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Impact of bottom trawling on sediment biogeochemistry: a modelling approach

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S.1. Data collection for parametrization

S.1.1. General sampling design

In September 2017, locations Coarse, FineH, and MudH were sampled in the Belgian Part of the North Sea (Toussaint et al., *in review*), whereas FineL and MudL were sampled in the Central-Northern North Sea in May-June of 2018 (De Borger et al., *in press*). The stations from Toussaint et al. (*in review*) have historic names as sampling stations in the Belgian Part of the North Sea: "330" for "Coarse", "780" for "FineH", and "130" for MudH (e.g. van der Zee and Chou (2004), Franco et al. (2010), Braeckman et al. (2014), Van De Velde et al. (2018)). A stainless steel NIOZ boxcorer was used to sample the sediments used to describe the different locations in this modelling study (30 cm ID, 50 cm height). At each location, triplicate intact boxcores were collected. From the September 2017 samples, a set of subcores was taken from each boxcore sample for: incubation purposes (Ø 19 Plexiglass sampling cores for coarse grained sediment to allow for a stirring mechanism for advective flows; Ø 10 cm for cohesive sediment, 10-15 cm deep + 10 cm of overlying water), to determine porewater nutrient profiles (Ø 10 cm Plexiglass sampling core), and to determine sediment characteristics (cut off syringe, upper 3 cm). Incubations were performed in the dark (to prevent photosynthetic activity), and in climate controlled laboratory conditions with disk (coarse) of teflon (cohesive) stirrers agitating the overlying water, and exchange rates of oxygen, dissolved inorganic carbon (DIC), and dissolved inorganic nitrogen (DIN) were measured.

In the May-June samples, ship-board incubations (dark) were performed using the entire boxcore sample, measuring the same parameters as previously mentioned. For this, the boxcore "bucket" containing the sediment was sealed with a Plexiglass lid containing a Teflon stirrer, and placed in a buffering vat on deck to maintain steady temperature. After this shipboard incubation, subcores were collected to measure porewater nutrient profiles (Ø 10 cm Plexiglass sampling core), oxygen microprofiles (Ø 5 cm Plexiglass sampling core), and sediment characteristics (cut off syringe, upper 2 cm).

S.1.2. Flux calculations

During incubations, the oxygen concentration in the overlying water was monitored using optode sensors (FirestingO2, Pyroscience, 2-point calibration), set at 1 Hz. At the same time, DIC and DIN concentrations were sampled from the overlying water with syringes at discreet time intervals. 5 – 10 mL were collected for DIN, and filtered through a 0.45 µm syringe filter, and stored at -20 °C until further processing. 6 - 10 mL of water were collected in headspace vials for DIC, and subsequently poisoned with 1 µL of saturated HgCl2 per mL sample for preservation and kept refrigerated at 4 °C until further processing. During incubations, O_2 concentrations did not decrease below 50 % of the initial oxygen concentration. As such, incubations in the 2017 samples lasted between 2 – 8 hours, and 24 – 36 hours in 2018.

Upon thawing, nutrient concentrations were determined by a SEAL QuAAtro segmented flow analyser (Jodo et al., 1992). DIC analysis was performed using a segmented flow analyser (San++ SKALAR) following (Stoll et al., 2001). Fluxes (in mmol m^{-2} d^{-1}) were calculated by fitting a linear regression through the concentration time series, and multiplying the regression coefficient by the height of the overlying water to convert from volumetric to surficial rates. For oxygen fluxes the same method was applied to a consistently decreasing section of the oxygen concentration data.

S.1.3. Porewater nutrient profiles

Porewater nutrients (DIN) were collected in 1-2 cm interval depth slices down to 12 cm deep, using rhizon samplers (0.15 µm pore size, Rhizosphere Research Products). The rhizons were inserted into the sediment core through pre-drilled holes in the core wall, and a maximum of 4 mL of porewater was extracted from each interval using a 5 mL syringe connected to the rhizon sampler (Seeberg-Elverfeldt et al., 2005; Dickens et al., 2007; Shotbolt, 2010). Further processing of the nutrient samples was done the same as for the nutrient flux samples.

