Cyfoeth Naturiol Cymru
Natural Resources Wales

Estimating the Carbon Sink Potential of the Welsh Marine Environment

ABPmer

Report No 428

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V1	Approved final report
V1.1.	Formatting changes made to ensure accessibility and to correct small errors in Appendix A

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Crynodeb Gweithredol

Er mwyn llenwi bwlch tystiolaeth pwysig, mae potensial carbon 'glas' cynefinoedd morol Cymru wedi cael ei amcangyfrif ar ran Cyfoeth Naturiol Cymru.

Carbon glas yw'r carbon sy'n cael ei storio a'i atafaelu gan gynefinoedd morol. Mae modd diffinio termau perthnasol fel a ganlyn:

- Cronfa ddŵr naturiol neu artiffisial yw **sinc** carbon sy'n cronni ac yn storio carbon;
- Mae **storfa** garbon yn cynnwys y carbon sydd wedi'i storio yn y golofn ddŵr, gwaddodion arwynebol a biomas fflora a ffawna. Gall y storio hwn fod yn storio tymor byr neu dymor hir. Lle caiff carbon ei storio yn y tymor hir, gellir ystyried ei fod yn cael ei **atafaelu**.

Er mwyn amcangyfrif potensial carbon glas dyfroedd Cymru, gan roi mwy o ddealltwriaeth o sut mae ecosystemau morol Cymru'n cyfrannu at wrthbwyso'r broses o ryddhau carbon drwy weithgareddau dynol, mae'r camau canlynol wedi cael eu cymryd ar gyfer yr astudiaeth hon:

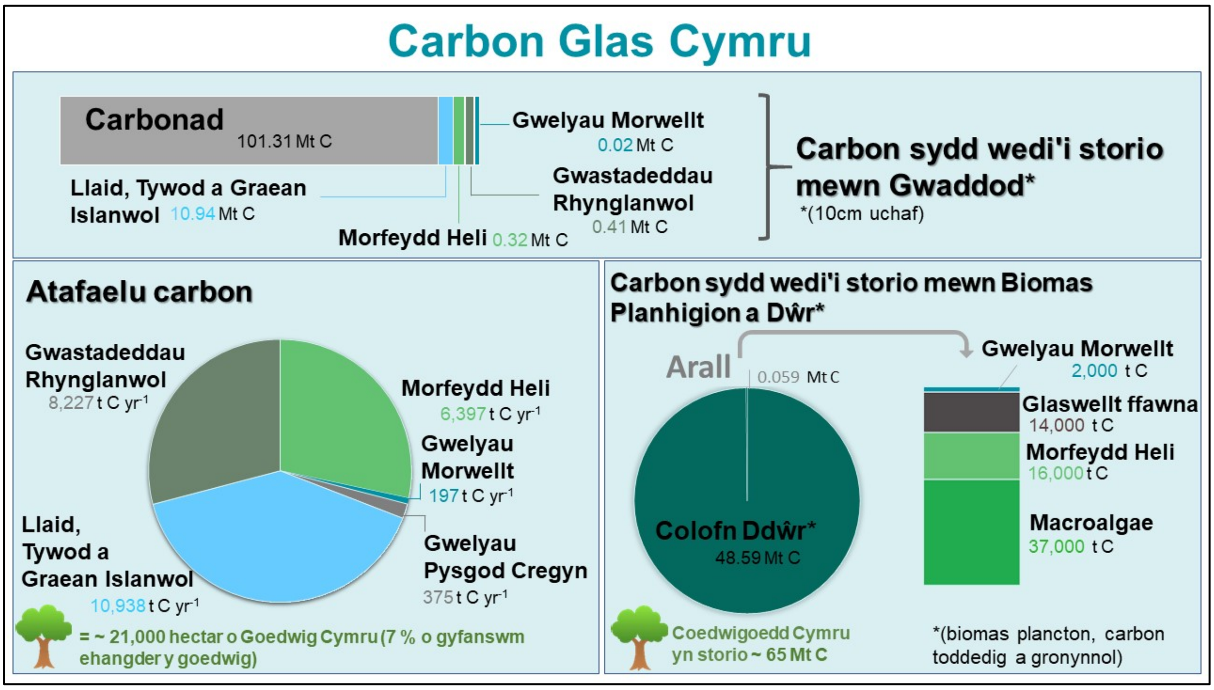
- Mae'r haenau data gofodol gorau a diweddaraf ar gyfer cynefinoedd carbon glas wedi cael eu nodi a'u cyfuno fel y gellid pennu cwmpas cyfartalog yng Nghymru ar gyfer pob un;
- Mae'r llenyddiaeth berthnasol wedi cael ei hadolygu i gael y gwerthoedd storio ac atafaelu carbon mwyaf perthnasol a fyddai wedyn yn cael eu cymhwyso igynefinoedd morol Cymru;
- Mae model rhifiadol dynodedig wedi cael ei ddadansoddi i gael (1) amcangyfrifon carbon colofnau dŵr (gan gynnwys biomas plancton); (2) amcangyfrifon o lif aer-môr o ran carbon deuocsid (CO_2) (h.y. faint o CO_2 sy'n mynd i'r golofn ddŵr ac sy'n cael ei droi'n ffurfiau amrywiol ar garbon), yn ogystal ag (3) amcangyfrifon o lif carbon ar draws ffin forol Cymru (h.y. faint o garbon sy'n gadael dyfroedd Cymru ac sy'n cael ei gludo i ddyfroedd bas a dyfnach cyfagos);
- Mae allbynnau afonol carbon hefyd wedi cael eu hamcangyfrif yn seiliedig ar werthoedd llenyddiaeth a gollyngiadau afonydd cyfartalog a ddarparwyd gan hydrolegwyr Cyfoeth Naturiol Cymru;
- Mae gwerthoedd carbon wedi cael eu cyfrifo a'u rhoi yn eu cyd-destun gyda chyfraddau daearol ('carbon gwyrdd'), yn ogystal ag allyriadau CO_2 Cymru.

Mae canlyniadau'r astudiaeth wedi cael eu crynhoi mewn ffeithlun, sydd wedi'i ddangos isod. Mae hwn yn dangos bod llawer o garbon eisoes wedi'i storio mewn gwaddodion morol yng Nghymru, o leiaf 113 miliwn o dunelli (Mt) yn y 10cm uchaf. Mae hyn yn cynrychioli bron 170% o'r carbon a geir yng nghoedwigoedd Cymru.

Mewn unrhyw flwyddyn, mae colofn ddŵr moroedd Cymru yn dal o leiaf 48.7 Mt arall o garbon, yn bennaf ar ffurf carbon anorganig sydd wedi toddi. Wrth gymharu â'r gwerth hwn, mae'r biomas carbon sy'n gysylltiedig â chynefinoedd macroalgal ac angiosberm yn weddol fach mewn cymhariaeth, sef 69,000 o dunelli o garbon (neu 0.07 Mt C), a choedwigoedd gwymon a morfeydd heli yw'r cynefinoedd mwyaf cynhyrchiol.

O ran carbon sy'n cael ei ddal/atafaelu bob blwyddyn, amcangyfrifwyd bod cynefinoedd morol Cymru'n atafaelu o leiaf 26,100 o dunelli o garbon (neu 0.03 Mt C) bob blwyddyn, gyda morfeydd heli a fflatiau rhynglanwol yn cyfrif am ganran fawr o'r gwerth hwn. Pan gaiff ei fynegi mewn unedau CO_2 cyfwerth, sef yr uned a ddefnyddir yn fwyaf mynych wrth adrodd am atafaelu, mae hyn gyfwerth â 95,900 t CO_2e (neu 0.096 Mt CO_2e). Mae hyn yn cynrychioli oddeutu 7% o'r swm a atafaelwyd gan goedwigoedd Cymru bob blwyddyn (felly oddeutu 21,000 ha o goedwigoedd).

Fesul hectar o gynefin, morfeydd heli sy'n atafaelu'r mwyaf o'r holl gynefinoedd, er ychydig yn llai na hectar o goedwig Cymru (oddeutu dau draean). Fodd bynnag, mae hyn yn ymwneud â gwaddodi, gyda gwerthoedd gweddol unffurf ceidwadol yn cael eu defnyddio gan yr astudiaeth hon. Ystyrir y byddai morfeydd heli mewn aberoedd â llwythi gwaddod crog uchel yn y golofn ddŵr, megis Aber Hafren, yn atafaelu mwy na choedwigoedd, a hynny'n debygol o fod o leiaf 1.5 gwaith gymaint.



Llun: Ffeithlun ar storio ac atafaelu carbon morol Cymru

Mae cyfyngiadau i'r data wedi cael eu nodi, er enghraifft, mewn perthynas â llif carbon i ardal forol Cymru ac oddi yno, ansicrwydd mewn dosbarthiad cynefinoedd ac mewn perthynas â rhai cyfraddau atafaelu. Mae lle i wella'r sylfaen dystiolaeth yn sawl un o'r ardaloedd hyn ac felly sicrhau dull gwell o fesur cyfraddau storio ac atafaelu carbon yn nyfroedd morol Cymru.

Mae potensial hefyd i wella'r dull o reoli ardal forol Cymru o ran carbon glas. Yn arbennig, gallai amddiffyn ac adfer cynefinoedd megis morfeydd heli a morwellt sy'n storio ac yn atafaelu carbon gyfrannu at gynnydd sylweddol mewn carbon glas. Gallai amddiffyn ardaloedd gwely'r môr sy'n cefnogi gwelyau deuglawr (neu sydd â'r potensial i'w cefnogi) hefyd gynyddu cyfraddau atafaelu carbon.

Executive Summary

In order to fill an important evidence gap, the 'blue' carbon potential of Welsh marine habitats has been estimated on behalf of Natural Resources Wales (NRW).

Blue carbon is the carbon stored and sequestered by marine habitats. Related terms can be defined as follows:

- A carbon **sink** is a natural or artificial reservoir that accumulates and stores carbon;
- A carbon **store** encompasses the carbon stored in the water column, surface sediments and floral and faunal biomass. This storage may be short or long-term. Where carbon is stored in the long-term, it can be considered to be **sequestered**.

In order to estimate the blue carbon potential of Welsh waters, and thus allow a greater understanding of how Welsh marine ecosystems contribute to offsetting the release of carbon through human activities, the following steps have been undertaken for this study:

- The best and most up to date available spatial datalayers for blue carbon habitats have been identified and combined so that approximate Welsh coverage could be determined for each;
- The relevant literature has been reviewed to obtain the most relevant carbon storage and sequestration values which would then be applied to Welsh marine habitats;
- A dedicated numerical model has been interrogated to obtain (1) water column carbon estimates (including plankton biomass); (2) estimates on air-sea flux of Carbon Dioxide (CO_2) (i.e. how much CO_2 enters the water column and is converted into various forms of carbon), as well as (3) estimates of carbon flux across the Welsh marine boundary (i.e. how much carbon leaves Welsh waters and gets transported to adjacent shelf and deeper waters);
- Riverine inputs of carbon have also been estimated based on literature values and average river discharges supplied by NRW hydrologists;
- Carbon values have been calculated and put into context with terrestrial ('green carbon') rates, as well as Welsh CO_2 emissions.

The results of the study have been summarised in an infographic, which is displayed below. This shows that a lot of carbon is already stored away in Welsh marine sediments, at least 113 Million tonnes (Mt) in the top 10 cm. This represents almost 170 % of the carbon held in Welsh forests.

In any given year, the Welsh seas' water column holds at least another 48.7 Mt of carbon, mostly in the form of dissolved inorganic carbon. When compared to this value, the carbon biomass associated with macroalgal and angiosperm habitats is relatively modest in comparison, at 69,000 tonnes of carbon (or 0.07 Mt C), with kelp forests and saltmarshes being the most productive habitats.

With regard to carbon locked away / sequestered every year, it has been estimated that Welsh marine habitats sequester at least 26,100 tonnes of carbon (or 0.03 Mt C) every year, with saltmarshes and intertidal flats accounting for a large percentage of

this value. When expressed in CO_2 equivalent units, which is the unit most commonly applied in sequestration reporting, this equates to 95,900 t CO_2e (or 0.096 Mt CO_2e). This represents around 7 % of the amount sequestered by Welsh forests every year (so by around 21,000 ha of forest).

Per hectare of habitat, saltmarshes sequester the most out of all the habitats, though slightly less than a hectare of Welsh forest (about two-thirds). This is however related to sedimentation, with relatively conservative uniform values having been applied by this study. It is considered that saltmarshes in estuaries with high suspended sediment loads in the water column, such as the Severn Estuary, would sequester more than forests, likely at least 1.5 times as much.

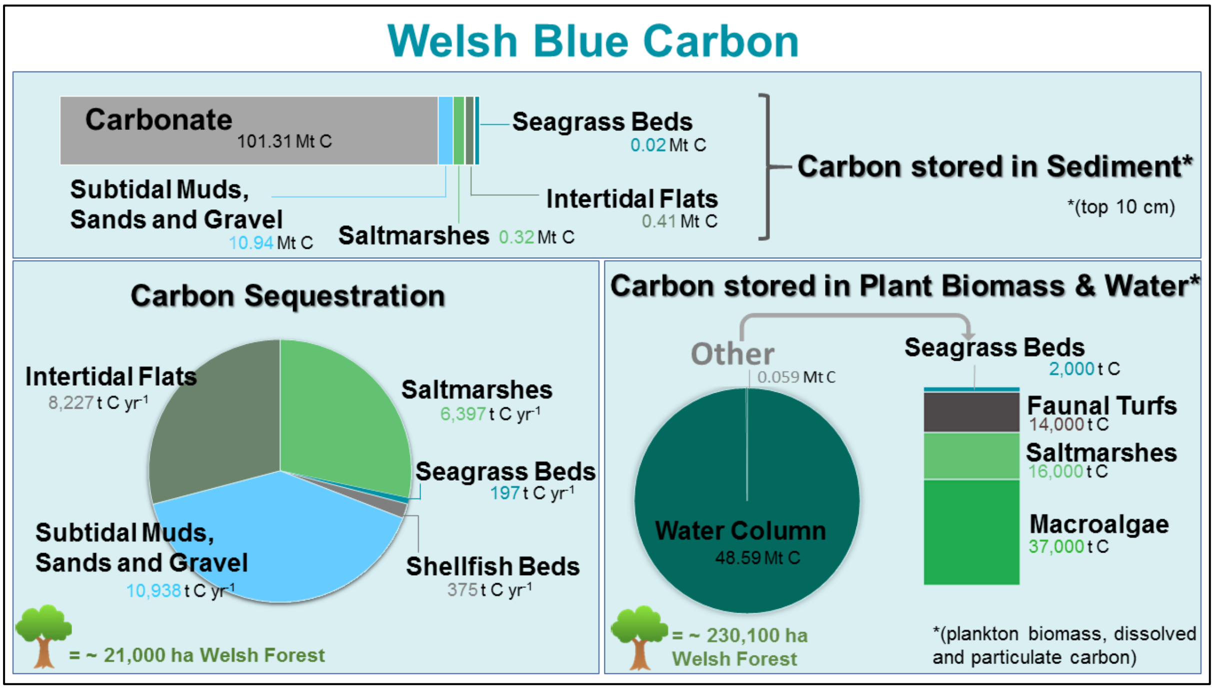


Image: Infographic on Welsh marine carbon storage and sequestration

Limitations to the data have been noted, for example in relation to carbon fluxes into and out of the Welsh marine area, uncertainties in habitat distribution and in relation to some sequestration rates. There is scope to improve the evidence base in many of these areas and thus better quantify carbon storage and sequestration in Welsh marine waters.

There is also the potential to improve the management of the Welsh marine area for blue carbon. In particular, the protection and restoration of habitats such as saltmarsh and seagrass which store and sequester carbon could contribute to significant increases in blue carbon. Greater protection of areas of seabed supporting (or with the potential to support) bivalve beds could also increase carbon sequestration.

1. Introduction

The Environment (Wales) Act 2016 requires the Welsh Government to reduce emissions of greenhouse gases (GHGs) in Wales by at least 80% for the year 2050 with a system of interim emissions targets and carbon budgets. In March 2019, the Welsh Government published its first low carbon plan, ‘Prosperity for All: A Low Carbon Wales’; this outlines the Government’s approach to cut emissions and transition to a low carbon economy in a way which maximises wider benefits for Wales, ensuring a fairer, healthier and more equal society. Furthermore, the Welsh National Marine Plan (WNMP), which was published in November 2019, contains amongst its general cross-cutting policies a commitment to ‘improve the understanding and enable action supporting climate change adaptation and mitigation’.

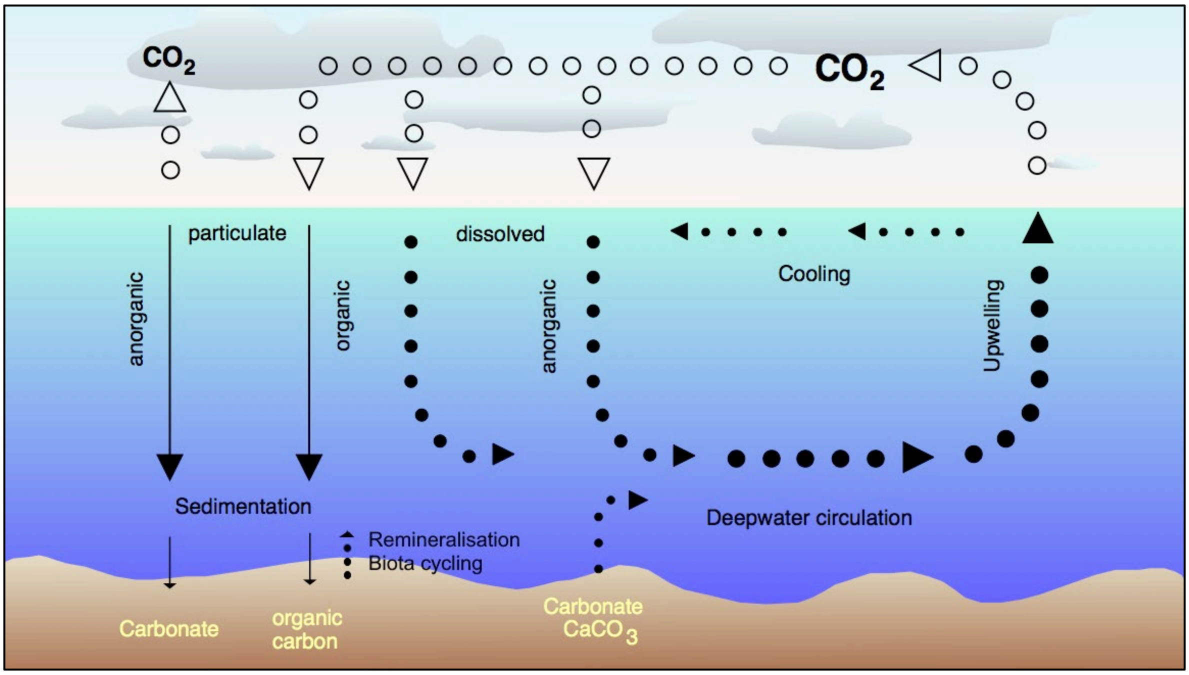
There is, however, currently relatively limited understanding of the role Welsh marine waters and environments play in carbon storage and sequestration, which is a key tool in facilitating climate change mitigation. It is worth noting that, at around 32,000 km², the Welsh marine area is 35% larger than the Welsh land mass (which measures just under 21,000 km²). This study set out to improve the understanding of this key ecosystem service provided by the Welsh marine environment by mapping and quantifying Welsh marine carbon storage and sequestration.

