Effects of beam and pulse trawling on the benthic ecosystem

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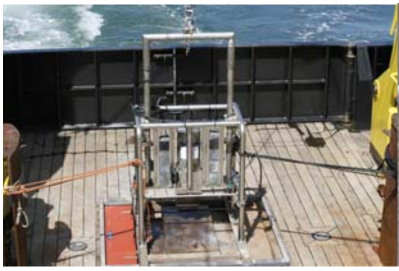

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Samenvatting

In dit rapport worden de effecten van visserij met sleepnetten op de zeebodem en bodemdieren bestudeerd. Een BACI - ontwerp experiment werd gebruikt om de effecten van een traditionele boomkor en een pulskor te onderzoeken. In de afgelopen jaren is als gevolg van lagere brandstofkosten en goede tong vangsten het gebruik van de pulskor techniek onder Nederlandse vissers toegenomen.

Het onderzoek is in het noordelijke deel van de Nederlandse Voordelta (Zuidelijke Noordzee, kustzone gebied, 15 - 22m diep, zandige habitat) in juni 2013 uitgevoerd. In dit experimentele gebied werd verstoring door de visserij als laag beschouwd, zodat inmenging met het experiment werd geminimaliseerd. Binnen het experimentele gebied werden voor het BACI experiment 3 deelgebieden (150m x 1000m) aangewezen: 1) een pulskor gebied; 2) een boomkor gebied; 3) een referentiegebied. De pulskor- en boomkor gebieden werden door een commercieel vaartuig (pulskor) en een onderzoeksschip (boomkor) voor één dag bevist. De gebieden werden voor en na de visserij activiteit bemonsterd met een multibeam, een sediment profiel camera (SPI) en een bodemschaaf.

Een vierde gebied werd gereserveerd voor het meten van de sediment resuspensie (d.w.z. het sediment zweeft in de waterkolom) van de twee type visserijen. Dit vierde gebied lag ook in het experimentele gebied.

De belangrijkste bevindingen voor elk van de bemonsteringsmethoden zijn:

Multibeam:
- Uit het onderzoek met de multibeam bleek dat sleepnet sporen van visserij (waarschijnlijk boomkor) voorafgaand aan de experimentele visserij het duidelijkst waren in het gebied van de sediment resuspensie metingen (vooral zuidelijke deel) en in het oostelijke deel van het pulskor gebied.
- Significante verschillen tussen binnen en buiten de sleepnet sporen (hierna genoemd 'indringdiepte') werden voor zowel de puls- als de boomkor visserij gevonden. De analyse toont tevens aan dat de boomkor dieper in het sediment dringt dan de pulskor.

Bodemschaaf:
- Uit de benthische gegevens bleek dat er een grote variabiliteit aan bodemdieren was tussen de gebieden en bleek het moeilijk om een effect te detecteren als gevolg van de visserij. Wel kon worden aangetoond dat de totale biomassa van bodemdieren was afgenomen na (boomkor en pulskor) vissen, maar deze afname werd ook in het referentiegebied geconstateerd.
- Er werden geen duidelijke consistente patronen van visserij effecten op de dichtheden van individuele soorten waargenomen.
- De gevangen bodemdieren werden op basis van hun gevoeligheid voor de sleepnet visserij ingedeeld in één van drie categorieën, namelijk resistent, intermediair of kwetsbaar. De hoogste dichtheden van bodemdieren behoorden tot de resistente categorie. Dit verklaart mogelijk het gebrek aan een effect.

Sediment resuspensie:
- De pulskor en boomkor bleken soortgelijke hoeveelheden sediment te mobiliseren. De pulskor had echter hogere waarden voor meer verschillende deeltjesgrootten. De totale concentraties van opgeloste deeltjes waren ook hoger voor de pulskor op 25m en 45m achter de boom.
- De vermindering van opgeloste zuurstof in het sediment na vissen met de pulskor en boomkor is vergelijkbaar en lijkt na vissen snel terug te keren naar het referentie niveau.

Er wordt momenteel nog gewerkt aan de sediment profiel gegevens. Dit hangt af van softwareontwikkeling voor beeldanalyse. De resultaten worden eind 2014 verwacht.

Summary

Here we study the effects of fishing trawl gear on the seabed and benthic organisms. A BACI-design experiment was used to examine the effects of a traditional beam trawl gear and the pulse trawl gear. The pulse trawl gear is gaining popularity amongst Dutch fishers in recent years due to reduced fuel costs and good sole catches.

The research was carried out in the northern part of the Dutch Voordelta (southern North Sea coastal zone area, 15 – 22m deep, sandy habitat) in June 2013. In this experimental area, fishing disturbance was considered to be low so interference with the experiment was minimalized. Within the experimental area 3 sub-areas (150m x 1000m) were established for the BACI experiment: 1) a pulse trawl area; 2) a beam trawl area; 3) a reference area. The pulse and beam trawl areas of the BACI experiment were trawled by a commercial vessel (pulse) and a research vessel (beam) for one day. Before trawling, the areas were sampled with a multibeam, a sediment profile imaging (SPI) camera and a benthic sledge. The same sampling was carried out after the trawling, as well as boxcore sampling.

An fourth area was set aside for measuring sediment resuspensions from the two types of trawls. This fourth area was located in the experimental area as well.

The key findings for each of the different aspects sampled are:

Multibeam:

- The multibeam showed that trawl tracks of fishing disturbance (most likely beam trawls) prior to experimental fishing were most evident in the area set aside for sediment resuspension measurements (mainly southern section), and in the eastern section of the pulse site.
- Significant differences inside and outside the trawl marks (hereafter called ‘penetration depth’) were found for the pulse an beam trawl treatments and beam trawls were shown to penetrate deeper into the sediment than the pulse trawl.

Benthic sledge:

- The benthic data revealed large variability between stations and it was difficult to detect an effect from fishing. Whilst overall biomass did decrease following (beam trawl and pulse trawl) fishing, this reduction was also found in the reference area.
- No obvious consistent patterns of fish trawling effect on the densities of individual species was noted.
- Based on various life history traits, the recorded benthic species were assigned to one of three categories describing their vulnerability to trawling: resistant to trawling, vulnerbale to trawling, or intermediate. Of the three categories, the highest densities were found in the resistant category, which is likely to explain the lack of trawling effect observed.

Sediment resuspension:

- The pulse and conventional beam trawl were shown to mobilise similar quantities of sediment, but the pulse trawl had higher values for more particle size bins. Total concentrations of resuspended particles were also higher for the pulse at 25 and 45m behind the beam.
- The reduction of dissolved oxygen in the water column following a the trawl of a pulse and that of a conventional beam trawls is similar, and oxygen levels appear to revert back towards the baseline levels soon after trawling.

Analysis of boxcore data (infauna and sediment characteristics) is still undergoing. Sediment profile image analysis is also undergoing pending software development for image analysis. These results can be expected at the end of 2014.

1. Introduction

This research is performed within "Beleidsondersteunend onderzoek (BO)" of EZ-programs and the North Sea Case Study of the FP7-project BENTHIS (contract 312088).

A large part of the Dutch fishing fleet targets flatfish: dover (common) sole (*Solea solea*) and plaice (*Pleuronectes platessa*). Traditionally, a beam trawl with tickler chains was used to catch these species. Recently, there has been a gradual change towards a new technique: pulse trawl. This technique is based on the beam trawl technique, but the tickler chains are replaced with electrodes generating electric pulses. The pulses between the electrodes generate muscle contraction in fish buried in the sediment so that they come up and get caught in the net. The new pulse technique is appreciated by many Dutch fishermen because of reduced fuel costs and good sole catches.

Fishing with pulse gear is only allowed with a permit, due to an existing regulation which prohibits fishing with electrical currents (EU control regulation 850/98). Since 2007 in the southern North Sea, each Member State has a permit for 5 percent of its entire beam trawl fleet is allowed to fish with a pulse gear. The Netherlands is currently making maximum use of this 5%. However, the amount of permits is insufficient as more fishermen would like to start fishing with the pulse technique. Therefore, the Dutch ministry and the Dutch flatfish fishery aim to either get a permanent admission of the pulse technique in European waters or get an increase of pulse permits. For this, agreement is needed with other member states on the regulation.

Other member states have doubts about the effects of the pulse technique. All kinds of studies have been conducted to study the effects of the pulse technique. One of the things that is underexposed is the direct impact of the pulse gear on the benthic ecosystem.

1.1 Assignment

The ministry of Economic Affairs asked IMARES to study the direct effects of pulse fishing targeting flatfish on the benthic ecosystem.

This research is also part of the European Research project BENTHIS. BENTHIS studies the impacts of fishing on benthic ecosystems and will provide the science base to assess the impact of current fishing practices. As part of this project, the effects of beam trawl fishing on the benthic ecosystem are studied in the same field experiment.

This report provides the results of both the effects of pulse and beam trawl fishing on the benthic ecosystem. As both studies were done side-by-side, the results also give an indication of the difference in effects on the benthic ecosystem between the pulse and beam trawl fishery.

1.2. Reading guide

In chapter 2 the methodology used to study the effects of pulse and beam trawling on the benthic ecosystem is explained. After this, the results are described in chapter 3. Finally in chapter 4 the results are discussed and the conclusions are presented.

2. Methodology

To assess the impacts of the trawl gear on the benthic organisms, the study was set up as a before-after-control-impact (BACI) field experiment whereby an area was selected within which sub areas were define for experimental fishing with a conventional tickler beam trawl and a pulse trawl, as well as a reference area. The areas were monitored prior to experimental fishing (T0) and around 48 hours post experimental fishing (T1) using various monitoring techniques (multi-beam, benthic sledge, boxcore, sediment profile imaging) to get a more complete insight into the potential disturbances of the gears. A separate area was designated for measurements on sediment re-suspension using a sediment suspension sledge and laser techniques. The details of the experimental setup and the methods for the multibeam, benthic sledge and sediment suspension sledge are given in the following sections. The sediment profile imaging, boxcore and laser techniques are described in Appendix A as the results are not yet available (expected 2015).

Three vessel were used to complete the experiment:

- **RV ISIS:** Experimental tickler beam trawling, Benthic sledge and sediment re-suspension measurements on tickler beam
- **SCH18 "de Boeier":** Experimental pulse trawling, re-suspension measurements on pulse trawl
- **RV Simon Stevin**: Multi-beam, boxcore, Sediment Profile Imaging

2.1. Experimental set-up

2.1.1. Study area

The experimental area (including the BACI areas and the sediment re-suspension plot) was located in the northern part of the 'Voordelta', a coastal zone area in the southwest of the Netherlands, in the southern North Sea (Figure 1). Four study sites were designated within the experimental area (Table 1):
- Reference area
- Pulse trawling with multiple passages (pulse site)
- Beam trawling with tickler chains and multiple beam trawl passages (m-tickler site)
- Beam trawling with tickler chains and single beam trawl passage (hereafter called s-tickler site)

Table 1: Location of the study sites (Figure 1): four study sites were located within the borders of the experimental area (1): (2) a reference area, (3) a pulse trawling area and two areas for beam trawling with tickler chains (one with multiple passages (4) for the BACI experiment, and one with a single passage (5) for the sediment resuspension measurements).

Study sites	Coordinates of the experimental plots			
	Corner 1	Corner 2	Corner 3	Corner 4
1. Experimental area	51° 57.1832'N 3° 51.4523'E	51° 57.1849'N 3° 53.3303'E	51° 16.1333'N 3° 53.3314'E	51° 56.1325'N 3° 51.4428'E
2. Reference area (no fishing)	51° 56.6970'N 3° 51.7428'E	51° 56.6978'N 3° 52.6153'E	51° 56.6148'N 3° 52.6133'E	51° 56.6171'N 3° 51.7431'E
3. Pulse site (multiple passages)	51° 56.4521'N 3° 51.7391'E	51° 56.4517'N 3° 52.6162'E	51° 56.3716'N 3° 52.6119'E	51° 56.3722'N 3° 51.3722'E
4. Tickler site (multiple passages)	51° 56.9396'N 3° 51.7487'E	51° 56.9404'N 3° 52.6190'E	51° 56.8585'N 3° 52.6193'E	51° 56.8582'N 3° 51.7444'E
5. Tickler site (single passages)	51° 56.9427'N 3° 52.8878'E	51° 56.9429'N 3° 53.0217'E	51° 56.3749'N 3° 53.0168'E	51° 56.3775'N 3° 52.8829'E

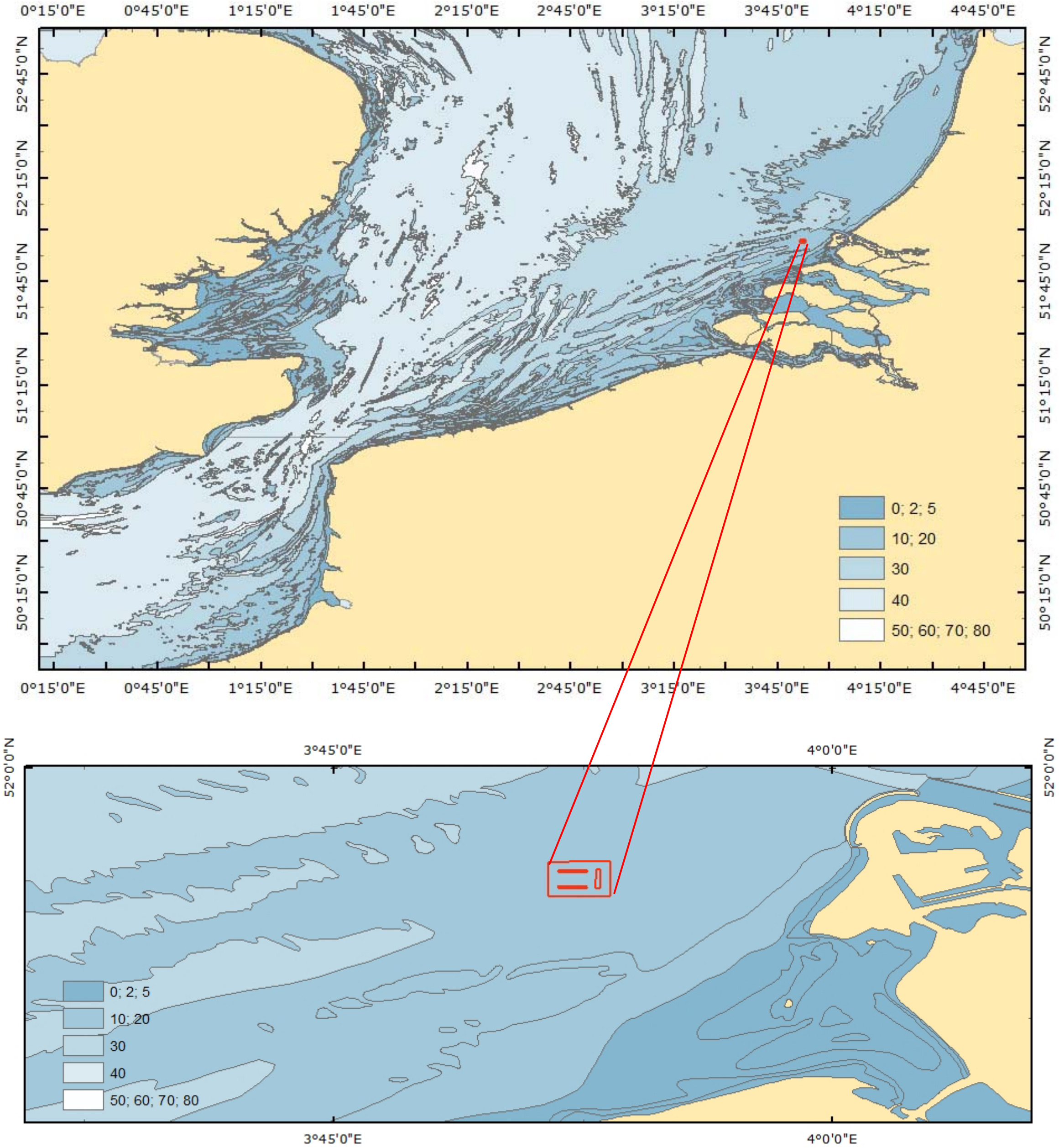

Figure 1: Location of the experimental area and three study sites. The east-west oriented rectangles were 1000m by 150m and subjected to multiple passages (north: tickler site, south: pulse site). The north-south oriented rectangle was 1350m by 150m. The closest distance between study sites was 300m

The study sites were 150m wide, and 1000m long (m-tickler and pulse site) or 1350m long (s-tickler site). Study sites were minimum 300m apart. The depth range of the experimental area was between 15m and 22m below sea surface in a shallow sandy habitat. It was classified as fine sand or muddy sand in the EUNIS 2007-11 classification system (Cameron & Askew, 2011), and is located at the bordering zone between infra- and circa-littoral. This implies that weather conditions potentially have an effect on the seabed, and hence fading of trawling marks may be faster than on fishing grounds located in deeper water. The experimental area is closed to beam trawlers >221kW and the coordinates were shared via the MaxSea system so other trawlers could avoid the experimental area during the course of the experiment. To what extent fishing still occurred in the area during the experimental time period was

shown with the multibeam (see section 3.1.1). The site was predominantly selected because of the limited trawling that had taken place in recent years in comparison to other available sites and because of the expected high abundance of benthic fauna (Craeymeersch pers. comm. - based on shellfish survey results). The study sites were selected on the basis of relative uniform seabed habitat, as well as limited trawling in recent years and high abundance of benthic fauna.

2.1.2. Experimental fishing

The experiment took place between 12 and 20 June 2013. The RV ISIS conducted one haul in the s-tickler site (for sediment resuspension measurements) on 19 June 2013 (between 8h35 – 8h45), and nine hauls in the m-tickler site (BACI experiment) on 18 June 2013 (between 10h45 – 17h35). The swept area in the m-tickler site was 20.55km², resulting in an area-based fishing intensity of 1.4 (=20.55/15km²; where 15km² is the area of the study site). The deployed beam trawl was a commercial trawl, provided by beam trawler WR244 'Margaretha Hendrika'. The gear had a beam width of 4.4m and an overall weight in air of 1065kg. The two trawl shoes had a surface of 0.72m² and five tickler chains attached to them with a diameter of 28mm, and one of 22mm. Seven tickler chains (so-called 'kietelaars' and 'snorren') were attached to the ground chain and had a diameter between 11 and 16mm. A commercial pulse trawler (SCH-18 'de Boeier') trawled in the pulse site (BACI experiment) on 15 June 2013 (between 7h25 – 15h20, 6 hauls), resulting in a swept area of 36.10km² or a fishing intensity of 2.4 (=36.10/15km²; where 15km² is the area of the study site). The pulse trawl was the 'Delmeco' trawl (Soetaert et al., 2013) with a beam width of 4.4m and an overall weight in air of 2500kg. The sole plates of the two trawl shoes were 0.34m². Electrodes were attached to the beam, resulting in 20 rubber tubes of 35mm towed in longitudinal direction. Ten of those rubber tubes had nine consolidated parts of 60mm in between the copper tubes of 30mm.

2.2. Sampling methods

2.2.1. Multi-beam measurements

The experimental sites were monitored with the Kongsberg EM2040 MBES mounted on the Research Vessel Simon Stevin (RV3609, 36m L.O.A., 2*520 kW engine power, 3.5m draught). 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 degree width at 300 kHz, a ping rate up to 50 Hz and a swath coverage sector up to 140 degrees (Horvei & Nilsen, 2010). On the Simon Stevin, the EM2040 MBES is interfaced with 4 auxiliary sensors allowing heading measurement of the vessel, real-time correction of the vessel movements, sound velocity evaluation, draught – water level measurement of the transducers and geo positioning of the data. Roll, pitch and heave are corrected using the Octans from IXBlue. The Octans also delivers the heading measurements. The Valeport mini SV sensor provides the sound velocity value at the transducer. Based on the value provided by the Valeport mini SV sensor, a sound velocity profile vertically constant is used during the measurement and updated according with the real time value from the sensor. High resolution positioning is managed by a MGB-Tech's RTK-GPS based on Septentrio OEM board. The draught is measured by an ATM draught sensor.

Apart from this specific project, several tests have been done to evaluate the standard-deviation of the soundings of Simon Stevin's EM2040 combined with its sensors. For a series of 3 lines surveyed on a flat sea bottom, the relative precision of the Simon-Stevin has been estimated by computing the difference between the raw soundings with a smoothed and a highly filtered model based on the same soundings. The results are impressive (Figure 2): the mean of the differences is virtually equal to 0 and the standard deviation is extremely low, 1.7 cm by mean from -70° to 70° (Degrendele & Roche, 2013). According with these results, the relative centimetre accuracy of this acoustic system is a perfect fit with the

purpose of this research. Note that any assessment of the absolute error has not yet been done for the Simon Stevin's EM2040.

