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Catch comparison of flatfish pulse trawls and a tickler chain beam trawl

B. van Marlen*, J.A.M. Wiegerinck, E. van Os-Koomen, E. van Barneveld

IMARES-Fishery part of Wageningen UR, P.O. Box 68, 1970 AB IJmuiden, The Netherlands

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ABSTRACT

Pulse trawling is used to a growing extent in the Dutch flatfish beam trawl fleet, and deemed as a promising alternative to tickler chain beam trawling. A comparative fishing experiment was carried out with one vessel using conventional beam trawls, and the other two using flatfish pulse trawls supplied by two different companies. Pulse trawl landings were lower both expressed in kg h^{-1} (67% based on auction data) or baskets per hectare (81%).

The pulse trawls had fewer fish discards (57%, $p < 0.0001$), including 62% undersized plaice (*Pleuronectes platessa* L.) ($p < 0.0001$), and 80% discarded weight of benthic invertebrates ($p = 0.0198$) per hectare. The pulse fishing technique resulted in a lower fuel consumption (37–49%), and consequently in spite of lower landings net revenues were higher. A downside of using pulse trawls is the possible spinal damage of marketable cod (*Gadus morhua* L.), but because total cod landings by beam trawls are low (4–5%), the implication will likely be limited.

1. Introduction

For many years there is concern about the impact of fishing on marine ecosystems. Particularly the use of towed gears and their effect on sensitive habitats and benthic fauna received attention (Jennings and Kaiser, 1998; Lindeboom and de Groot, 1998). Beam trawls are gears in this category that are intensively used in the North Sea fisheries of the Netherlands, Belgium, Germany, and the United Kingdom for catching brown shrimp (*Crangon crangon* L.) and flatfish, particularly sole (*Solea vulgaris* L.) and plaice. Beam trawling for flatfish is an efficient fishing method in terms of catches per unit of effort, but it requires a high level of energy input (typically 30,000–35,000 l of fuel/week), due to the high gear drag caused by the relatively heavy ground gear and high towing speeds (e.g. 6.5–7.0 knots, see Rijnsdorp et al., 2008). Consequently, this technique causes substantial mortality of undersized target fish, non-target fish, and changes in the species composition of invertebrates (Fonteyne and Polet, 2002; ICES, 1988; ICES, 1995; Jennings and Kaiser, 1998; Kaiser and De Groot, 2000; Lindeboom and de Groot, 1998; Piet et al., 2000). Paschen et al. (2000) reported that the penetration depth of tickler chain beam trawls varies between 10 and 80 mm, depending on the type of gear and substrate. Replacing tickler chains by electrical stimulation is seen as an alternative for diminishing the ecosystem effects of conventional beam trawling.

Research into the effects of flatfish pulse trawling using the Verburg (DELMECO) type of gear has been carried out by IMARES since 1998 by examining catch of target species, by-catch of undersized fish and benthos, and bottom impact, first with a 7 m prototype, then with a 12 m prototype beam trawl. The trials with the 7 m prototype showed that sole catches could reach the same level as in the conventional tickler chain beam trawl, but plaice catches reduced by about 50%. At the same time, catches of benthos were also reduced by ~50% (van Marlen et al., 1999, 2000). In addition it was found, that the median value of the direct mortality of benthic invertebrates could be reduced from 36% to 24% ($p = 0.09$) (van Marlen et al., 2001).

Using electricity in European fisheries is prohibited since 1988 through EC Regulation No. 850/1998, Article 3.1 (EU, 1998). The possibility of an introduction of electrical or pulse beam trawls in the flatfish fishery was considered by the European Scientific, Technical and Economic Committee for Fisheries (STECF) in 2006 and the International Council for the Exploration of the Sea (ICES) was asked to give advice. Questions were raised by ICES concerning changes in fishing mortality, species composition and the size of commercial fish species caught. ICES also wished to be informed about any effects of pulse trawling on non-target species that can come into contact with a pulse trawling gear in view of a widespread introduction of this technique. ICES was on the whole positive about the potential effects of the pulse trawl, but also raised some additional questions. The recommendation was given to conduct

* Corresponding author. Tel.: +31 317 487181; fax: +31 317 487326.
E-mail address: bob.vanmarlen@wur.nl (B. van Marlen).

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Table 1
Number of pulse trawlers in European member states, dated 01/01/2013.

Engine power	>300 hp	≤300 hp			Total
Country	Flatfish	Flatfish	Flatfish + shrimps	Shrimps	
Netherlands	25	13	1	3	42
Germany	3	1	0	1	5
United Kingdom	3	0	0	0	3
Belgium	0	0	0	1	1

Source of data: K. Taal, LEI, the Hague, the Netherlands.

further tank experiments to determine whether injury is being caused to fish escaping from a pulse trawl gear (ICES, 2006a,b,c,d). Following the ICES advice of 2006, IMARES conducted tank experiments on a range of fish and benthic species in 2007–2009 (de Haan et al., 2008; de Haan et al., 2009; van Marlen et al., 2009a; van Marlen et al., 2007), which were reviewed in 2009 and led to a renewed advice from ICES (ICES, 2009), followed up by additional tank experiments (de Haan et al., 2011; ICES, 2010, 2011, 2012). The occurrence of spinal damage in cod under some circumstances and future catch efficiency of pulse trawling were recognized as issues of concern, while the effects on sharks and invertebrates were deemed to be limited. Meanwhile in 2009 a total of 5% of the Dutch fleet was allowed to use pulse beam trawls (EU, 2009). This derogation worked on the basis of a maximum electrical power per unit beam length (1.25 kW/m), and a maximum effective voltage of 15 V on the electrodes.

The use of pulse trawling as an alternative to heavy tickler chains in sensitive Natura2000 areas has been advocated in policy documents recently, e.g. both in the Netherlands through the “Vibeg” agreement (Anon., 2012), as in Germany (Anon., 2011).

Since 2006 the development of pulse trawling systems continued, and new manufacturers entered the market. All research and evaluations carried out before 2011 were based on the specifications of the pulse trawls developed by Verburg Holland Ltd., Colijnsplaat, the Netherlands (recently acquired by the DELMECO-group, Goes, the Netherlands). Meanwhile, the ‘PulseWing’ was introduced in the Dutch beam trawler fleet by HFK Engineering, Baarn, the Netherlands, and so a new situation has emerged with two types of flatfish pulse trawl in use.

In January 2013 there were 51 vessels fishing with pulse trawls from various EU member states, i.e. the Netherlands, Germany, United Kingdom and Belgium. A total of 45 boats were fishing for flatfish, 1 for both flatfish and shrimp, and 5 for shrimp only. The vessel classes used are large beam trawlers (>300 hp), euro-cutters and shrimp trawlers (≤300 hp) (Table 1). They fish in ICES Area IV.

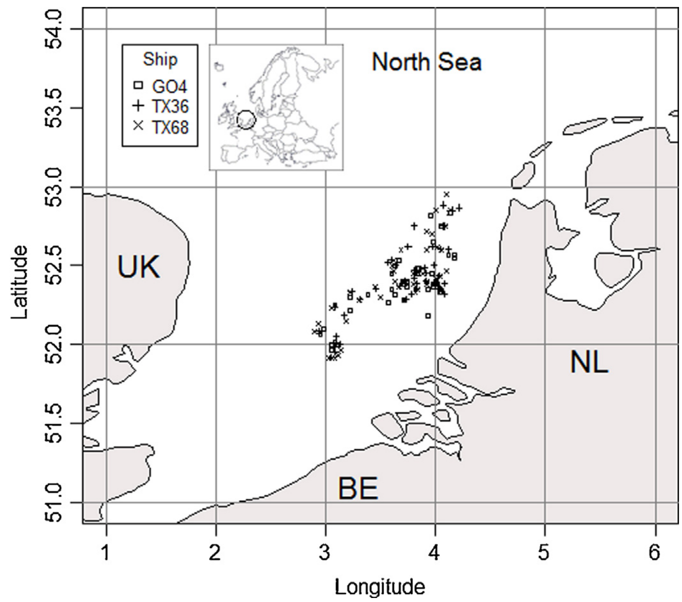

Fig. 1. Fishing positions of the three vessels in the North Sea during the catch comparison of 2011. BE = Belgium, NL = the Netherlands, and UK = United Kingdom.

This paper reports on a comparative fishing experiment in May 2011 between one commercial fishing vessel using traditional flatfish tickler chain beam trawls and two boats using either the DELMECO or the HFK flatfish pulse trawls. We were particularly interested to find out what the difference was between catches and by-catches of pulse trawls and a conventional beam trawl, the fate of cod in the pulse trawl catches, and their fuel saving potential. In addition, we compared differences in landings and discards of major target species, plaice and sole, and if they existed, whether they were length-related.

