Supplementary Material

Part A - Synthesis of carbon stock and flow estimates

This text details how the budget was synthesised, giving the references and reasoning behind the final figures for each stock and flow, given to 2 significant figures.

Coastal

Habitat areas

The area of salt marshes in the UK is between 45,000 ha (Boorman, 2003; Beaumont et al 2014; Luisetti et al., 2019) and 81,800 ha (Mcowen et al. 2017). The area in the German, Danish and Dutch Wadden Sea is approximately 35,500 ha (Dijkema, 1991). The Belgian, Irish, French and Spanish coasts also contain salt marshes but their areas are not well quantified. Assuming that British and Wadden Sea salt marshes comprise 67% of salt marshes on the shelf (Davidson et al., 1991) then the lower and upper estimate of salt marsh area on the NWES from the above is taken as 120,000 to 175100 ha.
Salt marsh area = 120,000 to 175,000 ha or 1.2x10^{9} to 1.75x10^{9} m^{2}

The area of intertidal mud and sand flats in the UK is approximately 270,000 ha (Maddock et al., 2008) and the area in the Wadden Sea is approximately 795,000 ha (Dijkema, 1991), which totals roughly 1,000,000 ha. If UK mud and sand flats are assumed to represent 15% of the area of these habitats on the shelf (Maddock et al., 2008) then an upper estimate of mud/sand flat area on the NWES is 1,800,000 ha. It is assumed that there are roughly equal areas of mud flats and sand flats.
Mud/sand flat area = 1,000,000 to 1,800,000 ha or 1x10^{10} to 1.8x10^{10} m^{2}

The area of seagrass beds in the UK is approximately 7,000 ha (WP1 of UKNEA - Maddock et al 2008) and the area in the Wadden Sea is roughly 7,300 ha (Essink et al., 2005). Assuming, as for salt marsh, that the UK and Wadden Sea represent 67% of this habitat across the NWES, this gives an upper estimate of roughly 21,000 ha.
Seagrass bed area = 14,000 to 21,000 ha or 0.14x10^{9} to 0.21x10^{9} m^{2}

The area of kelp forests in the UK, using the method of Burrows et al., (2014), is 480,000 to 770,000 ha. In the absence of wider, European area estimates we estimate that the UK represents roughly 50% of Kelp on the NWES, giving a shelf-wide total of 960,000 to 1,540,000 ha.
Kelp forest area = 960,000 to 1,540,000 ha or 9.6x10^{9} to 15.4x10^{9} m^{2}

Carbon stocks

We assume that inorganic carbon stocks are negligible compared to organic carbon stocks in coastal habitats.

Salt marshes (top 10cm)
The salt marsh carbon stock estimate was based on data from the CBESS (Coastal Biodiversity and Ecosystem Services Sustainability) project (Wood et al. 2015), including data from Skov et al. (2016) and Thornton et al. (2002). Some CBESS stock estimates are likely to be biased high due to the loss of clay-associated water during analysis (Barillé-Boyer et al. 2003) and have therefore been halved. The range of salt marsh carbon stocks used here is 188 to 358 mol m^{-2}.
Salt marsh stock = 188 to 358 mol m^{-2}
0.23 to 0.63 Tmol in total on the NWES

Mud/sand flats (top 10cm)
The CBESS sand flat stock estimate is 42.35 mol m^{-2} and the highest mud flat estimate is 274.5 mol m^{-2} which should be halved to 137.25 mol m^{-2} due to the loss of clay-associated water during analysis (Barillé-Boyer et al. 2003). This range is consistent with the stocks estimate for the Colne estuary of 112.5 mol m^{-2} for mud flats and 60 mol m^{-2} for mixed sediment, based on percentage organic carbon values of Thornton et al., (2002) and a bulk density of 0.6 g cm^{-3} (Adams et al., 2012).
Mud/sand flat stock = 42 to 137 mol m^{-2}
0.42 to 2.5 Tmol in total on the NWES

Seagrass beds (top 10cm)
Fourqurean et al. (2012) give a sediment carbon stock in seagrass beds of 48.7 ± 14.5 mol m^{-2}. This is for the top 1 m of sediment but we assume that there is negligible carbon stock below 10cm. The same authors also provide a carbon stock for the vegetation in N. Atlantic seagrass beds of 0.85 +- 0.19 mol/m^2.
Seagrass stock = 35 to 64 mol/m^2
0.0049 to 0.013 Tmol in total on the NWES

Kelp forests
Burrows et al. (2014) estimate a kelp carbon stock of 4-16 mol/m^2, based on UK kelp forests.
Kelp stock = 4 to 16 mol/m^2
0.038 to 0.25 Tmol in total on the NWES