S.1.4.Oxygen microprofiles

Oxygen-depth profiles in the sediment were measured using Clark-type O_2 micro-electrodes (50 µm tip diameter, Unisense) (Revsbech, 1989). Readings were taken at 100 µm intervals, starting 2000 µm (2 mm) above the sediment-water interface (water aerated to 100% O_2 saturation before the experiment) down to the depth in the sediment at which all oxygen was depleted. A two-point calibration was conducted prior to measurements using 100 and 0 % oxygen saturated seawater to represent water column and anoxic O_2 concentrations, respectively. In each sediment core, up to three replicate profiles were taken from different areas of the sediment (except in Coarse, where the risk of damage to the sensor due to coarseness of the sediment was determined too great).

S.1.5. Sediment characteristics

Sediment grain size was determined by laser diffraction on freeze-dried and sieved (< 1 mm) sediment samples in a Malvern Mastersizer 2000 (McCave et al., 1986). Grain size fractions were determined as volume percentages according to the Wentworth scale (Wentworth, 1922): clay/silt (< 63 µm), very fine sand (vfines: 63 – 125 µm), fine sand (fines: 125 – 250 µm), medium sand (250 – 500 µm), and coarse sand (500 µm – 1 mm). In this manuscript, the percentage of sand was calculated by summing grainsize classes between 63 and 1000 µm. The median grain size (MGS) was calculated on the fraction < 1 mm. Water content was determined as the volume of water removed by freeze drying wet sediment samples. The sediment density was determined by measuring the water displacement of a given weight of dried sediment. Sediment porosity was determined from water content and solid phase density measurements, accounting for the salt content of the pore water.