2. Materials and methods

2.1. Vessels

The fishing trials were conducted from the 5th to the 13th of May 2011 with three vessels (GO4, TX36 and TX68) fishing ‘side-by-side’ as much as possible given the differences in towing speeds (Fig. 1, Table 2). A total of was 45 hauls were done on-board the TX36 and the GO4, and 48 on the TX68, of which 33 hauls from each vessel were sampled for discards (Table 2). The TX36 was using HFK Pulse

Table 2
Main particulars of participating vessels, gears used and number of hauls carried out and sampled.

Vessel	GO4	TX36	TX68
Length o.a. [m]	40.11	42.35	41.15
Beam [m]	8.50	8.50	8.50
Depth [m]	4.71	5.15	5.30
Main engine power [hp]; [kW]	1995; 1467	1999; 1470	2000; 1471
Mean fishing speed [knots]	6.5	5.0	5.0
Gross Tonnage [GT]	417	494	438
Year built	1992	2000	1993
Fishing gear used	Tickler chain beam trawl 12 m	HFK Pulse wing 12 m	DELMECO pulse trawl 12 m
Cod-end mesh size [mm]	81.96 ± 2.68	80.75 ± 1.37	~80
Ground rope length [m]	34	36	32
Diameter discs on ground rope [mm]		200	240
Towing speed [knots]	6.44 ± 0.09 (6.5)	~5	5.0 ± 0.35 (5.0)
Total number of hauls	45	45	48
Number of hauls for which discards were sampled	33	33	33
Total number of hauls for which landings of plaice were sampled	32	15	13
Total number of hauls for which landings of sole were sampled	33	18	15

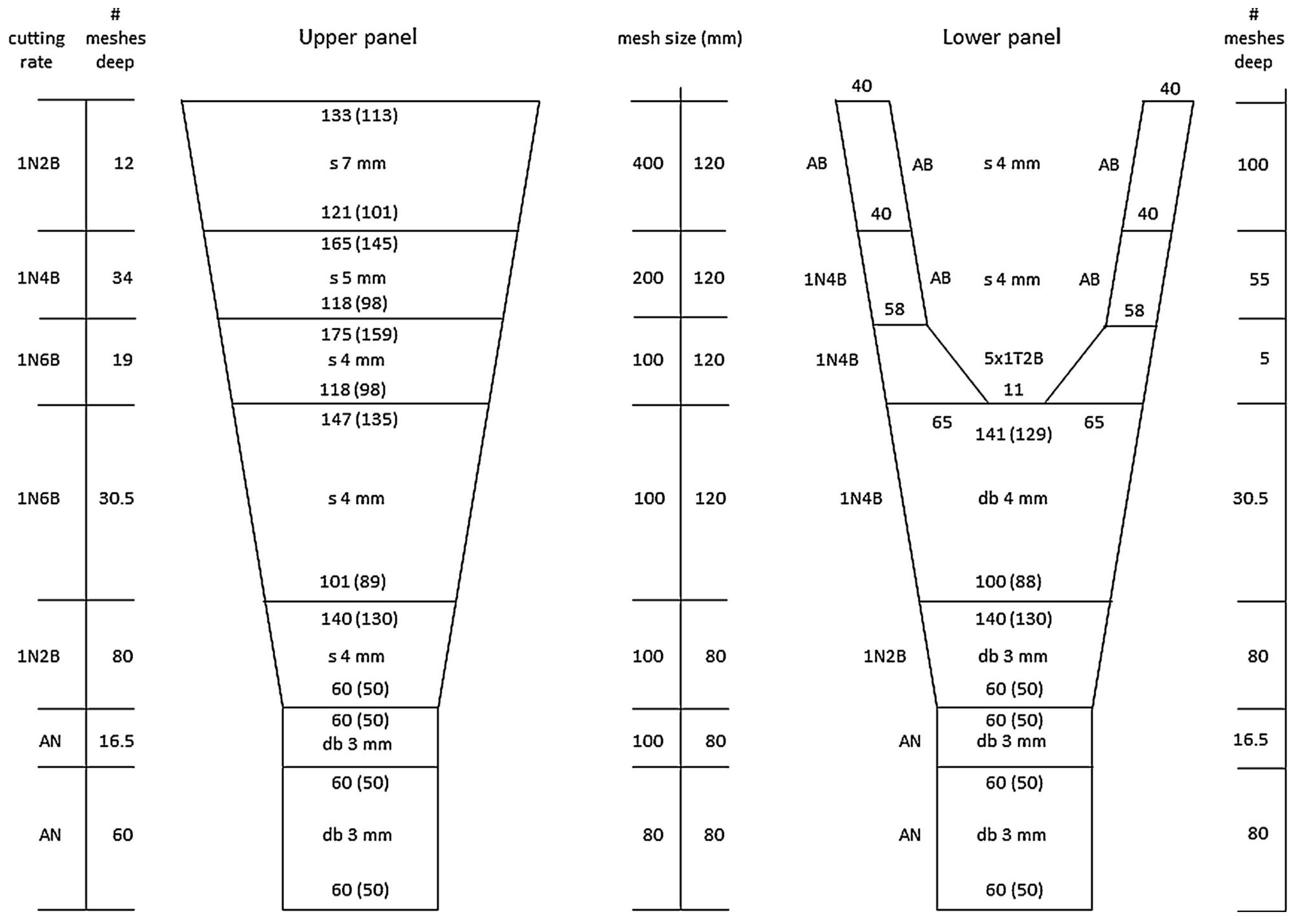

Fig. 2. Net drawing of G04. s = single braid, db = double braid, Number in brackets () = meshes between selvedges.

Wings, the TX68 DELMECO pulse trawls and the GO4 conventional tickler chain beam trawls.

2.2. Fishing gears

A pulse trawl is a gear in which electrical pulsating field are generated to stimulate flatfish to leave their position in the sediment and become susceptible to capture. A pulse fishing system consists of a electrical feeding cable, a winch, a pulse generator, and electrodes. Electrodes have insulating and conducting parts, which generate the electric field in sea water. Field strength, pulse frequency and pulse amplitude are the main variables determining the response of fish. More details on the two pulse systems used are given below.

All cod-ends were made of the same batch of netting with a nominal mesh size of 80 mm to avoid differences due to mesh size. GO4 fished with two conventional 12 m tickler chain beam trawls with conventional nets (Fig. 2). The gears were fitted with 8 tickler chains and 10 net ticklers (Table 3). TX36 fished with the 'PulseWing'. A total of 28 pulse modules spaced 41.5 cm apart are placed inside the wing and connected with parallel electrodes. The electrode array

Table 3
Tickler chains used by GO4.

Diameter [mm]	Length [m]
26 mm (n = 8) from shoes	25.6; 24.2; 22.9; 21.7; 20.5; 19.4; 18.4; 17.5
26 mm (n = 2) on groundrope	3.4; 3.7; 4.2
23 mm (n = 1)	5.3
18 mm (n = 2)	6.3; 7.5
16 mm (n = 4)	8.2; 9.2; 10.2; 11.2

Table 4
Overview of main pulse parameters of the two systems.

Pulse system	Unit	HFK TX36	DELMECO TX68
Electric power single gear	[kW]	7	5.5
Electrode voltage	[V^0 to peak]	45	50
Pulse frequency	[Hz]	45	40
Pulse duration	[μs]	380	220[a]
No of electrodes		28	25
Electrode distance	[m]	0.415	0.425
No of conductors		2; 10	6
Conductor length × diameter	[mm × mm]	125 × 27; 125 × 33	180 × 26

Source of data: de Haan et al., 2011.
[a] The pulse duration refers to a single pulse period.

