



Sedimentary blue carbon around decommissioned oil and gas platforms in the North Sea

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ABSTRACT

Shelf sea habitats contain significant sedimentary carbon stocks, due to their large spatial extent, and act as key ecosystems for global carbon cycling. These shelf sediments are subject to a range of anthropogenic pressures including seabed trawling, climate change and the introduction of man-made structures (MMS), such as oil and gas platforms. In the North Sea, following their production lifespan, MMS are required to be mandatorily decommissioned under OSPAR Decision 98/3. Understanding the impact of decommissioned MMS on sedimentary carbon stores is a significant research gap, as these platforms are widespread throughout many shelf seas, with many now exceeding or approaching the end of their designed lifespan. In this study we quantify carbon stocks, organic and inorganic carbon content, and sediment characteristics from shelf sediment cores taken at increasing distances (50–3200 m) away from two decommissioned North Sea oil and gas platforms, Miller and North West Hutton. Carbon accumulation rates were also determined for sediments collected around North West Hutton. Organic carbon content at Miller was highest within 50 m (24.55 ± 2.49 mg/g of sediment) of the decommissioned platform and significantly lower across all other sampling distances. Conversely, organic carbon content at North West Hutton did not vary greatly with distance; however, a significant decrease was seen at 200 m. These findings highlight that carbon dynamics around decommissioned oil and gas platforms are site-specific. Moreover, the absence of pre-decommissioning data limits our ability to disentangle the effects of decommissioning on sedimentary carbon.

1. Introduction

The North Sea has been extensively modified by anthropogenic activities including the introduction of man-made structures (MMS) (Fowler et al., 2020; Dannheim et al., 2018). The global footprint of MMS, such as oil and gas (O&G) platforms and offshore wind farms, is growing rapidly with projected expansion from 32,000 km² in 2018 to 39,400 km² by 2028 (Bugnot et al., 2021), driven by a rising demand for fossil fuels and renewable energy (Birchenough and Degraer, 2020). Within the Oslo and Paris Convention (OSPAR) maritime area alone there are over 1350 offshore oil and gas installations that require decommissioning in the coming decades (Fortune and Paterson, 2020). By 2040, it is estimated that 2000 offshore oil and gas platforms will have to be decommissioned worldwide (Vidal et al., 2022; Wei and

Zhou, 2024).

The effect of O&G platforms on the marine environment is still an expanding area of research, which has primarily focused on changes to marine biology, such as food webs (Fowler et al., 2020; Todd et al., 2018; Wright et al., 2020; Fujii and Jamieson, 2016), connectivity and invasive species (Coolen et al., 2020; van der Molen et al., 2018; Tidbury et al., 2020), fish attraction versus production (Todd et al., 2018; Brickhill et al., 2005; Grossman et al., 1997; Pickering and Whitmarsh, 1997) and seabird interaction (Ronconi et al., 2015). However, the effect of MMS on the seabed around these structures, and particularly on benthic carbon stocks, is poorly understood.

Shelf seas and the sediments therein play a key role in maintaining marine carbon stocks (Legge et al., 2020; Burdige, 2007; Smeaton et al., 2021) and supporting organic carbon sequestration potential (Graves

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et al., 2022; Atwood et al., 2020; LaRowe et al., 2020). Blue Carbon refers to organic carbon that is captured and sequestered in marine ecosystems, including coastal and ocean environments (Nellemann et al., 2009). This organic carbon is modified and remineralised while it descends through the water column (Soetaert et al., 2000). However, a proportion is stored within shelf sediment where it is further remineralised through diagenetic processes (Soetaert et al., 1996; Talin et al., 2002) or eventually, buried (Burdige, 2007). Despite covering only 7–10 % of worldwide ocean area, shelf seas contribute 80 % of organic carbon in sediments (Bauer et al., 2013), making them vital for climate change mitigation (Luisetti et al., 2020). It is estimated that global sedimentary blue carbon stocks are 2322 Pg C in the top 1 m of sediment (Atwood et al., 2020). Furthermore, the North-West European continental shelf area is estimated to have a standing organic carbon stock of between 230 and 882 Mt. of POC in the upper 10 cm of sediment (Diesing et al., 2017).

Previous blue carbon research has largely focused on vegetated coastal habitats as these sequester significantly more carbon than other terrestrial habitats (McLeod et al., 2011; Macreadie et al., 2017, 2019; Lovelock and Duarte, 2019). More recently, shelf sediment ecosystems are increasingly recognised for their significant storage of blue carbon due to their large spatial extent (Legge et al., 2020; Thomas et al., 2004; Luisetti et al., 2019; Diesing et al., 2017). However, shelf sediment is subject to substantial disturbance from activities such as trawling (Eigaard et al., 2017; Palanques et al., 2014; Dounas et al., 2007) and construction and decommissioning of offshore MMS (Birchenough and Degraer, 2020; Dannheim et al., 2020; Fortune and Paterson, 2020). While the effect of disturbance on carbon stocks remains unclear (Epstein et al., 2022), it is essential to determine potential impacts of anthropogenic activity, such as decommissioning of MMS, on shelf sedimentary carbon stocks.

Currently under OSPAR Decision 98/3, MMS in the North Sea are required by law to be fully removed from the sea at the end of its active life cycle, and the marine environment to be returned to its natural state prior to construction (Fortune and Paterson, 2020; Bull and Love, 2019; Fowler et al., 2014, 2020). Recent literature has started to explore the effect of disturbance to benthic carbon stocks, with an emphasis on trawling (Porz et al., 2024; Epstein et al., 2022; De Borger et al., 2021; Paradis et al., 2021). Any pressure which changes the degradation rates within upper sediment depth, or input of carbon to the seabed will likely disrupt the overall carbon stock and sequestration rates (Legge et al., 2020). Decommissioning of MMS, especially ‘whole removal’ which is preferred by OSPAR commission regulations (OSPAR, 1998) is a significant form of marine disturbance (Sommer et al., 2019).

Removing oil and gas structures typically involves abrasive water jetting, diamond wire cutting, hydraulic shears or explosives (Sommer et al., 2019). These methods not only cause complete mortality of attached invertebrates and nearby fish but likely impact the benthic environment during the removal of the steel jackets and concrete foundations (Jagerroos and Krause, 2016). With the mandatory decommissioning of many platforms approaching rapidly, it is vital to determine how these activities affect sedimentary organic carbon storage and sequestration rates. Exclusion zones, particularly the 500 m zones around active O&G platforms, provide an area free from disturbance by trawling and other extractive uses. These undisturbed zones could potentially safeguard carbon stocks and facilitate recovery (Epstein and Roberts, 2022). Moreover, decommissioned O&G platforms are often surrounded by drill cuttings piles (Breuer et al., 2004). These piles, produced during offshore hydrocarbon drilling operations, are composed of subsurface rock coated with hydrocarbons and drilling fluids (Bakke et al., 2013; Haanes et al., 2023), that could influence seabed carbon stocks. Including carbon stock considerations, alongside other factors such as expense and environmental impact (Hall et al., 2022; Sommer et al., 2019) into cost-benefit analysis of decommissioning methods (Fowler et al., 2014) could provide managers with more information to determine best practices (Fortune and Paterson,

2020; Zawawi et al., 2012). This is the first study to investigate the benthic carbon dynamics around decommissioned O&G structures in the North Sea, and with samples taken as close as 50 m. The overall aim of this study is to determine the effect of decommissioned O&G platforms on organic sedimentary carbon stocks and sedimentation/carbon accumulation rates, compared to areas which have not been excluded from anthropogenic extraction activities.

2. Methods

2.1. Study sites

Sediments at two decommissioned O&G platforms, North West Hutton (61°6′ 23.9508″, 1°18′32.9724″) and Miller (58° 43′ 19.7004″, 1° 24′ 7.4016″), were sampled between 24th and the 30th of June 2021, during a research cruise on the MRV *Scotia* (Fig. 1). The North West Hutton platform was installed in 1981, with oil production commenced in 1983 and continued until 2003 (Blacklaws and Johnston, 2013). Topsides of the platform were removed in 2008 and removal of the jacket structure was completed in 2009 (BP, 2005). Water depth at this platform is 144.3 m (BP, 2005), with prevailing currents in a NE/SW direction alongside weak residual currents (BP, 2005) with maximum current speeds being 0.73 m/s at the surface and 0.47 m/s at the seabed. The Miller platform was installed in 1991 and produced oil from June 1992 to September 2007 (BP, 2011). Topsides were removed between 2017 and 2018; jacket structure removal was completed in 2018 (BP, 2011). Water depth at the Miller platform is 103 m, with the Fair Isle/Dooley current affecting the Miller platform which flows in a SE/NW direction with maximum current speeds being 0.84 m/s at the surface and 0.43 m/s at the seabed (BP, 2011). For both sites the jacket footings and drill cuttings piles remain in-situ. Jacket footings were cut at 45 m and 20 m above the seabed for the North West Hutton and Miller platforms, respectively. The drill cutting pile at North West Hutton lies directly beneath the footings, while at Miller, it is offset to the southeast footing. These sites were selected due to age (over 40 years since installation) and decommissioning status. Where possible, triplicate sediment cores were taken at various distances along northern and southern transects extending away from the decommissioned platforms (50, 100, 200, 400, 800, 1600 m). Due to safety features of the research vessel, samples could not be taken any closer than 50 m away from the platforms. Control sites of similar sediment composition were selected at 3200 m away along each of the gradients. These control samples were known to not be near other oil rigs at any phase during their use (i.e., construction, operational or decommissioned). There were no visible signs of oil contamination on the sea surface during the survey.

