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Measuring and assessing the physical impact of beam trawling

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Beam trawling causes physical disruption of the seabed through contact of the gear components with the sediment and the resuspension of sediment into the water column in the turbulent wake of the gear. To be able to measure and quantify these impacts is important so that gears of reduced impact can be developed. Here we assess the physical impact of both a conventional 4 m tickler-chain beam trawl and a "Delmeco" electric pulse beam trawl. We measure the changes in seabed bathymetry following the passage of these gears using a Kongsberg EM2040 multi-beam echosounder and use a LISST 100X particle size analyser to measure the concentration and particle size distribution of the sediment mobilized into the water column. We also estimate the penetration of the gears into the seabed using numerical models for the mechanical interaction between gears and seabed. Our results indicate that the seabed bathymetry changes between ~1 and 2 cm and that it is further increased by higher trawling frequencies. Furthermore, our results suggest that the alteration following the passage of the conventional trawl is greater than that following the pulse trawl passage. There was no difference in the quantity of sediment mobilized in the wake of these two gears; however, the numerical model introduced in this study predicted that the tickler-chain trawl penetrates the seabed more deeply than the pulse gear. Hence, greater alteration to the seabed bathymetry by the tickler-chain beam trawling is likely to be a result of its greater penetration. The complimentary insights of the different techniques highlight the advantage of investigating multiple effects such as sediment penetration and resuspension simultaneously and using both field trials and numerical modelling approaches.

Keywords: bottom impact, multibeam echosounder, numerical modelling, penetration depth, seabed morphology, sediment resuspension, soft sediments.

Introduction

Towed demersal fishing gears have been shown to impact the benthic environment by modifying habitats, community structure, and geochemical processes (Lindeboom and de Groot, 1998; Kaiser *et al.*, 2002; Løkkeborg, 2005). Most impact studies have focused on the biological and environmental effects by either examining similar habitats with different levels of fishing effort or by carrying out Before-After Control-Impact experiments (Kaiser *et al.*, 2006; Hughes *et al.*, 2014). To fully appreciate the benthic impact of demersal fishing gears, we need to understand their immediate interactions with the benthic habitat. There will be (i) immediate biological effects such as direct damage and mortality to the benthos, (ii) geochemical effects such as release of nutrients or contaminated sediments (Durrieu de Madron *et al.*, 2005; Dounas, 2006; Roberts, 2012), and (iii) physical effects which can be categorized as being either geotechnical or hydrodynamic (O'Neill *et al.*, 2013a). While many research efforts have focused upon the direct biological effects, relatively few have considered the physical ones (Puig *et al.*, 2012).

The geotechnical impacts refer to the piercing of the gear into the sediment, and its subsequent lateral and vertical displacement (Ivanović et al., 2011). The associated pressures and shearing forces may damage benthic infauna and habitat. The hydrodynamic impacts refer to the turbulent shearing in the wake of the gear components which give rise to the mobilization of sediment into the water column (O'Neill and Summerbell, 2011; O'Neill et al., 2013a). An improved understanding of these processes is basic to the development of predictive methodologies to assess the biological and environmental effects of fishing, the design of gears of reduced impact and the assessment of fishing disturbance in relation to natural disturbances (Diesing et al., 2013; Depestele et al., 2014).

In recent years, a range of different technologies have been used to measure these processes and their impacts. The physical alteration to the seabed following the passage of a towed gear has been observed acoustically using methods such as sidescan sonar (Friedlander et al., 1999; Smith et al., 2007; Palanques et al., 2014) and a seabed classification system, RoxAnn, to estimate changes to the "roughness" and "hardness" of the seabed (Fonteyne, 1994, 2000; Humborstad et al., 2004). Optical methods such as camera and laser systems operated by divers or mounted on towed bodies, sledges, sediment profile imagery, ROVs, and drop-frames have been used to assess modifications to the seabed (Paschen et al., 2000; Smith et al., 2003; Dellapenna et al., 2006; O'Neill et al., 2009; Puig et al., 2012; Martín et al., 2014). Likewise, acoustic and optical methods (acoustic Doppler current profilers, multibeam echosounders, transmissometers, and particle size analysers) have been used to measure the sediment mobilized in the wake of towed gears (Durrieu de Madron et al., 2005; Dellapenna et al., 2006; O'Neill et al., 2013a,b). A number of authors have used combinations of technologies and in particular sidescan sonar has been used in conjunction with video images to improve resolution of vertical changes in sediment bathymetry and provide evaluations of fishing effort (Smith et al., 2007; Lucchetti and Salá, 2012; Handley et al., 2014).

Numerical models of the interaction of towed fishing gears and the seabed have also been developed in recent years (Igland and Søreide, 2008; Ivanović et al., 2011; Esmaeili and Ivanović, 2014). These models can predict the deformation of and the penetration into the seabed of individual towed gear elements and their associated contact and shearing forces. They have been used by Ivanović and O'Neill (2015) to estimate the impact of a wide range of cylinder shapes with varying geometries and dimensions on a range of sediment types.

It is widely acknowledged that beam trawlers contribute extensively to the physical impact on the seabed in the southern North Sea (Jennings et al., 2012; ICES, 2014) and that beam trawling can affect benthic invertebrate and demersal fish communities (Lindeboom and de Groot, 1998; Kaiser et al., 2006; Polet and Depestele, 2010; van Denderen et al., 2014). The penetration into the seabed can be up to 8 cm, depending on beam trawl weight, towing speed, and sediment type (Paschen et al., 2000). In recent years, ~80 Dutch beam trawlers have replaced tickler chains and their mechanical stimulus to raise fish into the path of the gear with electrodes and their electrical stimulus (Soetaert et al., 2013; van Marlen et al., 2014). These gears have greatly reduced fuel costs (van Marlen et al., 2014) and, it is claimed, have also reduced benthic impacts (Soetaert et al., 2014).

In this study, we investigate the geotechnical and hydrodynamic impact of a traditional tickler-chain beam trawl (hereafter called "tickler-chain trawl") and a "Delmeco" electrical pulse beam trawl (hereafter called "pulse trawl"). The geotechnical investigations focus on measuring the alteration to the seabed bathymetry using a Kongsberg EM2040 Multi-Beam EchoSounder (MBES) in conjunction with the fishing vessels' global positioning system (GPS). Not only does this approach permit the detection of trawl marks in a similar way to the study of Malik and Mayer (2007) but it also allows the quantification of vertical changes in sediment bathymetry before and after trawling. In particular, the alteration to seabed bathymetry is investigated for (i) a single pass of a tickler-chain beam trawl, (ii) multiple passages of a tickler-chain beam trawl, and (iii) pulse beam trawl.

The hydrodynamic investigations focus on the quantity and particle size distribution of sediment mobilized into the water column behind (i) a tickler-chain trawl and (ii) a pulse trawl. We mounted an optical particle size analyser (Sequoia LISST 100X) on a sledge which was positioned behind the trawl and towed directly from the beam of each beam trawl. This approach has been used by O'Neill et al., (2013a, b) to measure the sediment mobilized behind different gear components, scallop dredges, trawl doors, and roller clumps.

