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Report of the Working Group on Electric Trawling (WGELECTRA)

17 - 19 April 2018

IJmuiden, the Netherlands

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

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Contents

Executive summary

WGELECTRA chaired by Adriaan Rijnsdorp (the Netherlands) and Maarten Soetaert (Belgium) met from 17-19 April 2018 at Wageningen Marine Research, Haringkade 1, IJmuiden, the Netherlands. The working group was attended by 17 participants from five countries to address the request for advice from the Netherlands to compare the ecological and environmental effects of using traditional beam trawls or pulse trawls when exploiting the TAC of North Sea sole, on (i) the sustainable exploitation of the target species (species and size selectivity); (ii) target and non-target species that are exposed to the gear but are not retained (injuries and mortality); (iii) the mechanical disturbance of the seabed; (iv) the structure and functioning of the benthic ecosystem; and to assess (v) the impact of repetitive exposure to the two gear types on marine organisms. This report does not consider the pulse fisheries on shrimp or on razorclam.

In order to provide advice, WGELECTRA developed an assessment framework to evaluate the ecological and environmental effects of traditional beam trawls and of pulse trawls. The assessment is based on (i) a description of the changes in the beam trawl fleet targeting sole and plaice in the North Sea during the introduction of pulse trawls; (ii) a review of the scientific information on the effects of electrical stimulation on marine organisms; (iii) results of on-going research projects. In preparation for the working group meeting, the chairs circulated a work plan to the participants, including a draft table of content of this report and an outline of the assessment framework. The bulk of the information included in this report was made available to the participants prior to the meeting. The working group meeting was focussed on an in-depth discussion of the scientific evidence and the assessment. As several research projects are still on-going, part of the evidence being used in the assessment is in the preparation phase and has not yet been peer-reviewed.

At present about 89 mainly Dutch owned vessels operate under an exemption from the EU-legislation to catch sole using pulse trawls in the North Sea. In addition, 7 vessels deploy pulse trawls to catch brown shrimp during part of the year. In Scotland, 26 vessels have been granted licences to deploy an electrotrawl to catch razorclams as part of a trial fishery. The stimulus in the razorclam fishery is very different from that in the sole fishery. The current report is focussed on the pulse trawl fishery on sole. Unless specifically stated, where ”typical or commercial” stimulus is stated in this document it refers to the sole pulse.

Pulse trawls for sole were introduced in the Dutch flatfish fishery to reduce the high fuel cost and substantial environmental damage of the traditional beam trawl fishery with tickler chains. The fleet of today’s pulse licence holders land about 95% of the Dutch landings of sole. The fleet comprises two vessel types. The smaller Euro cutters (<= 221 kW) alternate pulse trawling for sole with the fishery for brown shrimps and the otter (twin) trawl fishery for other demersal fish or *Nephrops*. The larger vessels (>221 kW) use the pulse trawl to fish for sole throughout the year. Some vessels alternate pulse fishing for sole with traditional beam trawl fishing for plaice.

The total fleet directed sole fishing effort of today’s pulse licence holders (beam trawl and pulse trawl) has slightly decreased during the transition to pulse trawling between 2009 – 2017 while their contribution to the Dutch sole landings increased by 20% (from 75% to 95%). During the transition phase, pulse trawlers have shifted their distribution pattern in the southern North Sea. On local fishing grounds off the Thames and along the Belgian coast, fishing effort has increased. In other areas, fishing effort was either stable or has decreased.

Pulse trawls are more selective than traditional beam trawls when catching sole. The landing efficiency estimated from catch and effort data of the Dutch beam and pulse trawl fleet is 30% higher for sole and 40% lower for plaice. The improved species selectivity is also reflected in the 16% (small vessels) and 24% (large vessels) lower catch rate of discarded fish in the pulse trawl as observed in the discard monitoring programme. It is uncertain whether the pulse trawl has improved the size selectivity, e.g. catching fewer undersized fish relative to larger sized classes of the same species.

Pulse trawls are deployed at a lower towing speed than traditional beam trawls. Average towing speed is reduced by 22% from 6.3 to 4.9 knots in large vessels and by 15% from 5.4 to 4.6 in small vessels. The replacement of mechanical stimulation by electrical stimulation has reduced the physical disturbance of the seafloor. The average disturbance depth of an experimentally trawled study site was reduced from 4.0 cm with the traditional beam trawl to 1.8 cm in the pulse trawl (-55%). The lower towing speed and cleaner catch are expected to improve the survival of discarded flatfish.

The available literature on the potential negative effects of electrical stimulation of pulse trawling was reviewed. The impact of exposure to electrical pulses is determined by the frequency of exposure and the interval between successive exposures, as well as the sensitivity of the animal. Due to the reduced towing speed and slight reduction in fishing effort in the pulse fishery for sole, the overall exposure probability is reduced. Due to the heterogeneity of trawling, only 17% of the grid cells (1x1 minute) trawled have a trawling intensity of more than one time per year.

A number of laboratory experiments were carried out in which a selection of fish species were exposed to electrical stimuli to study possible adverse effects. These studies indicate that pulse stimulation used in the fishery for sole did not cause direct mortality during exposure but may cause spinal fractures and associated haemorrhages in gadoid round fish species (in particular cod), but not in flatfish species (sole, plaice, dab) or seabass. Preliminary results from an on-going project showed that 18% of 362 cod sampled from nine fishing trips of six pulse vessels showed a spinal fracture and/or full dislocation, while 24% showed smaller spinal abnormalities. Results suggest that the sensitivity is size dependent with lower incidence rate in small (<18 cm) and large (>65 cm) cod. Further studies are required to study the relationship between spinal fractures and body size and determine the differences in sensitivity towards spinal injuries across fish species. Data on sub-lethal effects and/or long-term effects are scarce and inconclusive. Small-spotted catshark *Scyliorhinus canicula* were still able to detect the bioelectric field of a prey following exposure.

Preliminary experiments with a range of benthic invertebrates generated variable results due to the low number of animals tested. More elaborate experiments with brown shrimp and ragworms did not find evidence for increased mortality when exposed to pulses similar to those used in the sole fisheries. However, when exposed 20 times during a 4-day period, an increased mortality was noted for brown shrimp compared to one of two control treatments, but not to mechanically stimulated shrimps.

Little is known on the effects of electrical stimulation on the development of eggs and larvae. One experiment exposing 8 early life stages of cod (embryos, larvae, early juveniles) to a very strong shrimp pulse stimulus, (a strength which only occurs very close to a commercial electrode), did not find differences in morphometrics between exposed and control animals, but observed a reduced developmental rate in one embryonic stage and an increased mortality in 2 larval stages following exposure.. No adverse effects were noted following exposure of two embryonic, two larval and one juvenile stage(s) in sole. Both experiments only studied possible short-term effects of the pulse and included a limited set of parameters to evaluate the sub-lethal effects. The effects of the sole pulse on reproduction have not been studied yet.

In contrast to the mechanical disturbance of the traditional beam trawl, preliminary results of recent studies on the effect of pulse stimulation on the biogeochemical functioning of the benthic ecosystem have not provided evidence that the electrical pulses used in the fishery for sole result in changes in sediment oxygen consumption, oxygen micro-profiles or surface chlorophyll levels. Effects on benthic ecological functioning has not yet been investigated.

Summarising the available evidence shows that the replacement of the tickler chain beam trawl with pulse trawl with electrodes to exploit sole results in a reduction of the environmental impacts: catch rate of fish discards (-16% to -24%), catch rate of benthos (-62% in large vessels and +6% in small vessels), trawling footprint (-18%), mechanical impact on seafloor and benthos (–50%) and CO_2 emissions (-46%). There is insufficient evidence to fully understand the impact of electrical pulse on marine organisms and the benthic ecosystems across the North Sea. The possible adverse effects of electrical pulses on marine organisms and the benthic ecosystem are still being investigated. The available evidence so far suggests that the spinal fractures induced by the cramp response to the sole pulse are observed in two roundfish species, but not in flatfish which comprise more than 80% of the catch. Various gaps in knowledge on the effects of electrical stimulation on marine organisms and ecosystem functioning still exist. The on-going research on the effects of electrical stimulation on marine organisms and ecosystem functioning will improve the scientific basis to assess the ecological effects on the scale of the North Sea.

1 Administrative details

Working Group name
WGELECTRA
Year of Appointment within the current three-year cycle
2018
Reporting year concluding the current three-year cycle
3
Chairs
Adriaan Rijnsdorp, the Netherlands
Maarten Soetaert, Belgium
Meeting venue(s) and dates
17–19 April 2018, Wageningen Marine Research, IJmuiden, the Netherlands (17 participants)

2 Terms of Reference

a) Produce a state-of-the-art review of all relevant studies on marine electrofishing. Yearly update it by evaluating and incorporating new research to it.

b) Compare the ecological and environmental effects of using traditional beam trawls or pulse trawls when exploiting the TAC of North Sea sole, on (i) the sustainable exploitation of the target species (species and size selectivity); (ii) target and non-target species that are exposed to the gear but are not retained (injuries and mortality); (iii) the mechanical disturbance of the seabed; (iv) the structure and functioning of the benthic ecosystem; and to assess (v) the impact of repetitive exposure to the two gear types on marine organisms.

c) Discuss and prioritise knowledge gaps, and discuss ongoing and upcoming research projects in the light of these knowledge gaps, including the experimental set up.

3 Introduction

Investigations in the use of electricity in catching target species have a long history (Soetaert *et al*., 2015b). In the North Sea, the studies focussed on the fishery for sole, *Solea solea*, and brown shrimp *Crangon crangon* (Boonstra and de Groot, 1970; Vanden Broucke, 1973, Stewart, 1977; Horn, 1977). The early studies were successful and indicated an improved catch efficiency for sole and a reduced bycatch of undersized fish (van Marlen *et al*., 1997). For the bottom trawl fishery for shrimps, Polet *et al*. (2005) showed that electrical stimulation could considerably reduce the bycatch of both fish and undersized shrimps. In 1988, the EU decided to include the electrified fishing in the list of illegal fishing methods on the basis that allowing an even more efficient fishing gear in the fishery for North Sea sole, could aggravate the over-capacity of the fleet and could in turn contribute to overfishing.

Around 2005, there was renewed interest in applying the pulse trawls in the beam trawl fisheries targeting sole *Solea solea* and plaice *Pleuronectes platessa* (van Balsfoort *et al*., 2006). The low TAC in combination with a high fuel price jeopardised the economic viability of the fleet while the growing concern about the disturbance of the sea floor and the benthic ecosystem and the high discard rate, had led to calls for the fishery to improve its practices. In 2006, the EU allowed North Sea member states to issue pulse trawl licences to up to 5% of their fleet. In 2011 and 2014, the Netherlands got permission from the EU to issue 20 and 42 additional licences up to a total of 84 (Haasnoot *et al*., 2015). In January 2018 about 84 vessels are using the pulse trawl to fish for sole, while 5 vessels were using the pulse trawl (during part of the year) to catch shrimps.

The use of electricity to catch sole raised concerns about the possible increase mortality of target and non-target species, including those that are not retained in the gear, about a possible increase in the fishing mortality of sole and plaice, and on delayed mortality, long-term population effects, and sub-lethal and reproductive effects on target and non-target species (ICES 2006, 2012, 2016). ICES (2012, 2016) recognised that conventional beam trawling has significant and well-demonstrated negative ecosystem impacts, and if properly understood and adequately controlled, electric pulse stimulation may offer a less ecologically damaging alternative. ICES (2016) therefore advised to undertake structured experiments that can identify the key pulse characteristics and thresholds below which there is no evidence of significant long-term negative impact on marine organisms and benthic communities. ICES (2016) also recommended that as part of the regulatory framework, information on the pulse parameters used during fishing operations is made available to the scientific community as this information is needed to conduct assessments of the ecological impact of the pulse fisheries. ICES (2016) recommended that a research programme should be set up to address outstanding issues, including long-term and/or cumulative effects of flatfish and shrimp pulse trawling.

In response to the concerns, several research projects have been started since 2006 to address specific concerns. Notably two PhD-projects were started in Belgium. Soetaert (2015) studied the effects of electric pulses on marine organisms and explored the safety range for marine species. Desender (2018) studied the impact of the shrimp pulse on a selection of marine fish species. In the Netherlands a 4-year research project was started in 2016 including two PhD-projects (https://www.pulsefishing.eu/research-agenda/impact-assessment-of-the-pulse-trawl-fishery).

The growth of the number of licences has fuelled criticism on the commercial scale of pulse trawling while the concerns about possible harmful effects are still being investigated (Kraan *et al*., 2015). Fishers in England, Belgium and France have voiced concerns about falling catches on their traditional fishing grounds, while the French environmental organisation, Bloom, campaigned against pulse fishing (Stokstad, 2018). In January 2018, the European Parliament voted against pulse trawling in the context of the revision of the technical measures. In 2018, in order to further inform and support the decision-making process, the Netherlands requested that ICES advise on the comparison of the ecological and environmental effects of using traditional beam trawls or pulse trawls when exploiting the TAC of North Sea sole.

In order to help provide this advice, WGELECTRA developed an assessment framework to evaluate the ecological and environmental effects of the traditional beam trawls and the pulse trawls. The assessment is based on a review of the scientific information. In preparation for the working group meeting, the chairs circulated a work plan to the participants, including a draft table of contents of the report and an outline of the assessment framework. The work plan and assessment framework were discussed by email and participants were invited to contribute specific sections of the report prior to the meeting. The working group meeting was focussed on an in-depth discussion of the scientific evidence and the assessment. As several research projects are still on-going, part of the evidence being used in the assessment is in the preparation phase and has not yet been peer-reviewed.

4 Assessment framework

The pulse trawls apply an electrical stimulus to catch flatfish. The electrodes in the pulse trawl replace the tickler chains in the traditional beam trawls that mechanically stimulate flatfish to leave the sea floor. The pulse trawls are particularly effective in catching sole. Pulse trawling is restricted in the southern North Sea south of 55^0 N and 56^0N where a mesh size of 80mm is permitted.

In the terms of reference, several criteria were specified to assess the ecological and environmental impacts of the pulse trawls and the traditional beam trawls. To make these criteria operational, sub-criteria were defined which can be quantified based on the available scientific knowledge (Table 4.1). The criteria and sub-criteria reflect the concerns expressed by stakeholders on possible adverse effects of pulse fishing on the marine environment and on the general concerns about the adverse effect of bottom trawls (Kraan *et al*., 2015; Kaiser *et al*., 2016). For each criterion, the scientific literature was reviewed for evidence that the pulse trawl has a lower, similar or higher impact, or where there is insufficient evidence to make conclusions, and where possible the impact was estimated quantitatively. The strength of the scientific support is assessed as proven, indicative or inferred. Proven is used when there is strong experimental or observational evidence available. Indicative is used when there is limited experimental or observational support. Inferred is used when there is no empirical evidence but when there is a mechanistic understanding about a causal chain of steps that suggests a conclusion.