2.2. Sediment core sampling and processing

Samples were obtained using a multi-corer, when weather permitted, to extract three replicate sediment cores (inner Ø 9.8 cm) at each sampling distance. When weather was too severe for the multi-corer, cores were collected using a grab, and cores taken from the grab only if the sediment surface was intact (see Supplementary Table 1 for full sample details). Depths of each core collected were noted. Cores were extruded onboard and sliced into 1 cm depth increments and stored in plastic bags at −20 °C until further analysis. Each sediment slice was measured for wet weight (g) and freeze dried to give dry weight to determine porosity and dry bulk density (DBD).

2.3. Biogeochemical analysis

Three homogenous powder subsamples of each 1 cm layer were analysed for organic and inorganic carbon using a Formacs^{HT} TOC Analyser with Primacs^{MCS} add-on module (SKALAR, The Netherlands). Between 50 and 100 mg of each sample was weighted into quartz crucibles, manually inserted into the analyser, and then heated to

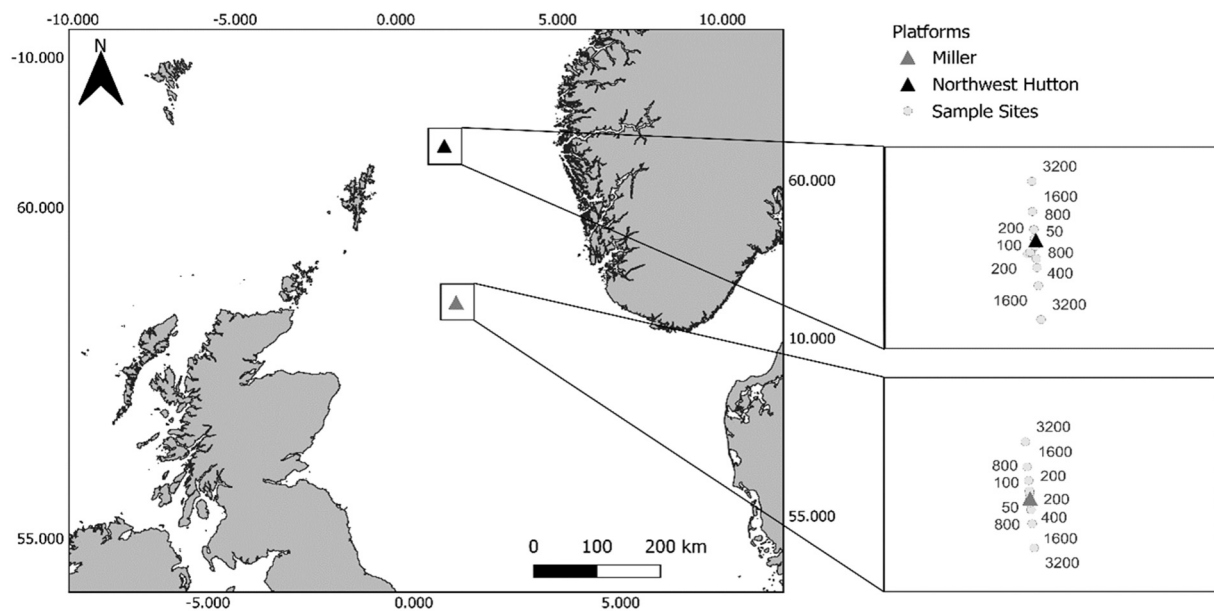


Fig. 1. Location of North West Hutton and Miller decommissioned platforms in the North Sea with sampling sites at varying distances (50–3200 m (Control)).

>1000 °C. For inorganic carbon, samples were acidified using 5 M phosphoric acid and resultant CO₂ was measured. For each sample, inorganic carbon was subtracted from total carbon to give a measurement of organic carbon, giving measures of total, organic and inorganic carbon for each core slice.

Particle size analysis (PSA) was conducted using the laser diffraction unit Betsizer S3 Plus (China). PSA methodology was adapted from the National Marine Biological Analytical Quality control (NMBAQC) scheme (Mason, 2022). Freeze dried sediment samples were analysed using laser diffraction. The quantity of sample entered was varied to ensure laser beam obscuration remained within 8 and 12 %. One replicate was analysed for each 1 cm depth of the core with the particle size analyser, taking another three replicate readings from each. Sediment characteristics statistics, mean and median grain size, skew, and kurtosis were calculated using GRADISTAT software version 9.1 (S. Blott, June 2020). Characterisation of sediment was determined using Folk description, assigning sites to one of the fifteen major textural groups as defined by the relative percentage of gravel (>2 mm), sand (0.0625–2 mm), mud (<0.625 mm) (Folk, 1954).

Preliminary GC–MS analysis of hydrocarbon content in sediment showed an insignificant contribution to total carbon content (<2 %) even at sampling points closest to both platforms (50 m) see Gregson et al., under review for methodology. Total hydrocarbon content (mg/g of sediment) at varying distances from both North West Hutton and Miller decommissioned platforms is included in supplementary Fig. 2 from the UK Benthos database v5.17 (Offshore Energies UK, 2015). As both measures indicate hydrocarbon content within sediment to be <8 % of measured organic carbon content this was not considered in this paper.

2.4. Estimated mass accumulation and sedimentation rates

Mass accumulation and linear sedimentation rates (MAR/LSR) were determined using the Constant Flux – Constant Sedimentation (CFCS) ²¹⁰Pb-based modelling approach (Krishnaswamy et al., 1972) from ten sediment cores collected at five distances (50, 100, 200, 400 and 3200 m) from each directional transect at North West Hutton. Approximately 27 g of each 1 cm slice were freeze dried, sieved down to 500 µm, compressed, and sealed into plastic containers. After a period of three weeks (to allow for secular equilibrium between ²²⁶Ra and ²¹⁴Pb), samples were analysed by gamma spectrometry using Broad Energy

Germanium detectors (ORTEC, GEM-FX 8530-S model, USA) to determine the total ²¹⁰Pb and ¹³⁷Cs activity concentrations with the emission peaks of 46.5 and 662 keV respectively. Activity concentrations of total ²²⁶Ra were indirectly measured using the peak at 352 keV from the presence of ²¹⁴Pb, one of its decay products. A certified reference material from International Atomic Energy Agency (IAEA) – IAEA-465 Baltic Sea Sediment was used as a reference for quantifying these radioelements in the studied samples (International Atomic Energy Agency, 2021).

2.4.1. Lead-210 based modelling and validation

Lead-210-based modelling approaches have been widely used to estimate organic carbon accumulation rates (OCAR) in marine sediment cores (de Haas, 1997; Masque et al., 2002; Arias-Ortiz et al., 2018). These approaches rely on the depth distribution of unsupported fraction of ²¹⁰Pb, directly sourced from the decay of radon gas (²²²Rn) present in the atmosphere and decaying at rate of 22.23 years. As the studied cores were relatively shallow (<15 cm) and many natural and anthropogenic disturbance were anticipated, including the presence of oil and gas produced water derived particles enriched in ²²⁶Ra, ²¹⁰Pb and stable elemental analogues, such as Ba and Pb (Ahmad et al., 2021; Haanes et al., 2023) the constant flux-constant sedimentation (CF-CS) modelling approach was favoured against other common modelling approaches and selected to estimate directly the mass accumulation rate (MAR) from each core. The CF-CS model was selected to enable the estimation of a mean MAR below a potential surface mixed layer and was assumed to be constant over time following Eq. (1):

$$^{210}\text{Pb}_x = ^{210}\text{Pb}_0 \cdot e^{-\lambda x / \text{MAR}} \quad (1)$$

With ²¹⁰Pb_x: activity concentration of unsupported ²¹⁰Pb at mass depth x (in Bq.kg⁻¹); ²¹⁰Pb₀: activity concentration of unsupported ²¹⁰Pb at water/sediment interface (in Bq.kg⁻¹); λ: decay constant of ²¹⁰Pb = 0.031 y⁻¹; m_x: accumulated mass stock (in g.cm⁻²) at depth x; MAR: mass accumulation rate (g.cm⁻².y⁻¹).

