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RESEARCH ARTICLE

Stratigraphic evidence of organic carbon depletion in an intensely trawled muddy seabed

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Abstract Understanding the long-term effects of bottom trawling on sedimentary organic carbon (OC) is crucial for assessing its role in carbon cycling and climate regulation. Most studies analyse effects on surface sediments (≤10 cm), leaving impacts on deeper sediments poorly resolved. This study investigates how bottom trawling influences sediment OC density (SCD) and OC content within 0–50 cm of the Western Irish Sea Mud Belt, representing sediments deposited from 1860 to 2022. SCD and OC content were lower in intensely trawled areas, declining by 0.031×10^{-2} gC cm^{-3} and 0.05 wt% per additional swept area ratio (+1 yr^{-1}). OC decreased by 0.007×10^{-2} gC cm^{-3} and 0.01 wt% for every centimetre into the sediment. Mud content had a significant effect on OC content, but not SCD, whereas *Nephrops* burrowing did not significantly affect either. These findings support evidence of trawlings potentially long-term negative impact on OC in muddy sediments.

Keywords Biogeochemical cycling · Blue carbon · Continental shelves · Fishing pressure · Organic carbon · Trawling

INTRODUCTION

Mobile bottom trawling causes widespread chronic disturbance of continental shelf sediments, which may reduce their capacity to store organic carbon (OC) and regulate the climate (Epstein et al. 2022). However, the magnitude of trawling impacts on sedimentary OC remains uncertain and debated (Sala et al. 2021; Atwood et al. 2023; Hiddink et al. 2023), highlighting the need for regional empirical assessments across different seabed environments (Porz et al. 2024).

Bottom trawling disturbs seabed sediments through mixing, resuspension, erosion, and lateral transport, altering sediment biogeochemistry and benthic ecosystem functioning (Coughlan et al. 2015; Paradis et al. 2020; Porz et al. 2024). Repeated disturbance can accelerate OC remineralisation by increasing oxygen exposure and microbial activity, particularly in intensively trawled muddy sediments (Martín et al. 2014a; Khedri et al. 2025). These processes may convert sedimentary OC into greenhouse gas emissions, a proportion of which could ultimately reach the atmosphere (Epstein et al. 2022; Atwood et al. 2024).

Empirical studies report mixed effects of trawling on sedimentary OC, ranging from negligible changes to both reductions and enhancements (Tiano et al. 2024; Epstein & Roberts 2022). Negative impacts are most evident in cohesive muddy sediments where low permeability, limited oxygen penetration, and high mineral surface areas favour OC preservation (Hemingway et al. 2019; Porz et al. 2024; Zhang et al. 2024). In contrast, trawling effects are often weaker in sandy, high-energy environments where natural sediment resuspension and oxygenation dominate sediment dynamics (Diesing et al. 2013; Palanques et al. 2014; Sciberras et al. 2016). Recent studies further suggest that higher trawling intensity (>1 yr^{-1}) could lead to greater OC depletion in muddy shelf sediments (Porz et al. 2024; Zhang et al. 2024).

While most empirical studies of trawling impacts focus on sedimentary OC content, reflecting changes in sediment

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chemistry, few assess sediment OC density (SCD), which quantifies volumetric OC and is therefore more directly related to absolute OC stocks (Porz et al. 2024; Diesing et al. 2025). Most research is also limited to surface layers (≤10 cm), leaving effects on older buried sediments poorly resolved (Epstein et al. 2022). However, surface sediment replenishment between trawling events may mask longer-term depletion that becomes evident only at depth (Paradis et al. 2019, 2020). Only a small number of studies have examined trawling impacts to 30 cm depth (Palanques et al. 2014; van de Velde et al. 2018; Paradis et al. 2019), with a single study extending to 50 cm based on two cores (Martín et al. 2014a), despite evidence that trawl gears can penetrate up to > 50 cm in muddy sediments (Martín et al. 2014b; Eigaard et al. 2016; Paradis et al. 2019). Consequently, long-term impacts of chronic trawling on deeper sedimentary OC stores remain poorly constrained.

This study investigates the effects of chronic commercial trawling on SCD and OC content within the upper 50 cm of muddy sediments in the Western Irish Sea Mud Belt (WISMB). The region is among the most heavily trawled muddy shelf systems globally (Eigaard et al. 2017; Amoroso et al. 2018), having supported an active *Nephrops norvegicus* fishery since the 1950s (Coughlan et al. 2015; ICES 2020). It also contains substantial OC-rich sediments (Diesing et al. 2017; Legge et al. 2020; Black et al. 2022; Muir et al. 2026), which accumulated beneath the Western Irish Sea cyclonic gyre (Belderson 1964; Coughlan et al. 2015, 2021). The WISMB therefore provides an ideal setting to assess long-term trawling impacts on sedimentary OC in muddy shelf sediments.

Here, we evaluate the influence of bottom trawling, sediment depth, mud content, and *Nephrops norvegicus* burrow density on SCD and OC content. Sediment chronologies are constrained using natural (^{210}Pb, ^{210}Po) and anthropogenic (^{137}Cs, ^{241}Am) radionuclides associated with historical Sellafield nuclear facility discharges (Kershaw et al. 1986; Gray et al. 1995; Muir et al. 2026), enabling assessment of trawling impacts on sediments deposited since the nineteenth century. We hypothesise that higher trawling intensity is associated with lower SCD and sedimentary OC content throughout the upper seabed (Epstein and Roberts 2022; Porz et al. 2024; Zhang et al. 2024).

MATERIALS AND METHODS

Field sampling, sediment processing, and radionuclide methods are described in detail in Muir et al. (2026), while only methods directly relevant to this study are summarised here.