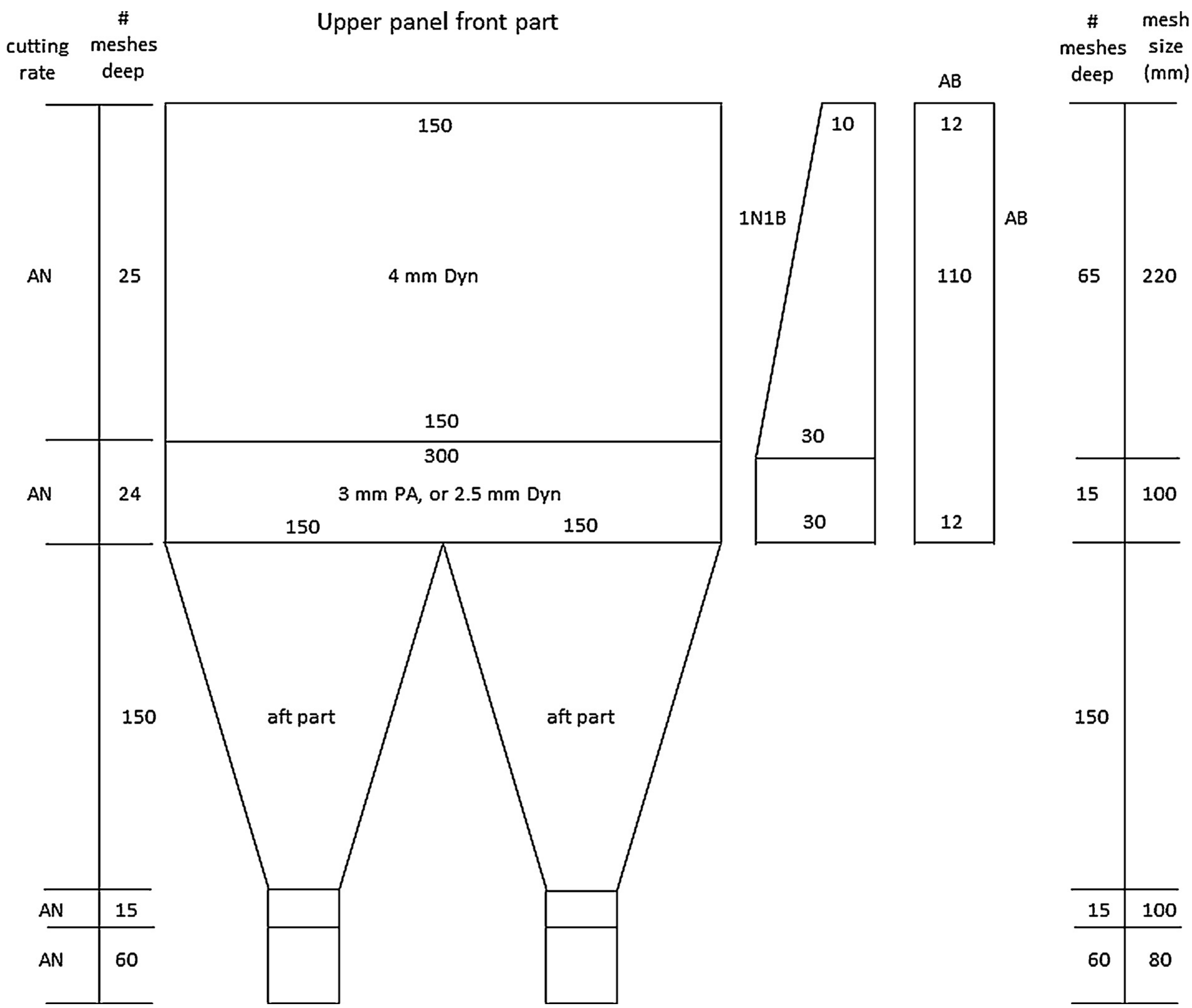

Fig. 3. Net drawing of TX36–Whole net.

extends over ~6 m. The nets differ from the conventional model. The aft part was made of two identical parts next to each other (Figs. 3 and 4). The TX68 fished with the DELMECO pulse trawl which has 25 electrodes across its width spaced 42.5 cm apart. The nets were derived from the conventional beam trawl design (Fig. 5). Details of the pulse stimulation are given in Table 4.

2.3. Data collection

The catch of each haul was processed by the crew that collected all commercial fish by market grade. The total catch weight and the weight (kg) of the landing fraction of sole and plaice, as well as the haul number, date–time and position of shooting, date–time and position of heaving, distance covered or towing speed, water depth, wind speed and wind direction, were recorded. The total discard volume (number of baskets that can contain 35 kg) was measured using special catch sampling valves fitted at the end of the fish processing conveyor belt on each boat with which the volume of material passing could be determined. The total catch volume was determined by adding the volume of the landings. Towing speed was recorded and checked using available VMS records (Table 2).

The size distributions (cm below) of the landing fraction of plaice and sole were recorded for a selection of hauls taken from either the port (TX68) or the starboard side (TX36, GO4) (Table 2). The total catch composition of the discard fraction was recorded from a subsample of one basket of the catch for the 33 sampled hauls. All species of fish in the sample were identified and their length distribution (cm below) was recorded. All benthic invertebrates were identified and counted. In addition there was a second data source related to the catches as the total landings of each vessel were made available from the sale slips of the auction (kg per market grade of commercial species). These data are presented separately.

2.4. Spinal injury

All cod that were captured on the TX36 and TX68 were measured and filleted, by which spines were made visible for inspection and digitally photographed. On the TX36 this was also done for whiting. During the trials cod were inspected visually on the GO4, but not internally investigated. At the time no spinal fractures were seen. Because there were still some doubts whether cod in the tickler chain beam trawl may suffer spinal damage, a box of landed cod was purchased from the GO4 in October 2011 and the fish were measured, filleted and photographed.

2.5. Data exploration and correction

The data recorded by the skippers were explored using visualization techniques in "R" to check for collinearity of covariates, correct outliers in the data, and find out the influence of covariates using several statistical models (Zuur et al., 2009; Zuur et al., 2010).

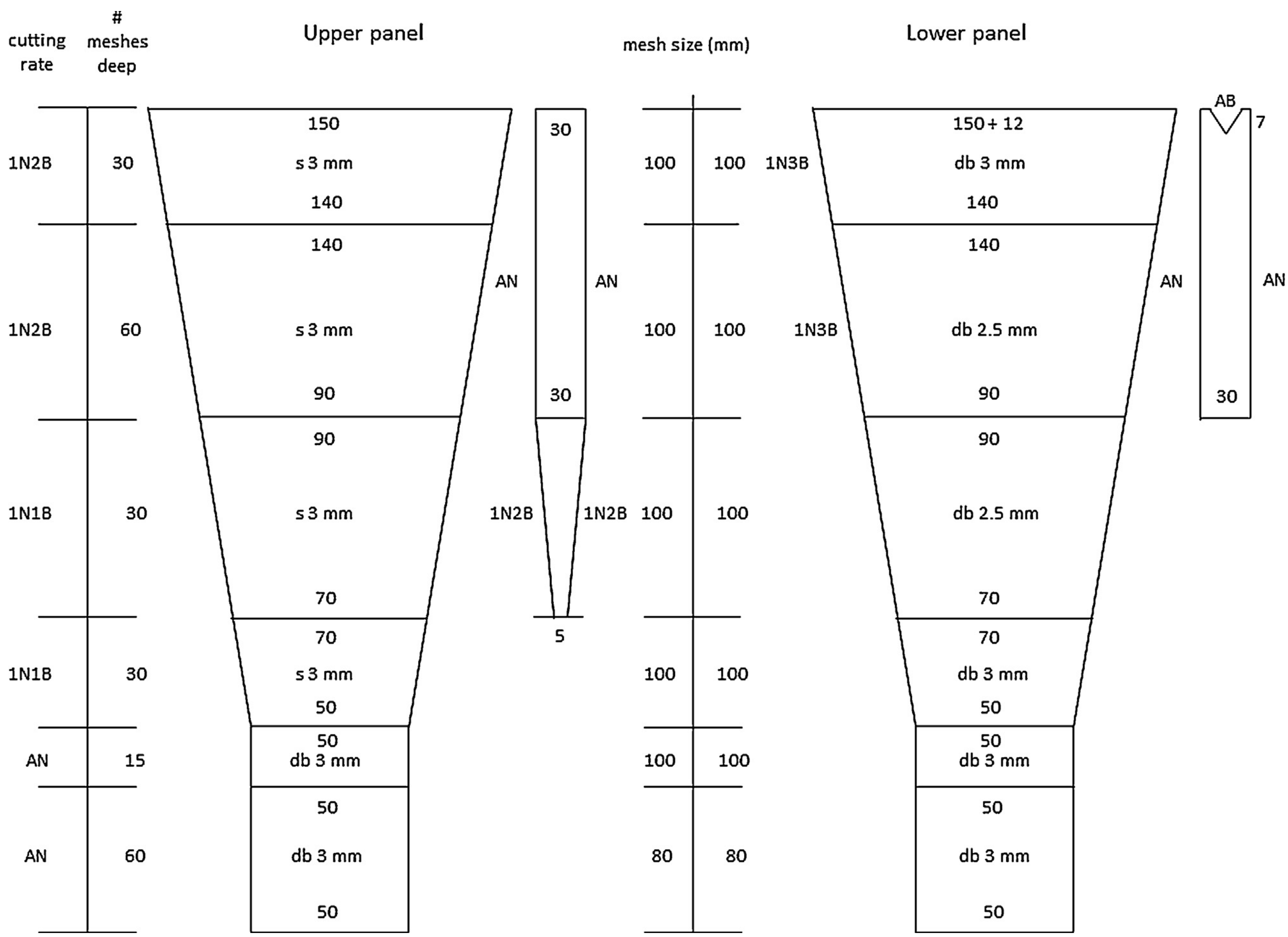

Fig. 4. Net drawing of TX36–Aft parts. s = single braid; db = double braid.

2.6. Statistical analysis of sampled hauls

Statistical analyses were carried out using the data from the sampled hauls. The species specific data were checked and corrected and then entered into a database, after which a SAS™ data-set was created for analysis (SAS, 2008).