Table 4.1. List of criteria used to assess the ecological and environmental impacts of the pulse trawls and the traditional beam trawls

Sustainable exploitation of the target species

- Catch efficiency (catchability)
- Species selectivity
- Size selectivity
- Discards (undersized commercial species)
- Bycatch invertebrates
- Discard survival
- Risk of overfishing
- Fishing effort
- Spatial distribution

Exposure

- Frequency of exposure
- Repetitive exposure
- Penetration depth of the gear (mechanical) into sediment
- Penetration of electric field into sediment
- Radiation of electric field around the pulse trawl

Target and non-target species exposed to gear but not retained

- Injuries
- Mortality
- Feeding
- Reproduction

Benthic invertebrates

- Adverse effect of mechanical disturbance

- Adverse effect of electrical stimulation (mortality, sub-lethal effects, reproduction)

Mechanical disturbance of sea bed

- Depth of disturbance
- Resuspension of sediment

Structure and functioning of the benthic ecosystem

- Benthos biomass
- Bio-geochemistry

Environment

- CO_2 emission
- Pollution
- Electrolysis

5 Electrofishing

5.1 Introduction

The term 'electrofishing' has been used since the 1950's, at which time it referred to a sampling technique for fish in freshwater whereby electric energy is passed into the water. Freshwater electrotrawling differs from pulse trawling electrofishing in almost every characteristic, as overviewed in Appendix 3. In the North Sea electrofishing is used in the fishery for sole, shrimp and razorclam *Ensis*, all with their own specific gear (Table 5.3.1). In this report, we focus on the electrofishing for sole using pulse trawls.

This report reviews the scientific knowledge and research questions relating to the pulse trawl targeting sole. This information should allow ICES to compare the ecological and environmental effects of using traditional beam trawl or pulse trawls when exploiting the TAC of North Sea sole as requested by the Dutch Government.

Note that the all following information is strictly related to pulse fishing on sole, except when explicitly stated differently. Therefore, any conclusions and recommendations only apply for pulse trawls targeting sole by means of a cramp pulse. More information on (the effects of) pulse trawling for shrimp or background information of the studies briefly summarized in the present report can be found in Appendix 3.

5.2 Pulse trawling in the North Sea

5.2.1 The number and distribution of pulse trawls in the North Sea

In total 89 vessels are using a pulse trawl to target sole and 7 are using a pulse trawl to catch shrimp (Table 5.2.1) in the North Sea.

Table 5.2.1. Number of active pulse vessels by country flag (1/1/2018) and fishery.

Country	Sole fishery	Brown shrimp fishery
Netherlands	78	4
Belgium	0	2
Germany	8	1
United Kingdom	3	0

Most pulse trawlers originate from the Netherlands, or are Dutch vessels flying the German, UK or Belgium flag. The temporal evolution of the licences used in the Netherlands is shown in Figure 5.2.1. Of the 84 pulse licences issued in the Netherlands (Haasnoot *et al*., 2016), 78 are in use (spring 2018) in the sole fishery: 20 licences are used by small vessels (engine power <= 221 kW) and 58 by large vessels (>221 kW). Four licences are used in the fishery for shrimps, depending on the season.

The licences were granted by the EU in the following steps:

- 22 under a derogation under Annex III (4) of Council Regulation (EC) No. 41/2006 allowing 5% of the beam trawler fleet by Member States fishing in ICES zones IVc and IVb to use the pulse trawl on a restricted basis, provided that attempts were made to address the concerns expressed by ICES (2006);
- 20 vessels based on Article 43,850/1998, which is a regulation for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms (2010);
- 42 temporary licences in the context of the landing obligation to explore in technological innovations to reduce discarding (2014).

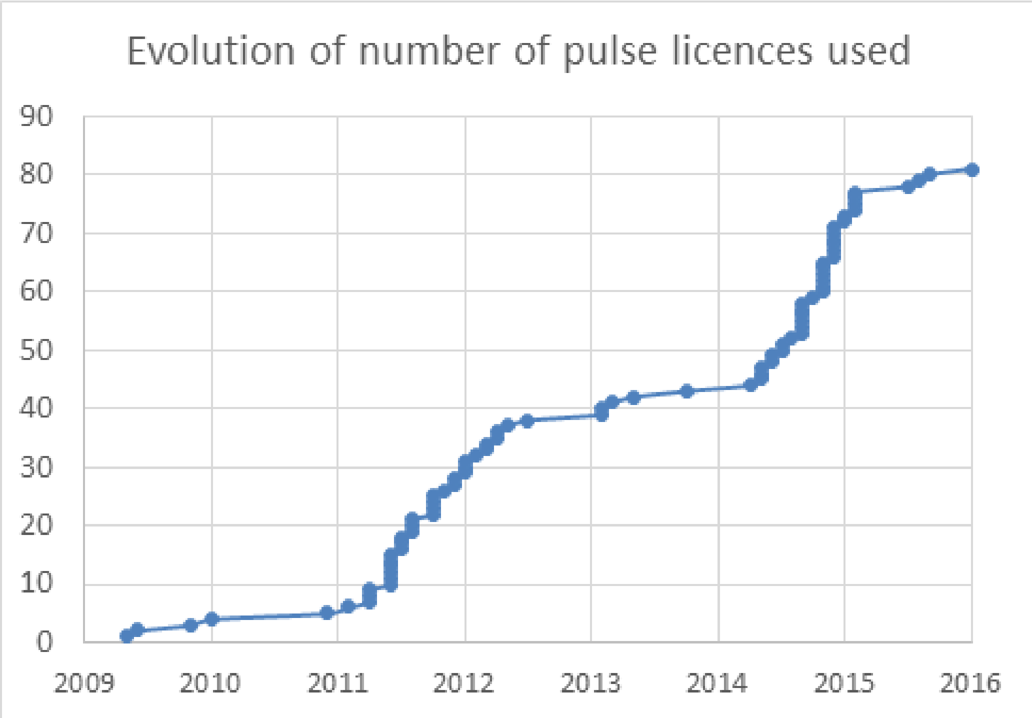


Figure 5.2.1. The evolution of the number of pulse licences used in the Netherlands.

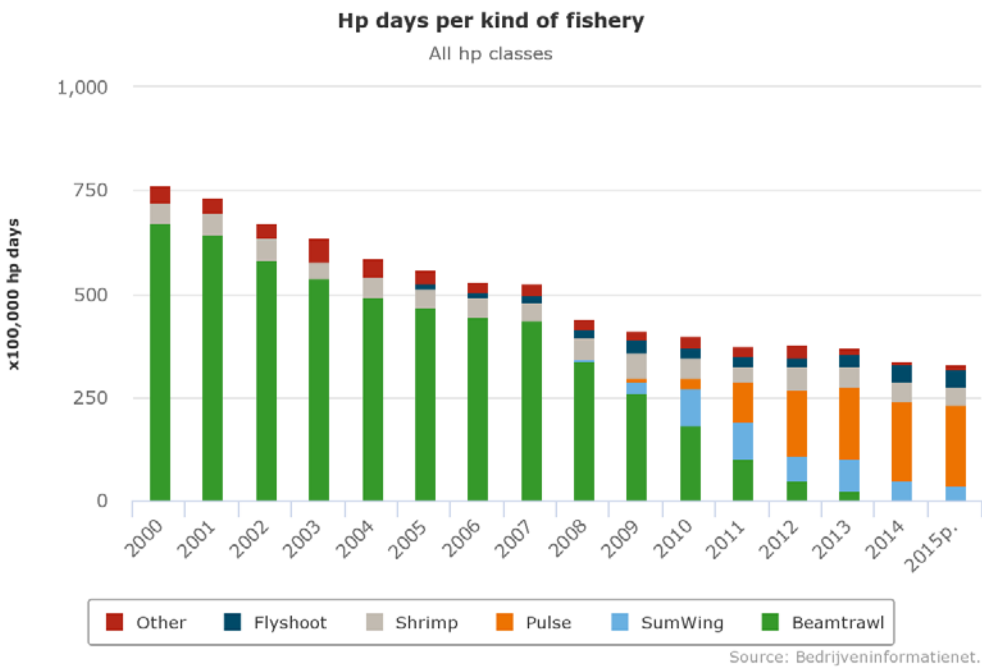


Figure 5.2.2. HP days (105) by fishing gear in the Dutch fleet between 2010 and 2015 (Source: Bedrijveninformatienet).

Figure 5.2.2 shows the gradual reduction in the beam trawl effort since 2000 and the shift to pulse trawling. The shrimp fishery is predominantly carried out with a conventional shrimp beam trawl with bobbins. The Sumwing gear deploys tickler chains comparable to the conventional beam trawl. The pulse includes both Pulsewing and Delmeco pulse trawl (see section 5.3).

5.3 Pulse trawls used in the fishery for sole

The pulse trawls targeting flatfish are currently constructed by 2 manufacturers (Figure 5.3.1). The majority of vessels are using the 'Pulsewing' of HFK engineering, combining electric stimulation with a Sumwing. This is a wing-shaped foil with a runner/ tow-point at the centre which is typically used on flatfish fishing grounds and reduces fuel consumption by about 10%. The other company, Delmeco Group, rigs the electrodes in a conventional beam trawl (with the tickler chains removed). The electrode design and pulse settings produced by each are listed in Table 5.3.1. The number of vessels using HFK pulse modules is about 5 times that using the Delmeco design (Turenhout *et al*., 2016).

Figure 5.3.1. HFK pulse wing (left) and Delmeco pulse beam trawl currently being used in the North Sea fishery for sole.

Pulse trawls receive electric power from the vessel by an additional cable that also provides communication between the wheelhouse and the fishing gear. In both Delmeco and HFK systems the electrodes are connected to pulse modules, i.e. small ceiled units with electronics, built-in to the beam or wing. The number and the configuration of the electrodes may vary according to the gear width and the manufacturer, although physical limits of the gear are described in a directive issued by the Dutch Ministry of Economic Affairs on 18 November 2016 (01. 20161111 "Nieuwe Voorschriften Pulstoestemming Platvis version 1.3") and refers to the conditions of electric gear application as described in article 31bis, lid 2 of the European reference for Technical Measures (EU 850/98).

The electrical pulses are characterized by the maximum voltage, frequency, pulse width and pulse shape. The product of pulse width and pulse frequency, which is called the duty cycle, gives the time that there is an electric current flowing between the conductors. The two flatfish pulse systems differ in their electrical characteristics and in the number and the design of the electrodes. In this report we will not differentiate between the HFK and Delmeco pulse trawls.

Table 5.3.1. Characteristics of two flatfish pulse systems (Delmeco, HFK), shrimp pulse system, *Ensis* fishery and fresh water electrofishing system (adapted and extended from WGELECTRA Report 2017)

	Flatfish pulse		Shrimp pulse	Ensis	Fresh water
	Delmeco	**HFK**	**Marelec**		
Towing speed (knots)	~5	~5	2.5-3.5	~0.1	0
Length electrodes	Max 4.75	Max 4.75		2.2	
Length conductor elements (cm)	18	12.5	150	2.2	
Number conductor elements	6-12	6-12	1	2,4 or 6	2
Diameter conductor elements (mm)	28	28	12	12.75	NA
Distance between electrodes (cm)	42	42.5	60	100	Variable
Maximum voltage between conductors (Vpeak)	55	55	65	24	100-500
V_{rms}*	±8	±8	±3		
Pulse type	PBC	PAC	PDC	AC Sine	DC &
Pulse frequency (Hz)	40	60-80	5	50	15-500
Pulse width (µs)	± 220	350-250	500	continuous	
Duty cycle (%time)	± 1.8	± 2	0.25	100	

* Root mean square of the voltage is used in the technical regulation and reflects the time averaged mean voltage.

The main differences between the pulse parameters in flat fish and shrimp fisheries are the frequency, i.e. the number of pulses per second expressed in Hz, and the pulse type which is determined by how the current runs. The frequency of the shrimp system is 5 Hz, whereas the pulse trawls on sole use a higher frequency between 40 and 80 Hz. Depending on the number of pulses used per second (frequency [Hz]), species and size classes investigated have shown different (behavioural) reactions ranging from a startle or escape response at frequencies below 20 pulses per second (20 Hz) to a cramp reaction when more pulses per second/higher frequencies are used. Based on these findings, different pulses are designed allowing shrimp to jump up from the seafloor (shrimp startle pulse) or to immobilize sole by inducing a muscular cramp response. The second important parameter is the electric current which can run in two ways: Direct Current (DC) which is the movement of electric charges in one direction and Alternating Current (AC), which is a bipolar current flow. Both types can be applied with intervals and hence will generate pulses. In case of DC this results in Pulsed Direct Current (PDC). In case of AC this results in either Pulsed Alternating Current (PAC) if 1 pulse consist of a positive and negative part, or in Pulsed Bipolar Current (PBC) if 1 pulse is successively positive or negative. A detailed description of all parameters involved will be submitted by Soetaert in the summer of 2018 (Soetaert & Boute, 2018) Note that the electrotrawls targeting *Ensis* do not use pulsed current, but instead apply a continuous alternating current.

All pulse systems use wired electrodes. The sole pulse electrodes comprise of alternating conductor and isolator elements. The electrical characteristics of the shrimp pulse are described in Verschueren *et al* (2014). The main difference between the sole pulse and the shrimp pulse system is the lower pulse frequency applied in the shrimp pulse.

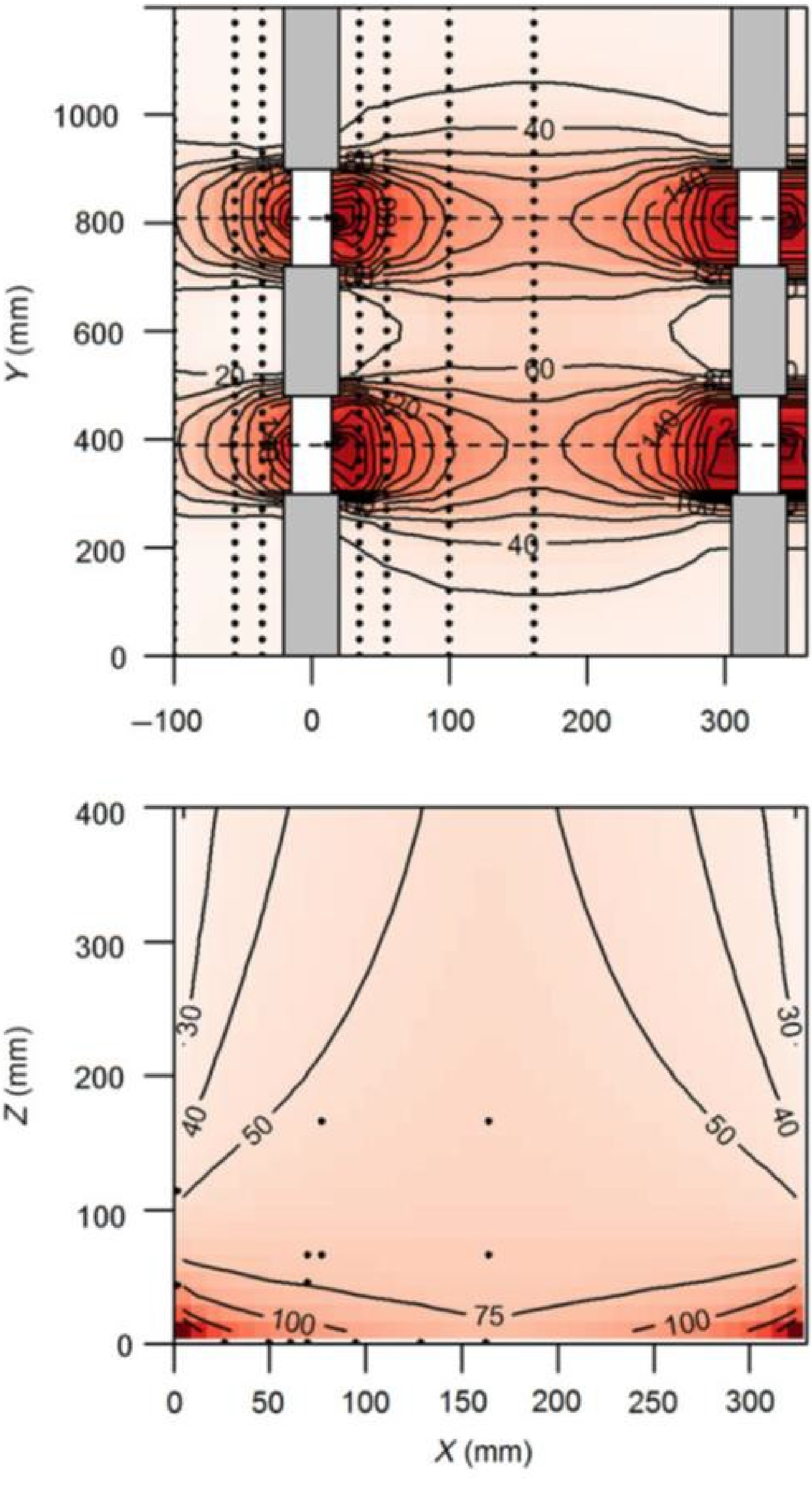


Figure 5.4.1. Contour plot of peak field strength (V/m) around a pair of Delmeco electrodes positioned at X=0 mm and X = 325 mm as measured in a tank. The field strength is shown in the horizontal X-Y plane (a) and the vertical X-Z plane (b). Locations of measurements are indicated by black dots. White parts show the conductor elements. The grey parts show the isolator elements. From de Haan *et al* (2016).