A large proportion of the WNMP area is subject to one or more nature conservation designations, with many Marine Protected Areas (MPAs) containing marine carbon sequestering habitats including saltmarsh, seagrass and kelp. There are 139 MPAs[1] in Welsh waters, that are made up of:

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

Oceans and seas play an important role in climate regulation / mitigation as part of a coupled system encompassing atmosphere, ocean, cryosphere and land surface. In particular, oceans and seas have a critical role in the exchange of greenhouse gases between air and water (particularly carbon dioxide (CO_2), methane, nitrogen oxides (NOx) and water vapour) (Bigg *et al.*, 2003). Coastal oceans are particularly important in processing inputs of terrestrial organic matter and exchanging of matter and energy with the open ocean (Gattuso *et al.*, 1998). Both biological and physical processes can be important in cycling, storing and sequestering carbon, illustrated in image 1.

[1] It should be noted that the number of sites within the MPA network is reported differently (140) by Welsh Government, 2018. This is assumed to be a function of the SSSI features that are considered to be coastal/marine within the respective counts. The latest details with respect to designations should be obtained from Lle – A Geo-Portal for Wales (inshore and coastal), or JNCC’s Protected Area Datasets (offshore).



Adapter from: Wikipedia / Alfred Wegener Institute, 2006
(Remineralisation and biota cycling inserted by ABPmer)

Image 1 Marine biological and physical pumps of carbon (dioxide)

Recent research has highlighted the valuable role that coastal and marine ecosystems play in storing and sequestering CO_2 from the atmosphere. Several studies have focused on the contribution of seabed habitats to carbon storage and sequestration – so-called blue carbon (see, for example, McLeod *et al.,* 2011; Burrows *et al.*, 2014).

As noted above, there are no published papers documenting a carbon budget for Welsh seas. In order to fill this gap, this project has sought to map and quantify marine carbon storage and sequestration in Welsh waters to allow a greater understanding of how Welsh marine ecosystems contribute to offsetting the release of carbon through anthropogenic activities. The key objectives for the study have been:

- To review the literature around the carbon sink potential of different marine habitats present in Wales;
- To develop a methodology for calculating the carbon sequestration potential of the Welsh marine environment; and
- To create and apply the method to estimate carbon storage and sequestration potential of the Welsh marine environment.

The remainder of this report is structured as follows:

Section 2: Methodology – describes the methodology applied during the study;
Section 3: Literature Review – summarises the findings of the literature review;
Section 4: Carbon Storage and Sequestration in the Welsh Marine Environment – describes the outputs from the study and confidence in the estimates of carbon storage and sequestration potential; and
Section 5: Conclusions and Recommendations – provides overall conclusions from the work and makes recommendations in relation to the further development of the method and its application.

Please note that, for the purpose of this report, the following terminology is used:

- A **carbon sink** is a 'natural or artificial reservoir that accumulates and stores carbon' (Committee on Climate Change, 2018) (habitats, the ocean, etc.);
- A **carbon store** is understood to encompass the carbon stored in the water column, surface sediments and floral and faunal biomass. This storage may be short or long-term. Where carbon is stored in the long-term, it can be considered to be **sequestered**.

In adopting these definitions, it is acknowledged that different interpretations are sometimes used in the literature, and there is no agreed definition of how long carbon needs to be stored in order to be sequestered.

2. Methodology

2.1. Introduction

In order to address the scope of requirements set out in the previous section, this study has sought to collate up-to-date information on the carbon storage and sequestration potential (and rates) of relevant / mappable potential sinks in Welsh waters through a literature and data review (Section 2.2). This information has then been used to parameterize a simple method which draws on datalayers to derive the spatial distribution of the relevant habitats. The information on storage and sequestration potential has been cross-checked against a basic carbon budget model for Welsh waters that draws on the outputs from a sophisticated numerical model and wider sources (Section 2.3). The derived carbon sequestration values have also been monetised and set into a Welsh context (Section 2.4).

2.2. Literature and data review

A literature and data review have been undertaken to inform the development of the methodology for estimating the blue carbon potential of the Welsh marine environment. The scope of the review focussed on the carbon storage and sequestration potential of the following key habitats / features known to be present in the Welsh marine environment:

- Water column (phytoplankton, zooplankton, etc.);
- Intertidal habitats:
  - Saltmarshes;
  - Mudflat and sandflats;
  - Intertidal macroalgae (vegetated rocky shores);
- Subtidal habitats which may have an intertidal element:
  - Seagrass beds;
- Subtidal habitats:
  - Shellfish beds (mainly horse mussel, blue mussel and oyster beds) (acknowledging that oyster and blue mussel beds can have intertidal elements);
  - Subtidal macroalgae (mainly kelp, but including maerl);
  - Brittlestar beds;
  - Faunal turf; and
- Subtidal muds, sands and gravel.

Some biogenic habitats that may be assumed to have a blue carbon function have been excluded. This is the case with habitats formed by reef-building polychaetes *Sabellaria alveolata* and *S. spinulosa,* as these consist of agglutinated sand grains and shell fragments (Naylor and Viles, 2000). These features therefore have very limited additional blue carbon potential and are not considered further in this report.

As a study undertaken for Scottish waters in 2014 (by Burrows *et al.*, 2014) had recently summarised available literature in relation to carbon potential of most of the marine habitats / features listed above. The literature review for this report thus focussed on augmenting and updating this work and obtaining data on those features not covered by the earlier review.

Information on the spatial distribution of relevant habitat features in the Welsh marine environment has been collected by identifying the most applicable / usable data layers (see Section 2.3.2 for more detail).

2.3. Development of spatial model

2.3.1. Understanding / estimating carbon fluxes within WNMP area

A simple model for carbon in Welsh seas has been created that takes account of estimates of carbon fluxes into and out of the WNMP area including:

- Air-sea flux of CO_2;
- Terrestrial / riverine carbon inputs;
- Carbon flux across the offshore WNMP boundary; and
- Carbon flux to / from habitats.

A schematic of this model is presented in Image 2 below.

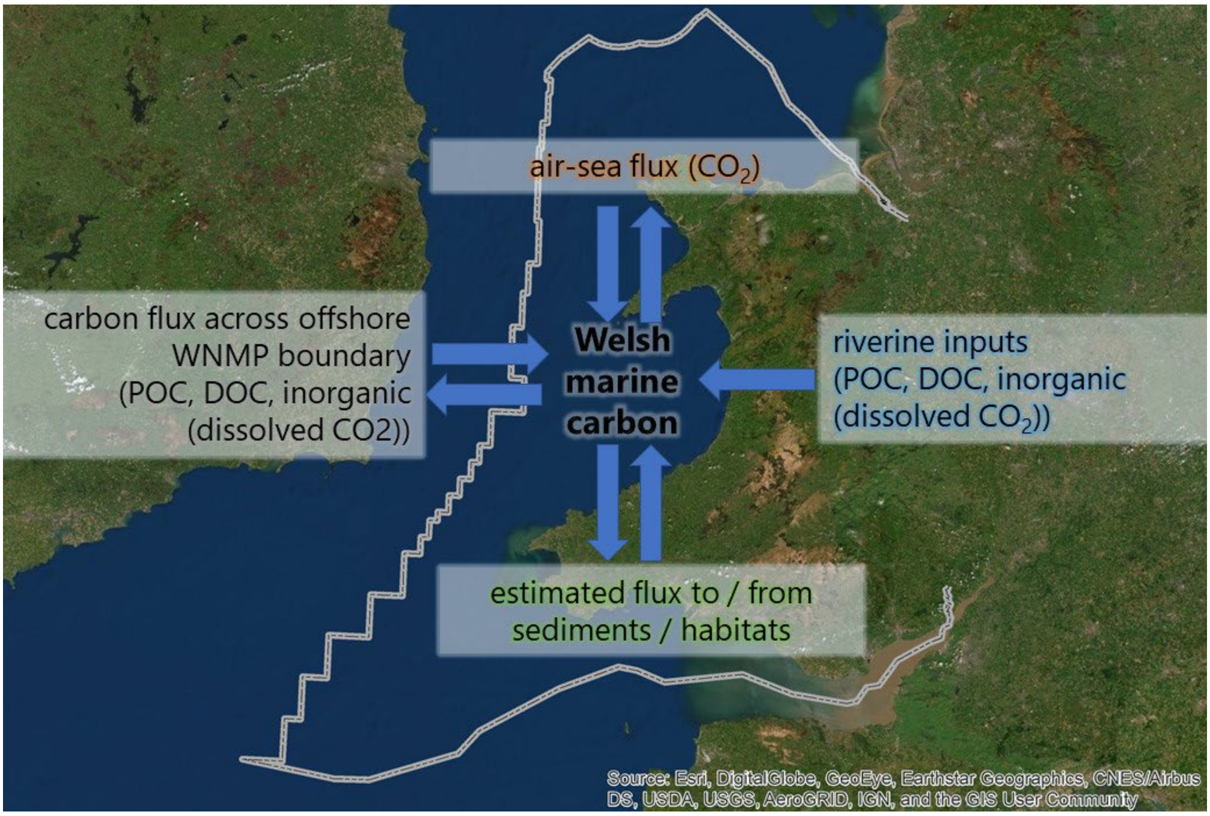
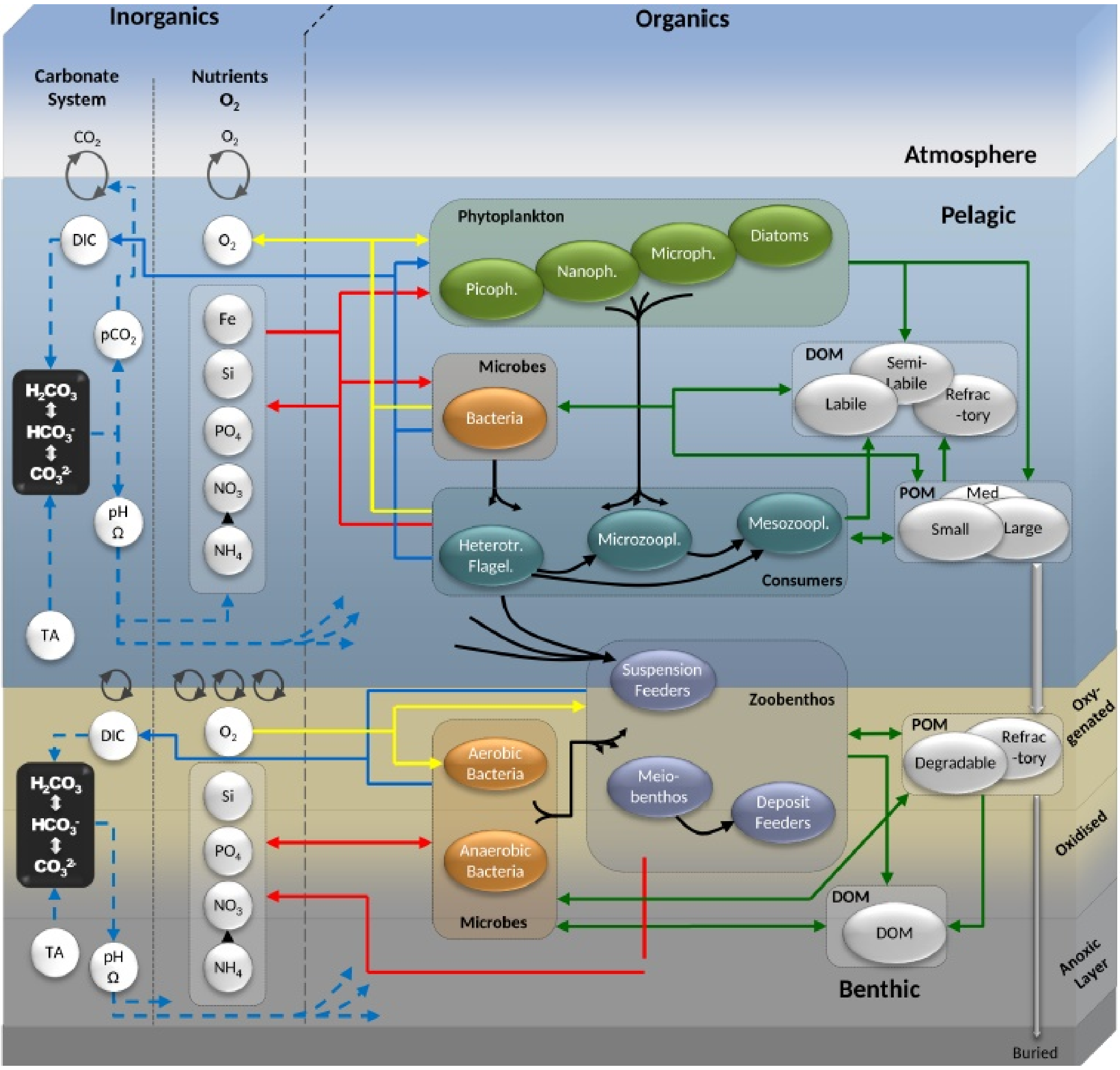


Image 2 Schematic of Carbon model applied for this study

Riverine inputs of particulate organic carbon (POC), dissolved organic carbon (DOC) and dissolved organic carbon (DIC) have been calculated based on values in the literature and an average annual average riverine discharge estimated for Wales by hydrologists from Natural Resources Wales (NRW) (see Section 4.2 for results / further detail).

Information on air-sea flux of CO_2 was obtained from Plymouth Marine Laboratory's (PML's) European Regional Seas Ecosystem Model (ERSEM) (Butenschön *et al.*, 2016). This provided annual average net air-sea flux estimates of CO_2 based on the period 2008 -2015 at an 8 km grid resolution for Welsh seas. ERSEM is a well-established ecosystem model for the lower trophic levels of the marine food web, covering northwestern European shelf seas including the entirety of Welsh waters.

The current model release[2] contains the essential elements for pelagic and benthic ecosystems, including the microbial food web, the carbonate system, and calcification (Butenschön *et al.*, 2016); see Image 3.



Source: Butenschön *et al.*, 2016

Image 3 ERSEM schematic showing how model components interact / influence each other

The ERSEM model is not well resolved inshore and does not take account of terrestrial inputs of carbon. It is, therefore, not accurate in estuarine or near-shore coastal waters. To address this limitation, literature values for estuarine and near-shore

[2] Version 15.06, coupled to POLCOMS for the water column data and NEMO for the air-water flux.

coastal CO_2 fluxes have been obtained and applied to transitional and coastal waterbodies (as delineated for Water Framework Directive (WFD) purposes).

Information on annual average net fluxes across the offshore WNMP boundary have been derived from the ERSEM model for POC, DOC and DIC (dissolved CO_2).

The approach to estimating fluxes to / from habitats and sedimentary areas is described below.

2.3.2. Mapping of relevant habitats / features

Based on the data review undertaken, a combined / merged habitat and sediment map has been created for Welsh waters in order to facilitate the calculation of carbon storage and sequestration totals for the WNMP area. This is presented as Figure 2 in Section 4.4. The data layers used to create this merged map are listed in Table 1. The ‘combined’ habitat map administered by the Joint Nature Conservation Committee (JNCC) has been used as the key layer for biogenic habitats, as this covers most of the WNMP area and is regularly updated, including with data supplied by Welsh government bodies. For some habitats, where more recent and / or refined data was available, separate data layers have been used and given priority. The ’HabMap’ sediment data layer has been used as the key datalayer for sedimentary habitats, with offshore gaps filled using the JNCC layer.

The relevant created datalayer has been supplied with MEDIN compliant metadata, and a detailed processing log created, explaining clearly how the data have been processed to create the outputs. A summary of the datalayer processing process as is provided in Section 9 / Appendix B.

Table 1 Datalayers used to create combined carbon storage / sequestration maps

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 (see Section 9 / Appendix B for further detail).

Habitat layers used to merge on top of base layers (as better information contained within)

Habitats; in priority order	**Data layer Origin / Name**	**Processing detail**
Saltmarshes	Lle Geo-Portal - Saltmarsh Extents	-
Seagrass Beds	Lle Geo-Portal - Priority Marine Habitats of Wales: Seagrass Beds	-
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
Maerl	Lle Geo-Portal - Environment (Wales) Act Section 7 and OSPAR: Marine Habitats	-
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	-
Shellfish Beds – Horse Mussel	Lle Geo-Portal - Priority Marine Habitats of Wales: Horse Mussel Beds	-
Shellfish Beds - *Musculus Discors*	Lle Geo-Portal - Section 7 *Musculus Discors Green crenella* Beds	-
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	-

2.3.3. Quantifying stores and sequestration

In order to parameterise carbon stores and sequestration for the mapped habitats in Welsh waters, the extent of each feature was calculated and multiplied with the selected values as identified from the literature review (see Section 3; summarised in Table 5 / Section 3.6).

The confidence for each value used has also been assessed, using the criteria set out in Table 2.

