Organic carbon in surface sediments of the North Sea and Skagerrak

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5 **Abstract.** Continental shelf sediments are places of both rapid organic carbon turnover and accumulation, while at the same time increasingly subjected to human-induced disturbances. Recent research suggests that shelf sediments might have a role to play as a natural climate solution, e.g. by protecting the seafloor against human-induced disturbance. However, we have an incomplete understanding about the centres of organic carbon accumulation and storage on continental shelves. To better constrain the rate of accumulation and the mass of organic carbon that is stored in sediments, we developed and applied a

10 spatial modelling framework that allows to estimate those quantities from sparse observations and predictor variables known or suspected to influence the spatial patterns of these parameters. This paper presents spatial distribution patterns of organic carbon densities and accumulation rates in the North Sea and Skagerrak. We found that organic carbon stocks and accumulation rates are highest in the Norwegian Trough, while large parts of the North Sea are characterised by low stocks and zero net-accumulation. The total stock of organic carbon that is stored in the upper 0.1 m of sediments amounted to

15 230.5 ± 134.5 Tg, of which approximately 26 % are stored in the Norwegian Trough. Rates of organic carbon accumulation in the Norwegian Trough are on par with those reported from nearby fjords. We provide baseline datasets that could be used in marine management, e.g. for the establishment of "carbon protection zones". Additionally, we highlight the complex nature of continental shelves with zones of rapid carbon cycling and accumulation juxtaposed, which will require further detailed and spatially explicit analyses to constrain sedimentary organic carbon stocks and accumulation rates globally.

20 **1 Introduction**

Marine sediments are an important sink for organic carbon (OC) on Earth, with estimates of OC burial in marine sediments ranging from 126 Tg yr^{-1} (Berner, 1982) to 350 Tg C yr^{-1} (Keil, 2017). The major hot spots for OC burial in the global ocean are the coastal margins (Bianchi et al., 2018). Burdige (2007) estimated that 80% (248 Tg C yr^{-1}) of all OC buried in marine sediments is occurring in continental margin sediments. However, other estimates do also exist (Bauer et al., 2013; Duarte et

25 al., 2005; Hedges and Keil, 1995), ranging from 45.2 to 300 Tg C yr^{-1}, and budgets are generally not well constrained (Burdige, 2007). Estimates of the amount of OC stored in marine surface sediments also vary considerably, ranging from 87 Pg (Lee et al., 2019) to 168 Pg (LaRowe et al., 2020) to 3117 Pg (Atwood et al., 2020). Such differences can be attributed only partly to differences in the reference depths being considered, ranging from 0 – 5 cm (Lee et al., 2019) to the bioturbated Holocene layer, assumed to be 0 – 10 cm (LaRowe et al., 2020), to 0 – 1 m (Atwood et al., 2020).

30   In recent years, attempts were made to construct carbon budgets for entire continental shelf systems. However, these studies did not include spatially explicit estimates of OC stock and burial (Fennel et al., 2019; Najjar et al., 2018) or concluded that both stocks and burial rates were associated with considerable uncertainty (Legge et al., 2020).

Given the importance of continental margins in OC cycling, it is therefore of great importance to develop adequate methods that better constrain stocks, flows and budgets of OC and quantify the uncertainty of the predictions. In particular, spatially

35   explicit methods that predict the variation of OC in space by means of geostatistics or machine-learning spatial prediction are promising, and much can be learned from related terrestrial disciplines such as digital soil mapping (Hengl et al., 2014, 2017; McBratney et al., 2003). Recent studies appear to prefer machine-learning over geostatistical approaches (Seiter et al., 2004) and estimates of OC stored in marine sediments at a global (Atwood et al., 2020; Lee et al., 2019) and sea-basin scale (Diesing et al., 2017; Wilson et al., 2018) have been derived. However, no spatially explicit estimates of OC accumulation

40   and burial rates exist to our knowledge.

Well-constrained estimates of OC stocks and accumulation rates are also required from a marine management point of view. The potential of so-called Blue Carbon ecosystems (mangroves, salt marshes, seagrass meadows and potentially macroalgae) to sequester and store OC is an important ecosystem service that has been highlighted in recent years (Duarte et al., 2005; Mcleod et al., 2011; Nellemann et al., 2009). More recently, it has been shown that fjord (Smeaton et al., 2016, 2017) and

45   continental shelf sediments (Diesing et al., 2017) harbour considerable amounts of OC. In the United Kingdom, the shelf sediment stock (205 Tg) accounts for 93% of OC stored in coastal and marine habitats (Luisetti et al., 2019) and outweighs combined seagrass and saltmarsh stocks (13.4 Tg) by a factor of ≈15. In Namibia, the marine sediment OC stock is estimated to be larger than the soil OC stock (Avelar et al., 2017). Determining national carbon stocks is essential for climate change mitigation actions; however, national assessments for greenhouse gas reporting do not account for marine stocks such as

50   organic carbon stored in shelf sediments (Avelar et al., 2017). In Norway, the government has underlined the significance of OC uptake by marine vegetation but OC burial in marine sediments is currently not considered (Anon, 2013). Consequently, the question has been raised whether those stocks should be considered as part of national carbon accounting and potential greenhouse gas mitigation projects and subject to management against human-induced disturbance (Avelar et al., 2017). The socio-economic importance of marine carbon storage has recently been assessed in a scenario analysis of increased human

55   and climate pressures over a 25-year period. It was estimated that damage costs of up to $12.5 billion from carbon release linked to disturbance of coastal and shelf sea sediment carbon stores could arise in the United Kingdom (Luisetti et al., 2019).

Marine Protected Areas (MPAs) might be a suitable management measure to effectively protect the carbon storage ecosystem service of Blue Carbon ecosystems against human pressures (Zarate-Barrera and Maldonado, 2015). Further

60   offshore, demersal fishing is an important and widespread pressure on continental shelf seabed habitats (Amoroso et al., 2018; Halpern et al., 2008). Chronic demersal fishing has negative impacts on benthic biomass, production, and species richness, and is leading to shifts in the composition of communities (Hiddink et al., 2006, 2017; Jennings et al., 2001; Tillin et al., 2006). Impact of demersal fishing on the biogeochemistry of the seafloor and OC storage is less well understood.

Several studies show lower OC contents in surface sediments of trawled areas (Bhagirathan et al., 2010; Martín et al., 2014b; Paradis et al., 2019; Pusceddu et al., 2014), while others report higher OC contents, presumably due to fertilization brought about by resuspension or uplifting of OC from deeper layers caused by trawling (Palanques et al., 2014; Pusceddu et al., 2005). In the short term, demersal fishing-induced sediment disturbance stimulates OC mineralisation in cohesive sediments, likely due to the enhanced decomposition of previously buried refractory OC (van de Velde et al., 2018). In the long-term, the expectable result of repeated and vigorous sediment mixing due to demersal fishing is a general impoverishment in OC (Martín et al., 2014a). Given the large areas affected ($\approx$10 million km^2) and the amount of sediment being resuspended ($\approx$22 Pg yr^{-1}) globally (Oberle et al., 2016), it is likely that the impact of demersal fishing on shelf sediment OC storage is substantial. Chronic seabed disturbance by demersal fishing might have a sizeable impact on the carbon cycle in cohesive sediments on continental shelves by keeping coastal seabed biogeochemistry in a transient state, which translates into reduced OC burial rates (van de Velde et al., 2018). Establishment of MPAs protecting against demersal fishing could not only facilitate the recovery of benthic species but also promote carbon uptake by seabed ecosystems, as well as prevent further loss of OC stored in sediments (Roberts et al., 2017).