S.2. Supplementary figures

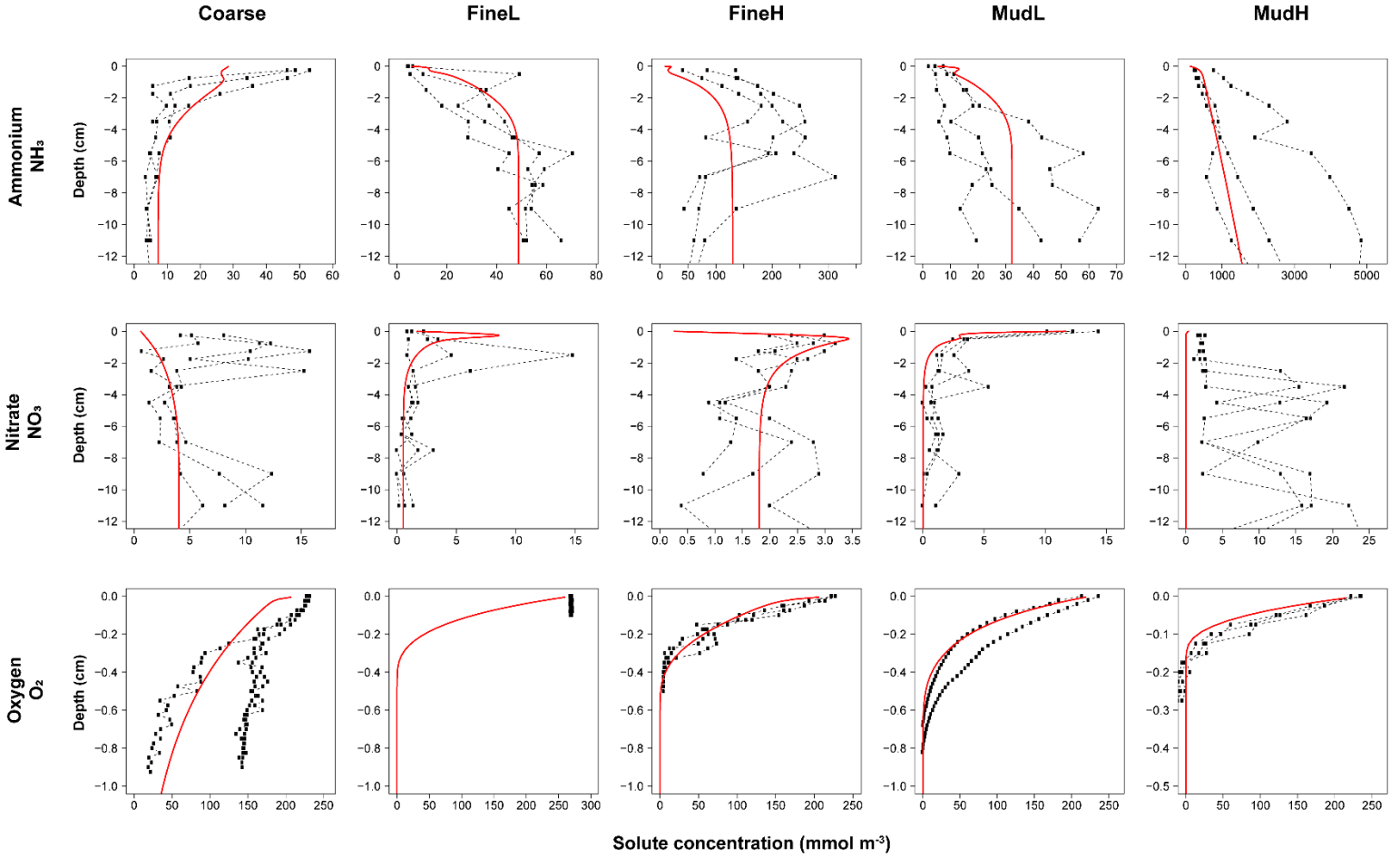

Figure S 1: Measured concentrations (black dots) and fitted profiles (red line) for ammonium, nitrate, and oxygen (mmol m^{-3}, rows) in the different types of sediment used as the basis for the disturbance simulations (columns).