Carbon flows

Salt marshes

Burial - Beaumont et al. (2014) provide a range for carbon sequestration in UK salt marshes of 5.3 - 18.3 mol m^{-2} yr^{-1}. This range also encompasses the estimates of Burrows et al (2014) of 17.5 mol m^{-2} yr^{-1} and Luisetti et al. (2018) of 8.7mol m^{-2} yr^{-1} and is consistent with the range of 5.2 - 11.7 mol m^{-2} yr^{-1} (Julian Andrews, unpublished data) which includes both organic and inorganic carbon. While estimates from individual marshes can exceed this range (Ouyang and Lee, 2014), we assume that it is representative of the NWES region as a whole.
Salt marsh burial = 5.2 to 18.3 mol m^{-2} yr^{-1}
0.0062 to 0.032 Tmol yr^{-1} in total on the NWES

Air-coastal flux - There are very few estimates of CO_2 flux between salt marshes and the atmosphere. Estimates for the net annual CO_2 uptake by salt marshes on the east coast of the US range from range of 17.8 (Artigas et al, 2015) to 25.2 mol m^{-2} yr^{-1} (Houghton and Woodwell, 1980). These estimates are unlikely to accurately represent European salt marshes due to differences in community and sediment accretion.
Salt marsh air-coastal flux = 17.8 to 25.2 mol m^{-2} yr^{-1}
0.021 to 0.044 Tmol yr^{-1} in total on the NWES

Coastal to pelagic flux was calculated as the residual of the air-coastal flux and burial in the marshes. This gives a range of -0.5 to 20 mol m^{-2} yr^{-1}. This residual estimate is consistent with measurements of DIC release made in eastern US salt marshes of 156 g m^{-2} yr^{-1} (13 mol m^{-2} yr^{-1}) (Wang and Cai, 2004), but lower than the recent measurement by Wang et al., (2016) of 414 g m^{-2} yr^{-1} (34.5 mol m^{-2} yr^{-1}). However, as mentioned above, the communities and accretion rates in US marshes are quite different to European marshes.

Salt marsh coastal to pelagic flux = -0.5 to 20 mol m^{-2} yr^{-1}
-0.00088 to 0.035 Tmol yr^{-1} in total on the NWES

<u>Mud/sand flats</u>

Burial - A collation of data (Julian Andrews, unpublished) gives a range of carbon burial in mud and sand flats of 1 - 1.75 mol m^{-2} yr^{-1}.
Mud/sand flat burial = 1 to 1.75 mol m^{-2} yr^{-1}
0.010 to 0.032 Tmol yr^{-1} in total on the NWES

Air-coastal flux - Net primary production estimates, derived from chl a data, for mud and sand flats in the UK, range from 1 to 29 mol m^{-2} yr^{-1} (Nedwell et al., 2016; Underwood et al., 2016; Wood et al., 2015).
Mud/sand flats air-coastal = 1 to 29 mol m^{-2} yr^{-1}
0.010 to 0.52 Tmol yr^{-1} in total on the NWES

The difference between the air-coastal CO_2 flux and carbon burial gives a coastal to pelagic flux for mud and sand flats of -0.75 to 28 mol m^{-2} yr^{-1}
Mud/sand flats coastal to pelagic flux = -0.75 to 28 mol m^{-2} yr^{-1}
-0.14 to 0.50 Tmol yr^{-1} in total on the NWES

<u>Seagrass beds</u>

Burial - Estimates of carbon burial in temperate seagrass beds range from 0.7 to 7 mol m^{-2} yr^{-1}. This doesn't include inorganic C which is assumed to be negligible in temperate seagrasses. Taking seagrass organic carbon production of 21.75 mol m^{-2} yr^{-1} (Burrows et al., 2017) and assuming that 15.9% of this POC is buried (Duarte et al., 2017), gives a burial estimates of 3.5 mol m^{-2} yr^{-1} which is consistent with this range.

Duarte et al. (2017) estimate that 24.3% of seagrass production is exported from the seagrass bed. However, the vast majority of this will be remineralised in the water column and only a small percentage will be buried in the sediment. We therefore assume that carbon exported from seagrass beds and stored long-term in the benthos is negligible on the scale of this budget.
Seagrass pelagic to coastal = 0.7 to 7 mol m^{-2} yr^{-1}
0.000098 to 0.0015 Tmol yr^{-1} in total on the NWES

Seagrass burial = 0.7 to 7 mol m^{-2} yr^{-1}
0.000098 to 0.0015 Tmol yr^{-1} in total on the NWES

<u>Kelp forests</u>

Krause-Jensen and Duarte (2016) estimate that 0 to 3% of global macroalgal net primary production is buried in sediments and Krause-Jensen et al., (2018) estimate that export from kelp beds to adjacent communities is roughly double that for macroalgae communities in general, so we assume that 0 to 6% of kelp production is buried. Given UK kelp production estimates ranging from 10 to 102 mol m^{-2} yr^{-1} and assuming that this production is representative of kelp production across the shelf, this gives a kelp to benthic flux of between 0 and 6.1 mol m^{-2} yr^{-1}. This also taken as the net amount of carbon which is taken up by kelp from the water column.
Kelp coastal to benthic = 0 to 6.1 mol m^{-2} yr^{-1}
0 to 0.094 Tmol yr^{-1} in total on the NWES