Table 2 Confidence criteria applied to carbon values used for calculations in Section 4

Confidence Score	Definition
High (H)	There is a good understanding of the carbon storage or sequestration function of the feature and the assessment is well supported by consistent evidence which is highly relevant / transferable to Welsh waters / habitats. There is consensus amongst the experts.
Medium (M)	Whilst there is some understanding of the carbon storage or sequestration function of the feature, this may be based on limited evidence and / or proxy information, or is only moderately relevant / transferable to Welsh waters / habitats. The literature reports a wide range of variation in the function and conflicting evidence / opposing views exist.
Low (L)	There is limited or no understanding of the carbon storage or sequestration function of the feature and / or the assessment is not well supported by evidence, or is not immediately relevant / transferable to Welsh waters / habitats. There is no clear agreement amongst experts.

Note: Evidence is defined as expert opinion or advice, data, methodology, results from data analysis, interpretation of data analysis, and collations and interpretations of scientific information (meta-analysis), peer-reviewed papers, grey literature, industry knowledge and anecdotal evidence

2.4. Monetising and contextualising carbon sequestration

Carbon sequestration estimates (tonnes CO_2 per year) have been converted into monetary values using the Department for Business, Energy and Industrial Strategy (DBEIS) non-traded carbon price for 2020. The values have also been set into the context of Welsh GHG emissions; see Section 4.5.

3. Literature Review on Carbon in Marine Habitats

3.1. Introduction

There is very little direct work that has focused on mapping carbon cycling, storage and sequestration in Welsh waters. A recent review of blue carbon for the National Assembly for Wales provided context on the blue carbon credentials of saltmarshes, maerl and seagrass beds, and mapped these habitats (based on existing NRW data) (Stewart and Williams, 2019). However, the work did not seek to quantify the amounts of carbon stored or sequestered within these habitats.

Despite the limited direct evidence from Welsh waters on the storage and sequestration potential of relevant marine habitats, comparable information is available from other parts of the UK and northwest Europe. For example, Burrows *et al.* (2014) reviewed the carbon storage and sequestration potential of key marine habitats relevant to Scottish waters. The study used available evidence to determine whether features were likely to act simply as short-term carbon stores or whether they might be longer-term (decadal) stores of carbon, and thus would be considered to sequester carbon. The study collated rates of sequestration and storage, and also estimated the overall carbon storage and sequestration of Scottish marine habitats. Most of the features assessed within this Scottish study are relevant to Wales, with the exception of serpulid reefs or cold-water corals, which are absent from Welsh waters.

A small number of other studies have also sought to develop spatial maps to indicate the location and scale / value of carbon sequestration within the marine environment, usually in the context of seeking to map the climate regulation ecosystem service. For example, Hull *et al.* (2014) modelled carbon sequestration for UK seas taking account of broad-scale physical processes such as the North Sea Carbon pump (Thomas *et al.*, 2005) and incorporating potential saltmarsh and sediment sequestration. The quantities of sequestered carbon were monetised using non-traded carbon prices. More recently, ABPmer *et al.* (2020) developed a simple spatial model representing the climate regulation ecosystem service in Irish waters. This was based on information on air-sea CO_2 flux across Irish waters, and the sequestration potential of two key coastal habitats - saltmarshes and sand dunes.

Most work hitherto has focused on carbon, particularly CO_2, with limited work done on other greenhouse gases such as methane and nitrous oxide. Methane has a global warming potential 28 to 36 times greater than CO_2 over 100 years and NOx 265-298 times greater. In order to fully understand the role of marine ecosystems in climate regulation it would be necessary to understand fluxes of methane and NOx as well as CO_2. This study focuses specifically on carbon storage and sequestration and, therefore, excludes NOx. While it also omits methane, the scale of methane exchanges to and from the marine environment are very small compared to other forms of carbon exchange (CO_2, organic) (Weber *et al.*, 2019) and, therefore, not material when considering carbon storage, flux and sequestration.

As noted in Section 2.2, a literature review was undertaken to inform the development of the methodology for estimating the carbon sink potential of the Welsh marine environment. The scope of the review focussed on the habitats and features listed in Section 2.2; and this Section is structured according to the following habitat / feature categories:

- Water column (Section 3.2);
- Intertidal habitats (Section 3.3);
- Shallow subtidal habitats (with intertidal elements) (Section 3.4.);
- Subtidal habitats (Section 3.5).

For each of the habitat / feature sections, brief general background information and some Welsh context are provided, and literature on carbon storage and sequestration summarised. A section at the end of each habitat / feature section highlights which value has been used in this study and briefly summarises the rationale for this. Please note that all values have been converted to kg m^{-2} for this study.

A summary table is provided in Section 3.6; this details the carbon rates selected for use in this study, together with a confidence assessment and a brief justification of the selection.

3.2. Water

3.2.1. Water column

Background / carbon storage and sequestration

The biological carbon pump (coupled with the solubility pump) is an important process in the ocean-wide (water column) sequestration of carbon. It refers to the photosynthetic uptake of CO_2 by marine plankton in surface waters, which results in a fraction of produced biomass being transferred to the deep ocean and subsequently buried (Burrows *et al.*, 2014). In this way, these photosynthetic micro-organisms convert dissolved inorganic carbon into organic forms of carbon, with the latter being mostly recycled in the upper waters of the sea (Smale *et al.*, 2013). It is a proportion of POC that sinks into deeper waters and is accreted into the sediment as material is buried when fresh sediment accumulates. Some plankton also armour themselves with calcareous scales or shells, which subsequently sink; becoming particulate inorganic carbon (PIC).

The flux of carbon from surface waters into marine sediments can be ‘simulated’ using the calculation of a ‘Net Microplankton Production’ (NMP) rate. NMP is less than ‘net primary production', because it takes account of consumption within the euphotic zone by pelagic grazers (such as zooplankton) and is intended to measure the amount of organic matter available for export from this zone. Some of the exported POC is consumed by zooplankters, although a part of what is eaten is defaecated. Therefore, the NMP rate joins sinking, live and dead phytoplankton to calculate the total flux into the bottom boundary layer. Burrows *et al.* (2014) calculated that a value of 10% NMP represented the flux of carbon transported to deep-sea sediments.

Welsh context

As noted in the Section 1, Welsh marine waters cover an area of some 32,000 km²; the depth of these waters ranges from 0 m to around 180 m. The waters would thus all be classed as belonging to the continental shelf.

Habitat summary

For the purpose of this study, PML's ERSEM model was utilised to obtain values for biomass carbon contained in the water column within WNMP boundaries. Outputs provided by PML indicate that the water column in Welsh waters holds some 48.6 Mt C (mega / million tonnes of carbon) at any one time (on average), with zooplankton, phytoplankton and non-living POC making up just under 5 % of this (and the remainder being mostly DIC, with some DOC) – please see Table 8 and Section 4.3 for more detail.

3.3. Intertidal habitats

3.3.1. Saltmarsh

Background

Saltmarshes are generally established in areas sheltered from wave action, such as in estuaries, lagoons, beach plains, natural harbours and barrier islands, where fine silt and clay sediments settle. Saltmarshes cover approximately 55,000 km² of the world's coastlines, with 26 species present within 470 km² of the UK's marshes (Beaumont *et al.*, 2014). Saltmarshes in Wales and on the west coast of the UK generally have a shallow organic-rich clay layer (<1 m) underlain by sandy substrate and are frequently grazed by livestock (May and Hansom 2003; cited in Beaumont *et al.*, 2014), whereas the marshes of the south and east UK coasts are characterised by a deep (>10 m) organic-rich clay substrate and are most commonly ungrazed (Beaumont *et al.*, 2014).

Welsh context

There are 76 km² of saltmarshes in Wales (as calculated from the 'saltmarsh extent' layer available on the Lle portal). Saltmarshes are widespread across the Welsh coast, where they are present in all major estuaries and inlets as well as in other more sheltered locations, including the lee of spits and in the shelter of islands (Welsh Government, 2018). The largest extents are found in the Severn Estuary and the estuaries of Carmarthen Bay. Whilst the Dee Estuary contains extensive stretches of saltmarsh, the majority of these are located on the English side of the estuary.

Saltmarshes are listed in Annex I of the Habitats Directive and are also a 'habitat of principal importance' under Section 7 of the Environment (Wales) Act 2016. Many Welsh saltmarshes are furthermore protected as features of SACs or SSSIs, and / or constitute supporting habitats for the bird interest features of many SPAs. SACs with saltmarsh features are listed in Table 3.

Table 3. Welsh designated sites where saltmarsh is a designated feature

European site	Annex 1 Feature
Dee Estuary SAC	Atlantic salt meadows; Salicornia and other annuals
Glannau Môn Cors Heli SAC	Atlantic salt meadows; Salicornia and other annuals
Pen Llŷn a'r Sarnau SAC	Atlantic salt meadows; Salicornia and other annuals, Mediterranean and thermo-Atlantic halophilous scrubs
Pembrokeshire Marine SAC	Atlantic salt meadows
Carmarthen Bay and Estuaries SAC	Atlantic salt meadows; Salicornia and other annuals
Kenfig SAC	Atlantic salt meadows
Severn Estuary SAC	Atlantic salt meadows

(Adapted from Welsh Government, 2018)

Carbon storage and sequestration

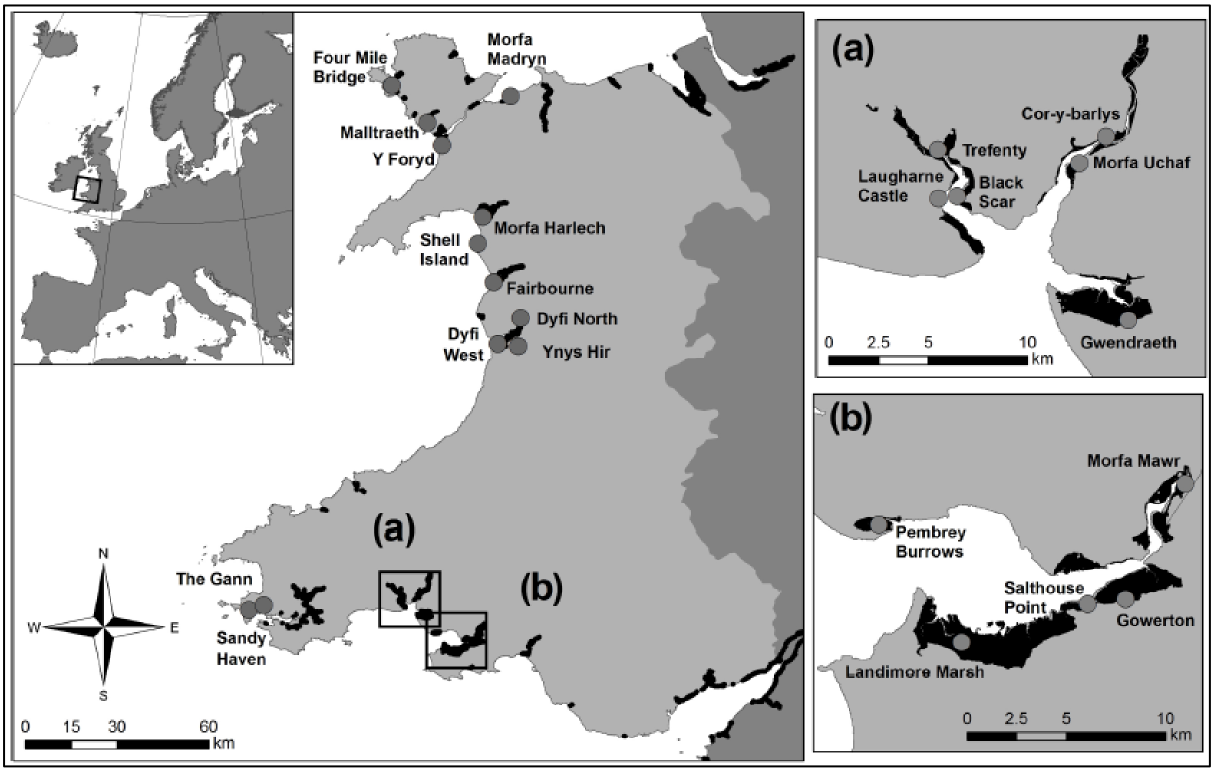
Saltmarsh carbon 'sinks' form when saltmarsh plants capture CO_2 from the surrounding air and water column and subsequently store this carbon in their roots and rhizomes. At the same time, saltmarsh roots physically bind together soil particles and encourage rhizomal microbes to do the same, trapping organic material (Ford *et al.*, 2016). It is this exuding of captured carbon and organic material into the soil that creates an anaerobic, carbon-rich sediment (Reid and Goss, 1981; cited in Ford *et al.,* 2016). This has the ability to accumulate carbon without reaching saturation (i.e. anaerobic conditions slow decomposition) and can potentially store carbon over millennial timescales (Stewart and Williams, 2019). As these habitats are dynamic however, and can be subject to die-back and physical remobilisation at intervals of decades or centuries (Burrows *et al.*, 2014), they may not be capable of storing carbon over very long timescales.

Carbon sequestration rates vary between complexes, with variability related to numerous factors, including hydroperiod (time spent submerged), salinity, nutrient input (i.e. from pollution) and suspended sediment supply (Nelleman *et al.*, 2009). Substrate type and thickness are also important factors in saltmarsh sequestration potential, with clay soils widely recognised as good stores of organic carbon due to the efficient adsorption of organics to clay particles (Ford *et al.,* 2019). Plant community composition and plant diversity are also important, as they largely determine root properties such as biomass, sediment turnover and carbon exudate rate. Ford *et al.* (2016) suggest that species-rich saltmarshes undergo a reduced soil erosion rate and hence may sequester carbon for longer than less-diverse marshes. Similarly, the relationship between soil stabilisation and plant diversity was found to be stronger in erosion-prone sandy soils compared to resilient clay soils (Ford *et al.*, 2016).

It is thought that saltmarshes have the highest carbon burial rate per unit area compared to other blue carbon habitats (Stewart and Williams, 2019), with total global sequestration rates of 5 and 87 Mt C yr^{-1} (Chmura *et al.*, 2003) and 10.2 Mt C yr^{-1} (Ouyang and Lee, 2014) quoted in the literature. Large amounts of carbon have been calculated to have already been buried / sequestered in saltmarsh sediments globally, with levels as high as 430 Mt quoted by Chmura *et al.* (2003) for the upper 50 cm of tidal saltmarsh sediments.

Sequestration rates in UK saltmarsh range from 64 – 219 g C m^{-2} yr^{-1} (Adams *et al.*, 2012), with typical figures around 120 – 150 g C m^{-2} yr^{-1} (Beaumont *et al.*, 2014). Burrows *et al.* (2014) applied a value of 210 g C m^{-2} yr^{-1} for their Scottish study.

A 2015 Welsh study reported on by Ford *et al.* (2019) sampled a total of 23 saltmarsh sites to determine carbon stocks (see Image 4). Plant and soil characteristics were analysed for each site, and the carbon stock determined for each of the sampling locations (51 in total across the 23 sites). Stored carbon calculated for the top 10 cm of soil varied from 32 t C ha^{-1} (or 3.2 kg C m^{-2}) for the *Atriplex portulacoides* vegetation class to 50 t C ha^{-1} for the *Juncus gerardii* vegetation class. Sandy soils were found to store less carbon (average 29 t C ha^{-1}) than non-sandy soils (43 t C ha^{-1}).



Source: Ford *et al.*, 2019

Image 4 Location of Welsh saltmarsh study sites investigated by Ford *et al.* (2019)

Source: ABPmer

Image 5 Saltmarsh (in the Dee Estuary)

Habitat summary

For the purpose of this study, the following values have been applied for saltmarsh:

- Biomass standing stock: 0.21 kg m^{-2}. This has been taken from the report by Burrows *et al.* (2014), prepared for Scottish Natural Heritage (SNH) for Scotland.
- Soil standing stock: 4.2 kg m^{-2} (top 10 cm). This is the average of values reported for 51 Welsh samples, as taken across 23 saltmarshes (see Ford *et al.* (2019) supplementary material).
- Sequestration: 0.084 kg m^{-2} yr^{-1}. This has been calculated as a 2 mm proportion of the soil stock value. 2 mm accretion per annum was assumed for this (and all other intertidal habitats)[3]. It is noteworthy that higher values of 0.125 to 0.21 kg m^{-2} yr^{-1} have been quoted in the literature. However, applying a proportion of the standing stock is a) consistent with the methodology adopted for other habitats (e.g. see seagrass below), and b) likely to be more applicable to Welsh conditions, as the stock value was derived from a Welsh study.

3.3.2. Mudflat and sandflat

Background

Intertidal mudflats and sandflats are areas of unconsolidated sediment (Lopez-Calderon *et al.,* 2015), characterised by marshy, muddy, sandy or mixed-sediments, that become exposed at low tide. Intertidal mudflats in the UK cover approximately 2,700 km².

Welsh context

There are around 434 km² of 'bare' intertidal flats in Wales (i.e. excluding those areas vegetated with seagrasses or populated by shellfish as mapped by this study), with the largest extents found in the Severn Estuary and Carmarthen Bay (and its estuaries). The area and quality of mudflats is thought to be declining in Wales, with increases in sea-level rise likely to have a significant impact on such habitats, particularly around estuaries and along sections of defended coast. It is possible that, depending on suspended sediment concentrations in the water column most UK mudflat environments could to keep pace with current rates of sea level rise due to accretion / sedimentation (and roll back) and thus potentially sequester carbon long-term (NRW, 2016). This is also dependent on management measures, such as those prescribed by Shoreline Management Plans (SMPs).

Intertidal mudflats and sandflats are listed in Annex I of the Habitats Directive and mudflats are also a habitat of principal importance under Section 7 of the

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[3] On the assumption that these habitats would be able to keep pace with some of the sea level rise taking place at present, although this would to some extent depend on local conditions, notably water column suspended sediment concentrations. Sea level has risen globally by around 0.2 m from 1901 to 2010, at an average rate of 1.7 mm yr^{-1} (Intergovernmental Panel on Climate Change (IPCC), 2013). An apparent change in rate to ~3 mm yr^{-1} has been observed during the past 30 years, as determined from a number of studies looking at satellite records of global mean sea level (e.g. Cazenave and Nerem, 2004; Church and White, 2006), as well as tide gauges worldwide (e.g. Menendez and Woodworth, 2010). The 2 mm assumption likely represents a conservative approach for Welsh saltmarshes. For example, Pye and French (1993) quote accretion rates of 3 to 6 mm yr^{-1} for saltmarshes at Angle Bay in Milford Haven, and 3 to 4 mm yr^{-1} for Severn Estuary saltmarshes between the 1940s and 1980s.