The North Sea and Skagerrak are among the most intensively researched regional seas with a wealth of data available for reuse. At the same time, it is also one of the regional seas most heavily impacted by human activities (Halpern et al., 2008). This makes the area ideal for our study which has the objectives to estimate OC stocks and accumulation rates of surface sediments in a spatially explicit way. These estimates will be accompanied by assessments of uncertainty in the predictions. With the help of these predictions, the following research questions will be addressed:

1. What is the importance of seafloor sediment OC stocks relative to other OC stocks?
2. Where are the centres of OC accumulation in the North Sea and Skagerrak?
3. Based on the previous results, can we differentiate between different zones of OC processing at the seafloor?
4. What are possible implications for marine management?

2 Regional setting

The study site encompasses the North Sea and Skagerrak regional seas as defined by IHO (1953). The surface areas of the North Sea and Skagerrak are approximately 526,000 km^2 and 32,000 km^2, respectively. The seafloor in the study site is mostly shallow and flat, generally deepening from south to north (Figure 1). The most prominent morphological feature is the Norwegian Trough, which follows the coast of southern Norway and reaches water depths of nearly 700 m in the Skagerrak. It forms a major accumulation area for fine-grained material (Eisma and Kalf, 1987; Van Weering, 1981). Large parts of the continental shelf outside the Norwegian Trough are erosional or non-depositional in nature (de Haas et al., 1997), with limited sedimentation occurring in the German Bight, the Elbe palaeo-valley, Oyster Ground, Inner Silver Pit, Outer Silver Pit and Devil's Hole (Eisma and Kalf, 1987; de Haas et al., 1997). Previous studies (de Haas et al., 1997, 2002; de

95 Haas and van Weering, 1997) have indicated that most of the OC accumulation occurs in the Norwegian Trough (≈ 1 Tg yr^{-1}), while OC accumulation in the remaining area is low (≈ 0.1 Tg yr^{-1}).

3 Data

3.1 Response variables

3.1.1 Linear sedimentation rate

100 Linear sedimentation rate (ω) data were initially sourced from the EMODnet-Geology portal (https://www.emodnet-geology.eu/), which provides a collation of values from the literature across European sea basins. The dataset was limited to the study site and sedimentation rates based on ^{210}Pb, to ensure a consistent integration time scale (Jenkins, 2018). Based on a half-life of approximately 22 yr, the associated integration time is roughly 100 yr (Jenkins, 2018). Data from Zuo et al. (1989) were excluded as these were deemed unreliable (de Haas et al., 1997).

105 The reported sedimentation rate data focussed on accumulation areas like the Norwegian Trough (Figure 2). However, to be able to spatially predict sedimentation rates across the study site it is necessary to include data from areas of erosion and non-deposition, which predominate in the North Sea. Therefore, the data of de Haas et al. (1997) were also included. This provided less than 20 data points of zero net-sedimentation, which was still deemed insufficient. Additionally, pseudo-observations (Hengl et al., 2017) were also included. These were randomly placed in areas of erosion and non-deposition

110 (based on the sedimentary environment layer, as described in chapter 3.2) and a sedimentation rate of 0 cm yr^{-1} was assigned. Some of the sedimentation rate values from non-depositional areas reported by de Haas et al. (1997) and van Weering et al. (1993) appeared too high, and after a review of the ^{210}Pb-profiles four of them were set to 0 cm yr^{-1}. The full dataset used for subsequent modelling is shown in Figure 2 and provided as Supplementary Data Table 1.

3.1.2 Organic carbon density

115 Previous studies have predicted OC concentrations and sediment porosity separately to calculate OC stocks (Diesing et al., 2017; Lee et al., 2019; Wilson et al., 2018). Here, we first calculate OC density from concurrent measurements of OC concentrations and sediment dry bulk densities or porosities. This has two advantages: First, there is no need to transform the response variable as would be necessary in the case of OC concentrations reported as weight-% or fractions. Second, only one model instead of two needs to be fitted.

120 OC density ρ_{OC} (kg m^{-3}) was calculated from data on OC concentration G (g kg^{-1}) and dry bulk density ρ_d (kg m^{-3}):

$$\rho_{OC} = G \cdot \rho_d \tag{1}$$

If not measured, dry bulk density was calculated from porosity φ and the grain density ρ_s (kg m^{-3}) according to:

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$$\rho_d = (1 - \varphi)\rho_s \tag{2}$$

In the majority of cases (52.8 %), the OC concentrations referred to the 0 – 10 cm depth interval, but other depth intervals were also present; most frequently 0 – 1 cm (17.7 %), 0 – 5 cm (16.4 %), 0 – 0.5 cm (6.7 %) and 0 – 2 cm (4.6 %). It was

130   assumed that the reported values were representative for the upper 10 cm of the sediment column. The full dataset used for subsequent modelling is shown in Figure 2 and provided as Supplementary Data Table 2.

3.2 Predictor variables

The initial selection of environmental predictor variables was based on availability and expected relevance. A previous modelling study highlighted mud content in surficial sediments, bottom water temperature and distance to the closest

135   shoreline as important predictors for OC (Diesing et al., 2017). Other environmental controls on OC accumulation that have been inferred are sedimentation rate (Müller and Suess, 1979), bottom-water oxygen concentration (Paropkari et al., 1992) and oxygen exposure time (Hartnett et al., 1998). There is less information available on relevant predictors for sedimentation rate, but it is assumed that sedimentation is favoured in deep basins with low current speeds and wave orbital velocities. Fine grained sediments prevail in these environments and might be indicative for areas of sediment accumulation.

140   Some predictor variables were derived from other data layers: The geomorphology layer was derived from Harris et al. (2014) and contained the geomorphic features shelf, shelf valley and glacial trough. The sedimentary environment was inferred from modelled Folk classes (Mitchell et al., 2019). Initially, areas covered with mud, sandy mud and muddy sand were assumed to be potentially accumulative. Boundaries were subsequently cleaned in ArcGIS to simplify the regions. Based on results on sedimentation rates in de Haas et al. (1997) and other studies discussed therein, potential areas of

145   sediment deposition were critically reviewed and removed if they were not deemed accumulative. The remaining main areas of net-deposition are shown in Figure 1. Oxygen penetration depth was derived by applying relationships between measured oxygen penetration depth and mud content (pers. comm. John Barry, Cefas) to the mud layer (Mitchell et al., 2019). Oxygen exposure time was derived by dividing oxygen penetration depth by the modelled linear sedimentation rate (Hartnett et al., 1998).

150   All datasets were projected to Lambert Azimuthal Equal Area projection with a resolution of 500 m. The full list of predictor variables is detailed in Table 1.