Kelp pelagic to coastal = 0 to 6.1 mol m^{-2} yr^{-1}
0 to 0.094 Tmol yr^{-1} in total on the NWES

Rivers

Inorganic
Wakelin et al., (2012) calculate a riverine inorganic carbon input of 2.6×10^{12} mol yr^{-1}. This is based on river discharge data from the Global River Discharge Data Base and the Centre for Ecology and Hydrology, and a fixed annual cycle of DIC with a mean of 2.12 mol m^{-3} for the Baltic outflow and 2.68 mol m^{-3} elsewhere. A recent study of UK rivers found a mean DIC concentration of 2.33 mol m^{-3} (Jarvie et al., 2017), which appears in good agreement with the values used by Wakelin et al., (2012). However UK rivers are likely to have higher DIC due to underlying calcareous geology and intensive weathering of agricultural tills over a large part of England (Jarvie et al.,2017), which suggests that 2.6 Tmol yr^{-1} might be an overestimate riverine DIC input to the whole shelf, and thus serves as a likely upper bound.

River discharge data used in NEMO-ERSEM model runs originates from the OSPAR ICG-EMO dataset. UK data was processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Northern Ireland) and the National River Flow Archive. French flow data was provided by Banque Hydro. German and Dutch riverine data was provided by the University of Hamburg. Irish flow data was provided by Hydrodata and the Environment Protection Agency (Hydronet). Norwegian flow data was supplied by NVE. The OSPAR ICG-EMO dataset was first presented by Lenhart et al. (2010). Total annual discharge to the NWES, including the Baltic outflow is 1.1e12 m^3 yr^{-1}.

Riverine DIC concentration was calculated as 1.08*TA, giving a mean riverine DIC concentration in the model of 1.96 mol m^{-3}. For rivers draining into the North Sea, TA was estimated using an endmember approach based on the relationship between salinity and TA in the CANOBA (CArbon and nutrient cycling in the North Sea and the Baltic Sea) dataset (Artioli et al., 2012). For rivers discharging elsewhere on the shelf, TA is taken as 2000 µmol kg^{-1} which is the mean riverine TA concentration (Artioli et al., 2012). Total riverine DIC input to the NWES is 2.156 Tmol yr^{-1}.
Riverine inorganic carbon input = 2.2 to 2.6 Tmol yr^{-1}

Organic

Abril et al. (2002) present DOC and POC concentrations for a series of major European rivers draining into the North Sea, Bay of Biscay and Portuguese Atlantic coast, from their own study and a synthesis of literature values. Taking the North Sea rivers only they present a concentration range of 0.042 to 1.5 mol m^{-3} POC and 0.24 to 0.68 mol/m^3 DOC, in good agreement with a recent synthesis of North Sea riverine end-member DOC concentrations of 0.31 to 6.6 mol m^{-3} (Chaichana et al. 2019), and the mean DOC concentration for UK rivers of 0.43 mol m^{-3} presented by Jarvie et al. (2017). Wakelin et al (2012) assume a riverine organic carbon input of 0.1 $\times 10^{12}$ mol yr^{-1} based on an average DOC+POC concentration of 0.097 mol m^{-3}, which is considerably smaller than the range of values of DOC and POC combined from Abril et al. (2002). Thomas et al. (2005) use a higher DOC+POC concentration of 0.293 mol m^{-3}, which is consistent with the low end of Abril et al. (2002) estimate. Rivers draining peatland soils can have DOC concentrations of over 1 mol m^{-3} (e.g. Liu et al. 2014, Räike et al. 2016) so we suggest that the mean total organic carbon concentration in rivers across the NWES must be greater than the lower estimate of 0.097 mol/m^{-3} presented here, which appears low even for the North Sea which probably has disproportionately low contribution from peatland-draining rivers with respect to the wider NWES. Using the maximum range of these values (0.097 to 2.18 mol m^{-3} total OC) multiplied by a total river flow of 1.1 $x10^{12}$ m^3 yr^{-1} gives a range of DOC fluxes from 0.1 to 2.4 Tmol yr^{-1}.

We can use IC:OC ratios to further constrain the range of likely concentrations of DOC as the current ranges of DIC and OC imply an unrealistically wide range of possible average DIC:OC values in rivers flowing into the NWES (~20 :1 to ~1:1). Previous studies suggest riverine inorganic to organic carbon ratios of between 10:1 (North Sea, Thomas et al. 2005) and 1:1 (Global estimate, e.g. Cole et al. 2007). However, carbon loads in tropical rivers are expected to be dominated by DOC (Jarvie et al., 2017), so we assert that the global average DIC:OC ratio of 1 is too low for the NWES. Indeed, Jarvie et al. (2017) find a mean ratio of around 5:1 across a broad range of UK rivers. However in the absence of a good synthesis of NWES rivers the lower constraint must be >1:1, which is currently satisfied by the upper end of the DIC and DOC estimates: 2.6(DIC)/2.4(OC) >1. However, we argue it is highly unlikely that the average DIC:OC ratio in rivers across the NWES is greater than 10:1, the estimate used by Thomas et al. (2005) for the North Sea and therefore use this for a constraint on the lower end concentrations of DOC. The lower bound on DOC thus becomes 0.1 x 2.2 Tmol yr^{-1} DIC = 0.2 Tmol yr^{-1} DOC. Therefore we revise our possible bounds on DOC inputs to be from 0.2 to 2.4 Tmol yr^{-1}.
Riverine DOC input = 0.2 to 2.4 Tmol yr^{-1}.