Environment (Wales) Act 2016. Intertidal flats also frequently form a major component of two encompassing ‘habitat’ features, namely ‘estuaries’ and ‘large shallow inlets and bays’. Many Welsh intertidal flats are furthermore protected as features of SACs or SSSIs, and / or constitute supporting habitats for the bird interest features of many SPAs. For example, the following SACs contain ‘mudflats and sandflats not covered by seawater at low tide’ as a designated feature (Welsh Government, 2018):

- Y Fenai a Bae Conwy / Menai Strait and Conwy Bay SAC;
- Dee Estuary / Aber Dyfrdwy SAC;
- Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd SAC;
- Pen Llyn a'r Sarnau SAC;
- Pembrokeshire Marine / Sir Benfro Forol SAC;
- Severn Estuary / Môr Hafren SAC; and
- Glannau Môn: Cors heli / Anglesey Coast: Saltmarsh SAC.

Carbon storage and sequestration

Mudflats and sandflats can store and sequester carbon in both organic and inorganic (carbonate) forms. Sanders *et al.* (2010) found intertidal mudflats close to mangrove forests, in Tamandare (Eastern Brazil), to be sites of large organic carbon accumulation; storing almost four times the global average for sequestration in mangrove forests. The authors suggest that large fluxes of organic carbon produced and sequestered in mangrove forests are deposited and stored in mangrove margins and intertidal mudflats. In this way, intertidal mudflats may be sites of higher total organic carbon accumulation compared to sediments from mangrove forests and may be considered significant in the coastal ocean total organic carbon budgets (Sanders *et al.,* 2010). Similarly, Cook (2002) found organic matter present in estuarine mudflats in Tasmania did not originate within the mudflats, instead having predominantly terrestrial sources, such as near shore estuarine transport (driven by riverine input) as well as direct terrestrial run-off and reworking of glacial and post-glacial sediments. Chaeho *et al.* (2019) studied organic carbon content in mudflat sediments (and other coastal wetlands) in South Korea and found that carbon storage in these tidal flats ranged from 18.2 to 28.6 kg C m^{-2}.

In England, Wood *et al.* (2015) collected surface sediment samples across English mud and sandflats in Essex and around Morecambe Bay. The available data shows that the percentage of carbon (dry weight) contained in intertidal flat sediments ranges from 0 to 7.5 %, with the average for Essex samples being 2.5 %, and the average for Morecambe Bay sites being 0.4 %; there being a clear correlation between mud and carbon content, as illustrated in Table 4. There was furthermore a relatively high $CaCO_3$ content in the samples, ranging from 1.3 % to 23 %, with averages listed in Table 4. Carbon can be assumed to make up 12 % of the mass of $CaCO_3$ (Van der Schatte *et al.,* 2018). In simplistic percentage terms, the inorganic carbon content in intertidal flats could add an additional 1 to 1.6 % of carbon to the carbon budget of intertidal flats. When undertaking their study of Welsh saltmarshes, Ford *et al.* (2019) did not take mudflat samples (personal communication H. Ford / ABPmer, February 2020).

Table 4 Sediment composition for Essex and Morecambe Bay intertidal flats

Parameter	**Average values across mudflat samples Morecambe (n=396)**	**Average values across mudflat samples Essex (n=396)**
% silt and clay	13.37	78.80
% Water*	23.90	48.36
% organic carbon*	0.36	2.47
% CO_2*	3.69	5.85
% $CaCO_3$*	8.39	13.31

* As % composition (dry weight)
Calculated using data available at: https://catalogue.ceh.ac.uk/documents/d4e9f0f7-637a-4aa4-b9df-2a4ca5bfaded (last accessed February 2019)

Source: ABPmer

Image 6 Sandflat habitat (in the Dee Estuary)

Habitat summary

For the purpose of this study, the following values have been applied for intertidal flats:

- Soil standing stock: 0.55 - 1.84 kg m^{-2} (top 10 cm). These values have been derived by multiplying the individual sediment class values calculated by Diesing *et al.* (2017) for subtidal habitats (please see Section 3.5.5) by a factor of two. This is due to the latter authors highlighting that nearshore sediments hold more carbon. It is considered that this likely represents a conservative approach. Please refer to Section 8 / Appendix A for individual values applied for each sediment class.
- Sequestration: 0.011- 0.037 kg m^{-2} yr^{-1}. This is a proportion of standing stock, assuming an accretion rate of 2 mm yr^{-1} (this has been applied for all intertidal habitats - please see Footnote 3 for rationale).

3.3.3. Vegetated rocky shores

Background

Rocky shore habitats are relatively stable and provide secure surfaces for living things to attach to and hide within. The typical rock, which makes up a shore will vary, which in turn determines the type of animals, plants and algae that will colonise the area.

Welsh context

There are around 31 km² of mapped intertidal vegetated rocky shores in Wales, most commonly vegetated by algal communities dominated in biomass by large wracks / *Fucus* species (F. *vesiculosus, F. serratus, F. spiralis*), as well as brown seaweeds *Pelvetia canaliculata, Ascophyllum nodosum* and *Laminaria digitata* (kelp). These habitats are found along all Wales' coastline, from estuaries to relatively exposed coasts. Notable areas include Pembrokeshire, the Lleyn Peninsula (Gwynedd) and Anglesey.

Many vegetated rocky shores types present in Wales form part of an Annex I (Habitats Directive) feature, namely 'reefs', which are defined as (mostly subtidal) 'rocky marine habitats or biological concretions that rise from the seabed'. This habitat is the amongst the primary reasons for designation for the following Welsh SACs (Welsh Government, 2018):

- Cardigan Bay / Bae Ceredigion;
- Pembrokeshire Marine / Sir Benfro Forol;
- Pen Llŷn a'r Sarnau / Lleyn Peninsula and the Sarnau;
- Severn Estuary / Môr Hafren; and
- Y Fenai a Bae Conwy / Menai Strait and Conwy Bay.

Furthermore, several rare seaweeds present in these Welsh habitats are listed as species of principal importance in Wales (under Section 7 of the Environment (Wales) Act 2016).

Carbon storage and sequestration

As burial of carbon is precluded in rocky habitats, there is limited insight into the role of rocky shore vegetation on carbon accumulation and transport. Studies like Hanley and La Pierre (2015) suggest that carbon storage and sequestration are limited in these habitats as '*detritus does not accumulate in rocky shore ecosystems and contribute to the formation of soil; instead, it is largely exported to adjacent beaches and other benthic marine ecosystems*' and, therefore, conclude there are limited opportunities for consumers to influence nutrient recycling within the ecosystem. It is then presumed that nutrients and energy stored within kelp are exchanged with adjacent ecosystems that are more influential to the carbon cycle. Similarly, macroalgal-derived matter is assumed to decompose too quickly to allow for long-range export and burial (Howard *et al.*, 2017; cited in Pessarrodona *et al.,* 2018).

There is growing evidence, however, that suggests macroalgae-derived carbon may be transported to habitats hundreds of kilometres away from the source and / or being sequestered in deep-sea surficial sediments (Hobday, 2000). This transfer of carbon is an invaluable input for habitats with low autochthonous productivity, such as offshore sedimentary habitats (Krumhansl and Scheibling, 2012) and can contribute to carbon storage if they accumulate within habitats with long-term carbon burial capacity, such as seagrass meadows or offshore depositional sediments (Hill *et al.*, 2015). Similarly, studies such as Smale *et al.* (2013) suggest that production by intertidal kelp ecosystems is simply overlooked (and therefore underestimated); they argue that an estimation by Dayton (1985), that '*kelp may account for 45% of primary production in UK coastal waters, and 12% of marine production in the entire UK*' did not include the extensive shallow subtidal rocky reef habitats found off England and Wales. Mann (2000; cited in Smale *et al.*, 2013) also suggested when primary productivity rates of intertidal macroalgae are compared with subtidal macroalgae, intertidal production is typically 10%-20% of that from the subtidal, suggesting intertidal kelp habitats assimilate enough carbon to contribute substantially to primary production in coastal waters off the UK and Ireland (Smale *et al.,* 2013).

Furthermore, Ning *et al.* (2019) suggest that a large fraction of carbon stored in consumer biomass in an intertidal rocky shore (Mirs Bay, China) originated from intertidal macroalgae and epiphytes within that habitat, and as such was acting as a blue carbon 'sink'. It was noted, however, that suspended particulate organic matter (SPOM) collected from offshore areas was the most important production source supporting the biomass of the consumers. It was suggested that the selected carbon source depends on the composition of species within a rocky shore and, therefore, on feeding mode; with filter-feeding invertebrates principally feeding on suspended macroalgal detritus (Kang *et al.,* 2008; cited in Ning *et al.,* 2019) and phytoplankton and grazer limpets and chitons selecting epiphytes. These primary consumers are then predated upon by intertidal and offshore-based secondary grazers and facilitate the transfer of detrital carbon into offshore areas, fuelling the sequestration of carbon in living biomass as well as detritus that will eventually settle in offshore sediments (Pessarrodona *et al.,* 2018).

Source: Andy Pearson

Image 7 Intertidal macroalgae

Habitat summary

For the purpose of this study, the following value has been applied for intertidal macroalgae biomass standing stock (noting that soil stock and sequestration are not applicable in this case, as discussed above): 0.047 kg m^{-2}. This represents 10% of the subtidal value (see Section 3.5.2) (applying a relationship quoted by Smale *et al.*, 2016).

3.4. Shallow subtidal habitats (with intertidal elements)

3.4.1. Seagrass beds

Background

Seagrass beds develop in intertidal and shallow subtidal areas, typically up to 10 m depth, which are sheltered from significant wave action. Three species of *Zostera* occur in the UK; Dwarf eelgrass (*Z. noltii*), narrow-leaved eelgrass (*Z. angustifolia*) and eelgrass (*Z. marina*).

Welsh context

There are around 7.3 km² of mapped seagrass beds in Wales, with the largest extents found around Anglesey and in Milford Haven. Seagrasses are deemed as scarce in Wales (present only in 16–100 ten km squares) (Stewart and Williams 2019), although not necessarily declining. NRW (2016) note that '*intertidal seagrass beds have increased in extent*' although the timescales over which this change has occurred are unclear.

Seagrass beds are a habitat of principal importance under Section 7 of the Environment (Wales) Act 2016. Many Welsh seagrass beds are furthermore located within designated sites, where they are protected as features of SACs or constitute a component of sheltered bays, although they are not an 'Annex I' habitat in their own right. Notable seagrass habitats are for example included in the Pembrokeshire Marine / Sir Benfro Forol SAC, which supports extensive beds of the narrow-leaved eelgrass *Z. angustifolia*. Also, seagrass is listed as a feature in the following SSSIs (Welsh Government, 2019):

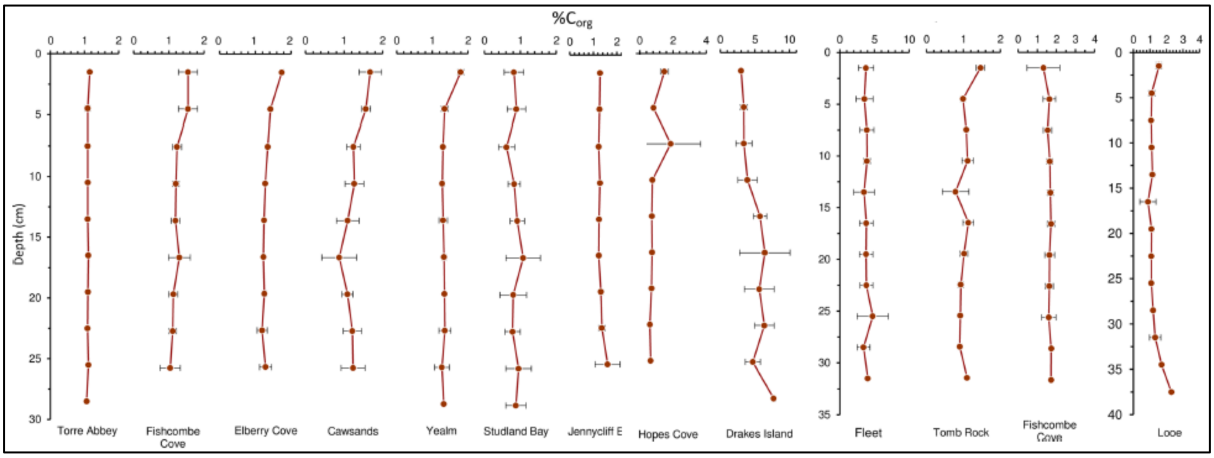
- Beddmanarch – Cymyran;
- Burry Inlet and Loughor Estuary;
- Milford Haven Waterway;
- Porth Dinllaen i Borth Pistyll;
- Severn Estuary;
- Tiroedd a Glannau Rhwng Cricieth ac Afon Glaslyn;
- Traeth Lafan;
- Twyni Chwitffordd, Morfa Landimor a Bae Brychdwn / Whiteford Burrows etc; and
- Y Foryd.

Carbon storage and sequestration

Seagrass foliage slows water movement and sequesters CO_2 dissolved in seawater; storing organic carbon in the roots and rhizomes before exuding carbon into the soil, creating an anaerobic organic-carbon-rich sediment. It is estimated that between 5 and 18% of carbon is exuded into the soil (e.g. Holmer and Bondgaard, 2001), with 100% of this carbon being utilised by anaerobic bacteria in the seagrass sediments (Moriarty *et al,* 1986). The anoxic nature of marine seagrass sediments, paired with continual accumulation of sediment by seagrass foliage, low sediment hydraulic conductivity and slower microbial decomposition rates, facilitate carbon burial and the accumulation of carbon (Guy, 2010). The combination of these processes can preserve organic carbon in seagrass sediments over decadal to even millennial time scales (Kennedy *et al.,* 2010; cited in Greiner *et al.,* 2013). As such, it has been suggested that, although these plants only cover a relatively small area of the global ocean floor (0.1-0.2%), they are responsible for between 10 and 18% of the total carbon storage in the ocean (Laffoley and Grimsditch, 2009; Green *et al.,* 2018).

The majority of blue carbon accumulated in seagrass habitats is stored in seagrass sediments; globally, an average of 2.51 ± 0.49 Mg C ha^{-1} is thought to be stored in the living biomass (roots and rhizomes) of seagrass compared to 194.2 ± 20.2 Mg C ha^{-1} in sediment (Green *et al.*, 2018). It has been estimated that seagrass sediment carbon accumulation ranges from 27.4 to as much as 48-112 Mt C yr^{-1} (Laffoley and Grimsditch, 2009; Green *et al.*, 2018). This translates to a mean net sequestration rate of 83 g C m^{-2} yr^{-1} and a total global storage of 19.9 Pg C (billion tonnes carbon) within the top 100 cm of the world's seagrass sediments (Green *et al.,* 2018).

A recent UK study demonstrated that carbon storage ability can increase with sediment depth; Green *et al.* (2018) compared carbon content in sediment cores taken from the upper 30 cm and 100 cm in subtidal seagrass sediments of 13 seagrass meadows in south-west England, and found 100 cm samples contained a carbon store three times higher than samples taken solely from the top 30 cm; 41.54 ± 4.54 Mg C ha^{-1} (30 cm depth), 140.98 ± 73.32 Mg C ha^{-1} (100 cm depth). Sediment profiles showed no change at depth (see Image 8). When converted to carbon stored to a depth of 25 cm, Green *et al.* (2018) determined that the studied (English) seagrass meadows fell within the upper range of those recorded in the rest of Europe. The authors state that 'across Europe, estimates of *Z. marina* carbon stock vary considerably, ranging from 500 ± 50.00 g C m^2 to 4,324.50 ± 1,188.00 g C m^{-2} in the top 25 cm of sediment. With an average carbon stock of 3,372.47 ± 1,625.79 g C m^{-2}, the UK is second only to Denmark'.



Source: Green *et al.*, 2018

Image 8 Depth profiles of the seagrass sediment cores taken by Green *et al.* (2018); organic carbon (OC) expressed as a percentage of the dry weight

The anoxic nature of marine seagrass sediments, paired with continual accumulation of sediment by seagrass foliage, low sediment hydraulic conductivity and slower microbial decomposition rates, facilitate carbon burial and the accumulation of carbon stores.

The dense seagrass canopy above can reduce fine-grained sediment resuspension up to three times that of unvegetated sediments (Greiner *et al.,* 2013), helping to trap sediments rich in organic matter. The combination of these processes can preserve organic carbon in seagrass sediments over decadal to even millennial time scales (Kennedy *et al.,* 2010; cited in Greiner *et al.,* 2013).

Source: Andy Pearson

Image 9 Seagrass

Habitat summary

For the purpose of this study, the following values have been applied for seagrass:

- Biomass standing stock: 0.26 kg m^{-2}. This has been taken from the report by Burrows *et al.* (2014), prepared for SNH / Scotland.
- Soil standing stock: 1.35 kg m^{-2} (top 10 cm). This was calculated by averaging values provided for 13 south-west English meadows by Green *et al.* (2018). As the latter authors only quoted values for the top 25 cm, a linear extrapolation was undertaken to arrive at a 'top 10 cm' value, after personal communication with the primary author of the study. This was to keep depth in line with that applied for all other habitats considered in this study (except for maerl (see Section 3.5.2)).
- Sequestration: 0.027 kg m^{-2} yr^{-1}. Calculated as a 2 mm proportion of the soil stock value, assuming an accretion rate of 2 mm yr^{-1} (as applied for all intertidal habitats, and also seagrasses, as they tend to be located in shallow subtidal to intertidal zones - please see Footnote 3 for rationale).