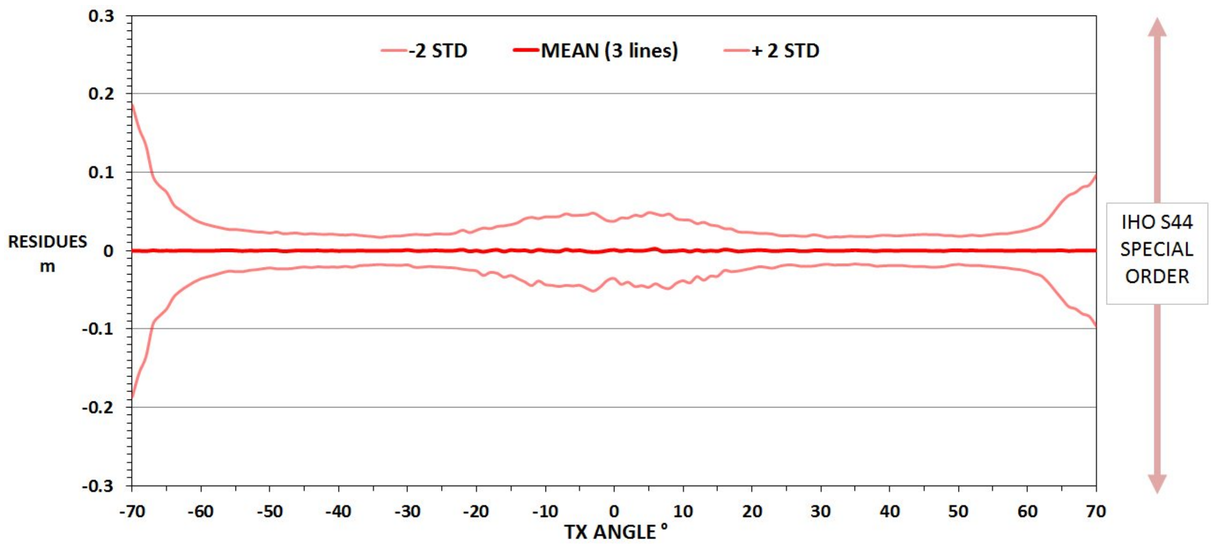

Figure 2: Relative precision of the Simon-Stevin EM2040: For a series of 3 lines surveyed on a flat sea bottom, the difference between the raw soundings with a smoothed and a highly filtered model based on the same soundings are computed. The mean of the differences is virtually equal to 0 and the standard deviation is extremely low, 1.7 cm by mean from -70° to 70°. With a relative centimetre mean accuracy the Simon Stevin EM2040 is of course fully IHO S44 special order compliant (Degrendele & Roche, 2013).

All the data have been surveyed with usual runtime settings and with the positioning system in DGPS mode. The pulse site was inspected at frequency of 300 kHz, while s-tickler and m-tickler site measurements were also complemented with measurements at 200 kHz. Recordings started and ended a few tens of meters outside the sites at a speed of about 8 knots and took place in longitudinal direction (Figure 3). Study sites were monitored prior and after experimental fishing (Figure 4). MBES survey line spacing was chosen to give full coverage of the seabed with an approximate overlap of 30%, except for the pulse site prior to fishing when only three survey lines were conducted due to time constraints. Three survey lines covered >75% of the area for 300 kHz measurements (Figure 5). The backscatter strength (BS) data have been logged for all the lines.

MBES data were processed with SonarScope from Ifremer (http://flotte.ifremer.fr/Presentation-de-la-flotte/Logiciels-embarques/SonarScope).

1. The MBES data recorded during the turns of the ship have been removed to avoid the negative impact the course changes have on the quality of the recordings.

2. The geo-referenced soundings are gridded in order to create a Digital Terrain Model (DTM) which can be integrated into a geographic information system for further analysis. In SonarScope the gridding process is done line by line. Taking into account the high density of soundings of the EM2040, an empty grid of 0.25m x 0.25m is created for each line. Line by line, the empty grid is filled up with the vector values from the nearest ping. (Augustin J.-M., 2013).

The resulting bathymetrical and geomorphological line by line DTMs provide detailed views of the experimental sites, enabling high resolution quantitative analysis to detect the potential disturbances caused by experimental fishing. Furthermore, the independent line by line DTMs can be combined to produce an overall map of the investigated area.

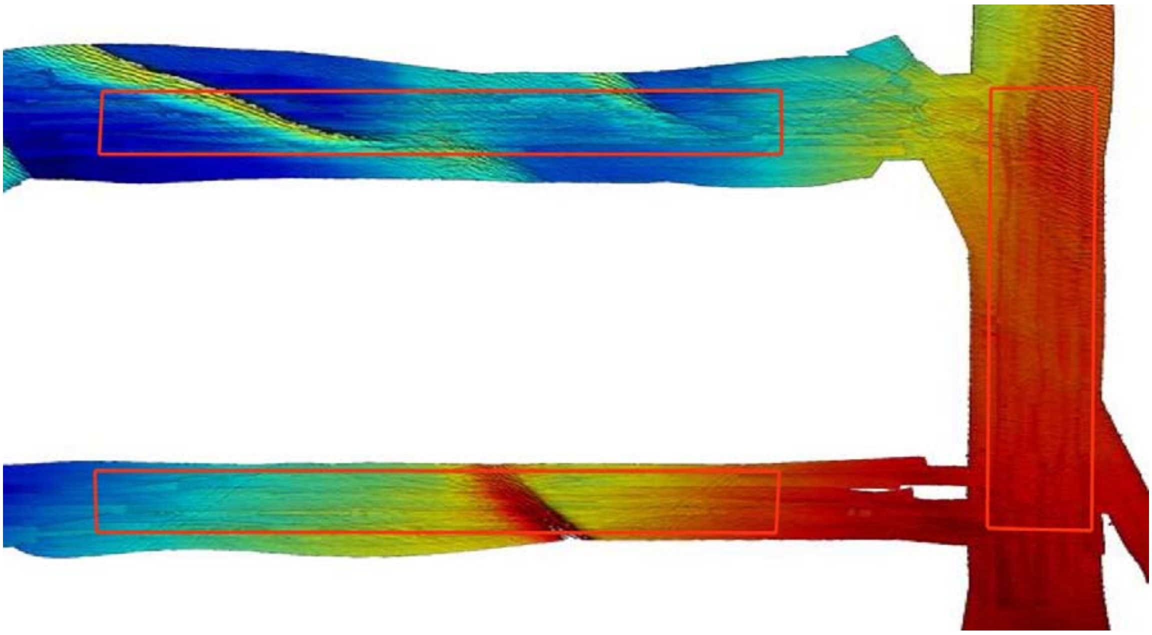

Figure 3: Bathymetric snapshot of the experimental area. Vertical site: s-tickler site (eastern), Horizontal sites: m-tickler (northern) and pulse site (southern). Depths vary between 15.4m (red) in the s-tickler site and 21.3m in the m-tickler site. The s-tickler site was relatively flat, characterised by ripples in the northernmost section. Sand dunes ran through the m-tickler and pulse site in north-south direction. Ripples were especially characterizing the dunes in the northern study site. Trawling took place in longitudinal direction. Remark that colours were not smoothened across survey lines. Images should thus only be interpreted within survey lines.

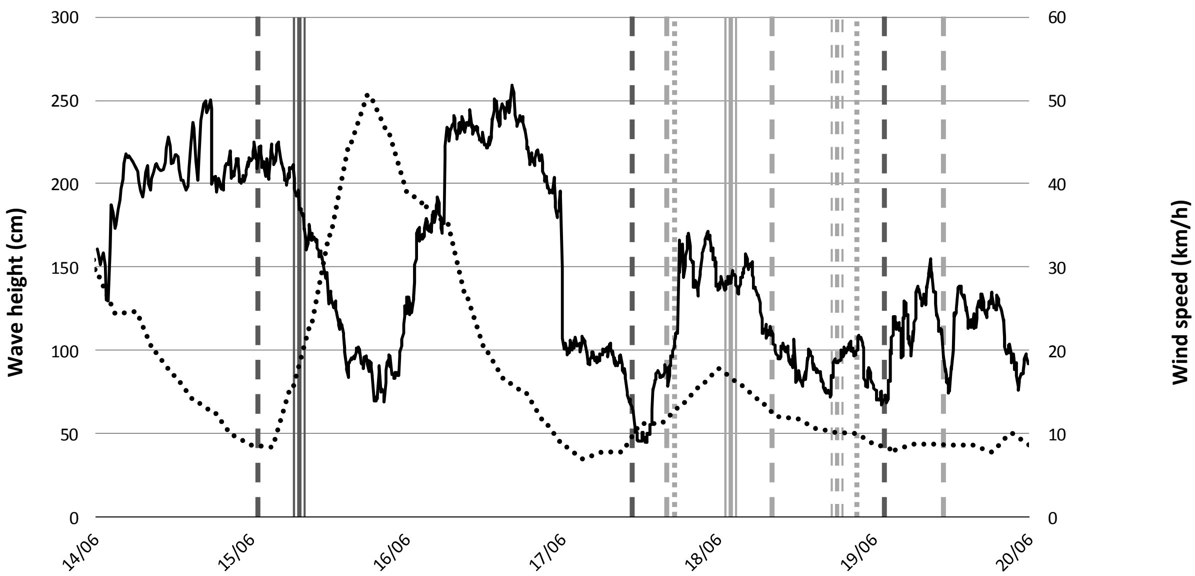

Figure 4: Experimental set-up and weather conditions. Fishing was conducted with a pulse beam trawl and multiple passages on 15/6 (7h25-15h20, triple dark grey), a tickler chain beam trawl with multiple passages on 18/6 (10h45-17h35, triple light grey) and a single passage in on 19/6 (8h35-8h45, triple dashed light grey line). Multi-beam measurements were taken prior and twice after pulse trawling (dashed dark grey lines) and multiple tickler chain beam trawl passages (dashed light grey lines). Multi-beaming took place prior and after single beam trawl passage (dotted light grey). Wave heights (dotted black line) were high after pulse trawling, while wind speeds (full black line) were high during pulse trawling and the first days afterwards.

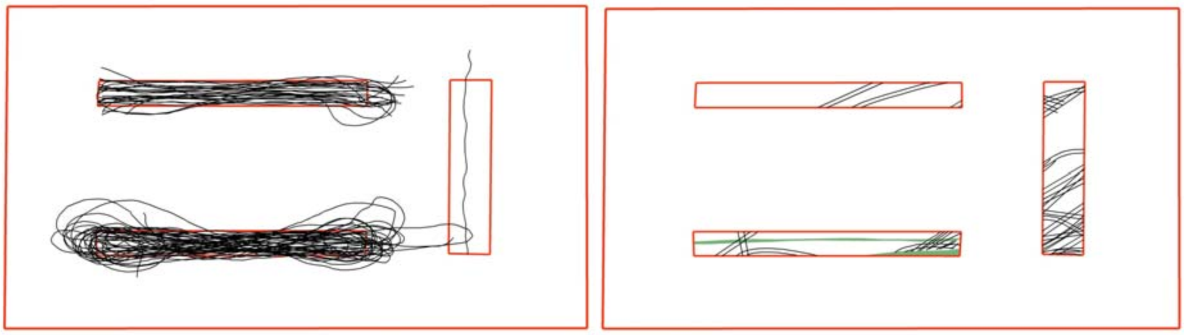

Figure 5: Identification of trawl marks in the experimental area: GPS positions of the experimental fishing were tracked and plotted (left panel), assisting identification of experimental trawl tracks in s-tickler, m-tickler and pulse sites. Trawl tracks prior to experimental fishing were visually detected from MB images in each study site (right panel). Note that survey lines prior to experimental fishing did not cover green coloured parts of the pulse site.

The backscatter strength data have been gridded using the same algorithmic as the bathymetrical data. For each line a 0.25m x 0.25m grid of BS levels (mosaic) is computed. As BS is frequency dependent, 200 kHz and 300 kHz data were treated separately. Not surprisingly, traces of trawling are clearly visible on both sonar images at 200 kHz and 300 kHz. However the quality of imaging at 300 kHz is much higher than at 200 kHz. Several reasons can be cited to explain this difference in image quality between the two transmission frequencies: beam widths (0.75x1.5 degrees at 200 kHz and 0.5x1 degrees at 300 kHz) and therefore the size of the insonified footprint on the seabed and differences in the penetration levels. Within the strict framework of this project, and compared to bathymetric data that allows a quantitative assessment of the impact from different types of trawling, the BS does not supply added value. However, differences in the BS mean level from one disturbance (trawling trail) to another could provide an additional measure of the relation between sediment type and impact and of the age of the impact.

<u>Statistical analysis of penetration depths</u>

Evaluation of penetration depths: MBES survey lines revealed marks of beam trawling prior to experimental fishing. These marks were visually identified based on the MBES images. Time referenced GPS positions of the fishing vessel were registered every 10 seconds together with setting and hauling time of the gear. Trawl tracks of experimental fishing were detected on the basis of these positions and visual inspection of MBES images, because beam trawls did not align perfectly with vessel position (Figure 6). Depth measurements were subsequently selected at regular intervals along the identified trawl tracks. Intervals were defined by dividing the total length of the identified tracks into equal parts. When aberrations were present due to image processing or due to tracks of fishing prior to the experiment, depth measurements were taken in the vicinity of the aberration. Blocks of depth measurements were selected inside the trawl marks at a radius of maximum 1.5m within the identified location, because 4.4m beam trawls were used for experimental fishing. Measurements outside the trawl track were taken at both sides of the selected track in blocks at a distance between three and four meter of the identified trawl track location (Figure 6).

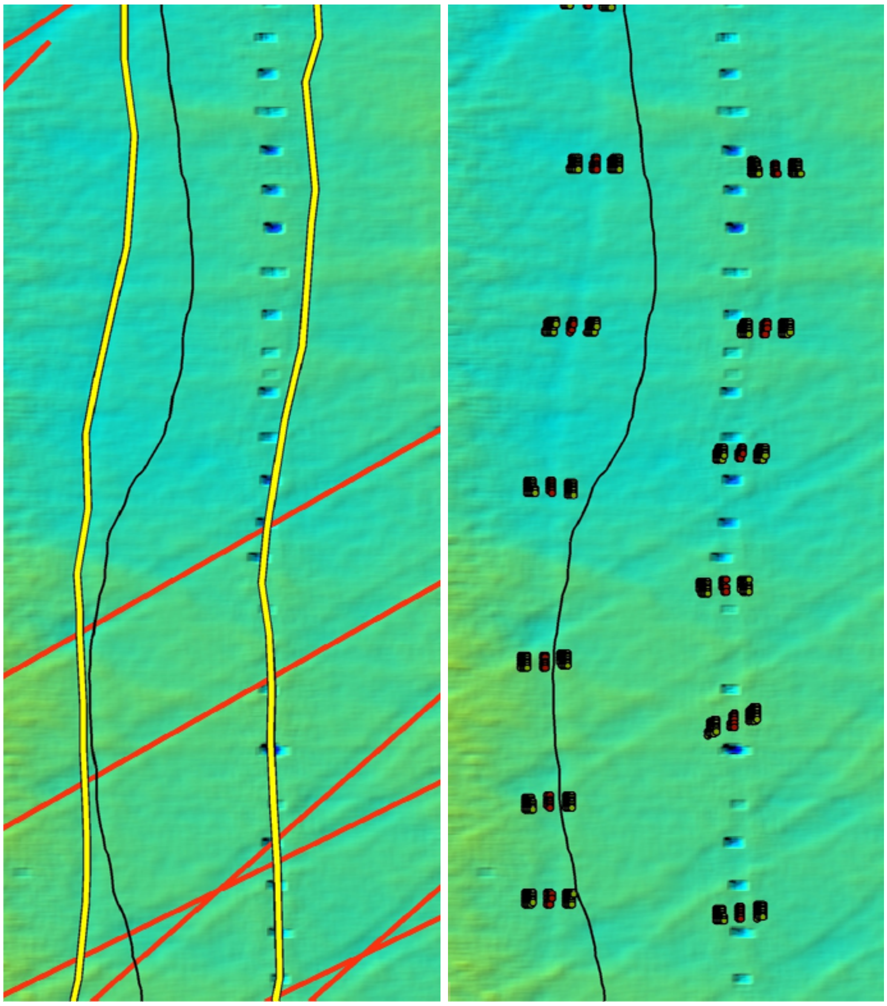

Figure 6: Detection of trawl marks and determination of penetration depths based on a 205kHz MB survey line in the s-tickler site. GPS locations (black line) indicated the vessel position. Beam trawl tracks (yellow lines) were based on visual inspection in conjunction with the vessel's position. If image aberrations (e.g. regularly spaced rectangles) or tracks of non-experimental beam trawling (red lines) were present, depth measurements were selected at a nearby location. Depth measurements were registered inside and at both sides outside of the fished track.

The procedure was applied to the s-tickler site, but was slightly modified for the m-tickler and pulse sites. In these cases, trawl tracks were only selected if marks were clearly visible, whereas for the s-tickler site, the fishing direction aided selection of slightly marked and/or hardly visible track sections. In contrast, tracks of multiple passage sites could have been modified as a consequence of multiple passages of the trawl across the same patches. Therefore, GPS positions of the vessel were insufficient to localize trawl positions, but necessitated visual inspection of potential marks. The identified tracks were thus exclusively visible tracks and could lead to overestimating penetration depths. Moreover, MBES survey lines in the m-tickler and pulse site were repeated at two time intervals (Figure 3), allowing the evaluation of fading velocity of the trawl marks. Depth measurements were taken from exactly the same positions as identified at first registration of trawling positions, i.e. 12h resp. <55h after trawling for m-tickler and pulse site (Figure A1). Total number of selected blocks differed however due to quality of MB images. Differences between total number of measured blocks were 6.1% for fading of trawl marks from 205kHz in the m-tickler site and 15.5% for 320kHz images, while the number of earlier registered measurements of the pulse site only differed by 2.1% with the last measurements. Measurements were only evaluated within one MBES survey line to reduce potential errors across MBES

lines. 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 using the software package R (Hollander & Wolfe, 1999; R Development Core Team, 2013). The procedure allowed evaluation of the overall penetration depth of the investigated fishing gear, i.e. not by gear components.

Comparison of trawl marks across treatments: Penetration depths were calculated for a range of depths measurements in selected blocks for each of the treatments (see above). Mean penetration depths of each block were used to compare physical disturbances between (1) single and multiple fishing intensities of the tickler chain beam trawl (treatment a and b, Table 3), (2) across fishing gears (treatment e and f, Table 3) and (3) over time (treatments b and c, d and e, f and g, Table 3). Penetration depths were evaluated by their cumulative distribution functions (CDF) to describe the general frequency distribution of penetration depths. CDFs were used instead of conventional statistical tests of the differences in means or medians, because of the heterogeneity in the variances. Non-linearity in the functional relationship was examined for each of treatments with Generalized Additive Models (GAMs):

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

where the response is the expected probability of occurrence (E[Y]), α is the intercept, and s is a one-dimensional smooth function of penetration depth X. The smooth function was estimated with the mgcv package in R using penalised regression splines, with an optimum degree of smoothing as defined by the generalised cross-validation criterion (Wood, 2006). A random resampling with replacement was applied to the observed penetration depths within each treatment. These bootstrap samples were used to fit the models, after which model output was saved. The process was iterated 250 times. Uncertainty of the model output was subsequently assessed by constructing confidence intervals of the model coefficients. The basic idea of bootstrapping penetration depths (random-x or case resampling) is that the best estimate for the data distribution is provided by the data themselves, and hence modelling did not rely upon specific assumptions of the underlying statistical distributions (Efron & Tibshirani, 1993). Unmodelled non-linearity, non-constant error variance or outlier effects were thus not carried over into the resampled data sets (Fox, 2002). Comparison between physical disturbances was evaluated from visual inspection of CDFs, e.g. overlap of confidence intervals.

2.2.2. Benthic sledge

Sampling methods: In order to sample the benthic fauna a benthic sledge was deployed from RV Isis. The trawled dredge, in general, resembles the one described by Bergman & van Santbrink (1994). The dredge is 2 m long, 1m wide and 0.65 m high and weighs about 350 kg. In the first part of the cage additional 280kg are fitted to keep the dredge at the seabed surface. The blade has a width of 10 cm. While towed, a strip of sediment is excavated and transported into the cage. The stainless steel cage has a mesh size of 0.5 cm. The back-side of the cage can be opened to collect the sample. The length of the haul is measured by a measuring wheel: a magnetic reed-contact counts the revolutions of the wheel.

Bad weather during the first days of the experiment limited the time available for the T0 sampling. Furthermore once sampling began it appeared that the original area selected was unsuitable (sediment too soft to allow trawling) and the area had to be shifted. Due to these time constraints only 11 benthic sledge samples were taken in the pulse area alongside the 15 taken in the reference and tickler beam area.

Table 2: Overview of benthic sledge sampling dates, haul numbers and associated photos of hauls for ID purposes. *Photos are available upon request*.

Study site	Sample date	T0/T1	Number hauls	Photo ID
(3) Pulse	12 Jun	T0	11	17-27
(4) Tickler	17 Jun	T0	15	28-37 + 64-68
(2) Reference	17 Jun	T0	15	38-47 + 59-63
(3) Pulse	17 Jun	T1	11	48-58
(2) Reference	20 Jun	T1	15	69-83
(4) Tickler	20 Jun	T1	15	84-98

The sledge was hauled diagonally through the areas (which are 150m wide) to allow for longer hauls (aim for 200m). Haul lengths were measured a wheel on the sledge. Hauls were kept >50m apart and deployment/hauling of the sledge was carried out within the boundaries of the designated areas. The diagonal lines were taken at opposite angles in T1 to T0 to avoid sampling through the same lines. As the catch was fairly homogenous, subsampling was used to speed up the process and achieve more hauls. 6 litres were subsampled from each catch and identified to species level following standard IMARES protocol. All data was entered into the IMARES database and quality checked.