Total riverine carbon input = 2.3 to 5.0 Tmol yr^{-1}

Pelagic

Stocks

Ranges of DIC, DOC, PIC and POC stocks were based on measurements from the literature, including the latest measured and modelled data from the Natural Environment Research Council (NERC) Shelf Sea Biogeochemistry (SSB) programme. Dissolved inorganic carbon concentrations are strongly seasonally variable and influenced by NAO (Clargo et al. 2015, Salt et al. 2013) and are increasing year-on-year (Figure. 7, main text). Looking across previous papers and datasets it is difficult to separate seasonal variability from climate-influenced variability but a range of mean values from the NWES of 2.03 to 2.13 mol m^{-3} is found (Thomas et al. 2005, Salt et al. 2013, Clargo et al. 2015). The shelf-wide observations of DIC under NERC SSB in all seasons in 2014/15 find mean concentration of 2.105 mol m^{-3} (Hartman et al. 2018), strongly indicating that the higher end of the literature mean values is more realistic for the present-day concentration. Present-day modelled values from the NERC-SSB model (after Butenschön et al. 2016) have a mean value of 2.17mol m^{-3} , possibly indicating the ongoing increase in DIC concentrations. Taking only post-2010 literature data and NERC SSB dataset we use a range of 2.061-2.17 mol m^{-3} as representative of the likely range of mean DIC concentrations between 2010 and 2020.

Mean DOC concentrations observed in the North Sea range from 0.06 to 0.2 mol m^{-3} (Suratman et al. 2009, Chaichana et al. 2019, Painter et al. 2018). Suratman et al. 2009 study a single fixed point time-series in the Southern North Sea, whereas the latter two studies present data from regional studies across the whole of the North Sea in summer, and observe mean concentrations between 0.06 and 0.11 mol/m^3. Davis et al. (2018) observe 0.057 to 0.072 mol m^{-3} across 4 NERC SSB cruises in the Celtic Sea. Shelf-wide data from the SSB programme (Carr et al. 2018) show concentrations ranging from 0.04 (the open ocean background) to 0.16 mol m^{-3}, with higher values associated with the North Sea in Spring. The high values (>0.1) mol m^{-3} observed in Suratman et al. (2009) are also associated with a spring peak so we assume these cannot be representative of the whole shelf mean and adopt a range of 0.05 to 0.11 (the latter number being the mean value from Painter et al. 2018) as representative of mean conditions over the NWES, in agreement with the NERC SSB preliminary modelling output of 0.08 +/- 0.03 mol m^{-3}.

Previous observations of mean POC concentrations in the North Sea range from 0.02 to 0.04 mol m^{-3} (Suratman et al., 2009; Weston et al., 2004; Buitenhuis et al., 1996). Data collected in the Celtic Sea as part of the NERC SSB programme (Davis et al., 2018) has a mean concentration of 0.007 mol m^{-3} and a standard deviation of 0.005 mol m^{-3}. Mean POC from the NERC SSB core model output (Butenschön et al. 2016) across the whole shelf is 0.0094, possibly reflecting in this average value the observed lower concentrations in the Celtic Sea. We adopt the range of 0.007 to 0.04 mol m^{-3}. PIC measurements on the NWES are rather scarce, and we adopt a range of 0.005 to 0.01 mol m^{-3} on the basis of observations by Buitenhuis et al. (1996) and Poulton et al. (2014).

This gives a total carbon concentration of between 2.123 and 2.33 mol m^{-3}. Multiplied by the volume of water on the shelf of 9.91 $\times 10^{13}$ m^3 (Wakelin et al., 2012), this gives a total non-living carbon stock of 210 to 230 Tmol.

The total fish biomass of the North Sea is estimated by Sparholt (1990) as 5.9 to 13.1 million tonnes wet weight. To convert to dry weight we assume a conversion factor of 0.25 after Mackinson and Daskalov (2007) and further assume 50% of dry weight is organic carbon (e.g. Lindlay et al. 1999; Czamanski et al. 2011, Clarke 2008). This yields a per-unit area estimate of 0.11 to 0.24 mol C/m^2. Mackinson and Daskalov (2007) North Sea estimate of pelagic marine organisms (excluding microscopic organisms) is 9.92 g/m^2 (ash free dry weight). This converts to 0.41 moles m^2, of which copepods make up about 40%. We therefore take this as the upper estimate giving a range of 0.11 to 0.41 moles carbon per square metre. Multiplied by the area of the NWES of 1.13$\times 10^{12}$ m^2 (Wakelin et al., 2012), this gives a total living carbon stock of 0.12 to 0.47 Tmol.