4 Methods

4.1 Framework for spatial prediction and uncertainty estimation

The same modelling framework was used for predicting sedimentation rates and OC densities. It is based on the quantile

155   regression forest (QRF) algorithm (Meinshausen, 2006) to make spatial predictions of the target variables and to estimate the

uncertainty in the predictions in a spatially explicit way. QRF is a generalisation of the random forest algorithm (Breiman, 2001), which aggregates the conditional mean from each tree in a forest to make an ensemble prediction. QRF also returns the whole conditional distribution of the response variable. This allows to determine the underlying variability of an estimate by means of prediction intervals or the standard deviation.

160 Prediction uncertainty may be divided into four main components: uncertainty in the response data, in the predictor variables, in the model and in variations of available data (Guevara et al., 2018). It was not possible to address uncertainty related to the first two components, as information on measurement error of the response variables or uncertainty associated with the predictor variables was not available. However, the modelling framework addresses uncertainty in the model by calculating the standard deviation of the QRF predictions. Furthermore, the sensitivity of the model to variations in the

165 available data was estimated by means of resampling. To that end, the response data were repeatedly (25 times in this case) split into training and test subsets at a ratio of 7:3 and 25 models were subsequently built based on these splits. This resampling scheme is known as Monte Carlo cross-validation. The sensitivity is derived by calculating the standard deviation of the 25 predictions for every pixel. The total uncertainty is the sum of the model uncertainty and the sensitivity. The methodology was adapted from Guevara et al. (2018).

170 Prior to model building, the predictor variables were submitted to a variable selection process. This was achieved via the Boruta variable selection wrapper algorithm (Kursa and Rudnicki, 2010), which identified important predictor variables. Random forest has been shown to perform well without parameter tuning. Our own experience shows that the gains made by random forest model tuning are comparatively small, while at the same time this step might be time consuming, especially when tuning an array of parameters. As QRF is based on random forest, we assume that the same holds true here. Only

175 limited model tuning was therefore carried out. The number of variables to consider at any given split (m_{try}) was tuned in a grid search using a 10-fold cross-validation scheme with three repeats on the training dataset. It is usually sufficient to set the number of trees in the forest (n_{tree}) to a high value; 500 was selected in this case.

The model performance was assessed based on the test data of 25 resampling iterations. The root mean square error (RMSE) was calculated according to:

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$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (3)$$

RMSE might range from 0 to infinity, with an ideal value of 0. It is reported in the same units as the predicted quantity. Similarly, the mean square error (MSE) is:

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$$MSE = \frac{1}{n} \cdot \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \qquad (4)$$

In both cases, n is the number observations, y_i the observed value of the i-th observation and $\hat{y}_i$ the respective predicted value. The variance explained (VE) by the model is subsequently calculated based on MSE and the variance of the observed values (σ^2):

$$VE = 1 - \frac{MSE}{\sigma^2} \tag{5}$$

Finally, the coefficient of determination (r^2) was calculated from the observed and predicted values.

The analysis was carried out in R 3.6.1 statistical software (R Core Team, 2018) and RStudio 1.2.1335. The full workflows are documented as R Notebook files (Supplement S1 and S2).

4.2 Calculation of OC stocks

The OC stock (m_{OC} in Tg) of surface sediments in the North Sea and Skagerrak was calculated by summing the predicted OC densities of all pixels and multiplying with the reference depth (d = 0.1 m) and the area of a pixel (A = 250,000 m^2):

$$m_{OC} = d \cdot A \cdot \sum \rho_{OC} \tag{6}$$

The total uncertainty of the predicted OC stock was calculated in the same way.

4.3 Calculation of OC accumulation rates

OC accumulation rates (OCAR in g m^{-2} yr^{-1}) were calculated by multiplying predicted OC densities with predicted sedimentation rates:

$$OCAR = \rho_{OC} \cdot \omega \tag{7}$$

Uncertainties were propagated by taking the square root of the sum of squared relative uncertainties:

$$\frac{\delta OCAR}{OCAR} = \sqrt{\left(\frac{\delta \rho_{OC}}{\rho_{OC}}\right)^2 + \left(\frac{\delta \omega}{\omega}\right)^2} \tag{8}$$

Whereby δ denotes the uncertainty of a quantity. The full workflow is documented as an R Notebook file (Supplement S3).

4.4 Regionalisation

An unsupervised classification was carried out to provide a regionalisation of the North Sea environment with regard to processing of OC at the seafloor. The following environmental variables were selected: bathymetry, tidal current speed, peak orbital velocity, oxygen penetration depth, OC density and OC accumulation rate. These are expected to have a strong impact on OC processing. A k-means clustering was conducted utilising the algorithm of Hartigan and Wong (1979). Prior to clustering, the input variables were normalised, and a principal component analysis was carried out to limit co-linearity in the input data. The first four principal components, accounting for 95.5 % of the variance, were selected for further analysis. The selection of the number of clusters to be requested was based on an elbow plot, which resulted in three clusters. The full workflow is documented as an R Notebook file (Supplement S4).

5 Results

5.1 Sedimentation rates

The model had an RMSE of 0.13 ± 0.03 cm yr^{-1}, an r^2 of 0.58 ± 0.09 and an explained variance of 0.13 ± 0.23. Predicted sedimentation rates range from 0 to 0.61 cm yr^{-1}, while the total uncertainty varies between 0.12 and 0.53 cm yr^{-1} (Figure 3). Sedimentation rates are highest in the Norwegian Trough. Zero net sedimentation occurs in large parts of the North Sea, with slightly elevated sedimentation rates linked to shallow basins such as the inner German Bight, the Elbe palaeo-valley, the Oyster Ground, the Outer Silver Pit and Devil's Hole. The patterns of prediction uncertainty follow those of the sedimentation rate.

5.2 Organic carbon density

The model had an RMSE of 2.16 ± 0.25 kg m^{-3}, an r^2 of 0.72 ± 0.06 and an explained variance of 0.58 ± 0.11. Predicted OC densities range from 1.11 to 13.59 kg m^{-3}, while the total uncertainty varies between 0.89 and 8.07 kg m^{-3} (Figure 4). OC densities are highest in the Norwegian Trough. Intermediate OC densities are found in the northern North Sea and shallow basins, while they are lowest on Dogger Bank, in the Southern Bight and along the Danish coast. Note that uncertainties in parts of the Norwegian Trough are comparatively low due to a high sampling density (Figure 2).

The OC stock of surface sediments of the North Sea and Skagerrak amounts to 230.5 ± 134.5 Tg, of which 59.7 ± 18.1 Tg are stored in the Norwegian Trough. This means that 25.9 % of the total OC stock is located within the Norwegian Trough, which accounts for 11 % of the surface area.

5.3 Organic carbon accumulation rates

OC accumulation rates vary between 0.02 and 66.18 g m^{-2} yr^{-1}, while the total uncertainty ranges from 0.20 to 57.90 g m^{-2} yr^{-1} (Figure 5). OC accumulation rates are effectively zero over large parts of the North Sea. Marked accumulation of OC is restricted to the Norwegian Trough, which accumulates 1.24 ± 1.30 Tg C yr^{-1}. This accounts for nearly 87% of the total OC accumulation of 1.43 ± 2.07 Tg yr^{-1} in the North Sea and Skagerrak.