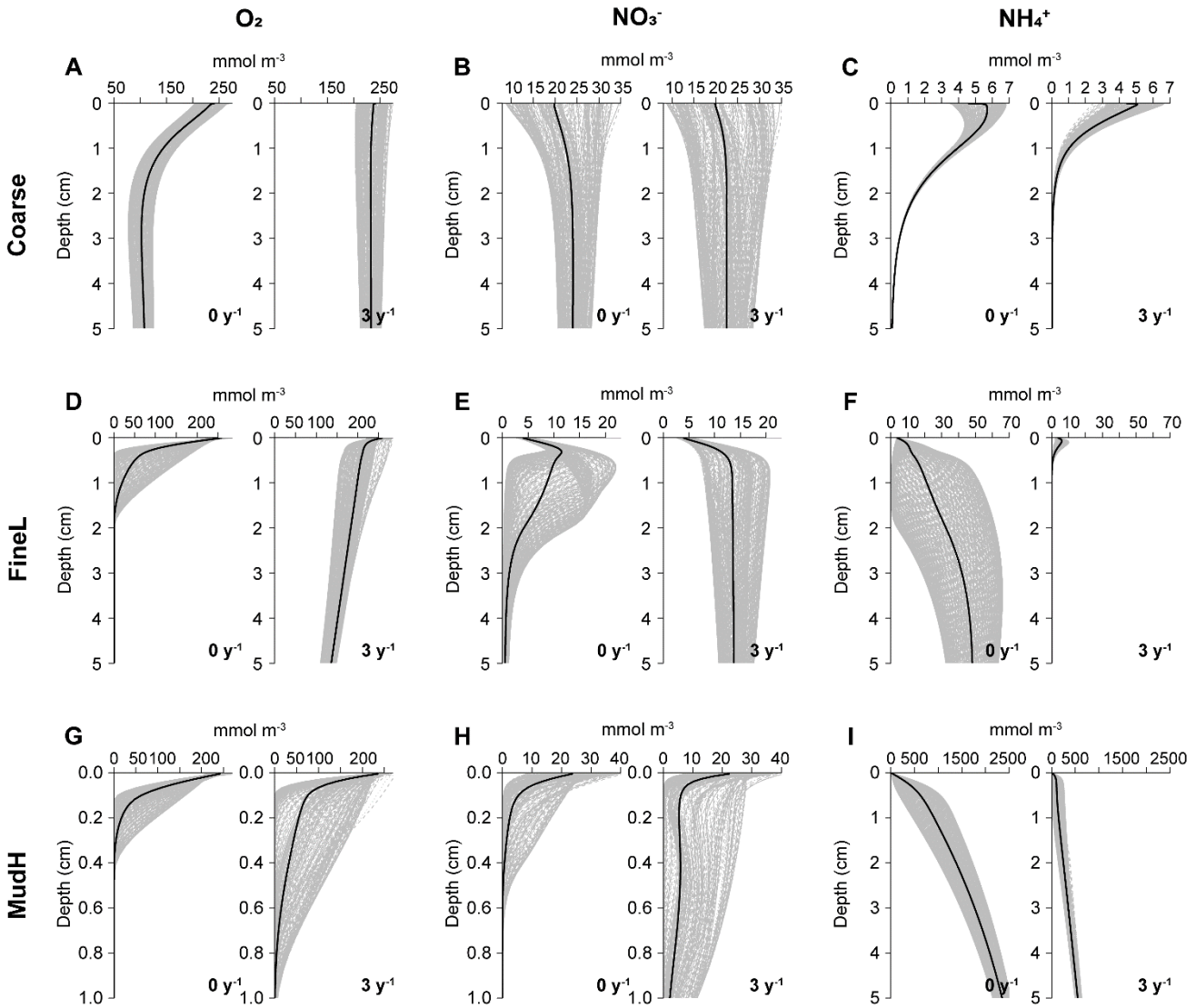

Figure S 2: Range of nutrient concentrations (gray lines) throughout the year, and average annual concentration (black line) in an untrawled sediment, and sediment trawled 3 y^{-1} of Coarse (A-C), FineL (D-F), and MudH (G-I). Nutrient concentrations in mmol m^{-3}. Note the difference in depth range (y-axis) shown for the different sediments.