5.4 Field strength measurements of the sole pulse

De Haan *et al*. (2016) measured the heterogeneity of the electric field around a pair of Delmeco electrodes at the level of the bottom of the tank and at several distances above the bottom (Figure 5.4.1). The heterogeneous electrical field shows highest field strength close to the conductor. The field strength decreases with increasing distance from the conductor both in the horizontal and vertical plane. As the electrodes are within 400 mm of the wings of the trawl, the field strength outside the trawl was estimated to be 17 V.m-1 at the wings of the trawl. Based on the exponential decrease in field strength with increasing distance to the nearest conductor (Table 2 in de Haan *et al*., 2016), the field strength outside the trawl drops from a level around 5 V.m-1 at 1 meter from the wings and 0.9 V.m-1 at 10m from the wing.

In order to study the electric field in situ and also to study the penetration of the electric field into the sediment, two experiments were conducted in the winter of 2016/2017 on two inshore locations: (1) Neeltje Jans rescue harbour on the seaward side of the Oosterschelde barrier dam; (2) Mokbaai shore south of the island Texel. The first location represents compact North Sea sand, the second a mixture of mud and sand. Both locations have an open connection to the North Sea. The methods involved three pairs of Delmeco conductors spread out over an area of 5x1 m and connected in parallel to a Delmeco pulse module system. The conductor distance was 325 mm, similar to the distance applied in earlier WMR laboratory studies. This distance is smaller than the electrode distance used in the commercial fishery (42 cm). Figure 5.4.2 shows the positions of the field measurements relative to the conductor pair.

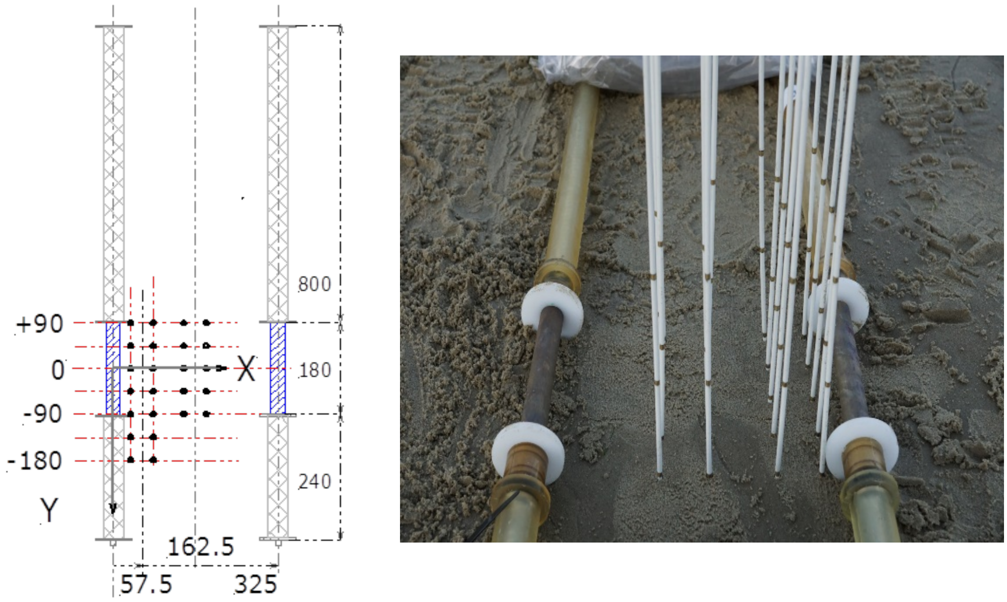


Figure 5.4.2. Measured positions in the horizontal plane between a pair of conductors with a field trial example for two positions of X (X=57.5 & 162.5) and five positions of (-90, -45, 0, +45, +90 mm). The vertical axis Z refers to 5 levels, in the water volume (+200, +100 mm), at the bottom (0) and in the sediment (-100, -200 mm). The centre of the conductor is defined as the origin of the coordinate system (X=0, Y=0 mm, Z=0).

Table 5.4.1. Maximum field strength results (V. m⁻¹) at 60V conductor voltage at two distance ranges (X) from a conductor. All values refer to 0-peak, (n) refers to the number of data series.

Close range X=57.5 mm				Mid-range X=162.5 mm					
	Mokbaai (1)	Neeltje Jans (8)	Mokbaai (9)	Neeltje Jans (1)	Neeltje Jans (1)	Neeltje Jans (1)	Mokbaai (1)	Mokbaai (1)	Mokbaai (1)
Z axis	Y=-180	Y=-45 to +45	Y=-45 to +45	Y=-45	Y=0	Y=+45	Y=-45	Y=0	Y=+45
+200	11	21-23	19-25	31	26	22	27	29	27
+100	19	67-70	48-75	71	66	55	61	66	60
0	22	220	263*	104	107	98	97	**	95
-100	18	46-52	42-65	58	64	66	62	59	59
-200	14	22-23	12-37	26	31	36	34	28	27

* *finding exceeded the voltage input ranges and is the extrapolated result of the linear conductor voltage trend.*
** *the results not used (unexplained error), all other results for Y confirmed the Neeltje Jans outcome.*

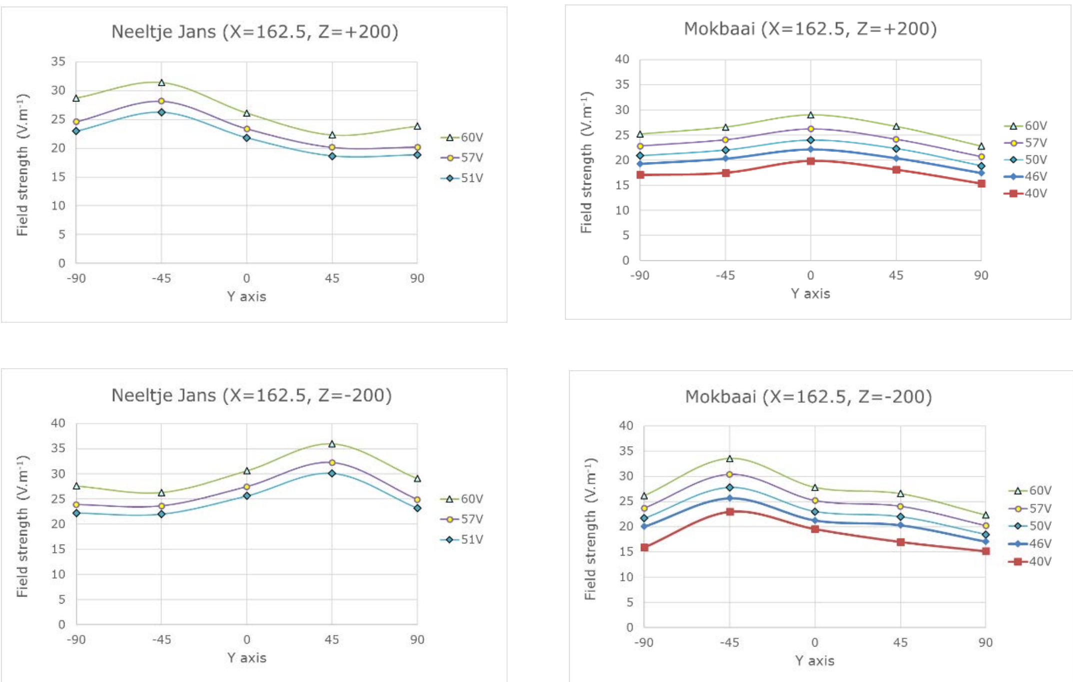


Figure 5.4.3. Field strength ranges at the boundaries of Z (+200 to -200 mm) as a function of conductor voltage of both measured locations.

A summary of results is presented in Table 5.4.1. The highest field strengths measured were in the range of 220 to 263 V.m-1 at bottom level closest to the conductor (X=57.5 mm, Y=0 mm, Z=0 mm). As the peak of field strength was not always opposite the centre of the conductor (Y=0 mm), as illustrated in Figure 5.4.3, the maximum values listed refer to three positions of Y (Y= -45 mm, Y=0mm, Y= +45mm). The lowest values for these references of X and Z were found opposite the isolator (Y = -180 mm).

The results of both sediment types fitted the expectation that at the boundaries of the vertical field (Z=+/-200 mm) the maximum field strength of 36 V.m-1 occurs at equal distance from the conductors (X=162.5 mm, Y=+/-45 mm) and reduced to 23 V.m-1 towards the conductor (X=57.5 mm).

When these vertical boundaries are narrowed (Z=-/+100mm) the maximum mid-range field strength increased to 66 V.m-1 for both levels of Z. Closer to the conductor (X=57.5 mm) maximum field strength in the sediment was similar (Z=-100 mm), but higher and more irregular (48-75 V.m-1) in the water volume of the Mokbaai location.

Replicate field strength measurements in the compact sandy sediment (Neeltje Jans) showed low variation and were all within 2-4 V.m-1. In the less compact sediment of sand and mud (Mokbaai), the results varied between replicates and also varied significantly between conductor pairs of a single experiment.

Conclusion

Field strength measurements in tanks showed that the field strength is highest close to the conductor and decrease exponentially with increasing distance from the conductor. Outside the trawl the field strength is reduced to < 17 V.m-1. The in situ measurements corroborate the field strength measurements carried out in tanks and showed that at 200mm below the seabed, the field strength is around one third of that at the seabed, and at least as high at 200mm above the seabed. This indicates that the soft sediments (sand and sandy-mud) of the typical fishing grounds of the sole fishery hardly reduce the electric field strength. This observation was most explicit equidistant from the conductors.

6 Sustainable exploitation

6.1 Introduction

Concern has been expressed about the potential negative consequences of the increased catch efficiency of the pulse trawl for the sustainable management of flatfish stocks, in particular for sole (ICES, 2006). This concern has been fuelled by the experience in China, where the introduction of an electrified trawl in the fisheries for shrimps increased the efficiency and resulted in an overexploitation of the shrimp stock. The Chinese pulse stimulus was similar to the one used today in the fishery for brown shrimp (5 Hz, 0.3 ms pulse width and 60 V), but the electrodes and exposure length were more than 20 times longer. Lack of regulation, however, resulted in (i) increased power output and reduced electrode distance to increase the strength of the field strength, which resulted in a poor size selectivity and high mortality of juvenile shrimp; (ii) unregulated increase in the use of the electrified trawls (Yu *et al.*, 2007). This chapter will analyse how the 78 vessels that obtained a pulse licence in 2017 have allocated their fishing effort over different métiers while switching from beam trawl to pulse trawl. This chapter further analyses the changes in the spatial distribution and in catch efficiency for the main target species.

6.2 Evolution of pulse trawl effort

Following the incremental deployment of pulse licences, pulse fishing effort has increased since 2009, while the fishing effort of traditional beam trawls targeting sole (TBB_SOL) has decreased (Figure 6.2.1). The fishing effort refers to the group of 78 vessels that had obtained a pulse licence by 2017 and excludes vessels that did not switch to pulse fishing. This group of 78 vessels is referred to here as pulse licence holders. These vessels are using the pulse trawl to target sole (PUL_SOL) with a codend mesh of 80mm, but may also deploy other gears during part of the year. Large vessels (>221 kW) may use conventional beam trawls with a mesh size of >100 mm during part of the year to target plaice (TBB_PLE). Small vessels (<=221 kW) may use conventional shrimp beam trawls with bobbins to target shrimps (TBB_CRG) or use otter (twin) trawls to target other demersal fish or *Nephrops* (OTHER).

During the transition period the fishing effort of large vessels was constant. The percentage of effort targeting sole decreased from 95% in 2009 to 87% in 2017, while the percentage effort targeting plaice increased. The increase in the percentage effort targeting plaice is due to some of the pulse vessels that switch back to the traditional beam trawl to utilise their plaice quota during part of the year. Total fishing effort of the Euro cutter licence holders showed a slight increase until 2013 and a decrease to the level at the start of the study period. The proportion of effort allocated in the sole fishery was around 70% without a trend and is not affected by the introduction of the pulse trawl.

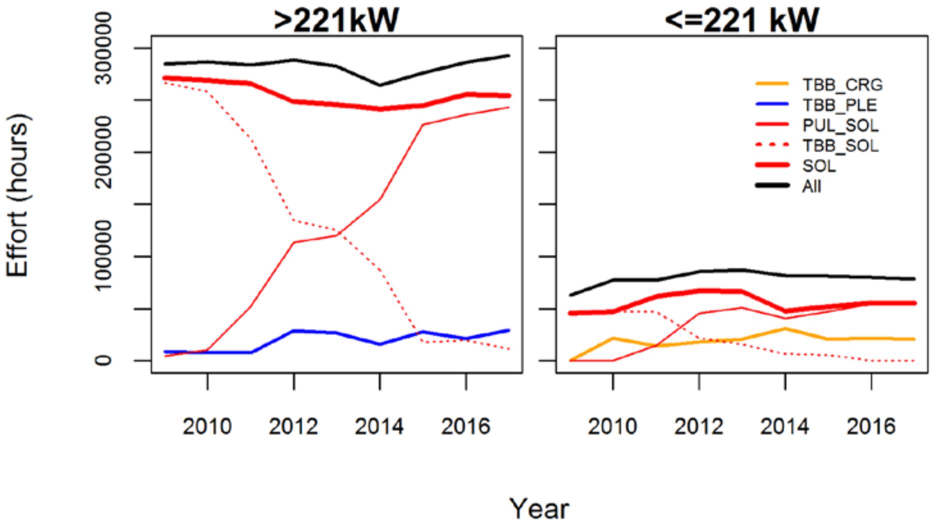


Figure 6.2.1 Effort by metier of all those vessels with a pulse licence in 2017. PUL_SOL = pulse trawl fishery targeting sole; TBB_SOL = beam trawl fishery with tickler chains targeting sole; TBB_PLE = beam trawl fishery targeting plaice (mesh size >=100mm); TBB_CRG = beam trawl fishery for shrimps. SOL represents the total effort in the sole fishery (TBB_SOL + PUL_SOL). All represents the total fishing effort of the todays pulse licence holders.