Linear sedimentation rates (LSR) could then be estimated at each studied location by dividing with the average dry bulk density of the core segment selected in the CF-CS model. Organic carbon accumulation rates (OCARs) were determined using MAR multiplied by percentage of organic carbon derived from the average along the entire core depth at each site (%OC).

Fractions of anthropogenic ²²⁶Ra were subtracted from the total

^{226}Ra activity concentrations prior to utilising the CF-CS model, by referring to barium (Ba) depth profiles, a chemical analogue of ^{226}Ra , and measured by ICP-MS following total microwave-assisted digestion, alongside other stable elements (Agilent, 7900ce model, USA).

Where possible, the 1978 Sellafield-derived ^{137}Cs signature (i.e., 1974–1975 peak discharge including a 4-year transient time from discharge point (Gray et al., 1995; Povinec et al., 2003) were also used to validate LSR results obtained from CF-CS modelling. For highly contaminated cores at 50 m, mid-core enrichment of ^{226}Ra was used as an estimate to validate ^{210}Pb excess based CF-CS modelling rather than to estimate MAR/LSR directly. This mid-core enrichment was determined as the mid-point of production from the platform. However, due to this contamination, MAR/LSR were not calculated at 50 m due to uncertainties without a clear fingerprinting tool.

2.5. Organic carbon stock calculations

Stock calculations of sedimentary carbon surrounding both platforms were calculated using methods and equations from (Diesing et al., 2017). Estimation of mass of particulate organic carbon (m_{POC}) was calculated by multiplying particulate organic carbon as a dimensionless fraction, dry bulk density (ρ_d), sediment depth (d) and area (A).

$$m_{\text{POC}} = \text{POC} \cdot \rho_d \cdot d \cdot A \quad (2)$$

2.5.1. Dry bulk density

Dry bulk density was calculated using Eq. (2). Where dry bulk density (ρ_d) was determined using porosity (φ) and grain density (ρ_s). Grain density was assumed to be 2650 kg m^{-3} .

$$\rho_d = (1 - \varphi)\rho_s \quad (3)$$

2.5.2. Porosity

Porosity was calculated using weight before ($\text{Weight}_{\text{Wet}}$) and after ($\text{Weight}_{\text{Dry}}$) freeze drying as well as the specific gravity of the sediment (SG_{Sed}) and density of water calculated based on salinity (ρ_{Water}). For offshore sediments of this nature this was assumed to be composed of mostly quartz/feldspar so specific gravity was assumed to be 2.7. Salinity for the density of water was assumed to be that of offshore water (35) and a density of 1.035 kg/l .

$$\varphi = \frac{\left[\text{SG}_{\text{Sed}} - \text{SG}_{\text{Sed}} \left(\frac{\text{Weight}_{\text{Wet}}}{\text{Weight}_{\text{Dry}}} \right) \right]}{\left[\text{SG}_{\text{Sed}} - \text{SG}_{\text{Sed}} \left(\frac{\text{Weight}_{\text{Wet}}}{\text{Weight}_{\text{Dry}}} \right) \right] + \left[\rho_{\text{Water}} - \rho_{\text{Water}} \left(\frac{\text{Weight}_{\text{Wet}}}{\text{Weight}_{\text{Dry}}} \right) \right]} \quad (4)$$

2.6. Statistical analysis

All statistical analysis was conducted using R version 4.2.1. All figures were generated using the 'ggplot2' (Wickham, 2010), 'corrplot' (Wei and Simko, 2021) and 'cowplot' (Wilks, 2020) packages. Data was initially tested for normality using Shapiro-Wilk tests (Shapiro and Wilk, 1965) and subsequent Bartlett tests (Bartlett, 1937) to determine homogeneity of variance between groups. Normally distributed data were tested for significance using ANOVAs, with p -values adjusted for multiple comparisons using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995), followed by a Tukey's HSD (Tukey, 1953) post hoc test within the 'agricolae' (De Mendiburu, 2020) package. Non-

normally distributed data were tested for significance using a Kruskal-Wallis test, with p -values adjusted for multiple comparisons with Bonferroni corrections (Bonferroni, 1936), followed by Dunn's post hoc test (Dunn, 1964) within the 'FSA' package (Ogle et al., 2020). Spearman correlation tests were applied to assess correlations between organic carbon content, inorganic carbon content, mud content, sand content sedimentation rates and distance from platform. To test for effect size of Kruskal-Wallis tests, Cohen's f (Cohen, 1988) was calculated using the 'rcompanion' package (Mangiafico, 2023), followed by a power analysis using the 'pwr' package (Champely, 2020) For pairwise comparisons Cliff's delta (Cliff, 1996) (with a large effect size being >0.474) was calculated with the 'effsize' package (Torchiano, 2020) and subsequent power analysis was calculated for each comparison with an acceptable threshold of 0.8.

3. Results

3.1. Sediment composition

Sediment classifications varied from sand to sandy mud across both sites and distance gradients. Sediment water depth, core type, classification and porosity are displayed in Supplementary Table 1. Mud content across all sites ranged from 1.58 % to 86.28 %, although North West Hutton had higher average mud content across all distances compared to Miller (Fig. 2). Highest average mud content was found at 50 m and 100 m away from North West Hutton, with average mud percentage being 59 % and 38 %, respectively. Average mud content at Miller was similarly high at the 50 m distance with an average of 47 %. Mud content remained lower with greater distance from Miller. Sediment composition at both sites was predominantly either sand or mud, with very few observed gravel particles, hence, mud and sand percentages inversely mirror each other. Sand content across all sites ranged from 13.72 % to 96.96 % (Fig. 2). Miller consistently had higher sand content across all distances compared to North West Hutton.

3.2. Organic carbon content

Organic carbon content ranged from 0.26 to 51.78 mg/g of sediment (Fig. 3). Highest average organic carbon content ($31.62 \pm 1.09 \text{ mg/g}$ of sediment; mean $\pm$ SE) was found 1600 m from North West Hutton,

followed by the control site (3200 m) ($27.78 \pm 1.12 \text{ mg/g}$ of sediment). Organic carbon content was significantly lower at 200 m ($17.86 \pm 1.22 \text{ mg/g}$ of sediment) away from North West Hutton (Kruskal-Wallis, $\chi^2 = 76.535$, $P = 1.854 \times 10^{-14}$, $1 - \beta = 1$) compared to all other sampling distances. Conversely, a different trend was seen at the Miller, with the highest average organic carbon content at the closest distance (50 m) ($24.54 \pm 2.49 \text{ mg/g}$ of sediment), which was significantly higher (Kruskal-Wallis, $\chi^2 = 66.084$, $P = 2.635 \times 10^{-12}$, $1 - \beta = 1$) than all other distances. On average, organic carbon content was higher at the North West Hutton compared to Miller, for example average organic carbon content at the control site of North West Hutton was up to 6.6-fold higher compared to sediment collected at the corresponding site at Miller. Pairwise comparisons of organic carbon of effect size and power between distance groups are shown in Supplementary table 2. Organic carbon depth profiles are displayed in supplementary Figs. 3 to 6.