We compared the experimental results with the predictions of the numerical models of Ivanović et al., (2011) and Esmaeili and Ivanović (2014) predicting the penetration depth of gear elements into soft sediments and with the empirical model of O'Neill and Summerbell (2011) which relates the hydrodynamic drag of a gear element to the sediment mobilized in its wake. We demonstrate how these methods can be used to quantify and assess the physical impacts on soft sediments and highlight the need to distinguish between alteration of seabed bathymetry and depth of penetration.

Material and methods

Empirical investigations

Study area and fishing gears

The study area (Figure 1) was located in a shallow coastal-zone area of the southern North Sea (15–22 m depth). This area was selected because of high abundance of benthic fauna, and trawling restrictions for beam trawlers >221 kW (European Commission, 2008). Alterations to the seabed bathymetry were tested in three experimental sites. The experimental site for evaluation of a single passage disturbance of tickler-chain trawl only was 150 m wide and 1350 m long and north–south oriented (hereafter called s-tickler site). The experimental sites for testing multiple passages of tickler chain and pulse trawl measured 150 × 1000 m and were east–west oriented (hereafter called m-tickler and pulse site; Figure 1). The locations of these sites were 300 m apart and located between 3.855–3.885°E and 51.935–51.950°N. The quantity of sediment mobilized into the water column was evaluated in an area south–west of these sites, between 51.8292–51.9507° N and 3.8138–3.8847°E (Figure 1).

Fishing with a tickler-chain trawl was conducted on-board the RV "ISIS". The gear was obtained from commercial fishers, and had a beam width of 4.4 m and an overall weight of 1065 kg in air (Figures 2 and 3). The two trawl shoes had a surface of 0.72 m^2, with five tickler chains of 28 mm diameter and one of 22 mm attached to them. Seven smaller tickler chains were attached to the ground chain and had a chain link diameter between 11 and 16 mm. The combined weight of the chains was ~450 kg and the netting weight was estimated to be ~20 kg. Hence, the weight of the beam and shoes was estimated to be ~595 kg. The pulse trawl was deployed from a commercial beam trawler (FV "de Boeier", SCH18), and had a beam width of 4.4 m (Figures 2 and 3). The

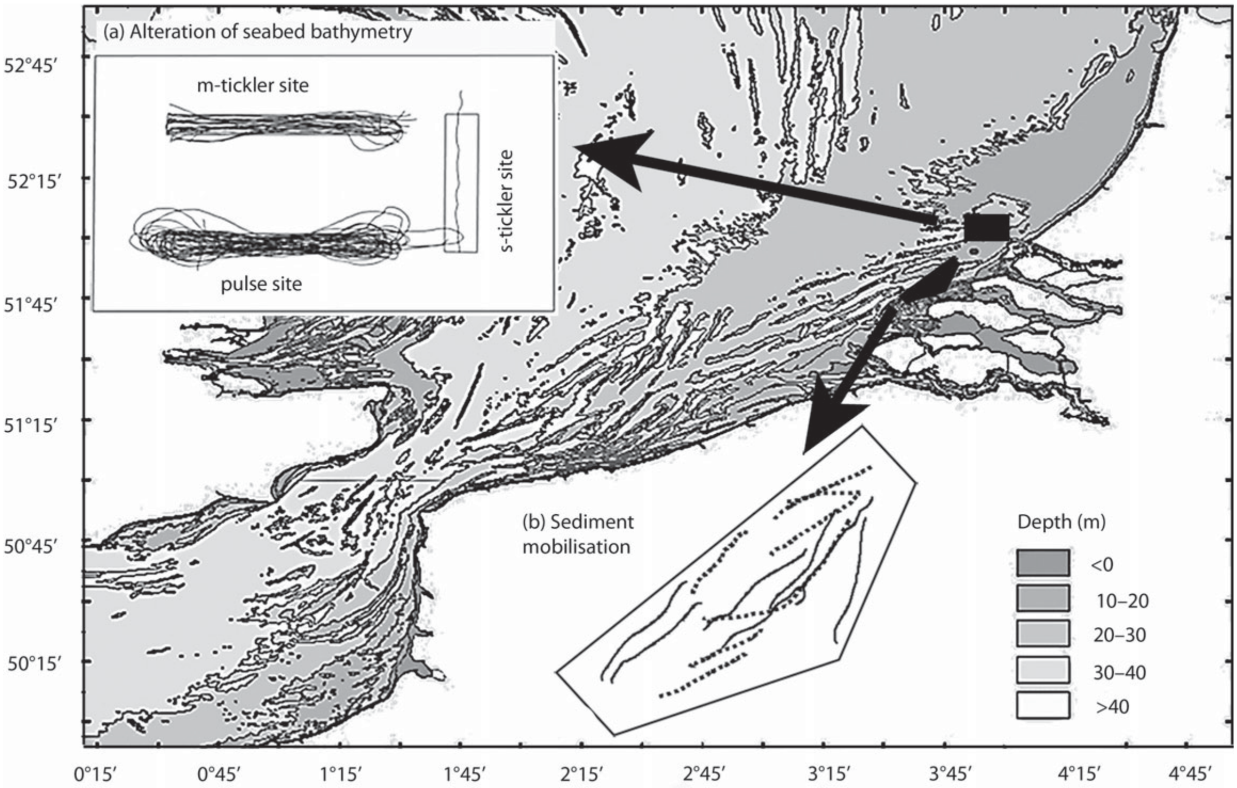

Figure 1. Location of the study area and experimental sites. (a) Alterations to the seabed bathymetry were tested for a single passage of a tickler-chain trawl, multiple passages of a tickler-chain and pulse trawl (s-tickler site: right; m-tickler site: upper left; pulse site: lower left rectangle). Lines indicate the conducted hauls. (b) The quantity of sediment mobilized was evaluated for hauls of a tickler-chain (solid) and pulse (dashed lines) trawl.

overall weight in air was 2500 kg, of which $\geq$75% was due to the beam and shoes. The sole plates of the two trawl shoes were 0.34 m^2. Electrodes were attached to the beam, resulting in 20 rubber tubes of 35 mm towed in longitudinal direction. Ten of those rubber tubes had nine consolidated parts of 60 mm in between the copper tubes of 30 mm.

Alteration of seabed bathymetry

Experimental design

Six hauls were carried out with the pulse trawl on 15 June 2013 (7h25–15h20) with a mean towing speed of 4.4 ($SD = 0.8$) knots. The swept area trawled in the pulse site was 0.361 km^2 resulting in a fishing intensity of 2.4 (=0.361/0.149 km^2) or 40 trawl passages. Nine hauls were conducted in the m-tickler site on 18 June 2013 (10h47–17h37) with a mean towing speed of 4.2 ($SD = 1.0$) knots. The swept area was 0.205km^2 which gave a fishing intensity of 1.4 (=0.205/0.151 km^2) or 25 gear passages. The intensity of tickler disturbance was <60% of the pulse disturbance, looking either at swept area or at the number of gear passages. A single haul was carried out in the s-tickler site on 19 June 2013 (8h35–8h45) at a mean speed of 4.4 ($SD = 0.2$) knots. Warp lengths were ~3.5–4 times the fishing depths. Setting and hauling the gear took place outside the experimental sites, except for one haul in the pulse and m-tickler site. The swept area was calculated from the beam widths and the distance travelled within the experimental sites. Distance travelled was calculated from time referenced GPS positions of the fishing vessels for each haul (at 10 s intervals).

