259 | As Intertidal Mud |
| Intertidal Muddy sandy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.85956 | As Intertidal Mud |
| Intertidal Muddy sandy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.01719 | As Intertidal Mud |
| Intertidal Sandy gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.57798 | As Intertidal Mud |
| Intertidal Sandy gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.01156 | As Intertidal Mud |
| Intertidal Gravel | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.55044 | As Intertidal Mud |
| Intertidal Gravel | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.011 | As Intertidal Mud |
| Rock | Soil standing stock | 0 / n/a | n/a (rock) |
| Rock | Sequestration | 0 / n/a | n/a (rock) |
| Saltmarsh | Biomass standing stock (kg $m^{-2}$) | 0.21 | Taken from Burrows *et al.* 2014 (compares Beaumont *et al.* 2014 values of 0.28 kg $m^{-2}$ (± 0.23 kg $m^{-2}$)) |
| Saltmarsh | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 4.2 | Based on average of 51 Welsh samples - see Ford *et al.* (2019) supplementary material (NB: lead author contacted to enquire whether mudflat cores were also taken, confirmed that this was not the case); |
| Saltmarsh | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.084 | Proportion of stock value, assuming 2 mm accretion $yr^{-1}$ (noting that Adams *et al.*, quoted 0.125 to 0.15 kg $m^{-2}$ $yr^{-1}$, and Burrows *et al.* (2014) 0.21 kg $m^{-2}$ $yr^{-1}$). |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Seagrass | Biomass standing stock (kg $m^{-2}$) | 0.261 | Taken from Burrows *et al.* 2014; |
| Seagrass | Soil standing stock (kg $m^{-2}$ (top 25 cm)) | 3.372 | Average value based on 13 SW England meadows quoted in Green *et al.* 2018; |
| Seagrass | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.027 | Assumed at 2 mm yr-1 as proportion of soil standing stock value (noting that Burrows *et al*. applied value of 0.083 kg m-2 yr-1). |
| Intertidal macroalgae | Biomass standing stock (kg $m^{-2}$) | 0.047 | 10% of subtidal value (relationship quoted by Smale *et al.*, 2016 / Mann, 2000). |
| Intertidal macroalgae | Soil standing stock | 0 / n/a | n/a (on rock) |
| Intertidal macroalgae | Sequestration | 0 / n/a | n/a (on rock) |
| Faunal turf | Biomass standing stock (kg $m^{-2}$) | 0.014 | Calculated using weight values quoted by Taylor (1998), and assuming 40% carbon (as per Lindley *et al*., 1999). |
| Faunal turf | Soil standing stock | 0 / n/a | n/a (on rock) |
| Faunal turf | Sequestration | 0 / n/a | n/a (on rock) |
| Oysters (Ostrea) | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 0.13 | Applied same relationships to soil stock for these as Burrows *et al.* 2014 did for horse mussel. |
| Oysters (Ostrea) | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.0013 | Fodrie *et al.* (2017) noted 0.13 kg $m^{-2}$ net annual sequestration for some (American) oyster reefs, whereas subtidal on sand ones tended to be net producers (emitting up to 0.71 kg per $m^{-2}$ $yr^{-1}$). Assumed 1% of that for Welsh beds due to very low densities in Welsh beds. |
| Horse mussel (*Modiolus*) | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 4.0 | Burrows *et al.* 2014 values (10 cm depth inferred) |
| Horse mussel (*Modiolus*) | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.04 | Burrows *et al.* 2014 values (10 cm depth inferred) |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Blue mussel (*Mytilus*) | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 0.4 | Using 10% of horse mussel values, as lower biomass assumed |
| Blue mussel (*Mytilus*) | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.004 | Using 10% of horse mussel values, as lower biomass assumed |
| Other (incl. discord mussel (*Musculus* etc.), | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 0.4 | Using 10% of horse mussel values, as lower biomass assumed |
| Other (incl. discord mussel (*Musculus* etc.), | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.004 | Using 10% of horse mussel values, as lower biomass assumed |
| Kelp | Biomass standing stock (kg $m^{-2}$) | 0.465 | Applied Smale *et al.* (2016) average of Welsh and SW English sites (as the 3 Welsh study sites were all adjacent to each other, so probably not fully representative). NB: for Scotland, the average for the Smale *et al.* sites was 0.97 kg $m^{-2}$. Burrows *et al.,* 2014 applied 0.187 kg $m^{-2}$, based on relatively old data. |
| Kelp | Soil standing stock | 0 / n/a | n/a (on rock) |
| Kelp | Sequestration | 0 / n/a | n/a (on rock) |
| Maerl - dead | Soil standing stock (kg $m^{-2}$ (top 60 cm) | 12.4 | One fifth of value applied by Burrows *et al.,* 2014 - as Welsh bed's species sequesters less, and likely less healthy. |
| Maerl - live | Biomass standing stock (kg $m^{-2}$) | 0.095 | 10 times sequestration (same relationship as applied by Burrows *et al*., 2014). |
| Maerl - live | Soil standing stock (kg $m^{-2}$ (top 60 cm) | 12.4 | One fifth of value applied by Burrows *et al*., 2014 (as Welsh bed's species sequesters approx. that proportion less (as per Table 3 of Burrows *et al*. 2014), and likely less healthy (NRW pers comm). |