3.5. Subtidal habitats

3.5.1. Shellfish beds

Background

Four shellfish bed varieties have been considered for the purpose of this study, namely those formed by[4]:

- The native oyster *Ostrea. edulis*; this is associated with highly productive estuarine and shallow coastal water habitats on firm bottoms of mud, rocks, muddy sand, muddy gravel with shells and hard silt.
- *Musculus discors*, a small bivalve; this is found in scattered, gregarious clumps growing epiphytically on the holdfasts of seaweeds and amongst faunal turfs from the lower intertidal to the circalittoral subtidal on most substrata.
- The common mussel *Mytilus edulis*; this from the high intertidal to the shallow subtidal attached by fibrous byssus threads to suitable substrata. Found on the rocky shores of open coasts attached to the rock surface and in crevices, and on rocks and piers in sheltered harbours and estuaries, often occurring as dense masses.
- The horse mussel *Modiolus modiolus*; this is part-buried in soft sediments or coarse grounds or attached to hard substrata, forming clumps or extensive beds or reefs. May be found on the lower shore in rock pools or in laminarian holdfasts, but more common subtidally to ca 280 m.

Welsh context

15.7 km² of shellfish beds have been mapped for the purpose of this study; 8.7 km² of this is horse mussel beds and 6.9 km² blue mussel beds. 0.01 km² of oyster beds have also been mapped; the locations of which are considered sensitive, and hence are not discussed here (but they have been included in the calculations). 0.16 km² of *M. discors* beds have been mapped; these are all located off the Lleyn Peninsula (Gwynedd). Significant horse mussel beds can be found to the north of the Lleyn Peninsula and Anglesey, whereas blue mussel beds have been mapped along the majority of the Welsh coastline. Native oyster and horse mussel beds around Wales have been suffering significant habitat loss since 2008 (NRW, 2016).

Please note that, for most shellfish beds, particularly horse mussels which, of all the species studied here, are found at the greatest depths, there is a large amount of uncertainty regarding the locations of such habitats. This is due to the mapping of these (and other subtidal) habitats relying heavily on observational surveying methods (including underwater video), and as such exact maps are difficult and time-consuming to obtain[5]. Thus, it is considered highly likely that the areas quoted above represent an underestimate of these habitats in Welsh waters.

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[4] Habitat information obtain from The Marine Life Information Network (MarLIN), 2020.

[5] Horse mussel beds can however be surveyed for extent-mapping purposes using side-scan sonar and / or multibeam bathymetry surveying techniques, due to the distinct acoustic signature they often provide, signalling wave-like bedform properties. This is especially true of the horse mussel beds lying off the North of the Llyn peninsula (NRW, personal communication).

With regard to conservation importance, *M. discors*, horse mussel and blue mussel beds are habitats of principal importance, and native oyster are designated as a species of principal importance, under Section 7 of the Environment (Wales) Act 2016.

Carbon storage and sequestration

Shellfish assimilate carbon in the form of calcium carbonate, via shell production (Hickey 2008; cited in Van der Schatte *et al.,* 2018), with carbon comprising (on average) 11.7% of shell material (Van der Schatte *et al.,* 2018). During the calcification process, CO_2 is formed; potentially leading to an increase in the partial pressure of CO_2 in surface waters and the release of CO_2 to the atmosphere, especially in shallow well-mixed coastal waters where shellfish are typically farmed. As such, the calcification process, and therefore shellfish bed habitats, are often considered to be a source of atmospheric CO_2 (Fodrie *et al.,* 2017).

Most of the studies on carbon sequestration / storage potential of oysters have focussed on American species. Fodrie *et al.* (2017) sampled 22 eastern oyster reefs (*Crassostrea virginica*) in Northern Carolina, United States, and found that only a subset of restored reefs had functioned as net CO_2 sinks, namely those fringing saltmarshes and those located in the shallow subtidal. Conversely, their data highlight that '*CO_2-related climate mitigation is not a service that should be expected / promoted for intertidal reefs constructed over unstructured sandflats*'. They concluded that 'the role of shellfish reefs as CO_2 sources or sinks ultimately depends on the relative balance between organic and inorganic carbon burial', with the filtration and subsequent deposition of particulate organic matter (as faeces) being the route to organic carbon burial.

Hickey (2008) calculated the amount of carbon sequestered per year in oyster farms, using shell carbon content, spat weight, grow-out time and stocking density, to be between 3.81 and 17.94 t C ha^{-1} yr^{-1}. Similarly, Higgins *et al.* (2011) estimated that one (American / Chesapeake Bay) oyster bed could remove a total of 13.47 ± 1.00 t C ha^{1} yr^{1} in a single growing season at a density of 286 oysters m^{2}.

These values are, therefore, highly dependent on oyster densities, even if American oysters were to have similar carbon producing characteristics to European oysters. Whilst Fodrie *et al.* (2017) did not specify density in writing, a figure contained within the paper indicates that live density would tend to be high (with a minimum around 100 individuals m^{-2}). Welsh oyster beds are likely to be much more impoverished; for example, for two Welsh beds, Seasearch (2017) reported very low densities of 0.17 to 0.05 individuals m^{-2}.

Many authors however argue that carbon stored in shell represents a long-term store; Collins (1986) studied a horse mussel bed at 160-190 m depth in the Firth of Lorn, Scotland and estimated a standing stock value of 8,543 t of $CaCO_3$ in the top 5 cm of superficial sediments, representing 1,025 t of stored carbon.

Horse mussels are large bivalves with robust shells that occur in dense beds, and as such, the accumulation of empty shells may be important sources of biogenic carbonate. *M. modiolus* beds are identified as habitats of principle importance (HPI) within the UK and Wales, and as such may store carbon for as long as they remain undisturbed. In the Firth of Lorn, *M. modiolus* accounted for 94% of carbonate standing stock in the mussel bed community, but only 38% of the estimated carbonate production (Collins, 1986). Instead, brachiopods, brittlestars, barnacles and 'mussel mud'; an anoxic layer comprising of faeces, pseudo-faeces and sediment, accounted for the remaining community production. The very low production / biomass (P/B) ratio of *M. modiolus* (0.05) was attributed to a long lifespan (*circa* 40 years) and slow growth rate (Burrows 2014), and in consequence has a low area-specific carbonate production rate, estimated as 330 g CaCO3 m^2 yr^{-1} in the Firth of Lorn (Collins, 1986; cited in Burrows *et al.,* 2014) equivalent to 40 g C m^2 yr^{-1}. Most carbonate degradation is believed to take place at the sediment-water interface, with bioerosion on temperate shelves thought to require a timescale of centuries to several millennia for total shell destruction (Smith and Nelson, 2003), especially for large, robust shells such as those of *M. modiolus.* Furthermore, thick deposits of horse mussel shells have the potential to store carbon over a timescale of 1,000 years (Burrows *et al.,* 2014), with 'mussel mud' potentially storing carbon for longer (Mainwaring *et al.*, 2014).

No relevant literature on carbon sequestration rates in relation to blue mussel or *M. discors* beds could be located; instead, assumptions have been made based on the horse mussel and oyster literature presented above (see Table 5 for details).

Habitat summary

For the purpose of this study, the following values have been applied for shellfish:

- Biomass standing stock: not available / applicable; shell 'calcimass' would essentially be incorporated into soil standing stock (see Burrows *et al.*, 2014).
- Soil standing stock: 0.13 to 4 kg m^{-2} (top 10 cm) (lowest values for oysters, highest for horse mussel, see Appendix A for all values). Taken from Burrows *et al.*, 2014 for horse mussels; for all other shellfish categories: derived by applying same relationship as used by latter authors for horse mussels.
- Sequestration: 0.001 to 0.04 kg m^{-2} yr^{-1} (lowest values for oysters, highest for horse mussel, see Appendix A for all values). Oyster value is 1 % of US value quoted by Fodrie *et al.* (2017), on the basis that Welsh oyster beds tend to have very low densities when compared with US beds, as noted above. Horse mussel values taken from Burrows *et al.*, 2014. For blue mussels and all other mussels, 10 % of the horse mussel value was applied as an estimate on the basis that horse mussels are significantly larger than these other mussels.

3.5.2. Macroalgae

Background

Subtidal macroalgae have a global distribution, being present along around 25% of the world's coastlines in temperate and polar regions. They are generally found living attached to rock or other hard substrates in the shallow region of coastal areas and can range in size from microscopic phytoplankton and small coralline algae which form spikey underwater maerl 'beds', to large kelps that form vast underwater 'forests'.

UK coastlines are home to more than 650 species of macroalgae, representing approximately 14% of the world's known marine seaweeds, and host seven out of 14 European kelp species (Stewart and Williams, 2019).

Two key types of subtidal macroalgae have been considered for this report; kelp and maerl. Kelps are defined as large brown seaweeds that make up the order Laminariales. Key species present within the WNMP include *Laminaria digitata* and *L. hyperborea*; which are found attached to bedrock or other suitable hard substrata in the lower intertidal and sublittoral fringe, down to a maximum depth of 20 m to 30 m in clear waters (MarLIN, 2020).

Unlike fleshy macroalgae, maerl has a calcium carbonate skeleton and does not break down quickly, thus forming long-lasting maerl beds that are populated by invertebrate and vertebrate biota (Burrows *et al.,* 2014). Two key maerl species are observed in British waters, *Phymatolithon calcareum* (common maerl) and *Lithothamnion corallinoides* (coral maerl). Both are typically found together, in less than 20 m depth on sand, mud or gravel substrata in areas that are protected from strong wave action but have moderate to high water flow (MarLIN, 2020).

Welsh context

This study estimates that there are at least 80.4 km² of subtidal macroalgae in Wales, most commonly vegetated by kelp, although 0.2 km² of 'live' maerl can be found. The latter is exclusively located in Milford Haven, whereas the mapped kelp beds are located along much of the Welsh shoreline with lower suspended sediment loads, with notable concentrations around the Lleyn Peninsula (Gwynedd), Anglesey, and in Milford Haven.

With regard to kelp, it should be noted that there is a large amount of uncertainty regarding the locations of subtidal kelp beds around Wales; the mapping of these habitats relies heavily on observational surveying, and as such exact maps are difficult and time-consuming to obtain. For this study, the data has been taken from the JNCC EUNIS Combined Map (see Section 2.3.2), where specified, and the area quoted above is considered to be an underestimate.

With regard to conservation importance, no macroalgae beds are listed in Annex I of the Habitats Directive. Kelp beds are not considered to be of principal importance in Wales (under Section 7 of the Environment (Wales) Act 2016), but maerl beds are (as both habitats and plant species). Many kelp beds, however, fall within designated sites; for example, kelp is mentioned as an important component of the 'reef' feature in the Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau SAC.

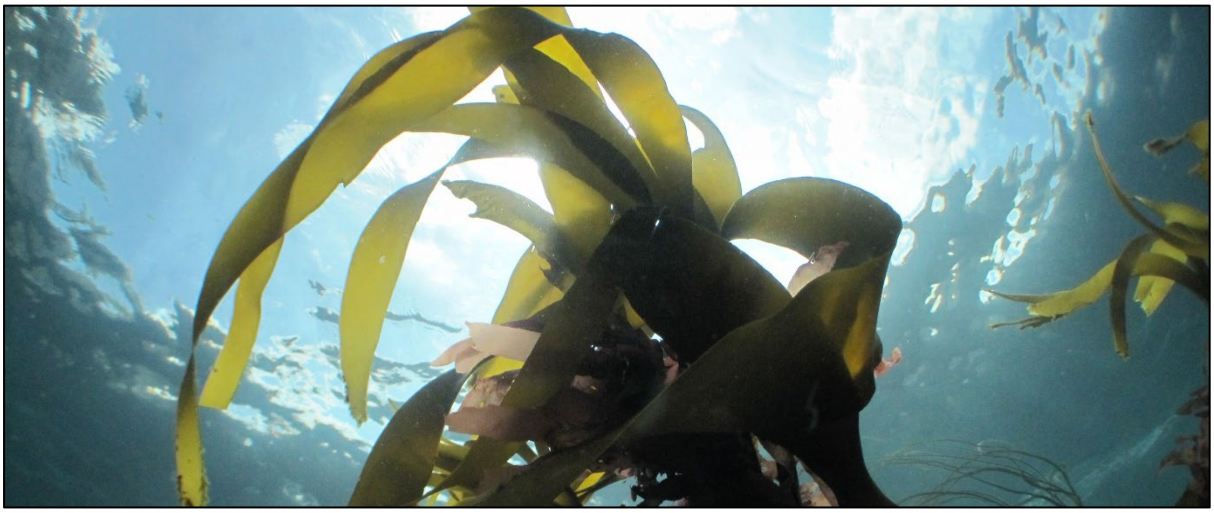
Carbon storage and sequestration

Kelp

Like intertidal macroalgae, it is thought that carbon from subtidal kelp is not stored long-term within kelp beds and instead algal detritus is exported to other habitats via dislodgement and transport or through consumption and egestion / defecation by consumers. Thus, kelp supports numerous coastal food webs, particularly benthic suspension-feeding organisms in rocky areas (such as mussels and barnacles), grazers such as limpets, and organisms in soft sediment areas. It has been theorised however that the majority (>80%) of kelp production enters the carbon cycle as detritus / DOC (Smale *et al.*, 2013); also, the readiness with which kelp detrital material is consumed by detritivores and broken down by microbial activity suggests a minimal amount of production is incorporated into long-term stores.

Kain's (1979) study determined that standing stock of kelp diminishes rapidly with depth, with only 10% of surface value density present at 12-25 m depth when compared to shallower kelp stocks (0-9 m range). Burrows *et al.* (2014) applied a value of 187.7 g organic carbon m^{-2} for their Scottish study, for areas where kelp was identified as being 'abundant' (>20% cover).

Smale *et al.* (2016) surveyed 12 UK kelp forests dominated by *L. hyperborea*, three of which were in Wales (all near St. Brides, Pembrokeshire), three in Devon (south-east of Plymouth) and the rest in Scotland. The depth at these sites ranged between 4 m and 7 m. It was found that regional averages for total standing stock of carbon differed markedly between the two northernmost regions and the two southernmost regions; with values in the two Scottish regions being highest (Region A: 1,146 ± 380 g C m^{-2}; Region B: 808 ± 324 g C m^{-2}), followed by the Devon sites (575 ± 96 g C m^{-2}), with the carbon stock at the Welsh sites being lowest (355 ± 38 g C m^{-2}). The authors did not elaborate on reasons for different values for their 'southern' sites (i.e. Wales and Devon), but suggested that Scottish values are higher due to a combination of cooler water temperatures, higher light levels, longer summer days and often increased wave exposure, all of which promote greater kelp biomass. The Smale *et al.* (2016) study-wide average for carbon contained within kelp forests was 721 ± 140 g C m^{-2}, with the vast majority (~86%) stored in canopy-forming, rather than sub-canopy, plants.



Source: Andy Pearson

Image 10 Kelp

Maerl

Maerl deposits act as a longer-term store for organic and inorganic carbon and lock-in calcifying biota. The rate of maerl deposit accretion is generally slow (0.25 mm yr^{-1}); however, beds can be extensive. Scottish species-specific accretion rates varied from 420 to 1,432 g $CaCO_3$ m^{-2} yr^{-1} in a study by Freiwald and Henrich. (1994) (cited in Burrows *et al.,* 2014). Live maerl deposits on the west coast of Scotland can reach at least 60 cm depth with some dead deposits residing significantly deeper (Kamenos, 2010). Burrows *et al.* (2014) applied an annual (inorganic) carbon sequestration rate of 0.074 kg m^{-2} for the purpose of their Scottish study.

As noted above, Welsh maerl covers a very small area, limited to Milford Haven, and is currently classed as 'degraded'. As such, it is unlikely that Welsh maerl contributes substantially to carbon sequestration in Welsh waters, and a smaller rate has thus been applied for the purpose of this study (see Table 5 for more detail).

Habitat summary

For the purpose of this study, the following values have been applied for subtidal macroalgae:

- Kelp: 0.47 kg m^{-2} for biomass standing stock (noting that soil stock and sequestration are not applicable in this case, as discussed above). This value was calculated by averaging numbers derived by Smale *et al.* (2016) for three Welsh and three Devon sites. As the three Welsh study sites were all immediately adjacent to each other, they were considered not fully representative, and Devon being relatively close to Wales, Devenish kelp was considered as being in the same bioregion. It is worth noting that the Scottish sites studied by Smale *et al.* (2016) averaged 0.97 kg m^{-2}, whereas Burrows *et al.* (2014) applied a value of 0.19 kg m^{-2} for Scottish beds

- Maerl:
  - Biomass standing stock: 0.09 kg m^{-2} (for live maerl). This represents one fifth of the value applied by Burrows *et al.*, 2014 (as Welsh beds are dominated by *P. calcareum* species, which sequesters approximately one fifth less than *Lithothamnion glaciale*, and also as Welsh beds are considered degraded (see above));
  - Soil standing stock: 12.4 kg m^{-2} (top 60 cm) (for live and dead maerl beds). Again, this is one fifth of the value applied by Burrows *et al.* 2014, for same reasons as quoted in previous bullet.
  - Sequestration: 0.0095 kg m^{-2} yr^{-1}. Represents minimum sequestration rate quoted for *P. calcareum* by Burrows *et al.* 2014.

3.5.3. Brittlestar beds

Background

The main bed-forming brittlestar species, the common brittlestar (*Ophiothrix fragilis*), has five fragile arms that are long and spiny. It is found from the lower shore to circalittoral offshore habitats on hard substrata including bedrock, boulders and on coarse sediment, and most abundant on tide-swept rock and on mixed coarse sediments. In the intertidal, the species is found in crevices and under boulders (MarLIN, 2020).