Seabed bathymetry was measured acoustically with the Kongsberg EM2040 MBES mounted on RV "Simon Stevin". The EM2040 is a high-resolution modular MBES with a frequency range from 200 to 400 kHz, 400 narrow-beams of 0.5 by 1° width at 300 kHz (or a footprint of 0.17 × 0.35 m at the nadir, 20 m depth), a ping rate up to 50 Hz and a swathe coverage sector up to 140°. Several tests were conducted to evaluate the vertical resolution of the EM2040 combined with its sensors on-board the RV "Simon Stevin". Three survey lines were inspected on a flat seabed. The relative precision of the survey line measurements was estimated by computing the difference between the raw soundings and a smoothed and highly filtered model based on the same soundings. The standard error was 3.4 mm on 25 repeated water depth measurements for the entire swathe (beam angles from −70 to 70°) within a single survey line (Degrendele and Roche, 2013). The millimetre accuracy of the EM2040 fulfilled the requirements to obtain reliable estimates of the changes in seabed bathymetry due to fishing (Fonteyne, 2000; Paschen *et al.*, 2000).

Changes in seabed bathymetry following fishing disturbance were calculated based on differences in bathymetrical measurements from MBES survey lines before and after experimental fishing. Recordings of MBES survey lines started and ended a few tens of metres outside the experimental sites and were conducted at a speed of eight knots. MBES survey lines were orientated parallel with the longest side of the rectangular experimental sites. Survey line spacing was chosen to give full coverage of the seabed with an approximate overlap of 30%, except the pulse site before

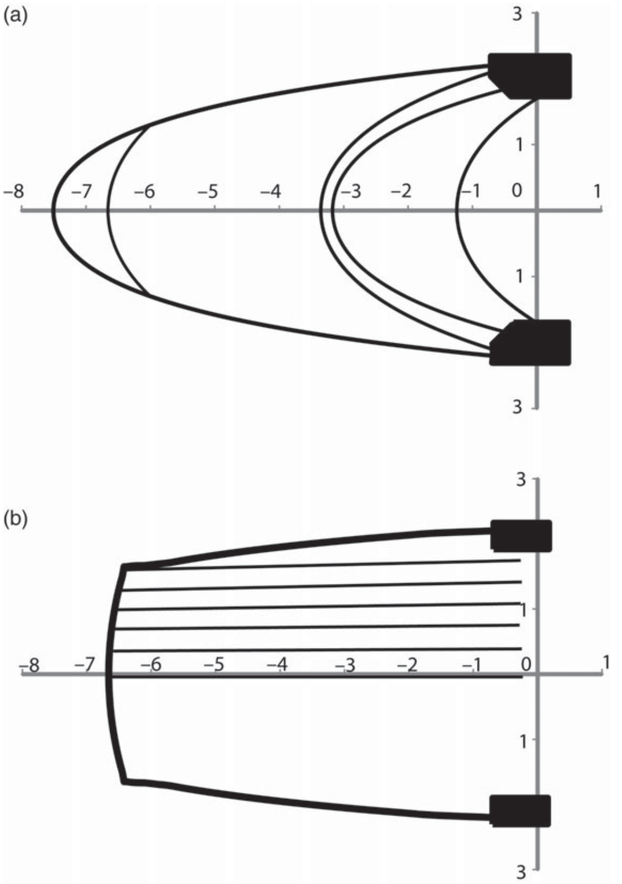

Figure 2. Gear components in contact with the seabed for the tickler-chain (a) and pulse (b) trawl. Tickler chains with a chain link diameter of 28 mm are attached to the trawl shoes, whereas the tickler chains of 11 – 16 mm are attached to the groundgear (only one is shown).

experimental fishing. Only three survey lines were conducted due to time constraints. The three survey lines covered >75% of the area. The experimental sites were monitored at different time intervals with an MBES frequency of 205 or 320 kHz. MBES surveys in the s-tickler and m-tickler sites took place at 205 kHz, before trawling and within 12 h after trawling. The m-tickler site was additionally surveyed at 320 kHz, before, within 12 h and within 44 h after trawling. MBES survey lines in the pulse site were recorded at 320 kHz before trawling and within 55 and 107 h after trawling. Trawling intensity, gear, MBES frequency, and time interval before or after trawling determine the different treatments (Table 1). Treatments are summarized in relation to weather conditions (wave height and wind force) in Figure 4.

Data analysis

Details of the alterations of seabed bathymetry were revealed by the wide-area coverage of the MBES bathymetric data, which provided a means to generate digital elevation models (DEMs) of the seabed. DEMs were created for each MBES survey line by gridding the geo-referenced soundings in SonarScope (Ifremer, 2013). An empty grid of 0.25 × 0.25 m was filled with vector values of water depth from the nearest ping. This resulted in DEMs for each MBES survey line. The line by line DEMs enabled inspection of the bathymetry of the experimental sites, as well as detection of trawl tracks by beam trawlers. Beam trawlers have two outrigger booms and tow two trawls simultaneously at equal distance apart. This facilitates identification of the trawl tracks. First, we analysed the MBES survey lines that were recorded before experimental fishing, because we did not want to measure trawl tracks of unknown gears. Indeed, parallel trawl tracks of ∼4 m wide and 11 m apart were present before experimental fishing. These trawl tracks were attributed to "eurocutters", beam trawlers with an engine power <221 kW and fishing in the study area (ICES, 2014). The locations of their trawl tracks were eliminated from further analysis. Second, we analysed the MBES survey lines that recorded disturbance by experimental fishing. Experimental trawl tracks were visually detected in ArcGIS software. Identification of the trawl tracks was evaluated by locating the fishing vessels during experimental trawling using the GPS positions and by estimating the distance between trawl tracks and the approximate widths of each track. Changes in seabed bathymetry due to multiple passages of the tickler chain or pulse trawl were estimated at two time intervals of MBES monitoring to assess short-term fading of trawl marks. We identified the trawl tracks in the shortest time interval between experimental trawling and the MBES survey, and used the same locations for evaluating the trawl marks after the longer time interval.

Changes in seabed bathymetry were evaluated by comparing water depths inside and outside the trawl track within MBES survey lines. Water depth measurements were selected at equally spaced intervals along the identified trawl tracks (hereafter called "blocks of measurements"). Measurements outside the trawl track were taken at both sides of the selected track at a distance between 3 and 4 m of the centre line of the identified track (Figure 5). Water depth measurements inside the identified tracks were taken at a radius of maximum 1.5 m from the centre line of the trawl track. This procedure resulted in at least 30 blocks of measurements per treatment with a mean number of >45 measurements inside the track and >90 outside the track (Table 1). Depth measurements inside and outside the track were compared with a non-parametric Friedman rank sum test following a single factor (depth) within subject (block measurements) design (Figure 5). Measurements were only evaluated within MBES survey lines to reduce potential errors across MBES lines. The variability of the differences between water depths inside and outside the trawl track within each block of measurements was high (*SD* up to 25 mm) and differed across treatments (Table 1). Because of the heterogeneity of the variances between treatments, we described the frequency of occurrence of depth differences by modelling the cumulative distribution function (CDF) with a generalized additive model (GAM) (Equation 1).

$$f(E[Y]) = \alpha + s(X), \qquad (1)$$

where the response is the expected probability of occurrence of a depth difference ($E[Y]$), α is the intercept and s is a one-dimensional smooth function of the difference in depths inside and outside the trawl track. The smooth function was estimated using penalized regression splines, with an optimum degree of smoothing as defined by the generalized cross-validation criterion (Wood, 2006). A random resampling with replacement was applied to the observed depth differences within each treatment, enabling the estimation of 95% confidence intervals of the model coefficients. Differences in seabed morphological alterations were evaluated across treatments from visual inspection of CDFs.