Sampling site selection

Twenty sediment cores (≥50 cm length) were collected in June 2022 in the WISMB within Isle of Man territorial waters (Fig. 1). Sites were distributed on a regular spatial grid to achieve broad regional coverage across a gradient of bottom-trawling intensity. Sites targeted muddy sediment habitats, which were identified from the BGS Seabed Sediments 250k dataset (mud, sandy mud, gravelly mud and slightly gravelly mud, and slightly gravelly sandy mud; British Geological Survey 2024), at water depths of 60–130 m (Fig. S2; GEBCO Compilation Group 2024). Water depths recorded on site were corrected for tidal state prior to analysis. Kriged *Nephrops norvegicus* burrow density estimates for Functional Unit 15 (2013–2022; Agri-Food and Biosciences Institute 2023) were plotted in ArcGIS Pro and sampling sites were attributed with the nearest point value, to assess bioturbation effects on sedimentary OC content (Fig. S1). Regional tidal and wave-induced bed stresses are relatively uniform and low across the WISMB (Williams et al. 2019; Coughlan et al. 2021), and were therefore not included in the analyses.

Fishing pressure estimates

Data source

Bottom-trawling intensity was quantified using swept area ratio (SAR, yr^{-1}), to evaluate the impact of bottom trawling on SCD and sedimentary OC content across a trawling intensity gradient. Mean annual SAR was estimated from satellite-based vessel monitoring system (VMS) data for fishing vessels > 12 m carrying bottom-contact fishing gears operating in Isle of Man and Northern Irish territorial waters during 2016–2021 (6 years). Data were provided by the Marine Management Organisation. Data coverage for vessels > 12 m is near-complete, as VMS is mandatory for enforcement purposes in European waters. Vessels < 12 m were not legally required to have VMS installed during 2016–2021 (Gerritsen 2023), so data coverage may under-represent these vessels.

Data preparation

Data were filtered before calculating SARs to retain towed benthic fishing gears and exclude static benthic fishing gears, pelagic gears, and vessels carrying only "unknown" gear codes (Table S1). Towed benthic fishing gears included boat dredge (DRB), bottom otter trawl (OTB), multi-rig otter trawl (OTM), bottom pair trawl (PTB), and beam trawls (TB, TBB, TBN). Scottish seine (fly dragging) was excluded as these were not widespread within the study

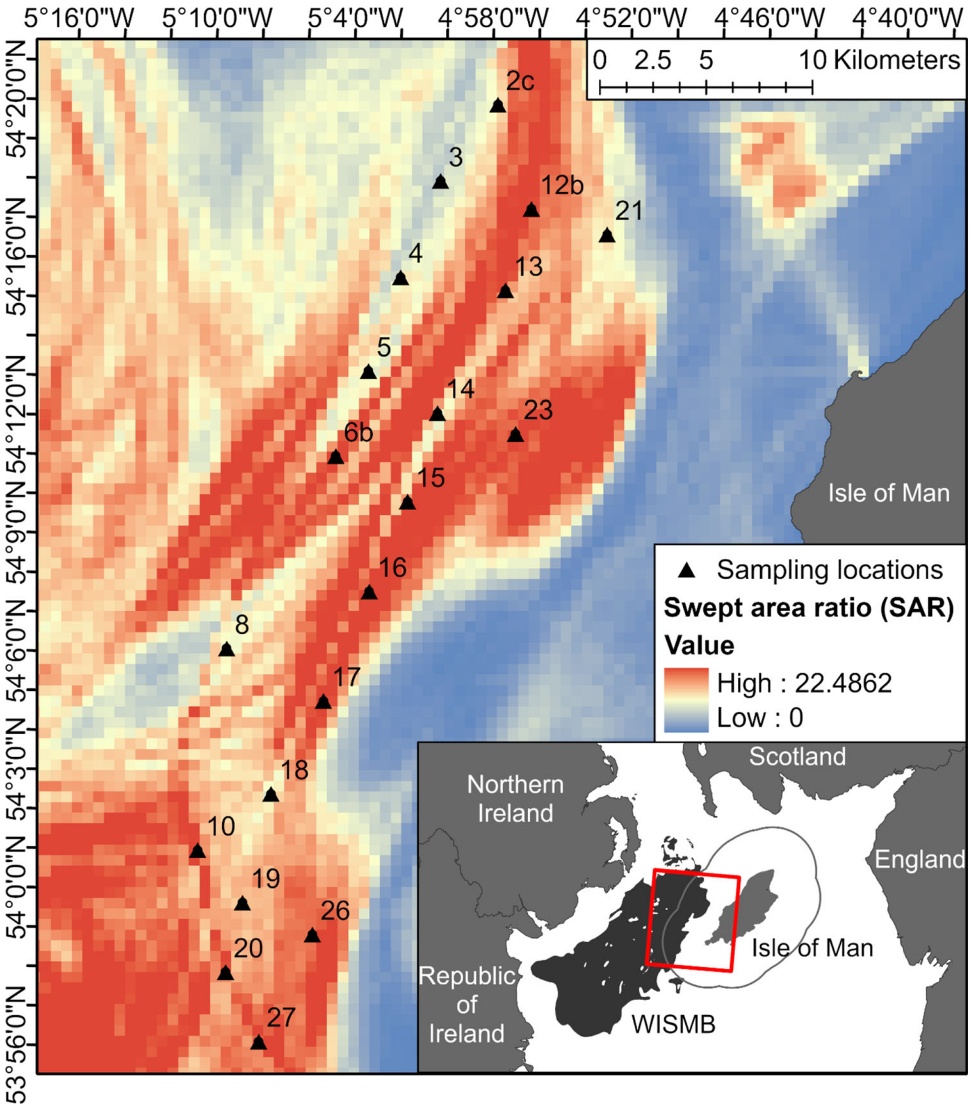

Fig. 1 Map of surface swept area ratio (SAR, yr^{-1}) for the period 2016–2021 in the Western Irish Sea Mud Belt (WISMB) reconstructed using anonymised vessel monitoring system (VMS) data provided by the Marine Management Organisation. Sampling site locations (black triangles) are labelled with sediment core identification codes. The inset map shows the WISMB (based on muddy sediments classified by the British Geological Survey Seabed sediments 250k dataset (British Geological Survey 2024)) in the Irish Sea relative to neighbouring countries. The study region is highlighted by a red box