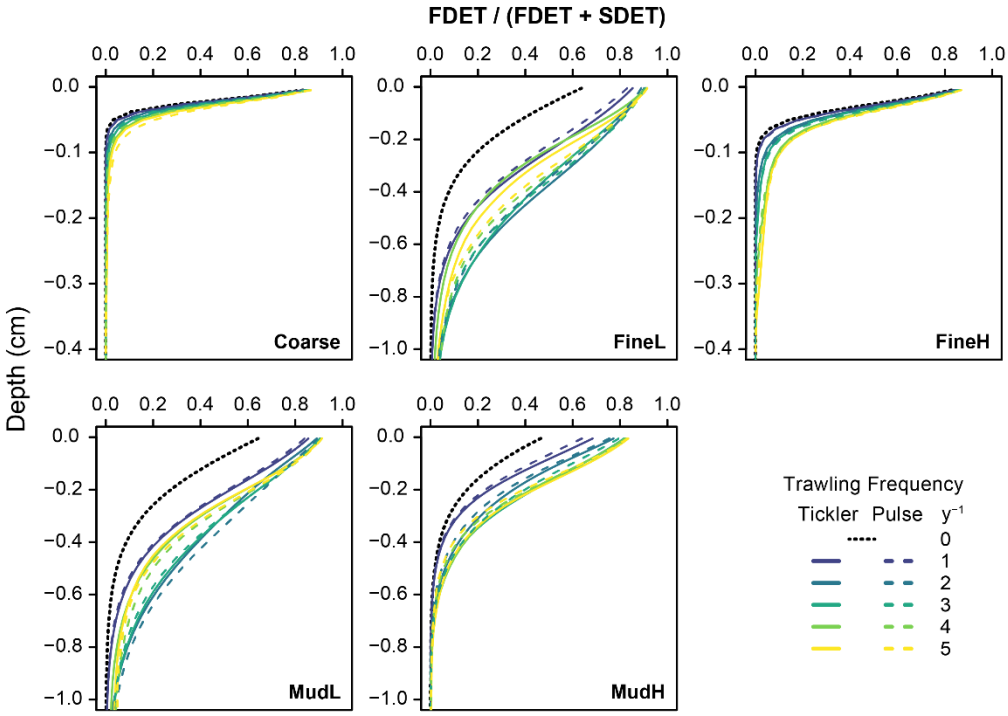

Figure S 3: Annually averaged modelled quality of the reactive organic carbon pool in the surface sediments (note different depths on y-axis between figures for visualization purposes). The carbon quality (x-axis) is represented as the proportion of fast degrading detritus (FDET, labile org. C) in the summed labile and semi-labile org. C pool (FDET + SDET). Black dotted line is the 0 trawl default, full and dotted coloured lines are tickler and pulse gear respectively, with increasing trawling frequencies as different colours.

S.3. Supplementary tables

Table S 1: Overview of effect of increasing trawling intensities for tickler gears, and pulse gears (columns) on sedimentary concentrations of O_2, NO_3^-, NH_4^+ (top 5 cm) and organic carbon (top 10 cm). The baseline scenario (frequency = 0) is displayed as the absolute concentration (mmol m^{-3}), increasing frequencies (1 – 5 y^{-1}) are shown as % change of the baseline rate (+ = increase, - = decrease). Concentrations are the average annual concentrations, in mmol m^{-3} for solutes, and mol m^{-3} for organic carbon.