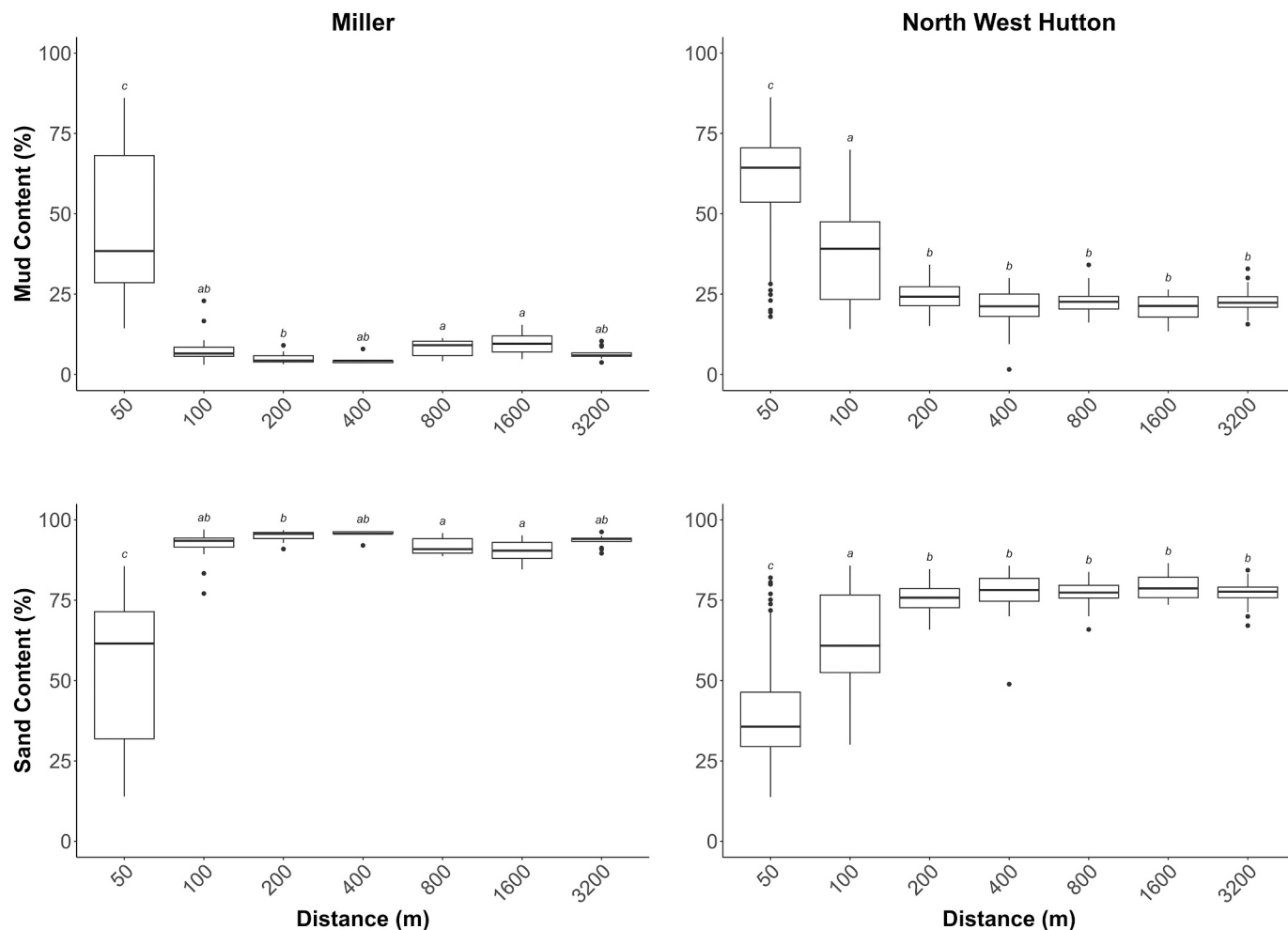


Fig. 2. Mud and sand content (%) of 1 cm sediment core slices collected at increasing distances (50–3200 m) away from two decommissioned oil and gas platforms, Miller and North West Hutton. Sediment was analysed to 10 cm at North West Hutton and 6 cm at Miller. Letters above boxes (a, b, c) indicate significant differences between distances ($P < 0.05$, Kruskal-Wallis test followed by Dunn's post hoc test); different letters indicate significant differences.

3.3. Inorganic carbon content

Inorganic carbon content ranged from 0.14 to 45.14 mg/g of sediment across both decommissioned platforms (Supplementary Fig. 1). A similar pattern was observed for inorganic carbon content, that was also seen for organic carbon content. A significantly higher average inorganic carbon content (Kruskal-Wallis, $\chi^2 = 133.16$, $P = 2.2e^{-16}$) was found at the control site of North West Hutton (24.29 ± 0.62 mg/g of sediment), when compared to closer distances (e.g. 50, 100, 200, 400 and 800 m) away. The lowest average inorganic carbon content was found at the 50 m distance, closest to North West Hutton (6.04 ± 0.66 mg/g of sediment). Conversely, at Miller, average inorganic carbon content was significantly higher (Kruskal-Wallis, $\chi^2 = 82.07$, $P = 1.334e^{-15}$) closer, at 50 m distance (7.27 ± 1.19 mg/g of sediment) than all other distances (100, 200, 400, 800, 1600 and 3200 m). On average, organic carbon content was higher at North West Hutton compared to Miller. For example, average inorganic carbon content at the control site of North West Hutton was up to 20.4-fold higher compared to sediment collected at the same site at Miller.

3.4. Sediment organic carbon stocks

Average sediment organic carbon stocks ranged from 0.59 to 5.01 kg m^{-2} across both sites and distances (Fig. 4). Resolution of stocks ranged from 3 cm to 10 cm with consistently higher resolution at North West

Hutton (ten sampling sites had 10 cm depths analysed). Miller resolution ranged from 3 to 10 cm, but had an average depth of 6 cm. Estimated carbon stocks were averaged and extrapolated to 10 cm (Fig. 4; represented by hashed portions of each bar). The largest average organic carbon stocks were found at 800 m on the southern transect from North West Hutton (5.01 ± 0.62 kg m^{-2}) and lowest was found at 400 m on the southern transect of Miller (0.59 kg m^{-2}), though this distance only had one replicate to 5 cm depth.

Miller had highest organic carbon stocks at 50 m on both the northern and southern transects with averages of 1.47 ± 0.53 kg m^{-2} and 3.74 ± 0.36 kg m^{-2} , respectively. At greater distances (100 to 3200 m) along the southern transect, organic carbon stocks remained consistently lower with an average of 0.88 ± 0.13 kg m^{-2} , at 100 m distance, to 0.72 ± 0.05 kg m^{-2} , at 1600 m, and 0.68 kg m^{-2} at 3200 m, however at 3200 m there was only one core available. A similar trend occurred on the northern transect with average organic carbon stocks of 0.65 ± 0.04 kg m^{-2} , at 100 m, and 0.65 ± 0.03 kg m^{-2} at 3200 m.

Comparatively, North West Hutton had consistently higher organic carbon stocks than those found at Miller, which generally remained constant with distance. Along the southern distance transect, average organic carbon stocks at 50 m were 2.44 ± 0.223 kg m^{-2} which gradually increased to 3.65 ± 0.35 kg m^{-2} at 400 m. At 800 m, organic carbon stocks increased to 5.01 ± 0.63 kg m^{-2} , but subsequently decreased to 3.27 ± 0.67 kg m^{-2} at 3200 m. Along the northern transect at North West Hutton, average organic carbon stocks increased from

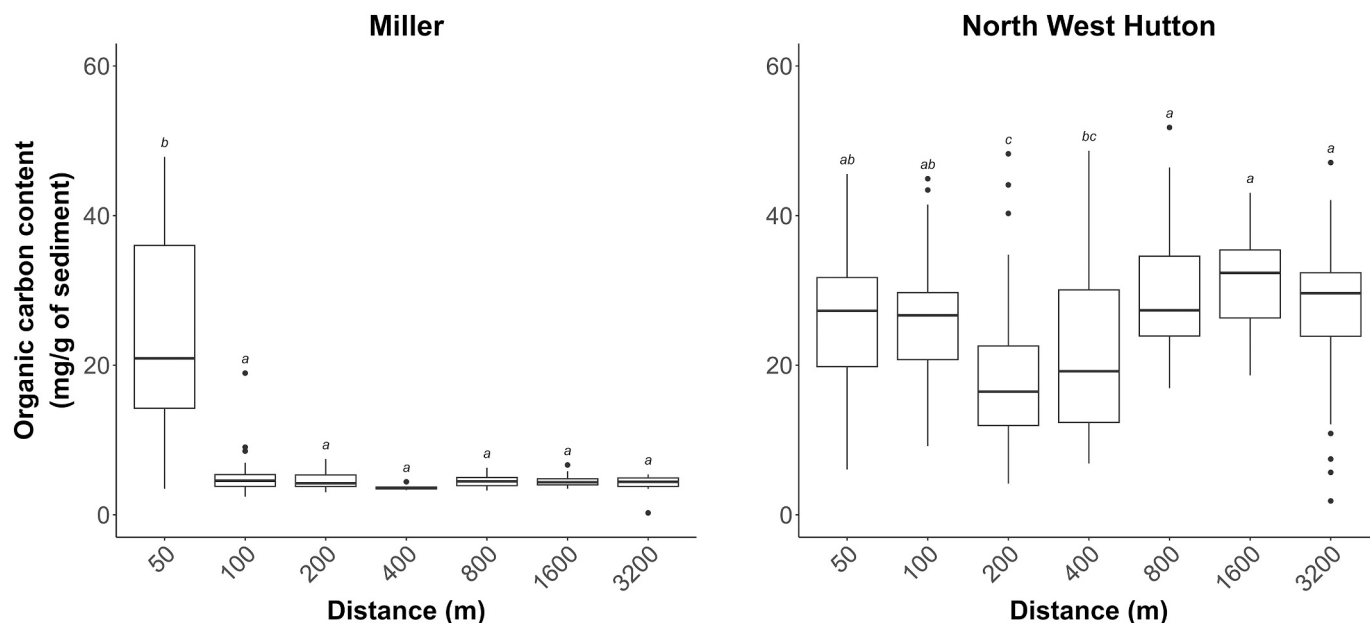


Fig. 3. Organic carbon content (mg/g of sediment) of 1 cm sediment core slices collected at increasing distances (50–3200 m) from two decommissioned oil and gas platforms, Miller and North West Hutton. Sediment was analysed to 10 cm at North West Hutton and 6 cm at Miller. Letters above boxes (a, b, c) indicate significant difference between distances ($P < 0.05$ Kruskal-Wallis test followed by Dunn's post hoc test) with differing letters indicating significant differences.