Statistical analysis: Densities (numbers per m squared) and biomass (weight per m squared) of each species were calculated for each station within each area based on numbers within the sub-sample and the length of the haul. In order to assess effects of the different trawls on direct mortality of the organisms, the densities during T0 were then compared to the T1 densities by area.

Direct effects on densities within an area were assessed with a t-test comparing T1 to T0 for each area separately. In order to compare the effects of the different trawls a generalised linear model (GLM) was used to test for the interaction between sampling time (T0/T1) and area. If trawls have an effect on densities, or there are differences between the effects of the two trawl types, then the interaction term should be significant ($p < 0.05$) in the model, indicating a different trend in changes in densities between areas.

2.2.3. Sediment re-suspension measurements

<u>Sediment mobilisation from the pulse and the conventional beam trawl</u>

Pulse beam trawl sediment re-suspension work was carried out on board the commercial fishing vessel Boeier (SCH18) on Friday 14th of June, and for the conventional beam trawl on the research vessel ISIS on Wednesday 19th June. The sampling equipment (Sequoia LISST 100x, RBR dissolved oxygen and RBR dual conductivity and temperature sensors) was attached to a modified Nephrops TV survey sledge to measure the particle size and concentration of the sediment and dissolved oxygen in the plume of the beam trawls 35 cm above the seabed. The LISST and DO2 sensor were configured to record one sample every second, and the CT sensor every 3 seconds (CT sensors maximum). An underwater video camera and light was also installed to obtain footage to confirm the sledge was in the sediment plume and upright during sampling.

The sledge was fitted with a 5 meter long towing bridle and swivel arrangement for all samples (Figure 7). For control samples where it was not towed behind a beam trawl, this was connected to a 90 meter rope or warp and towed directly from the vessel (Figure 7a). For samples behind the trawls, it was connected to a dyneema towing line that was fixed to the centre of the beam and passed through the trawl and out the cod-end (Figure 7b). Two safety features were installed in case the towing line parted, a safety line and a float line was attached to the sledge to allow recovery. The area where the re-

suspension work was conducted lay to the south west of the closed area utilised for the other experiments (Figure 8). The longer tows and space required to prevent contamination between tows meant the area was too large to be included within the standard Benthis area. The re-suspension site was kept close to the Benthis area so the sediment composition would be similar.

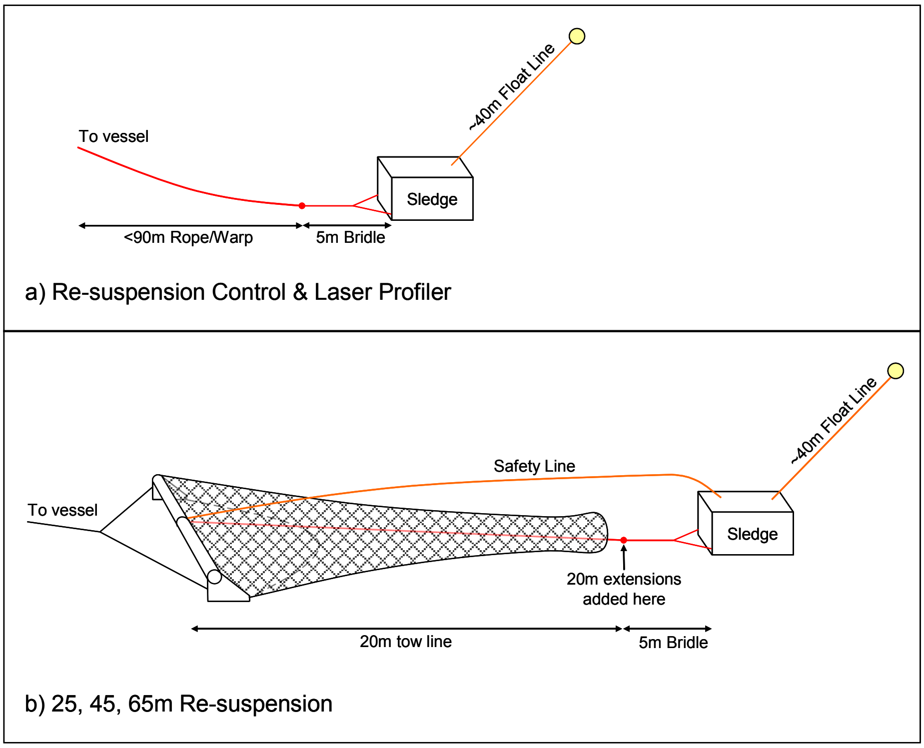

Figure 7: Towing arrangements for the sledge during re-suspension and laser profiling experiments

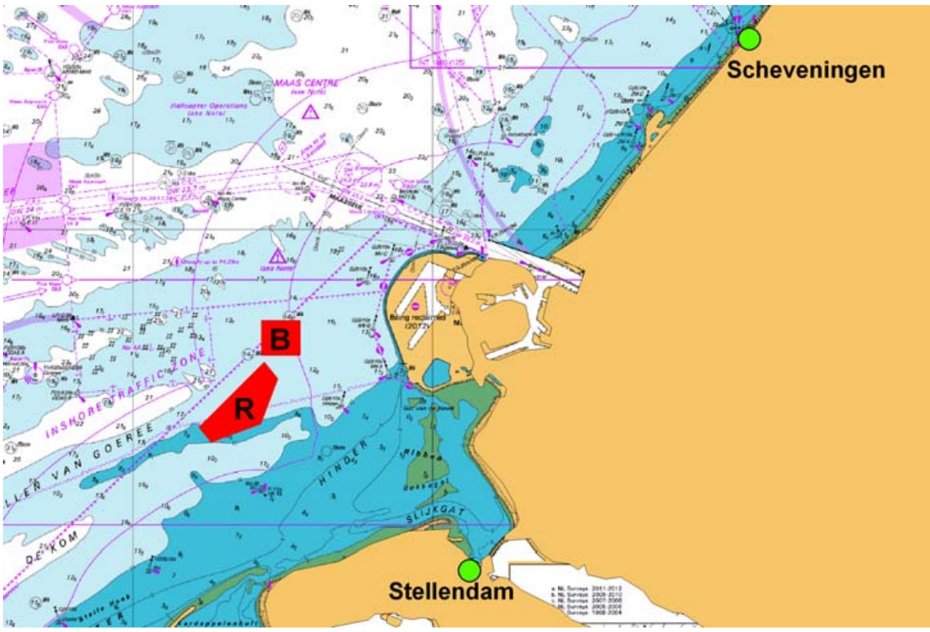

Figure 8: Location of the re-suspension experimental area (R) in relation to the experimental area (B).

On both vessels the first tow was a control sample to obtain background measurements of the water with no fishing gear in the water. Once complete the sledge was hauled back and secured to the side of the vessel. The 20m towing line from the beam trawl was connected to the 5m bridle of the sledge (25m total length from the beam), and two tows were conducted in opposite directions to negate tidal effects. While turning between the tows the beam and sledge remained on the seabed. The data obtained during this turning period has not been included in subsequent analysis. Once the second 25m tow was complete the sledge was hauled back and secured to the side of the vessel. Two further sets of two hauls were conducted, by adding an additional 20m to the towing line each time (45 and 65m total length) (Figure 7b). After the tows were completed the sledge was hauled aboard and all the data from the instrumentation downloaded.

All tows were conducted into or with the tide to ensure the plume and instrumentation were positioned centrally behind the gear. Towing speed was kept constant at around 4kn and the codends were left open during sampling to reduce variation between hauls. The duration of each tow was around 10 minutes for the pulse beam trawl, but it was around 15 minutes for the conventional beam trawl as there was more time available on RV ISIS (Table C1). The pulse beam was trawled with both beams out, whereas the conventional beam was fished with only the port beam trawl. Using only one trawl will not affect the comparison in re-suspension figures as the instruments only sampled the actual beam trawl it was towed behind.

3. Results

3.1. Multi-beam measurements of gear penetration depths

3.1.1. Evaluation of penetration depths

A bathymetrical snapshot indicated that depth measurements were taken between 15 and 22m depth. The s-tickler site was characterized by a limited depth range and ripples which were most pronounced in the northern section. The relief of the m-tickler and pulse sites was more pronounced. The pulse site had a steady slope with a sand dune running in the middle from north to south. The m-tickler site was deeper and roughness was more pronounced across the site. A dune ran from the north-western to the middle-southern section (visible in
Figure 3). The selection of measurement blocks occurred at limited depth ranges (between 0.9 and 1.4m) except for MB survey lines at 205kHz in m-tickler site (Table 3). Trawl tracks of fishing disturbance prior to experimental fishing was most pronounced in the s-tickler site (mainly southern section), and in the eastern section of the pulse site. Fishing disturbances were presumably caused by flatfish beam trawls, because of the appearance of parallel marks of 4m width each typically deployed by 'eurocutters'.

Table 3: Penetration depths of tickler chain and pulse beam trawling in shallow sandy habitats for different treatments (trt) based on type of beam trawl (T = Tickler, P = Pulse), trawling frequencies (Freq), time lapses after trawling (Time) and frequency of the MB signal (MB freq). N = number of selected blocks for measuring trawl marks. Minimum (min), median (med) and maximum (max) penetration depths are given as well as Q1: first quartile, Q3: third quartile.

Trt	Freq	Time (hr)	MB freq (kHz)	Depth range (m)	N	Penetration depth (cm)					χ^2 df=1	P-value
						min	Q1	Med	Q3	max		
T1	Single	<12	205	15.4 – 16.3	31	0.09	0.57	0.88	1.71	2.85	17.06	<1e-4
T2	2.18	<12	205	16.9 – 19.9	173	0.02	0.94	1.61	2.68	8.23	37.65	<1e-9
T3	2.18	<44	205	16.9 – 21.3	153	0.03	0.74	1.72	2.52	7.77	24.14	<1e-6
T4	2.18	<12	320	17.1 – 18.4	112	0.00	0.76	2.04	3.49	12.79	54.00	<1e-12
T5	2.18	<44	320	17.3 – 18.5	82	0.05	1.14	2.02	3.44	10.68	10.98	<0.001
P1	3.91	<55	320	16.3 – 18.1	246	0.00	0.57	1.21	2.21	5.84	81.97	<1e-5
P2	3.91	<107	320	16.3 – 18.1	236	0.00	0.47	0.96	1.59	4.65	21.97	<1e-5

Significant differences inside and outside the trawl marks (hereafter called 'penetration depth') were found for each of the treatments (Table 3; Figure 9). Median penetration depth was minimal for a single passage of a tickler chain beam trawl measured within 12h after disturbance at MB frequency of 205kHz, and for the longest time lapse of observation, i.e. for <107h after pulse trawling. Penetration depths were maximal for multiple passages of a tickler chain beam trawl, measured at 320kHz. When median penetration depths of a treatment were higher, variability in penetration depths was considerable, which was also reflected in the deepest penetrations (Table 3; Figure 9).

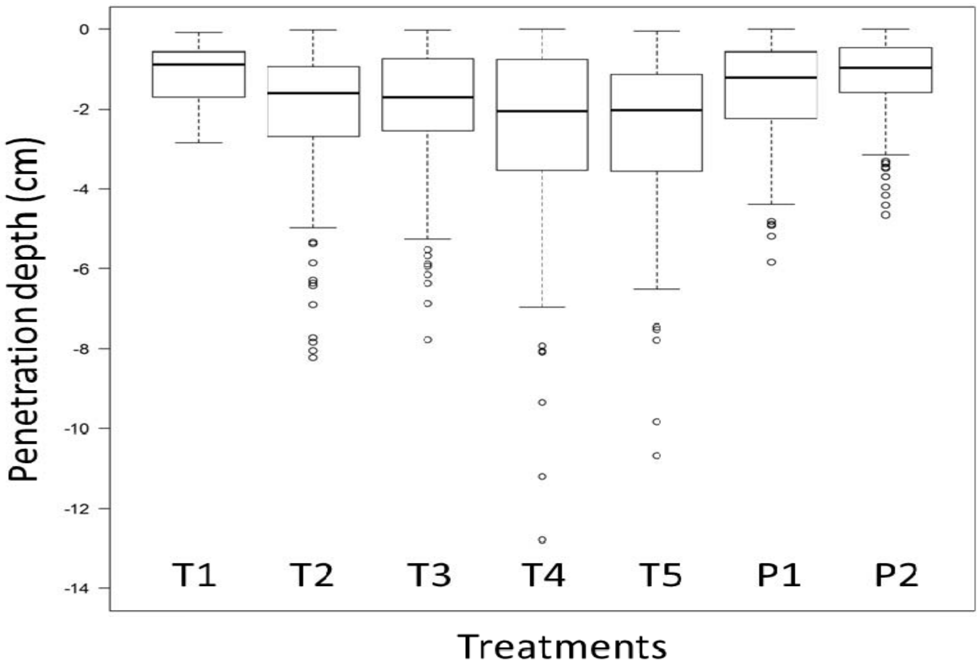

Figure 9: Penetration depths of tickler chain and pulse beam trawling for treatments as specified in Table 2.

3.1.2. Comparison of penetration depths across treatments

All CDFs increase to a certain point and then level off (Figure 10, Figure 11), indicating the highest frequency of limited penetration depths and a decreasing frequency of deep trawl marks. There is 50% probability that penetration depths of the different treatments are about 2cm or less. Cumulative probabilities up to 90% indicate that penetration can reach depths of 4cm (treatment b), 5.6cm (treatment e) or 6cm (treatment d). Overlap of 95% confidence intervals is limited between treatments, except for treatment d and e (indicating the fading of trawl marks at 320 kHz for tickler chain beam trawling). While general patterns appear, different treatments allow the comparison of the effect of fishing intensity, fishing gear and fading of trawl marks.

Fishing intensity

There is a distinct difference of penetration depths at a 205kHz multi-beam frequency between a single passage of a tickler chain beam trawl and multiple passage (fishing intensity of 2.18). There is no overlap between CDFs, and multiple passage indicate a 50% probability that the trawl penetrate up to 1cm while this is 1.8cm for multiple passage. The trawl tracks of a higher fishing intensity go up to 4cm at a 90% cumulative probability of occurrence, while this is 2.5cm for a single passage (Figure 10).

Gear effect

The effect of pulse trawling can be compared with tickler chain trawling at 320 kHz multi-beam frequency and after about one day of trawling (<44h resp <55 h after trawling) (Figure 11). There is a probability of only 25% that penetration depths between both gears will be fairly similar at values of <0.6cm. However, penetration depths of tickler chains are considerably higher at 50% cumulative probability (2cm versus 1.4 for pulse trawling), and this trend continues with increasing cumulative probabilities. 75% of the observations indicate that penetration depths of tickler chain trawls are less than 3.1cm, while this is 2.3cm for pulse trawls. At 90% the differences are even more extinct, varying between 5.6cm for tickler chain trawling and 3.1cm for pulse trawling.

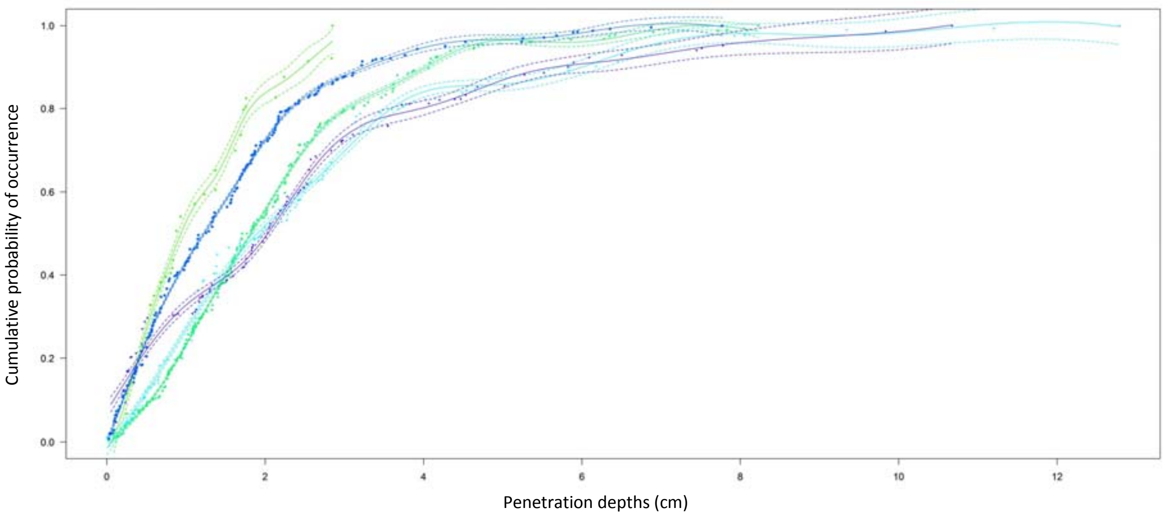

Figure 10: Cumulative distribution functions of penetration depths for different treatments of the tickler chain beam trawl. Treatments are specified in Table 3: Penetration depths of tickler chain and pulse beam trawling in shallow sandy habitats for different treatments (trt) based on type of beam trawl (T = Tickler, P = Pulse), trawling frequencies (Freq), time lapses after trawling (Time) and frequency of the MB signal (MB freq). N = number of selected blocks for measuring trawl marks. Minimum (min), median (med) and maximum (max) penetration depths are given as well as Q1: first quartile, Q3: third quartile. and related to the following colors in increasing order of penetration depths: (a) green, (c) dark blue, (b) greenish blue, (e) purple and (d) light blue. Single passage of a tickler chain beam trawl (trt a) penetrates the least deep. Multi-beam measurements at 320kHz (trt d and e, resp. light blue and purple) do not indicate a clear fading of trawl marks over time, while at 205 kHz the penetration depths are less deep (trt b and c, from greenish blue to dark blue). Dashed lines indicate the lower and upper limits of 95% confidence intervals.

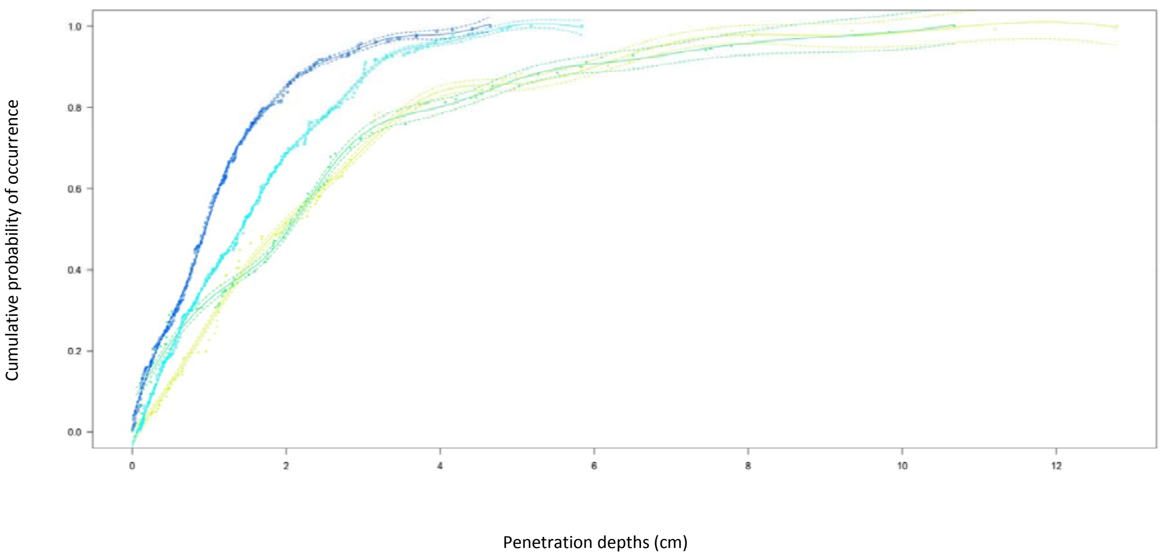

Figure 11: Cumulative distribution functions of penetration depths measured at 320kHz after multiple trawling passages: multiple passage of a pulse trawl at two time steps: <55h after trawling (trt f, light blue), <107 after trawling (trt g, dark blue). Trawl marks fade over time. The greenish blue CDF (trt e) can directly be compared with pulse trawling and indicates higher probabilities of deeper penetration in the seabed. The yellowish light green CDF (trt d) illustrates the penetration depth at <12 h. Dashed lines indicate the lower and upper limits of 95% confidence intervals.