		Tickler						Pulse					
		Conc.	% Change					Conc.	% Change				
	station	0	1	2	3	4	5	0	1	2	3	4	5
O_2 *mmol m^{-3}*	Coarse	117.1	96 ± 7	97 ± 4	98 ± 3	99 ± 3	99 ± 4	117.1	98 ± 8	98 ± 3	100 ± 3	99 ± 4	97 ± 2
	FineL	8.1	239 ± 169	805 ± 280	1211 ± 387	1637 ± 270	1604 ± 347	8.1	133 ± 136	447 ± 195	1013 ± 300	1335 ± 364	1584 ± 323
	FineH	9.3	656 ± 142	1081 ± 79	1075 ± 165	1036 ± 254	965 ± 253	9.3	686 ± 322	1053 ± 202	1153 ± 158	1196 ± 217	1129 ± 212
	MudL	8.5	467.4 ± 182	1010 ± 208	1296 ± 272	1512 ± 311	1517 ± 287	8.5	296 ± 154	891 ± 169	1340 ± 392	1578 ± 351	1619 ± 264
	MudH	1.8	-28.8 ± 4	-25 ± 38	14 ± 57	27 ± 53	52 ± 57	1.8	-25 ± 4	-27 ± 21	-9 ± 44	52 ± 61	81 ± 49
NO_3^- *mmol m^{-3}*	Coarse	23.5	11.3 ± 7	10 ± 8	6 ± 9	1 ± 9	0 ± 8	23.5	13 ± 7	9 ± 9	6 ± 10	4 ± 9	-4 ± 4
	FineL	2.2	991 ± 135	1038 ± 52	967 ± 90	882 ± 87	909 ± 129	2.2	866 ± 251	1044 ± 44	981 ± 53	932 ± 87	882 ± 105
	FineH	2	584 ± 88	690 ± 100	655 ± 108	585 ± 132	565 ± 132	2	559 ± 202	685 ± 115	690 ± 89	675 ± 79	626 ± 89
	MudL	1.2	1598 ± 114	1733 ± 81	1779 ± 128	1822 ± 246	1912 ± 253	1.2	1464 ± 312	1687 ± 60	1662 ± 119	1675 ± 167	1741 ± 187
	MudH	0.2	-51 ± 10	-40 ± 61	39 ± 123	70 ± 117	123 ± 125	0.2	-50 ± 11	-47 ± 31	-12 ± 85	114 ± 136	188 ± 104
NH_4^+ *mmol m^{-3}*	Coarse	0.9	-53 ± 2	-57 ± 3	-59 ± 2	-62 ± 2	-63 ± 2	0.9	-52 ± 4	-57 ± 3	-59 ± 2	-62 ± 2	-64 ± 2
	FineL	41	-97 ± 2	-99 ± 0	-99 ± 0	-100 ± 0	-99 ± 1	41	-94 ± 6	-99 ± 1	-99 ± 0	-99 ± 0	-100 ± 0
	FineH	125.6	-98 ± 1	-99 ± 0	-99 ± 1	-98 ± 3	-97 ± 6	125.6	-96 ± 6	-99 ± 1	-100 ± 0	-99 ± 1	-99 ± 2
	MudL	50.7	-98 ± 1	-99 ± 0	-99 ± 0	-99 ± 1	-99 ± 0	50.7	-97 ± 3	-99 ± 0	-99 ± 0	-99 ± 0	-99 ± 0
	MudH	21612	-50 ± 7	-62 ± 3	-65 ± 6	-63 ± 6	-61 ± 9	2162	-43 ± 8	-59 ± 5	-64 ± 4	-68 ± 6	-68 ± 7
Organic C *mol m^{-3}*	Coarse	78.4	-87 ± 2	-92 ± 2	-94 ± 1	-95 ± 1	-96 ± 1	78.4	-86 ± 2	-92 ± 2	-94 ± 2	-95 ± 1	-96 ± 1
	FineL	94.9	-72 ± 7	-84 ± 3	-87 ± 3	-90 ± 2	-91 ± 1	94.9	-65 ± 12	-81 ± 6	-86 ± 2	-89 ± 2	-91 ± 1
	FineH	326.3	-86 ± 3	-93 ± 2	-95 ± 1	-96 ± 1	-96 ± 1	326.3	-84 ± 4	-93 ± 2	-94 ± 2	-96 ± 1	-96 ± 1
	MudL	92.4	-71 ± 8	-84 ± 4	-87 ± 2	-89 ± 2	-90 ± 2	92.4	-65 ± 12	-84 ± 5	-87 ± 3	-89 ± 2	-91 ± 1
	MudH	2456	-70 ± 11	-82 ± 6	-90 ± 3	-90 ± 1	-91 ± 0	2456	-63 ± 15	-75 ± 11	-83 ± 6	-85 ± 3	-90 ± 1

Table S 2: Overview of effect of increasing trawling intensities for tickler gears, and pulse gears (columns) on the total organic matter mineralization, and the different mineralization processes. The baseline scenario (frequency = 0) is displayed as the absolute rate (mmolC m^{-2} d^{-1}), increasing frequencies (1 – 5 y^{-1}) are shown as % change of the baseline rate. Mineralization rates are the average annual concentrations.