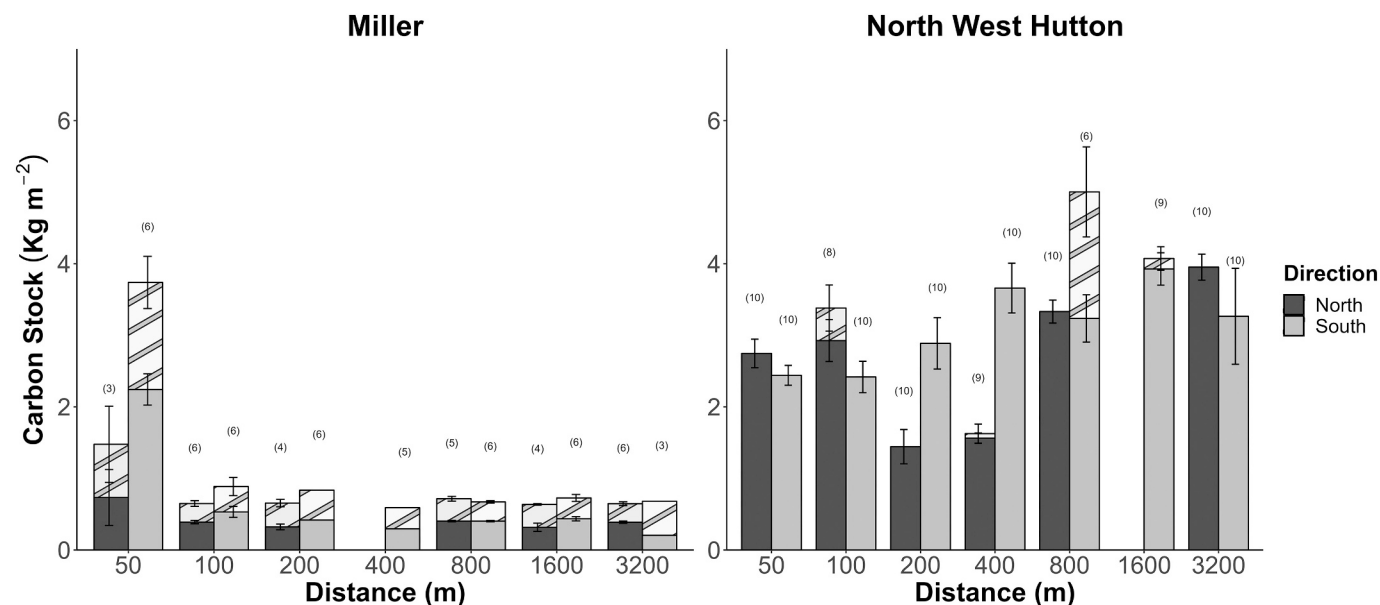


Fig. 4. Mean $\pm$ SE of sediment organic carbon stocks (kg m^{-2}) at increasing distances (50, – 3200 m) from two decommissioned oil and gas platforms, Miller and North West Hutton. Numbers in brackets indicate deepest sampling depth (cm). Where sampling depth was < 10 cm, stocks were averaged and extrapolated to 10 cm (this is represented by hashed portion of each bar). Where bars are missing this indicates no samples taken at that distance.

$2.75 \pm 0.20 \text{ kg m}^{-2}$ at 50 m to $3.38 \pm 0.32 \text{ kg m}^{-2}$ at 100 m. However, average organic carbon stock decreased at 200 and 400 m to $1.44 \pm 0.24 \text{ kg m}^{-2}$ and $1.63 \pm 0.13 \text{ kg m}^{-2}$ respectively. Organic carbon stocks then increased at 800 and 3200 m to $3.33 \pm 0.16 \text{ kg m}^{-2}$ and $3.95 \pm 0.18 \text{ kg m}^{-2}$ respectively.

3.5. Mass accumulation and sedimentation rates

Radiometric depth profiles of total ^{210}Pb , total ^{226}Ra , ^{137}Cs as well as stable Ba and Pb depth profiles at 50 m North/South and 3200 m North/South (control) are displayed in Figs. 5 and 6, respectively.

As shown in Fig. 5, the depth profiles at 50 m North and South of

North West Hutton presented enhanced concentrations of ^{226}Ra in the top 10 cm, a clear signature from the legacy discharges of oil and gas produced water. This observation was confirmed when measuring its chemical analogue Ba (Fig. 6), showing a net increase of barium in the top 9 cm in the 50 m North core and 10 cm depth in the 50 m South core, suggesting the presence of radiostrontobarite particles (Ahmad et al., 2021). These industrially derived signatures were subsequently used to estimate LSR at these two locations. As the fate of radium particles remains unclear (Ahmad et al., 2021) and operational discharge information was not available, the middle of the two contaminated core segments (i.e., 4.5 cm in the 50 m North and 5 cm in the 50 m South) were assumed to correspond to the middle of the operational life of

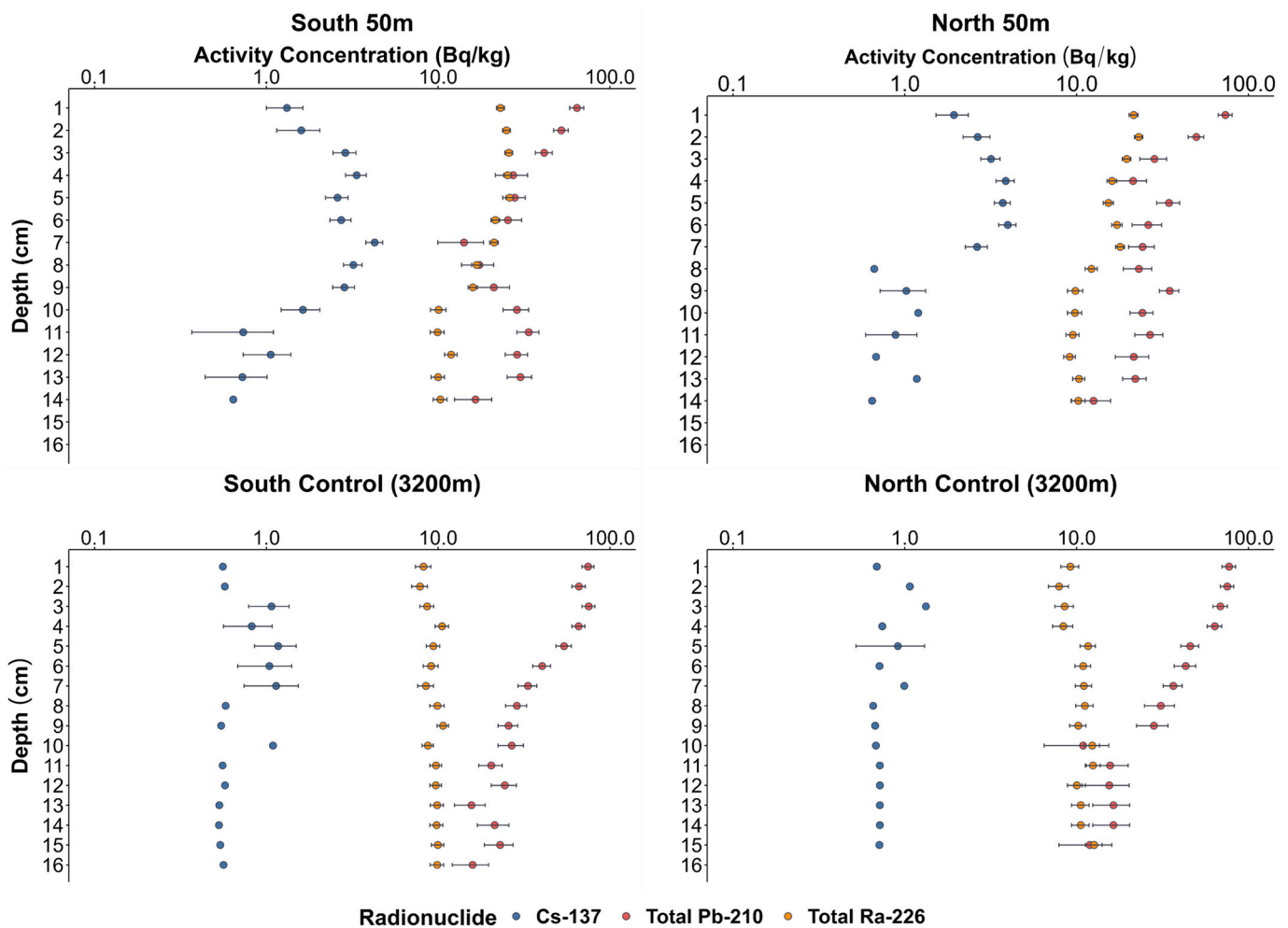


Fig. 5. Depth (cm) profiles of activity concentration (Bq/kg) of three radionuclides (Cs-137, Total Pb-210, Total Ra-226) in four sediment cores taken at 50 and 3200 m away from North West Hutton decommissioned platform on both North and South transects. Error bars indicate unsupported fractions of each radionuclide. Absence of error bars indicates radionuclide levels were below the limit of detection. Fig. 6.