Figure 3. Commercial tickler-chain beam trawl (a) and pulse trawl (b) used in the experiments.

Sediment mobilization

Experimental design

Experimental trials were conducted with FV "de Boeier" on 14 June 2013 and with the RV "ISIS" on 19 June to measure the sediment mobilized in the wake of the pulse trawl and the tickler-chain trawl, respectively. The particle size distribution and concentration of the sediment mobilized into the water column was measured using a Sequoia LISST 100X particle size analyser. The LISST 100X uses the laser diffraction principle to measure the concentration of particles in 32 logarithmically increasing size ranges between 2.5 and 500 μm and was set to take measurements at a rate of 1 Hz. It was mounted on a towed sledge with the sampling head positioned 35 cm above the seabed.

Seven tows were conducted on both vessels with the sledge. The first one in each case was a control sample to obtain background measurements with no fishing gear in the water and where the sledge was connected to a 90 m warp and towed directly from the vessel. To obtain measurements of the sediment in the wake of the beam trawls the sledge was connected to a Dyneema towing line that was fixed to the centre of the beam and passed through the trawl and out the codend. In addition, a safety line and a float line were attached to the sledge to allow recovery if the towing line parted. Dyneema towing lines of length 20, 40, and 60 m were used. Taking into account the 5 m towing bridles of the sledge these lengths permitted measurements to be made at distances of 25, 45, and 65 m from the beams. Two tows were conducted at each station, one into the tide and one with the tide. Towing speed was kept constant at ∼4kn and the codends were left open during sampling to reduce variation between hauls and to ensure that changed seabed bathymetry was due to the catching mechanism (tickler-chains or pulse electrodes) rather than to the catch. The duration of each tow was ∼10 min for the pulse trawl and ∼15 min for the tickler beam trawl.

Data analysis of LISST 100X data

The concentration measurements in each of the 32 size ranges were averaged to provide a mean concentration and particle size distribution for each of the control and beam trawl tows. The control measurements were then subtracted from the respective beam trawl tows to estimate the mean concentration and particle size distribution of the sediment mobilized into the water column due to the passage of the gear. These values were then further summed across size ranges to give a total mean volume concentration of sediment mobilized during each tow. The standard deviations of the concentrations were also calculated and are used to indicate whether there is a difference between measurements. To estimate the mass of sediment remobilized per metre towed we assume

$$m = 2.65\, p_{\mathrm{h}}\, p_{\mathrm{w}} c/10^6, \qquad (2)$$

where the relative density of the sand particles is assumed to be 2.65, p_{h} and p_{w} are estimates of the height and width of the plume,

Table 1. Alterations to the seabed bathymetry for different treatments (trt).

Trt	Beam trawl	Trawling intensity	Time lapse (hour)	MBES frequency (kHz)	Depth range (min – max, m)	Number of selected blocks for measuring trawl marks	Alterations to seabed bathymetry (mm)						χ^2 (d.f. = 1)	*p*-value
							Mean (s.d.)	Min	Q1	Med	Q3	Max		
a	Tickler	1	<12	205	15.4 – 16.3	31	11.6 (7.8)	0.9	5.7	8.8	17.1	28.5	17.06	<1 E − 4
b	Tickler	1.4	<12	205	16.9 – 19.9	173	20.8 (17.1)	0.2	9.4	16.1	26.8	82.3	37.65	<1 E − 9
c	Tickler	1.4	<44	205	16.9 – 21.3	153	18.9 (15.1)	0.3	7.4	17.2	25.2	77.7	24.14	<1 E − 6
d	Tickler	1.4	<12	320	17.1 – 18.4	112	25.7 (23.9)	0.0	7.6	20.4	34.9	127.9	54.00	<1 E − 12
e	Tickler	1.4	<44	320	17.3 – 18.5	82	26.0 (22.4)	0.5	11.4	20.2	34.4	106.8	10.98	<0.001
f	Pulse	2.4	<55	320	16.3 – 18.1	246	15.0 (11.8)	0.0	5.7	12.1	22.1	58.4	81.97	<0.1 E − 5
g	Pulse	2.4	<107	320	16.3 – 18.1	236	11.7 (9.2)	0.0	4.7	9.6	15.9	46.5	21.97	<0.1 E − 5

Treatments were based on type of beam trawl (tickler-chain trawl or pulse trawl), trawling intensities (1 for s-tickler; 1.4 for m-tickler and 2.4 for the pulse site), time lapses before or after trawling and frequencies of the MBES signal. Note differences in median alterations of seabed bathymetry (Med), and its variability (min, minimum; Q1, first quartile; Q3, third quartile; max, maximum).

c (μl/l) is the concentration of remobilized sediment and ρ is the density of water.

Predicting sediment mobilization

O'Neill and Summerbell (2011) relate the quantity of sediment mobilized in the wake of a gear component to its hydrodynamic drag. This expression is updated in O'Neill and Ivanović (submitted) to take into account the silt fraction of the sediment on which the component is towed. Here we assume that only the turbulence associated with the hydrodynamic drag of the lower netting panels and of the gear components in contact with the seabed contribute to the mobilization of sediment behind the gears. The hydrodynamic drag of (i) the netting panel is calculated from Reid (1977), (ii) the chain from Xu and Huang (2014), and (iii) the electrodes, groundgear, and beam shoes from experiments on similar shaped objects from Hoerner (1965). These estimates of hydrodynamic drag are then used with the updated expression of O'Neill and Ivanović (submitted) to predict the sediment mobilized into the water column behind each of the two beam trawls tested (Table 2).

Numerical modelling

Esmaeili and Ivanović (2014) model the physical interaction between groundgear components and the seabed using the finite element coupled Eulerian Lagrangian approach with Abaqus software. In granular soil, the stress required to cause a yielding is strongly dependent on the pressure; therefore, the Mohr–Coulomb constitutive model was used in this study, which has a pressure dependent yield surface and which is widely used in the modelling of granular material (sand in this case). The behaviour of the material is represented by the Young's modulus and assumed to be elastical as long as the stress level in the soil stays within the yield surface. The model is dynamic and run to a steady state. The sand obtained from the sea trials (grab samples) was tested by sieve test and triaxial tests to obtain mechanical properties. The results obtained are median grain size (d_{50}) = 144 μm, angle of internal friction, $\phi = 32°$, dilation angle of 1°, and density of sand of 2500 kg m^{-3}, modulus of elasticity of 10 MPa, and Poisson's ratio of 0.3. The soil model with these properties is applied here to model the impact of the tickler-chain and the pulse trawl. A rectangular segment of the seabed with dimensions 9 × 5 × 0.3 m is modelled where the mechanical properties of the sediment are measured from sieve and triaxial tests of the grab samples obtained during the sea trials. Given the complexity of the gear designs it is necessary to model the impacts of the beam shoes, the groundgear, the chains, and the electrodes separately. Furthermore, chains and "cookie" groundgears, which are assumed to take on a catenary shape when towed, were modelled by cylindrical elements with the appropriate weight per unit length.