region (e.g. activity only recorded in 2016–2018, with only 15 records in 2018). The proportion of unknown gear codes for years 2016–2019 were typically less than 0.01% but increased to ~ 10% in 2021. Most vessels carrying "unknown" gear codes travelled at speeds outside the 1–6 knots fishing threshold (see below); for example, only 1.6% of vessels travelling 1–6 knots in 2021 carried "unknown" gears.

The retained data were filtered to remove "NULL" or "blank" values from the speed column. Histograms for 2016–2021 were used to determine the fishing speed threshold (Fig. S3). Histograms had a broad peak at 1–5 knots representing fishing activity, a spike at < 1 knot representing stationary/turning vessels, and a broad peak at > 6 knots representing steaming vessels. The speed rule was determined as 1–6 knots, excluding stationary (< 1 knots) and steaming (> 6 knots) vessels from the dataset. This fishing threshold aligned with the Joint Nature Conservation Committee (JNCC) and previous studies (Lee et al. 2010; Church et al. 2016).

Swept area ratio (SAR)

Swept area (SA) was calculated in ArcGIS Pro by connecting consecutive VMS pings into daily polylines using anonymised vessel ID and timestamps. Polylines were clipped to a regular 500 m × 500 m grid (UTM 30N), summed within each cell, and multiplied by surface-gear-specific widths recommended by the JNCC (Table S2) (Church et al. 2016). Gear widths and other vessel-specific parameters (e.g., engine power, tow speed), which influence seabed contact and penetration (Eigaard et al. 2016), were not provided in the anonymised VMS dataset. SA was divided by grid-cell area and averaged over 6 years to derive SAR, whereby higher SAR reflects greater trawling intensity.

This approach avoided double counting from duplicate pings and excluded erroneous joins between fishing events. Although SAR estimates are subject to uncertainty due to fixed gear-width assumptions, spatial trawling pressure patterns around the British Isles are temporally consistent (Stelzenmüller et al. 2008; ICES 2021), supporting the use of modern fishing pressure (2016–2021) as a proxy for chronic disturbance.

Sediment sampling and processing

Sediment cores were collected using a UWITEC gravity corer (120-cm length; 9-cm internal diameter), split lengthwise, and subsampled at the British Ocean Sediment Core Research Facility (BOSCORF). Samples were freeze-dried, homogenised, and analysed throughout the upper 50 cm using 2-cm intervals for 0–20 cm and 5-cm intervals for 20–50 cm.

Sediment analysis

Elemental analysis

Sediment dry bulk density (g cm^{-3}, DBD) was calculated as dry mass (g) divided by sample volume (cm^3). OC content (wt%) was determined from acidified samples using a Flash 2000 Elemental Analyser (Thermo Fisher Scientific). SCD ($\times 10^{-2}$ gC cm^{-3}) was estimated as OC content (wt%/100) multiplied by DBD, then converted to OC stock (MgC ha^{-1}).

Particle size analysis

Particle size distributions were measured at alternate depth intervals (e.g. 0–2 cm, 4–6 cm, etc.) using a Malvern Mastersizer 3000 laser microgranulometer following dispersion in 1% sodium hexametaphosphate, to determine sediment type. Samples from Sites 2c and 6b were sieved through a 1000 µm mesh prior to analysis to remove coarser particles, to prevent damage to sample intake tubes. Sediments were classified as clay (< 3.9 µm) and silt (3.9–62.5 µm), grouped as mud (< 62.5 µm), and sand (62.5–2000 µm).

Radionuclide analysis

Radionuclide analyses were conducted on seven cores (Sites 4, 8, 14, 15, 20, 21, 27) spanning the range of SAR, sediment type, water depth, and *N. norvegicus* burrow density, to estimate sediment accumulation rates and age. Freeze-dried samples were analysed at 1-cm resolution to 40 cm depth.

^{210}Pb, ^{137}Cs, and ^{241}Am activities were measured by gamma spectrometry using Mirion Canberra High Purity Germanium (HPGe) well-type gamma spectrometers (GAU-Radioanalytical, University of Southampton, ISO/IEC17025). Alpha spectrometry (Ortec Octete) was used to measure ^{210}Po, which is in equilibrium with ^{210}Pb, for three sediment cores (Sites 4, 8, and 20), to validate ^{210}Pb activities, which were close to the instrumental limit of detection and had higher uncertainty.

Average sediment accumulation rates were estimated from excess ^{210}Pb and ^{210}Po using a constant flux–constant sediment accumulation (CF–CS) model, validated using the ^{137}Cs peak corresponding to the 1975 Sellafield nuclear facility discharge maximum and cumulative ^{241}Am Sellafield 1950's discharge onset (Gray et al. 1995). Average linear sediment accumulation rates were estimated from ^{210}Pb, ^{210}Po, and ^{137}Cs activity profiles, where data were reliable, and used to estimate sediment ages to 50 cm depth.

Statistical analysis

Data were grouped into 10-cm depth layers (Table S3). Statistical analyses were performed on 18 sites. Sites 2c and 6b were excluded from statistical analysis due to methodological differences in particle size analyses, which prevented accurate mud content estimates.