5.4 Regionalisation

The unsupervised classification resulted in regions that were distinct regarding bathymetry, hydrodynamics, oxygen penetration and OC (Figure 6). Region 2 (green) is characterised by shallow water, strong hydrodynamics, deep oxygen penetration, low OC densities and OC accumulation close to zero. Region 3 (dark blue) is characterised by deep water, weak
250 hydrodynamics, shallow oxygen penetration, high OC densities and high OC accumulation. Region 1 (light blue) has characteristics that lie intermediate between those of regions 2 and 3.

6 Discussion

We have presented estimates of OC stocks and accumulation rates and their associated spatially explicit uncertainties that were derived with the same modelling framework. The presented method is generally transferrable to other areas of the
255 ocean and different spatial scales. The method was developed in the R programming language and free software environment for statistical computing and graphics. The scripts are provided as R Markdown documents as supplementary materials (Supplements S1-4). Researchers are encouraged to re-use and build upon these scripts.

6.1 Relevance

The upper 5 cm of the global ocean seafloor contains about 87 ± 43 Pg C in organic form (Lee et al., 2019). Clipping the
260 map of Lee et al. (2019) to the extent of the global continental shelf (Harris et al., 2014) yields a stock of 12.1 Pg C. Organic carbon concentrations decrease with depth in the upper few decimetres (e.g. Arndt et al., 2013). It can therefore be assumed that OC densities decrease, too, although this decrease might be partly compensated by increasing dry bulk densities due to higher sediment compaction with depth. It is therefore safe to assume that the sediment slice between 5 and 10 cm will contain between 0 % and 100 % of the OC stock of the upper 5 cm. Therefore, OC stocks of the global continental shelf
265 sediments likely contain between 12.1 and 24.2 Pg C. This range of values is confirmed by recent independent estimates of the OC content of bioturbated Holocene shelf sediments (0 – 10 cm) predicted to fall between 9.6 and 25.0 Pg C (LaRowe et al., 2020). Hence, sediments in the North Sea and Skagerrak store approximately 0.9 – 2.4 % of the global stock in an area that accounts for ≈1.7 % of the global shelf.

When comparing uncertainties in OC stock estimates with other reported values of spatial predictions at a regional to global
270 scale, we find that our value of 58 % is similar to that reported by Lee et al. (2019) amounting to 49 %, while other studies did not report any estimates of uncertainty (Diesing et al., 2017; LaRowe et al., 2020). Lower uncertainties have been reported from local studies (e.g. Hunt et al., 2020), presumably due to a tighter coupling between response and predictor variable. It should also be considered that the ways how uncertainty is estimated and reported vary, thereby limiting the scope of such comparisons. We have modelled our uncertainty assessment on methodology developed for soil organic
275 carbon mapping (Guevara et al., 2018) and believe that this approach is very robust as it estimates uncertainty in the model and in variations of available data.

Previous estimates of OC stocks in the upper 10 cm of the sediment column of the northwest European continental shelf amount to 230 – 882 Tg C (Diesing et al., 2017). The estimated stock of 230.5 ± 134.5 Tg contained in the upper 10 cm of the sediments of the North Sea and Skagerrak, which account for approximately 50 % of the area of the North-West European continental shelf, falls well within this estimate. Of this stock approximately 60 Tg or 26 % are stored within the Norwegian Trough, indicating the importance of this glacial feature as a store of OC.

Coastal habitats (saltmarsh, seagrass, kelp and tidal flat) on the northwest European continental shelf store between 8.3 and 40.8 Tg C in the upper 10 cm (Legge et al., 2020). This indicates that shelf sediment stocks are approximately an order of magnitude larger, even without accounting for the smaller area of the North Sea and Skagerrak.

Soils are the largest carbon store on land; collectively they are estimated to hold 1325 Pg C in the upper 1 m (Köchy et al., 2015). Topsoil (0 – 10 cm) OC stocks based on SoilGrids250m (Hengl et al., 2017) of the countries bordering on the North Sea and Skagerrak are shown in Table 2. While marine sediment OC stocks are generally lower than their soil counterparts, marine stocks are not negligible in several countries. These additional OC stocks amount to 7.5 %, 7.1 % and 6.6 % of topsoil stocks in Denmark, the Netherlands, and the United Kingdom, respectively. Furthermore, some countries have Exclusive Economic Zones (EEZs) considerably larger than their share of the North Sea and Skagerrak considered here. Hence, there is potential for an even larger marine OC stock. However, marine sediment stocks are presently not considered in the context of national carbon inventories for greenhouse gas reporting and the question has been raised whether those stocks should be considered as part of national carbon accounting and potential greenhouse gas mitigation projects and subject to management against human-induced disturbance (Avelar et al., 2017).

The accumulation of OC is effectively limited to the Norwegian Trough, with the highest rates found in the Skagerrak. Predicted OCARs vary between approximately 4 and 66 g m^{-2} yr^{-1} in the Norwegian Trough, with a mean OCAR of 19.4 g m^{-2} yr^{-1}. Reported OCARs measured in fjord sediments in Norway and Sweden bordering on the North Sea range from 12 to 54 g m^{-2} yr^{-1} (Huguet et al., 2007; Müller, 2001; Nordberg et al., 2001, 2009; Skei, 1983; Smittenberg et al., 2004, 2005; Velinsky and Fogel, 1999), indicating that OCARs in the Norwegian Trough are of a comparable magnitude. However, the area of the Norwegian Trough is much larger than even the largest fjords in Norway. Additionally, fjords in Scotland and Ireland have been shown to be heterogeneous in sediment distribution and OC concentrations (Smeaton and Austin, 2019), and hence also OC accumulation. Judging from published sediment maps (e.g. Elvenes et al., 2019), the same applies to fjords in Norway. Conversely, the Norwegian Trough is characterised by fine-grained sediments and OC accumulation occurs throughout the geomorphological structure, albeit with varying rates.

Collectively, the sediments of the Norwegian Trough accumulate 1.24 Tg C yr^{-1} over an area of approximately 62,000 km^2, but the uncertainty in this estimate is on the same order of magnitude as the estimate. Nevertheless, this estimate is in good agreement with an earlier published value of 1 Tg C yr^{-1} (de Haas and van Weering, 1997). For comparison, 3.53 ± 2.90 Tg C yr^{-1} are accumulated in the muddy basins of the Baltic Sea (area: 164,800 km^2) (Leipe et al., 2011). Coastal habitats (saltmarsh, seagrass, kelp and tidal flat) on the northwest European continental shelf have been estimated to accumulate 0.2 – 0.7 Tg C yr^{-1} (Legge et al., 2020).