Initial simulations demonstrated that the penetration depth of successive elements was not cumulative, i.e. the penetration of one individual element was the same as that of up to five of the same element. Hence, for the tickler-chain trawl, it was sufficient to model only one of the five 28 mm diameter tickler chains that are attached to the beam shoe, and only one of the seven 11 and 16 mm diameter tickler chains that are attached to the groundgear chain. Equally, the penetration depth across the path of each of the two groundgear assemblies is assumed to be that of the element that penetrates most along a particular track. Similarly, initial simulations of the electrodes of the pulse trawl groundgear demonstrated that one individual electrode penetrated the seabed to the same depth as a number in parallel. Hence, the penetration

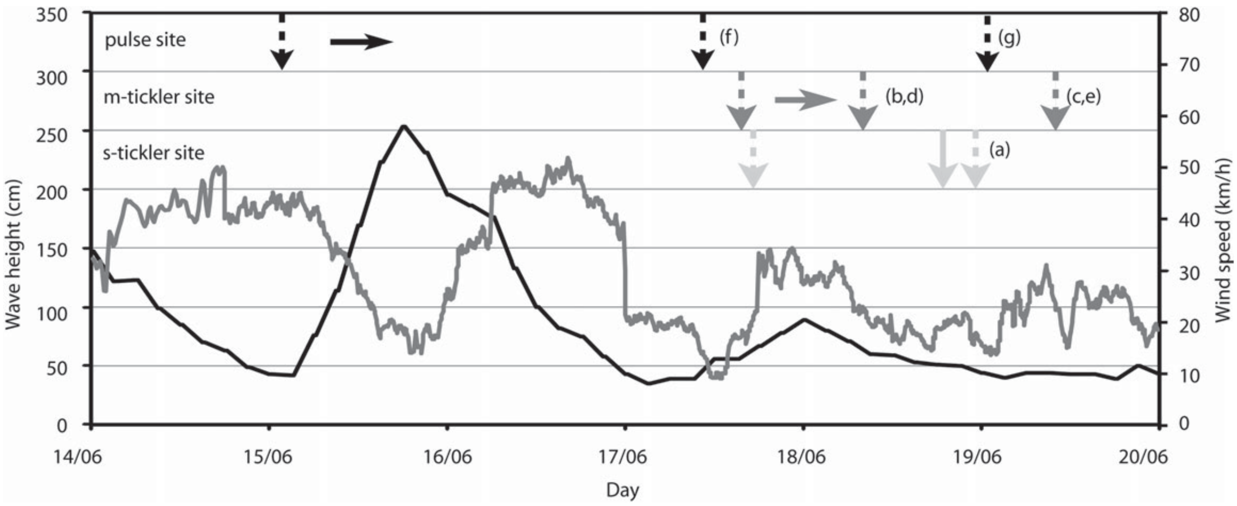

Figure 4. Experimental set-up and weather conditions. Experimental fishing took place at different times for each experimental site: pulse site (black horizontal arrow), m-tickler site (dark grey horizontal arrow), and s-tickler site (solid light grey vertical arrow). MBES measurements took place prior and after experimental fishing in each experimental site (dotted vertical arrows). Treatment specifications (a) – (g) refer to Table 1. Wave heights (black line) were high after pulse trawling, while windspeeds (grey line) were high during and after pulse trawling.

depth of this gear can be characterized by the distribution of the deepest penetrating components along a particular path.

Results

Alteration of seabed bathymetry

Water depths inside and outside the trawl marks were statistically different for all the investigated combinations of gear, trawling intensities, MBES frequency, and time intervals after fishing (see treatments in Table 1). Alterations to the seabed bathymetry were highest for multiple passages of a tickler-chain trawl, and lowest for a single passage of a tickler-chain trawl. Trawl tracks tended to fade away on a short term, as the differences in seabed bathymetry were smallest after 107 h after multiple passages of the pulse trawl.

The variability in depth differences inside and outside the trawl tracks are illustrated by the CDFs, which all have a J-shaped curvature (Figures 6 and 7). The CDF curves indicate that depth differences are $\leq$20 mm at 50% probability, but trawl tracks resulting from multiple passages of a tickler-chain trawl were occasionally up to 40–60 mm (considering a 90% probability). A single passage had a 50% probability that depth differences reach up to 10 mm while this was 18 mm for multiple passages (measured at 205 kHz). Changes in seabed bathymetry were more variable for the multiple passages, occasionally reaching values $>$30 mm. Trawl marks were fading by $\sim$1–2 mm within the investigated time intervals (Figures 6 and 7). The tickler-chain trawl affected seabed bathymetry to a greater extent than the pulse trawl, when comparing depth differences at 320 kHz. Depth differences were $<$6 mm for both gears at a 25% probability, but the changes to the seabed bathymetry at a 50% probability were up to 20 mm for tickler-chain trawling and 14 mm for pulse trawling. The trend of increasing differences in seabed bathymetry between tickler and pulse trawl continued at increasing cumulative probabilities, although interpretation requires caution (see Discussion).

Sediment mobilization

The mean total volume concentration of the sediment in the water column was 5.2 and 20.3 $\mu l\, l^{-1}$ before the pulse and tickler beam tows, respectively. The higher concentrations observed during the tickler control tow may be a result of the intensive sediment dredging and fishing activities conducted in the neighbouring closed site over the two previous days.

Figures 8 and 9 compare the average particle size distribution of both the tickler and pulse trawls measured at 25, 45, and 65 m from the respective beams. The standard deviations of the mean measurements (Figures 8 and 9) demonstrate that we cannot detect a significant difference of the sediment mobilized into the water column in the wake of both these gears. The mean total volume concentrations presented in Figure 9 are even more similar with values of $\sim$650, 360, and 80 $\mu l\, l^{-1}$ at 25, 45, and 65 m from the towing beam. This reduction in sediment with distance from the beam reflects both the diffusion of the sediment cloud and the settling of particles. We do not have estimates of the dimensions of the sediment plume of beam trawls but if we assume at 25 m it has a height between 1.5 and 2.5 m (Main and Sangster, 1981), then a volume concentration of 650 $\mu l\, l^{-1}$ corresponds to a mass of sediment of between 2.6 and 4.3 kg m^{-2} swept area or a surface layer of sediment with a thickness of between 1.6 and 2.7 mm m^{-2} swept area (assuming a porosity of 0.4).

Table 2 contains the estimates of hydrodynamic drag of the lower netting panels, the chains, the electrodes, rubber discs, and the beam shoes at towing speed of 4.4 knots. The overall hydrodynamic drag of the two gears is very similar and helps explain the similarity in the measured amount of sediment mobilized. There are however marked differences between the netting panels, such as the thinner twine netting used in the tickler-chain gear, which has a much lower hydrodynamic drag. Contrastingly, the combined hydrodynamic drag of the tickler chains is much greater than that of pulse trawl groundgear assembly. The analysis of O'Neill and Ivanović (submitted) predicts that the corresponding quantity of sediment (assuming a 5% silt fraction) is $\sim$4.2 kg m^{-2} swept, which is in the range of values estimated from the concentration measured.