North West Hutton (1993) and indicated the LSR to be ranging between 0.16 and 0.18 $\text{cm} \cdot \text{y}^{-1}$.

Due to the presence of low activity concentrations of ^{137}Cs observed near North West Hutton, unconfirmed at control distances, as well as the potential presence of other ^{137}Cs sources (i.e., from major nuclear fallout events such as Chernobyl), the use of this nuclear-derived fingerprint was not further considered in this study.

Also, as shown in Fig. 6, the Pb depth profiles did not follow the same pattern as Ba profiles, implying the ratio of anthropogenic ^{226}Ra /anthropogenic ^{210}Pb to be variable over time. Therefore, it was not possible to estimate the fraction of anthropogenic ^{210}Pb accurately close to the platform (50 m). It is worth noting that the direct measurement of ^{210}Pb by gamma spectrometry in sediment materials highly contaminated in Pb and other heavy metals such as Zn, Ba, Sr, would have also suffered from high matrix self-attenuation (Dal Molin et al., 2018), limiting event further the application of ^{210}Pb based modelling approaches for these contaminated sediment cores above 10 cm. In addition, the levels of unsupported natural ^{210}Pb observed below 10 cm were found to be very low and associated with high uncertainties from gamma counting. Consequently, the CF-CS ^{210}Pb modelling approach could not be applied in cores collected within 200 m N/S from North West Hutton. Nevertheless, a negligible influence was observed at 400 m and 3200 m N/S (control), enabling the use of the full core ^{210}Pb excess profiles for CF-CS modelling at these four sampling locations (see supp Fig. 2).

Averaged MARs were found to be approximately 0.27 and 0.19 g

$\text{cm}^{-2} \cdot \text{y}^{-1}$ within the North and South transects, respectively (Table 1). Organic carbon accumulation rates (OCARs) ranged from 0.003 to 0.009 $\text{g} \cdot \text{cm}^{-2} \cdot \text{y}^{-1}$ across both transects. The subsequent LSRs were estimated to be averaging at 0.21 $\text{cm} \cdot \text{y}^{-1}$ within the North transect and found to be slightly lower within the South transect, ranging between 0.14 and 0.15 $\text{cm} \cdot \text{y}^{-1}$ and agreeing with the estimations from ^{226}Ra fingerprinting.

3.6. Correlation analysis

Spearman's correlation analysis between the measured variables was separated by site (Fig. 7). Where Spearman's ρ values are positive this shows a positive correlation and where they are negative this shows a negative correlation. For Miller, organic carbon was significantly positively correlated to mud content (Spearman's $\rho = 0.65$, $P = 2.2 \times 10^{-16}$), porosity (Spearman's $\rho = 0.59$, $P = 1.19 \times 10^{-15}$), inorganic carbon (Spearman's $\rho = 0.39$, $P = 8.07 \times 10^{-7}$) and gravel content (Spearman's $\rho = 0.18$, $P = 0.03$) and significantly negatively correlated with distance (Spearman's $\rho = -0.49$, $P = 9.37 \times 10^{-11}$), dry bulk density (Spearman's $\rho = -0.59$, $P = 1.19 \times 10^{-15}$), mean grain size (Spearman's $\rho = -0.52$, $P = 2.2 \times 10^{-16}$) and sand content (Spearman's $\rho = -0.65$, $P = 2.2 \times 10^{-16}$). Conversely, organic carbon content at North West Hutton was weakly positively correlated with distance (Spearman's $\rho = 0.18$, $P = 0.001$), dry bulk density (Spearman's $\rho = 0.25$, $P = 1 \times 10^{-6}$), sand content (Spearman's $\rho = 0.13$, $P = 0.01$) and weakly negatively correlated with

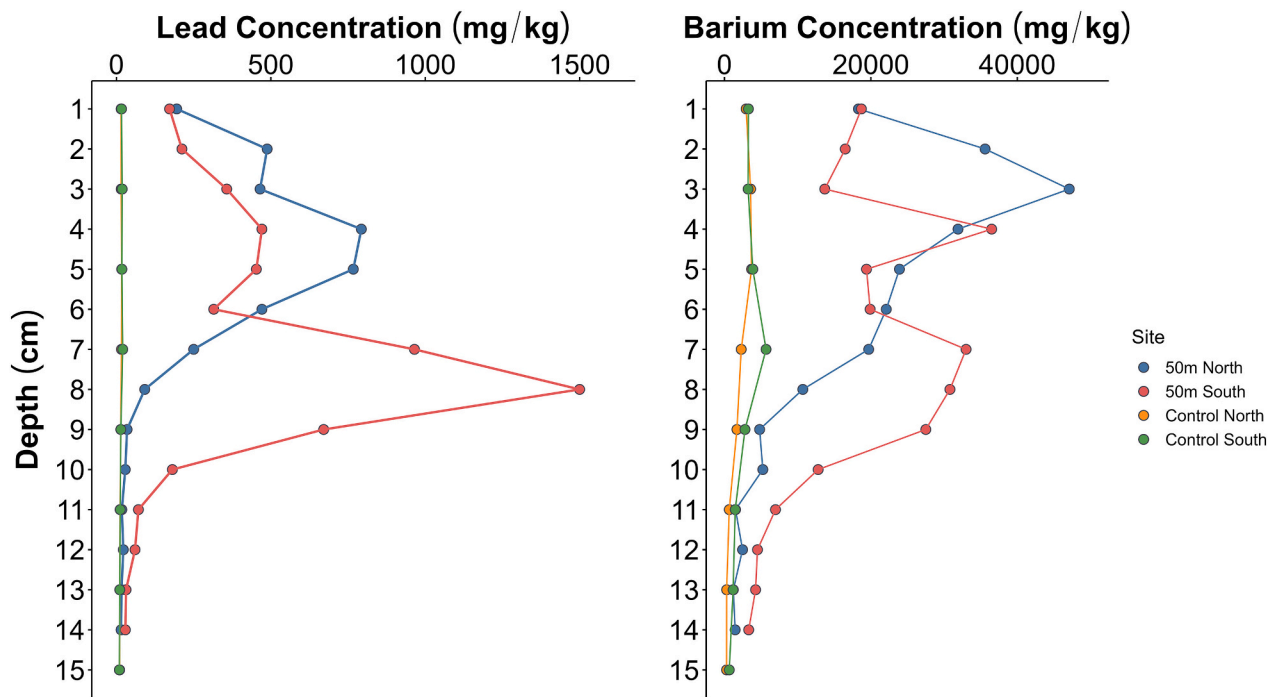


Fig. 6. Depth (cm) profiles of stable lead and barium concentrations (mg/kg) of within four sediment cores taken at 50 and 3200 m away from North West Hutton decommissioned platform on both North and South transects.

Table 1
Linear sedimentation rates from traditional ^{210}Pb radiometric dating techniques and novel ^{226}Ra oil and gas attributed fingerprint, average dry bulk densities (DBD), ^{210}Pb mass accumulation rates (MAR) and ^{210}Pb organic carbon accumulation rate (OCAR) of six cores collected at increasing distances (50–3200 m) along two directional gradients (North and South) from North West Hutton decommissioned platform.

Distance (m)	Direction (N/S)	^{210}Pb LSR (cm/y)	Mean dry bulk density (DBD)	^{210}Pb MAR (g/cm ² /y)	Average carbon content (%)	Pb OCAR (g/cm ² /y)	^{226}Ra LSR O&G fingerprint (cm/y)
50	North	^a	1.102	^a	2.83	^a	0.161
400	North	0.211	1.211	0.258	1.26	0.003	N/A
3200	North	0.216	1.330	0.286	3.24	0.009	N/A
50	South	^a	1.056	^a	2.78	^a	0.179
400	South	0.141	1.252	0.176	2.45	0.004	N/A
3200	South	0.154	1.292	0.199	3.16	0.006	N/A

^a not estimated.

mud content (Spearman’s $\rho = -0.11$, $P = 0.04$), porosity (Spearman’s $\rho = -0.25$, $P = 1\text{e}^{-6}$).

4. Discussion

4.1. Organic carbon content/stock variability between sites

Organic carbon content of sediments varied spatially around both study sites with distinct trends observed at each. North West Hutton showed consistently higher average organic content across all sampling distances compared to Miller. Additionally, the relationship between organic and distance varied between sites, with North West Hutton carbon content increasing slightly with distance, whereas Miller displayed elevated levels closer to the structure (50 m), with consistently lower levels at increasing distance. Overall, organic carbon content in this region of the North Sea was higher than modelled studies such as Diesing et al. (2017, 2021) and Wilson et al. (2018). In these estimations, carbon percent ranges from 0.39 % at North West Hutton and 0.68 % at Miller (Wilson et al., 2018). However, these predictive models do not account for the presence of MMS which likely explains their inability to capture the site-specific trends observed in this study.