Pelagic carbon stock = 210 to 230 Tmol

Air-sea flux

Air- sea CO_2 flux estimates for the NWES were based on shelf-wide modelling and observational studies. All studies find the shelf to be a net sink of atmospheric CO_2 with a net annual flux ranging from 1.3 Tmol yr^{-1} (Shutler et al., 2016; 200 m isobath plus Norwegian Trench) to 3.3 Tmol yr^{-1} (Wakelin et al., 2012; for the years 1989-2004). Kitidis et al., (submitted) calculate a net annual flux of 2.2 Tmol yr^{-1} for the shelf (for 2013) and the latest NEMO-ERSEM run (1990-2015) from the NERC SSB Programme (after Butenschön et al. 2016) finds an annual mean flux of 2.6 Tmol yr^{-1} for the shelf within the 200 m isobath and 0.25 Tmol yr^{-1} in the Norwegian Trench, giving a total of 2.9 Tmol yr^{-1}. The potential reasons for differences between these estimates include i) temporal variations or evolution in the sink itself, ii) differences in the calculation methods used and iii) differences in the shelf sea boundary definitions with respect to the open ocean and the near-shore.
Net annual air-sea CO_2 flux = 1.3 to 3.3 Tmol yr^{-1}

Cross-shelf exchange

Inorganic
Using the POLCOMS-ERSEM model, Wakelin et al. (2012) find a net inorganic carbon transport of 112.1 Tmol yr^{-1} onto the shelf in the upper layer of the water column (above 180 m) and 117.5 Tmol yr^{-1} off of the shelf in the lower layer, giving a total off-shelf inorganic carbon flux of 5.4 Tmol yr^{-1}, with an uncertainty of +- 1 Tmol yr^{-1}. The equivalent net flux of inorganic carbon off of the shelf,

derived from the latest NEMO-ERSEM run (1990-2015) is 3.45 Tmol yr^{-1}, which is comprised of 0.7 Tmol yr^{-1} off-shelf from the Norwegian Trench and 2.75 Tmol yr^{-1} off-shelf across the rest of the shelf break.
Net annual inorganic carbon transport off of the NWES = 3.45 to 6.4 Tmol yr^{-1}

Organic
Wakelin et al. (2012) find a net off-shelf organic carbon transport of 0.3 Tmol yr^{-1} whereas the most recent NEMO-ERSEM run (1990-2015) estimates this flux as 0.01 Tmol yr^{-1}, which is the residual of a net on-shelf transport of 0.49 Tmol yr^{-1} into the Norwegian Trench and a net off-shelf transport of 0.5 Tmol yr^{-1} across the rest of the shelf break.

Using global measurements of DOC in coastal waters Barrón and Duarte (2015) estimate a range of off-shelf DOC transport of 14.7 to 90 Gg yr^{-1} km^{-1}. As the NWES is wide relative to most shelf seas we expect that a large proportion of terrestrial DOC is remineralised on the shelf, reducing the net off-shelf transport (Painter et al. 2018, Chaichana et al. 2019). Therefore, taking the lower end of their range (14.7 Gg yr^{-1} km^{-1}) and multiplying it by the length of the NWES shelf edge (3714 km) gives an estimate of 4.55 Tmol yr^{-1}. However, Barron and Duarte (2015) assume a net water transport of 1Sv per 1000km of shelf edge which is far greater than the mean shelf edge transport on the NWES. Scaling this estimate to a total shelf edge water transport of 1.5 Sv across the whole NWES break (Spingys, 2017) gives a net off-shelf DOC transport of 1.84 Tmol yr^{-1}.
Net annual organic carbon transport off of the NWES = 0.01 to 1.84 Tmol yr^{-1}

Total net annual off-shelf carbon transport = 3.5 to 8.2 Tmol yr^{-1}.

<u>Benthic</u>

<u>Stocks</u>

Benthic stocks have been divided into regions 1 to 11 of Wakelin et al. (2012) (Skagerrak and Kattegat, Southern North Sea, Shetland, Norwegian Trench, Northern North Sea, Irish Shelf, Amorican Shelf, Central North Sea, Irish Sea, English Channel and Celtic Sea), plus the sediment in Norwegian fjords and Scottish lochs. Total loch area is 1221 km^2 (Edwards and Sharples, 1986) and the area of fjords within our study area is taken as 13600 km^2. Areas of the remaining regions are taken from Wakelin et al. (2012).