Catch rates were analysed by generalized linear modelling (SAS PROC GLM) of the form:

$$\log(\text{CPUE}i) \sim \beta_0 + \beta_1 \text{gear}i + \varepsilon,\ \varepsilon \sim N\left(0, \sigma^2\right)$$

CPUE was expressed in terms of baskets (of 35 kg) per hour or per swept hectare (total catch, landings and discards), kg per hour (for plaice and sole), or numbers (n) per hectare (species and habitat groups, taxonomic groups, plaice and sole individually). The catch rate expressed per unit swept area allows us to test whether the catch efficiency of the gears differed, irrespective of the differences in towing speed. The CPUEs were log-transformed for the statistical test to ensure normality of the residuals, but the values in Tables 7 and 9 are the untransformed ones. With PROC GLM we investigated whether the independent variable gear (pulse trawl vs. conventional beam trawl) contributed significantly to the variance of the response variable, in other words whether CPUE differences were really caused by gear type. Data for both pulse trawls were collected under gear type 'pulse' as the differences between the two systems are not very large (Table 4), but in the relative difference between pulse and conventional beam trawling.

In this analysis we examined catches in overall categories – landings and discards (benthos and undersized target species, and non-target species), as well as landings by the two major target species, plaice and sole. The auction data covered only one record by species and market grade at the end of the week, and these were therefore not used for statistical analysis.

In order to test whether the pulse trawl and the tickler chain beam trawl differed in catch efficiency for animals living in different habitats, species were classified according to their affinity to the sea bed (fish: benthic, demersal or pelagic; invertebrates: in-fauna, epi-fauna). In addition, specific groups representing abundant species were analysed (fish: ammodytes, clupeids, flatfish, gadoids, gurnards, and other; invertebrates: anthozoa, bivalves, cephalopods, crustaceans, echinoderms, gastropods, and molluscs). Tables 5 and 6 give an overview of all species recorded during the study and their classification.

In addition generalized linear models (GLM) were used in "R" to explore the effects of covariates (gear, time of day, latitude and longitude) on the variance of the results in terms of Catch Per Unit of Area (CPUA) (Zuur et al., 2009; Zuur et al., 2010).

2.7. Length selectivity for sole and plaice based on sampled hauls

We selected the hauls for which landings and discards were sampled for both plaice and sole and compared the pooled catches of TX36 and TX68 (pulse trawl, denoted PULS) with those of the GO4 (conventional gear, denoted CONV). Length frequency distributions were made for numbers per unit area (10,000 m^2). The CPUE data were also analysed per unit area and per hour using the method of Holst and Revill (2009) explained below. This analysis requires a paired haul technique. Although in our experiment, the time and position of shooting and heaving could not be completely

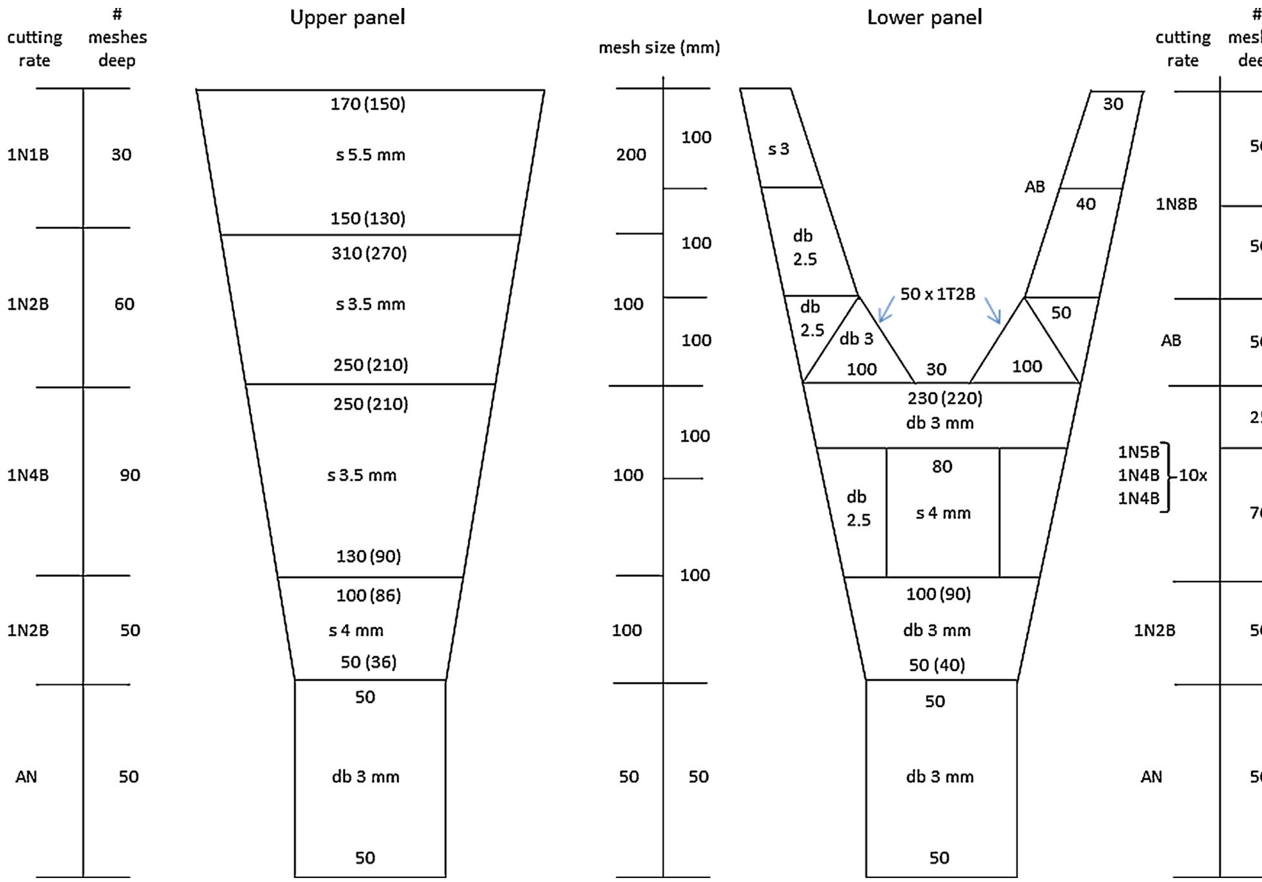

Fig. 5. Net drawing of TX68. s = single braid, db = double braid, Number in brackets () = meshes between selvedges.

Table 5
Classification of the fish species caught.

English name	Scientific name	Habitat	Taxonomic group
Brill	*Scophthalmus rhombus*	Benthic	Flatfish
Dab	*Limanda limanda*	Benthic	Flatfish
Flounder	*Platichthys flesus*	Benthic	Flatfish
Greater sand-eel	*Hyperoplus lanceolatus*	Benthic	Ammodytes
Lemon sole	*Microstomus kitt*	Benthic	Flatfish
Lesser weever	*Echiichthys vipera*	Benthic	Other
Plaice	*Pleuronectes platessa*	Benthic	Flatfish
Scaldfish	*Arnoglossus laterna*	Benthic	Flatfish
Sole	*Solea solea*	Benthic	Flatfish
Solenette	*Buglossidium luteum*	Benthic	Flatfish
Turbot	*Psetta maxima*	Benthic	Flatfish
Ammodytes	*Ammodytes sp.*	Benthic	Ammodytes
Bib	*Trisopterus luscus*	Demersal	Gadoids
Bull-rout	*Myoxocephalus scorpius*	Demersal	Gadoids
Cod	*Gadus morhua*	Demersal	Gadoids
Dragonet	*Callionymus lyra*	Demersal	Other
Grey gurnard	*Eutrigla gurnardus*	Demersal	Gurnards
Hooknose	*Agonus cataphractus*	Demersal	Other
Lumpsucker	*Cyclopterus lumpus*	Demersal	Other
Reticulated dragonet	*Callionymus reticulatus*	Demersal	Other
Sea scorpion	*Taurulus bubalis*	Demersal	Other
Tub gurnard	*Trigla lucerna*	Demersal	Gurnards
Whiting	*Merlangius merlangus*	Demersal	Gadoids
Goby	*Pomatoschistus sp.*	Demersal	Other
Herring	*Clupea harengus*	Pelagic	Clupeids
Horse mackerel	*Trachurus trachurus*	Pelagic	Other
Mackerel	*Scomber scombrus*	Pelagic	Other
Sprat	*Sprattus sprattus*	Pelagic	Clupeids

synchronized, paired hauls were created by grouping hauls that started within 30 min difference, and for which both landings and discards were sampled. Catches were converted to numbers per hectare to avoid differences due to variations in haul duration and towing speed. This resulted in 25 paired hauls for plaice and 33 pairs for sole.