The proportion of the sole landings caught in pulse trawling increased from 2% in 2009 to 95% in 2017 for large vessels and from 0% in 2010 to 99% in Euro cutters. The proportion of plaice caught by pulse trawlers lagged behind the increase in fishing effort. In 2017, large pulse trawlers landed 53% of the plaice with 83% of the fishing effort, while traditional beam trawlers landed 43% with 14% of the effort.

These changes in absolute effort and the allocation to the sole fishery following the transition to the pulse gear is due to the improved efficiency of the pulse trawl to catch sole and the reduced efficiency to catch plaice. It could be expected that an estimated increase in the catches (landings) efficiency for sole of 30% (see section 6.6) would have resulted in a similar decrease in effort allocated to sole fishing, but this was not observed in the effort data. The proportion of effort allocated to sole fishing (TBB_SOL and PUL_SOL) did not show a decreasing trend in Euro cutters and showed a slight (9%) decrease in large vessels (Figure 6.2.2). However, when compared with the total sole landings by Dutch fishing vessels, pulse licence holders increased their share from 75% in 2009 to 95% in 2017, while the share of plaice decreased from 70% in 2009 to 59% in 2017 (Figure 6.2.3). These changes were observed in large vessels (sole: 79% to 95%; plaice: 73% to 64%) and Euro cutters (sole: 46% to 92%; plaice: 40% to 23%). The 27% (95/75) increase in the share of sole landings corresponds to an estimated increase in catch (landings) efficiency of 30%. The increase in their share of the landings is likely due to the trade and lease of sole quota.

Figure 6.2.2. Proportion of the fishing effort of pulse licence holders targeting sole (TBB_SOL + PUL_TBB). Euro cutters (red) and large vessels (blue).

Figure 6.2.3. Contribution of vessels with a pulse licence to the total landings of sole and plaice by Dutch vessels.

6.3 Changes in towing speed

The change from beam trawl to pulse enables a reduction in towing speed (Table 6.3.1). The average towing speed of the vessels (>221 kW) that obtained a pulse licence declined by 19% from 6.3 knots in 2009 to 5.1 knots in 2017 when fishing for sole or plaice. For the Euro cutters, overall towing speed when fishing for sole or plaice declined by 14% from 5.4 knots in 2009 to 4.6 knots in 2017.

Table 6.3.1 Mean towing speed by fishing trip as recorded with VMS for pulse trawls (PUL_SOL) and traditional beam trawls deployed in the fishery for sole (TBB_SOL) and

plaice (TBB_PLE) with small (<=kW) and large (>221kW) vessels. N denotes the number of fishing trips.

	<=221kW			>221kW		
gear	mean	sd	n	mean	sd	n
PUL_SOL	4.63	0.31	4182	4.90	0.27	11119
TBB_PLE	4.55	0.00	2	6.32	0.48	1392
TBB_SOL	5.36	0.40	2497	6.31	0.48	11320

6.4 Spatial distribution of the pulse and beam trawl fishery

The spatial distribution of the pulse licence holders targeting sole (80mm mesh size) with a traditional beam trawl or the pulse trawl shows a change towards fishing grounds in the southern North Sea south of 53o30’N (Figure 6.4.1). Hot spots of pulse trawling are apparent on the Norfolk Sandbanks and off the Thames estuary. The maps show the average distribution patterns over the period 2009-2017. Absolute fishing effort has decreased over large parts of the fishing area in the German Bight and remained relatively stable in the other areas. In the most southerly part of the North Sea, fishing effort has increased in some of the rectangles, for instance in the rectangle off the Thames Estuary (32F1) and to a lesser degree in 32F2 off the Belgium coast (Table 6.4.1). No increase in fishing effort was observed on the Norfolk Sandbanks (34F1, 34F2) rather a shift in gear from traditional beam trawl to pulse trawl. The shift in the spatial distribution of the sole fishery implies that a larger proportion of the sole landings is caught in the southern North Sea (Table 6.4.2).

The changes in spatial distribution are likely related to changes in seafloor habitats fished. Anecdotal information from the fisheries indicates that pulse trawlers are able to fish in habitats, in particular muddy habitats, which were previously inaccessible to beam trawls.

Table 6.4.1. Fishing effort (hours) of the pulse licence holders fishing with the traditional beam trawl (TBB_SOL) or with the pulse trawl (PUL_SOL) by ICES rectangle.

	2009	2010	2011	2012	2013	2014	2015	2016	2017
TBB_SOL + PULS_SOL									
31F1	269	883	658	1211	643	494	460	822	761
31F2	23115	22162	24555	23879	18325	22694	21950	26387	28865
31F3	2030	1812	1994	809	1432	624	1013	1291	2814
32F1	229	186	3063	5861	5437	4206	4127	3850	2950
32F2	28513	30384	35902	45600	45027	43025	41277	39908	37786
32F3	16695	16915	13797	14254	19138	17521	13862	14814	18057
32F4	95	224	277	310	1309	243	1730	195	1639
33F1	0	0	256	0	0	0	103	0	100
33F2	13790	12476	13886	12501	11597	8185	11294	13001	20870
33F3	19135	20518	21300	18124	20941	22899	23918	16461	22979
33F4	9217	9218	14479	14561	14363	10602	12307	15667	10873
34F1	0	0	97	162	104	0	99	0	0
34F2	30030	27758	30195	24084	27723	25031	23684	23698	28202

34F3	18722	20241	18253	20052	18888	11788	17039	19079	19642
34F4	12218	17793	18868	13890	7364	5831	9377	9719	7901

TBB_SOL									
31F1	269	883	557	179	345	0	0	0	96
31F2	23115	22162	23918	11776	8097	4615	0	0	158
31F3	2030	1812	1350	557	98	39	0	0	0
32F1	229	186	85		101	0	0	0	0
32F2	28513	30384	34204	19972	10389	4212	184		99
32F3	16695	16915	10547	5817	10210	8226	2864	225	0
32F4	95	224	180	45	0	0	0	0	0
33F1	0	0	153	0	0	0	0	0	0
33F2	13790	12476	11944	7155	5334	699	427	98	
33F3	19033	20518	18442	14709	15564	13844	969	388	185
33F4	9217	9218	7922	2134	3205	1713	1473	152	157
34F1			97						
34F2	28200	22467	12529	6781	8963	4027	2508	108	461
34F3	18587	18942	14649	11277	12060	6311	415	473	884
34F4	11807	17793	15563	8410	4976	2328	943	579	466

PUL_SOL									
	2009	2010	2011	2012	2013	2014	2015	2016	2017
31F1	0	0	101	1032	298	494	460	822	665
31F2	0	0	637	12102	10228	18080	21950	26387	28707
31F3	0	0	644	252	1334	585	1013	1291	2814
32F1	0	0	2978	5861	5336	4206	4127	3850	2950
32F2	0	0	1698	25628	34638	38812	41092	39908	37687
32F3	0	0	3249	8438	8929	9294	10998	14589	18057
32F4	0	0	98	265	1309	243	1730	195	1639
33F1	0	0	103	0	0	0	103	0	100
33F2	0	0	1942	5346	6263	7486	10867	12903	20870
33F3	102	0	2857	3415	5378	9056	22949	16073	22795
33F4	0	0	6557	12428	11157	8890	10834	15515	10716
34F1				162	104		99		
34F2	1830	5291	17666	17303	18761	21004	21177	23590	27741
34F3	135	1300	3604	8775	6828	5477	16623	18606	18758
34F4	411		3305	5480	2389	3503	8433	9141	7435

Table 6.4.2. Landings of sole (103 kg) of the Dutch pulse licence holders fishing with the traditional beam trawl (TBB_SOL) or with the pulse trawl (PUL_SOL) by ICES rectangles in the southern North Sea

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
TBB_SOL + PUL_SOL									

31F1	5	30	15	32	20	14	23	30	32
31F2	739	769	602	765	671	949	959	1104	1097
31F3	19	20	35	20	42	16	25	41	66
32F1	7	3	91	167	185	163	145	168	100
32F2	916	825	860	1421	1676	1748	1613	1534	1363
32F3	272	244	202	292	513	501	367	497	451
32F4	0	2	3	4	32	8	50	6	32
33F1	0	0	4	0	0	0	3	0	4
33F2	311	258	312	321	400	261	369	479	681
33F3	338	351	369	388	501	638	640	493	601
33F4	102	102	211	298	326	224	261	475	222
34F1	0	0	1	5	3	0	3	0	0
34F2	746	606	656	637	933	793	705	871	805
34F3	324	387	318	386	468	265	368	576	456
34F4	188	249	268	267	176	127	201	302	171

TBB_SOL

31F1	5	30	10	4	12	0	0	0	4
31F2	739	769	588	369	237	132	0	0	6
31F3	19	20	15	14	3	2	0	0	0
32F1	7	3	0	0	2	0	0	0	0
32F2	916	825	818	524	327	146	7	0	4
32F3	272	244	142	111	225	205	28	2	0
32F4	0	2	1	1	0	0	0	0	0
33F1	0	0	3	0	0	0	0	0	0
33F2	311	258	268	154	133	15	7	1	0
33F3	336	351	314	302	352	360	8	12	6
33F4	102	102	102	33	79	30	19	3	7
34F1	0	0	1	0	0	0	0	0	0
34F2	690	440	221	135	251	92	56	1	8
34F3	323	346	240	204	272	111	8	10	19
34F4	181	249	215	149	111	43	15	17	12

PUL_SOL

	2009	2010	2011	2012	2013	2014	2015	2016	2017
31F1	0	0	5	28	8	14	23	30	28
31F2	0	0	14	395	433	818	959	1104	1091
31F3	0	0	20	6	40	15	25	41	66
32F1	0	0	90	167	183	163	145	168	100
32F2	0	0	42	897	1349	1602	1606	1534	1360
32F3	0	0	61	181	288	297	340	495	451
32F4	0	0	2	3	32	8	50	6	32
33F1	0	0	2	0	0	0	3	0	4
33F2	0	0	44	167	267	245	361	478	681
33F3	2	0	56	86	149	278	633	481	595

33F4	0	0	109	266	247	195	242	472	215
34F1	0	0	0	5	3	0	3	0	0
34F2	56	166	435	502	681	701	649	870	797
34F3	1	41	78	182	197	154	360	566	437
34F4	7	0	52	118	64	84	186	285	158

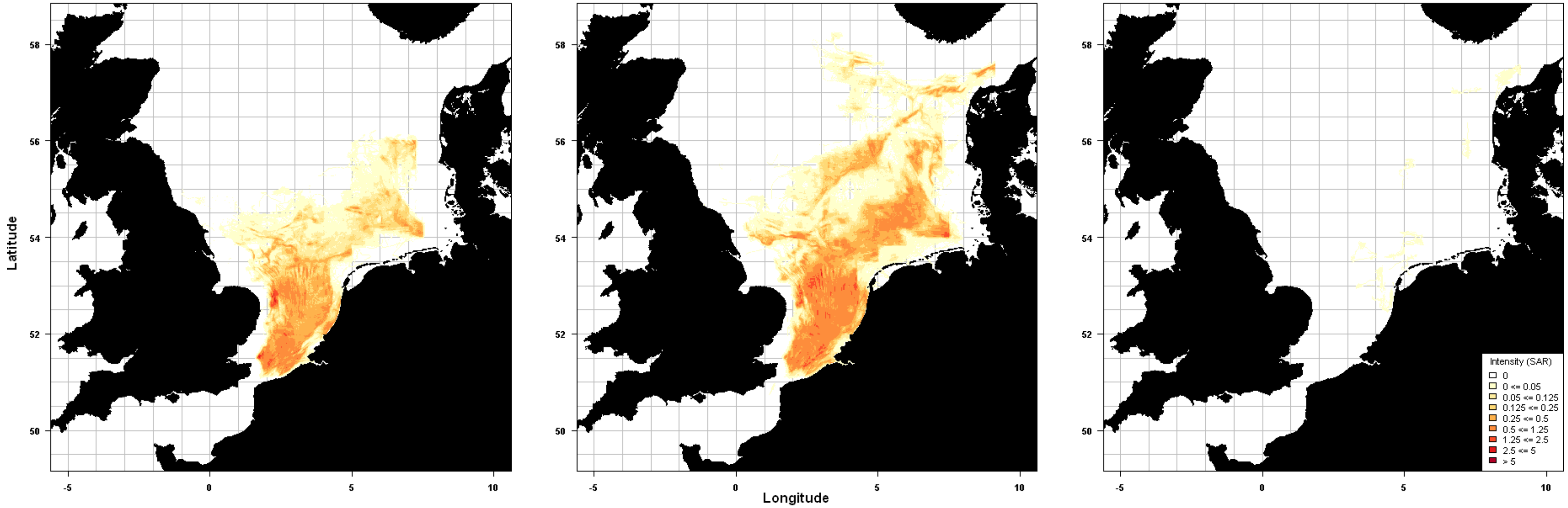


Figure 6.4.1. Average annual trawling intensity (swept area ratio of 1x1 minute grid cells) of the pulse trawls (left: PUL_SOL), traditional beam trawl (middle: TBB_SOL) and traditional beam trawl targeting plaice (right: TBB_PLE) in the period 2009 – 2017.

6.5 Catch rate and species composition of discards

The composition of the catch provides information on the species that encounter the fishing gear. Table 6.5.1 presents the numerical catch composition of the fish species for the discard samples provided by Dutch fishing vessels using the traditional beam trawl and the pulse trawl. The catch composition is heavily dominated by flatfish, ranging between 81% in small pulse trawlers to 95% in small traditional beam trawlers. The flatfish proportions in the discards of large vessels was 88% and 91% in pulse and traditional beam trawlers, respectively. Differences in catch composition between pulse and traditional beam trawls relate to the differences in species selectivity. The relative proportion of sole discards is higher in the pulse trips (small pulse: 7.0%; large pulse: 2.7%) as compared to the beam trawl trips (small TBB: 2.6%; large TBB: 1.4%). The proportion of gadoids discarded ranged between 0.1% (beam trawl) and 9% (pulse) in small vessels and between 4% (beam trawl) and 5%(pulse trawl) in large vessels.

Table 6.4.1. Average catch rate (number.hr-1) of discards in the pulse and traditional beam trawl (TBB) fishery for sole (mesh size 80 mm) as recorded in the observer trips in the period 2010-2017. N denotes the number of trips sampled. Data WMR (unpublished).