Fading of trawl marks

The penetration depths were registered at different time intervals Figure 10; Figure 11; Table 3). Tickler chain beam trawls were registered within 12h after trawling and at <44 hours after trawling, both at 205 kHz and 320 kHz. Deeper trawl marks were more apparent at the shorter time interval for tickler chain beam trawling at 205kHz, varying between 1.0 and 2.7cm and between 0.5 and 2.1cm for a cumulative probability of 25% and 75%. However, this pattern was considerably reduced to almost absent for 320kHz measurements. There was 25% probability that penetration depths were 0.9cm at the short interval and 0.6cm at the longer time scale, while 75% of the cumulative probability indicated that penetration depths were 3.3 cm shortly after trawling and 3.2cm one day later. The pulse trawl marks were registered after about one and two days respectively. There was a probability of 75% that trawl marks were less than 2.3cm deep after one day, while this depth diminished to 1.5cm after about two days.

The main results of the multi-beam can be summarized as follows:

- Both tickler chain and pulse trawl tracks are visible on the multi-beam, i.e. a trawl track is left in the sediment
- Overall it can be concluded that the tickler chains are more likely to penetrate deeper than the pulse trawl, i.e. penetration depths of 1-2cm can be attributed to either gears, but the deeper the penetration depths (down to 8cm) the more likely they are to come from tickler chains.
- Multiple passages of the tickler chain can markedly increase the penetration depth. The same could not be tested for the pulse.
- Fading of the tickler trawl marks was not observed within 2 days following trawling. There is some indication of fading of the pulse trawl tracks.

3.2. Benthic sledge data

In total, at least 23 species (Table 4) were caught within the benthic sledge across the areas and sampling times. In order to determine effects of trawling in terms of direct mortalities, and compare the different types of trawling, it is necessary to consider the variability in the benthic communities between the different experimental areas during T0 (Table 4).

In a preliminary exploration of the benthic data, boxplots were compared for the T0 and T1 sampling of the three experimental areas (see Appendix D for all figures). The changes in abundances of the benthic species in the tickler chain and pulse area from T0 to T1 were compared against the reference area for any differences. If the trawling had an impact, it can be expected that abundances decrease in the trawled areas but remain the same (or decrease to a lesser extent) in the reference area. Differences between the two types of trawling could also be explored in this way.

The findings are summarised here:

- *Actinaria* showed a decrease in all areas from T0 to T1.
- *Asterias rubens* showed a decrease in the Reference and Tickler Area but a steady to increasing trend in the pulse area.
- *Liocarcinus holsatus* showed an increase in the reference are but remained stable in the tickler and pulse area.
- *Lutraria lutraria* decreased in the pulse area.
- *Pagurus bernahardus* decreased in all areas.
- *Psammechinus miliaris* increased in the tickler and reference areas but decreased in the pulse area.
- *Spisula subtruncata* decreased in the pulse area.
- *Tellina fabula* increased in the reference and pulse area but remained stable or possibly declined in the tickler area.

Table 4: Densities (Nm2) of species caught across the three experimental areas and the number of stations (N) at which there were found with the respective areas during T0. p = significance of differences in densities between areas during T0; sel = the species selected for further analysis.

Species	Nm² Ref	N	Nm² Tickler	N	Nm² Pulse	N	p	sel
Abra alba	0.661	10	0.441	8	3.910	8	0.014*	
Asterias rubens	2.203	15	1.494	14	2.693	11	0.087	✓
Actinaria sp.	0.973	14	0.776	13	1.117	11	0.358	✓
Carcinus maenas	0.041	1	0	0	0	0	x	x
Corystes cassivelaunus	0.008	1	0	0	0.015	2	0.321	x
Diogenes pugilator	0	0	0.015	1	0	0	x	x
Ensis sp.	10.381	15	14.041	15	12.605	11	0.424	✓
Euspira pulchella	1.920	14	1.605	15	1.846	11	0.753	✓
Liocarcinus arcuatus	0.175	8	0.187	6	0.199	8	0.958	✓
Liocarcinus depurator	0.019	1	0.101	5	0.069	5	0.175	x
Liocarcinus holsatus	0.231	6	0.157	8	0.178	9	0.813	✓
Lutraria lutraria	0.451	10	0.513	11	0.715	8	0.512	✓
Macoma balthica	0	0	0	0	0.018	1	x	x
Nassarius reticulatus	6.286	15	4.101	15	0.560	11	0.001**	
Nassarius nitidus	0.299	7	0.380	12	7.224	10	0.219	✓
Ophiura albida	2.137	14	4.481	15	5.824	10	0.040*	
Ophiura ophiura	16.691	15	8.780	15	24.680	11	<0.001***	
Pagurus bernhardus	0.675	14	0.789	14	0.810	11	0.684	✓
Psammechinus miliaris	0.135	6	0.040	3	0.169	8	0.084	x
Spisula elliptica	0.021	1	0	0	0	0	0.431	x
Spisula subtruncata	0.099	5	0.100	5	0.255	9	0.051	✓
Tellina fabula	3.526	14	5.723	15	4.257	9	0.128	✓
Thia scutellata	0.017	1	0.028	2	0.009	1	0.740	x

The only significant changes between T0 and T1 however was a decline in *Asterias rubens* in the beam area (t = 3.66, df = 26.08, p-value = 0.001) and a decline in *Pagurus bernhardus* in the pulse area (t = 2.88, df = 19.469, p-value = 0.009). The boxplots (Appendix D) thus showed no obvious consistent patterns of trawling effect on the densities of individual species recorded, a conclusion which is supported by the outcome of the statistical analysis (described in 2.2.2.), which showed no significant interactions between sampling time and area for all species tested (Table 5).

The absence of significant effects of trawling may be related to the type of species caught and their susceptibility to trawling effects. All species were therefore categorised into either "resistant", "intermediate" or "susceptible" to trawling and the same analysis was performed at this grouped level. The boxplots (Figure 12) indicate that numbers of resistant species declined slightly in the beam trawl area but the difference in not significant (t-test t = 0.690, df = 27.94, p-value = 0.496). In the reference and pulse areas numbers remained stable (t = -0.633, df = 22.84, p-value = 0.533 and t = 1.372, df = 13.15, p-value = 0.193 respectively). For intermediate and susceptible species a general decline in numbers is observed across all treatment areas but these are not significant for the intermediate group (t-test: t = 0.956, df = 27.88, p-value = 0.347; t = 1.268, df = 25.41, p-value = 0.216; t = 0.672, df = 20, p-value = 0.510, for beam, reference and pulse area respectively) and marginally significant for the susceptible group (t-test: t = 2.049, df = 27.97, p-value = 0.050, t = 1.916, df = 27.14, p-value = 0.066, t = 2.144, df = 15.79, p-value = 0.048). However as the decline is also observed in the reference area (although it is the least significant), in the absence of trawling this pattern cannot be related to the trawling alone, but may be related ot the dynamic nature of the shallow coarse habitat. No significant

interactions were found between treatment and sampling period for any of the groups indicating that no effect of beam or pulse trawling could be detected (Table 6).

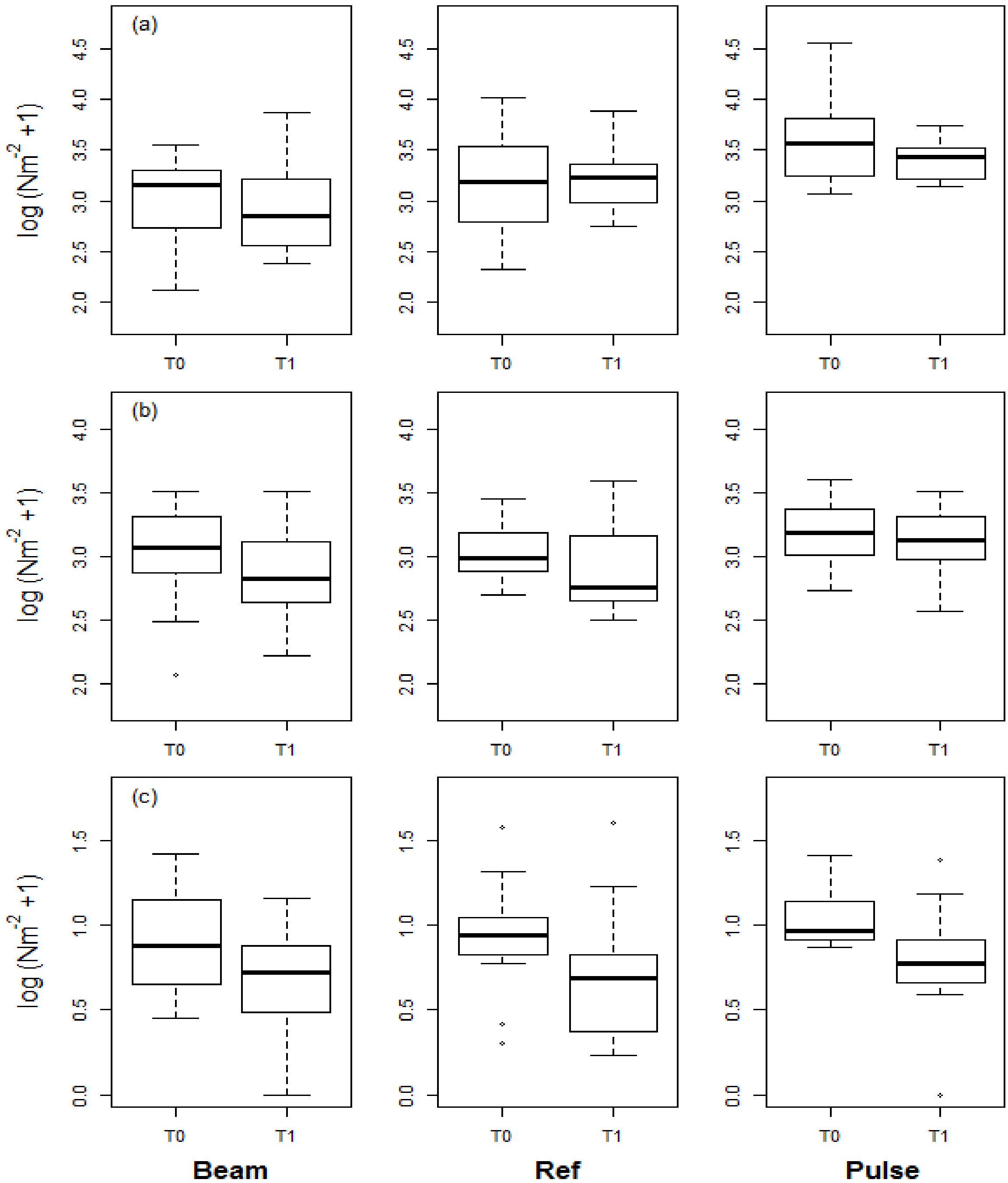

Figure 12: Boxplot of log-transformed summed densities of all species categorised as (a) resistant, (b) intermediate and (c) susceptible to trawling before (T0) and after (T1) experimental trawling in the three treatment areas.

Table 5: Results from the Chi-square test of the significance of the interaction between area and time of sampling. Df = degrees of freedom, p = significance. A p-value of < 0.05 would indicate a significant interaction.

Species	Df	Deviance	p	Sensitivity Score	Group
Abra alba	78	-0.895	0.208	33	Resistant
Asterias rubens	78	-0.427	0.207	41	Intermediate
Actinaria	78	-0.028	0.882	51	Susceptible
Ensis sp.	78	-0.006	0.986	40	Intermediate
Euspira pulchella	78	-0.131	0.602	37.5	Resistant
Liocarcinus arcuatus	78	-0.044	0.610	39	Intermediate
Liocarcinus holsatus	78	-0.0001	0.997	39	Intermediate
Lutraria lutraria	78	-0.189	0.417	39	Intermediate
Nassarius reticulatus	78	-0.056	0.838	39.5	Intermediate
Nassarius nitidus	78	-0.210	0.217	39.5	Intermediate
Ophiura albida	78	-0.458	0.512	36	Resistant
Ophiura ophiura	78	-0.144	0.694	36	Resistant
Pagurus bernhardus	78	-0.070	0.580	44	Susceptible
Psammechinus miliaris	78	-0.075	0.110	36	Resistant
Tellina fabula	78	-0.851	0.410	33	Resistant
Spisula elliptica	78	-0.036	0.462	47	Susceptible

Table 6: Results from the Chi-square test of the significance of the interaction between area and time of sampling. Df = degrees of freedom, p = significance. A p-value of < 0.05 would indicate a significant interaction.

Group	Df	Deviance	p
Resistant	78	-0.348	0.362
Intermediate	488	-0.072	0.9568
Susceptible	242	-0.004	0.984

In order to increase the power of the analysis, the data was all pooled by summing the densities per sensitivity group per station and using the summed densities in the model:

*Densities (summed by station, group) ~ Treatment * Sampling time * Sensitivity,*

Where * indicates that an interaction was tested for. The significance of the possible interactions was tested by comparing a Null model with all interactions included versus a model with one interaction with a Chi-square test. Non-significant interactions were dropped and the test repeated until only significant factors were left in the model. No interactions showed up as significant and so the final model was:

Densities (summed by station, group) ~ Treatment + Sampling time + Sensitivity (Table 7)

Densities were shown to be significantly lower during T1 (estimate = -0.142 ± 0.05 SE, t-value = -3.12, p = 0.002) and significantly higher in the pulse area compared to the beam area (estimate = 0.301 ± 0.06, t-value = 5.21, p < 0.001). The susceptible group show significantly lower densities than the intermediate group (estimate = -2.26 ± 0.06, t-value = -40.43, p < 0.001), which does not differ significantly from the resistant group (estimate = 0.027 ± 0.06, t-value = 0.475, p = 0.635)

Table 7: Results of the generalised linear model on log-transformed densities of the species grouped by station and sensitivity. DF = degrees of freedom, SS = sum of squares and p = significance value.

Parameter	DF	SS	F-value	P
Treatment	2	3.61	14.07	<0.001
Sampling time	1	1.24	9.71	0.002
Sensitivity	2	282.62	1102.45	<0.001
Residuals	240	30.76		

Despite the decrease in densities between T0 and T1, the lack of a significant interaction between treatment and sampling time again indicates no differences in the direction and amplitude of change between T0 and T1 between the different treatments. In other words, the two treated areas did not behave significantly differently to the reference area and no effect could be determined.

While there is some indication in the plots that the susceptible group may have responded to the trawling treatments more than the intermediate and resistant groups, the statistical significance is still marginal and the decrease is also evident in the reference area. The data was therefore pooled again to increase statistical power. Total benthic biomass per station was then considered as a function of treatment area and sampling time (Figure 13) and the same analysis was carried out on this level:

*Densities (summed by station) ~ Treatment * Sampling time* (Table 8)

Where * indicates that an interaction was tested for. The results of the model are shown in Table 8. Again, although a significant effect of sampling time was found, i.e. a decrease in biomass between T0 and T1, the effect (decrease) was also seen in the reference area and could therefore not be attributed to the fishing pressure.

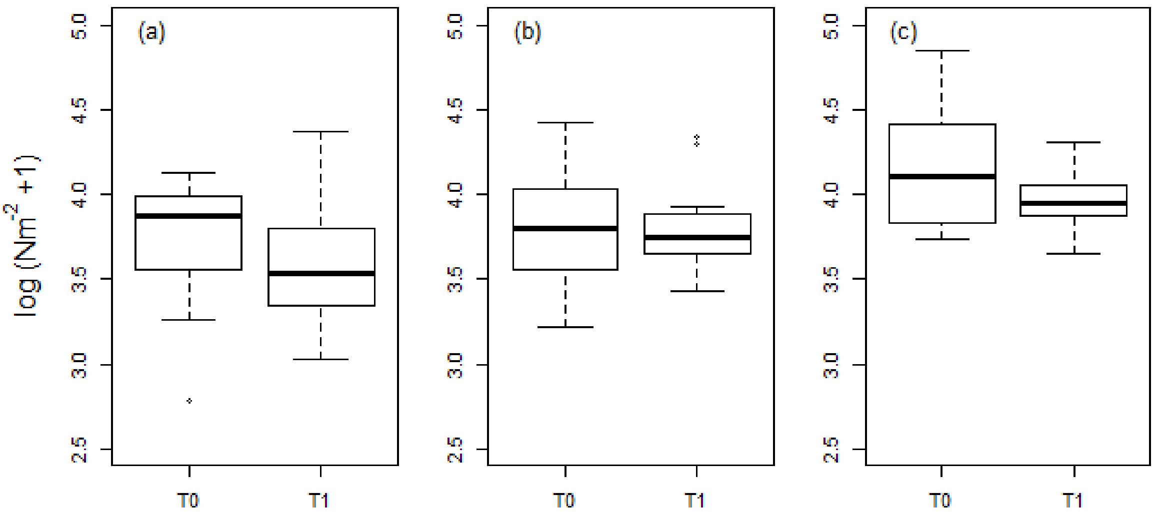

Figure 13: Boxplot of log-transformed summed densities of all species in the (a) tickler area, (b) reference area and (c) pulse area, before (T0) and after (T1) experimental trawling.

Table 8: Results of the generalised linear model on log-transformed densities of the species grouped by station. DF = degrees of freedom, SS = sum of squares and p = significance value.

Parameter	DF	SS	F-value	p
Treatment	1	0.228	1.976	0.164
Sampling time	2	2.003	8.675	< 0.001
Treat*Sampl time	2	0.080	0.346	0.709
Residuals	76	8.772		

3.3. Sediment resuspension

Overall fourteen tows were conducted during the re-suspension experiments. Pulse or conventional beam trawls were in place for six of these each and there were two control tows without any beam trawl present. The data obtained from the instruments has been cropped so that only the sections one minute after the start to one minute before the finish of each haul is utilised. This is to allow time for the fishing gear/instrumentation to settle down and remove any discrepancies in synchronisation between instrument and ship time. Examination of the GPS records has revealed the sledge was towed over a previous trawl track (45-60 min afterwards) on two occasions (Figure 14). Although tides in the area were strong and the sediment plume might have dissipated, any data near another track has been excluded from subsequent analysis. On one occasion the conventional trawl was towed over the track of the control (sledge only) track 135 min afterwards. The minimal disturbance created by the sledge and the longer time before crossing over the track would mean contamination of the sample is highly unlikely so hasn't been removed. The LISST 100x measures the volume concentration of particles at a rate of 1Hz (measured in µl/l). These are presented in 32 logarithmically increasing size ranges between 2.5 and 500 µm. Up to 480 measurements for each 8 min (pulse) or 780 measurements for each 13 min (conventional) tow were recorded. These are averaged to yield the mean volume concentration in each size range, and then summed to give the total mean volume concentration.

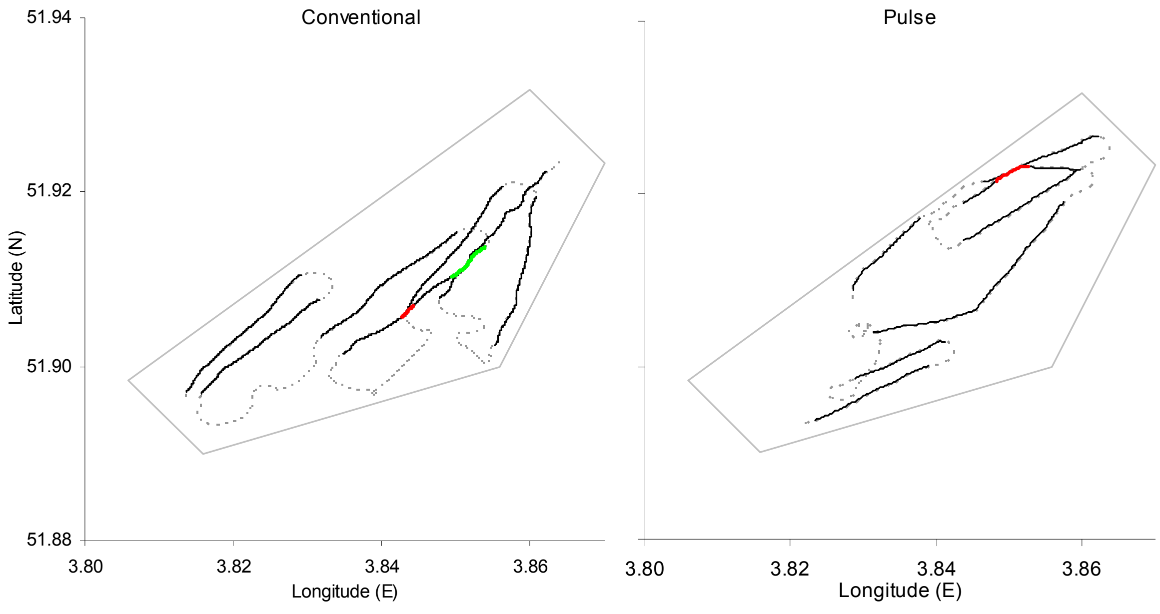

Figure 14: GPS tracks for the conventional beam and pulse beam trawl during re-suspension work (red indicates crossover of tracks and data removed from analysis, green indicates crossover of control track so not removed, dashed indicates between hauls).

The background water clarity was measured during the control tows prior to the pulse and conventional beam trawl tows (Figure 15). The mean total volume concentration was 5.2 µl/l and 20.3 µl/l before the pulse and conventional beam tows respectively. The elevated concentrations observed in the conventional control might be a result of the intensive sediment dredging and fishing activities conducted in the neighbouring BENTHIS site over the two previous days.