Software code was developed in 2009 in "R" for analysing catch comparisons to appraise the catch efficiency (at length) of one gear relative to that of another gear, which deviates from the classical selectivity experiment where one of the gears is assumed to catch the entire population (Holst and Revill, 2009; R Development Core Team, 2012). The method used 'Generalised Linear Mixed Models (GLMM)' and polynomial approximations for the logit function describing the probability of retaining a fish at length in what they call the 'test' gear, related to the total catch in the 'test' and 'control' gear. The probability of a fish being retained in the 'test' codend given it enters the entire gear follows from:

$$Pr\left\{\text{PULS}/\left(\text{PULS}+\text{CONV}\right)\right\} = 1/\left(1+e^{-\left(\beta_0+\beta_1\times\text{length}+\beta_2\times\text{length}^2\right)}\right)$$

A binomial error distribution was used because the response variable is the probability of the number of fish caught in the pulse gear given they enter both gears per haul by 1-cm size class. The method produces a curve with 95% confidence bands expressing this probability. The line of 0.5 corresponds with equal catches in both gears. The method starts with 3rd order polynomials, and reduces the order until all terms are significant. The R function glmmPQL was used to fit the GLMM model. We extended the method by plotting the underlying data points.

Table 6
Classification of the benthic species caught.

English name	Scientific name	Habitat	Taxonomic group
Sea anemones and corals	*Anthozoa*	Epi-fauna	Anthozoa
Common mussel	*Mytilus edulis*	Epi-fauna	Bivalva
Squid	*Loligo sp.*	Epi-fauna	Cephalopoda
Common shrimp	*Crangon crangon*	Epi-fauna	Crustacea
Contracted crab	*Hyas coarctatus*	Epi-fauna	Crustacea
Hermit crab	*Pagurus bernhardus*	Epi-fauna	Crustacea
Marbled swimming crab	*Liocarcinus marmoreus*	Epi-fauna	Crustacea
Sandy swimming crab	*Liocarcinus depurator*	Epi-fauna	Crustacea
Swimming crab	*Liocarcinus holsatus*	Epi-fauna	Crustacea
Velvet swimming crab	*Necora puber*	Epi-fauna	Crustacea
Crab	*Hyas sp.*	Epi-fauna	Crustacea
Brittle star	*Ophiura ophiura*	Epi-fauna	Echinodermata
Common starfish	*Asterias rubens*	Epi-fauna	Echinodermata
Green sea urchin	*Psammechinus miliaris*	Epi-fauna	Echinodermata
Sea urchins	*Echinidae*	Epi-fauna	Echinodermata
Common whelk	*Buccinum undatum*	Epi-fauna	Gastropoda
European common squid	*Loligo subulata*	Epi-fauna	Mollusca
Norway cockle	*Laevicardium crissum*	In-fauna	Bivalva
Razor clams	*Ensis sp.*	In-fauna	Bivalva
Surf clams	*Spisula sp.*	In-fauna	Bivalva
Edible crab	*Cancer pagurus*	In-fauna	Crustacea
Masked crab	*Corystes cassive-launus*	In-fauna	Crustacea
Purple heart urchin	*Spatangus purpureus*	In-fauna	Echinodermata
Sea potato	*Echinocardium cordatum*	In-fauna	Echinodermata

Table 8
Summary of Catches Per Unit of Effort (CPUEs) based on auction data.

Gear type Species	Conv. [kg h^{-1}]	Pulse [kg h^{-1}][a]	Pulse/Conv. [%]
Plaice	34.9	24.9	71.4
Sole	17.6	15.1	85.9
Dab	3.4	3.6	104.6
Turbot	3.6	2.9	81.8
Brill	2.00	2.03	101.7
Cod	1.8	0.6	30.7
Whiting	2.7	0.7	25.1
Other	24.1	10.7	44.4
Landings	90.1	60.5	67.1

[a] Calculated average over the two pulse trawl vessels.

3. Results

3.1. Total catch volume of landings and discards based on data logged by the skippers.

The pulse trawl caught significantly less than the conventional beam trawl (Table 7). The total catch volume, expressed as the number of baskets h^{-1}, for the pulse trawl vessels was 37% of the total volume of the conventional beam trawler. Pulse trawl landings were 62%, and discards 33% of the conventional beam trawl. Expressed as the catch rate per unit of fished area, the pulse trawl catches were 48%, 81% and 43% of the conventional beam trawl rates for total catch, landings and discards, respectively. Based on these recorded catches of marketable plaice and sole by haul, the pulse gear caught 72% ($p < 0.05$) of plaice and 79% ($p < 0.001$) of sole in kg per hour as compared to the conventional beam trawl, values corresponding well with those found at the auction. The catch rate of the plaice and sole, however, did not differ significantly when compared on a swept area basis (Table 7).

3.2. Landings based on auction data

Based on auction data and total fishing time the pulse trawl caught fewer marketable fish per unit of time, i.e. 60.5 kg h^{-1} vs. 90 kg h^{-1} on average (67%) (Table 8). The split in species is also given in this table. The CPUE for plaice was about 71%, and for sole 86% compared to the tickler chain beam trawl. Cod on the two pulse trawl vessels were not actually landed as they were cut open to reveal spinal damage, but their weights by market grade were

Table 7
Mean total catch, landings and discards in baskets h^{-1} and in baskets hectare^{-1}, and landings in kg h^{-1} and in kg hectare^{-1} of major target species over hauls for which discards were sampled, recorded by the skippers.

Gear		CONV			PULS			PULS/CONV	*p*-Value based on log_cpue/cpua
Item	Unit	*n*	Mean	Std. dev.	*n*	Mean	Std. dev.	%	
Total catch	[baskets h^{-1}]	33	19.74	5.07	66	7.34	2.10	37.2	<.0001
	[baskets hectare^{-1}]	33	0.68	0.18	66	0.33	0.09	48.3	<.0001
Landings	[baskets h^{-1}]	33	2.81	0.75	66	1.75	0.49	62.2	<.0001
	[baskets hectare^{-1}]	33	0.10	0.03	66	0.08	0.02	80.9	0.0004
Discards	[baskets h^{-1}	33	16.94	4.94	66	5.59	1.95	33.0	<.0001
	[baskets hectare^{-1}]	33	0.59	0.17	66	0.25	0.09	42.9	<.0001
PLE landings	[kg h^{-1}]	33	38.62	20.65	63	27.89	9.47	72.2	0.0016
	[kg hectare^{-1}]	33	1.34	0.71	63	1.26	0.43	93.9	0.8776
SOL landings	[kg h^{-1}]	33	17.07	5.08	66	13.46	3.51	78.9	<.0001
	[kg hectare^{-1}**]**	33	0.59	0.18	66	0.61	0.16	102.5	0.6214

PLE = plaice, SOL = sole, statistical tests based on log-transformed data, boldface is significant. 1 basket = 35 kg.

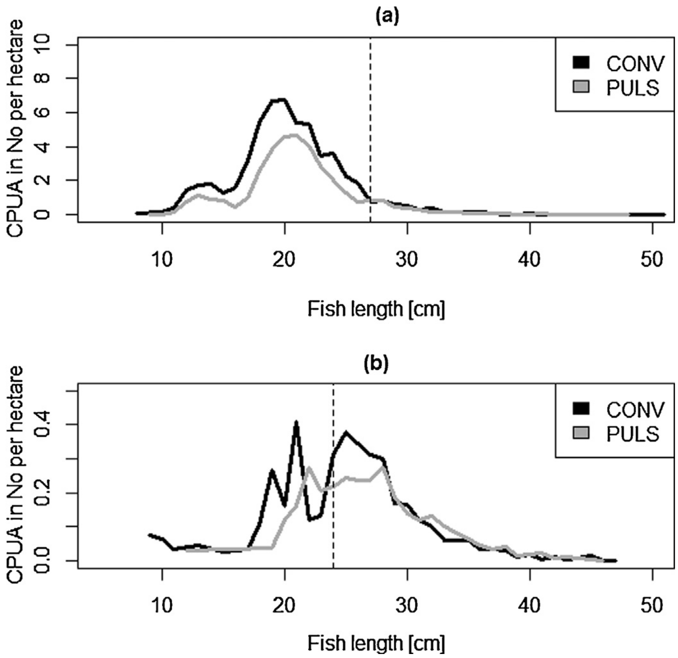

Fig. 6. Length distribution of plaice (a) and sole (b) in numbers per hectare from hauls when landings and discards were both sampled, CONV = conventional tickler chain beam trawl, PULS = pulse trawls (taken together), the dotted vertical lines represent the Minimum Landing Size (MLS).