Numerical modelling

Table 3 presents the depth of penetration of the individual gear components in contact with the seabed for each of the two beam trawl

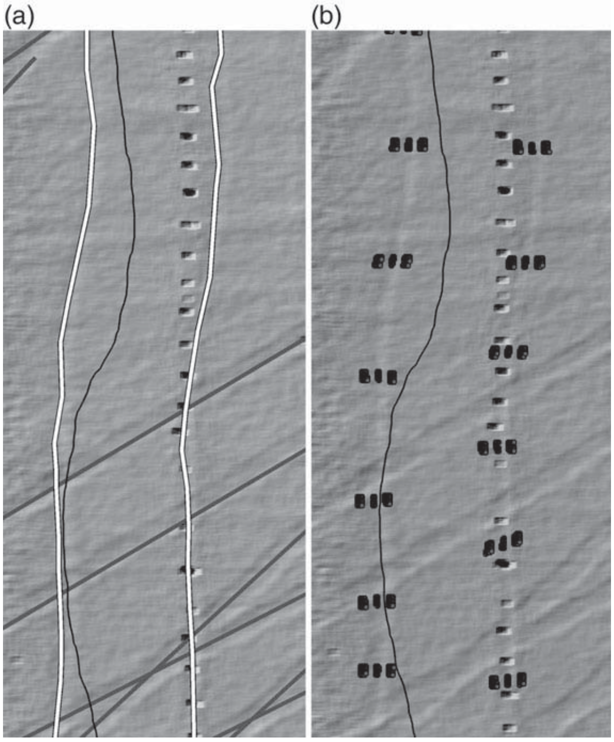

Figure 5. Detection of trawl tracks and locations of depth measurements for a 205 kHz MBES survey line in the s-tickler site. GPS locations (black line) indicated the vessel position. Beam trawl tracks from experimental fishing were identified along the vessel position, i.e. two parallel tracks, indicated by double lines from north to south (a). Beam trawl tracks of commercial fishing were indicated by diagonal black lines (a). Depth measurements inside and outside the track were registered at regularly spaced intervals ("blocks") but not within trawl tracks from commercial fishing (oriented from north – east to south – west). Multiple depth measurements within each block were once taken inside the track and twice outside the track (three sets of measurements per block). The three sets of depth measurements within each block are indicated by multiple, overlapping dots in panel (b).

Table 2. Estimates of the hydrodynamic drag on the lower panel netting panels, the groundgear assemblies, and the beam trawl shoes.

	Hydrodynamic drag (*N*)				Total
	Lower netting panels	Tickler and groundgear chain	Electrodes and groundgear	Shoes	
Tickler gear	4,150	3,440	–	1,770	9,360
Pulse gear	7,150	–	1,510	1,090	9,750

The hydrodynamic drag of (i) the netting panel is calculated from Reid (1977), (ii) the chain from Xu and Huang (2014), and (iii) the electrodes, groundgear, and beam shoes from experiments on similar shaped objects from Hoerner (1965). Hydrodynamic drag was calculated for a towing speed of 4.4 knots.

designs (Figure 2). The mean depth of penetration of the tickler-chain trawl is predicted to be ~9 mm across the full swept area of the gear. The electrodes and the rubber discs of the pulse trawl are predicted to have penetrations of 3.5 and 5 mm, respectively, which across the tow path, between the trawl shoes, averages to be 3.6 mm. The pulse trawl shoes penetrate to ~60 mm. These are by far the deepest penetrating components which are due to the fact they have the largest weight per unit surface area in contact with the seabed.

Discussion

The physical effects of beam trawls are expected to be high due its close contact with the seabed (Suuronen *et al.*, 2012) and the infaunal benthic impact it causes (e.g. Lindeboom and de Groot, 1998; Kaiser *et al.*, 2006). Surprisingly, only a few (grey literature) studies have quantified the physical effects of beam trawling. These studies focused on (i) changes in seabed bathymetry estimated from boxcore sampling or physical modelling of individual gear components (Paschen *et al.*, 2000), and they also investigated (ii) compaction and (iii) changes in sediment composition by RoxAnn surveys, sidescan sonar imagery, and by estimating the pressure of individual gear components on the seabed (Fonteyne, 1994; Leth and Kuijpers, 1996; Lindeboom and de Groot, 1998; Fonteyne, 2000). Our experiments contribute to resolving these data gap by investigating the geotechnical and hydrodynamic effects on soft sediments of a traditional tickler-chain beam trawl and the newly developed pulse trawl. Bathymetrical changes after beam trawl disturbance have, up till now, only been deducted from the living position of certain benthic species (Bergman and Hup, 1992), physical modelling of individual gear components, and boxcore sampling (Paschen *et al.*, 2000). The hydrodynamic effects refer to sediment mobilization which was measured using a particle size analyser, and which also has not been quantified before for beam trawls (Løkkeborg, 2005; Polet and Depestele, 2010). Additionally, we have employed predictive models to evaluate the physical impacts of these gears and have used the empirical model of O'Neill and Ivanović (submitted) to estimate the quantity of sediment mobilized in their wake and the model of Esmaeili and Ivanović (2014) to predict their penetration into the seabed.

We have focused, in particular, on the effect of a single passage of a tickler-chain beam trawl. The MBES measurements revealed that depth differences of the seabed bathymetry, between inside and outside the trawl path, after a single beam trawl passage is 8.8 mm with a maximum depth difference of 28.5 mm. This difference may have been due to several physical processes, such as the mobilization of sediment, compaction, and/or the displacement of sediment (Kaiser *et al.*, 2002; Smith *et al.*, 2003; Lucchetti and Salá, 2012; Martín *et al.*, 2014). The measurements of sediment mobilization suggested that ~2.7 mm of the depth difference could be due to sediment being put into the water column; however, some of this will have resettled in the trawl path, the extent of which would have depended on the local hydrographic conditions at the time of trawling. Thus, it would appear that sediment compaction is of primary importance in explaining the results, a hypothesis that is supported by RoxAnn surveys in the southern North Sea (Fonteyne, 1994, 2000), which indicated increasing hardness immediately after beam trawling ("E2-values"). The 8.8 mm depth difference falls within the lower range of earlier findings from boxcore sampling where bathymetrical changes varied between 10 and 70 and 7.5 and 55 mm for medium and coarse sand, respectively (Paschen *et al.*, 2000). There are probably a number of reasons why these measurements differ, not least of which is that Paschen *et al.* (2000) used different beam trawl configuration (up to 12 m beam width, more tickler chains and heavier gear). Also the MBES sampling methodology presented here was such that it measured