| Sedimentary Area / Habitat | Parameter (unit) | Value | Source / Justification |
|---|---|---|---|
| Maerl - live | Sequestration (kg $m^{-2}$ yr-1) | 0.0095 | Applied min sequestration for *Phymatolithon calcareum* quoted by Burrows *et al*. 2014 in their Table 3 (min used as Welsh bed less healthy (NRW pers comm)). NB: Burrows *et al*., 2014 applied 0.074 kg $m^2$ value. |
| Brittlestar beds | Biomass standing stock | unknown / negligible | No values found in literature |
| Brittlestar beds | Soil standing stock | 0.289 | Applied same value as subtidal sandy gravel, as brittlestars normally found on coarse sediment. |
| Brittlestar beds | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.082 | Burrows *et al.* 2014 value |

# Appendix B: Carbon value literature review

Table B1 A comparison of carbon values between NRW report 428 (Armstrong *et al*., 2020) and recent literature values

| Habitat Type | Parameter (Unit) | Value | Justification in NRW Report 428 (Armstrong *et al.*, 2020) | Recent Literature Values | Location of Study |
|---|---|---|---|---|---|
| Subtidal mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.51 – 0.92 | Derived from Diesing *et al*., 2017 (contacted author to ensure calculations are correct, as no per area stock values supplied *per se*). | 0.31 – 1.23 (Parker *et al*., 2021) | England, Ireland and Wales review |
| Subtidal sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.33 – 0.73 | Refer to subtidal mud | 0.04 – 0.76 (Parker *et al*., 2021) | England, Ireland and Wales review |
| Intertidal mud | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.02 – 1.84 | Subtidal values from Diesing *et al*., 2017 multiplied by 2 - on the assumption that nearshore sediments hold more carbon (likely underestimates stock). | 0.54 – 3.56 (Parker *et al*., 2021) | England, Ireland and Wales review |
| Intertidal sand | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 0.67 – 1.47 | Refer to intertidal mud | 0.13 – 1.86 (Parker *et al*., 2021) | England, Ireland and Wales review |
| Saltmarsh | Soil standing stock (kg $m^{-2}$ (top 10 cm assumed)) | 4.2 | Based on average of 51 Welsh samples - see Ford *et al.* (2019) supplementary material. | 5.11 (Austin *et al*., 2021)<br><br>3.6 ( Parker *et al* 2021)<br><br>5.64 (Porter *et al*., 2020) | Scotland<br><br>England, Ireland and Wales review<br><br>Orkney, Scotland |
| Saltmarsh | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.084 | Proportion of stock value, assuming 2 mm accretion $yr^{-1}$ (noting that Adams *et al*., quoted | 0.096 (Parker *et al* 2021) | England, Ireland and Wales review |

| Habitat Type | Parameter (Unit) | Value | Justification in NRW Report 428 (Armstrong *et al.*, 2020) | Recent Literature Values | Location of Study |
|---|---|---|---|---|---|
| | | | 0.125 to 0.15 kg $m^{-2}$ $yr^{-1}$, and Burrows *et al.* (2014) 0.21 kg $m^{-2}$ $yr^{-1}$). | 0.112 (Lockwood *et al.*, 2021) | Essex, England |
| Seagrass | Soil standing stock (kg $m^{-2}$ (top 10 cm)) | 1.35 | Average value based on 13 SW England meadows quoted in Green *et al.* 2018. | 1.37 (Parker *et al.*, 2021)<br>1.1 (Potouroglou *et al.*, 2021)<br>0.8 (Lima *et al.*, 2020)<br>2 – 5 (Hendricks *et al.*, 2020) | England and Ireland review<br>East to west coast Scotland<br>Solent, England<br>European review |
| Seagrass | Sequestration (kg $m^{-2}$ $yr^{-1}$) | 0.027 | Assumed at 2 mm yr-1 as proportion of Soil standing stock value (noting that Burrows *et al.* applied value of 0.083 kg m-2 yr-1). | 0.086 (Parker *et al.*, 2021) | England and Ireland review (but value based on non-UK study) |
| Kelp | Biomass standing stock (kg m-2) | 0.465 | Applied Smale et al. (2016) average of Welsh and SW English sites. | 0.31 (Parker et al 2021)<br>0.21 (Porter et al., 2020)<br>0.5 – 0.9 (Hendricks et al., 2020) | England and Ireland review<br>Orkney, Scotland<br>European review |