POC and PIC stocks in the top 0.1 m of sediment have been estimated for each of the regions in Wakelin et al (2012) using measurements and spatial modelling. POC stocks were derived from the spatial predictions of Diesing et al. (2017), explaining 78% of the variance of the data, and the application of this approach to a wider area by Wilson et al. (2018). Where these two predictions overlapped the mean was taken. PIC concentrations in the surface sediment were spatially predicted based on available seabed samples from BGS Geoindex Offshore (http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html), dbSEABED (http://instaar.colorado.edu/~jenkinsc/dbseabed) and ICES (http://www.ices.dk/marine-data/data-portals/Pages/default.aspx) and predictor variables (Bio-ORACLE; Tyberghein et al., 2012, Assis et al., 2017) using the random forest algorithm (Breiman, 2001). Initially, predictor variables included bottom temperature, salinity, dissolved oxygen and primary productivity as well as spatial location (x, y) and water depth. Using only the latter three predictors yielded the most successful model that explained 63% of the variance of the data. Pearson's r of a correlation between predicted values and test values (n = 4179) not used in the prediction was 0.789. PIC concentrations (percentage of weight) were converted into stocks (kg m^{-2}) following Burrows et al. (2014). The mean stocks of POC and PIC in each of the 11 regions in the budget is presented in Table A1.

Table A1. Mean POC and PIC stocks estimates for the 11 regions shown in Fig 1. All values given to 3 significant figures. *Values based on Stahl et al. (2004), explained in text below.

Region number (name)	***PIC stock (Tmol)***	***POC stock (Tmol)***
1 (Southern North Sea)	55.2	2.94
2 (Central North Sea)	57.6	5.76
3 (Northern North Sea)	94.4	8.67
4 (English Channel)	63.3	1.68
5 (Skagerrak and Kattegat)	29.1	0.86 - 1.33*
6 (Norwegian Trench)	27.0	5.63
7 (Shetland Shelf)	71.0	2.70
8 (Irish Shelf)	181	6.28
9 (Irish Sea)	76.7	1.86
10 (Celtic Sea)	297	7.43
11 (Armorican Shelf)	52.4	2.69
Total	1000	45.6 (excluding region 5)

The uncertainty on these predicted POC and PIC stocks were estimated based on the inverse of the variance explained by the predictive method above. For PIC, 37% of the mean, shelf-wide total was subtracted/added from the mean shelf-wide total, giving a range of 630 to 1400 Tmol. For POC, 22% of the mean, shelf-wide total was subtracted/added from the mean shelf-wide total, giving a range of 36 to 56 Tmol. This is a crude approximation and does not fully account for the data transformations used to derive the predicted stocks, or, in the case of POC, uncertainty on the bulk density values used. Based on a simple scaling to the shelf, Diesing et al (2017) estimated a POC range of 230 to 882 MtC (19 to 73 Tmol) on the NWES, based on the 5th and 95th percentiles, although using on a slightly different area to that used here. Based on these ranges we give benthic POC stocks in regions 1 to 11, excluding region 5 (Figure 1) a range of 20 to 70 Tmol, and we give benthic PIC stocks in regions 1 to 11 a range of 500 to 1500 Tmol.

Carbon stocks were calculated separately for the top 0.1 m of sediment in lochs, fjords, and the Skagerrak and Kattegat, based on literature values of density and the percentage of organic and inorganic carbon in sediments. Scottish lochs have a dry bulk density of approximately 1.02 g cm^{-3} (Smeaton et al., 2017) and a percentage of organic carbon ranging from 1.8 to 5.3 % (Loh et al., 2008; Burrows et al., 2017; Smeaton et al., 2017), giving a range of POC stock of 15.3 to 45.1 mol m^{-2}. The percentage of inorganic carbon in loch sediment ranges from 0.3 to 1.82 % (Loh et al 2008; Smeaton et al 2017; Burrows et al., 2017), giving a PIC stock of 2.55 to 15.49 mol m^{-2}. Fjord POC stocks were calculated using the same dry bulk density (Smeaton et al., 2017) and a percentage of organic carbon ranging from 1.02 to 12.4 % (Smith et al., 2015), giving a range of 8.66 to 105.4 mol

m^{-2}. POC stocks in the Skagerrak and Kattegat were calculated using a dry bulk density of 1.12 g cm^{-3} (Flemming and Delafontaine, 2000) and surface organic carbon measurements ranging from 2.308 to 3.56 % (Stahl et al., 2004), giving a range of 21.5 to 33.2 mol m^{-2}. PIC stocks in the Skagerrak and Kattegat were calculated as part of the spatial prediction, discussed above.

Stocks of dissolved carbon in sediment pore water are very small compared to particulate carbon stocks and are a small proportion of the total benthic carbon stocks. Sediment profiles of DOC in the Skagerrak (Stahl et al 2004) and a porosity of 0.7 (Loh et al., 2010) were used to estimate a range of DOC stock of 0.007 to 0.056 mol m^{-2}. Modelled DIC profiles in Krumins et al. (2013) combined with a porosity of 0.7 (Loh et al 2010), yield stocks of 0.175 mol m^{-2} at the sediment water interface and 0.56 mol m^{-2} at 0.1 m .This is consistent average bulk sediment DIC stocks across the NWES estimated using the NERC SSB ERSEM runs (after Butenschön et al. 2016), of 0.298 mol m^{-2}.

The non-living benthic carbon stock on the NWES is estimated to be 520 to 1572 Tmol.