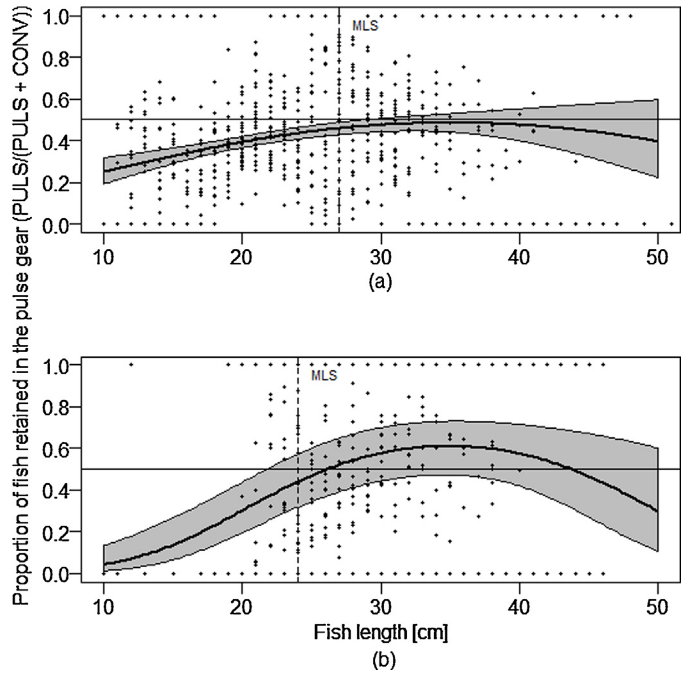

Fig. 7. Proportion of fish retained in the pulse gear (=PULS/(PULS + CONV)) vs. length for plaice (a) and sole (b). The value of 0.5 means both gears catch equal numbers, the solid line gives the mean, and the grey band gives the 95% confidence limit). The sampling ratios were corrected by fished area. Data points are given in black dots. Pulse = TX36 and TX68, CONV = GO4. MLS is Minimum Landing Size (plaice: 27 cm, sole: 24 cm).

calculated from the length measurements using a length-weight key (Coull et al., 1989). On average the catch was about 31% in the pulse trawl.

3.3. Discards based on sampled hauls

The pulse trawl caught considerably less fish discards, 57.1% in terms of weight per unit of area, and 43.9% in terms of weight per fishing hour, when expressed as the ratio of the tickler chain beam trawl catch. The fraction of benthic fish was largest, followed by demersal fish, and only a few pelagic fish. Of the benthic fish most were flatfish, with some ammodytes. The demersal fish consisted of gadoids, and gurnards. All these were caught considerably less in the pulse trawl. Significant were the differences in flatfish (56.1% per area, 43.2% per hour) and gadoid fish (48.7% per area, 37.4% per hour), plaice (62% per area, 48% per hour), but not for sole (46% per area, 35.2% per hour), see Tables 9 and 10.

Overall the pulse trawls caught about 80% in benthos per unit of area and 61.6% per hour ($p < 0.05$) as compared to the conventional beam trawl. Most of the benthos by-catches consisted of epi-fauna species. When looking into species composition, the pulse trawls caught less epi-fauna (75% per area, 57.7% per hour: $p < 0.01$). The pulse trawls caught substantially more in-fauna more than 5 times as much ($p < 0.001$), although the overall catches of in-fauna species were low. For the individual taxonomic groups, the differences were generally not statistically significant except for the echinoderms (72.1% per area and 55.5% per hour, $p < 0.01$) and gastropods (0%, $p < 0.05$), while expressed in numbers per hour also significantly more cephalopods (195.4%, $p = 0.0477$) and fewer crustaceans (72.5%, $p < 0.01$) were found, see Tables 9 and 10.

3.4. Length-related catch difference for plaice and sole

The length distribution plots indicate that the pulse trawl caught relatively less smaller sized plaice and sole (Fig. 6). The Holst–Revill analysis corroborated this. In both comparisons, the fitted catch comparison curve shows that the pulse trawl has a significant lower probability to catch undersized plaice or sole, while the probability to catch marketable sized plaice does not differ, and that there is a tendency of catching somewhat more marketable sole (Figs. 7 and 8). The parameters and standard errors of the fitted mean probability functions are presented in Tables 11 and 12. A quadratic fit had the lowest p-values. The length selectivity we found corresponds to the prediction of Stewart (1975), stating that large fish are more strongly affected than small fish.

3.5. Analysis of the effect of covariates

The log-transformed CPUEs in kg h^{-1} of marketable sole showed a trend of dependence on the time of day, with higher values at dusk and dawn, but this was not the case for marketable plaice. There was also a trend of higher CPUEs for marketable plaice with higher latitude and more easterly longitude, but this was not the case for total catch, landings, discards and marketable sole. We checked the influence of factor gear and the time on log-transformed total catch by area using GLM-models in "R", and found that gear had the largest effect (64.3%), while time explained only 5.4% of the variance. The percentage variance explained was 64.2% for log-transformed discards, and 12.3% for log-transformed landings for factor gear only, while time and location were no longer significant. A GLM-model for the log-transformed marketable plaice CPUE by area did not show significance for factor gear, while with CPUE by hour only 10.1% of the variance could be explained. This was also true for marketable sole, with a percentage explained by factor gear by hour of 14.6%. In other words the pulse gear clearly affects total catch and discards by area, but not the catches of individual marketable species sole and plaice, as can also be seen from the p-values in Table 7.

3.6. Economic performance based on overall results

Despite of the lower earnings, the net revenue per fishing hour of the pulse trawl was substantially higher than that of the

Table 9
Mean CPUE in n hectare^{-1} of discards of main categories over sampled hauls.

Gear	CONV			PULS			PULS/CONV	*p*-Value based on log_cpua
Species group	*n*	Mean	Std. dev.	*n*	Mean	Std. dev.	[%]	
fis	**33**	**108.4**	**41.1**	**66**	**61.9**	**24.5**	**57.1**	**<.0001**
fis_ben	**33**	**98.2**	**41.9**	**66**	**55.3**	**23.5**	**56.3**	**<.0001**
fis_dem	**33**	**9.4**	**4.7**	**66**	**6.5**	**5.0**	**68.9**	**0.0005**
fis_pel	**33**	**0.8**	**1.6**	**66**	**0.1**	**0.3**	**13.0**	**0.0013**
Ammo	33	0.9	1.5	66	0.5	0.9	57.2	0.3575
Clup	33	0.1	0.3	66	0.0	0.0	8.0	0.2892
Flat	**33**	**96.6**	**41.2**	**66**	**54.2**	**23.4**	**56.1**	**<.0001**
Gado	**33**	**4.8**	**3.8**	**66**	**2.3**	**4.0**	**48.7**	**0.0022**
Gurn	33	2.4	2.0	66	1.4	1.3	60.3	0.1409
Othe	33	3.7	3.9	66	3.4	2.8	93.7	0.7106
ben	**33**	**177.4**	**86.8**	**66**	**142.0**	**84.4**	**80.0**	**0.0198**
ben_epi	**33**	**175.4**	**86.6**	**66**	**131.4**	**73.9**	**75.0**	**0.0056**
ben_inf	**33**	**2.0**	**2.2**	**66**	**10.5**	**20.9**	**515.8**	**<.0001**
Anth	33	0.1	0.5	66	0.0	0.1	23.9	0.4042
Biva	33	0.2	0.7	66	0.1	0.3	33.1	0.1798
Ceph	33	0.1	0.3	66	0.2	0.4	254.1	0.0756
Crus	33	63.8	27.7	66	60.1	34.4	94.3	0.2287
Echi	**33**	**113.1**	**68.8**	**66**	**81.6**	**62.0**	**72.1**	**0.0052**
Gast	**33**	**0.1**	**0.4**	**66**	**0.0**	**0.0**	**0.0**	**0.0142**
Plaice	**33**	**52.4**	**24.8**	**66**	**32.7**	**15.4**	**62.4**	**<.0001**
Sole	33	1.3	1.5	66	0.6	0.7	45.7	0.1396

fis = fish discards, fis_ben = benthic fish, fis_dem = demersal fish, Ammo = Ammodytes, Flat = flatfish, Gado = gadoids, Gurn = gurnards, Clup = clupea, Othe = other; ben = benthos discards, ben_epi = epifauna, ben_inf = infauna, Anth = Anthozoa, Gast = Gastropods, Ceph = Cephalopods, Biva = bivalves, Crust = crustaceans, Echi = echninoderms; statistical tests based on log-transformed data, boldface is significant.

Table 10
Mean CPUE in n h^{-1} of discards of main categories over sampled hauls.