Pearson correlations were used to assess collinearity among environmental and sediment variables to guide predictor selection. Water depth, DBD, and sand, silt, and clay content were excluded in favour of mud content and sediment depth, which typically influence OC preservation (Burdige 2007). Final predictor variables also included SAR and *N. norvegicus* burrow density as sources of sediment mixing (Table S3). SCD was selected as a response variable to evaluate effects associated with physical disturbance of the sediment structure, packing, and compaction; while OC content was selected to assess disturbance-related changes in sediment chemistry and OC composition.

Linear mixed-effects models were fitted separately for SCD and OC content using Site as a random intercept to account for non-independence among repeated measures. Predictors were z-standardised to allow comparison of effect sizes (importance of predictors). Candidate models included main effects only, main effects with a random slope for mud content, and main effects plus selected two-way interactions, and the same structures were also evaluated using log-transformed SCD and OC content to normalise the residuals. Models were fitted using maximum likelihood and compared using AIC (Akaike Information Criterion)/BIC (Bayesian Information Criterion), whereby model selection prioritised BIC for parsimony. Model assumptions were evaluated using residual diagnostics (residual plots of residuals vs fitted, Q–Q, scale–location, residuals vs leverage, and a histogram of standardised residuals), Shapiro–Wilk tests, influence diagnostics (Cook's distance and leverage), and Variance Inflation Factors (VIFs), whereby VIF < 3 indicated low collinearity (Kock and Lynn 2012).

RESULTS

Mean annual SAR, derived from the 0.25 km^2 fishing-pressure grid, ranged from 2.34 to 10.14 yr^{-1} across sampling sites, within a broader regional range of 0–22.49 yr^{-1} (Fig. 1; Table 1). Spatial gradients in fishing pressure were evident along the margins of the WISMB and around seabed infrastructure (e.g., cables and pipelines). *N. norvegicus* burrow densities were relatively uniform among sites, ranging from 0.61 to 1.26 m^{-2} (average: 0.96 ± 0.16 m^{-2}), while water depths were 66–132 m across sites (Figs. S1, S2; Table 1).

The 20 sediment cores were 50–88 cm length (Table 1) and most sediments were classed as mud or sandy mud (Table S3). Sites 2c and 6b contained unclassified gravel fractions, so were excluded from subsequent analyses. Across the remaining 18 sites, mean mud content within the upper 50 cm was 87.06% ± 5.98%, comprising 23.94% ± 3.78% clay and 63.12% ± 2.99% silt. Mud content remained broadly constant with sediment depth, whereas clay increased and silt decreased downcore. OC content generally declined with sediment depth, whereas DBD increased.

Linear radionuclide-derived sediment accumulation rates from five cores ranged from 0.26 cm yr^{-1} to 0.37 cm yr^{-1} (average: 0.29 ± 0.02 cm yr^{-1}), equivalent to approximately 27–39 years (average: 33-years) of accumulation per 10-cm interval (Fig. 2). Sites with lower accumulation rates (0.26 cm yr^{-1}; Sites 15, 20, and 27) coincided with lower OC contents and SCDs, shallower water depths (66–98 m), higher *N. norvegicus* burrow densities (0.89–1.26 m^{-2}), and greater fishing pressure (7.01–8.82 yr^{-1}) (Table 2). In contrast, sites with higher sediment accumulation rates (0.31 cm yr^{-1} (Sites 4) and 0.37 cm yr^{-1} (Site 8)) coincided with higher OC contents

Table 1 Sampling site IDs, latitude, longitude, water depth (m) corrected for tidal state, sediment core length (cm), *Nephrops norvegicus* burrow density (m^{-2}) and swept area ratio (SAR, yr^{-1}) estimated in this study

Site ID	Latitude	Longitude	Core length (cm)	Water depth (m)	*N. norvegicus* burrow density (m^{-2})	SAR (yr^{-1})
2c	54.3368	− 4.9623	50	108	0.88	5.50
3	54.3038	− 5.0022	74	132	0.90	2.34
4	54.2626	− 5.0290	88	119	0.95	3.05
5	54.2225	− 5.0503	64	120	1.00	4.62
6b	54.1862	− 5.0721	52	110	1.01	8.92
8	54.1035	− 5.1465	83	116	0.93	3.95
10	54.0178	− 5.1629	73	72	1.09	10.14
12b	54.2930	− 4.9360	58	98	0.94	8.47
13	54.2583	− 4.9531	61	103	0.93	8.64
14	54.2056	− 4.9996	69	100	0.97	4.09
15	54.1678	− 5.0194	73	98	0.89	7.00
16	54.1294	− 5.0451	67	96	0.70	9.40
17	54.0825	− 5.0758	74	90	0.61	9.54
18	54.0426	− 5.1114	68	77	0.87	3.54
19	53.9963	− 5.1296	73	68	1.20	5.96
20	53.9667	− 5.1403	83	66	1.21	8.52
21	54.2830	− 4.8808	77	68	0.94	4.92
23	54.1978	− 4.9430	62	86	0.89	8.55
26	53.9837	− 5.0788	59	73	1.05	7.75
27	53.9377	− 5.1150	76	68	1.26	8.11