6.2 Zones of organic carbon processing at the seafloor

The regionalisation based on selected characteristic parameters pertaining to OC accumulation and storage has shown that the North Sea and Skagerrak can be divided into distinct zones. The results indicate that shelf sediments can act in distinctly different ways in the context of OC processing at the seafloor. In a way, they also reflect the scientific discourse over the last

315   half century or so: Initially, process studies on OC cycling on the continental shelf focussed on fine-grained sediments associated with hydrodynamically quiet environments, relatively constant sediment accumulation and diffusion-dominated porewater transport. This has led to the notion of rapidly accumulating coastal sediments associated with high sedimentation, high OC burial rates and low oxygen penetration depths (Aller, 2014; Canfield, 1994; Middelburg, 2019; Middelburg et al., 1997).

320   However, approximately 50 % (Hall, 2002) to 70 % (Emery, 1968) of the global shelf consist of coarse-grained sediments (gravel and sand) with high permeabilities. Unidirectional and wave orbital water flows interacting with microscale topography (e.g. ripples and biogenic mounds) at the water-sediment interface lead to increased fluid exchange rates compared to exchange by molecular diffusion (Huettel et al., 1996; Precht and Huettel, 2003). Interaction of flows with surface microtopography increases oxygen penetration depths (Huettel and Rusch, 2000). As a consequence of advective

325   porewater flows, permeable sediments may act as biocatalytic filters, notable for their high reaction rates, intense recycling, and extreme spatial and temporal dynamics of biogeochemical processes (Huettel et al., 2003, 2014).

The seafloor in the Southern Bight, on Dogger and Fisher Banks and in the proximity to west-facing coastlines (apart from the Norwegian west coast) is characterised by shallow water depths, high tidal current speeds, and wave orbital velocities. The probability that the seabed gets disturbed by waves and currents to a depth of 3 cm at least once a year is above 50 % in

330   these areas (Aldridge et al., 2015: Fig. 17a). It can therefore be assumed that ripples are present in these areas at least temporarily and that the interaction of unidirectional and oscillatory currents with these roughness elements leads to enhanced fluid exchange, as sediments are sufficiently permeable. The advective supply of oxygen to the sedimentary microbial community facilitates the effective degradation of OC (Huettel et al., 2014). Consequently, oxygen penetrates deep into these sediments and OC density is low. The potential for longer-term accumulation of OC is very low, as these

335   environments are characterised by repeated erosion-redeposition cycles. This zone of rapid OC processing might equate to the turnover zone of Huettel and Rusch (2000).

Conversely, the seabed of the Norwegian Trough is characterised by water depths in excess of 200 m and experiences very subdued wave and current agitation. Fluid transport in the sediment is therefore driven by molecular diffusion, mediated by bioturbation. Lack of advective oxidation (Huettel et al., 2014; Huettel and Rusch, 2000) combines with mineral protection

340   (Hedges and Keil, 1995; Hemingway et al., 2019; Keil and Hedges, 1993; Mayer, 1994) and short oxygen exposure times (Hartnett et al., 1998) due to shallow oxygen penetration depths and relatively high sedimentation rates. Collectively, this leads to high OC densities and accumulation rates. This zone might be termed burial zone according to Huettel and Rusch (2000).

A third zone is situated in the northern North Sea and the shallow depositional areas of the southern North Sea. It has a
345   transitional character with water depths, current speeds, wave orbital velocities and oxygen penetration depths intermediate
between those of the turnover and the burial zones. OC densities are also intermediate, while OC accumulation is negligible
in this transitional zone.

6.3 Implications for management

We have shown that seabed sediments of the North Sea and Skagerrak are an important store of OC. Furthermore, the
350   Norwegian Trough is an important centre of OC accumulation, with rates on par with neighbouring fjords. Based on those
results it was possible to identify zones of rapid OC turnover and zones of OC burial. These zones act differently in terms of
OC processing and storage and hence will have different relevance in the context of managing OC stores at the seabed.

While the importance of Blue Carbon ecosystems for OC drawdown has been highlighted in the past (Duarte et al., 2005;
Mcleod et al., 2011; Nellemann et al., 2009), the total annual rate in the North Sea region is less than that of seafloor
355   sediments at a sea basin scale. It might therefore be prudent to further explore the idea of MPAs as a tool to mitigate climate
change by protecting and enhancing marine sedimentary OC stores (Roberts et al., 2017), especially as the climate mitigation
potential of marine natural climate solutions (Griscom et al., 2017) has so far been overlooked.

Although more research is needed, it is becoming clearer now that seabed disturbance by demersal fishing leads to increased
OC mineralisation in cohesive sediments in the short-term (van de Velde et al., 2018) and a general impoverishment in OC
360   in the long-term (Martín et al., 2014a). Protecting regional hotspots of OC accumulation from fishing-induced disturbance
might therefore be a suitable measure to increase the climate mitigation potential of the seabed. Likely sites that might
benefit from protection are to be found in the burial zone (i.e. the Norwegian Trough), while it is unlikely that the turnover
zone yields any potential areas worth protecting in this context. Our results could be used jointly with maps showing the
footprint of demersal fishing (Eigaard et al., 2016) and other resources to identify potential sites for the establishment of
365   "carbon protection zones". Such management measures that limit the impacted surface area, allowing carbon stocks and
faunal communities in the sediment to recover from a disturbance, and resulting in the recovery of carbon burial, might be
preferable over technical modifications that reduce the penetration depth of fishing gear (De Borger et al., 2020).

6.4 Suggestions for future research

We have utilised a modelling scheme that allowed us to estimate the uncertainty in the model and in variations of available
370   data. This robust methodology led to relatively high uncertainties in the predictions. We assume that the most likely reason
for this is the nature of the available sample datasets. As we utilised archived samples collected over many years by different
organisations for various purposes, this has led to a somewhat heterogeneous dataset with biases regarding coverage of the
temporal, geographical and environmental (i.e. predictor variable) space. While we believe that making best use of existing
data is important and yields worthwhile insights, this study also highlights the limitations of such an approach.
375   Consequently, there is a need for the collection and analysis of new samples. Sampling design might be guided by the

uncertainty maps provided here. The information gain additional data could give is expected to be highest in areas of high predictive uncertainty. Reducing uncertainty in predictions might have large economic benefits, as has recently been demonstrated for the biological carbon pump (Jin et al., 2020). It may be assumed that sizeable economic benefits could also be achieved by reducing the uncertainty in the predictions of seafloor OC stocks and accumulation rates.

380 Alternatively, if the goal was to create a new baseline dataset covering the whole North Sea and Skagerrak, this might be best achieved by sampling the environmental variable space in a representative way. The relative importance of environmental variables is relatively well known both based on general knowledge and the results of this and other modelling studies. Several methods for optimising sampling design exist, including generalised random tessellation stratified (Stevens Jr and Olsen, 2003) and conditioned Latin hypercube sampling (Minasny and McBratney, 2006) among others.

385 These could be utilised to effectively sample seafloor sediments, thereby minimising sampling effort and prediction uncertainty at the same time. Finally, future process studies might compare results from different zones of OC processing as shown in Figure 6.

Further gains could be achieved by the standardisation of the collection of OC measurements. This includes sampling methods, the measured sediment fraction, defined depth horizons, and the reporting of results, among others. Such a

390 standardisation would increase the comparability of the collected data and could be modelled on the experience of the global soil mapping community (Hengl et al., 2014). The establishment of facilities to store and retrieve quality-controlled global shelf OC data centrally would also be advantageous.