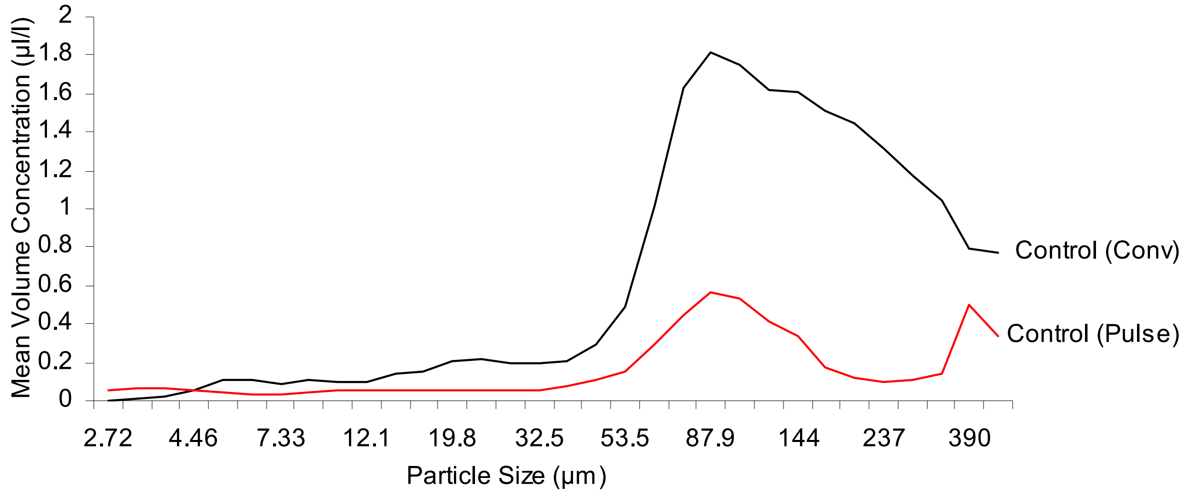

Figure 15: Particle size distributions of the control samples prior to each set of beam trawl tows

Each beam trawl was sampled at 25, 45 and 65m behind the beam by two tows in opposite directions, with and against the tide. Both mean volume concentrations were added together for each distance and the background concentrations deducted to give the true concentration of sediment mobilised at distance by each beam trawl type (Figure 16, Figure 17, Figure 18). Figure 16 and Figure 18 show how the sediment concentrations decrease with distance from the beam trawls. Figure 17 and Figure 18 indicate the pulse and conventional beam trawls mobilise similar quantities of sediment, but the pulse trawl had higher values for more size bins and the total concentrations at 25 and 45m behind the beam.

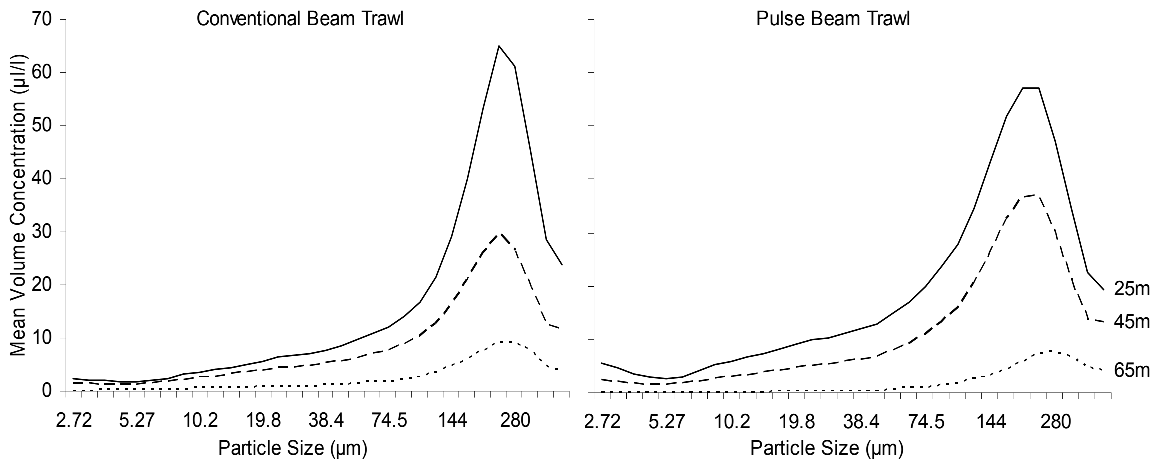

Figure 16: Particle size distributions within sediment plumes at different distances behind the beam.

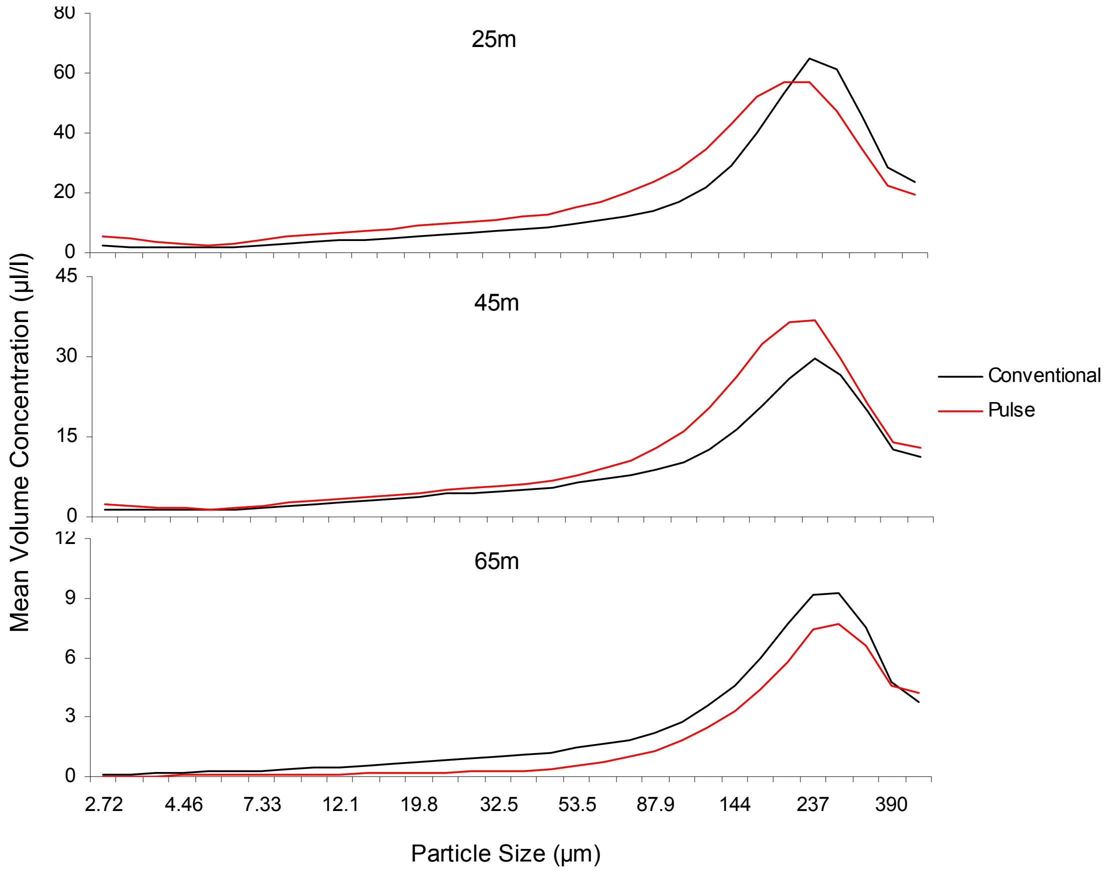

Figure 17: Particle size distributions within sediment plumes at different distances behind the

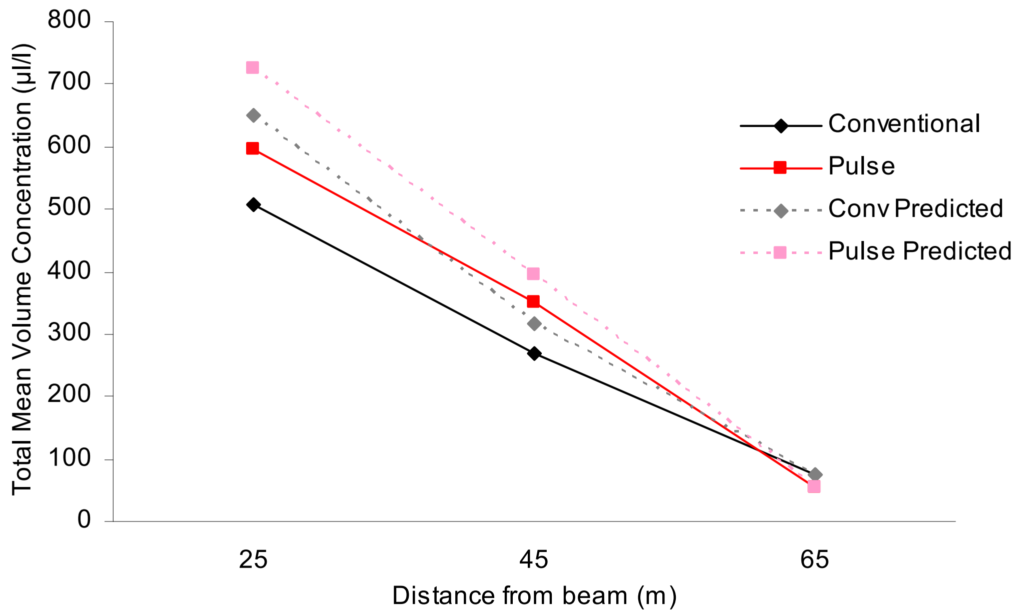

Figure 18: The total mean volume concentration within sediment plumes at different distances behind the beam (dashed lines are predicted by assuming obscured LISST records have a total volume concentration of 780.26 µl/l).

There were instances during the 25 and 45m tows of both gears when the laser beam was totally absorbed or deflected and nothing was received by the LISST 100x detector (laser transmission of zero) (Table 9). This could be a result of the sediment concentration being too high, or larger objects such as shells or brittle stars blocking the laser. When the laser transmission is zero the corresponding particle concentration values are recorded as zero µl/l. These entries were excluded from the calculations of the mean and total mean volume concentrations. However, if the laser was obscured as a result of high sediment loads then the mean and total mean volume concentrations will be underestimated. Figure 19 shows that the LISST 100x is unable to measure particle concentrations below a laser transmission value of ~0.08. Using the exponential regression line fitted it is possible to calculate that at 0.08 laser transmission the total volume concentration will be (approximately) 780.26 µl/l. If this concentration is entered in the obscured records then predicted values for total mean volume concentration can be obtained (Figure 18), these values may still underestimate the concentration, but are potentially more realistic. The pulse beam trawl still mobilises more sediment at 25 and 45m, but the difference between gears is slightly reduced. If re-suspension experiments are conducted in this area in the future, a reducer optic should be fitted to the LISST 100x. This limits the water volume sampled by 80 or 90% so enables higher concentrations to be measured.

Table 9: Summary of LISST measurements.

Beam Trawl	Distance	Records	Used	Obscured	
Conventional	25	1536	599	937	(61.0%)
	45	1442	1295	147	(10.2%)
	65	1456	1456	0	(0.0%)
Pulse	25	992	281	711	(71.7%)
	45	1446	1287	159	(11.0%)
	65	901	901	0	(0.0%)

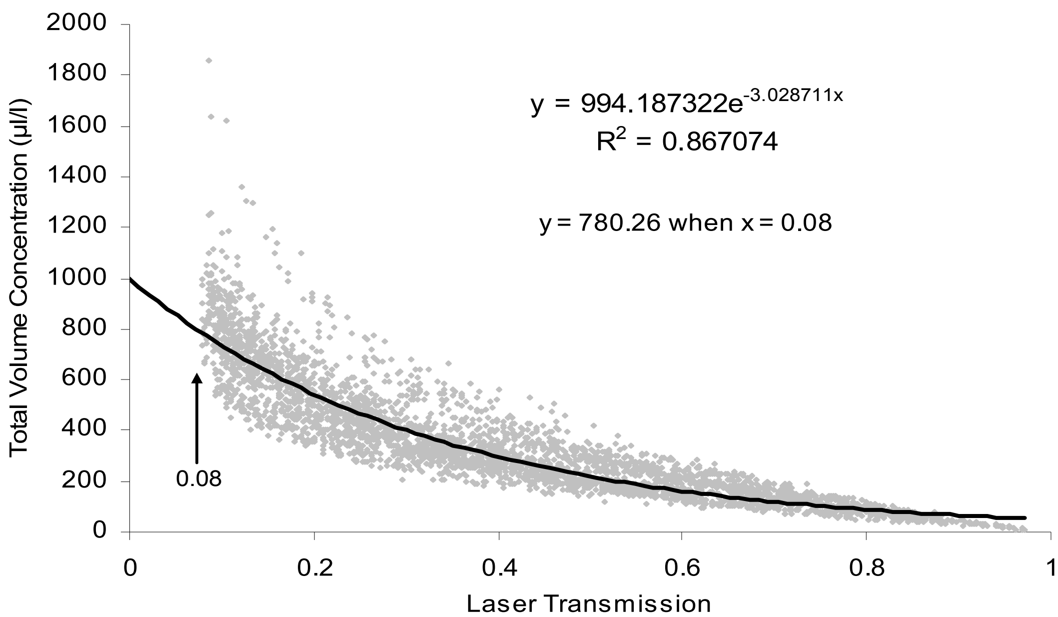

Figure 19: LISST 100x data regression showing the cut off in laser transmission as total volume concentration increases (values do not have background concentrations deducted).

The data from the dissolved oxygen sensor and the dual conductivity and temperature sensor were isolated to the same time periods used for the LISST 100x. The temperature and conductivity (converted to salinity) values remained relatively constant throughout each of the days sampling (Table 10). The mean temperature and salinity values were used in RBR's Ruskin software to fine tune the calibration file used to calculate the dissolved oxygen concentrations and saturation values (
Figure **20**). The background levels of oxygen in the pulse control tow was 0.42 ml/l or 8.81% lower than during the conventional control. This significantly exceeds the reduction in dissolved oxygen caused by the beam trawls (Figure 21). Both the pulse and conventional beam trawls reduction in dissolved oxygen are similar, and appear to revert back towards the control levels quickly.

Table 10: Mean temperature and salinity values recorded during the re-suspension tows.

Beam Trawl	Temperature (^{o}C)	St.Dev	Salinity (PSU)	St.Dev.
Conventional	13.29	0.03	29.48	0.11
Pulse	12.41	0.03	29.38	0.12

The dissolved oxygen saturation values during the conventional beam trawl sampling are in excess of 100% (supersaturated). The weather over the two days prior to the conventional sampling (and post pulse sampling) was strong sunshine and virtually no wind. Under these conditions phytoplankton could generate high levels of pure oxygen, yet the calm water surface would limit the equalisation of oxygen with the atmosphere, thus create the supersaturated conditions. These levels are also comparable with values obtained in the area by Hoppema (1991).

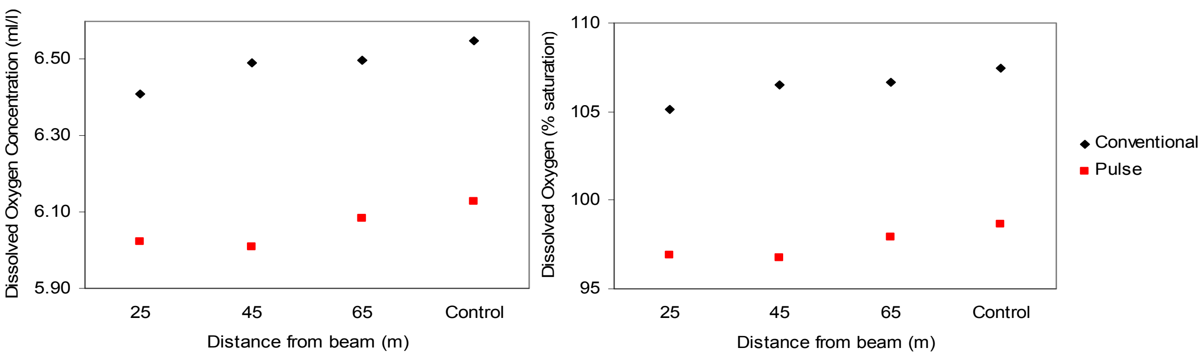

Figure 20: The dissolved oxygen concentration and saturation within the sediment plumes at different distances behind the beam.

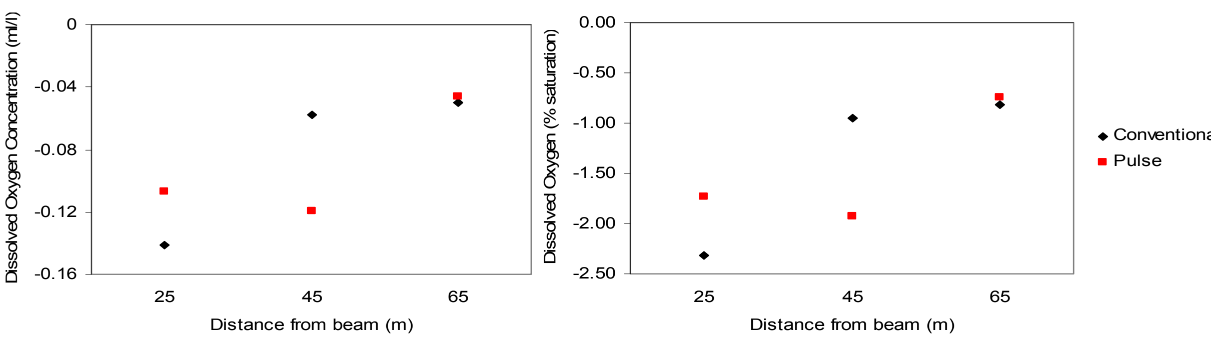

Figure 21: The reduction in dissolved oxygen concentration and saturation within the sediment plumes at different distances behind the beam.

4. Discussion and conclusions

This study contributes to our understanding of the effects of physical disturbance from beam trawl fishing. Benthic biological communities often experience rapid and often profound changes as a consequence of burial and exhumation by sediments (Kaiser et al. 2006). Physical disturbance, both of human and natural origin, is a driving force effecting diversity of benthic communities (Storlazzi et al., 2013). Moderate levels of disturbance coincide with maximum biodiversity (intermediate disturbance hypothesis, Harris & Hughes, 2012; Polet & Depestele, 2010). However, the surplus of human disturbance brings changes in natural occurring diversity levels, and moreover, human disturbance is inherently different from natural disturbance (Schratzberger et al., 2009). Fishing disturbance might or might not cause negative impacts depending on the physical nature and the dynamics of the environment (Sciberras et al., 2013). Diesing et al. (2013) found a strong relationship between biological zones and fishing disturbance.

4.1. Physical impacts

A large part of beam trawl fishing effort takes place in shallow circalittoral habitats, which can be subjected to disturbance above background levels of natural disturbance. In this study, trawl marks indicate that disturbance is obvious directly after trawling as well as five days after trawling, despite natural sediment resuspension which was caused by currents and high waves (up to 2.5m) which occurred during one day in the 5 day period. However, the extent of physical disturbance varies along fishing intensity gradients and gears, as examined through the penetration of beam trawls in the sediment.

A single passage of a beam trawl revealed that penetration depths were less profound than multiple passages. However, caution should be paid when extrapolating these results, as the selection of observations was inherently different for s-tickler and m-tickler sites due to the nature of the fishing intensity. A single passage allowed for a systematic selection of positions for measuring penetration depths, while multiple passages required a more delicate selection of trawl marks. A random selection procedure was not possible, and hence only clear trawl tracks were selected for measurements, leading to a potential overestimation of the penetration depths. However, overall penetration depths were within the range of earlier trials, i.e. within 1 to 8cm (Fonteyne, 2000; Polet & Depestele, 2010). Differences in seabed bathymetrical features is not expected to have influenced differences in penetration depths, although the northern part of the s-tickler site was clearly marked by ripples, while the m-tickler site contained some small dunes.

Differences in gear components, notably the replacement of tickler chains by pulse electrodes, also led to differences in physical disturbance, specifically in penetration depths. Tickler chains are used to stimulate fish into the path of the gear and can be responsible for 30% of the resistance of a beam trawl. The pulse gears replace the tickler chains and the associated physical stimulus with electrodes and an electrical stimulus (Soetaert et al., 2013) leading to greatly reduced fuel costs (Van Marlen et al., 2011) and, it is thought, benthic impacts (Soetaert et al., 2013). This study confirms the stipulations in Soetaert et al. (2013) that the higher the cumulative probability of penetration depths, the more distinguished the differences between the gears are. In other words, both gears penetrate the seabed to some extent, but the range of penetration depths of the tickler chain is larger and deeper penetrations depths are more likley to occur than with the pulse.