In this study, Miller exhibited an enrichment of organic carbon

within close proximity (50 m) to the structure, displaying a ‘halo’ effect, likely linked to activity from the O&G platform during its active production stage. The combination of a large effect size and statistical power indicates that this is a reliable and reproducible result (Supplementary table 2). This enrichment could be caused by the presence of attached epifauna on the remaining jacket footings, potentially increasing organic carbon content through deposition of faecal matter (Schutter et al., 2019). Artificial structures can support significantly higher biomass (up to 500 times more) than soft sediments, due to the availability of hard substrate for epifauna attachment (Maar et al., 2009). Organisms that colonise artificial structures tend to be fouling attached epifauna dominated by filter feeders (Schutter et al., 2019). These organisms may act as a large-scale biofilter, depleting organic matter from the water column while enriching nearby sediment with faeces, larvae, dissolved organics, and nutrients (Coates et al., 2014; Maar et al., 2009). For example, in Maar et al.’s model, sedimentation rate around an offshore wind structure in the North Sea significantly increased up to 40 m from the foundation due to the excretion of faecal pellets (Maar et al., 2009). Similar patterns are observed at southern North Sea windfarms, where colonizing organisms accumulate carbon during operation and only a small proportion (0.50 ± 0.06 %) of the area is disturbed by decommissioning activities (Heinatz and Scheffold,

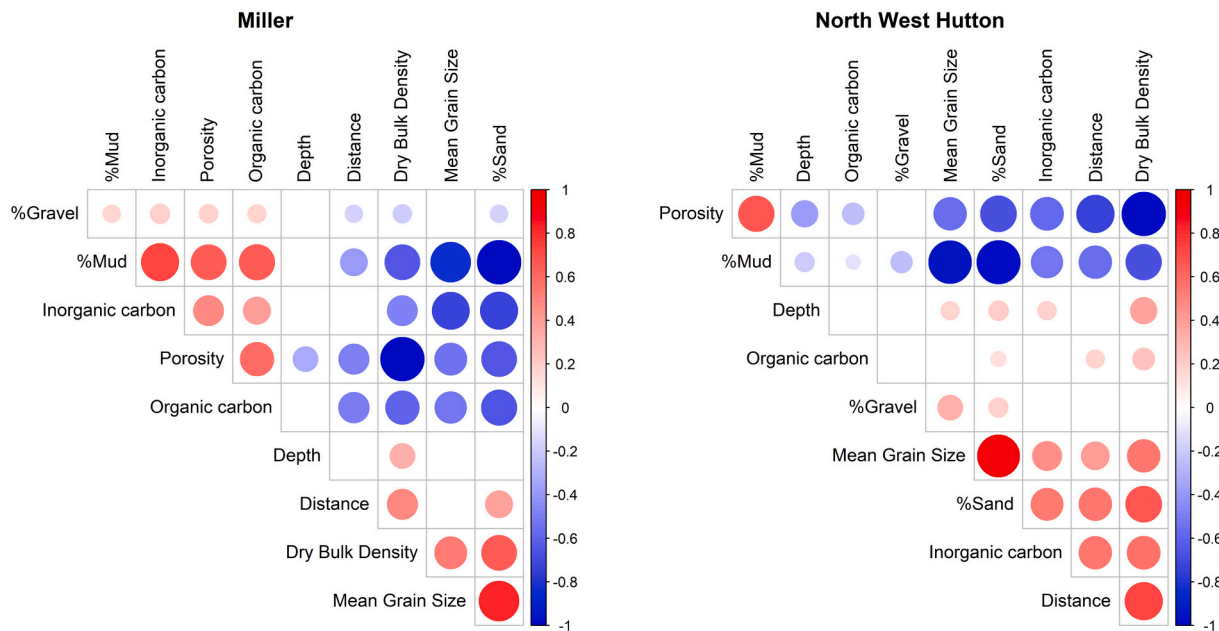


Fig. 7. Correlogram of spearman's correlation (ρ) ($P < 0.05$) between measured variables, organic carbon, inorganic carbon, porosity, dry bulk density, distance from site, mean grain size, percentage sand, percentage mud and percentage gravel from sediment cores at Miller and North West Hutton. Size of circles represent level of significant with larger circles indicating higher significance. Colour of circles indicates direction (blue = positive, red = negative). Relationships without significance are left blank. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2023). In this study, measurements of attached epifauna were not taken, however, other offshore platforms in the North Sea have been shown to be fully covered with marine fouling organisms (van der Stap et al., 2016), particularly at the depth of the Miller footings. Despite O&G platforms having less structures in each area compared to wind farms, the principle of localised carbon enrichment through biodeposition could explain the higher carbon content close to the Miller platform. Without epifauna or associated carbon flux values, future work determining organic carbon composition could further qualify this conclusion. This also highlights a significant knowledge gap to fill in pre-decommissioning assessments.

The 'halo' trend seen at Miller is consistent with environmental impact assessments of other decommissioned North Sea platforms. At the Ninian Northern decommissioned platform, sediment organic matter was higher near the structure (4.9–5.5 % at 0 m) compared to more distant sites (0.9–3.8 % at 100–10,000 m) (CNR International, 2017) mirroring the elevated carbon content near Miller. Similarly, sediment near the Murchison decommissioned platform showed elevated organic carbon at 250 m and 500 m (3 and 4 % respectively) when compared to sites up to 8000 m, where values remained below 1 % (CNR International, 2013). This pattern was attributed to drilling activity at the site, which elevated the proportion of fine-grained sediment and organic matter content (CNR International, 2017), with some of this likely being hydrocarbons. This aligns with Miller sediment composition results, where higher fines were observed at 50 m compared to the rest of the distances, indicating a localised halo area of mud content (fines) and organic carbon. However, having data pre and post decommissioning of other platforms would allow for comparison and ability to determine relative effects of decommissioning on carbon stocks.

While elevated mud content was also observed at North West Hutton, its weak negative correlation with organic carbon suggests that this factor alone does not fully explain the observed variance with distance. The higher sediment carbon content near the platform could be due to elevated epifauna based faeces, increased fine-grained sediments, increased hydrocarbons, or a combination of these factors. Regardless, this halo effect at Miller has implications for decommissioning practice of specific platforms to protect the seabed integrity, and the carbon

stored within them. MMS (active or decommissioned) will likely have distinct signatures and impacts on the seabed, linked to environmental context such as water depth, distance from MMS, and time and activity since decommissioning (change in trawling activity on seabed since decommissioning and removal of exclusion zone). As current OSPAR regulations require complete removal of these structures, except for a few derogations (such as those presented in this study), this practice of removing embedded structures causes a significant disturbance to the seabed carbon (Fortune and Paterson, 2020; Birchenough and Degraa, 2020).

In contrast to Miller, sediments at North West Hutton, exhibited the lowest organic carbon at 200 and 400 m with similar levels at all other distances. Comparisons between 200 m and distances other than 400 m showed large effect size and high statistical power which indicates that this is a reliable result avoiding type I/II errors (Supplementary table 2). This lower carbon content may reflect increased carbon mineralisation from microbes or bioturbation from macrofauna (Burdige, 2007) present from a lack of sediment disturbance. During the operation of the platform, the 500 m exclusion zone limits disturbance from activities, such as trawling (Sciberras et al., 2016; De Borger et al., 2021; van der Molin et al., 2013) which would alter macrofauna assemblages within sediment (Eigaard et al., 2017). Carbon mineralisation rates are strongly impacted by physical organic carbon removal through trawling-induced resuspension of sediment, which is further exacerbated by removal of bioturbating macrofauna (De Borger et al., 2021). Bioturbation is the movement of sediment particles by organisms, such as bivalves, and burrowing polychaetes, which create burrows and move sediment (and carbon) within the surface layers (Kristensen and Blackburn, 1987; Michaud et al., 2006). This movement oxygenates sediment which enhances mineralisation through oxidation (Soetaert et al., 1996; Talin et al., 2002) causing a reduction in organic carbon content in the surface layers (Glud et al., 2016). The lack of trawling activity within the exclusion zone would increase the presence and abundance of these bioturbators, (De Borger et al., 2021) increasing the oxic status of the sediments and reducing the amount of carbon sequestered in the surface sediments. The observed dip in carbon content at 200 and 400 m may therefore have resulted from long term exclusion of trawling and

distance from localised contaminants. Trawling is known to cause mortality of benthic organisms (Sciberras et al., 2016; Hiddink et al., 2017; Epstein and Roberts, 2022; Eigaard et al., 2017), which may explain why the amount of carbon increases again outside of the set exclusion zone distance, and at 800 m (the next distance increment) the carbon content is similar to what is seen at the control site (3200 m), where reduced bioturbation enhances carbon content in surface sediments.