Finally, it would be desirable to complement OC data with measurements on C/N-ratios and $\delta^{13}C$ to estimate the marine versus terrigenous fraction of OC (e.g. Faust and Knies, 2019). A quantification of the autochthonous and allochthonous OC

395 contributions could be achieved with a two-end-member mixing model (Thornton and McManus, 1994). Knowledge of the sources of OC is required for a better understanding of OC sequestration in shelf sediments, but would also be a basic requirement in the context of carbon offset-credits (Macreadie et al., 2019), should such a system be extended to include shelf sediments. For example, the Verified Carbon Standard VM0033 (https://verra.org/methodology/vm0033-methodology-for-tidal-wetland-and-seagrass-restoration-v1-0/), the first voluntary market methodology for blue carbon ecosystems,

400 stipulates that offset-credits are not allocated under the framework for allochthonous OC because of the risk of duplicating C sequestration gains that may have been accounted for in adjacent ecosystems (Macreadie et al., 2019).

7 Conclusions

This work highlights distinct zones of OC processing at the seafloor of the North Sea and Skagerrak. While rapid OC processing and turnover are commonplace in the southern and eastern parts of the North Sea, the Norwegian Trough stands

405 out as a hotspot of OC accumulation with rates on par with nearby fjords. We expect that this dual character of the continental shelf in terms of OC processing and storage can be found across the global shelf, requiring further detailed and spatially explicit analyses to constrain sedimentary OC stocks and accumulation rates globally. Such estimates are urgently

needed to better understand the potential of shelf sediments as a natural climate solution, e.g. by protecting suitable areas against human disturbance.

Code availability

The following R Markdown documents are provided as supplements:

Supplement S1: Sedimentation Rates and Uncertainty

Supplement S2: Organic Carbon Density and Uncertainty

Supplement S3: Organic Carbon Accumulation Rates and Uncertainty

Supplement S4: Regionalisation of the Environment

Data availability

Grids of sedimentation rates, OC density, OC accumulation rates and their associated uncertainties will be made available on pangaea.de.

Sample availability

The following data tables are provided as supplements:

Supplementary Data Table 1: Linear sedimentation rates

Supplementary Data Table 2: Organic carbon densities

Author contribution

Conceptualization – MD, TT, LRB; Data curation – MD; Formal Analysis – MD; Funding acquisition – TT, LRB; Investigation – MD; Methodology – MD; Project administration – LRB, TT; Validation – MD; Visualization – MD; Writing – original draft – MD; Writing – review & editing, TT, LRB

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Predictor variables used in the sedimentation rate and OC density models.

Predictor variable	Unit	Model	Source
Bathymetry	m	Both	EMODnet Bathymetry Consortium (2018) Mitchell et al. (2019)
Euclidean distance to shoreline	m	Both	Calculated
Mud content	%	Both	https://doi.org/10.14466/CefasDataHub.63 Mitchell et al. (2019)
Sand content	%	Sedimentation rate	https://doi.org/10.14466/CefasDataHub.63 Mitchell et al. (2019)
Gravel content	%	Sedimentation rate	https://doi.org/10.14466/CefasDataHub.63 Mitchell et al. (2019)
Folk textural class	-	Sedimentation rate	https://doi.org/10.14466/CefasDataHub.63 Mitchell et al. (2019)
Suspended particulate matter (summer)	g m^{-3}	Both	http://marine.copernicus.eu/ Mitchell et al. (2019)
Suspended particulate matter (winter)	g m^{-3}	Both	http://marine.copernicus.eu/ Mitchell et al. (2019)
Tidal current speed (M2 constituent)	m s^{-1}	Both	https://doi.org/10.14466/CefasDataHub.62 Mitchell et al. (2019)
Peak orbital velocity	m s^{-1}	Both	https://doi.org/10.14466/CefasDataHub.62 Mitchell et al. (2019)
Ratio of tidal boundary layer thickness to water depth	-	Sedimentation rate	Williams et al. (2019)
Geomorphology	-	Sedimentation rate	Derived from Harris et al. (2014)
Sedimentary environment	-	Sedimentation rate	Derived from Mitchell et al. (2019)
Bottom water oxygen (mean)	mol m^{-3}	OC density	http://www.bio-oracle.org/index.php Assis et al. (2018), Tyberghein et al. (2012)
Oxygen penetration depth δ	cm	OC density	Calculated from mud content (pers. comm. John Barry, Cefas): $\delta = e^{(1.0745-0.1431\cdot mud)}$ for mud ≤ 8.0 % $\delta = e^{-0.0706}$ for mud > 8.0 %
Oxygen exposure time	yr	OC density	Calculated from sedimentation rate and oxygen penetration depth:

			$OET = \dfrac{\delta}{\omega}$
Bottom water temperature (mean)	ºC	OC density	http://www.bio-oracle.org/index.php Assis et al. (2018), Tyberghein et al. (2012)
Sea surface primary production (mean)	g m⁻³ day⁻¹	OC density	http://www.bio-oracle.org/index.php Assis et al. (2018), Tyberghein et al. (2012)
Sedimentation rate ω	cm yr⁻¹	OC density	Modelled (this study)

Table 2: Breakdown of topsoil (0-10 cm) OC stocks by country, compared with marine sediment OC stocks. Topsoil OC stocks
710 **refer to the entire area of the respective country bordering on the North Sea and Skagerrak.**