Pulse trawls penetrate less deep into the seafloor, and although experimental conditions differed, our estimates are conservative based on three arguments:

(1) First, the specific configuration of the tested pulse trawl weighed more (2500kg) than the tickler chain trawl (1065kg). Notwithstanding the higher weight of the pulse trawl, a lower penetration depth was detected. Moreover, the tested pulse trawl (Delmeco type) is the heavier of the two main pulse trawl types. The HFK PulseWing replaces trawl shoes with a wing and central runner (see Soetaert et al., 2013 for details). The tested tickler chain beam trawl was similar to the ones typically utilized in the northern Netherlands. Tickler chain beam trawls in the southern Netherlands are generally heavier. The trawl tracks which were present prior to experimental fishing were therefore measured. These tracks are likely from eurocutters of the southern Netherlands, given their width of 4m and the limited distance between the trawl tracks (Figure 5; Figure 6). Incidental measurements of the tracks highlighted a deeper penetration depth than those of experimental tickler chain beam trawling. Differences were in an order of magnitude of about 1-2 cm. This might indicate that reduction in penetration depths by replacing tickler chain trawls with electrodes can be even more pronounced in the southern Netherlands or with the use of the HFK PulseWing. These findings partly confirm the hypotheses by Polet & Depestele (2010), i.e. that the impact of one beam trawl is not the other. Differences between specific beam trawls might thus lead to differences in physical disturbance, depending on the sediment characteristics and dynamic conditions of the fishing grounds.

(2) The second indication of conservative estimates is timing of the experiments. Tickler chain and pulse trawling would ideally be conducted at the same time, but logistical constraints prevented simultaneous experimental trials. More severe weather conditions during pulse trawling could have led to a deeper penetration of the pulse trawl in the sediment due to increased up and downward movement of the vessel and hence gear. As the gear may be lifted off the seabed due to the swell, it is likely to hit the ground heavier with the downward movement of the vessel. However, even if this was the case, penetration depth of the pulse trawl is shallower.

The weather conditions however introduced a potential confounding factor, as trawl tracks from pulse trawling could have filled up as a consequence increased sediment transport. Wind speed and subsequent wave height was high after pulse trawling (up to 7 bft). Sediment transport is based on the bed form and the bed shear stress exerted by waves and currents. The influence of bed form and currents is similar for both tickler chain and pulse trawling, but wave heights were up to 2.5m following pulse trawling, while a maximum wave height of 1m followed tickler chain beam trawling (Figure 3). This difference of 1.5m wave height might have induced increased sediment transport and filling up of the pulse trawl tracks. Penetration depths of pulse trawling could only have been reduced on the condition that erosion of the sediment was higher after pulse than tickler chain beam trawling. We argue that this was not the case. Structural erosion of cohesive, muddy sediments can occur when waves induce a hydrodynamic shear stress that exceeds critical values in the range of 4 – 10 N/m^2 (Diesing et al., 2013), but the maximum shear stress of the experimental area does not exceed 4.5 N/m^2 and occurs on average only once per year, based on measurements from 1979-2002 (Kroon & Van Leeuwen, 2009). Mean wave heights are highest during winter time and reach heights up to 3m (Poot, 2006). This renders it very unlikely that the wave height of 2.5m during the experimental trials considerably filled up the trawl marks to a larger extent than under conditions of 1m wave heights. The potential effect of sediment transport from shallower areas of the Voordelta is unknown.

Additionally, one should note that in general the experimental area has <20% probability that the seabed shear stress exceeds 1.5 N/m^2, based on both tidal and wave currents (Heinis & Deerenberg, 2011). As tidal effects were present for both gears, the probability of a confounding effect of a wave height difference of 1.5m diminishes even more. Although a differential difference between the weather

conditions is very unlikely, seabed current and wave induced shear stress did nevertheless influence fading of the trawl tracks.

4.2. Biological impacts

Despite the expected impacts of the trawl gear on direct mortality of benthic fauna, the benthic sledge data showed no clear response to either traditional beam trawling or pulse trawling. A number of reasons can be considered as to why no effect was detected:

(1) It is evident that the highest densities of benthic fauna detected in the sledge data are categorised as resistant species (6 species, based on the benthic traits analysis, Bolam et al. 2013), with lower densities attributed to the intermediate group (7 species) and even lower in the susceptible. group (3 species). This indicates that the area was mainly occupied by species that are more resistant to trawling prior to the experiment, making it more difficult to detect mortality effects due to trawling. The experiment that is planned for June 2014 is expected to sample a muddier area with higher biodiversity and more susceptible species.

(2) Another factor to consider is the depth distribution of the organisms. If infauna is found mainly in deeper layers, out of reach of the tickler and/or pulse trawl, then mortality effects can be expected to be low. The boxcore data (available by summer 2014) will give some information on this aspect.

(3) Although a reduction in densities was found between T0 and T1, no treatment effect could be detected, i.e. the densities also decline in the reference area. A reason for this could be an effect of the sampling gear (benthic sledge) which may have caused some mortality in the reference area. However, it is expected that the effect of sampling gear is negligible as sampling was carried out in different directions in T0 and T1 to avoid any substantial overlap of tracks.

(4) Mortality effects may be confounded by mobility and decolonisation of the trawl tracks by scavengers moving in.

(5) High spatial variability and patchiness in the benthic communities reduce the power of the statistical analysis to detect any significant changes.

4.3. Summary of conclusions

Differences in the physical impacts of the two gear types are evident, with tickler chains penetrating the seabed to a larger extent then the pulse gear. Note also that due to the gears used and the weather conditions encountered, the estimates of these differences may be conservative.
In terms of sediment resuspension, no clear differences are found between the gears.

Biological impacts were more difficult to ascertain. It is expected that the coarse bottom and dynamic nature of the experimental area could make it a less vulnerable habitat to trawling. A large proportion of the biomass encountered was described as resistant to trawling to start with. Trawling impacts are likely to be context-dependant with habitats where species are adapted to a more dynamic nature being less vulnerable than stable habitats where natural disturbances are very low or infrequent.

In order to address the habitat dependant nature of the trawling impact, a second BENTHIS campaign was carried out in June 2014 on the muddy grounds of the Frisian Front. Results are expected by 2015.

Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

Rapport C098/14
Project Number: 4308101058 BO20 13 Benthos effecten puls

The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of IMARES.

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Appendix A. Methods of additional programmes

Additional data was collected which is not yet available for the report. The methods are listed below. Results will be available in the final BENTHIS report (2015).

Appendix A1 - Methods Boxcore

Boxcore samples were obtained for two separate objectives: 1) to determine the sediment characteristics (particle size, porosity, chlorophyll a, total organic carbon) and 2) to determine the vertical distribution of infauna. A circular boxcore (ø = 30cm) was deployed within all three experimental (reference area, pulse area, tickler area (multiple passages), see Table 1) areas during the T1. It was not possible to collect any T0 samples due to bad weather in the first sampling week.

The boxcore was deployed 5 times within each area. Only cores which remained intact were used for further processing. Two sub-cores (ø = 5cm) were taken from each core for sediment characteristics. Both subcores were sliced at 0.5 cm (top 1 cm) and 1 cm (1 to 10 cm depth) intervals and stored in the dark, frozen at -20°C. One of the sub-cores is subsequently used for particle size analysis (PSA) and TOC, the other for porosity and chlorophyll *a*. Six sub-cores (ø = 5cm) were taken from each core and sliced at 0-5cm, 5-10 cm and >10cm. All slices from the same vertical layer were added together for one infaunal sample. The slices were sieved over a 1mm mesh with all remaining on the sieve being stored in 7% formaldehyde/seawater solution. The sediment leftover from the core after the sub-cores were taken was also processed as all infaunal samples to give a complete view of total fauna from the original boxcore.

The infauna data is now available awaiting further analysis. The sediment characteristics data will become available later in the year. Samples are currently stored at ILVO awaiting analysis.

Appendix A2 - Methods Laser profile imaging of the sediment disturbance by the conventional beam trawl

The laser profile work was conducted onboard the RV ISIS on the morning of the 19th June. The laser profiling procedure is outlined in O'Neill et al (2009). During previous experiments this system was deployed at fixed locations on the seabed by SCUBA divers. This, however, was not possible in this experiment. Therefore some alterations were needed. The frame housing the synchronised laser and camera was mounted within a modified Nephrops TV sledge. The digital stills camera was replaced with a GoPro Hero 3 Black video camera in an underwater housing; and set to NTSC, 1280x720 pixels, Narrow FOV and 120 frames per second. The high frame rate helps compensate for the movement of the sledge when sampling and result in relatively clear images. The sledge was also fitted with a standard definition underwater video camera and lighting (used in the re-suspension work) which was positioned to give a higher and wider perspective to help locate trawl tracks, and illuminate the seabed to allow features (shells, ect) to be used to quickly determine the field of view.

The laser profile imaging work was conducted within a dedicated area that was closed off to other activities (Figure 1). This was to prevent contamination to both the tracks from the beam trawls and to the surrounding (control) area. The conventional beam trawl tracks were made by towing the paired gear down the centre of the site, at 4kn for approximately 9min. The port beam was disconnected from the warp and the sledge with laser profiling equipment attached directly (Figure 7a). The sledge was then deployed and made five perpendicular passes over the trawl path (Figure and Appendix C. Supporting table for the sediment resuspension methods

Table). The vessel towed the sledge as slow as possible but had to maintain manoeuvrability. When going partially into the tide it could tow at approx 1.4kn, yet with the tide behind it had to tow at approx 2kn. Passes 1 and 2 were towed with 64m of warp, this was extended to 94m for tows 3 to 5 as the angle of the warp from the outrigger appeared to be too steep. Once complete the sledge was hauled aboard and the video footage from both cameras was downloaded.

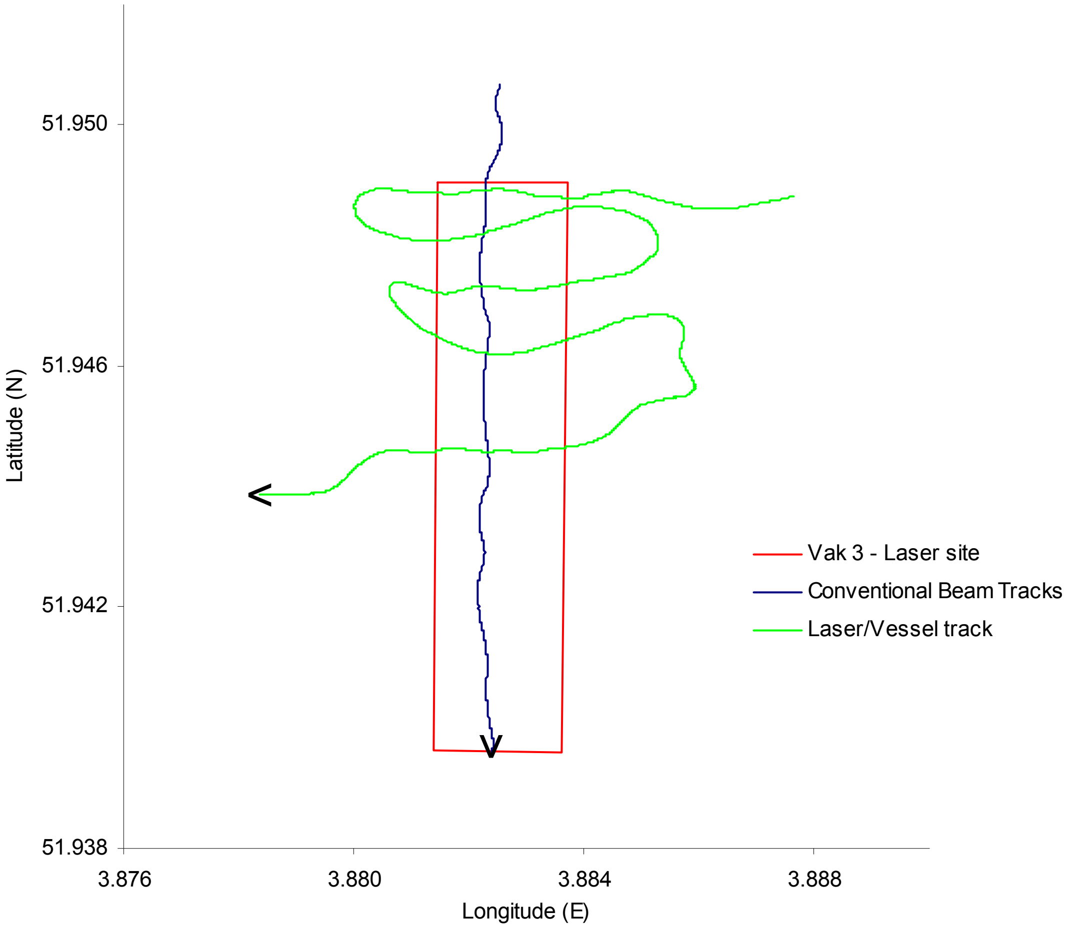


Figure A2-1: GPS track of RV ISIS while conducting both the conventional beam trawl disturbance and the laser profiling tows.

Unfortunately, however, it was discovered the background lighting had failed, this resulted in very dark video footage from both the GoPro camera (laser profiling) and the general overview camera. The laser line footage reveals some small sediment plumes periodically obscuring the laser line. Indicating the towing bridle and warp might have been dragging on the seabed creating the plumes and disturbing the seabed. The sledge also appears to drift slightly sideways during the passes relative to the seabed. This might be due to the vessel turning too soon or sharply after crossing the beam tracks.

Due to the uncertainty over the profiling data being compromised by additional disturbance, coupled with the sideways movement of the sledge, and the very dark video footage; the laser profile images will not be analysed so no results were obtained for this work.

Appendix A3 – Methods Sediment profile Imaging

A sediment profile imaging (SPI) camera (for general principles, see Rhoads & Cande 1971, Figure A3-1) was used to obtain *in situ* images (15 × 21.5 cm = 322.50 cm2) of the sediment profile. The imaging module is based around a Nikon D100 camera (2000 × 3000 pixels = 6 mega pixels, effective resolution = 75 × 75 µm per pixel), set to an exposure of 1/60 and a film speed equivalent to ISO 400. A surface video camera (specifications) was attached to the SPI frame to record surface images of the seabed, as well as to track the camera real-time and check the expected quality of each deployment.

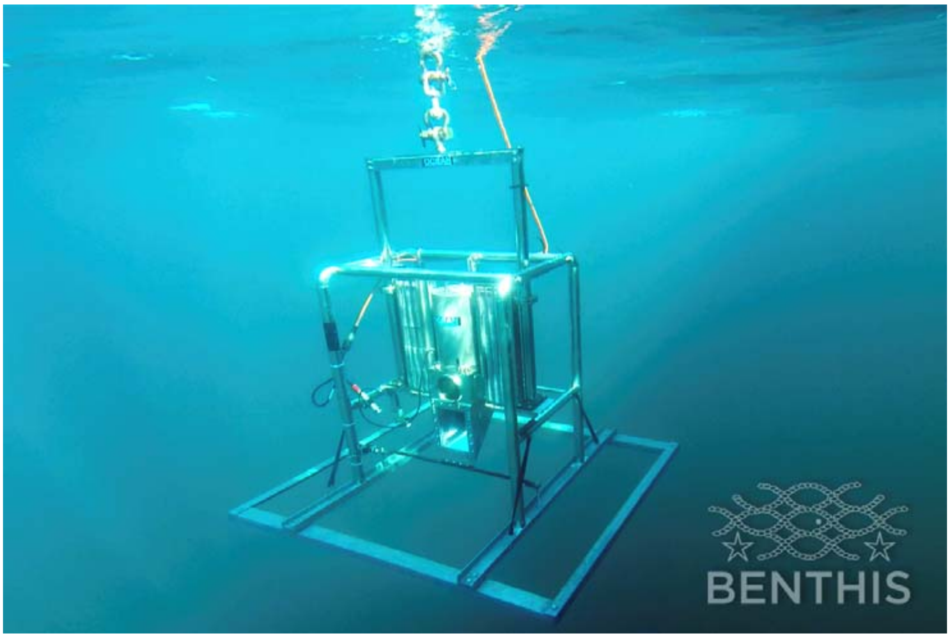


Figure A3-1: The Sediment Profile Imaging camera (SPI) sinking through the water column to the seabed. Foto: Oscar Bos (IMARES).

Figure A3-2: The Sediment Profile Imaging camera (SPI) penetrating the seabed to take a profile image. The surface camera takes an image of the sediment surface (Foto from June 2014 campaign).

The camera was deployed in each experimental area before and after the trawling impact (T0, T1). Due to bad weather at the start of the fieldwork, it was only possible to get images in the reference area during the T1. Within each area and at each time-point (T0 and T1), the camera was dropped at 10 locations and two photos (~5m apart) were taken (n = 20 per area per time). If the surface video indicated there may be a problem with the deployment (i.e. the camera was pulled during its time on the seabed), the drop was repeated. Due to weather issues the T0 images of the beam trawl area were spread over two separate days, 14.6. and 17.6.

All image analysis was performed using a custom-made, semi-automated macro (modified from Solan et al. 2004) within ImageJ (ver. 1.38), a Javabased public domain program developed at the US National Institutes of Health (available at http://rsb.info.nih.gov/ij/index.html). Because colour is represented as a 3-dimensional number (red, green and blue [RGB] intensity), all images were converted to grey scale. Each pixel within an RGB layer is then converted into an 8-bit grey scale (i.e. 256 shades) and averaged with equal weighting to provide a pixel specific grey scale intensity value. The sediment water interface was manually traced on each image using the segmented line tool to define the upper limit of the region of interest. All pixel columns were then vertically realigned in relation to the segmented line to flatten the sediment-water interface. Grey scale intensity values of each pixel across each pixel horizon were summed and the mean grey scale intensity calculated for each pixel row. The step-change in image intensity (reflecting a visual transition from red/brown to olive green/grey/black) was delineated using standard threshold analysis of 8-bit (greyscale) tagged image file format (TIFF) images. The upper limit of the region of interest was delineated by the sediment water interface, whilst the lower limit of the region of interest was determined by using the most appropriate threshold level that distinguished the oxidised sediment (higher reflectance) from the underlying reduced sediment (lower reflectance). The depth recognised by the step-change in grey scale intensity, hereinafter referred to as the mixing depth

derived from image analysis (MDI), is defined as the mean vertical distance of the sediment area that has grey scale intensities above this user-defined threshold value. Sediment underlying the MDI is hereinafter referred to as the underlying historic layer (UHL).

As software for improved image analysis is still being developed, the SPI results are not expected until 2014.

Appendix B. Supporting figure for the multibeam results

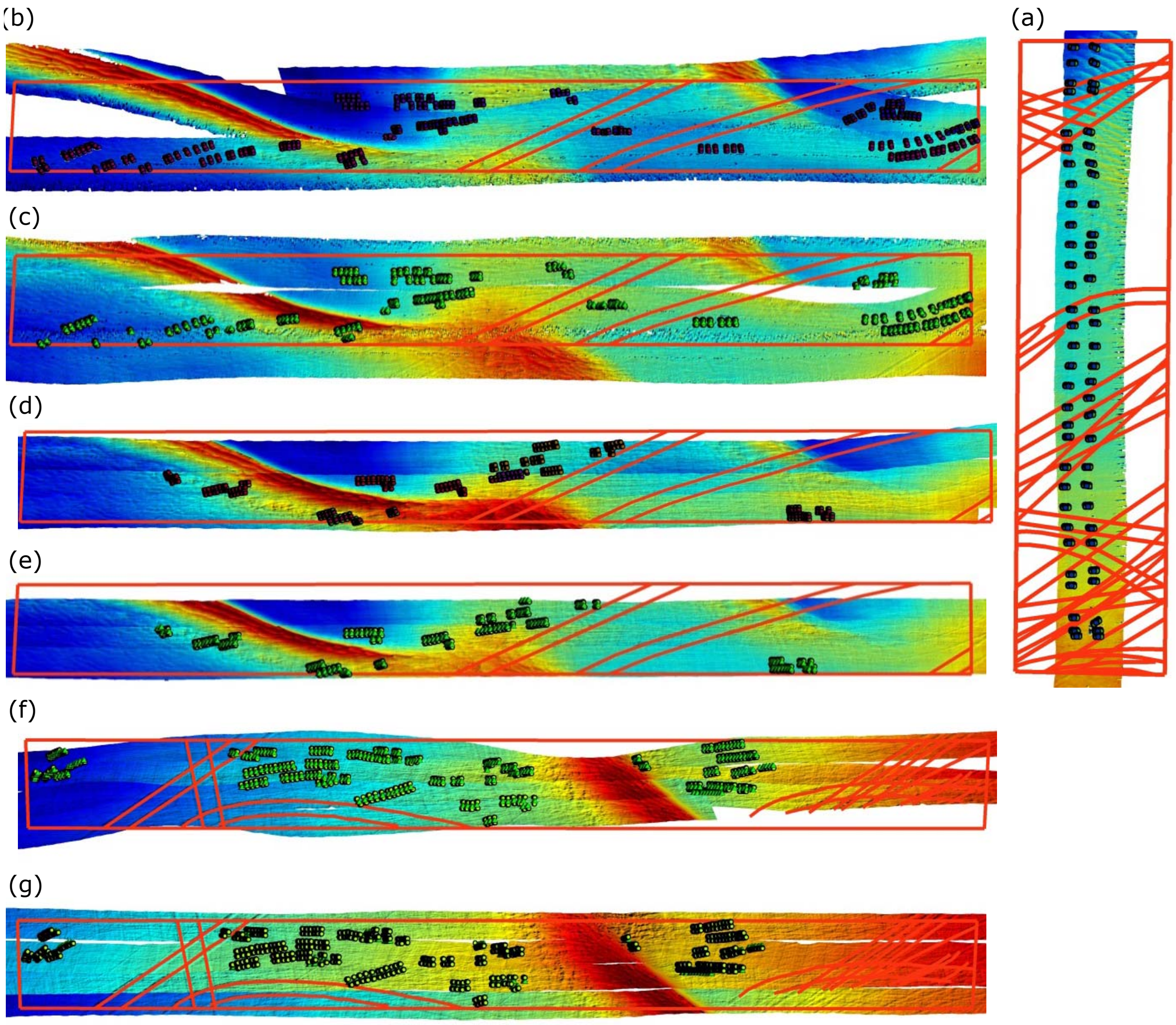


Figure B1: Localisation of trawl tracks was based on GPS positions of the fishing vessel and visual inspection of trawl marks. Trawl marks were equally spaced for the s-tickler site (a), but multiple passages did not allow following uniquely the GPS positions of the fishing vessel for the detection of trawl marks. A selection (non-random) of visible trawl marks was included for m-tickler site at 205 kHZ and <12h (b), at 205 kHz and <44h (c), at 320 kHZ and <12h (d), at 320 kHz and <44h (e), and for the pulse site at 320kHz and <52h (f) and <102h (g) after fishing. Depth positions at subsequent time intervals were equal, e.g. a-b, c-d and e-f, unless there were image aberrations.