		Tickler						Pulse					
		Rate	% Change					Rate	% Change				
	station	0	1	2	3	4	5	0	1	2	3	4	5
Total *mmol C m^{-2} d^{-1}*	**Coarse**	13.6	-5 ± 0	-8 ± 13	-12 ± 10	-19 ± 9	-22 ± 10	13.6	-5 ± 0	-7 ± 7	-13 ± 11	-17 ± 7	-21 ± 5
	FineL	8.1	-5 ± 3	-13 ± 15	-20 ± 12	-21 ± 5	-27 ± 5	8.1	-6 ± 4	-8 ± 8	-18 ± 7	-22 ± 5	-24 ± 4
	FineH	30.0	-7 ± 2	-15 ± 16	-17 ± 13	-24 ± 8	-27 ± 7	30.0	-7 ± 3	-11 ± 13	-17 ± 8	-23 ± 8	-29 ± 6
	MudL	8.6	-5 ± 2	-15 ± 19	-18 ± 10	-23 ± 8	-27 ± 6	8.6	-6 ± 4	-11 ± 13	-17 ± 9	-21 ± 5	-25 ± 7
	MudH	85.0	-7 ± 2	-12 ± 12	-20 ± 10	-22 ± 5	-26 ± 6	85.0	-6 ± 3	-11 ± 9	-17 ± 8	-25 ± 8	-26 ± 5
OxicMin *mmol C m^{-2} d^{-1}*	**Coarse**	12.0	-4 ± 1	-8 ± 13	-12 ± 10	-18 ± 9	-21 ± 10	12.0	-4 ± 1	-7 ± 7	-13 ± 10	-17 ± 7	-21 ± 5
	FineL	6.5	8 ± 4	-1 ± 17	-8 ± 14	-7 ± 6	-15 ± 6	6.5	7 ± 4	5 ± 9	-5 ± 8	-10 ± 6	-12 ± 5
	FineH	23.3	-1 ± 2	-10 ± 17	-13 ± 14	-20 ± 8	-23 ± 7	23.3	-2 ± 3	-6 ± 14	-13 ± 9	-19 ± 9	-25 ± 6
	MudL	6.1	11 ± 3	0 ± 22	-2 ± 12	-7 ± 10	-11 ± 7	6.1	10 ± 4	5 ± 15	-1 ± 10	-5 ± 6	-9 ± 8
	MudH	23.1	40 ± 10	50 ± 19	48 ± 21	54 ± 15	56 ± 12	23.1	32 ± 5	46 ± 12	45 ± 16	48 ± 22	56 ± 15
AnoxicMin *mmol C m^{-2} d^{-1}*	**Coarse**	0.9	-20 ± 14	-24 ± 17	-20 ± 16	-23 ± 15	-24 ± 12	0.9	-23 ± 12	-20 ± 14	-18 ± 19	-25 ± 10	-24 ± 8
	FineL	1.0	-77 ± 3	-79 ± 4	-79 ± 2	-78 ± 2	-80 ± 2	1.0	-75 ± 5	-77 ± 3	-79 ± 2	-80 ± 2	-80 ± 1
	FineH	6.6	-26 ± 4	-31 ± 13	-33 ± 11	-38 ± 6	-41 ± 6	6.6	-26 ± 5	-27 ± 11	-32 ± 8	-38 ± 8	-42 ± 5
	MudL	1.5	-74 ± 1	-78 ± 5	-80 ± 3	-82 ± 3	-83 ± 2	1.5	-73 ± 2	-76 ± 4	-80 ± 3	-81 ± 2	-83 ± 2
	MudH	57.7	-27 ± 6	-39 ± 9	-49 ± 10	-54 ± 7	-61 ± 7	57.7	-22 ± 3	-36 ± 9	-43 ± 8	-57 ± 7	-60 ± 5
Denitrification *mmol C m^{-2} d^{-1}*	**Coarse**	0.6	11 ± 14	9 ± 20	-2 ± 20	-14 ± 14	-20 ± 14	0.6	11 ± 16	8 ± 19	-6 ± 14	-8 ± 17	-19 ± 9
	FineL	0.5	-25 ± 7	-42 ± 15	-57 ± 13	-70 ± 9	-74 ± 8	0.5	-19 ± 6	-30 ± 11	-49 ± 9	-60 ± 11	-68 ± 9
	FineH	0.1	0 ± 22	-11 ± 22	-11 ± 22	-22 ± 11	-22 ± 11	0.1	0 ± 22	-11 ± 22	-11 ± 22	-22 ± 11	-33 ± 11
	MudL	0.8	1 ± 4	-13 ± 20	-22 ± 12	-31 ± 9	-35 ± 6	0.8	4 ± 5	-6 ± 15	-20 ± 12	-28 ± 9	-33 ± 6
	MudH	4.2	35 ± 15	46 ± 26	39 ± 20	48 ± 17	50 ± 9	4.2	26 ± 15	42 ± 17	41 ± 17	42 ± 19	49 ± 11