	Euro cutters (<=221kW)		**Large cutters (>221kW)**	
Species	Pulse	TBB	Pulse	TBB
	N=8	N=2	N=17	N=13
Amblyraja radiata	0.0	0.0	0.0	0.5
Leucoraja naevus	0.0	0.0	0.1	0.1
Raja brachyura	0.0	0.0	1.5	1.5
Raja clavata	0.5	0.0	3.0	3.9
Raja montagui	0.2	0.0	2.9	10.6
Raja sp.	0.0	0.0	0.0	0.1
Alosa fallax	0.1	0.0	0.1	0.0
Clupea harengus	1.0	0.6	0.3	5.3
Sprattus sprattus	0.0	0.8	0.4	5.8
Lophius piscatorius	0.0	0.0	0.1	0.1
Ciliata mustela	0.5	0.0	0.0	0.2
Enchelyopus cimbrius	0.3	0.0	3.2	11.3
Gadus morhua	0.5	0.0	2.1	7.0
Gaidropsarus vulgaris	0.0	0.0	0.4	0.0
Merlangius merlangus	107.8	2.2	108.3	286.9
Molva molva	0.0	0.0	0.1	0.3
Trisopterus luscus	5.6	0.8	12.2	2.7
Trisopterus minutus	0.2	0.0	3.0	0.8
Coryphaenoides delsolari	0.0	0.0	0.0	0.0
Belone belone	0.0	0.0	0.0	0.1
Zeus faber	0.0	0.0	0.1	0.0
Hippocampus guttulatus	0.0	0.0	0.0	0.0
Syngnathus acus	0.2	0.0	0.0	0.2

Syngnathus rostellatus	0.1	0.0	0.0	0.0
Chelidonichthys cuculus	0.0	0.0	14.3	1.9
Chelidonichthys lucerna	6.6	6.4	11.5	24.8
Eutrigla gurnardus	3.7	8.1	23.6	162.1
Myoxocephalus scorpius	15.6	25.9	6.1	14.9
Taurulus bubalis	0.0	0.0	0.0	0.0
Agonus cataphractus	64.1	8.0	13.2	24.4
Cyclopterus lumpus	0.0	0.0	0.1	0.0
Liparis liparis liparis	1.6	0.0	0.0	0.6
Liparis montagui	1.9	0.0	0.0	0.0
Trachurus trachurus	0.0	32.7	0.1	4.2
Mullus surmuletus	0.3	0.0	9.8	4.6
Dicentrarchus labrax	0.1	0.0	0.2	0.1
Echiichthys vipera	1.4	2.0	41.8	47.4
Trachinus draco	0.0	0.0	0.6	0.1
Parablennius gattorugine	0.1	0.0	0.0	0.0
Ammodytes sp.	10.7	0.0	3.0	23.2
Ammodytes tobianus	0.0	14.8	0.2	2.0
Hyperoplus lanceolatus	1.1	3.4	4.1	20.0
Callionymus lyra	20.1	24.4	43.1	95.0
Callionymus maculatus	0.0	0.0	0.0	0.1
Callionymus reticulatus	0.0	1.9	0.5	1.2
Gobius niger	0.0	0.0	0.0	0.0
Neogobius melanostomus	0.0	0.0	0.1	0.0
Pomatoschistus minutus	0.0	13.1	0.6	0.7
Pomatoschistus sp.	0.6	3.3	0.4	3.9
Scomber scombrus	0.0	0.0	0.0	0.7
Arnoglossus laterna	33.5	90.4	69.5	320.4
Phrynorhombus norvegicus	0.0	0.0	0.2	0.5
Scophthalmus maximus	2.3	1.8	3.7	4.5
Scophthalmus rhombus	3.8	1.5	1.1	2.9
Glyptocephalus cynoglossus	0.0	0.0	0.2	0.7
Hippoglossoides platessoides	0.0	0.0	0.4	6.0
Limanda limanda	555.6	1561.7	1093.6	3733.5
Microstomus kitt	2.6	0.6	16.0	44.0
Platichthys flesus	8.7	3.4	4.3	11.2
Pleuronectes platessa	302.1	827.0	905.1	2964.8
Buglossidium luteum	31.4	107.8	63.4	338.8
Microchirus variegatus	0.0	0.0	0.2	0.0
Pegusa lascaris	0.0	0.0	0.0	0.2
Solea solea	89.6	74.0	69.3	113.8

6.6 Catch efficiency for target species sole and plaice

The change in the catch efficiency in the sole fishery was analysed based on the official landings and effort data reported for each fishing trip. Pulse fishing trips were assigned based on the towing speed recorded in the VMS data. Towing speed clearly changed when vessels switched from the traditional beam trawl gear, with a typical towing speed between 6 to 7 knots, to the pulse gear with a typical towing speed of around 5 knots (Figure 6.6.1).

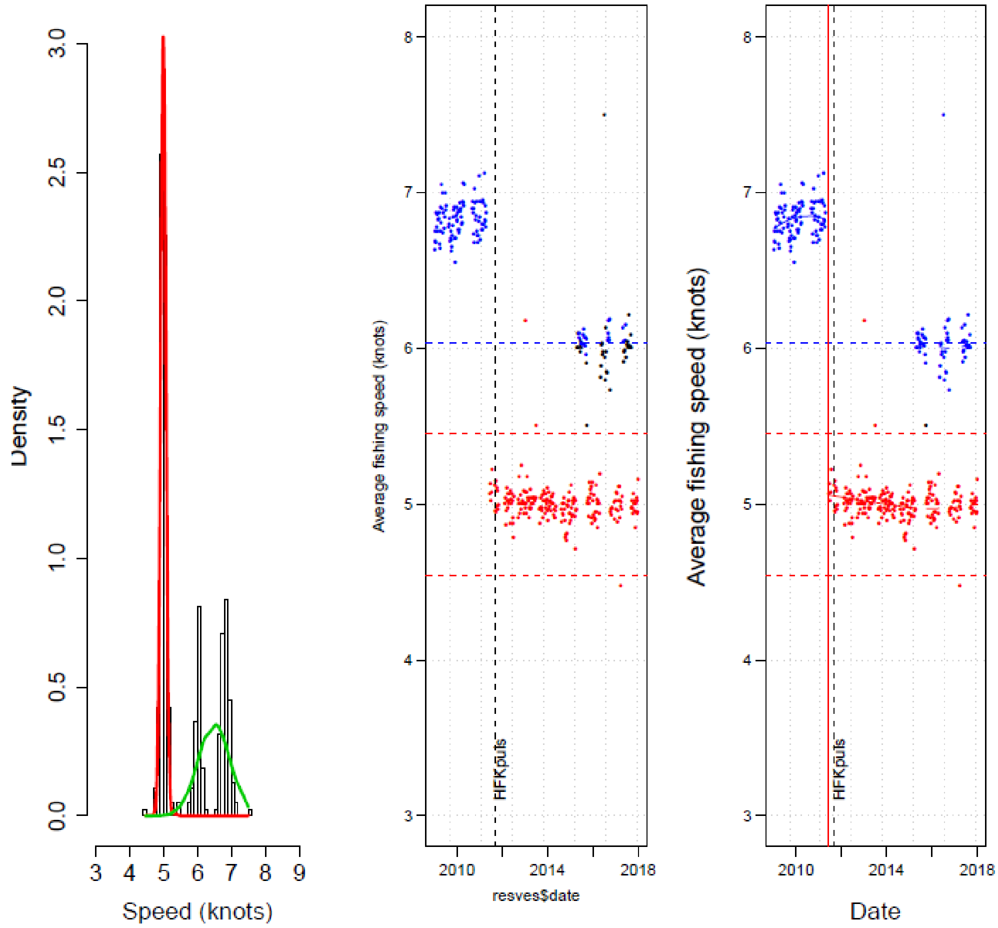


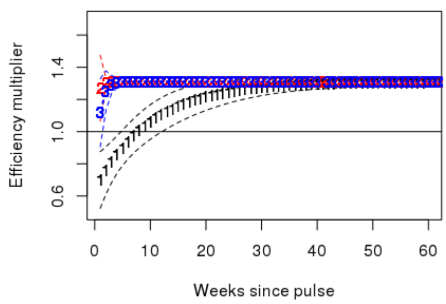
Figure 6.6.1. Example of the recorded towing speed of a large beam trawler that switched to pulse fishing in 2011. The left panel shows the three distribution modes of the fishing activities prior to the switch and the two modes after the switch. In 2015, 2016 and 2017, the vessels switched back to the TBB gear for a number of weeks. Blue and red dots denote fishing trips with the traditional beam trawl and pulse trawl, respectively.

The catch efficiency was estimated using a non-linear multiplicative model. The model links predicted landings to observed landings using likelihood function, assuming data is log-normally distributed. The model was constructed in TMB (github.com/kaskr/adcomp)

$$L = X_1\beta_1 f(t)\beta_2 \log(E)$$

X_1 is the design matrix for the week*location combinations, E is the engine power of the vessel and f(t) is a function for the change in catch efficiency with time (t) since the switch. The model assumed that the relative catch efficiency increased in time after the switch to pulse trawling to reach an asymptote.

The analysis showed that the pulse trawl landed about 30% more sole and almost 40% less plaice than the traditional beam trawl per hour fishing (Figure 6.6.2). The first group of vessels that switched to pulse trawling between 2010 and 2012 had a lower catch efficiency for sole in the first weeks after the switch. The catch efficiency increased and reached the asymptote after about 25 weeks. The vessels that switched to pulse trawling in 2012 and 2014 almost immediately increased their catch efficiency and reached the asymptote. For plaice, no change in landing efficiency was apparent.



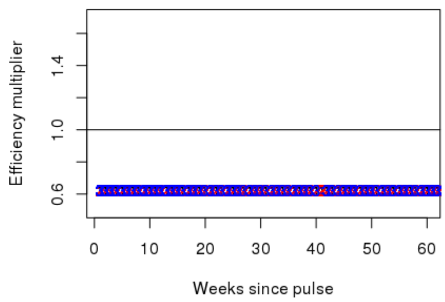


Figure 6.6.2. Changes in the catch rate (kg.hr-1) multiplier of the pulse trawl relative to the traditional beam trawl for sole (left) and plaice (right) as a function of the time since the switch to pulse trawling. The symbols (1, 2, 3) refer to the three groups of vessels switching to pulse trawling in 2010, 2012 and 2014 (Poos *et al.* in prep).

6.6.1 Conclusion

The transition from traditional beam trawls to pulse trawls in the sole fishery has considerably improved the species selectivity of the fishery. The landings efficiency for sole has increased by about 30% while the efficiency for plaice has decreased by about 40%.

6.7 Species and size selectivity

The comparative fishing experiment carried out by van Marlen *et al* (2014) and van der Reijden *et al.*, in prep), that compared the selectivity of the pulse and the traditional beam trawl gear, provided evidence for an improved selectivity of sole as compared to other fish species, while the evidence for an improved size-selectivity (reduced catch efficiency for undersized fish) was inconclusive (ICES, 2017). The species selectivity was further explored by analysing the catch rate of the different species groups as recorded in the discard sampling programme carried out by WMR. A total of discard estimates (N.hr-1) from 58 observer trips and 588 self-sampling trips collected in the period 2010-2017 were available for analysis (Table 6.7.1). It is noted that there is little validation of the self-sampling data and therefore the quality and the consistency between vessels, species, components of the catch are largely unknown.

The catch rate (N.hr-1) by trip of the different species groups was modelled as a function of the gear (pulse, traditional beam), fleet (small vessels <=221kW, large vessels >221kW) and the monitoring programme (observer, self-sampling). Table 6.7.2 presents the parameter estimates of the model. Models explained >95% of the deviance, except for the catch rate of sole discards (84%). Pulse trawl discarded 73%-81% more sole than traditional beam for both small and large vessels, respectively (Table 6.7.3). For all fish or all flatfish, the pulse gear caught 16%-24% and 22%-27% less discards than the traditional beam. For non-flatfish, pulse trawl caught 11%-55% more than the traditional beam. Compared to the catch ratio of sole (+73%-81%), all species groups showed a lower catch ratio, corroborating the improved selectivity of the pulse trawl to catch sole and a reduced selectivity to catch other species.

Table 6.7.1. Discard monitoring: number of commercial sole fishing trips (80 mm mesh size) sampled by observer trips and self-sampling trips on board of commercial pulse trawlers and traditional beam trawl trawlers (TBB) with an engine power of <=221kW (small) and >221kW (large). Data WMR.

	Observer trips				**Self-sampling trips**			
	Pulse >221kW	Pulse <=221kW	TBB >221kW	TBB <=221kW	Pulse >221kW	Pulse <=221kW	TBB >221kW	TBB <=221kW
2010			8				66	21
2011	1		7				67	18
2012	2	1	2	1	20	3	42	17
2013	1		5	1	18	8	39	9
2014	2	2	2		1		6	
2015	4	3	2		27	6	4	1
2016	4	1	3		59	25	19	
2017	3	1	2		69	23	20	
total	17	8	31	2	194	65	263	66

Table 6.7.2. Parameter estimates of the generalised linear model of the catch rate (n.hr-1) per trip as for different components of the discards as a function of the gear (Pulse large, Pulse small, TBB large, TBB small), monitoring method (observer trips, self-sampling) and the year of sampling. The model used a Poisson error and log-link function. Data WMR.

	Fish (all)		**Sole**		**Flatfish**		**Non flatfish**		**Benthos**	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
PULSE_large	7.724	0.004	4.307	0.028	7.572	0.004	5.839	0.012	8.462	0.002
PULSE_small	7.209	0.005	4.671	0.029	7.051	0.005	5.371	0.014	9.271	0.002
TBB_large	7.994	0.003	3.758	0.024	7.884	0.003	5.731	0.010	9.431	0.002
TBB_small	7.385	0.004	4.076	0.027	7.295	0.005	4.936	0.014	9.212	0.002
2011	0.028	0.003	0.146	0.022	0.042	0.003	-0.102	0.009	0.210	0.001
2012	0.143	0.003	0.376	0.021	0.151	0.003	0.041	0.010	0.330	0.001
2013	0.364	0.003	0.241	0.022	0.384	0.003	0.156	0.009	0.607	0.001
2014	0.322	0.006	0.315	0.038	0.312	0.006	0.367	0.016	0.514	0.003
2015	-0.069	0.004	-0.198	0.029	-0.113	0.005	0.096	0.012	-0.174	0.003
2016	0.306	0.003	-0.633	0.026	0.357	0.003	-0.172	0.011	0.337	0.002
2017	0.091	0.003	-0.306	0.024	0.128	0.003	-0.262	0.011	0.124	0.002
Self-sampling	-0.123	0.003	0.017	0.019	-0.125	0.003	-0.098	0.008	-0.266	0.001
%deviance explained	0.967		0.837		0.965		0.927		0.926	

Table 6.7.3. Ratio of the catch rate of the pulse relative to the traditional beam trawl (TBB) for the fish and benthos discards, as well as different subsets of fish. Data WMR.

Catch rate ratio	Fish(all)	Sole	Flatfish	Other fish	Benthos
Large pulse/TBB	0.76	1.73	0.73	1.11	0.38
Small pulse/TBB	0.84	1.81	0.78	1.55	1.06
%deviance explained	0.967	0.837	0.965	0.927	0.926

The comparative fishing experiments showed a substantial reduction in the bycatch of benthic invertebrates in the pulse trawl as compared to the traditional beam trawl: -38% (van Marlen *et al.*, 2014) and –72% van der Reijden *et al.* (in prep). This result is corroborated by the catch ratio of the large vessels which showed a 62% reduction in bycatch of benthic invertebrates, but not for the small vessels (Table 6.7.3). The latter may be related to the large numbers of sea stars caught in the coastal waters where the smaller vessels tend to fish. A problem in the comparison of the bycatch of invertebrates between the pulse trawl and the traditional beam trawl is the damage imposed by tickler chains in the traditional beam trawls on fragile organisms such as sea urchins which will lead to an underestimate of their numbers caught.