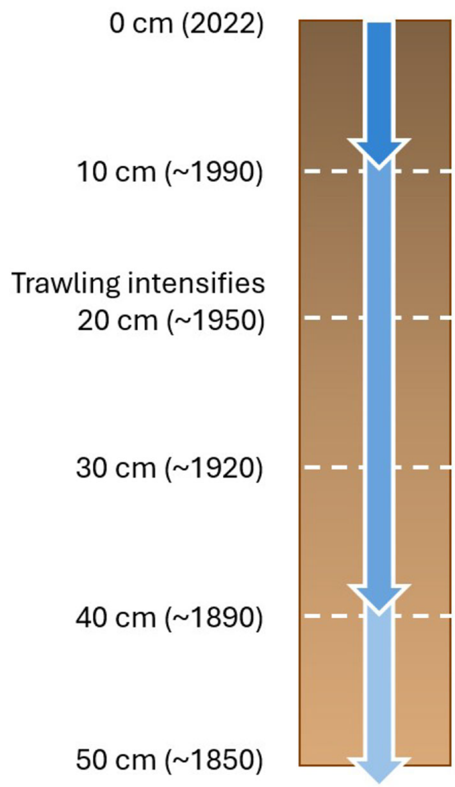

Fig. 2 Schematic representing the top 50 cm of sediment in the Western Irish Sea Mud Belt (WISMB) divided into 10 cm segments (white dashed lines) and labelled with average sediment deposition dates based on the average linear sediment accumulation rate of 0.29 ± 0.02 cm yr.$^{-1}$ estimated from 5 sediment cores (Muir et al. 2026). Example dredge and trawl gear penetration depth maxima are represented by blue arrows from the sediment surface to ≤ 10 cm for most components, and to 40 cm (sometimes ≥ 50 cm; Paradis et al. 2019) for otter trawl doors (Eigaard et al. 2016; Martín et al. 2014b)

and SCDs, deeper water (116–119 m), average *N. norvegicus* burrow densities (0.93–0.95 m^{-2}), and lower fishing pressure (3.05–3.95 yr^{-1}) (Table 2). Surface mixed-layer depths inferred from radionuclide profiles ranged from approximately 4–11 cm. In contrast, extensive sediment mixing at Sites 14 and 21 down to 20–40 cm precluded accumulation rate estimates, despite moderate *N. norvegicus* burrow densities (0.94–0.97 m^{-2}) and SARs (4.09–4.92 yr^{-1}), and comparable water depths (68–100 m) (Table 2; Figs. S4–S10).

Linear mixed-effects model outputs are summarised in Table 3, with Pearson correlation plot and residual diagnostics provided in Figs. S11–S15. Based on BIC model selection (Tables S4, S5), the optimal structure for both SCD and OC content was a main-effects random-intercept model including SAR, mud content ("MUD"), sediment depth ("Layercont"), and *Nephrops* burrow density ("NEPHROPS") as z-standardised fixed effects, with (1|Site) is Site as a random intercept:

$$\mathrm{SCD} \sim \mathrm{z\_SAR} + \mathrm{z\_MUD} + \mathrm{z\_Layercont} + \mathrm{z\_NEPHROPS} + (1|\mathrm{Site})$$

$$\mathrm{OC} \sim \mathrm{z\_SAR} + \mathrm{z\_MUD} + \mathrm{z\_Layercont} + \mathrm{z\_NEPHROPS} + (1|\mathrm{Site}).$$

BIC (lowest among candidates) was - 88.42 (SCD) and - 94.70 (OC content), which was not improved by interaction terms, random MUD slopes, or log(SCD) or log(OC) (Tables S4, S5). For both SCD and OC content, SAR and sediment depth showed significant negative effects, while mud content had a positive effect on OC content but not SCD (Table 3). *Nephrops* burrow density was not a

Table 2 Average sediment accumulation rate ± standard deviation (cm yr^{-1}) estimated from ^{210}Pb, ^{210}Po, and ^{137}Cs radionuclide analysis for sediment cores from Sites 4, 8, 14, 15, 20, 21, and 27 (Muir et al. 2026), and their corresponding water depth (m, corrected for tidal state), *Nephrops norvegicus* burrow density (m^{-2}), swept area ratio (SAR, yr^{-1}), organic carbon (OC) content (wt%), and sediment OC density (gC cm^{-3}) at 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm sediment depths (tabulated as mid-point depths), and surface sediment mixing depth (cm) estimated from radionuclide activity

Site ID	Sediment accumulation rate (cm yr^{-1})	Water depth (m)	*N. norvegicus* burrow density (m^{-2})	SAR (yr^{-1})	Sediment depth (cm)										Surface mixing depth (cm)
					5	15	25	35	45	5	15	25	35	45	
					Organic carbon content (wt%)					Sediment organic carbon density (gC cm^{-3})					
4	0.31± 0.01	119	0.95	3.05	1.41	1.32	1.14	0.93	0.86	1.22	1.13	0.89	0.86	0.83	0–6
8	0.37? ± 0.00	116	0.93	3.95	1.59	1.35	1.11	1.01	0.99	1.38	1.19	0.92	0.86	0.91	0–11
14	N/A	100	0.97	4.09	1.32	1.36	1.38	1.32	1.22	1.05	1.17	1.23	1.17	1.28	0–40
15	0.26 ± 0.03	98	0.89	7.01	0.89	0.75	0.74	0.53	0.50	0.89	0.83	0.77	0.58	0.54	0–8
20	0.26 ± 0.04	66	1.21	8.52	0.92	0.83	0.70	0.48	0.49	1.00	1.02	0.87	0.60	0.61	0–7
21	N/A	68	0.94	4.92	0.77	0.73	0.62	0.69	0.75	0.90	0.94	0.75	0.90	0.90	0–19
27	0.26 ± 0.03	68	1.26	8.12	0.78	0.60	0.49	0.49	0.47	0.85	0.73	0.60	0.54	0.55	0–4