Gear	CONV			PULS			PULS/CONV	*p*-Value based on log_cpue
Species group	*n*	Mean	Std. dev.	*n*	Mean	Std. dev.	[%]	
fis	**33**	**3131.6**	**1188.7**	**66**	**1376.1**	**543.7**	**43.9**	**<.0001**
fis_ben	**33**	**2836.5**	**1209.1**	**66**	**1229.3**	**522.1**	**43.3**	**<.0001**
fis_dem	**33**	**272.8**	**135.5**	**66**	**144.6**	**110.5**	**53.0**	**<.0001**
fis_pel	**33**	**22.3**	**45.3**	**66**	**2.2**	**5.7**	**10.0**	**0.0069**
Ammo	33	27.2	41.9	66	11.9	19.6	44.0	0.6923
Clup	33	1.6	9.3	66	0.1	0.8	6.1	0.4127
Flat	**33**	**2790.9**	**1189.3**	**66**	**1204.5**	**520.8**	**43.2**	**<.0001**
Gado	**33**	**138.0**	**110.8**	**66**	**51.7**	**88.7**	**37.4**	**0.0090**
Gurn	33	68.4	58.9	66	31.7	28.5	46.4	0.4102
Othe	33	105.6	113.8	66	76.2	63.3	72.1	0.7791
ben	**33**	**5125.0**	**2506.4**	**66**	**3154.9**	**1875.4**	**61.6**	**<.0001**
ben_epi	**33**	**5066.1**	**2501.4**	**66**	**2921.2**	**1643.2**	**57.7**	**<.0001**
ben_inf	**33**	**58.9**	**63.6**	**66**	**233.7**	**464.7**	**396.8**	**<.0001**
Anth	33	3.3	13.1	66	0.6	2.4	18.4	0.6594
Biva	33	7.0	20.5	66	1.8	6.8	25.4	0.2241
Ceph	**33**	**2.0**	**8.0**	**66**	**3.9**	**9.0**	**195.4**	**0.0477**
Crus	**33**	**1842.9**	**800.6**	**66**	**1336.2**	**764.2**	**72.5**	**0.0009**
Echi	**33**	**3266.8**	**1988.7**	**66**	**1812.5**	**1377.7**	**55.5**	**<.0001**
Gast	**33**	**3.2**	**11.1**	**66**	**0.0**	**0.0**	**0.0**	**0.0129**
Plai	**33**	**1515.0**	**715.4**	**66**	**727.6**	**342.5**	**48.0**	**<.0001**
Sole	33	37.7	44.5	66	13.3	14.7	35.2	0.6126

Table 11
GLMM parameters from comparison of pulse trawls with conventional beam trawl with CPUE in numbers per hectare.

Comparison	Species	Model	DF	Parameter	Value	Standard error	*p*-Value
Pulse vs. conv.	Plaice	Quadratic	696	β_0	−2.1007	0.44542	0.0000
				β_1	0.1162	0.03554	0.0011
				β_2	−0.0017	0.00068	0.0155
Pulse vs. conv.	Sole	Quadratic	485	β_0	−6.5684	1.3326	0.0000
				β_1	0.4017	0.0883	0.0000
				β_2	−0.0058	0.0015	0.0001

DF = degrees of freedom.

Table 12
GLMM parameters from comparison of pulse trawls with conventional beam trawl with CPUE in numbers per hour.

Comparison	Species	Model	DF	Parameter	Value	Standard error	*p*-Value
Pulse vs. conv.	Plaice	Quadratic	696	β_0	−2.3631	0.44542	0.0000
				β_1	0.1162	0.03554	0.0011
				β_2	−0.0017	0.00068	0.0155
Pulse vs. conv.	Sole	Quadratic	485	β_0	−7.011632	1.56984	0.0000
				β_1	0.430055	0.09156	0.0000
				β_2	−0.006190	0.00150	0.0000

DF = degrees of freedom.

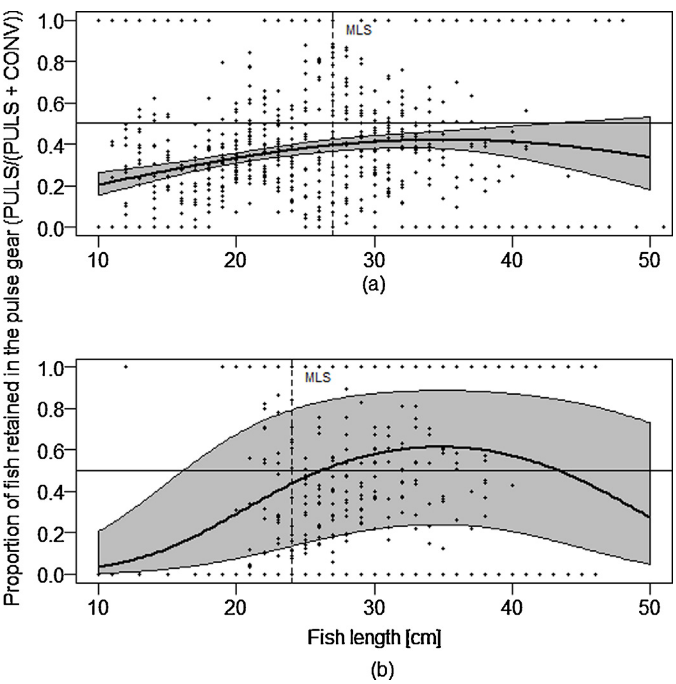

Fig. 8. Proportion of fish retained in the pulse gear (=PULS/(PULS + CONV)) vs. length for plaice (a) and sole (b), (value 0.5 means both gears catch equal numbers, the solid line gives the mean, and the grey band gives the 95% confidence limit). The sampling ratios were corrected by tow duration. Data points are given in black dots. Pulse = TX36 and TX68, CONV = GO4. MLS is Minimum Landing Size (plaice: 27 cm, sole: 24 cm).

conventional beam trawl (ratio 139–172%), mainly because of the lower fuel consumption due to the reduced fishing speed (Table 13). The gross revenues were about the same for both pulse trawl vessels.

3.7. Spinal damage

In the cod caught by pulse trawls, spinal fractures appeared both in juvenile and in marketable fish. There were frequent haemorrhages in cod from the pulse trawls and occasional fractures in their spines. Spinal fracture was seen in 2 (with length 20 and 55 cm) of the 27 individuals (length 55.0 ± 15.9 cm) of cod caught by TX36 (7%), and 2 (length 23 and 27 cm) of 18 individuals (length 48.7 ± 16.2 cm) caught and examined from the TX68 (11%). In contrast, this was not the case for the cod caught in the conventional beam trawl. Of the 48 cod caught by the GO4 (length 56.8 ± 11.1 cm) only one fish (length 55 cm) showing a haemorrhage near the spine in the tail section, but no fracture was seen.

Whiting caught by TX36 and TX68 were also examined. Of a total of 47 individuals only one fish (2%, length 0.32 m) on TX36 showed spinal fracture. The filleted fish hardly showed any haemorrhages. On TX68 a total of 10 individuals were taken from the catch and filleted, but not photographed. These fish showed no fractures or other damages.

4. Discussion

The comparison of the catch efficiency (catch per unit area swept) of the pulse trawls and the conventional beam trawl provided evidence that the pulse trawl caught fewer undersized plaice and had a substantial lower by-catch of benthic invertebrates, while the efficiency for the larger marketable sized flatfish does not differ significantly.

Differences in catch may be due to many factors. The results are determined by the combined effect of differences in mechanical and electrical stimulation between the three fishing gears. The nets deployed on TX36 were very different than the usual beam trawl nets with a rectangular square and double aft parts, but the electric parts and electrodes were almost identical. We avoided a confounding effect from differences in cod-end mesh size by making all cod-ends from the same bale of netting.

Comparing the results of the present study with experiments conducted in 2006 (van Marlen et al., 2005; van Marlen et al., 2006), we found that the ratio of the catch rates of the landings (kg h^{-1}) of the pulse trawl related to the conventional beam trawl were in the same order of magnitude varying for landings between 59%–95%, 53%–90% for plaice, and 66%–122% for sole (Table 14). We also compared the results in terms of discards of plaice and sole and of two indicator benthic species, i.e. common starfish (*Asterias rubens*), and swimming crab (*Liocarcinus holsatus*) with the experiments in 2006 (van Marlen et al., 2006), based on sampled hauls. Discards of plaice were considerably lower for the pulse trawls in 2011. The same was found for sole, but the result was not significant, while it was in 2006. The decrease in common starfish was more pronounced in 2011, but not for swimming crab (Table 15).

The decrease in the catches of benthic invertebrates and demersal fish is likely attributable to the replacement of the tickler

Table 13
Summary of overall performance for three vessels for week 19 of 2011.

Ship	Fuel [×1000 l]	Fuel [l h^{-1}][a]	Fuel [%]	Fuel costs [€]	Fuel costs [€ h^{-1}][a]	Landings [kg]	Landings [kg h^{-1}][a]	Gross revenue [€]	Gross revenue [€ h^{-1}][a]	Net revenue [€]	Net revenue [€ h^{-1}][a]	Net revenue [%]
GO4	35	476	**100**	19,600	267	6620	90	29,000	395	9400	128	**100**
TX36	14	176	**37**	7840	99	4580	58	25,366	319	17,526	220	**172**
TX68	19	233	**49**	10,640	130	5078	62	25,192	308	14,552	178	**139**

Fuel costs are calculated based on the price of €0.56 per liter.
[a] Calculated on the basis of fishing duration: GO4: 73.5 h, TX36: 79.6 h, TX68: 81.7 h.

Table 14
Comparison of overall, plaice and sole landings in 2011 with experiments in 2005 based on measured weight data by haul (van Marlen et al., 2005), and 2006 (van Marlen et al., 2006).