Country	Soil OC (0-10 cm), Tg	Marine sediment OC (0-10 cm), Tg	Marine sediment OC % of Soil OC	Mapped area % of total EEZ
Belgium	109.3	0.7	0.7	95.3
Denmark	236.6	17.8	7.5	55.1
France	2026.1	0.4	0.0	0.5
Germany	1808.9	8.8	0.5	64.4
Netherlands	198.0	14.1	7.1	91.5
Norway	2253.6	83.9	3.7	13.7
Sweden	3333.2	5.0	0.1	3.7
United Kingdom	1572.3	103.1	6.6	32.7
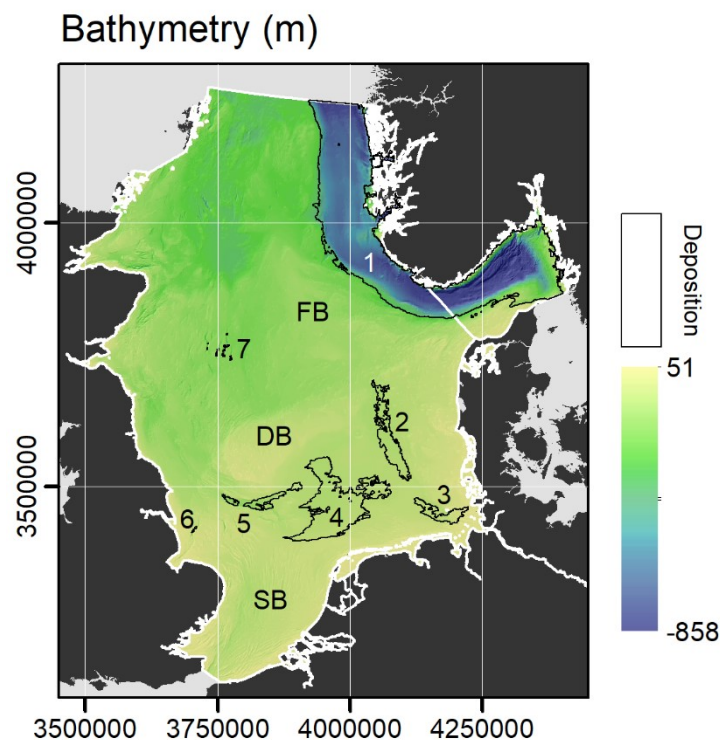
Figure 1: Overview of the study site. Letters refer to localities: DB – Dogger Bank; FB – Fisher Bank; SB – Southern Bight.
715 **Numbers refer to areas of sediment deposition: 1 – Norwegian Trough; 2 – Elbe palaeo-valley; 3 – German Bight; 4 – Oyster Ground; 5 – Outer Silver Pit; 6 – Inner Silver Pit; 7 – Devil's Hole**
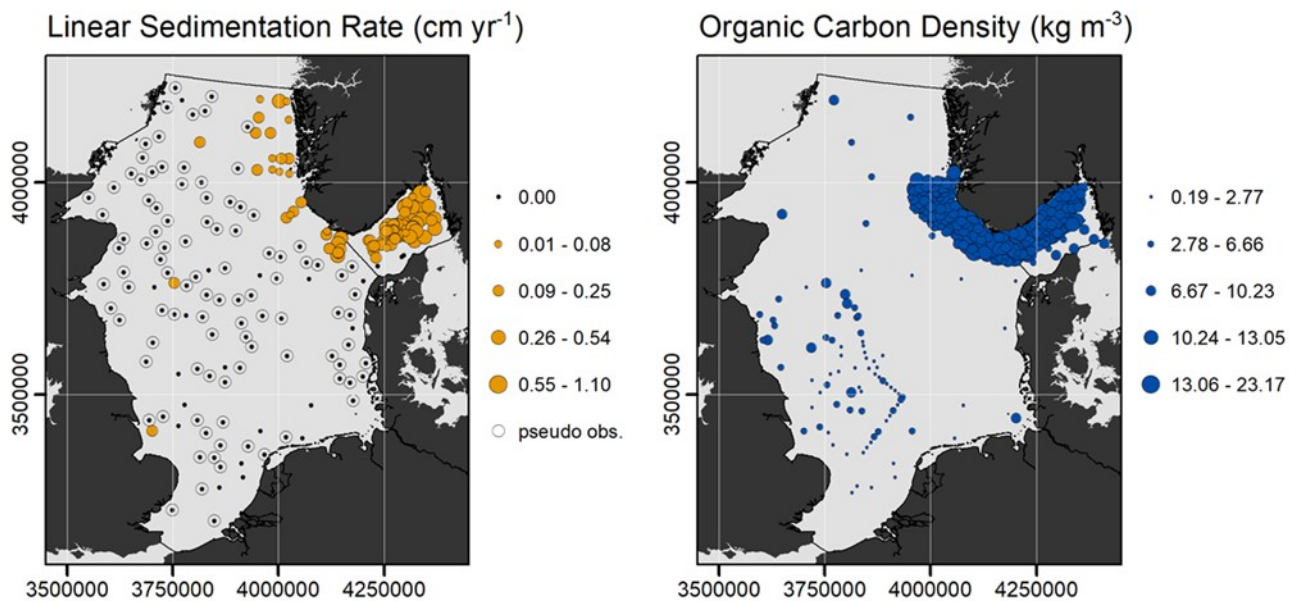
Figure 2: Available samples on sedimentation rate (left) and OC density (right)