Table 3 Summary of the linear mixed-effects model describing the relationship between sedimentary organic carbon density (SCD, × 10^{-2} gC cm^{-3}) and organic carbon (OC) content and z-standardised predictor variables: fishing intensity (swept area ratio, SAR), mud content (%), sediment depth (cm), and *Nephrops norvegicus* burrow densities (m^{-2}). Estimates represent fixed effects; se=standard error; df = degrees of freedom

Dependent variable	Parameter	estimate	se	df	t-value	*p*-value	Effect per + 1-unit change
SCD	Intercept	0.906	0.025	17.110	36.038	0.000	–
	SAR	− 0.076	0.027	19.321	− 2.776	0.012	−0.031
	Mud content	0.021	0.023	43.823	0.899	0.374	0.003
	Sediment depth	− 0.102	0.011	72.917	− 8.979	0.000	− 0.007
	N. norvegicus burrow densities	0.010	0.025	17.275	0.400	0.694	0.064
OC	Intercept	0.885	0.032	12.511	27.307	0.000	–
	SAR	− 0.114	0.034	14.357	− 3.294	0.005	− 0.046
	Mud content	0.071	0.025	61.411	2.788	0.007	0.012
	Sediment depth	− 0.146	0.010	67.142	− 14.278	0.000	− 0.010
	N. norvegicus burrow densities	− 0.003	0.033	12.641	− 0.107	0.917	− 0.022

significant predictor in either model. Standardised fixed effects are shown in Table 3. These coefficients represent the change in SCD and OC content per one SD increase in each predictor, enabling direct comparison of effect sizes. Converted to original units, SCD and OC content declined by -0.031 × 10^{-2} gC cm^{-3} and 0.046 wt% per additional unit of SAR and by -0.007 ×10^{-2} gC cm^{-3} and 0.010 wt% per additional unit of sediment depth, and increased by + 0.003 × 10^{-2} gC cm^{-3} and 0.012 wt% per additional unit of mud content, while *N. norvegicus* burrow density had no detectable effect (Tables S6, S7).

The random intercept (Site) variance was 0.009 (SCD) and 0.017 (OC content) and residual variance 0.011 (SCD) and 0.009 (OC content). Model assumptions were met, whereby model residuals were approximately normally distributed (Shapiro−Wilk: $p > 0.360$ (SCD); $p > 0.500$ (OC content)) and multicollinearity was low (VIF: ≤ 1.28; Table S8). Three influential observations (Cook's D > 4/N) were identified (deepest layers at Sites 13, 14, and 21 (SCD, Table S9) and at Sites 14, 15, and 21 (OC content, Table S10)), but sensitivity analyses excluding influential observations produced consistent results (Tables S11, S12). These findings indicate that model conclusions are robust and not driven by a small number of influential observations.

Marginal effect plots showed declining SCD and OC content with increasing SAR across all mud-content levels, with consistently higher values in muddier sediments (Fig. 3). No significant 'SAR × MUD' interaction was identified, indicating that the effect of trawling intensity on OC stores was broadly constant across the observed mud-content gradient. Narrow 95% confidence intervals across most of the SAR range, while holding sediment depth and *N. norvegicus* burrow density at their means, indicate stable effect sizes under the model assumptions.

DISCUSSION

Intense, chronic bottom trawling was associated with reduced SCD and OC content throughout the upper 50 cm of muddy sediments in the WISMB, deposited since the mid-1800s. The effect on SCD suggests trawling may impact sediment structure, while the effect on OC content suggests trawling may impact OC composition. On average, SCD and OC content declined by 0.03 × 10^{-2} gC cm^{-3} and 0.05 wt% per additional SAR (+ 1 yr^{-1}) unit, respectively. These results suggest that areas exposed to very high SARs (up to 22.49 yr^{-1} in the WISMB) could experience even greater OC depletion.

These findings align with modelled predictions of SCD depletion in North Atlantic surface sediments (Epstein and Roberts 2022; Porz et al. 2024; Diesing et al. 2025), empirical studies reporting lower OC content in trawled versus untrawled muddy sediments to 30–50 cm depth (Martín et al. 2014a; Paradis et al. 2019), and recent North Sea observations showing reduced OC content in the upper 10–20 cm under high trawling intensities (> 1 yr^{-1}) (Zhang et al. 2024). Conversely, Tiano et al. (2024) reported increased OC content in chronically fished areas across trawling gradients, potentially reflecting a preference for meso-eutrophic habitats.

One mechanism by which trawling has been found to deplete OC content in surface sediments is through erosion of modern OC-rich layers, exposing older OC-poor sediments, that are typically denser with depleted excess ^{210}Pb, relative