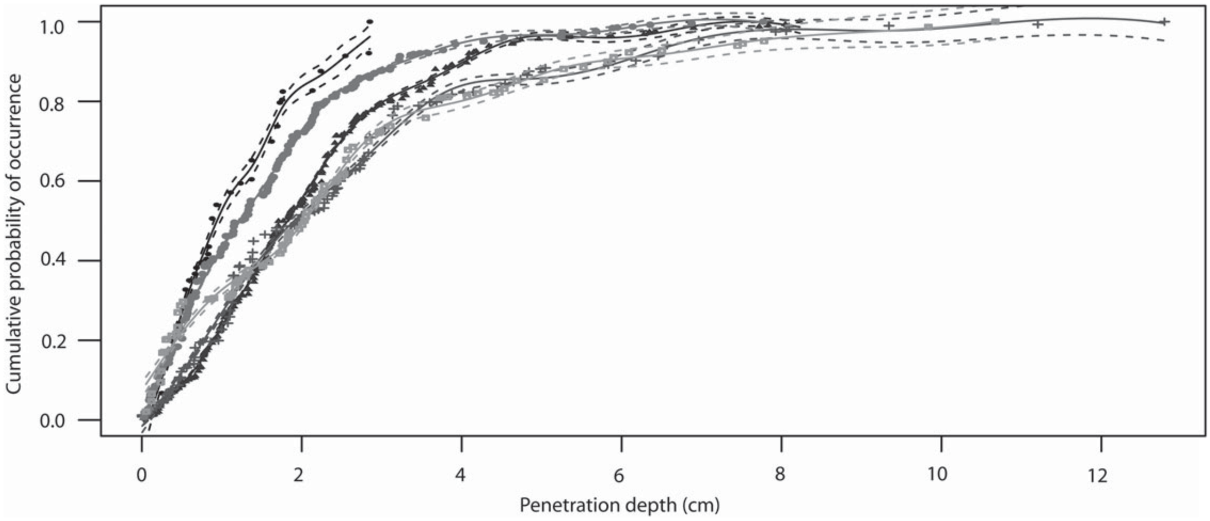

Figure 6. Cumulative distribution functions of alterations to seabed bathymetry for different treatments of the tickler-chain trawl. Treatments are specified in Table 1 and related to the following colours in increasing order of alterations to seabed bathymetry: (a) black dots, (c) dark grey dots, (b) black triangles, (e) grey squares, and (d) black crosses. Single passage of a tickler-chain trawl (trt a) causes the least of alterations to seabed bathymetry. Multi-beam measurements at 320 kHz (trt d and e, resp. black crosses and grey squares) do not indicate a clear fading of trawl marks over time, while at 205 kHz the alterations to seabed bathymetry are lower (trt b and c, from dark black triangles to dark grey dots). Dashed lines indicate the lower and upper limits of 95% confidence intervals.

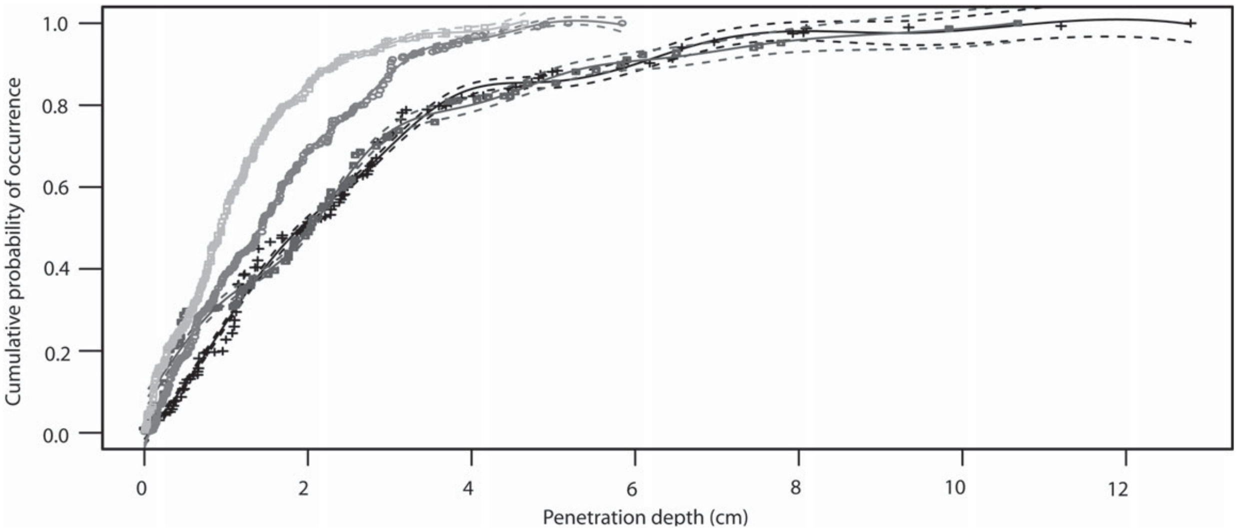

Figure 7. Cumulative distribution functions of alterations to seabed bathymetry measured at 320 kHz after multiple trawling passages: multiple passage of a pulse trawl at two time steps: <55 h after trawling (trt f, open grey circles), <107 after trawling (trt g, open light grey squares). Trawl marks fade over time. The dark grey squares CDF (trt e) can directly be compared with pulse trawling and indicates higher probabilities of higher alterations to seabed bathymetry. The black crosses CDF (trt d) illustrates the alterations to seabed bathymetry at <12 h. Dashed lines indicate the lower and upper limits of 95% confidence intervals.

1.5 m either side of the centre line of the trawl path, thus sampling was restricted to measuring the alteration due to the chains and groundgear and did not measure from the path of the beam shoes.

There is very good agreement between the experimental measurements and the numerical predictions. The average penetration depth across the full swept area of the gear was predicted to be 9 mm and while this value compares very well with the MBES measurements we must also emphasize that they are not directly comparable as the MBES measurements are taken after the passage of the trawl. The alterations in seabed bathymetry measured by the MBES cannot be considered to be measurements of the gear's penetration into the sediment, as they will also comprise changes in seabed bathymetry due to backfilling of sediment behind the chains and the groundgear and to sediment mobilization and resettlement. Moreover, the model investigated gear elements separately, whereas the MBES measurements also include interactions between gear elements. A more valid comparison may be with the measurements of penetration depth of individual chains in a sand

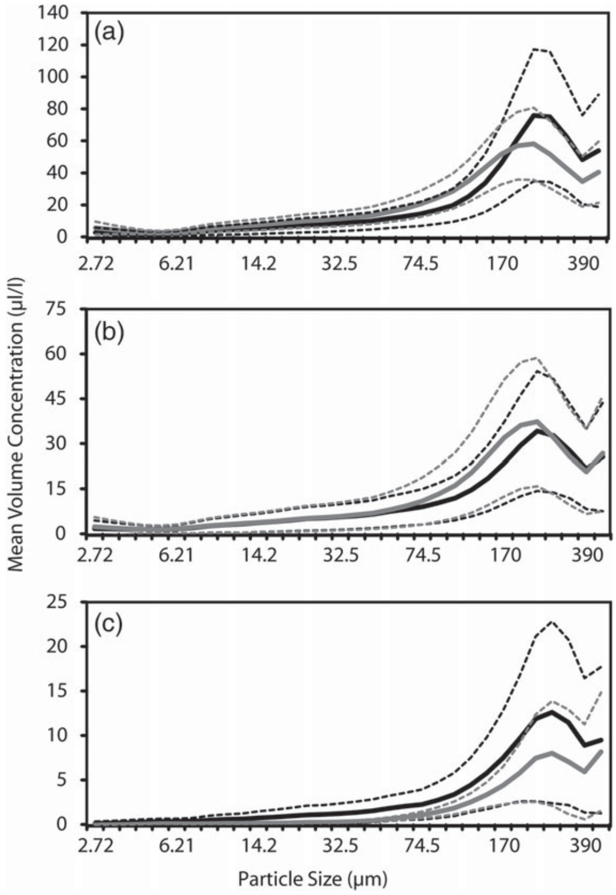

Figure 8. Mean particle size distribution of tickler-chain and pulse beam trawls measured at 25 (a), 45 (b), and 65 m (c) from the respective beams (solid lines) ± 1 *SD* (dashed lines).