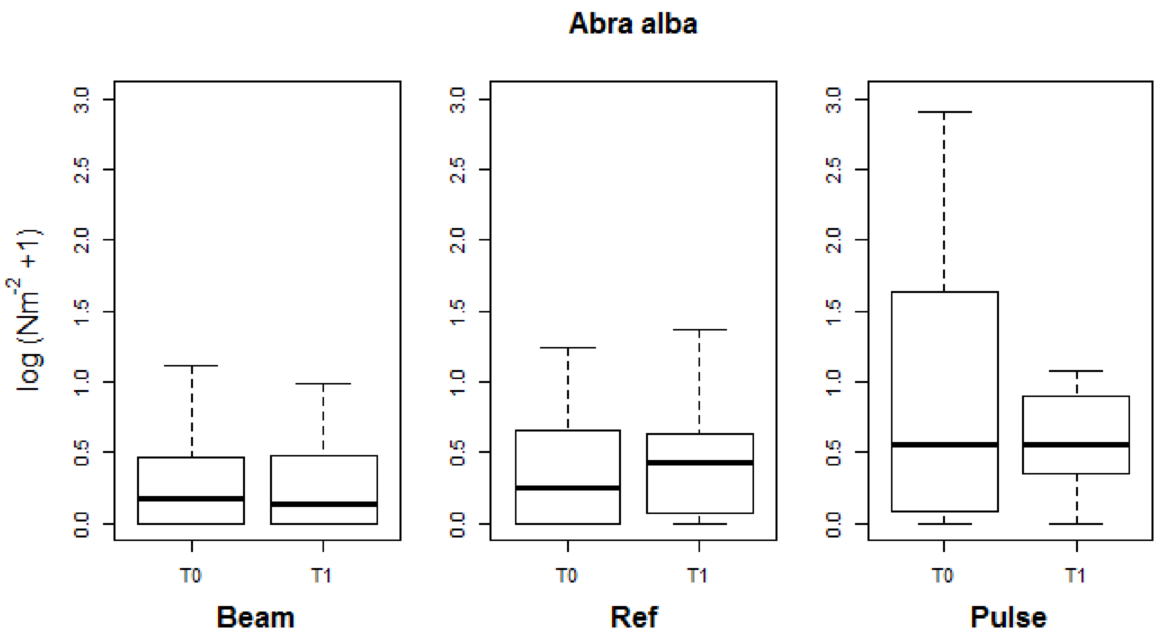
Appendix C. Supporting table for the sediment resuspension methods

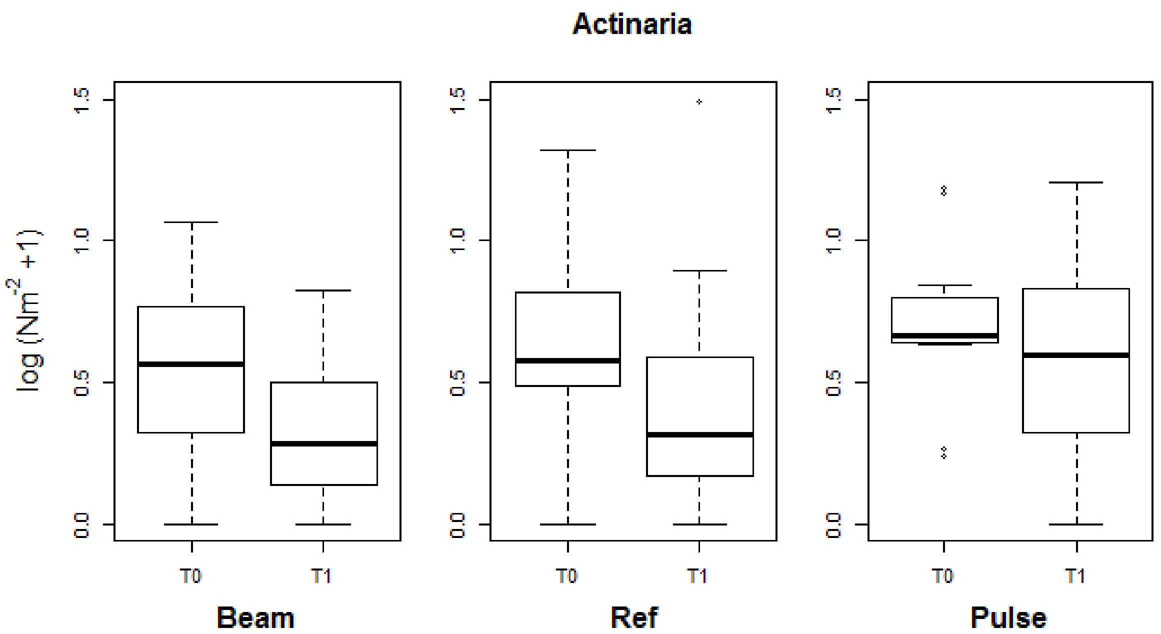
Table C1: Haul summary details (hauls 1-7 were pulse beam re-suspension, 14-20 for conventional beam re-suspension, and 8-13 for laser profile imagery).

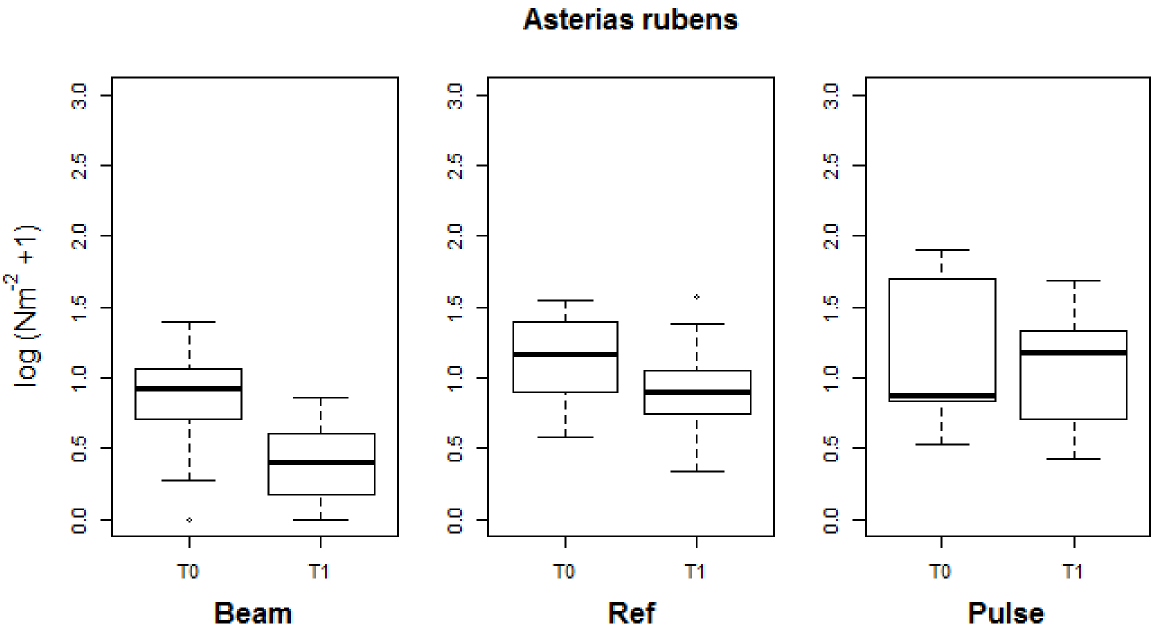
					Start			Finish			Duration				
Haul	Vessel	Date	Beam Trawl	Sledge	Time (UTC)	Lat	Long	Time (UTC)	Lat	Long	Min:Sec	SOG	Heading		Tide
1	SCH18	14/06/13	n/a	Control	08:21:00	51.9088	3.8287	08:32:00	51.9171	3.8377	11:00	3.4	50	NE	SW
2	SCH18	14/06/13	Pulse	25	09:00:00	51.9214	3.8465	09:10:00	51.9266	3.8622	10:00	4.0	55	NE	SW
3	SCH18	14/06/13	Pulse	25	09:15:00	51.9228	3.8593	09:26:00	51.9147	3.8438	11:00	4.1	228	SW	SW
4	SCH18	14/06/13	Pulse	45	09:44:00	51.9190	3.8437	09:55:00	51.9228	3.8598	11:00	3.8	51	NE	SW
5	SCH18	14/06/13	Pulse	45	09:59:00	51.9191	3.8575	10:20:00	51.9041	3.8315	21:00	4.1	230	SW	SW
6	SCH18	14/06/13	Pulse	65	10:53:00	51.8986	3.8288	11:03:00	51.9029	3.8411	10:00	3.2	56	NE	SW
7	SCH18	14/06/13	Pulse	65	11:07:00	51.9001	3.8389	11:17:00	51.8938	3.8233	10:00	4.2	237	SW	SW
8	ISIS	19/06/13	Conventional	n/a	08:35:49	51.9507	3.8825	08:44:58	51.9396	3.8824	09:09	4.4	181	S	SW
9	ISIS	19/06/13	n/a	Laser	09:42:55	51.9489	3.8823	09:45:35	51.9489	3.8803	02:40	1.7	269	W	SW
10	ISIS	19/06/13	n/a	Laser	09:49:01	51.9482	3.8822	09:51:50	51.9486	3.8847	02:49	2.0	74	E	SW
11	ISIS	19/06/13	n/a	Laser	09:58:32	51.9473	3.8822	10:01:48	51.9474	3.8807	03:16	1.1	275	W	SW
12	ISIS	19/06/13	n/a	Laser	10:04:27	51.9462	3.8823	10:07:54	51.9469	3.8854	03:27	2.1	72	E	SW
13	ISIS	19/06/13	n/a	Laser	10:16:29	51.9446	3.8823	10:19:30	51.9446	3.8807	03:01	1.3	279	W	SW
14	ISIS	19/06/13	n/a	Control	11:51:25	51.9223	3.8621	12:06:25	51.9079	3.8478	15:00	4.2	211	SW	SW
15	ISIS	19/06/13	Conventional	25	12:31:05	51.9024	3.8552	12:46:20	51.9195	3.8608	15:15	4.2	37	NE	SW
16	ISIS	19/06/13	Conventional	25	12:49:20	51.9207	3.8562	13:04:26	51.9062	3.8433	15:06	4.0	209	SW	SW
17	ISIS	19/06/13	Conventional	45	14:04:15	51.9015	3.8348	14:19:19	51.9137	3.8539	15:04	4.1	44	NE	NE
18	ISIS	19/06/13	Conventional	45	14:22:50	51.9154	3.8501	14:37:50	51.9034	3.8318	15:00	4.0	223	SW	NE
19	ISIS	19/06/13	Conventional	65	15:04:40	51.8969	3.8157	15:19:40	51.9077	3.8317	15:00	4.0	42	NE	NE
20	ISIS	19/06/13	Conventional	65	15:24:10	51.9106	3.8292	15:39:05	51.8971	3.8138	14:55	4.0	215	SW	NE

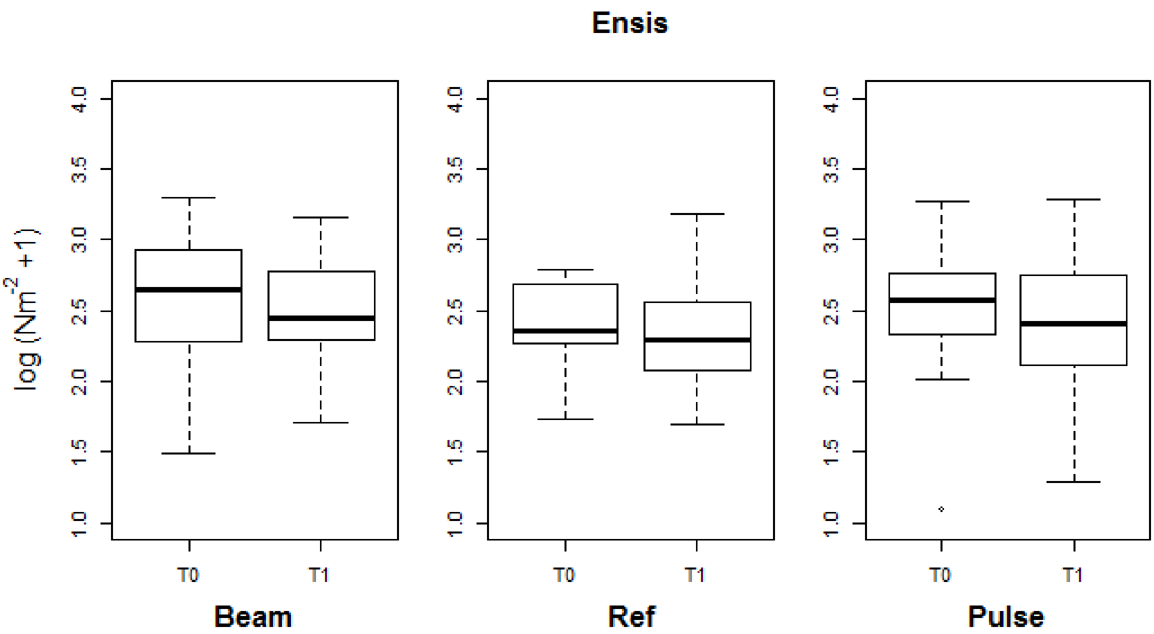
Appendix D. Supporting figures for the benthic sledge results

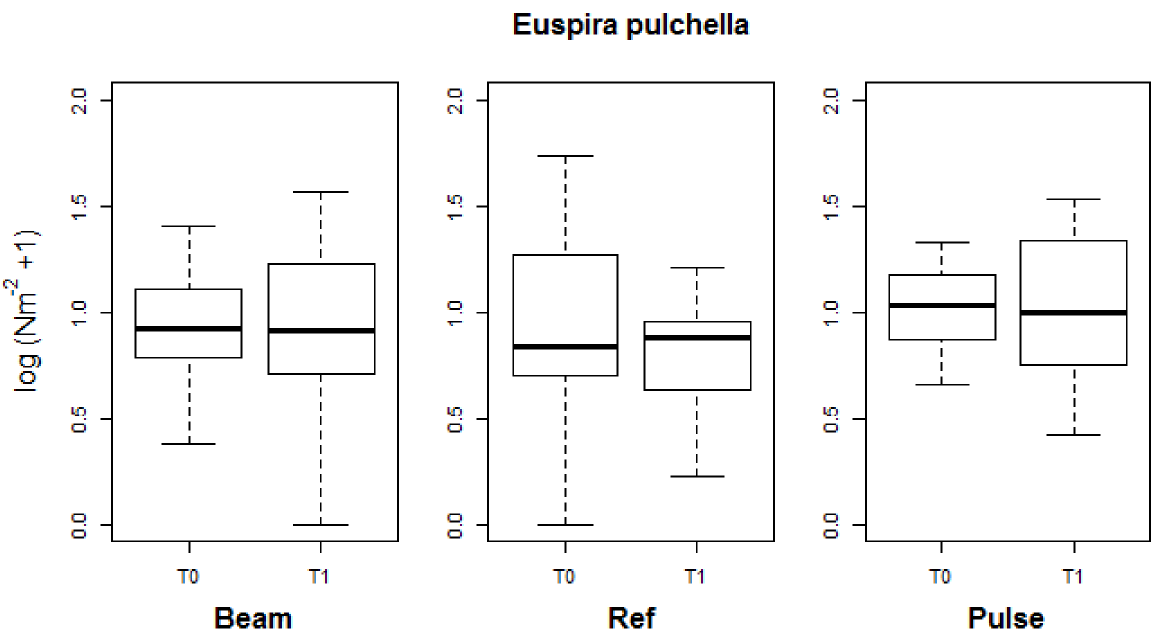
Figures D1-16: Boxplots of log-transformed summed densities of all individual species caught during the study in the three study areas, before (T0) and after (T1) experimental trawling.