6.7.1 Conclusion

The available discard observations indicate that the pulse trawl catches fewer undersized fish and benthos relative to sole compared with a beam trawler. While the reduction in discards of flatfish is clear, pulse trawls still catch substantial quantities of unwanted small fish, in particular, small dab and plaice. It is uncertain whether the pulse trawl is more efficient in catching larger sized classes when compared to the catch of smaller size classes of the same species.

6.8 Cod-end selectivity

In 2016, a mesh selection experiment was conducted studying the effect of pulse stimulation on the probability of sole and plaice escaping through the meshes. The study was carried out in the context of the FP7-BENTHIS project on board a Pulsewing vessel (TX43). The vessel was fishing with her normal gear (mesh size 88 mm) and a small-meshed (37 mm) cover to collect the fish that had escaped through the cod-end mesh. During the experiment the electrical stimulation of the starboard and port net was alternately switched on and off. The analysis showed that the electrical stimulation had a small but significant effect on the slope of the selection ogive for sole but not for plaice (Figure 6.8.1). Larger soles showed a higher retention when exposed to the electrical stimulation as compared to the reference without electrical stimulation.

The reduced retention of larger soles when the electrical stimulation is switched off is likely due to the escape through the front of the net. Direct observations of the behaviour of sole and plaice in the net of pulse trawls showed that soles before entering the cod-end hold themselves against the bottom panel of the net and may swim forward. The electrical stimulation will prevent soles from escaping through the net opening. Plaice are shown to move quickly through the net to the cod-end and do not show swimming behaviour toward the front of the net (https://www.wur.nl/nl/Expertises-Dienstverlening/Onderzoeksinstituten/marine-research/show-marine/Platvis-in-Beeld-1.htm).

The estimates of the selection factor and selection range for the pulse trawl are compared to the average values obtained from a series of experiments carried out on

Dutch beam trawlers around 1980 (van Beek *et al*., 1981; 1983). The comparison indicated that the selection factor in the pulse trawl is lower than in the historic experiments. It is unlikely that the historic selection experiments are representative for the contemporary beam trawl fishery. Since the 1980s, the towing speed and size of the beam trawl has increased (Rijnsdorp *et al*., 2008). Similarly, it is likely that the rigging of the net is changed. Since the reports from the 1980s do not specify the details of netting material and the rigging of the nets, it is impossible to interpret how the changes in the net design may have influenced the cod-end selectivity.

Table 6.8.1. Selection factor (SF) and selection range (L75%-L25%) of sole and plaice caught in pulse trawl nets.

		Sole		Plaice	
Year	Gear	SF	range	SF	range
2016	Pulse trawl	2.9	4.2	1.9	2.0
1979-1981*	Traditional beam trawl	3.3	3.5	2.2	3.6

**Van Beek et al 1981. Results of mesh selection experiments on North Sea plaice with a commercial beam trawl in 1981. ICES CM 1981/B:32; van Beek et al. 1983. Results of mesh selection experiments on sole and plaice with a commercial beam trawl vessels in 1981 ICES 1983/B:16.*

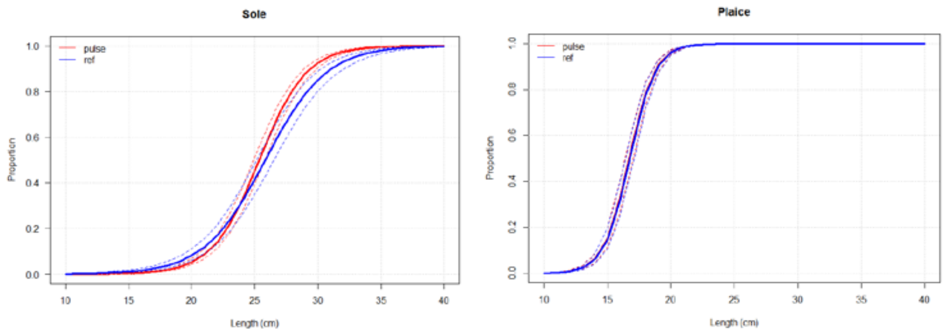


Figure 6.8.1. Pulse trawl cod-end selection ogives and 95% confidence limits for sole (top panel) and plaice (bottom panel) estimated in 2016 with electrical stimulation switched on (red) and off (blue).

6.8.1 Conclusion

The mesh selection experiments carried out with the pulse trawl show that the electrical stimulation does not affect the mesh selection in plaice but improves the retention of larger sized sole. This is probably due to the escape of sole through the front of the net in absence of electrical stimulation. The differences in selectivity parameters between traditional beam trawls as currently used and pulse trawls have not been studied, and therefore are not known.

6.9 Survival of fish caught in pulse and beam trawl fishery

The survival of fish discards caught with commercial pulse trawl vessels has been estimated in survival tanks for a study period of up to 21 days. Plaice, sole and dab were collected on board of 7, 6 and 1 trip, respectively. Survival of plaice (n=349; 7 trips), sole (n=226; 6 trips), and dab (n=187; 1 trip) was assessed as 15% [95% CI: 11–19%], 29% [95% CI: 24–35%], and 16% [95% CI: 10–26%], respectively (van der Reijden *et al*., 2017).

In a follow up project, the survival of discards in pulse fisheries was assessed for undersized plaice (n=558), sole (n=274), turbot (*Scophthalmus maximus* n=111), brill

(*Scophthalmus rhombus* n=90), thornback ray (*Raya clavata* n=99) and spotted ray (*Raya montagui* n=23). Fish were collected between May 2017 and January 2018 during 9 trips on three large commercial pulse vessels and monitored in special captive observation monitoring units. Survival was monitored on board and afterwards ashore in a climate chamber for 15 to 18 days after the capture process similar to van der Reijden *et al*., (2017). The observed mean and range of survival rates observed across the nine sea trips were for plaice 14% (1-22%); sole 19% (0-50%); turbot 31% (0-63%); brill 13% (0-33%); thornback ray 53% (0-82%). Survival of spotted ray discards was only measured during two sea trips in which survival rates of 23% and 67% were observed. Clearly survival of discards varies among sea trips in response to the variability in mechanical damage imposed during the catch process (Schram & Molenaar, in prep).

There is one recent study that compared the reflex-impairment of discards caught in pulse trawls and beam trawls. Reflex-impairment are believed to be a measure of the mortality rate. It was shown that discards caught in pulse trawls showed a lower reflex impairment (better condition) as compared to those caught by beam trawls (Uhlman *et al*., 2016).

Survival rate of flatfish caught in traditional beam trawl gear was studied by van Beek *et al* (1990) showing survival rates of less than 10%. Discard survival is known to be affected by many variables and their relative effects are not understood. These studies were undertaken more than 30 years apart, under different technical and environmental conditions using different methods, and are therefore not considered comparable.

6.9.1 Conclusion

Survival experiments carried out on board pulse trawlers showed discard survival rates of about 14% and 24% for plaice and sole, respectively. While it might be anticipated for a pulse trawl to have higher survival owing to the reduced stressors associated with lower towing speed and the lower catch volume, there is currently insufficient evidence to confirm this.

6.10 Competition between fishers using pulse trawls with those using other gear

The transition from the traditional beam trawl to the pulse trawl in the fishery for sole resulted in a shift in the effort distribution. Fishing effort increased in areas off the Thames Estuary and the Belgian coast (section 6.4). Shifts in distribution of fishing effort of pulse trawlers may give rise to local competition between pulse vessels and fishers already fishing in those areas using other gears. Sys *et al*. (2016) showed that the landing rates of sole by the Belgian traditional beam trawlers (>=221 kW) from 2006 to 2013 were lower during weekdays than during weekends when the Dutch traditional beam trawler fleet is in harbour, while no such an effect was found for plaice. After the increase in numbers of pulse trawlers in 2012 and 2013, the negative weekday effect in the sole landing rates was much more pronounced. This increased loss of efficiency during weekdays, as a result of increased competition with the Dutch pulse trawler fleet, coincided with a reallocation of fishing effort by the Belgian traditional beam trawler fleet.

6.10.1 Conclusion

The case study of the interaction between the Dutch and the Belgium beam trawl fishery for sole off the Thames Estuary provides support for an increased competition between both fleets since the transition to the pulse trawl. Based on the redistribution of pulse effort into areas with historical fishing effort from other fisheries, it is likely that there will be competition issues in these regions.

6.11 Discussion

The transition from traditional beam trawls to pulse trawls in the sole fishery has considerably improved the selectivity of the fishery. The landings efficiency for sole has increased by about 30%; assuming the effect on landed and discarded components of the catch has been the same, and the catch sorting process has remained constant, then this can be described as a 30% increase in catch efficiency. The landings efficiency for plaice has decreased by about 40%, this can be viewed as a 40% reduction in plaice catch efficiency assuming the discard rate and catch sorting has been constant. The change in species selectivity is likely due to the difference in the cramp response between fish species. The pulse stimulus causes a cramp response that immobilises the fish, but only sole will bend in a U-shape which not only immobilises the fish but makes it also more accessible to the gear. The lower catch efficiency of the pulse trawl for plaice and other fish species is partly due to the lower towing speed (-22%), although it is also lower per unit swept area, suggesting that some of the immobilised fish will pass underneath the ground rope and will not be caught.

The higher catch efficiency of the pulse trawl for sole implies that the sole quota can be caught in less fishing time than with the tradition beam trawl. Indeed the proportion of fishing effort with the pulse trawl fleet decreased by 9% between 2009 and 2017, while the fleet's share of the Dutch quota increased by 27%.

The higher catch efficiency for sole does not necessarily imply an increased risk of overexploitation because the sole fishery will be constrained by the sole quota. As the landing efficiency for other species is lower, one would expect that fishers will deploy the more efficient traditional beam trawl or twin trawl to target other species such as plaice, *Nephrops* or shrimps. Indeed, pulse licence holders did not all deploy the pulse trawl throughout the year but temporarily switched to other gear, such as large meshed traditional beam trawl or otter (twin) trawl, to target plaice, shrimp trawls to target shrimp, or otter (twin) trawl to target *Nephrops*.

The available evidence on the size selectivity of the pulse trawl is inconclusive. The available comparative fishing experiments do not support the conclusion of van Marlen *et al*. (2014) that pulse trawls are less efficient in catching undersized sole and plaice. Nevertheless, we expect that the pulse trawl will catch less discards per unit of sole than the traditional beam trawl because of the difference in species selectivity. This inference is supported by the results of the discard monitoring. The discard monitoring results, however, cannot be considered to provide definitive proof as the difference in the discard catch rate between commercial trips will not only be affected by differences in selectivity but also by differences in the abundance and species composition on the fishing grounds.

The analysis of the distribution patterns of the traditional beam trawl and the pulse trawl revealed that pulse trawl fishing has increased locally, such as in areas off the Thames estuary and along the Belgium coast. The change in spatial distribution is related to the lighter weight of the pulse trawl which can be used on softer grounds than the traditional beam trawl. The change in distribution, and the subsequent increase in fishing intensity in areas where beam trawling was rare, may have resulted in an increased competition with other fishers. This increased competition is supported by the analysis of the catch rate in the Belgium beam trawl fleet fishing in the western part of the southern North Sea.

7 Repetitive exposure

7.1 Introduction

Concern has been expressed about the impact of repetitive sub-lethal exposures to the pulse stimulus (Kraan *et al*., 2015). There are two parameters that will determine the impact in the natural environment: (i) the sensitivity of organisms and (ii) the time interval between successive exposures. We expect that the relevant time scale of repetitive sub-lethal exposures will be in the order of hours or days. In this chapter we estimate how often organisms may be exposed to a successive pulse stimulus and estimate the distribution of time intervals between successive exposures with a focus on the time intervals between successive exposures of up to 1 week. The temporal aggregation of trawling events at the time scale of weeks or months has been studied by van Denderen *et al*. (2015).

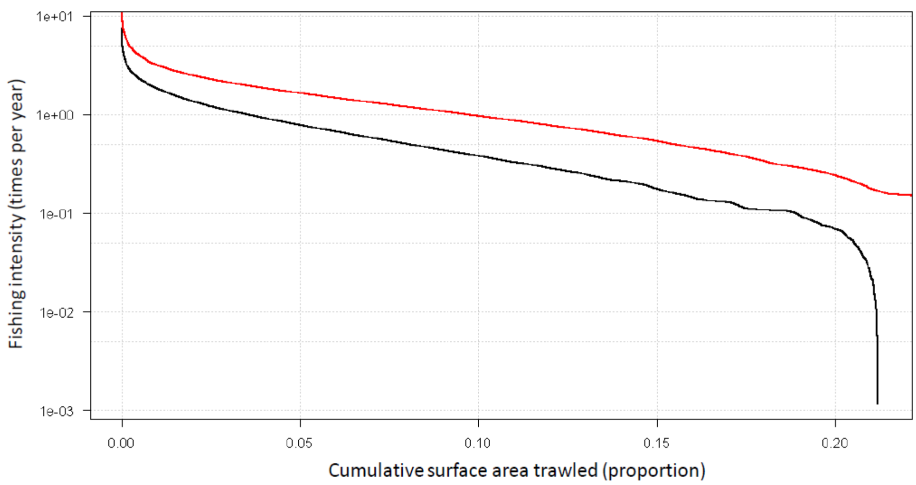


Figure 7.1. Trawling intensity profile for large pulse (black, in 2015-2016) and traditional beam-trawlers (red, in 2008-2009) in the North Sea showing the trawling intensity (Y-axis) as a function of the cumulative surface area trawled (X-axis, proportion of the North Sea seafloor trawled).

7.2 Frequency of exposure

Bottom trawling is highly aggregated is space (Eigaard *et al*., 2017; Amoroso *et al*., 2018). Figure 7.1 shows mean annual trawling intensity profiles of beam trawl (2008-2009) and pulse trawl (2015-2016) fisheries illustrating the heterogeneous spatial distribution. The trawling intensity profile shows the distribution of the mean annual trawling intensity by 1x1 minute grid cells as function of the cumulative surface area of grid cells after sorting gird cells according their trawling intensity. Trawling intensity profiles provide information on the proportion of the surface area trawled at a minimum intensity. For example, the proportion of the surface area of grid cells trawled at least once per year is about 10% for the beam trawl and 2% for the pulse trawl. The total surface area of the grid cells trawled by pulse trawlers is about 22%. This estimate includes the untrawled parts of grid cells with a trawling intensity of <1 $year^{-1}$. The surface area trawled by pulse trawlers >1 $year^{-1}$ is about 3.6%, corresponding to 17% of grid cells trawled.

7.3 Repetitive exposure: theoretical approach

Due to aggregated distribution of bottom trawling, the concern about sub-lethal effects of repetitive exposures will only apply to the main fishing grounds where most fishing effort occurs. Figure 7.1 shows that 3.6% of the North Sea (about 17% of the grid cells trawled by the pulse fishery) is trawled by pulse trawlers at an intensity of >1 years^{-1}. Since trawling is randomly distributed within 1x1 minute grid cells (about 1.7 km^2 at 60^{o}N) (Rijnsdorp *et al*., 1998; Ellis *et al*., 2014), the number of trawling events at the scale of the gear (24x24m) – we will use pixel to refer to this - is given by the Poisson distribution. For the example above, the proportion of pixels with 0, 1, 2, 3 and 4 trawling events is 0.368, 0.368, 0.184, 0.061, respectively.