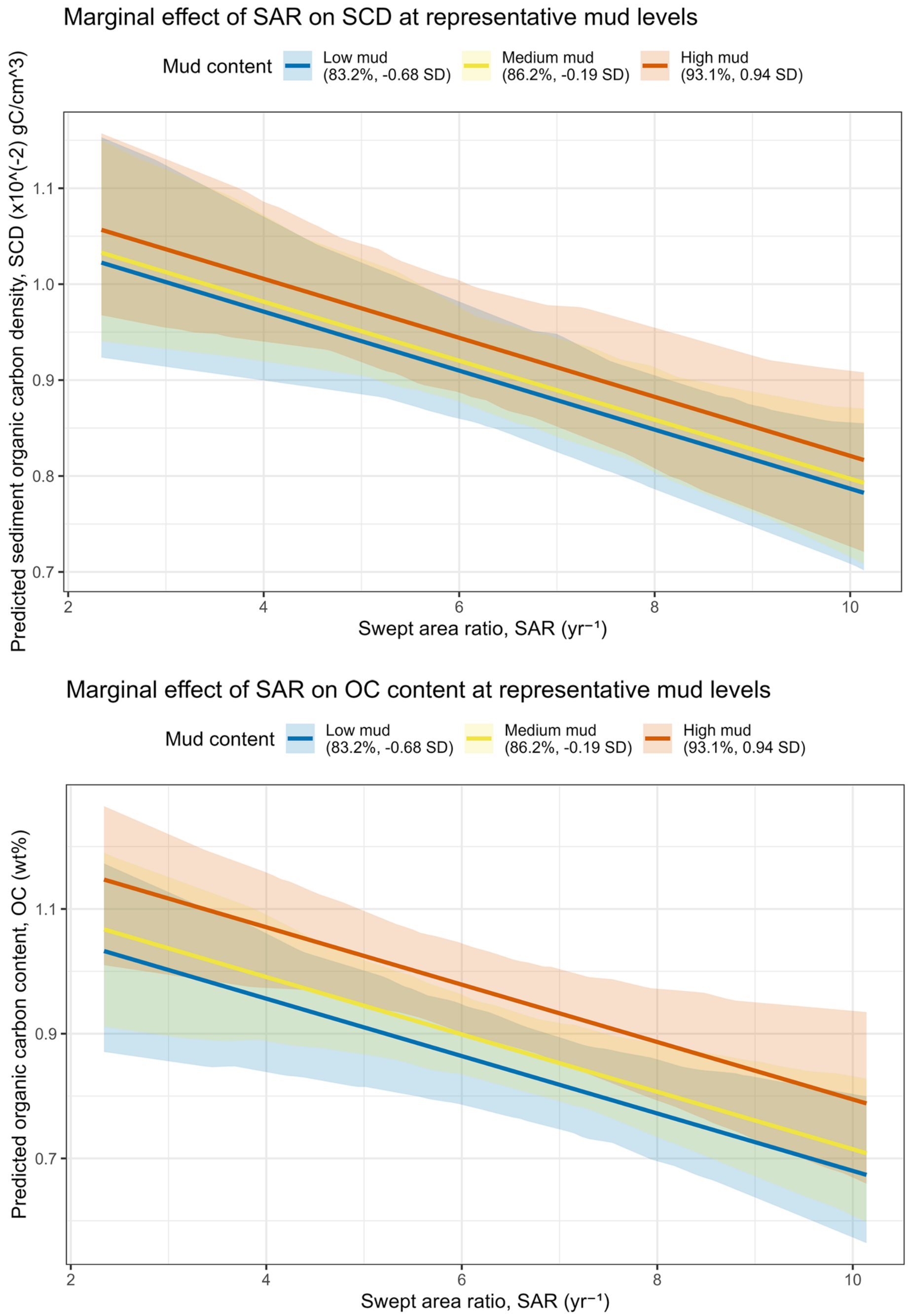

Fig. 3 Marginal effect of swept area ratio (SAR, yr^{-1}) on sediment organic carbon density (SCD, $\times 10^{-2}$ gC cm^{-3}; Top) and sediment organic carbon content (OC, wt%; Bottom), predicted from a linear mixed-effects model. Lines show modelled relationships at representative mud contents (25th, 50th, and 75th percentiles), corresponding to low (83.2%,− 0.68 SD), medium (86.2%,−0.19 SD), and high (93.1%, + 0.94 SD) mud levels. Shaded ribbons represent 95% confidence intervals, reflecting uncertainty in fixed effects. Other covariates (sediment depth and *Nephrops* burrow density) are held at their means

to untrawled sites (Martín et al. 2014a; Paradis et al. 2019, 2020). However, unlike canyon and shelf-edge settings where trawling drives sediment export, the WISMB exhibits net sediment accumulation (0.26−0.37 cm yr^{-1}) and retention, despite intense trawling. Cyclonic circulation, weak bed shear stresses, and a narrow benthic boundary layer likely promote sediment trapping and limit permanent export in the region (Williams et al. 2019).

Down-core profiles of DBD, excess ^{210}Pb, and OC content resembled those reported from trawled and untrawled sites in La Fonera Canyon (Martín et al. 2014a), suggesting a gradient of trawling-induced mixing in the WISMB. Lower sediment accumulation rates occurred at the most intensely trawled sites; however, these were also shallower and therefore could be subject to greater storm- and tide-driven resuspension, which can mimic trawling effects by increasing oxygen penetration (Pusceddu et al. 2005; Diesing et al. 2013; Palanques et al. 2014). Spatial interpretation is further limited by radionuclide data from only five sites.

Because sediment appears largely retained rather than exported, enhanced OC remineralisation driven by sediment mixing and repeated resuspension–settling cycles may be the dominant mechanism of OC loss in the WISMB (Khedri et al. 2025). Alternating oxic–anoxic conditions can accelerate degradation of labile OC by increasing microbial activity (Aller 1994; van de Velde et al. 2018; Paradis et al. 2020; Song et al. 2022). Trawling may also promote surface sediment coarsening and OC loss through winnowing of OC-rich particles, by enhancing sediment resuspension and advection (Palanques et al. 2014; Paradis et al. 2020). Across the study region, increasing silt and decreasing clay contents towards the sediment surface support coarsening, potentially reflecting trawling intensification over the past century. However, broadly stable mud contents reflect overall retention of fine sediments in the WISMB (Williams et al. 2019).

Within these retained sediments, OC content was greater in muddier sediments (0.01 wt% per additional 1% mud), whereas SCD was unaffected. This likely reflects established sedimentological controls, whereby low permeability, greater surface area, and reduced oxygen penetration enhance OC preservation in fine cohesive muds (Burdige 2007; Sciberras et al. 2016). Whereas lower DBDs in finer sediments offsets OC enrichment, decoupling OC content from volumetric OC stocks. This highlights the importance of accounting for DBD when assessing OC stocks, as OC content alone may overestimate long-term OC storage in fine sediments. The absence of a mud*SAR interaction may reflect the narrow gradient of mud content (74–98%) across the study region, unlike studies reporting stronger remineralisation in muddier sediments (Zhang et al. 2024). These findings are therefore likely representative of trawling impacts across the wider WISMB.