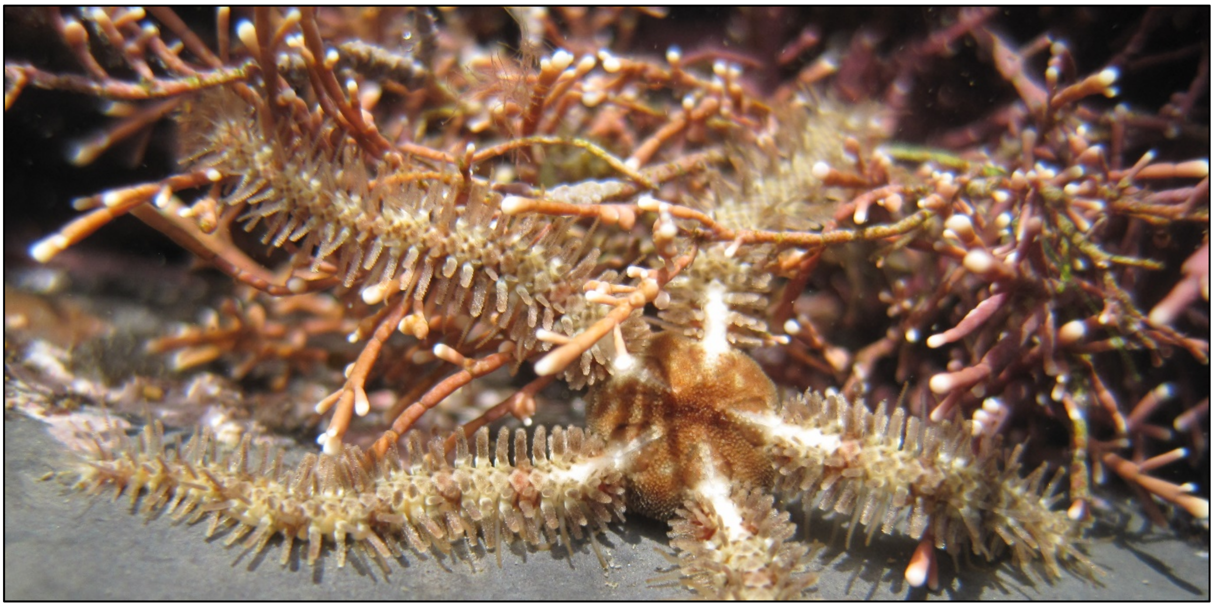
Welsh context

This study mapped only 0.07 km² of brittlestar beds, mostly off the Pembrokeshire coast. This is likely to be a large underestimate, as individual records of brittlestars indicate very widespread presence in Wales (see, for example, the NBN Atlas, 2020). Similarly, drop-down video surveys of the Wylfa Newydd Development Area in the North of Anglesey, as well as NRW surveys in this area, have found extensive brittlestar beds (NRW, personal communication). Thus, more beds are likely to exist.

Brittlestars or their beds are not listed in Annex I of the Habitats Directive, nor are they considered to be of principal importance in Wales (under Section 7 of the Environment (Wales) Act 2016), as either a species or habitat.

Carbon storage and sequestration

As echinoderms, brittlestars have an endoskeleton of calcareous plates, and due to their abundance in virtually all benthic environments, they may play an important role in the marine carbon cycle (Lebrato *et al.,* 2010; cited in Burrows *et al.,* 2014). For example, a one-year study of an *O. fragilis* bed located in the Dover Strait, England found that this averaged 1,229 individuals m^{-2}, representing 555 g $CaCO_3$ m^{-2}, equivalent to 66.2 g C m^{-2}. A sequestration rate was also calculated for the same bed, at a rate of 82 g C m^{-2} yr^{1} (Migné *et al.,* 1998; cited in Burrows *et al.,* 2014).



Source: Andy Pearson

Image 11 Brittlestars

After death, brittlestar skeletons will disaggregate and individual calcareous plates will become incorporated into the bottom sediments (Lebrato *et al.*, 2010; cited in Burrows *et al.,* 2014), forming ‘Echinoderm sands’ containing a high proportion of echinoderm skeletal particles, along with fragments of other shell-forming organisms that have been described within the coastal zone of Australia (Brunskill *et al.,* 2002;

cited in Burrows *et al.,* 2014). Brittlestar skeletal fragments will be subject to the same processes of bioerosion and chemical dissolution as carbonates produced by corals, serpulids or bivalves, and their longevity in sediments will, therefore, depend on the local environment (Walker and Goldstein, 1999; cited in Burrows *et al.,* 2014).

Habitat summary

For the purpose of this study, the following values have been applied for brittlestar beds:

- Biomass standing stock: None, as no value could be found in the literature, and as the brittlestar contribution to biomass stock in Wales would be negligible due to the limited area mapped (see above).
- Soil standing stock: 0.0116 kg m^{-2} (top 10 cm). No specific value could be found in the literature for brittlestar beds, but this study applied the same value as derived for subtidal sandy gravel (see Appendix A), as brittlestars are normally found on coarse sediment.
- Sequestration: 0.082 kg m^{-2} yr^{-1}. Taken from Burrows *et al.*, 2014.

3.5.4. Faunal turf

Background

'Faunal turfs' are assemblages of attached animals growing on hard substrata. These organisms can vary substantially in growth form, 'turf' being used in a highly generic sense. They will range from low encrusting forms less than a centimetre high, such as many ectoprocts (sea mats) and sponges, to tall erect forms such as alcyonarians (soft corals) and gorgonians (sea fans) which may exceed 25 cm in height (Hartnoll, 1998).

Welsh context

2.1 km^2 of Welsh subtidal faunal turf was mapped for the purpose of this study. The presence of larger extents of such turfs is expected, as individual records for the species typically present in such turfs abound in Wales (e.g. NBN Atlas (2020) records for the bryozoan *Alcyonidium diaphanum*, the hydroid *Halecium halecinum* and the sponge *Scypha ciliate*, to name but a few of the fauna typically present amongst such turfs).

Faunal turfs are not listed in Annex I of the Habitats Directive, nor are they considered to be of principal importance in Wales (under Section 7 of the Environment (Wales) Act 2016).

Carbon storage and sequestration

Literature on carbon content or storage associated with faunal turfs is sparse. Two papers were used to estimate a carbon storage rate for these habitats (see Table 5). Firstly, a paper from New Zealand (Taylor, 1998) which gives examples of ash free dry weight of similar faunal turf habitats (urchin barrens and turf flats) as 26 to 42 g m^{-2}. No literature on carbon content of faunal turf could be located, but a paper on such content of *Euphausiacea* determined a range of 36-46% carbon (as a proportion of total dry weight) (Lindley *et al.*, 1999).

Habitat summary

For the purpose of this study, the following biomass value has been applied for faunal turf (noting that soil standing stock and sequestration are considered not applicable for this study, as this habitat is mostly found on rock): 0.014 kg m^{-2}. This value was calculated for this study using the weight values quoted by Taylor (1998), and assuming 40% carbon (as per Lindley *et al.*, 1999).

3.5.5. Sedimentary habitats (surficial sediment)

Background

Connor *et al.* (2004) define subtidal sediments as: ‘Sediment habitats in the sublittoral near shore zone, typically extending from the extreme lower shore down to the edge of the bathyal zone (200 m)’. For the purpose of this study, any sedimentary habitat which is not rock has been classed according to the Folk system and mapped.

Welsh context

There are 29,514 km² of subtidal muds, sands and gravels in Welsh waters; 7% of this is predominantly muds, 52% sands and 41% gravels.

‘Sandbanks which are slightly covered by sea water all the time’, ‘estuaries’ and ‘large shallow inlets and bays’ are all ‘habitats’ listed in Annex I of the Habitats Directive which contain subtidal sedimentary habitats. Several Welsh marine SACs contain such habitats, and they often constitute supporting habitats for the bird interest features of Welsh SPAs. For example, one of the primary reasons for the selection of the Severn Estuary / Môr Hafren SAC as such a site is its ‘estuaries’ feature; with ‘sandbanks which are slightly covered by sea water all the time’ being listed as a qualifying feature. The following sublittoral sediment categories are considered habitats of principal importance in Wales (under Section 7 of the Environment (Wales) Act 2016):

- Tidal swept channels;
- Subtidal mixed muddy sediments;
- Mud habitats in deep water; and
- Subtidal sands and gravels.

Carbon storage and sequestration

Surficial sediments, and particularly deep-sea sediments, are the primary marine store of biologically-derived carbon (Burrows *et al.*, 2014). Carbon may be sequestrated as precipitated carbonates or as POC, with the latter being a small proportion of the POC present in the water column (either produced there or derived from terrestrial sources) which has sunk to the seabed and has then been incorporated into surface sediments. Sedimented carbon can potentially remain sequestered in the seabed for decades to centuries, depending on physical processes (such as particle movement, bedform migration due to storms and tides, water column temperature) and biological processes (including infaunal activity and mode of feeding). Additionally, POC supply, incorporation and storage may be disturbed by human activities such as bottom trawling (Jenness and Duineveld, 1985; Diesing *et al.,* 2017; Luisetti *et al.*, 2019).

Sediment characteristics are also thought to influence carbon sequestration capacity; Diesing *et al.* (2017) analysed 849 sediment samples taken from the north-west European continental shelf adjacent to the North–East Atlantic Ocean, and calculated POC concentration and dry-bulk density for each sample according to sediment class, based on Folk (1954). The authors' results supported "*the concept that the highest concentrations of POC are associated with muddy sediments*". However, the study determined that these did not always translate into the highest values in terms of mass per unit area, as dry bulk densities of muddy sediments were usually low. Rather counterintuitively, Diesing *et al.* (2017) found that muddy sediments (mud, slightly gravelly mud, slightly gravelly sandy mud, sandy mud, gravelly mud) contributed little to the total POC stock 'due to their spatially restricted areas and low dry bulk densities'. Conversely, sand, slightly gravelly sand and gravelly sand contributed 71 % of the POC stock 'due to high dry bulk densities and widespread occurrence in the study area'. An average of 390.4 t POC km^{-2} for the standing stock of POC in the top 10 cm of shelf sediments was concluded, and a total POC stock value of 476 Mt C calculated for the top 10 cm of sediments on the NW European Continental Shelf (1,111,812 km^2).

Similarly, Burrows *et al.* (2014) calculated a total standing stock of organic carbon in Scotland's marine sediments to be 18.1 Mt C (covering an area of approximately 470,000 km^2), and that of inorganic carbon to be 1,738 Mt C. The authors assumed that Burrows *et al.* (2014) estimated carbonate storage for Scottish marine sediments using British Geological Survey (BGS) data on carbonate content from sediment cores and estimate carbonate storage in surficial sediments based on sediment type. Carbonate content varied from less than 10% in some offshore muddy sediments to up to 30-90% in carbonate rich gravels. The amount of carbon associated with carbonates was then calculated on the assumption of the density of calcite being around 2,800 kg m^{-3}, and 12 % of that being carbon. Further multiplying the total volume of carbonate by density and percentage carbon in calcite provided the estimate of carbon mass as standing stock. It is noteworthy that the authors remarked that Scottish sediment generally held more carbonate than other UK regions, but did not provide values for other areas.

Habitat summary

For the purpose of this study, the following values have been applied for subtidal sediments

- Biomass standing stock: not applicable.
- Soil standing stock:
  - 0.28- 0.92 kg m^{-2} (top 10 cm, per sediment type) for POC. These values were derived from Diesing *et al.*, 2017 (noting that the lead author was contacted to ensure the correct formula was applied, as no direct unit values were supplied in this paper); 3.36 kg m^{-2} (top 10 cm) for carbonate. This value has been calculated based on relationships quoted in Burrows *et al.*, 2014, and a conservative assumption of 10% carbonate across all sediments. Please note that this carbonate value was also applied to intertidal sedimentary habitats, as well as non-rocky biogenic habitats.
- Sequestration: 0.0003 - 0.0009 kg m^{-2} yr^{-1}. This has been calculated as a 0.1 mm proportion of the soil stock value per sediment type. 0.1 mm accretion per annum was assumed for all subtidal sedimentary habitats (as sedimentation over subtidal habitats is typically negligible, but some would occur, particularly in the shallower nearshore areas, and in areas such as the Bristol Channel where suspended sediment loads are relatively high (e.g. Collins, 1983)). This compares with annual sequestration values applied by Burrows *et al.*, 2014 of 0.041 kg m^{-2} yr^{-1} for fine sediments and 0.0002 kg m^{-2} yr^{-1} for coarse sediments. Further, Nelleman *et al.* 2009 estimated shelf sequestration at 0.02 m^{-2} yr^{-1}, whilst Thomas *et al.* 2005 stated that shelf sequestration was negligible.

3.6. Overall summary

Table 5 below summarises the carbon storage and sequestration values adopted for this study, based on the above literature review, for those habitats relevant to Welsh waters. For ease of comparison, all values are reported in kg per square metre. A brief justification is again included in the table, and confidence in the presented / derived rates assessed. For an extensive table providing a more comprehensive breakdown of values, as well as justification and comparison with other values in the literature, please refer to Appendix A (presented as Section 8). Where no value is given, then a given carbon function is not applicable to the habitat in question (e.g. no sequestration on rocky habitats such as kelp).

Table 5 Summary of carbon sequestration and storage values per studied habitat

Intertidal (organic carbon)

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

Shellfish beds (incl. intertidal) (organic and inorganic carbon)

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

Subtidal (organic and inorganic carbon)

Sedimentary area / habitat	Carbon Rate	Parameter (unit)	Source / Justification	Confidence
Seagrass (may have intertidal element)	0.26	Biomass standing stock (kg m^{-2})	Taken from Burrows *et al.*, 2014	M
	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	H
	0.027	Sequestration (kg m^{-2} yr^{-1})	Proportion of stock value (2 mm yr^{-1} accretion)	M-H
Macroalgae - kelp	0.47	Biomass standing stock (kg m^{-2})	Average of six sites (Smale *et al.,* 2016)	H
Macroalgae - maerl	0.10	Biomass standing stock (kg m^{-2})	10 times sequestration (same relationship as applied by Burrows *et al.*, 2014)	L-M
	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)	L-M
	0.010	Sequestration	From Table 3 of Burrows *et al.*, 2014	L-M
Brittlestar Beds	unknown	Biomass standing stock	No values found in literature	-
	0.29	Soil standing stock	Applied same value as subtidal sandy gravel, as brittlestars normally found on coarse sediment.	M
	0.082	Sequestration (kg m^{-2} yr^{-1})	Taken from Burrows *et al.*, 2014	M
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.	L
Subtidal Muds, gravels and sand (POC)	0.28- 0.92	Soil standing stock (kg m^{-2}*)	Derived from Diesing *et al.*, 2017	M-H
	0.0003 - 0.0009	Sequestration (kg m^{-2} yr^{-1})	Proportion of stock value (0.1 mm yr^{-1} accretion)	M
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.	L
	0	Sequestration	n/a (or see shellfish beds)	-

*top 10 cm
$^{\Delta}$top 60 cm

4. Carbon Storage and Sequestration in the Welsh Marine Environment

4.1. Introduction

This section provides the results of this study in five sections. First, the carbon flux into / out of the Welsh marine environment is estimated in Section 4.2. Then, in Section 4.3, the total amount of carbon stored in the Welsh marine environment is estimated. As noted in Section 1, storage may be temporary, for example, in the water column and floral and faunal biomass or potentially longer-term when stored in sediments. In Section 4.4, annual sequestration of carbon (addition to long-term stores) has been estimated. Lastly, the carbon stored and sequestered is valued and contextualised in Section 4.5.

4.2. Carbon flux into / out of WNMP boundary

In order to estimate the total amount of carbon potentially available for sequestration in Welsh marine waters, parts of the box model outlined in Section 2.3.1 (Image 2) have been estimated as follows:

- Air-sea flux values have been:
  - Obtained from PML's ERSEM model for offshore waters;
  - Calculated for transitional and coastal waters based on literature values (with total Welsh area derived from WFD waterbody datalayers);
- River inputs have been calculated based on literature values (with annual average riverine input provided by NRW's hydrology team).

It had initially been intended to calculate a net flux value of carbon across the WNMP boundary from the ERSEM mode (i.e. approximately how much carbon in the form of POC, DOC or DIC leaves Welsh waters and gets transported to adjacent shelf and deeper waters). While the analysis provided plausible estimates for the net flux of POC and DOC, the, estimates for DIC suggested a very large negative flux (of -10.74 to -42.56 Mt C yr^{-1}) across the offshore boundary. The confidence in this value is very low as the indicative values are an order of magnitude greater than any carbon inputs to the WNMP. It is concluded that it not possible to derive an accurate estimate of the net flux of DIC across the WNMP boundary using this model due to the relative coarseness of the model and issues with calculating DIC fluxes across adjoining deep cells. Thus, it has been decided to disregard the DIC offshore boundary flux values for this study. The offshore boundary flux values for POC and DOC estimated from the ERSEM model appear more in keeping with other flux data, although uncertainty remains concerning the absolute values. Such uncertainties around DIC values are a function of the model used, and such modelling being relatively novel; to better estimate boundary fluxes, significant additional modelling and assessment effort would be required, which has been outside of the scope of this study.

Table 6 summarises the outcome of the carbon flux calculation exercise. In total, this exercise estimates a net input of 0.07 to 1.16 Mt of carbon to Welsh marine waters from the air, offshore boundary and the rivers, with the majority being derived from the air. It is likely that the influx constitutes an under-estimate, and that a flux of 1.16 Mt C would be an upper bound chiefly due to a likely offshore DIC flux. This agrees with the general scientific understanding, which indicates that shallow shelf seas (such as Welsh waters) are net-exporters of carbon (e.g. Chen and Borges, 2009).

Table 6 Carbon flux into / out of Welsh marine waters

Parameter	**Area / volume**	**Rate applied**	**Total Value (Mt C yr^{-1})**
Air-sea flux – offshore*	24,253 km²	n/a	0.76*
Air-sea flux– Transitional*	434 km²;	-575.4 t C km-^{2} yr^{-1};	-0.25**
Air-sea flux– Coastal*	4,264 km²; Other inshore: 1,828 km² (counted as coastal)	+10.91 t C km^{-2} yr^{-1}	0.07**
River inputs: POC & DOC	~ 700 m³ s^{-1}, or 22,000,000 Ml (Megalitres) yr^{-1} ***	n/a	0.08#
River inputs: DIC		10 mg l^{-1} ##	0.22
WNMP offshore boundary flux: DOC	n/a	n/a	-0.83 to 0.175###
WNMP offshore boundary flux: POC	n/a	n/a	0.023 to 0.107###
Net flux (sum)	**n/a**	**n/a**	**0.07 to 1.16**

* Offshore value derived from PML's ERSEM model. For inshore, 6 % (or 1,828 km²) of the WNMP area was not covered by either the ERSEM model nor WFD transitional or coastal waterbodies; these areas have been counted as coastal in the above calculations, as most are relatively close to the shore (see 'other' inshore).

** Based on values provided by Chen and Borges (2009) (for transitional) and Borges *et al* (2006) (average of seven non-upwelling marginal seas for coastal); with CO_2 converted to carbon. Negative values denote export of carbon.

*** Annual average; valued provided by NRW hydrologists. Includes the River Severn.

9% of British total quoted in Hope *et al.*, 1997 (as per Welsh percentage quoted by same author).