In a comprehensive study of North Sea biomass, Mackinson and Daskalov (2007) estimate the benthic macrofaunal community biomass (ash-free dry weight of all infauna and epifauna) to be approximately $1.35x10^{14}$ g. Assuming approximately 50% of dry weight is carbon in marine organisms (e.g. Lindlay et al. 1999; Czamanski et al. 2011, Clarke 2008) and dividing by the total area used by Mackinson et al (2008) gives a per unit area benthic macrofaunal organic carbon content of 9.8 mol m^{-2}. In the Fladen Ground in the northern North Sea de Wilde et al. (1986) found a combined macrofaunal and meiofunal biomass of 11 g m^{-2}. Assuming approximately half of this is carbon, this represents 0.46 mol m^{-2}. We therefore give the living benthic organic carbon stock a range of 0.46 to 9.8 mol m^{-2}. This gives a living benthic carbon stock of 0.52 to 11 Tmol.

Benthic PIC stock = 500 and 1500 Tmol
Benthic POC stock = 21 and 73 Tmol
Total benthic carbon stock = 520 and 1600 Tmol

Pelagic - benthic flux

A paucity of data prevents this flux from being quantified in the same regional detail as the benthic POC and PIC stocks. Instead, the flux of carbon between pelagic and the benthic components of budget was estimated for five regions: Skagerrak and Kattegat, Norwegian Trench, lochs, fjords and finally, the remaining seabed in the study area. Measurements and modelling data have been synthesised to derive a range for each flux.

POC

POC flux in the Skagerrak and Kattegat has been estimated based on a survey of the Skagerrak by Stahl et al., (2004), giving a range of 2.19 to 9.97 mol m^{-2} yr^{-1}. POC flux in the Norwegian Trench is given a range of 1.9 mol m^{-2} yr^{-1}, which is derived from a hindcast (1990-2015) model run (after Butenschön et al. 2016), to 9.97 mol m^{-2} yr^{-1} which is the upper limit of POC flux in the Skagerrak (Stahl et al. 2004). POC flux in two fjords in western Norway was measured by Duffield et al. (2017). They found POC burial to be lower at the seaward end than at the head of fjords with a range of 1.08 to 14.25 mol m^{-2} yr^{-1}. This large range encompasses a global estimate of 4.5 mol m^{-2} yr^{-1} (Smith et al. 2015). POC flux in Lochs is given a range of 7.3 mol m^{-2} yr^{-1} (Burrows et al., 2017) to 14.25 mol m^{-2} yr^{-1}, which is the upper estimate from fjords (Duffield et al., 2017).

For the rest of the shelf sediment POC flux was given a range of 3.42 to 4.89 mol m^{-2} yr^{-1}. The lower estimate corresponds to POC burial estimates for fine and coarse sediments of 3.52 and 3.23 mol m^{-2} yr^{-1} respectively (Burrows et al., 2017), multiplied by the approximate proportions of these sediment types on the shelf of 67% and 33% respectively (Diesing et al., 2017). The upper estimate is the seasonal average POC flux measured at the L4 time series, where the sediment is fine sand/muddy sand and the water depth is 48m (Queiros et al., 2019). A global shelf sea estimate of POC flux of 4.37 mol m^{-2} yr^{-1} (Krumins et al., 2013) is consistent with this range.

PIC

PIC burial data are scarce. A global shelf sea estimate of PIC flux of 0.27 mol m^{-2} yr^{-1} (Krumins et al. 2013) is used as the lower estimate across all areas of the NWES. PIC burial in lochs of 2.49 mol m^{-2} yr^{-1} (Burrows et al. 2017) is taken as the upper estimate of PIC burial in boths lochs and fjords.

For the rest of the shelf, the upper estimate of PIC flux was taken as 1.02 mol m^{-2} yr^{-1}. This corresponds to PIC burial estimates for fine and coarse sediments of 1.36 and 0.33 respectively (Burrows et al., 2017), multiplied by the approximate proportions of these sediment types on the shelf of 67% and 33% respectively (Diesing et al., 2017).

DOC and DIC

DOC flux in the Skagerrak and Kattegat was given a range of 0.073 to 0.37 mol m^{-2} yr^{-1} from the sediment to the water, based on the measurements of Stahl et al. (2004). Across the rest of the shelf, a range of 0 to 0.91 mol m^{-2} yr^{-1} from the sediment to the water was used based on Skoog et al (1996).

A global shelf sea estimate of DIC flux of 4.63 mol m^{-2} yr^{-1} (Krumins et al. 2013) was used as the upper estimate of DIC flux (from sediment to water) across the shelf. Results from a hindcast (1990-2015) model run (ERSEM) were used as the lower estimate of DIC flux for the Skagerrak and Kattegat (2.93 mol m^{-2} yr^{-1}), and the Norwegian Trench, lochs and fjords (1.90 mol m^{-2} yr^{-1}). Measurements from the L4 time series provide the lower estimate of DIC release across the rest of the shelf, with a seasonal average of 1.09 mol m^{-2} yr^{-1} (Queiros et al., 2019). This is lower than the value suggested by hindcast model data of 1.96 mol m^{-2} yr^{-1} (Butenschön et al. 2016).