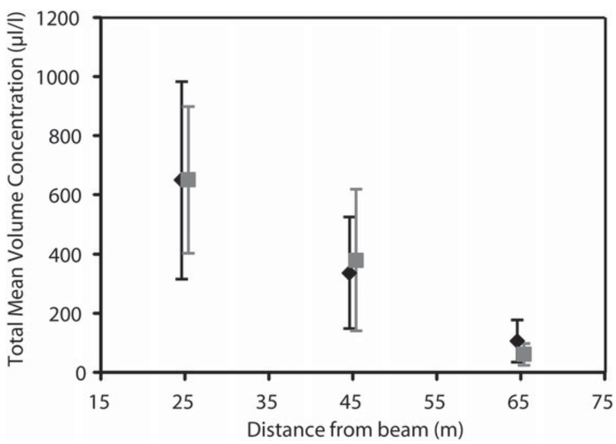

Figure 9. Mean total volume concentrations (± 1 *SD*) of mobilized sediment at three distances behind a tickler-chain (black) and pulse (grey) beam trawl.

channel by Paschen *et al.* (2000) which ranged between 3 and 17 mm.

In addition to investigating the single passage of a beam trawl, we also evaluated some of the fishery-related factors associated with different trawling intensities. MBES measurements were taken for two gear types at several times after trawling. Owing to logistic difficulties, trawling with both gears could not take place at the same time with the result that the MBES measurements was not aligned. Furthermore, limited *a priori* knowledge of the possibilities of detecting beam trawl tracks with the EM2040 in this sediment type (Malik and Mayer, 2007) required testing different MBES frequencies. The higher MBES frequency was used because of a higher resolution in bathymetry and resulting DEMs, whereas analysing the backscatter of the lower MBES frequency was envisaged for identification of trawl tracks (based on our experience with the EM3002 on the RV "Belgica"). Surprisingly, trawl tracks were clearly present and identifiable in DEMs at both MBES frequencies, enabling the analysis of DEMs for both identification of trawl tracks and measurements of seabed alterations. Despite these constraints, our investigations suggest how gear configuration and trawling intensity may cause differences in seabed bathymetry. The variability of bathymetrical differences is higher for any of the measurements after repeated trawling (multiple passages) than for the single beam trawl passage. Despite the different ways of selecting data points in the sites with multiple and single passages, these measurements suggest that repeated beam trawling within a certain area increases the bathymetrical differences and creates a landscape that is interspersed with higher relief. This is in contrast to small-scale changes in bathymetry, such as ripples, which were found to level off after beam trawling (Fonteyne, 1994). Our results also prompt the question of how much variability can be induced after repeated trawling and to what extent the fishing gear plays a role. The intensity of pulse trawling was about twice as high as tickler-chain trawling, yet the variability in seabed bathymetry of pulse trawling was lower (*SD* of changes in seabed bathymetry <12 mm) than of tickler-chain trawling (>15 mm). On the one hand these results suggest that multiple passages increase changes in seabed bathymetry, but on the other hand the difference between a relatively "heavy" pulse trawl and a relatively "light" tickler-chain trawl seem to play an important role as well. While we do not know whether bathymetrical changes level off at increasing trawling intensities due to an increased occurrence of compacted sediment (Paschen *et al.*, 2000; Smith *et al.*, 2003; Martín *et al.*, 2014) or whether fishing gear is affecting bathymetrical changes to a greater extent than trawling intensity, our investigations highlight that both factors (gear and trawling intensity) have a substantial influence in changing seabed bathymetry and require further research attention.

Table 3. Modelled penetration depths of individual gear components in contact with the seabed: tickler-chain and pulse trawl.

Gear component	Depth of penetration (mm)
Tickler-chain trawl	
Tickler chain 28 mm	9
Tickler chain 16 mm	7
Tickler chain 11 mm	2
Trawl shoe	8
Pulse trawl	
Electrodes	5
Groundgear (parallel rubber discs)	3.5
Groundgear (perpendicular rubber discs)	3.5
Trawl shoe	60

While the reduction of bathymetrical changes by replacing tickler-chains with electrodes is potentially confounded with trawling intensity in the *in situ* investigations, the numerical model illustrated that the electrodes penetrated approximately half as deep than the tickler chains. The numerical model highlights the importance of the gear components. The overall impact of a pulse trawl was predicted to be lower over the full swept area than of a tickler-chain trawl, but the trawl shoes of the pulse trawler penetrated much deeper than those of the tickler-chain trawl. The modelled penetration depths of the gear components indicated that the configuration of the tested gears, either tickler-chain or pulse trawl, complicates our ability to generalize the physical impacts of a certain gear type. The difficulty of extrapolating findings to the level of the beam trawler fleet is further strengthened by the trawl tracks found in the experimental sites, but which were not due to any of the experimental gears. While the configuration of the gears causing these tracks could not be identified, the width of the two parallel tracks suggested that they were caused by "*eurocutters*". The 4 m beam trawls used by this unidentified beam trawler had a higher mean penetration depth (>20 mm) than the trawl tracks from the experimental gears used in our experiment. The tickler-chain beam trawl used in our experiment was a light gear, which had trawl shoes with a wide contact surface with the seabed. The gear was a fully operational trawl, borrowed from a commercial beam trawler ("WR244") in the northern part of the Netherlands. The beam trawls used by fishers in the northern part of the Netherlands tend to be lighter than those used in the southern part of the Netherlands. The "Delmeco" pulse trawl, used in the experiment, tends to be the pulse beam trawl with more bottom contact than the HFK PulseWing which is also used by commercial fishers (Soetaert *et al.*, 2013). Our study hereby illustrates that the gear developments in the beam trawler fleet (Poos *et al.*, 2013) require further attention and that caution is needed when experimental results are extrapolated to the whole fleet. The occurrence and persistence of the trawl marks of the "unidentified" gear also illustrate that trawl marks did not fade over the course of 1 week. Similarly, the trawl marks of the tickler-chain trawl did hardly change between 12 and 44 h after trawling, whereas the trawl marks of the pulse trawling faded somewhat more between 55 and 107 h after trawling. Trawl marks remained detectable up to at least 4 d after trawling. The persistence of trawl marks and a continuously changing seabed bathymetry affect benthic community structure and biogeochemical processes (Guichard and Bourget, 1998; Cutter *et al.*, 2003; Handley *et al.*, 2014). Our results illustrate that beam trawling has the potential for contributing substantially to these physical impacts, but also that differences in gear configurations and fishing intensities affect the variability of these physical impacts.

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