This trend in decreasing carbon with distance, as seen in the carbon stock values, from the MMS was also seen in a study around the L7A decommissioned platform (in the Southern North Sea), where decreasing carbon content at greater distances away from the structure was observed in 3 out of 4 directional transects (Klunder et al., 2018). The L7A platform is located much further south, but this suggests that decommissioned platforms may affect organic carbon differently depending on a variety of factors such as sediment composition and subsequent natural background particular organic carbon, decommissioning practices, sedimentation rates, current regimes, drill cutting composition and time of production (Klunder et al., 2018). The L7A platform, in a different location, combined with the carbon dynamics seen around North West Hutton and Miller in this study, implies patterns of carbon storage around different decommissioned platforms are site specific and cannot be generalized for all MMS; each needs to be assessed on a case-by-case basis considering the different environmental variables and age of structures.

Interestingly, organic carbon results correlated differently with mud percentage between sites with a positive correlation at Miller and a weak negative correlation at North West Hutton. A positive relationship between organic carbon and mud/fines content is typical of shelf sediment (De Falco et al., 2004; Diesing et al., 2017; Leipe et al., 2011; Smeaton et al., 2021). However, we observed a weak reverse correlation, indicating that there are some underlying and unknown variables, perhaps the presence of North West Hutton, may alter this relationship, as despite highest mud content occurring at 50 and 100 m, these were sites with the lowest recorded organic carbon content.

This study presents both organic carbon content (mg/g of sediment) and organic carbon stocks (kg m⁻²) in sediments surrounding these decommissioned platforms. By calculating organic carbon stocks (which include porosity and dry bulk density) (Graves et al., 2022) this provides a more comprehensive understanding of carbon dynamics than content alone. Carbon stock values are a useful indicator of how sediment composition affects carbon content. Uniquely, unlike other carbon stock assessments this study provides mass accumulation rates for the North West Hutton site, allowing quantification of the rate that carbon accumulates over time (g cm⁻² yr⁻¹) which is rarely directly measured in offshore shelf sediment, with the exception of de Haas (1997) and Lerida-Toro et al. (2022). Comparing carbon stocks between the two sites was limited by poor resolution of sediment core depths at the Miller decommissioned platform, necessitating the extrapolation of stock measurements from shallow core depths. Despite this, a clear trend was still seen at this site with significantly higher carbon content at the 50 m distance. Furthermore, due to limitations in sampling opportunities, this study was unable to fully disentangle the effects of decommissioning on sedimentary carbon stocks without pre-decommissioning sample collection.

4.2. Naturally occurring radioactivity from legacy oil and gas produced water discharges and impact on sedimentation rate estimations

Elevated levels of ²²⁶Ra were observed in the top 10 cm fraction of the cores collected within 200 m from North West Hutton likely reflecting the legacy discharge of produced water during the platform's operational phase (Olsgard and Gray, 1995; Ahmad et al., 2021). While the radiological and chemical impacts of these industrial contaminants on benthic communities remain unclear, these site-specific signatures offer a powerful tool for assessing the spatial and temporal extent of the

impact of wastewater contamination to nearby sediment and help estimate sedimentation rates near oil and gas platforms.

The combination of ²²⁶Ra and Ba concentrations provides a novel tool in environmental forensic science to determine the impact of offshore oil and gas platforms on local sedimentary processes in the North Sea. This method may overcome limitations associated with traditional nuclear tracers like ¹³⁷Cs (from Chernobyl and Sellafield), which are less effective offshore due to multiple sources and low concentrations (Arias-Ortiz et al., 2018). Determining offshore carbon accumulation rates remains a constraint on UK shelf sea carbon budgets (Luisetti et al., 2019). Currently, there are few novel forensic approaches including less conventional nuclear derived isotopes such as ¹²⁹I, but these approaches are generally limited to specific UK marine regions (Lerida Toro et al., 2022). As demonstrated in this study, using known operational timelines of offshore platforms allows the tracking of sedimentation and carbon accumulation rate in recent timescales. While current carbon stock measurements offer valuable insight into carbon dynamics, accurate accumulation rates are essential for understanding temporal changes and improving carbon budget estimates for the UK shelf (Graves et al., 2022; Luisetti et al., 2019). In turn, we can disentangle the long-term impacts of man-made structures from other anthropogenic activities and determine how carbon stock dynamics vary across the shelf in an area of ocean which has historically had a poor resolution of mass accumulation of sediment.

Mass accumulation rates could not be determined accurately for sediment cores taken within 400 m of North West Hutton through traditional lead-210 measurement by gamma spectrometry, as these sediments showed elevated levels of heavy metals, including Pb and Ba causing high levels of matrix self-attenuation during gamma counting (Dal Molin et al., 2018). In this context, the use of the alternative alpha spectrometric method for measuring polonium-210, ²¹⁰Po, a direct decay product of ²¹⁰Pb, would offer a more suitable analytical alternative.

4.3. Influence of drill cuttings pile

Both sites sampled in this study exhibit extensive drill cutting piles near the decommissioned structures, resulting from drilling operations that return hydrocarbon-rich rock to the seafloor (Ball et al., 2012). Drill cuttings often consist of drilling fluids (oil-based fluids, synthetic fluids, and water-based fluids) depending on the age of the structure and the drilling practice at the time of construction (Breuer et al., 2004). The higher mud content close to each site, and the subsequent change in sediment composition to finer, carbon rich particles, could be due to drill cuttings, which remain close to the drilling well (Breuer et al., 2004). At North West Hutton, wells were drilled with two types of drilling fluid, water-based fluids, for shallower (1000 m) sections of the well, and oil-based fluids for deeper drilling (BP, 2005). Similarly, at Miller, oil-based fluids were used throughout production as drilling fluids (Aquatera Ltd, 2007). Despite the presence of oil-based drilling fluid within drill cuttings piles at North West Hutton, organic carbon content at 50 m to 100 m was similar to 800 m to 3200 m, indicating that the pile had little effect on carbon content likely due to the final trawling operations during decommissioning (BP, 2005) that would resuspend and disperse carbon enriched sediment. Conversely, Miller showed elevated organic carbon at 50 m suggesting possible enrichment from the cutting's pile. However, the influence of elevated hydrocarbons on sediment carbon storage from drill cutting piles was determined as an insignificant proportion of total organic carbon from measurements from the UK Benthos Database (Offshore Energies UK, 2015) (Supplementary Fig. 2). Determining the contaminant composition and hydrocarbon influence on carbon stored around oil and gas decommissioned platforms would help identify the effect of drill cuttings piles on local microbes and fauna involved in carbon cycling.

4.4. Local current regime

Organic carbon stocks vary between direction of transects, particularly at North West Hutton. One potential influence is the local hydrodynamics. A study by Klunder et al. (2018) observed a 'shadow' effect at the L7A decommissioned platform in the southern North Sea where the predominant current direction dictated a depleted gradient of total organic carbon with increasing distance; explained by a biofilter effect of epifauna and acceleration of flow due to the physical structure causing a deposition of particles at greater distance. However, North West Hutton is located on the edge of the North East Atlantic Current and only experiences small residual currents below 0.1 m/s (De Dominicis et al., 2018; Winther and Johannessen, 2006) with a maximum current speed of 0.43 m/s at the seabed (BP, 2005). Therefore, it is unlikely that hydrodynamics was the driver in different benthic measurements. Despite being affected by the Fair Isle/Dooley current, very little difference in organic carbon was seen between the North and South transects at Miller. However, hydrodynamics would likely play a larger role in more dispersive environments, such as the Southern North Sea, where the 'shadow' effect has previously been recorded (Klunder et al., 2018), and where drill cuttings piles do not persist due to dispersive hydrodynamics.

5. Conclusion

In conclusion, this study finds that carbon dynamics around decommissioned platforms are site specific and therefore extrapolating carbon dynamics from one or two decommissioned sites across the North Sea is not recommended. Decommissioning practice and activity may have an impact on organic carbon stocks and dynamics within surface sediments; however, this requires sampling pre and post decommissioning to disentangle the effects. Future work could include carbon stock, sediment composition, and carbon accumulation assessments during all phases of oil and gas activity to determine the overall effect of these structures on sedimentary blue carbon throughout their operational and then decommissioning lifespan. By sampling pre-construction, during operational phase and pre- and post-decommissioning could provide greater insight into the effect of oil and gas activity on sedimentary blue carbon. This would also give an insight into OSPAR mandatory decommissioning; partial removal may reduce the impact on sedimentary blue carbon and maintenance of a small-scale exclusion zone at specific sites could provide protection for this elevated carbon.

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CRediT authorship contribution statement

Hugo Woodward-Rowe: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Franck Dal Molin:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Benjamin H. Gregson:** Writing – review & editing, Visualization, Software. **Claire Mason:** Writing – review & editing, Methodology. **Ruth Parker:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Natalie Hicks:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data produced as part of this research is included in the manuscript and supplementary material.

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