Furthermore, SCD and OC content declined with sediment depth, decreasing by 0.007×10^{-2} gC cm^{-3} and 0.01 wt% per additional centimetre, respectively. This pattern is consistent with observations from trawled Mediterranean (Martín et al. 2014c; Paradis et al. 2019) and North Sea sediments (Zhang et al. 2024). Depth-related declines in SCD and OC content likely reflect progressive remineralisation of labile OC over time despite sediment compaction, leaving deeper sediments enriched in more refractory OC fractions, potentially compounded by historically lower phytoplankton productivity in the Irish Sea (Allen et al. 1998; Evans et al. 2003; Muir et al. 2026).

The absence of a depth*SAR interaction suggests that the magnitude of trawling effects on SCD and OC content was constant at all depths. This depth-invariant SAR effect may indicate long-term spatial stability in trawling effort around the British Isles, whereby sediments currently buried at depth experienced similar disturbance histories to surface sediment (Stelzenmüller et al. 2008; Davie and Lordan 2011; Coughlan et al. 2015; ICES 2020, 2021). Alternatively, deeper penetration by some trawl gear components could influence deeper layers directly. However, the preservation of radionuclide and OC content and SCD profiles below ~ 10 cm suggests that deep physical disturbance may be limited across most sites (dark blue arrow, Fig. 2). If historical spatial shifts in trawling intensity occurred but were not captured by modern SAR estimates, the observed relationships may underestimate long-term trawling impacts on sedimentary OC. Ultimately, statistical assumptions of the model inhibit its ability to fully resolve the depth-invariant SAR-effect herein.

Altered excess ^{210}Pb profiles within the upper ~ 10 cm at all sites analysed for radionuclides indicate widespread sediment mixing, potentially reflecting the combined effects of trawling-induced resuspension–redeposition cycles (Thompson et al. 2017), regional hydrodynamics including tidal currents and the seasonal cyclonic gyre (Williams et al. 2019; Coughlan et al. 2021), and biological mixing, particularly burrowing by *N. norvegicus*. These processes can enhance oxygen exposure, remineralisation, and seabed disturbance, thereby accelerating OC loss over time (Song et al. 2022).

More extensive mixing at Sites 14 and 21 was reflected in flatter radionuclide and OC profiles, where deeper excess ^{210}Pb prevented sediment accumulation rate estimates. Moderate trawling intensity and *N. norvegicus* burrow densities at both sites (Table 2) suggest elevated localised sediment disturbance. This likely reflects direct impacts from deeply penetrating trawl gears (paler blue arrows, Fig. 2) or redeposition of resuspended sediments (Martín et al. 2014c; Paradis et al. 2020; Porz et al. 2024), which can obscure trawling effects by elevating surface OC, as observed at Site 14 (Paradis et al. 2019; Zhang et al. 2024).

Although trawling can alter benthic community structure and bioturbation (Palanques et al. 2014; Sciberras et al. 2016), *N. norvegicus* burrow density had no significant effect on OC content or SCD and exerted weaker effects than SAR or mud content. This suggests physical disturbance, sediment type, and sediment age primarily control sedimentary OC in the WISMB (Rice and Chapman 1971; Coughlan et al. 2015). However, the relatively narrow burrow-density gradient (0.96 ± 0.16 m^{-2}) may have limited the ability to resolve bioturbation effects on OC herein.

Considering the comparatively low sediment accumulation rates in the WISMB (0.26–0.37 cm yr^{-1}) relative to trawling disturbance within the upper ~ 10 cm of sediments accumulated over 27–38 years, together with evidence that recovery of sediment OC may require multiple decades of trawl cessation (Paradis et al. 2020; Zhang et al. 2024), our results support management measures that reduce chronic disturbance in muddy shelf seas. Potential measures include trawl-free areas, trawling effort caps, and spatial redistribution of trawling pressure away from OC-rich regions. Because sediments are largely retained in the WISMB, reducing trawling frequency may be particularly effective in lowering oxic exposure and sediment mixing, promoting burial and preservation of more labile OC fractions.

CONCLUSION

This study demonstrates that chronic bottom trawling is associated with reduced SCD and OC content throughout the upper 50 cm of muddy shelf sediments in the WISMB. Sediment depth, mud content, and trawling intensity emerged as the primary controls on sedimentary OC storage, while *N. norvegicus* burrowing showed no detectable influence under current disturbance conditions. The results suggest that persistent trawling has likely depleted OC stored in sediments deposited since the nineteenth century through sediment mixing, repeated resuspension, and enhanced remineralisation of retained organic matter. Despite continued sediment accumulation within the WISMB, relatively low accumulation rates compared to the frequency of disturbance may limit long-term OC recovery. These findings add to growing evidence that intensive bottom trawling can reduce the capacity of muddy shelf sediments to function as long-term carbon sinks and climate regulators. Given the apparent sensitivity of OC-rich muddy sediments to chronic disturbance, management approaches that reduce trawling intensity in OC-rich shelf environments may help support long-term OC preservation.

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Author contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by Hannah C. Muir, James A. Strong, Rowan Henthorn, Jacqui Keenan, and Claire Evans. Data analysis was performed by Hannah C. Muir, James A. Strong, David G. Reading, and Phillip E. Warwick. Statistical analysis was performed by Hannah C. Muir, James A. Strong, and Jan G. Hiddink. The first draft of the manuscript was written by Hannah C. Muir and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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