Trawling may also be aggregated in time which implies that the time interval between trawling events will be shorter within the aggregation period, while the time interval between aggregation periods will be longer than would be expected assuming random trawling events (van Denderen *et al*., 2015). The temporal aggregation may be related to the seasonal pattern in the occurrence of their target species, and due to temporary occurrence of high concentrations of target species at certain localised grounds. Beam trawl fishers exploit local aggregations for 1-2 days (Rijnsdorp *et al*., 2011), and may return to these grounds for up to 2 to 3 weeks (Poos and Rijnsdorp, 2007).

7.3.1 Time interval between trawling events

If trawling events occurs randomly in time at a rate λ, the distribution of intervals (x) between successive trawling events is given by the exponential distribution (de Smith, 2015)

$$f(x;\lambda) = \lambda e^{-\lambda x}, x \geq 0, \lambda > 0$$

Based on the exponential distribution, the interval between successive trawling events was estimated for a range of trawling intensities (λ) (Figure 7.2). At the observed maximum trawling intensities of about 10 year^{-1} the percentage of the sea floor in a grid cell that is trawled at a time interval <1 day is a few percent. This proportion will increase if the trawling is aggregated in time. For instance, if the trawling is restricted to 10% of the year, the trawling intensity in a grid cell during the trawling period will increase to 100 and the proportion of the surface area of the grid cell with a trawling interval of less than 1 day will increase to about 25%. As the surface area trawled at this high intensity of 10 year^{-1} is very small (Figure 7.1), the proportion of the seafloor of the North Sea that is trawled repetitively within 1 day is estimated at 0.002*0.25 = 0.0005 (0.05%).

If we are interested in evaluating the surface area (pixels) trawled repetitively over a longer time period, we evaluate the upper bound as it will apply to the ICES rectangles trawled most intensively at an average annual trawling intensity of 5. Figure 7.2 shows that in such a rectangle about 10% of the pixels will be trawled for a 2nd time within a week, about 35% within a month and about 70% within three months. If the ICES rectangle was being trawled seasonally and all trawling occurred over a period of six months, raising the trawling intensity to 10, 18% of the pixels would be trawled for a 2nd time within a week, almost 60% within a month and about 90% within three months.

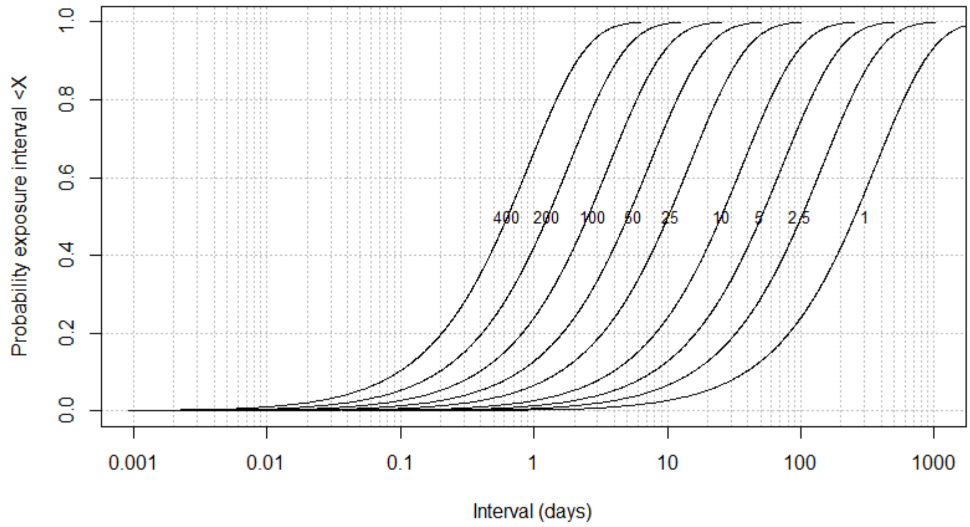


Figure 7.2. The cumulative probability distribution of trawling intervals (days) of a pixel (24x245m) trawled at an annual intensity between 1 and 400. The cumulative probability lines show the proportion of the pixels that will be trawled at a given interval. For example, with an annual trawling intensity of 400, just over 60% of the pixels will be trawled twice within 1 day. At an annual trawlin intensity of 25, the proportion of pixels that will be repetitively trawled within 1 day is less than 10%.

7.4 Empirical approach

The time interval between repetitive exposures were estimated at the scale of the fishing gear for four of the most intensively ICES rectangles with diverse habitats (32F2, 34F2, 33F3 and 37F7). Each ICES rectangle was sub-divided into ~6.5 million pixels of 24 x 24m and the timing of the fishing events were estimated for each pixel by week. Only pixels outside the 12-mile zone and Plaice box were considered.

7.4.1 Methods

VMS fishing positions were selected for two years for the traditional beam trawl gear (2008-2009) and for the pulse trawl vessels (2015-2016). Fishing tracks between successive VMS recordings were interpolated according to Hintzen *et al*. (2010, 2012) and fishing events were estimated at the pixel scale (size) and hourly time steps. If the re-constructed trawl track crossed a pixel it was assumed to be fully trawled once. For each pixel*week combination, the minimum time interval between two successive fishing events was calculated. During each week, a variable number of pixels is trawled with each a specific interval rate. Sorting these pixels results in a relationship between the number of pixels with low and high interval rates. We assumed that pixels that were not trawled during a week were given an artificial interval rate of 200h which clearly is an overestimation of trawling repetition but was needed to make between-week comparisons possible as different weeks had different amounts of pixels with trawling activity. Where pixels are trawled more than twice in a week, the lowest interval rate is taken.

7.4.2 Results

Figure 7.3 shows the estimated percentage of pixels in the ICES rectangle studied that is fished repetitively with an interval of less than the time interval shown on the X-axis.

The analysis shows that the proportion of pixels trawled twice within one week ranges between 0.007-0.17% (Traditional beam) and 0.006 - 0.08% (Pulse). The percentage of pixels trawled twice within one hour is very small and ranges between 3.1 x 10-5 – 0.02% (Traditional) and 0 – 0.002% (Pulse). These percentages are based on 95% CI.

Appendix 2 provides the results for three other intensively trawled rectangles (33F3, 34F2 and 37F7) showing that the maximum proportion of pixels trawled for a second time within one week is less than 0.3% for the pulse trawl (37F7) and less than 0.8% for the beam trawl (37F7).

The percentage of pixels can be considered to represent the percentage of the population of sessile organisms exposed to a second exposure.

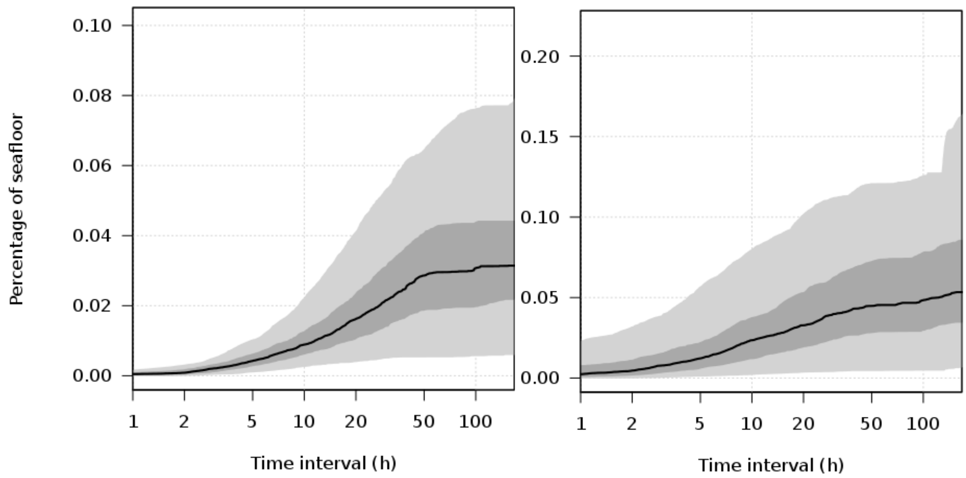


Figure 7.3. Percentage of seafloor being trawled with a specific time-interval for ICES rectangle 32F2. Black solid line presents the median interval-percentage relationship out of 2-years * 52-weeks combinations. The dark-grey area represents the 50% CI while the light-grey area represents the 95% CI. Left: Pulse trawl. Right: Traditional beam trawl. Note difference in scaling of Y-axis.

7.5 Discussion

The part of the seabed that is disturbed repetitively is very small. Only up to 0.3 (pulse) - 0.8% (beam trawl) of the pixels of the most intensively trawled ICES rectangles may encounter a repetitive exposure with intervals of less than one week. These estimates are based on the most intense traditional beam or pulse-trawl fished areas in the North Sea. At time intervals taken within a day, these percentages drop further down to <0.16% and <0.5% for pulse trawl and traditional beam trawl, respectively. These estimates, using a strict interpretation of only using the shortest interval between any repetitive exposure, can be considered a worse-case. In reality, the average interval time often determines habitat recovery and are higher than the strict interpretation. At North Sea scale, the proportion of 1x1 minute grid cells that is trawled more frequently than once per year is less than 1% for the large traditional beam-trawl / pulse fleet. This estimate assumes the entire North Sea provides a suitable habitat, which is unlikely given that the target species abundance nor economic considerations would allow fishermen to fish North Sea wide.

The above conclusion assumes that organisms occurring in the trawl track of the full width of the gear are exposed above their sensitivity threshold. Because, the electric field in the trawl track is heterogeneous (de Haan *et al.*, 2016), the width of the gear where animals are exposed above their threshold may be wider or narrower than the actual width of the gear.

The calculations further assumed that all organisms are sessile. If organisms are attracted to the fishing grounds trawled by pulse trawlers, the estimated exposure probability will increase and the intervals between repetitive exposures would theoretically be shorter. Along the same lines, for animals that are repelled by the electric field the exposure will be less and the interval between repetitive exposures would theoretically be longer.

When results of the exposure experiments become available, the analysis of repetitive exposure may be refined. If we assume that sub-lethal exposures within 1 day may have an adverse effect on the functioning of the individual organism, accepting the caveats described above, we can conclude that the repetitive exposure of an organisms is a very rare event that may occur in less than 0.016% of the area most intensively trawled by pulse fisheries. For a weekly time interval, the surface area with a repetitive exposure increases to 0.3%.

8 Target and non-target species

Trawling causes damage to fish and benthic invertebrates that come into contact with the gear due to mechanical disturbance. Pulse trawling exposes animals to an electrical stimulus which may cause additional damage. Also, other stressors such as barotrauma, thermal trauma and (partial) suffocation will influence the consequences for each animal, in particular for those that are being discarded.

The main difference between pulse trawls and traditional beam trawls is that electrical stimulation replaces a part of the mechanical stimuli, resulting in reduced bottom impact, lower fuel consumption and less bycatch. The removal or reduction of mechanical stimulators, such as tickler chains, will result in a reduced mechanical impact on the animal and associated external damage (such as scale loss and skin lesions) and internal damage (such as haemorrhages, spinal fractures, and spinal dislocations). However, these effects should be evaluated against potential negative side-effects of the exposure to the electrical stimulus. An overview of current knowledge on the effect of mechanical and electrical stimulation on fish and invertebrate species is given below.

8.1 Damage due to mechanical impact

Species caught by a trawl endure different types of mechanical disturbance in different stages of the process. It starts upon first contact with the fishing gear, where animals may be impacted by those parts of the trawl that contact the sediment such as the trawl shoes, the tickler chains, chain matrices or bobbin rope, the electrodes or the footrope. Afterwards, fish pass through the net and eventually end in the codend, where they will not only make direct contact with the net material but also with fish, hard bodied invertebrates such as sea urchins and crabs, stones, litter and passing clouds of suspended sediment, all of which may cause external (scale loss, open wounds, loss of mucus layer) or internal (bruising, bleeding) lesions. Note that fish escaping through the meshes may also be exposed to these kinds of damage. Finally, the net is hauled to the surface, the catch will be emptied on deck and sorted by the crew which exposes the fish to stressors such as barotrauma, thermotrauma and possible suffocation but also to additional mechanical impact before and during the sorting process causing more external and internal lesions. When comparing pulse trawling and traditional beam trawling, a lower physical impact on the animal is suggested in every stage of the process (excluding any electrical effect).

During the initial stimulation in front of the ground rope, the mechanical damage inflicted on animals will most likely be lower in a pulse trawl because the tickler chains are removed and the fishing speed is reduced up to 30% from 6-7 kn to 4-5 kn. Although this may result in fewer incidents of external damage, it is unclear how this relates to the potential impact of the additional electrical stimulus in a pulse trawl. When comparing the mechanical damage encountered in the net during the fishing process, it can be concluded that this will be lower for the pulse trawl. Firstly, the lower fishing speed as well as the reduced sediment re-suspension (Depestele *et al*., 2016) will favour selectivity and reduce the pressure on and possible sandblasting of the catch. Secondly, fewer organisms will be impacted since the smaller surface area fished and higher selectivity will reduce the bycatch. Thirdly, the lower volumes of benthos and stones (up to 80% according to van Marlen *et al*., 2014) will reduce external damage and crushing of the animals in the cod-end. For the same reason, the mechanical impact experienced in the last stage, the catch processing on deck, will also be smaller. Due to the smaller catch volumes, the catch in the hoppers will be less compacted and the processing will be faster resulting in a shorter air exposure which is also beneficial for the survival of the discards (Uhlmann *et al*., 2016; van der Reijden *et al*., 2017). Therefore, it may be concluded that it is most likely that the overall mechanical impact on the animal as caused by the fishing gear will be smaller when caught by a pulse trawl, which is confirmed by the higher reflex-impairment response in flatfish discards caught by beam trawls (Uhlman *et al*., 2016).

8.2 Damage due to electrical stimulation (fractures, mortality)

It is not yet fully understood as to how electric current interferes with fish physiology. Fish can be considered to be an electrical network composed of resistors and capacitors. The membrane and tissues act as the dielectric of a capacitor with the ability to by-pass frequencies as well as frequency attributes expressed in the leading and trailing edges of the pulse (Sternin *et al*., 1976; Sharber *et al*., 1999). Given the differences in the physiology of fish species, the response to an electric stimulus will differ across species (Halsband, 1967; Emery, 1984). The interaction with the electric field is also affected by the pulse settings and the environment. In addition, other pulse parameters can affect the impedance of tissues (Finlay *et al*., 1978), resulting in different electric doses and effects. The conductivity of the surrounding medium is also decisive. Whereas in fresh water high amounts of current may flow through the fish's body as it conducts current better than the surrounding water, this will not occur in fish surrounded by seawater with a much higher conductivity (Lines and Kestin, 2004). On the other hand, relatively higher field strengths will be found in the immediate surroundings of a fish in seawater, which might indirectly affect the flow of ions in the fish body, the charge on neurons, the polarity of membranes and tissues, and muscle activity. The differences and poorly understood phenomena highlight that prudence is warranted when extrapolating results from fresh water studies.