| Habitat Type | Parameter (Unit) | Value | Justification in NRW Report 428 (Armstrong *et al.*, 2020) | Recent Literature Values | Location of Study |
|---|---|---|---|---|---|
| Maerl - live | Biomass standing stock (kg $m^{-2}$) | 0.095 | 10 times sequestration (same relationship as applied by Burrows *et al.*, 2014) | 0.7 (Porter *et al.*, 2020) | Orkney, Scotland |
| Maerl - live | Soil standing stock (kg $m^{-2}$ (top 60 cm) | 12.41 | One fifth of value applied by Burrows *et al.*, 2014 (as Welsh bed's species sequesters approx. that proportion less (as per Table 3 of Burrows *et al.* 2014), and likely less healthy (NRW pers comm); | 68.8 (Porter *et al.*, 2020)<br><br>62.0 (Hendricks *et al.*, 2020) | Orkney, Scotland<br><br>Used Burrows *et al.* (2014) values |

*Values from the literature were converted to kg C m-2 and standardised to reflect the top 10 cm of soil where appropriate.*

# Appendix C: Maps of carbon storage and sequestration

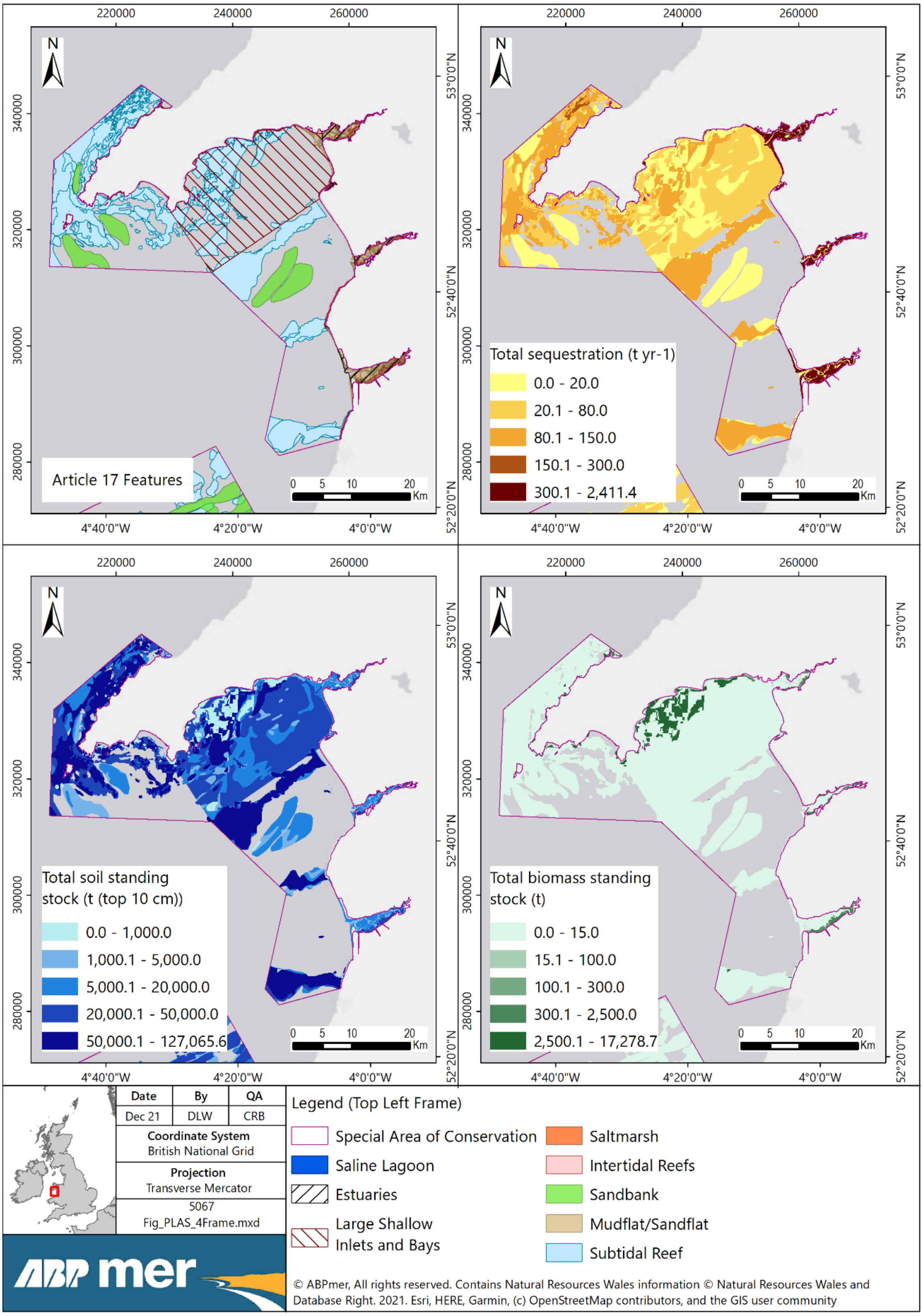


**Figure C1** The Annex I features within the Lleyn Peninsula and the Sarnau SAC and the associated carbon sequestration rate, soil stock and biomass stock.

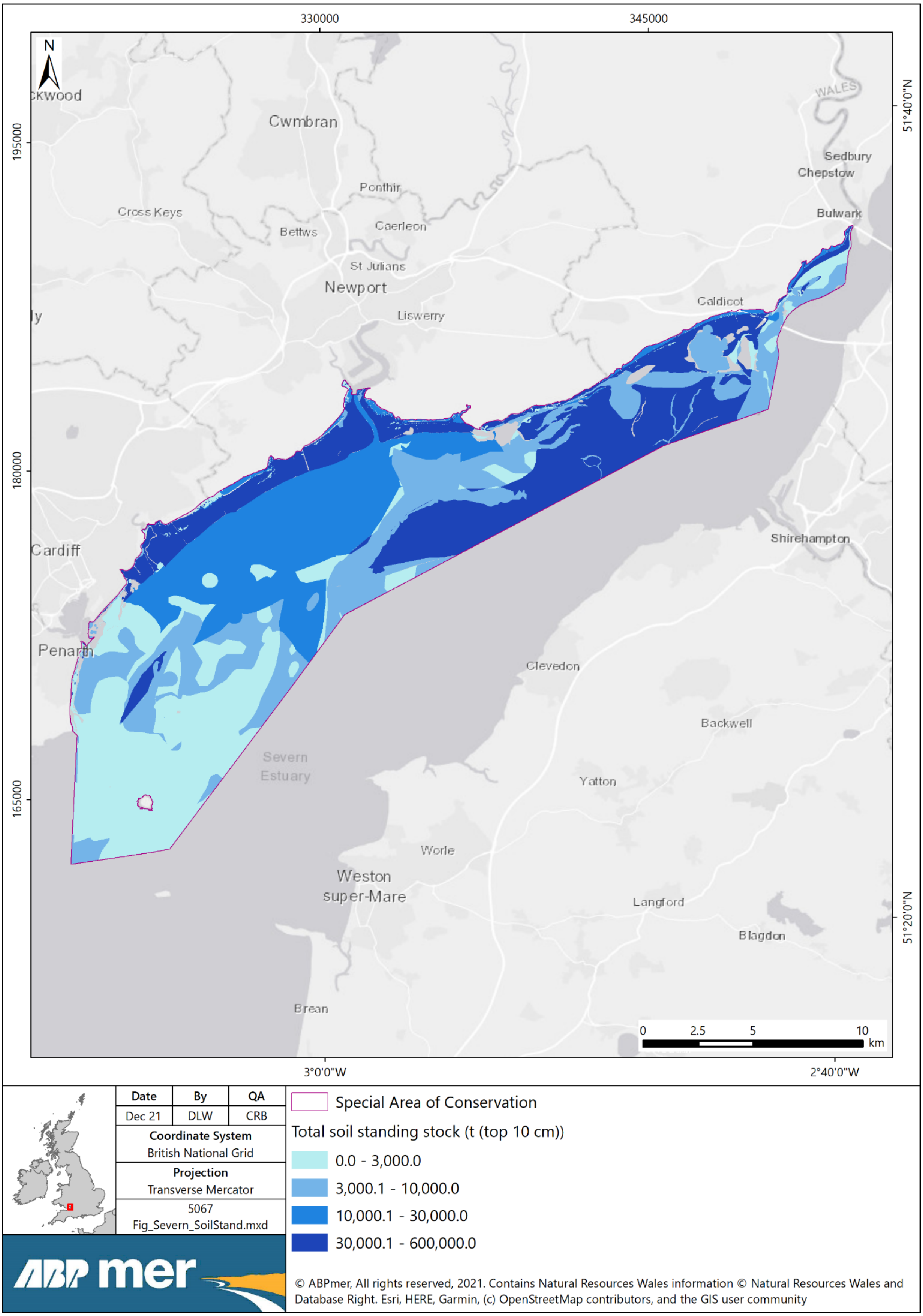


Figure C2 Carbon soil standing stock of Annex I features in the Severn Estuary SAC