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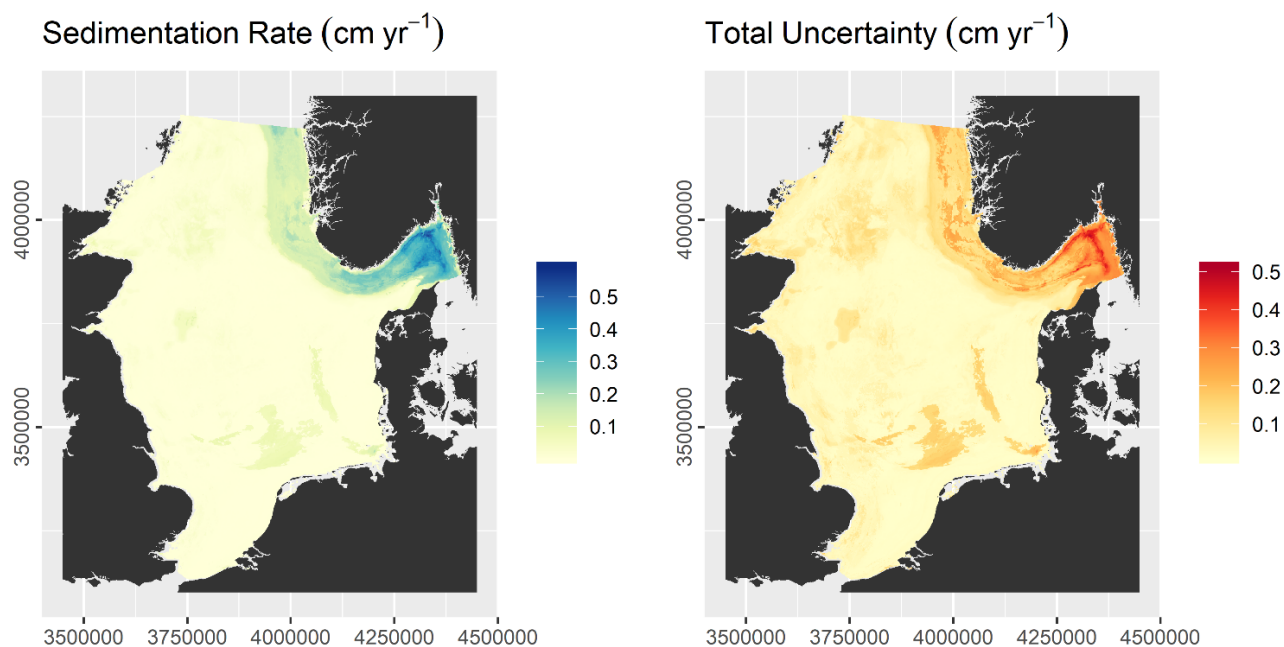
Figure 3: Predicted sedimentation rate (left) and associated uncertainty in the predictions.
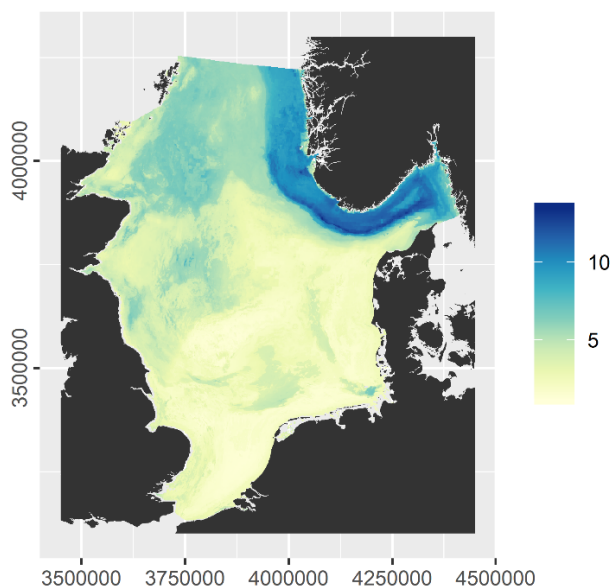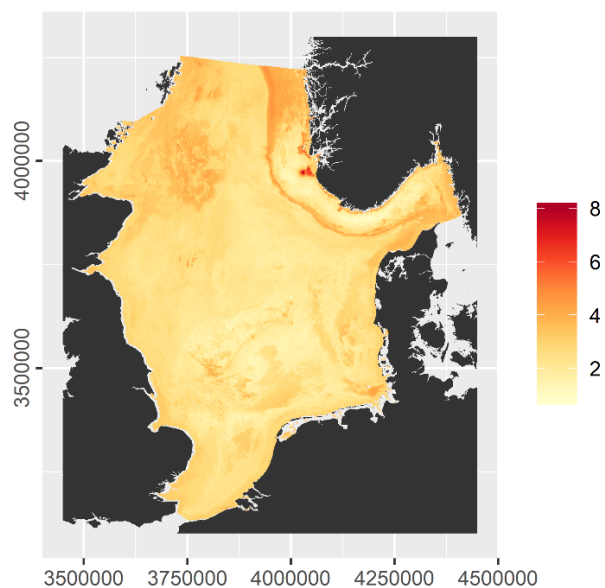
Figure 4: Predicted OC density (left) and associated uncertainty in the predictions (right).
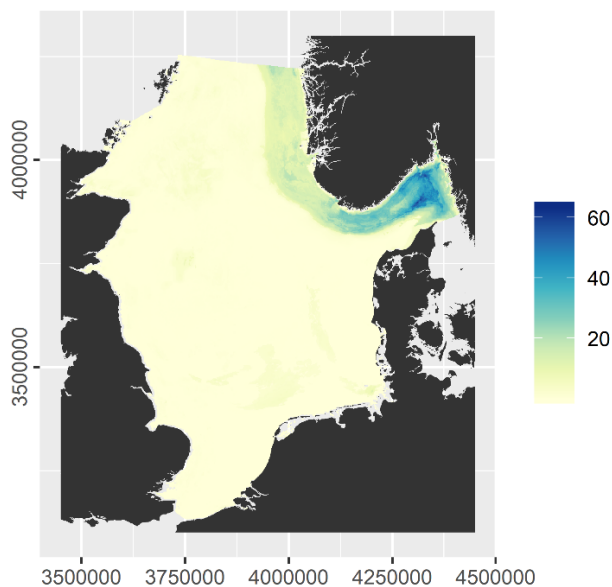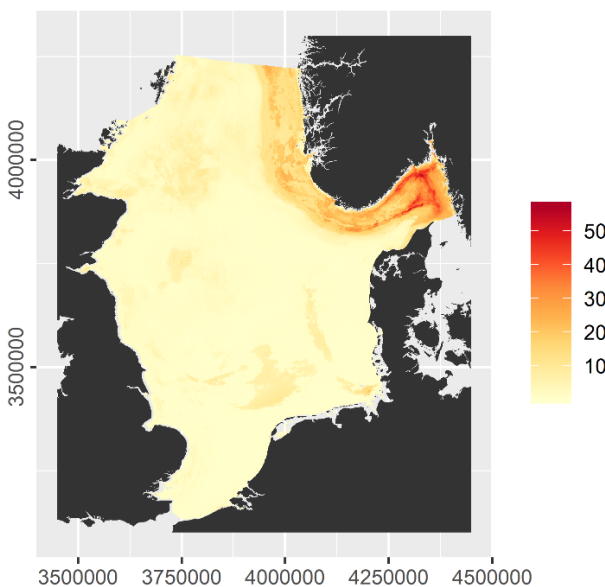
Figure 5: Calculated OC accumulation rate (left) and associated uncertainty (right)
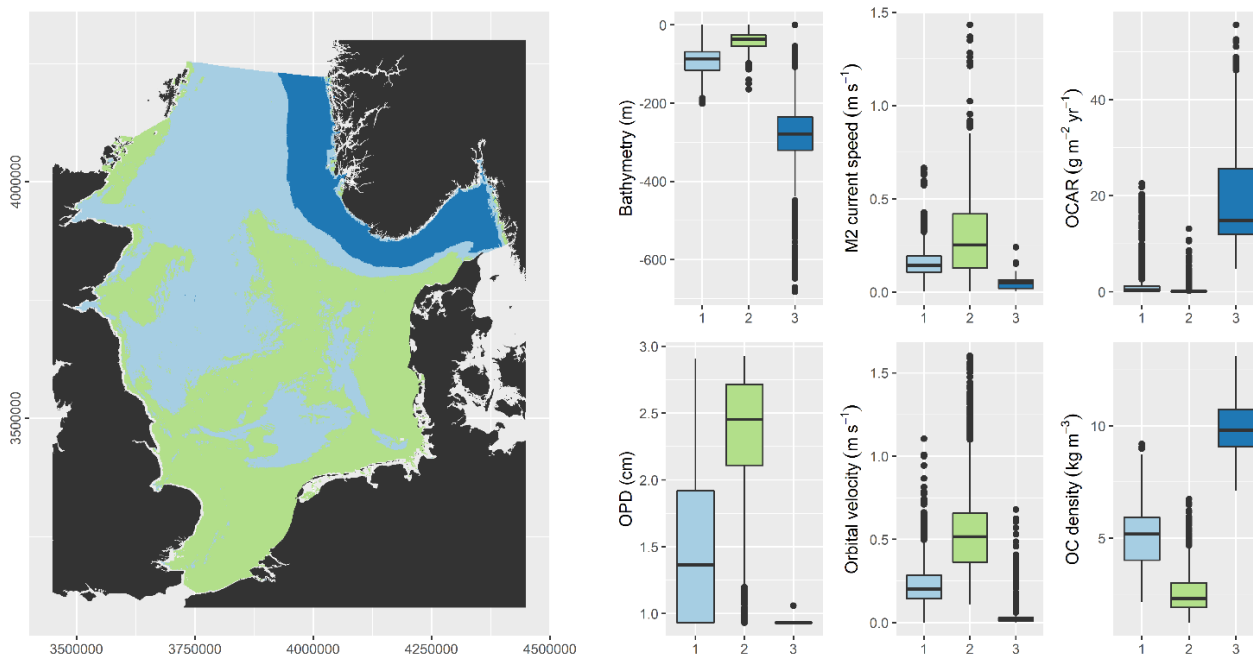
Figure 6: Regionalisation of the North Sea and Skagerrak: Region 1 (light blue) – transition zone; Region 2 (green) – turnover zone; Region 3 (dark blue) – burial zone. Note that boxplots are based on 10000 randomly placed points, rather than all pixels.