Derived from Jarvie *et al.*, 2017 (supplementary tables).

Provided by PML. Positive values represent fluxes into the WNMP area; negative values denote export of carbon. Excludes DIC due to very low confidence in value derived, see text above table.

4.3. Carbon storage

Carbon sinks in Welsh marine waters have been mapped and rates obtained from the literature (see Table 5) applied in order to estimate how much carbon is stored in the water column and / or biomass of flora, fauna and sediments every year, either temporarily or longer term in the WNMP area.

Results are summarised in Table 7. With regard to the extents quoted for the habitats, please note that these have been derived from a dedicated datalayer created for carbon calculation purposes, with the caveat that that there are known uncertainties and mapping gaps for some habitats, notably subtidal biogenic habitats such as kelp. Table 7 shows that at least 113 Mt of carbon are already stored in the top 10 cm of the Welsh marine environment, excluding rocky habitats. The table also shows that, in any given year, the Welsh water column holds at least another 48.7 Mt of carbon, mostly in the form of DIC (see Table 8). When compared to this value, the cumulative carbon biomass held in vegetated habitats is relatively modest in comparison, at 69,000 tonnes of carbon (or 0.07 Mt C), with kelp and saltmarshes being the most productive habitats.

Table 7 Carbon stored in Welsh marine sediments and habitats

Habitat	**Mapped area (km²)***	**Carbon stored in sediments (Mt C)**	**Carbon stored in biomass and / or water column (annual storage) (Mt C)**
Saltmarsh	76.1	0.32	0.016
Intertidal flats	434.0	0.41	n/a
Intertidal macroalgae (vegetated rocky shores)	30.9	n/a	0.000
Seagrass beds	7.3	0.02	0.002
Shellfish beds	15.7	0.04	0.000
Subtidal macroalgae	80.4	n/a	0.037
Brittlestar beds	0.07	0.000005	n/a
Faunal turfs	2.12	n/a	0.014
Subtidal muds, sands and gravel – organic carbon	29,514.1	10.94	n/a
All (bar carbonate habitats) – carbonate	30,140.5**	101.27	n/a
Water column (average)	n/a	n/a	48.59
Total		113.00	**48.66**

* Habitat areas mapped and calculated using available evidence sources outlined in Table 1 and therefore may not represent the total extent of these habitats.
** excludes carbonate producing habitats, i.e. shellfish, brittlestar and maerl beds.

Table 8 Water column carbon store as derived from ERSEM model

Variable	**Peak month**	**Lowest month**	**Peak C (Mt C)***	**Lowest C (Mt C)***	**Average C (Mt C)***
DIC	February	August	47.06	45.75	46.41
DOC	September	March	2.44	1.47	1.95
Non-living POC	July	February	0.17	0.02	0.09
Zooplankton Biomass	June	February	0.10	0.01	0.05
Phytoplankton Biomass	April	January	0.17	0.03	0.09
Total	**-**	**-**	**49.95**	**47.28**	**48.59**

* Values derived from 10-year (2011-2021) average of monthly means, based on Representative Concentration Pathway (RCP) 4.5. Please note that the model does not cover Welsh inshore waters, see, for example, Figure 1.

Figure 1 indicates peak average months for the different water column variables across the 10-year modelling period.

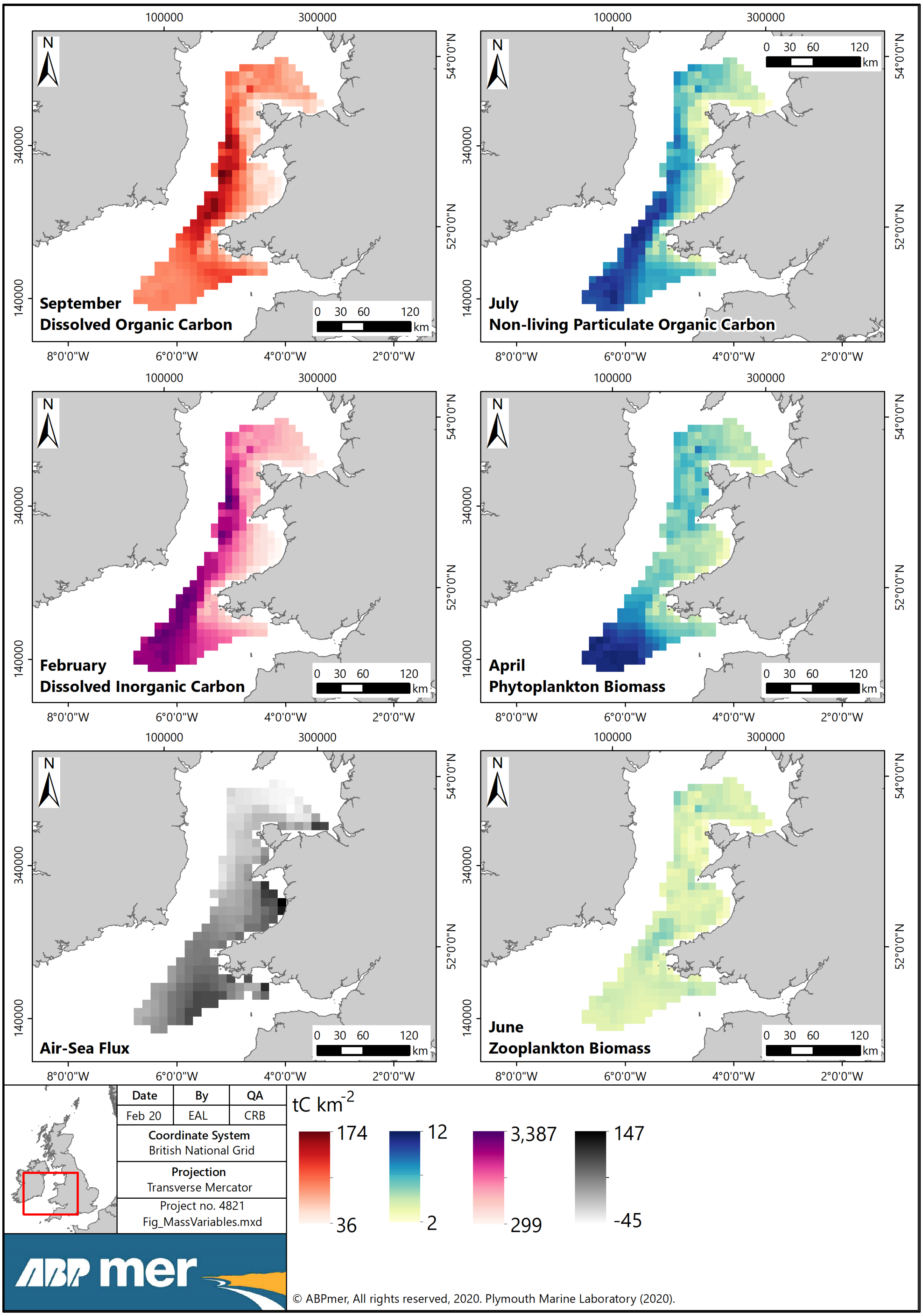


Figure 1 Peak months for mass variables and air-sea flux total

The amount of carbon stored in Welsh marine sediments is likely to be an underestimate. This is firstly due to only the top 10 cm having been considered. Also, relatively conservative values were generally applied, including for carbonate content of Welsh sediments. Analysis of BGS sampling data could for example be undertaken to derive specific carbonate values for Welsh sediments.

With regard to biomass, as noted in Section 3.5.2, kelp is garnering a lot of attention in the media as a carbon 'donor' habitat. It is thought that more than the 80.4 km² of subtidal kelp habitat is likely to exist in Welsh waters; however, due to the mapping of such subtidal habitats largely relying on observational surveying, more exact maps may be difficult to obtain. Thus, modelling as undertaken by Burrows *et al.* (2014) for Scotland may be warranted. This was, however, outside the scope of this study.

4.4. Carbon sequestration potential

With regard to carbon sequestration, as summarised in Section 3, not all habitats will sequester carbon. Notably, any habitats on rock are considered not to fulfil this function. Sequestering habitats have been mapped to facilitate the carbon calculations for this study, using the best available datalayers, whilst noting uncertainties and mapping gaps as outlined in Section 4.3. Figure 2 depicts this datalayer; please note that a processing summary is provided in Appendix B / Section 9, to show how this datalayer has been assembled. Carbon storage and sequestration rates have been obtained from the literature (see Table 5) and applied to the calculated areas in order to estimate how much carbon is sequestered in the Welsh marine environment every year.

Results are summarised in Table 9. It is estimated that at least 26,100 tonnes of carbon (or 0.03 Mt C) are potentially sequestered in the Welsh marine environment every year, with saltmarshes and seagrasses accounting for the bulk of this value on a per unit area basis. When expressed in CO_2 equivalent units, which is the unit most commonly applied in sequestration reporting, this equates to 95,900 t CO_2e (or 0.096 Mt CO_2e).

Table 9 Annual carbon sequestration in Welsh marine habitats

Habitat	**Mapped area (km²)**	**Sequestration (tonnes C yr^{-1})**
Saltmarsh	76.1	6,397
Intertidal flats	434.0	8,227
Intertidal macroalgae (vegetated rocky shores)	30.9	n/a
Seagrass beds	7.3	197
Shellfish beds	15.7	375
Subtidal macroalgae	80.4	n/a
Brittlestar beds	0.07	5
Faunal turfs	2.12	n/a
Subtidal muds, sands and gravel	29,514.1	10,938
Total	**-**	**26,140**

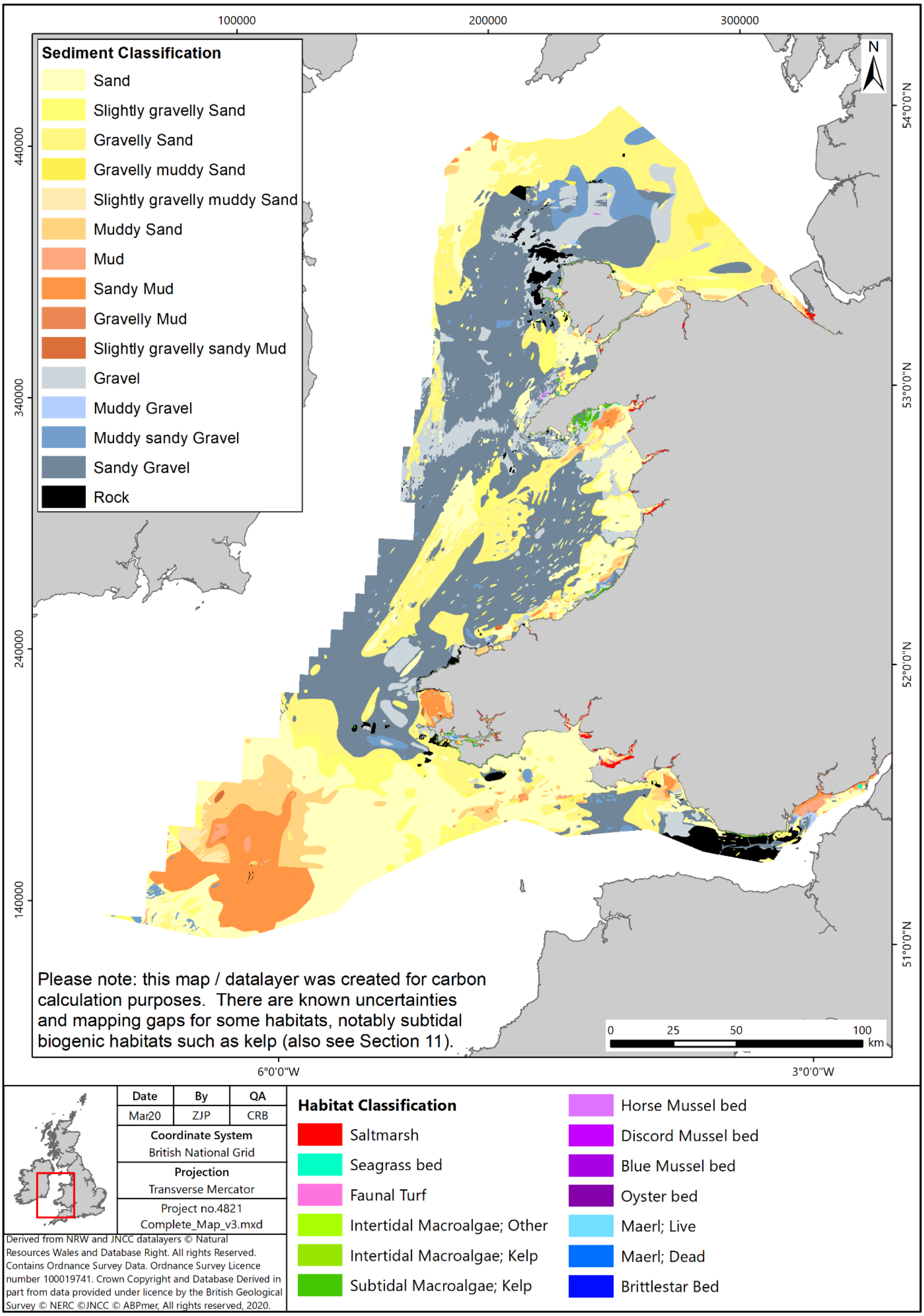


Figure 2 Sedimentary and habitat areas as mapped for the WNMP area for blue carbon calculation purposes.

It is considered likely that the sequestration value discussed above constitutes a slight under-estimate of the Welsh marine environment's potential for sequestration. For example, relatively conservative accretion rates have been applied across intertidal areas (2 mm^{-1} yr^{-1}) and subtidal habitats (0.1 mm yr^{-1}); such rates are known to be higher after storm events (e.g. Kirby, 1986) and also vary across Wales. Also, some sequestering habitats may not have been sufficiently mapped, for example, brittlestar beds are thought to be much more widespread in Wales than the currently available mapping indicates (see Section 3.5.3). It is also noteworthy that uncertainty remains on the extent of rocky habitats, with these areas likely to have been slightly underestimated in this study due to mapping limitations and the occurrence of rock within mosaic habitats (see Appendix B / Section 9, specifically HabMap processing). Thus, carbon values may have been overestimated in those areas. However, it is considered that these uncertainties would not, on balance, have led to an over-estimation of sequestration potential.

4.5. Welsh blue carbon – monetary value and context

This study has estimated that around 0.03 Mt of 'blue' carbon are sequestered annually in the Welsh marine environment (see Table 9 above). This equals 0.096 Mt CO_2e (or 95,900 t CO_2e), and equates to 0.2 % of Welsh carbon emissions (in 2017)[6].

At least 113 Mt C are already stored in Welsh marine habitats; this equates to almost 10 years' worth of Welsh carbon emissions. It furthermore represents over 170 % of the carbon held in Welsh forests[7].

Just under 49 Mt C are held in the Welsh marine environment in any given year, with the vast majority of this being in the water column (POC, DOC, DIC, plankton), and a comparatively small amount of less than 0.07 Mt C (or 69,000 tonnes C) contained in the plants of biogenic habitats such as kelp, saltmarshes and seagrasses. This overall blue carbon store is around 75 % of that held within Welsh forests (which has been estimated as 64.7 Mt C, see Footnote 6 for explanation).

Carbon sequestration is classed as a 'climate regulation' ecosystem service provided by marine areas and habitats. Ecosystem services are defined as services provided by the natural environment that benefit people. The blue carbon sequestered by Welsh marine habitats has been converted to monetary values using the 2020 non-traded (central) price for CO_2e (£69 per tonne) (DBEIS, 2011). On this basis, the sequestration benefits of marine habitats in 2020 are worth approximately £6.6 million yr^{-1} across the WNMP area. Based on projected increases in the non-traded price of carbon, this value would more than treble by 2050 (2050 non-traded carbon price of £221). This monetary value is an estimate of the benefit relating to current carbon sequestration. In the future, there will be variations in annual sequestration

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[6] 2017 emissions were 41.75 Mt CO_2e (Jones *et al.*, 2019), which equals approximately 11.38 Mt C (applying assumption that 3.67 t of CO_2 contain 1 t of carbon).

[7] As calculated by extrapolating the stock value quoted in NRW, 2018 (for the NRW estate only), using total woodland values reported in National Assembly for Wales, 2017 (306,000 ha in total). A Welsh woodland stock value of 64.7 Mt C was thus estimated.

due to a wide range of factors, including climate change, sea level rise, erosion / drowning of sequestering habitats, etc.

The estimated carbon sequestration in the Welsh marine environment every year is equivalent to the average annual fuel consumption of 64,800 cars[8], or 115,600 return flights from Cardiff to the Canary Islands[9]. When comparing 'blue carbon' habitats with 'green carbon' (terrestrial) habitats, Welsh marine habitats sequester around 7 % as much as Welsh woodlands, and their carbon sequestration strength equates to that of 210 km^2 of woodland[10].

Table 10 below ranks Welsh marine habitats in order of their carbon sequestration potential (using the rates applied by this study), and compares them with Welsh woodlands. As can be seen, 1 ha of woodland sequesters more than any one of the marine habitats, with saltmarshes sequestering the most out of all Welsh marine habitats, at 66 % of woodlands' rates. As noted in Section 3 however, marine habitat sequestration rates are very much dependent on rates of accretion, and could thus be significantly higher in areas where sedimentation rates are typically higher than the rates which have been assumed for this study. It is considered that saltmarshes in estuaries with high suspended sediment loads in the water column, such as the Severn Estuary, would sequester more than woodlands, likely more than 1.5 times as much[11]. Further research is recommended on this aspect, see Section 5.2.1.

Table 10 Marine habitat carbon sequestration per unit area, compared with woodlands

Parameter	**Rate applied (kg m^{-2} yr^{-1})**	**Rate applied (t ha^{-1} yr^{-1})**	**% when compared with sequestration of 1 ha of Welsh woodland***
Saltmarsh	0.084	0.84	66
Horse mussel (*Modiolus*)	0.04	0.4	32
Seagrass	0.027	0.27	21
Intertidal muds, gravels and sand (POC) – lower bound	0.011	0.11	9
Intertidal muds, gravels and sand (POC) – upper bound	0.037	0.37	29
Other mussels (*Mytilus, discord*, etc.)	0.004	0.04	3
Oysters (*Ostrea*)	0.001	0.01	0.8
Subtidal muds, gravels and sand (POC) – lower bound	0.0003	0.003	0.2
Subtidal muds, gravels and sand (POC) – upper bound	0.0009	0.009	0.7

* which is assumed to be 1.3 t ha^{-1} yr^{-1}, see Footnote 8 for explanation.