Scaling these per-unit-area fluxes to the area of shelf gives a net pelagic to benthic carbon burial for the whole NWES of between -2.2 and 6.0 Tmol yr^{-1}.
Pelagic to benthic carbon flux = -2.2 and 6.0 Tmol yr^{-1}

Part B - Hierarchical tables of the ranges of stocks and flows of carbon on the NWES, given to two significant figures. The percentage uncertainty on each stock and flow shows the range as a percentage of the mid point in the range. Cells are coloured based on percentage uncertainty, with relatively well constrained stocks or flows coloured more green and relatively poorly constrained stocks or flows coloured more red.

STOCKS (Tmol)											
class	min	max	% uncert.	class	min	max	% uncert.	class	min	max	% uncert.
Pelagic	210	230	9	DIC	200	220	5				
				DOC	5.0	11	75				
				POC	0.69	4.0	140				
				PIC	0.50	0.99	67				
				Living	0.12	0.46	115				
Benthic	520	1600	101	Regions 1 to 11	520	1600	100	PIC	500	1500	100
								POC	20	70	111
								DIC	0.20	0.63	104
								DOC	0.0078	0.063	156
				Lochs	0.022	0.075	109	PIC	0.0031	0.019	143
								POC	0.019	0.055	99
								DIC	0.00021	0.00068	105
								DOC	0.0000085	0.000068	156
				Fjords	0.15	1.7	166	PIC	0.035	0.21	143
								POC	0.12	1.4	170
								DIC	0.0024	0.0076	105
								DOC	0.000095	0.00076	156
				Living	0.52	11	182				
Coastal	0.69	3.40	132	saltmarshes	0.23	0.63	94				
				seagrass	0.0049	0.013	93				
				flats	0.42	2.5	142				
				kelp	0.038	0.25	146				

FLOWS (Tmol/yr)											
class	min	max	% uncert.	class	min	max	% uncert.	class	min	max	% uncert.
Air-sea CO2	1.3	3.3	87								
Riverine input	2.3	5.0	76	Inorganic	2.2	2.6	19				
				Organic	0.10	2.4	184				
Off-shelf transport	3.5	8.2	82	Inorganic	3.5	6.4	60				
				Organic	0.010	1.8	198				
Pelagic to benthic	-2.2	6.0	439	Skag and Kat.	-0.10	0.32	386	POC	0.087	0.40	128
								PIC	0.011	0.041	116
								DOC	-0.015	-0.0029	133
								DIC	-0.18	-0.12	45
				Norwegian Trench	-0.22	0.59	436	POC	0.12	0.65	136
								PIC	0.018	0.066	116
								DOC	-0.059	0.0	200
								DIC	-0.30	-0.12	83
				Lochs	0.0025	0.018	152	POC	0.0089	0.02	65
								PIC	0.00033	0.00	161
								DOC	-0.0011	0.00	200
								DIC	-0.0057	0.00	83
				Fjords	-0.057	0.20	358	POC	0.015	0.19	172
								PIC	0.0037	0.034	161
								DOC	-0.012	0.00	200
								DIC	-0.063	-0.026	83
				Elsewhere	-1.9	4.9	449	POC	3.5	4.9	35
								PIC	0.27	1.0	116
								DOC	-0.92	0.0	200
								DIC	-4.7	-1.1	124
Kelp to sediment	0.0	0.094	200	kelp	0.00	0.094	200				
Coastal to pelagic	-0.11	0.54	302	Saltmarsh	-0.00088	0.035	210				
				Seagrass	-0.0015	-0.00010	175				
				Flats	-0.014	0.50	211				
				Kelp	-0.094	0.0	200				
Air-coastal CO2	0.031	0.57	179	Saltmarsh	0.021	0.044	69				
				Flats	0.010	0.52	192				
Coastal burial	0.016	0.065	120	Saltmarsh	0.0062	0.032	135				
				Seagrass	0.00010	0.0015	175				
				Flats	0.010	0.032	104				

Part C - Estimated carbon burial reduction in coastal habitats due to habitat loss caused by sea level rise. Data sources for habitat loss rates: Nottage and Robinson (2005); Jones et al., (2011); Luisetti et al., (2019).

Habitat type	Saltmarsh		Mud/sand flats		Seagrass		Total	
	lower	upper	lower	upper	lower	upper	lower	upper
Area on NWES (m2)	1.20E+09	1.75E+09	1.00E+10	1.80E+10	1.40E+08	2.10E+08	1.13E+10	2.00E+10
Carbon burial rate (mol/m2/yr)	5.2	18.3	1	1.75	0.7	7	-	-
Annual area loss (%)	0.16	2	0.16	2	1	1	-	-
Annual area loss (m2)	1.92E+06	3.50E+07	1.60E+07	3.60E+08	1.40E+06	2.10E+06	1.93E+07	3.97E+08
Annual carbon burial reduction (mol/yr)	9.98E+06	6.41E+08	1.60E+07	6.30E+08	9.80E+05	1.47E+07	2.70E+07	1.29E+09

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