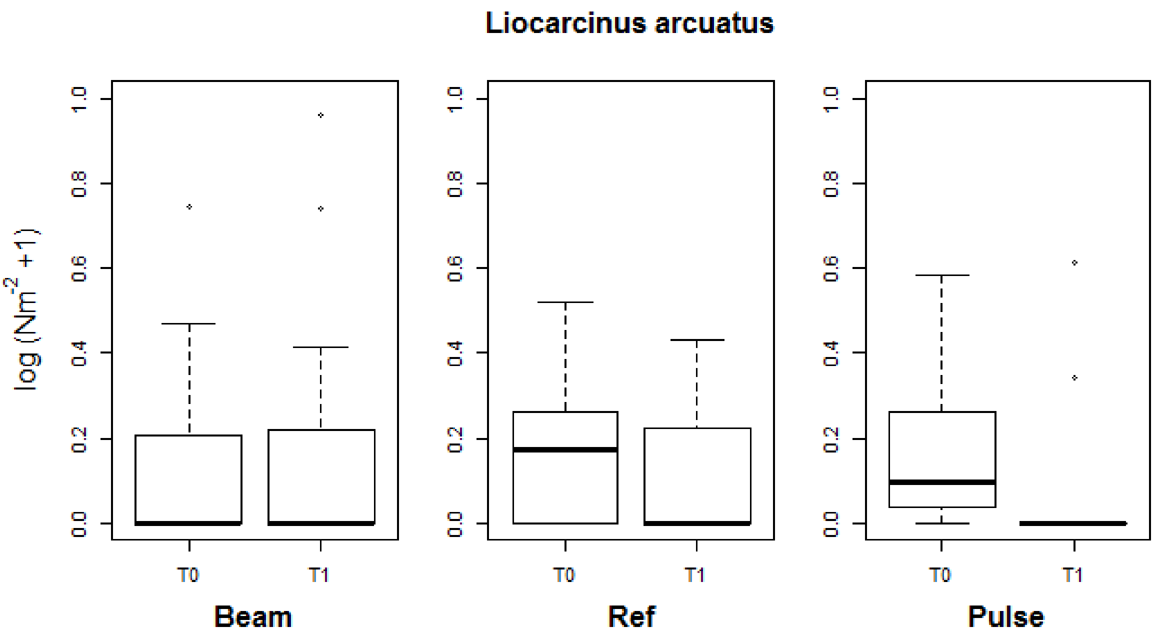


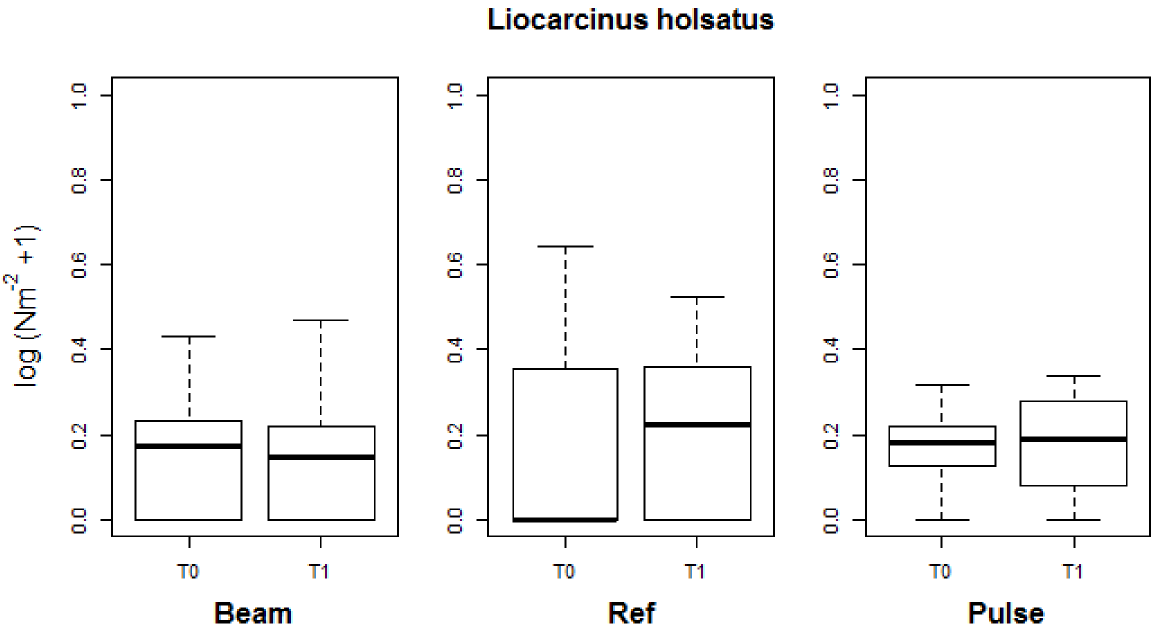


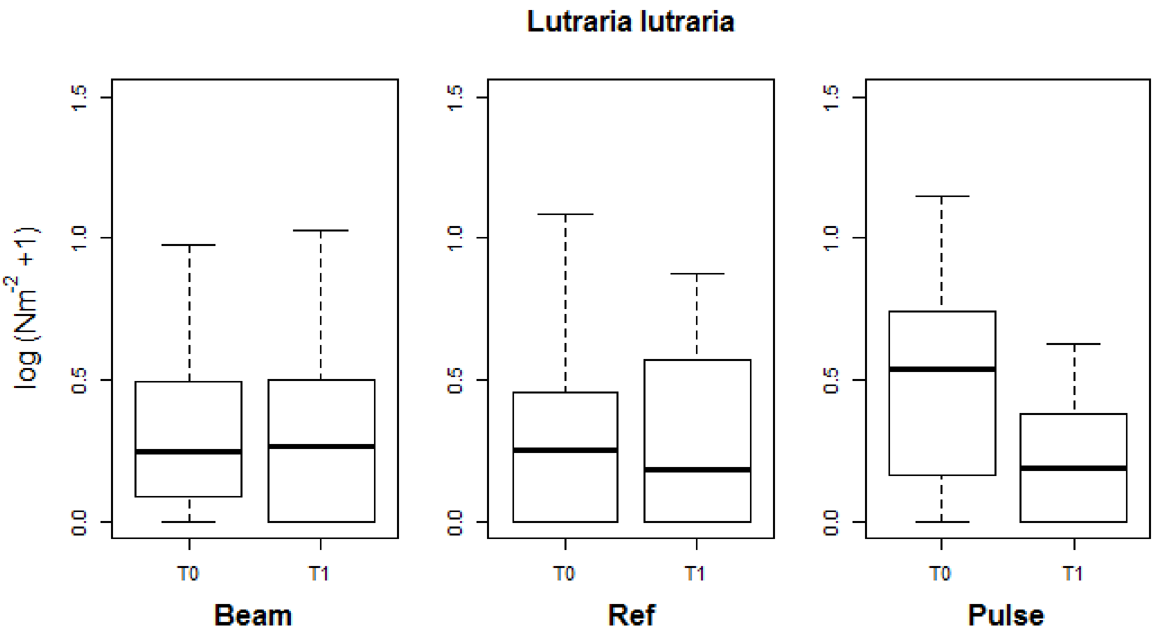

Asterias rubens
log (Nm^-2 +1)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
T0
T1
Beam
Ref
Pulse

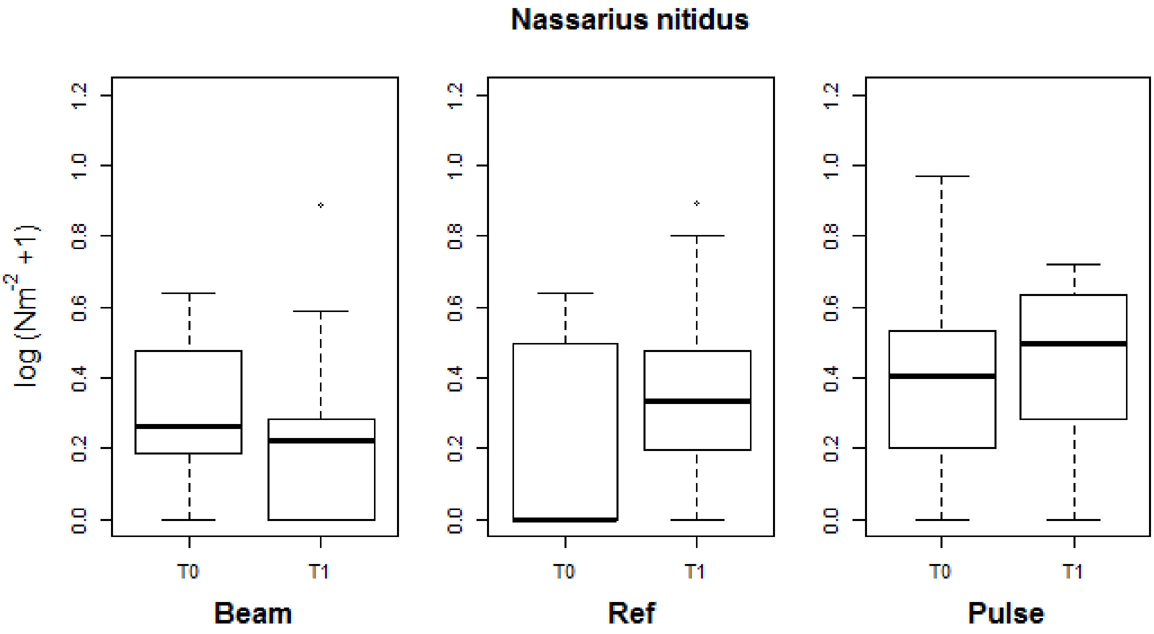

Ensis
log (Nm^-2 +1)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
T0
T1
Beam
Ref
Pulse

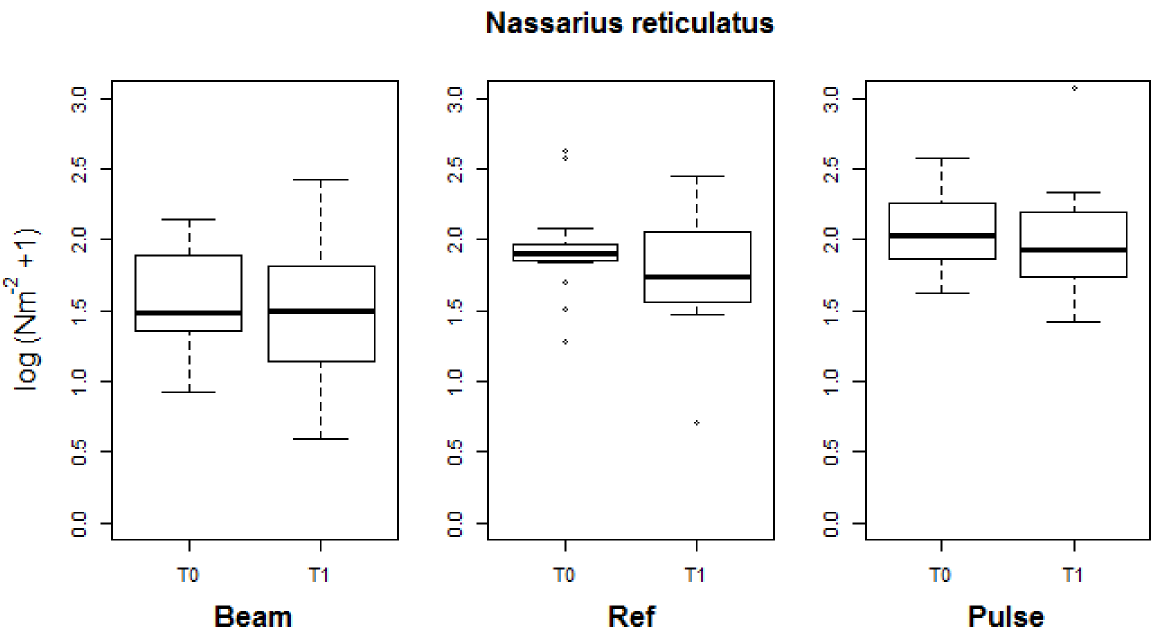

Euspira pulchella
log (Nm-2 +1)
0.0
0.5
1.0
1.5
2.0
T0
T1
Beam
Ref
Pulse

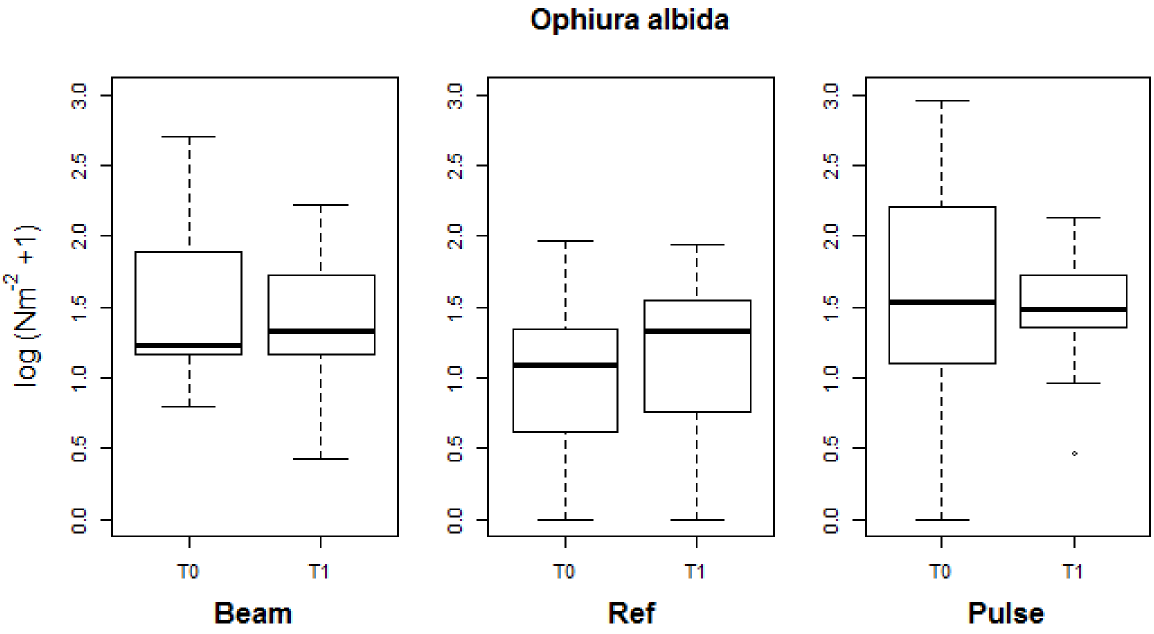

Liocarcinus arcuatus
log (Nm-2 +1)
0.0
0.2
0.4
0.6
0.8
1.0
T0
T1
Beam
Ref
Pulse

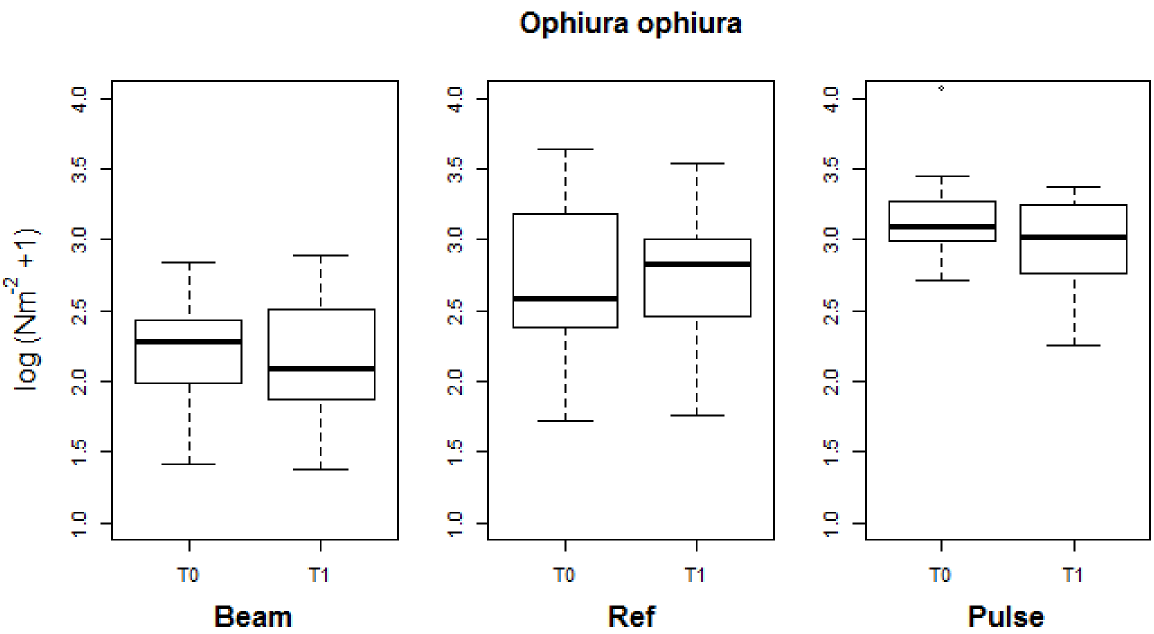

Liocarcinus holsatus
log (Nm-2 +1)
1.0
0.8
0.6
0.4
0.2
0.0
T0
T1
Beam
Ref
Pulse

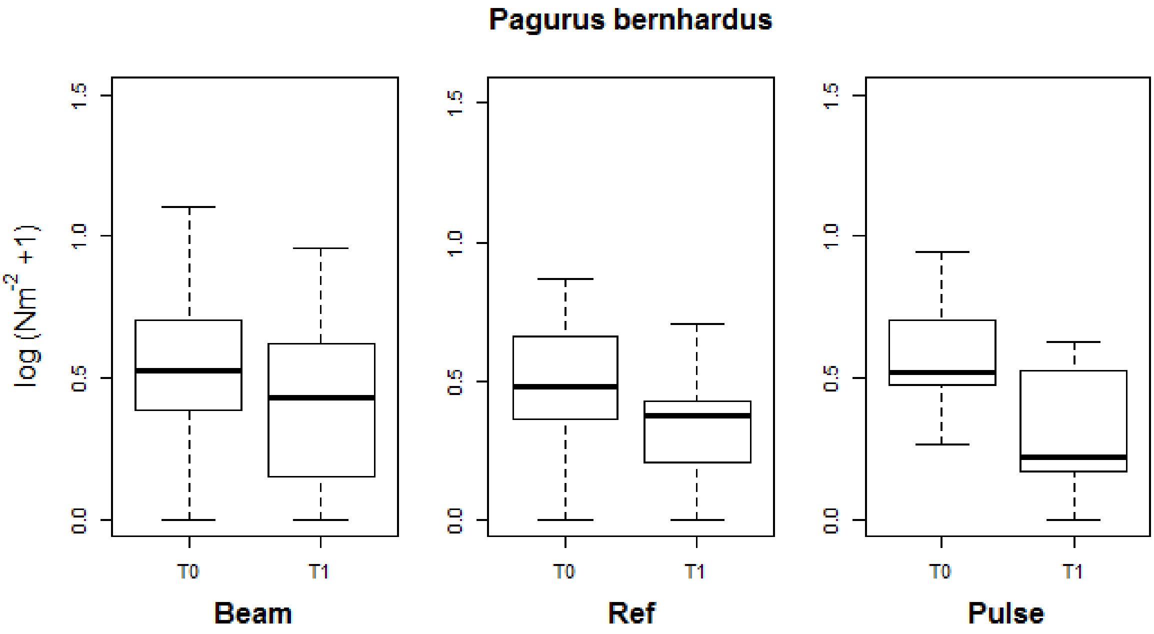

Lutraria lutraria
log (Nm-2 +1)
1.5
1.0
0.5
0.0
T0
T1
Beam
Ref
Pulse


Nassarius nitidus
log (Nm-2 +1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
T0
T1
Beam
Ref
Pulse

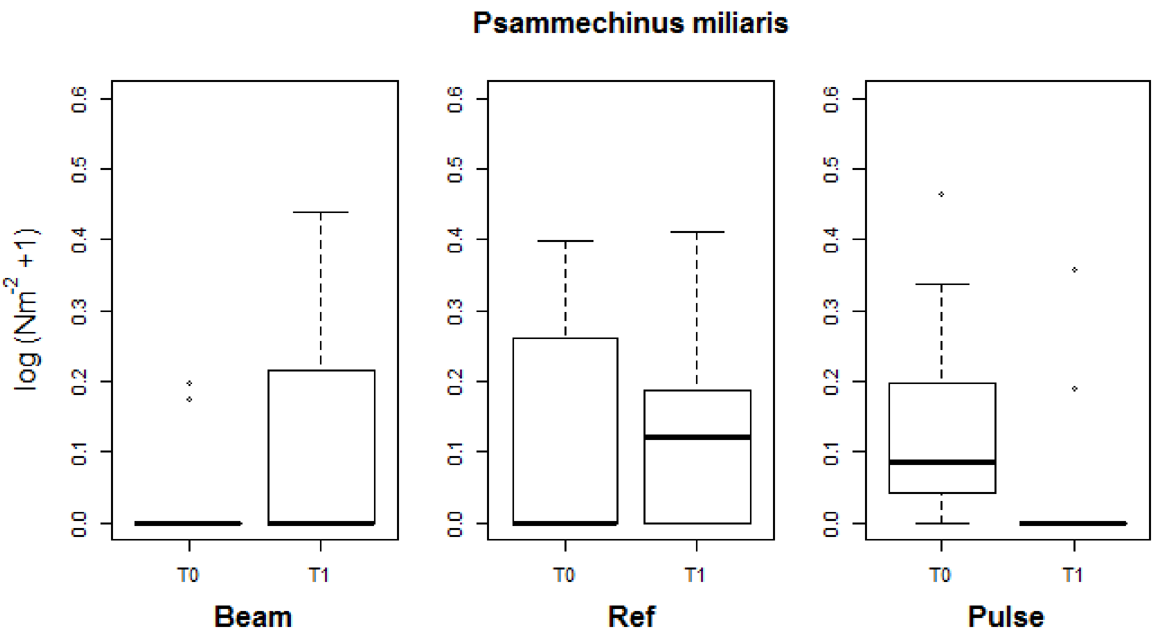

Nassarius reticulatus
log (Nm-2 +1)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
T0
T1
Beam
Ref
Pulse


Ophiura albida
log (Nm-2 +1)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
T0
T1
Beam
Ref
Pulse


Ophiura ophiura
log (Nm-2 +1)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
T0
T1
Beam
Ref
Pulse

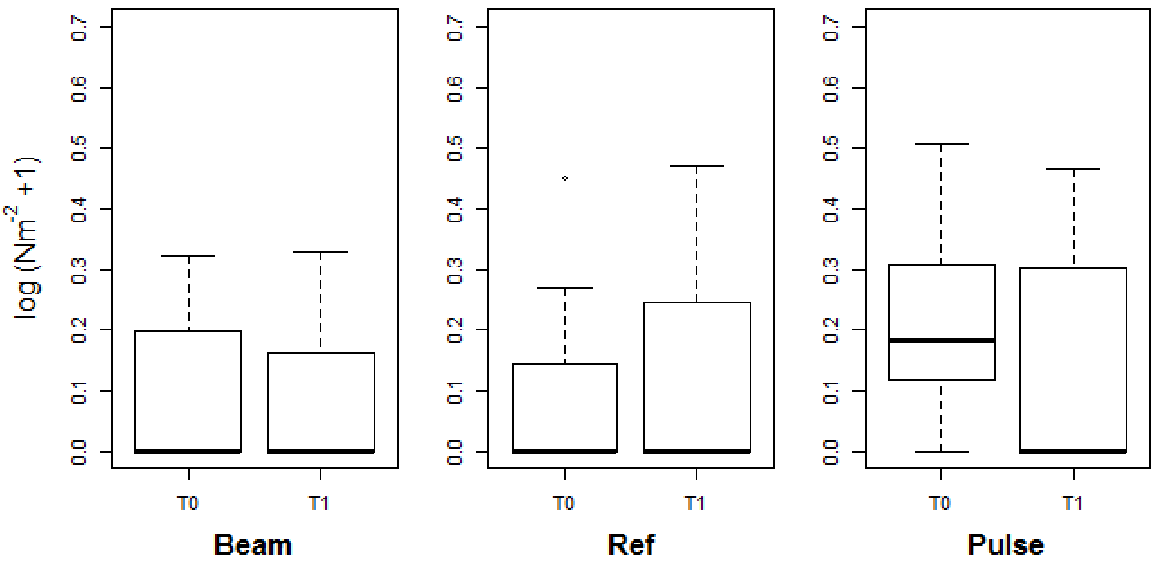


Pagurus bernhardus
log (Nm-2 +1)
0.0
0.5
1.0
1.5
T0
T1
Beam
Ref
Pulse



Psammechinus miliaris
log (Nm-2 +1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
T0
T1
Beam
Ref
Pulse

Spisula subtruncata



Tellina fabula