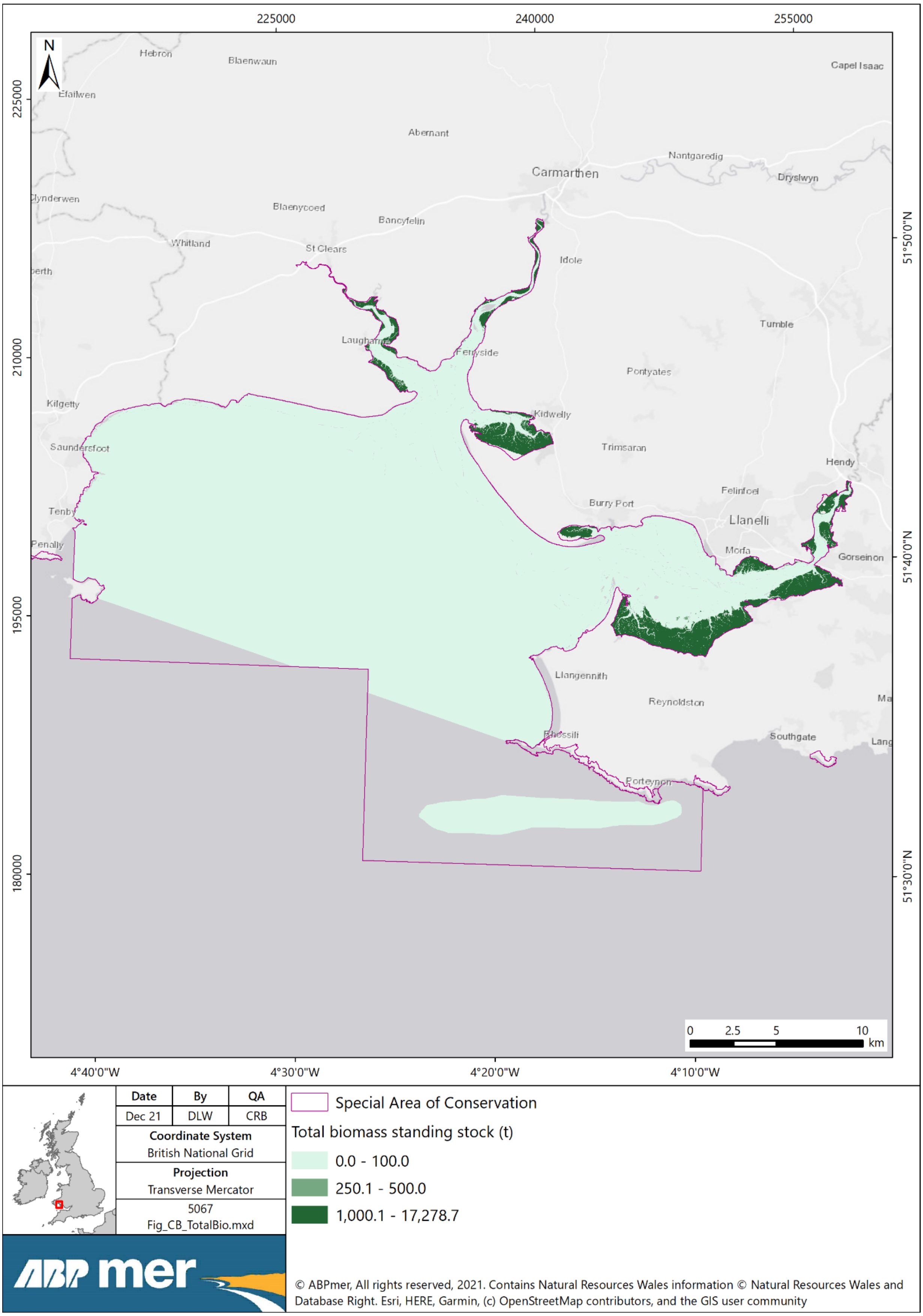


Figure C3 Carbon biomass standing stock of Annex I features in the Carmarthen Bay and Estuaries SAC

# Data Archive Appendix

Data outputs associated with this project are archived in [NRW to enter relevant corporate store and / or reference numbers] on server–based storage at Natural Resources Wales.