[8] Based on 2018 average car emissions of 121.0 g of CO_2 km^{-1} (as reported by The Guardian, 2019), and a 2018 UK average mileage of 7,600 miles (or 12,231 km) (as reported by NimbleFins, 2019).
[9] Noting that other carbon calculators return different values, e.g. MyClimate (2020) suggests 0.97 t CO2 for the same round trip.
[10] Calculated based on woodland sequestration value of 1.42 Mt of CO_2e quoted by National Assembly for Wales, 2017 and area extent noted in Footnote 6.
[11] Using 4 mm accretion rate quoted for the Severn by Pye and French, 1993.

5. Discussion, Conclusions and Recommendations

5.1. Discussion

This study has sought to compile information on carbon storage and sequestration within the Welsh marine environment. Limitations in the data mean that is not possible to present a complete carbon budget for Welsh waters. A key information gap relates to the lack of available evidence on carbon flux across the WNMP offshore boundary, particularly for DIC. There are also significant uncertainties relating to air-sea flux estimates, particularly in inshore coastal and estuarine waters, which are not covered by PML's ERSEM model. There are furthermore substantial uncertainties concerning riverine inputs, due to limited information on river discharge volumes and on the concentrations of DIC, DOC and POC in Welsh rivers. Some of the biogenic habitats are furthermore considered to be under-represented in the maps, notably subtidal habitats such as kelp.

Evidence on carbon stores indicates that the great majority (>95%) of the estimated average of 48.7 Mt of carbon stored in the water column in Welsh waters is dissolved CO_2, with most of the remainder present as dissolved organic carbon. This study's figures suggest that less than 0.3% of marine carbon is stored in living biomass in Welsh waters (either within the water column or on / within the seabed).

It is estimated that around 113 Mt of carbon has already been sequestered in sediments within the Welsh marine environment; this equates to almost 10 years' worth of Welsh carbon emissions and furthermore represents over 170 % of the carbon held in Welsh forests. The 113 Mt C value is likely to be an underestimate, as the figure only includes the top 10 cm of sediments. 10% of this total is associated with organic carbon contained in muds, sands and gravels, the predominant habitat types in Welsh waters, and 89 % with carbonate (inorganic carbon) stored in sediments or below existing vegetated habitats. While biogenic habitats such as saltmarshes, seagrass beds, brittlestar beds and shellfish beds have high sequestration potential, their very small spatial extent in Welsh waters means that they contribute relatively little to the amounts of carbon already stored longer term in the Welsh marine environment (just under 0.4 Mt C out of 113 Mt C), compared with sedimentary habitats. The 113 Mt C value compares with Scottish estimates of 174 Mt of inorganic and 28 Mt of organic carbon estimated as being stored in Scottish sediments (Burrows *et al.*, 2014). Separately, Diesing *et al.* (2017) calculated that at least 476 Mt of organic carbon is stored in the top 10 cm of sediments of the north-western European Continental Shelf.

This study has calculated an initial estimate of annual carbon sequestration in Welsh waters as 26,100 tonnes of carbon (or 0.03 Mt), with subtidal sediments accounting for the largest percentage of this, followed by intertidal flats, saltmarshes and seagrass beds. This sequestration figure is uncertain. The estimated net flux of carbon into the WNMP area (which could provide an upper bound for carbon sequestration) is 0.07 to 1.16 Mt C, although this does not include potential negative flux of DIC from WNMP area. 43 %of the estimated 0.02 Mt is estimated to be sequestered within intertidal sediments and saltmarshes. The remainder is largely sequestered in subtidal muds, sands and gravels. This 0.03 Mt C yr^{-1} value compares with Scottish estimates derived by Burrows *et al.* (2014) of 7.2 Mt of organic and 0.44 Mt of inorganic carbon being sequestered in Scottish waters every year. These large values for Scottish waters are a function of the size of the area, which is almost 15 times that of the WNMP area, and the high rates applied to, and large spatial area of, fine shelf sediments (which has a reported sequestration potential of 7 Mt C yr^{-1}).

5.2. Recommendations

Recommendations are presented in two sections, firstly recommendations relating to improving the evidence, and secondly recommendations for policy and management

5.2.1. Evidence

This study set out to fill an important evidence gap related to blue carbon and has in itself revealed some additional gaps which could usefully be investigated further.

First, there is uncertainty concerning carbon fluxes into and out of Welsh waters. Collecting robust data on carbon fluxes into / out of the Welsh marine environment is, however, likely to prove challenging, particularly across the offshore boundary. To obtain better estimates of offshore boundary fluxes, particularly for DIC, significant additional effort would be required and confidence in any estimates would likely remain low. To better estimate fluxes in near shore coastal waters and estuaries, downscaled models would be required which simulate relevant processes at smaller spatial scales. Modelling of all Welsh estuaries is not realistic, but it may be possible to gather information for a small number of Welsh estuaries to better inform overall flux estimates for Wales. Better information on riverine inputs would also be helpful, particularly in terms of average concentrations of DIC, DOC and POC at the downstream limits of main rivers.

Better information is also required on carbon sequestration rates for some of the habitats studied here, although relevant rates have been obtained for key habitats such as saltmarshes, seagrass beds and subtidal sediments. However, for habitats such as shellfish and brittlestar beds, no Welsh (or southern UK) values could be determined, and proxy values from elsewhere have thus been employed which may over or underestimate rates due to differences in environmental conditions. Also, there is considerable uncertainty related to the amounts of carbonate stored in Welsh sediments, with a lower bound estimate applied for this study. Dedicated (and likely higher) Welsh values might be obtained from the interrogation of BGS sediment records and mapping values against sediment type extent.

There is further uncertainty concerning the rates of sequestration both in intertidal and subtidal sediments – this is mostly a function of long-term sedimentation rates, for which monitoring data is scarce. Estimates of annual carbon sequestration could thus be improved through a better understanding of sedimentation rates in the marine environment, particularly the subtidal zone. This could potentially be achieved through the analysis of core samples using radiocarbon dating.

Lastly, this work has focused on carbon, particularly CO_2, due to the limited work done on other greenhouse gases such as methane and nitrous oxide. In order to fully understand the role of marine ecosystems in climate regulation, it would however be necessary to understand fluxes of methane and nitrous oxide as well as

CO_2, particularly as these gases have a greater global warming potential than CO_2 (e.g. the global warming potential of methane is 28 to 36 times greater than CO_2).

5.2.2. Policy and management

The evidence provided in this report indicates that potentially a wide range of marine habitats contribute to carbon sequestration. Subtidal muds, sands and gravel were found to sequester the greatest amount of carbon, followed by intertidal flats and saltmarshes.

Protecting these areas from damaging activities is therefore likely to be important. There is limited evidence on how human activities may disrupt carbon sequestration by marine habitats, in particular how sequestration rates may vary with habitat condition. Further work to understand how the ecosystem service varies with habitat condition would be helpful in refining carbon sequestration estimates. Studies such as Luisetti *et al.* (2019), however, have proposed that the cessation of bottom trawling would promote improved carbon storage in subtidal sedimentary habitats. Further evidence of the impacts of activities on subtidal sedimentary habitat carbon storage, and building subsequent knowledge into management of the marine environment, may thus have increased benefits over and above those associated with biodiversity improvements.

Restoring intertidal and shallow subtidal habitats would yield the greatest per unit area benefit in terms of increased carbon sequestration; there are various techniques which have been used to achieve this, with managed realignment being the most commonly applied (and proven) method for creating intertidal habitats. This has, for example been undertaken an Morfa Friog in Gwynedd (NRW, 2015). For some shallow subtidal biogenic habitats such as seagrasses and oyster beds, creation should be feasible based on foreign examples, but UK restoration success has often not been proven to a sufficient extent, or at all. For example, seagrass restoration has been conducted for over 50 years globally, but successful UK examples have been scarce (e.g. MMO, 2018). A noteworthy pilot project has recently been initiated near Dale in West Wales, led by Swansea University (Project Seagrass, 2020). Further such pilot projects should be promoted / encouraged in order to increase the evidence base around blue carbon habitat restoration techniques and ultimately facilitate the increased application of such methods.

Given the amount of evidence available on the importance of marine habitats in relation to carbon storage and sequestration, which has been supported by this study, it is perhaps surprising that marine habitat creation projects are not currently able to access most carbon offsetting funds. This is related to difficulties with accurately calculating all the bio-geochemical processes, but also with issues around the source of the carbon. Thus, government funding to fill this gap could facilitate the meeting of Verified Carbon Standards by key habitats such as saltmarshes and seagrasses and could in turn greatly bolster restoration efforts.

6. References

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7. Acronyms

BGS	British Geological Survey
C	Carbon
$CaCO_3$	Calcium Carbonate
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DBEIS	Department for Business, Energy and Industrial Strategy
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
ERSEM	European Regional Seas Ecosystem Model
EUNIS	European Nature Information System
GHGs	Greenhouse Gases
ha	Hectare
HabMap	Habitat Mapping for Conservation and Management of the Southern Irish Sea
HPIs	Habitats of Principle Importance
IC	Inorganic Carbon
IPCC	Intergovernmental Panel on Climate Change
JNCC	Joint Nature Conservation Committee
kg	Kilogram
m	Metre
MarLIN	Marine Life Information Network
MCCIP	Marine Climate Change Impacts Partnership
MCZ	Marine Conservation Zone
MEDIN	Marine Environmental Data and Information Network
Ml	Megalitres
MPA	Marine Protected Area
Mt CO2e	Million tonnes of Carbon Dioxide equivalent
NBN Atlas	NBN Atlas Partnership
NEMO	Nucleus for a European Model of the Ocean
NMP	Net Microplankton Production
NOx	Nitrogen Oxides
NRW	Natural Resources Wales
O_2	Oxygen
OC	Organic Carbon
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
Pg C	billion tonnes of carbon
PIC	Particulate Inorganic Carbon
PML	Plymouth Marine Laboratory
POC	Particulate Organic Carbon

POLCOMS	Proudman Oceanographic Laboratory Coastal Ocean Modelling System
Ramsar	Wetlands of international importance, designated under The Convention on Wetlands (Ramsar, Iran, 1971)
RCP	Representative Concentration Pathway
SAC	Special Area of Conservation
SMP	Shoreline Management Plan
SNH	Scottish Natural Heritage
SPA	Special Protection Area
SPOM	Suspended Particulate Organic Matter
SSSI	Site of Special Scientific Interest
t	Tonnes
tC	Tonnes of Carbon
UK	United Kingdom
US	United States (America)
WFD	Welsh Water Framework Directive
WNMP	Welsh National Marine Plan

8. Appendix A – Full Carbon Rates Table

The table below constitutes are more comprehensive version of that presented in Section 3.6.

Table 11 Applied carbon sequestration and storage values per studied habitat

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

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
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
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

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
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).
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

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
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))	1.36906	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})	0.01101	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})	0.21000	Taken from Burrows *et al.* 2014 (compares Beaumont *et al.* 2014 values of 0.28 kg m^{-2} (± 0.23 kg m^{-2}))

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
Saltmarsh	Soil standing stock (kg m^{-2} (top 10 cm assumed))	4.20000	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})	0.08400	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}).
Seagrass	Biomass standing stock (kg m^{-2})	0.26100	Taken from Burrows *et al.* 2014;
Seagrass	Soil standing stock (kg m^{-2} (top 25 cm))	3.37200	Average value based on 13 SW England meadows quoted in Green *et al.* 2018;
Seagrass	Sequestration (kg m^{-2} yr^{-1})	0.02698	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})	0.04650	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})	0.01400	Calculated from various sources; see Section 3.5.4.
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))	0.13000	Applied same relationships to soil stock for these as Burrows *et al.* 2014 did for horse mussel.

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
Oysters (Ostrea)	Sequestration (kg m^{-2} yr^{-1})	0.00130	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))	4.00000	Burrows *et al.* 2014 values (10 cm depth inferred)
Horse mussel (*Modiolus*)	Sequestration (kg m^{-2} yr^{-1})	0.04000	Burrows *et al.* 2014 values (10 cm depth inferred)
Blue mussel (*Mytilus*)	Soil standing stock (kg m^{-2} (top 10 cm assumed))	0.40000	Using 10% of horse mussel values, as lower biomass assumed
Blue mussel (*Mytilus*)	Sequestration (kg m^{-2} yr^{-1})	0.00400	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))	0.40000	Using 10% of horse mussel values, as lower biomass assumed
Other (incl. discord mussel (*Musculus* etc.),	Sequestration (kg m^{-2} yr^{-1})	0.00400	Using 10% of horse mussel values, as lower biomass assumed
Kelp	Biomass standing stock (kg m^{-2})	0.46500	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)

Sedimentary area / habitat	Parameter (unit)	Value	Source / Justification
Maerl - dead	Soil standing stock (kg m^{-2} (top 60 cm)	12.41127	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})	0.09500	10 times sequestration (same relationship as applied by Burrows et al., 2014)
Maerl - live	Soil standing stock (kg m^{-2} (top 60 cm)	12.41127	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);
Maerl - live	Sequestration (kg m^{-2} yr-1)	0.00950	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 m2 value
Brittlestar Beds	Biomass standing stock	unknown / negligible	No values found in literature
Brittlestar Beds	Soil standing stock	0.01156	Applied same value as subtidal sandy gravel, as brittlestars normally found on coarse sediment.
Brittlestar Beds	Sequestration (kg m^{-2} yr^{-1})	0.08200	Burrows *et al.* 2014 value

9. Appendix B – Datalayer Processing Summary

Introduction

This Appendix provides of a brief summary of the processing undertaken in order to create a combined / merged habitat and sediment map for Welsh waters so as to facilitate the calculation of carbon storage and sequestration totals for the WNMP area. It should be noted that a detailed (separate) processing log has been produced and provided to NRW, together with the final datalayer and a metadata sheet.

A map of this datalayer has been presented in Figure 2 (Section 4.4) above. The 11 datalayers used to create this merged map have furthermore been listed in Table 1 in Section 2.3.2, together with high level processing comments.

The two key habitat layers were the following:

- The ‘combined’ EUNIS habitat map administered by JNCC; and
- The ’HabMap’ sediment datalayer, held and supplied by NRW.

In addition to these two key layers, several habitat-specific datalayers have been utilised, notably for saltmarshes, intertidal flats, seagrass beds and shellfish beds.

The following high-level processing steps are now discussed in the sub-sections below:

- Habitat-specific datalayer processing;
- HabMap processing;
- JNCC combined map processing; and
- Datalayer merge and clipping.

Species habitat-datalayers processing

Most of these habitat-specific datalayers were downloaded from the Lle Geoportal, and not processed prior to being merged with the other layers. Notable exceptions were:

- The intertidal flats datalayer, whereby each polygon was categorised according to the Folk system (see HabMap processing Section 9.3 for more detail);
- Macroalgal polygons only were extracted from the ‘NRW Intertidal Phase 1 Habitat Survey’ datalayer (as all other intertidal blue carbon habitats had other, more up to date, datalayers associated with them);
- The oyster bed point files, whereby points were buffered (by 25 m) and merged with the polygon file.

HabMap processing

The HabMap sediment map was used to obtain information about the sedimentary habitats in subtidal areas within the Welsh WNMP area. In the HabMap, sedimentary areas are classified using four schemes (Robinson *et al.*, 2009);

1) Folk (1954);

2) A new classification scheme focussing on cobbles, pebbles and granules;

3) A new classification scheme focussing on mixed sediments; and

4) Classifying areas of 'Mosaics with Rock'.

This 2020 carbon sequestration study required the sedimentary habitats to be classified as in Folk (1954) only, to be in-keeping with Diesing *et al.* (2017) and hence required areas classified using the last three schemes to be re-classified.

This was done as follows:

- All HabMap areas designated using Scheme 2 were reclassified as 'Gravel' in the new combined map. This is because Diesing *et al.* (2017) classified areas of 'Rock' as areas of Bedrock only, not cobbles/granules/pebbles, and 'gravel' is the closest designation to these habitats that Folk (1954) offers.

- All areas designated using Scheme 3 were reclassified using the latter letters. In this way, areas of 'Mimsg' were reclassified as areas of 'Muddy sandy Gravel', in-keeping with Folk (1954) designations. 'Mi' – 'Mixture (unknown)' areas were reclassified as 'Gravel'.

- HabMap areas designated using Scheme 4; 'Mosaics with Rock' (MoR_) were also reclassified using the latter letters of the classification (where provided); e.g. MoRS - mosaic of rock and sand would have been reclassified as sand for the purposes of the calculation process.

- The Article 17 Subtidal reefs GIS layer, and the JNNC combined map, were brought into the GIS environment to compare classifications for added reassurance. This step may have led to an underestimation of rock habitats.

JNCC combined map processing

The JNCC combined map was utilised for the following purposes:

- To fill gaps left by HabMap in order to completely fill the offshore WNMP area (HabMap does not include the Northern-most and Southern-most corner areas of the WNMP areas). These areas were re-classified in a similar fashion to that outlined above for HabMap.

- To extract subtidal macroalgae and brittlestar bed polygons, where these were identified in the higher EUNIS class information in the 'habitat type' column.

Datalayer merge and clipping

The last processing steps involved the merging of the various original and derived datalayers, and clipping the final datalayer to the outer WNMP boundary. Inner / near shore extents were determined by the upper boundaries of the individual layers, notably for saltmarshes and intertidal flats, which, it was found, can extend beyond the terrestrial WNMP boundary line. The merging process included an overlap removal process.

Data Archive Appendix

Data outputs associated with this project are archived on server–based storage at Natural Resources Wales.

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats.

[B] A series of GIS layers on which the maps in the report are based and data processing log providing details of the data

[C] Microsoft Excel spreadsheets of the processing log and carbon values used in the report.

[D] Infographics in English and Welsh in Microsoft PowerPoint.

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue https://libcat.naturalresources.wales (English Version) and https://catllyfr.cyfoethnaturiol.cymru (Welsh Version) by searching 'Dataset Titles'. The metadata is held as record no 124741.

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