Gear test	Wk, year	CPUE Landings in [kg h^{-1}]			CPUE (>MLS) Plaice in [kg h^{-1}]			CPUE Sole(>MLS) in [kg h^{-1}]		
		Conv.	Pulse	Pulse/Conv. [%]	Mean Conv.	Mean Pulse	Pulse/Conv. [%]	Mean Conv.	Mean Pulse	Pulse/Conv. [%]
1	Pooled 2004–2005	46.90	44.67	95.2	30.94	25.79	83.4	10.47	12.78	122.1
1	41, 2005	69.3	65.7	94.8	28.56	25.56	89.5	20.74	19.30	93.1
2	44, 2005	87.8	57.8	65.8	46.79	24.69	52.8	21.74	17.52	80.6
3	05, 2006	145.7	86.2	59.2	93.43	56.02	60.0	11.92	8.51	71.4
4	09, 2006	75.5	50.2	66.5	29.85	21.66	72.6	11.66	7.93	68.0
5	11, 2006	87.4	61.2	70.0	28.87	20.09	69.6	15.62	10.33	66.1
6	Pooled 2005–2006	95.4	64.6	67.7	46.13	29.76	64.5	16.45	12.87	78.2
1	19, 2011	90.1	60.5	67.1	34.90	24.90	71.4	17.60	15.10	85.9

Data for 2004 and 2005 was recorded with both gear types (Pulse and Conv.) on a research vessel, other by comparing two or more vessels fishing with one gear type each.

chains. Paschen et al. (2000) found that the penetration depth of tickler chain beam trawls varies between 10 and 80 mm depending on the sediment type. Using data of Paschen et al. (2000) it was estimated that the combination of a SumWing with electrical stimulation could reduce the penetration depth by 50% (van Marlen et al., 2009b). Experiments with electrical stimulation in the 1970s already revealed the potential of chasing particularly sole and to a lesser extent plaice, dab and lemon sole out of their burrowed position in the seabed (de Groot and Boonstra, 1970; Stewart, 1977). The effect of pulse stimulation on benthic species varies, with some showing a jerky or jumping response, e.g. ragworm (*Nereis virens* L.), common prawn (*Palaemon serratus* L.), European green crab (*Carcinus maenas* L.), and Atlantic razor clam (*Ensis directus* L.). Others do not show a similar response, e.g., subtruncate surf clam (*Spisula subtruncata* L.), and common starfish (*Asterias rubens* L.) (van Marlen et al., 2009a). The differences in benthos catches were probably caused mostly by the differences in mechanical stimulation between the pulse trawl and the tickler chain beam trawl.

In terms of fisheries management implications the pulse trawl offers a fuel saving alternative for catching particularly sole in mixed fisheries and reducing discards of fish and benthos. An earlier study revealed that there was an indication that direct mortality of invertebrates is reduced in pulse trawling (van Marlen et al., 2001). A downside is that cod can suffer spinal damage when coming close to the electrodes. This happens primarily in larger fish that are caught anyhow, and apparently to a limited extent (e.g. ~10%). The effect was also seen in laboratory studies (de Haan et al., 2011), and more data is needed over longer periods of time to make a more solid quantitative estimate. The total landing of cod by beam trawls (BT2, 80 ≤ mesh size ≤ 120) compared to all gears in use in the Eastern Channel, North Sea, and Skagerrak are in the order of 4–5% based on data from 2010 and 2011(STECF, 2012a). If 10% of these fish would suffer spinal damage, this would only mean 0.4–0.5% of the total landing. Laboratory studies on cod showed that small fish (12–16 cm) were not affected by electrical stimuli, and the effect on larger fish may be reduced by increasing the pulse frequency (de Haan et al., 2011). The spinal injury found in one whiting on TX36 may have been caused by the electrical stimulus or by mechanical forces during haul-back and discharge on deck. This fish was 32 cm long while longer fish did not show any damage. Still unknown are long-term effects on fish and benthos that come in contact with the pulse trawl, but are not retained.

Pulse trawls have continuously been improved, e.g. the DELMECO-group offer a wing-shaped beam instead of the usual cylindrical in their new versions, but with two trawl shoes per side contrary to HFK's pulse wing. This means that our conclusions should be restricted to the technical state of the gears as they were tested in May 2011. On the other hand, when pulse specifications remain unchanged we do not expect great differences with the results produced here.

Discarding is still a major issue in European fisheries, particularly in the beam trawl metiers. The Dutch discard monitoring programme revealed that fish and benthos discards can exceed the volume of landings. Among benthic (invertebrate) species most discarded are: common starfish (*Asteria rubens*); sand star (*Astropecten irregularis*); swimming crab (*Liocarcinus holsatus*); and serpent star (*Ophiura ophiura*). Non-target fish species include: dragonet (*Callionymus lyra*); grey gurnard (*Eutrigla gurnardus*); scaldfish (*Arnoglossus laterna*); solenette (*Buglossidium luteum*); and lesser weaver (*Echiichthys vipera*), while of commercial fish species, common dab (*Limanda limanda*) and European plaice are most frequently discarded. For example, large beam trawlers (mesh size 70–99 mm, >300 hp) discard on average 74 kg h^{-1} of dab while landing 12 kg h^{-1}, and discard 70 kg h^{-1} of plaice while landing 83 kg h^{-1}. These values show the relevance of techniques aimed at discard reduction (van Helmond et al., 2012; Uhlmann et al., 2013).

The ICES advice of 2006 called for avoiding unlimited growth in capture efficiency of pulse trawls and a proper control and enforcement regime in relation to sustainable development in fisheries as was experienced in China (Yu et al., 2006). The need for this was recently repeated by the European Scientific, Technical and Economic Committee for Fisheries (STECF, 2012b). In the Netherlands a

Table 15
Comparison of discards of plaice, sole, common starfish and swimming crab in 2011 with experiments in 2006 (van Marlen et al., 2006).

Category/species	Year	Obs	Comparison of means		[%]	Significance
		(hauls)	Average Conv [n h^{-1}]	Average Pulse [n h^{-1}]		
Fish discards						
Plaice < 27 cm	2006	324	948	997	105.2	n.s.
	2011	33, 66	1515	728	48.0	+++
Sole < 24 cm	2006	182	19	15	75.3	+++
	2011	33, 66	38	13	35.2	n.s.
Benthic fauna discards						
Common starfish (*Asterias rubens*)	2006	294	679	511	75.3	++
	2011	33, 66	1375	760	55.3	+++
Swimming crab (*Liocarcinus holsatus*)	2006	303	3969	2117	53.3	+++
	2011	33, 66	1544	1036	67.1	+++

special task group on the control and enforcement issue was established, with representatives of the Dutch fishing industry, pulse trawl manufacturers, the Animal Supply Chain and Animal Welfare Department (DAD) of the Dutch Ministry of Economic Affairs, researchers of IMARES and LEI, ILVO Ostend, and University Ghent in Belgium, and the Dutch inspection services to address these issues (ICES, 2012). This group has recently provided recommendation for additional procedures and new requirements on electrical power, voltage used and possibly other important electro-technical variables, and explored the idea of certification of pulse trawls. The results of this catch comparison were used in the discussions of this group. In addition desires were expressed for further monitoring of catches, by-catches and pulse system variables on-board commercial pulse trawl vessels.

5. Summary of major conclusions

The application of pulse fishing technology can help to release the economic pressure on beam trawl flatfish fishery due to rising fuel prices. Higher net revenues were obtained for the beam trawlers (TX36 and TX68) fishing with pulse trawls in May 2011 (on average 156%) than for the vessel with conventional beam trawls (GO4), mainly due to their lower fuel consumption (on average 43%). This was caused by the lower towing speed of the pulse trawls, and the absence of heavy tickler chains. More detailed measurements are needed to quantify both effects.

The total catch in the pulse trawls was considerably lower, only 37% of the conventional trawl. Based on the auction data, the vessels fishing with pulse trawls caught much less main target species (67%), including plaice (71%) and sole (86%), but the loss of income was compensated by the lower fuel costs.

There are important ecosystem advantages, as fewer discard fish (57%) and benthic discards (80%) were caught by hectare fished compared to the vessel fishing with conventional beam trawls in this period and on these fishing grounds. The discards of the main target species are also lower, for plaice the ratio by hectare was 62%, and for sole 46%, which was confirmed by the analysis of the length effect.

Pulse beam trawls may cause spinal damage in cod. It occurred in about 10% of the cod catches on-board the pulse trawlers, and mainly in larger individuals, that are usually landed. However, it should be noted that the average catch of cod is lower than with the traditional beam gear (31% in $\mathrm{kg\,h^{-1}}$), and the total landings of cod in flatfish beam trawling in the Eastern Channel, North Sea, and Skagerrak are relatively low, i.e. some 4–5%. There was only one spinal fracture in whiting which might have been caused by mechanical loads. It should be noted however, that the numbers involved were low and more data is needed for statistical analysis and firm conclusions.

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