8.2.1 Field samples pulse vessels

The best known and most commonly expressed concern about the side-effects induced by pulse stimulation is the occurrence of spinal injuries in Atlantic cod. Van Marlen *et al*. (2014) examined all cod and whiting caught by the two pulse trawls and the traditional beam trawl participating in their direct catch comparison experiment. This short-term and limited comparison revealed spinal damage in 9% of the cod (4 out of 45) and 2% of the whiting (1 out of 47) caught by pulse trawls whereas this phenomenon was not observed in the traditional beam trawl. A similar observation was made by Soetaert *et al*. (2016d). They found paravertebral haemorrhages in 8% (4 out of 52) cod exposed to an electrified benthos release panel, whereas no damage was observed in cod caught by the reference net.

More detailed sampling on board pulse vessels using sole pulse, including a systematic X-ray analysis to reveal possible hidden fractures and dislocations, is currently being carried out. Preliminary results are presented based on part of the data set, which therefore do not allow final conclusions.

The preliminary results of 362 Atlantic cod sampled on 9 fishing trips made by 6 different pulse trawlers using sole pulse indicated that in total 42.5% of the Atlantic cod showed a spinal abnormality (Table 8.2.1). Spinal abnormalities were categorised on a 5-point scale. A score of 0 means absence of spinal abnormalities, and 5 the severest fracture including spinal dislocation or detachment. A class 4 abnormality is a full fracture without dislocation. Class 3 is a luxation of several vertebrae without fracture; class 2 is an abnormality in several vertebrae without fracture and class 1 is a similar abnormality limited to a single location.

Table 8.2.1. Proportion of Atlantic cod (n=362) per spinal abnormality class as scored based on dorso-ventral and lateral X-ray photographs (Boute *et al.* (in prep)).

	Spinal abnormality class					
	0	1	2	3	4	5
Percentage	57.5	3.6	5.0	15.7	7.7	10.5

The percentage of severe spinal injuries (class 4 & 5) observed in the sampled cod (18%) is higher than the 10% of comparable fractures reported by van Marlen *et al.* (2014).

The effect of standard length (SL) on the spinal abnormality/injury probability (P) was analysed using a generalised additive model:

$$P = intercept + s(SL) + B + \varepsilon$$

where s(SL) is the smoother for standard length SL, B is the factor representing the different pulse vessels, and ε is the binomial distributed error term (model choice based on lowest AIC) (Figure 8.2.1). The model explains 11.2% of the deviance in the data. The effect of pulse vessel was significant ($p < 0.05$). The effect of fish size was not significant ($p = 0.0552$), although a dome-shaped pattern of the injury probability and fish length is suggested. Additional research is required to reduce the uncertainty in the estimated relationships, and to distinguish between injuries caused by electrical sole pulse exposure, as opposed to mechanical processing.

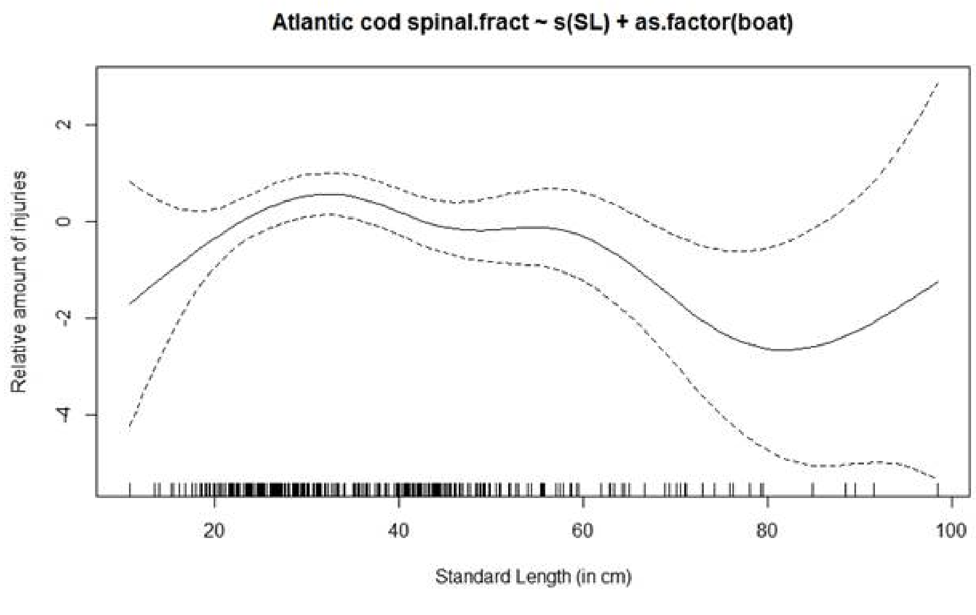


Figure 8.2.1. Effect of fish length on the probability of having a spinal abnormality in Atlantic cod caught by commercial pulse trawls using sole pulse. The relationship was estimated using a generalised additive model (n=362) (Boute *et al.*, in prep).

The suggestion of a lower sensitivity for spinal fractures is important to assess the potential impact on the stock of this species. If small juvenile cod <15 cm are sensitive, although perhaps less than intermediate sized cod (see also section 8.2.2), this would have led to additional pressure on the stock which could have gone unnoticed since animals of this size escape through the cod-end. However, although the variability in cod warrants prudence, the study of de Haan *et al.* (2016), exposing cod of 12-16 cm 4 times in the near field, did not report a single injury. The injuries observed in larger cod remains an unwanted side-effect, but their potential impact on the biomass is much more limited for two major reasons. Firstly, fewer cod are captured by pulse trawls compared to beam trawl (van Marlen *et al*., 2014) which can be attributed to the lower fishing speed. Second, cod larger than 36 cm are landed anyway, whereas cod below MLS shows only very limited survival rates when discarded, mainly as a result of barotrauma.

8.2.2 Laboratory experiments with sole pulse exposure

Invertebrates

Preliminary studies with the sole pulse by Smaal and Brummelhuis (2005) and Van Marlen *et al*. (2009) exposing over 20 different species to worst-case pulse conditions showed no consistent negative effects. Compared to the control groups, they observed a significant reduction in the survival rate of exposed Ragworm *Allita virens* and European green crab *Carcinus maenas* of 3% and 5%, respectively. Atlantic razor clam *Ensis directus* displayed a significant 7% reduction in survival rate after exposure at 10 cm from the electrode, but higher survival rate at 20 cm from the electrode. Furthermore, food intake was significantly reduced with 10 to 13% in the European green crab. No significant effects were found for Common prawn *Palaemon serratus*, Surf clam *Spisula solidissima* and Common starfish *Asterias rubens*. The variable results suggest that insufficient animals were tested to exclude the variability due to natural mortality.

A more elaborate study in which shrimp and ragworm were exposed up to four times did not reveal any mortality or injuries after 14 days (Soetaert *et al*., 2014). A follow-up study (Soetaert *et al*., 2016c) exposed shrimp 20 times in 4 days between commercial electrodes to the sole pulse and monitored them for another 10 days. The electrical exposed group showed a reduced survival rate compared to the control group which was exposed to electrodes but had not received an electric stimulus. However, their survival was not significantly lower compared to the control group which was not disturbed at all, nor to shrimps which had been mechanically stimulated with a chain. Moreover, the group which had been mechanically stimulated showed the lowest percentage of molts, significantly lower than the non-electric exposed control group, which may suggest a sub-lethal effect due to the mechanical stimulation.

Fish

Various experiments show that the impact of electrical pulses differs between fish species. The two experiments using small-spotted catshark as a model species for cartilaginous fish did not reveal any injuries or mortality. Desender *et al*. (2017) used a single exposure and de Haan *et al*. (2009) exposed animals four times in a row and monitored them afterwards for nine months. Similarly, no side-effects have been found in a selection of flatfish species. De Haan (2015) did not find injuries, ulcerations or mortality in dab exposed to the sole pulse. A study by Soetaert *et al*. (2016a) exposed sole to 47 different pulse parameter combinations of which most were (much) stronger than the pulses used in commercial pulse trawls and monitored the animals for 14 days. None of the sole died and no external nor histological abnormalities were observed.

Clear effects of pulse exposure have been seen in cod. The laboratory studies of de Haan *et al*. (2016) with farmed cod showed that when exposed near the electrodes (<10 cm) up to 70% of the adult cod could displayed spinal injuries with associated paravertebral haemorrhages but the injury probability decreased when exposed to a lower field strength (Figure 8.2.2 c, g). This was illustrated by the lack of injuries in cod exposed at distance 20cm above or 40 cm alongside of the electrodes. The experiments suggested also that the injury probability show a dome-shaped relationship with fish size. Small (12-16cm) cod exposed to high field strength next to the conductor did not develop spinal injuries, whereas the injury probability decreased with fish size over the size range of 35-60cm. A dome-shaped relationship was also suggested by the preliminary analysis of the samples collected on board of commercial pulse vessels, although the statistical effect was not significant (P=0.055; see section 8.2.1).

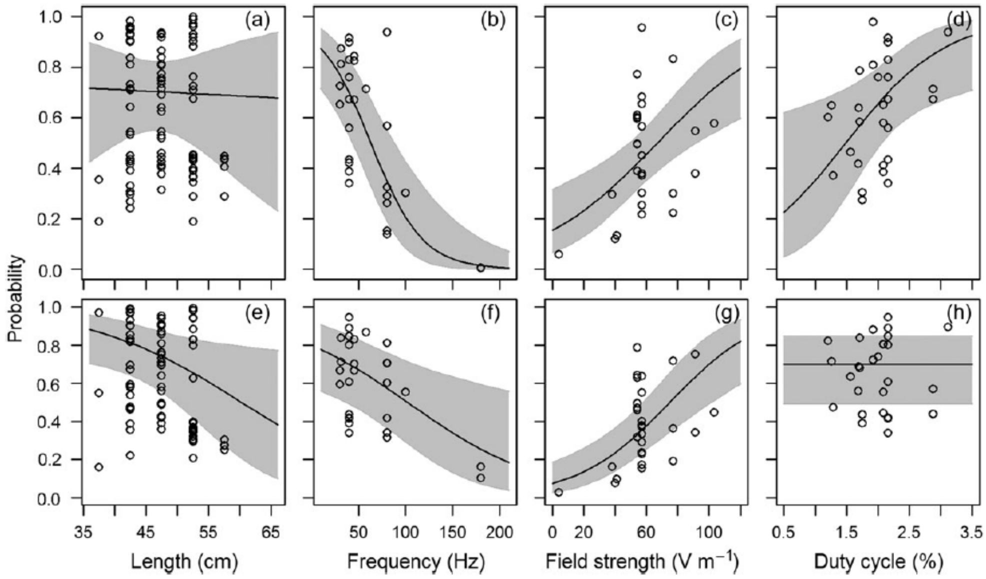


Figure 8.2.2. The predicted probability of haemorrhages (top panels) and spine fracture (bottom panels) of market-sized cod in relation to body size (cm), pulse frequency (Hz), field strength (V m-1), and duty cycle (%). The grey areas show the 95% confidence range. Probabilities were estimated for a HFK pulse type with a frequency of 40 Hz, field strength of 100 V.m-1, and body size of 50 cm. Open circles show the observed probabilities standardized to the settings of the covariables. From de Haan *et al* (2016).

The high injury rate observed by de Haan *et al* (2016) could not be reproduced when a (nearly) identical experimental set-up was used at the same institute, nor with farmed cod obtained from another institute. In the latter experiments, a maximum of 5% of the animals was harmed after exposure against the electrode (Soetaert *et al.*, 2016b). These results indicate that the occurrence of spinal injuries caused by electric tetany in cod can be highly variable and that the morphological or physiological decisive parameters are poorly understood. Seabass were exposed near to sole pulse electrodes, but none of the fish developed injuries or died. This indicates that cod's susceptibility to spinal injuries cannot be extrapolated to all round fish species. An elaborate and systematic investigation of electric induced injuries of (round) fish in the catch of pulse trawls is currently being undertaken by Boute (Wageningen University) to determine which species are vulnerable to developing fractures, and to build a mechanistic framework to better understand how pulse stimulation causes lesions. Results are expected in 2019.

8.3 Behaviour

During exposure near to a sole pulse electrode, the muscles of fish contract and the fish becomes immobilized. The intensity of the reaction decreases with distance and may become barely visible at a distance of 40 cm from the electrodes, as observed in cod by de Haan *et al.* (2008). Immediately after exposure, the muscles relax and the fish show an escape response by reburying (de Haan *et al*., 2009 & 2015, Soetaert *et al*., 2016a, b & 2018). Exposure to the sole pulse will also result in temporary cramp in shrimps and squirming in ragworms, while for ragworm, irrespective of the frequency, no cramp reactions were seen (Soetaert *et al*., 2014 & 2016c). Other species such as surf clam or starfish did not show any reaction at all (van Marlen *et al*., 2009).

Special attention was given to electro-sensitive species (elasmobranchs) which have electro-sensitive organs to locate their prey. Since these organs detect very weak electric fields, there is concern that they may be damaged by exposure to the electric fields used in sole pulse trawls. From conservation perspective, these species are of particular interest as they are among the species most vulnerable to trawling imposed mortality. Two different experiments with small-spotted catshark concluded that (repetitive) exposure to the commercially used electric pulses did not affect the behaviour of these animals (de Haan *et al*., 2009) nor altered their foraging behaviour towards an electrically simulated prey (Desender *et al*., 2017a).

Research on the effect of an electromagnetic field (induced by transportation of electric current in cables) on elasmobranchs (small-spotted catshark notably) has been carried out in the context of the potential impact of windfarms. Gills (2001) studied the effect of electric and electromagnetic fields on small-spotted catshark in terms of attraction and avoidance of electric fields. Gill *et al*. (2005) reported that elasmobranchs are attracted by electric fields generated by DC between 0.005 and 1 $\mu V\ cm^{-1}$, and repelled by electric fields of approximately 10 $\mu V\ cm^{-1}$ and higher. For benthos, there is lack of knowledge for effects (Taormina *et al*., accepted). Since pulse trawls don't use DC with a 100% duty cycle but AC pulses with duty cycles below 2%, it is unclear if this repulsion or attraction could also occur as a reaction to commercial pulse trawls. Pulses from trawling also occur for a short period of timeat any one place as the gear is towed at a speed of 4-5 knots, which cannot be compared to the static field generated by power cables. This also makes it much more difficult for animals to locate the location and direction of the electric field or to approach it voluntarily. However, there is still insufficient evidence to exclude the possibility that the presence of pulse trawls generating multiple moving electric fields can impact the behaviour of elasmobranchs.

Several studies have monitored (feeding) behaviour of fish for up to 2 weeks after exposure. No deviating behaviour was observed compared to the control treatments or the days prior to exposure for lesser spotted dogfish (de Haan *et al*., 2009; Desender *et al*., 2017), sole and Atlantic cod (Soetaert *et al*., 2016a & 2016b) or brown shrimp and ragworm (Soetaert *et al*, 2014 & 2016c). Long term effect were only included in one study (de Haan *et al*. 2009), who kept lesser spotted dogfish in captivity for as long as nine months after the repetitive exposure without reporting increased mortality or adverse effects on behaviour. However, all these studies, except that of Desender *et al*. (2017) examined the effect on (feeding) behaviour qualitatively and not per individual, which makes it impossible exclude more subtle effects. No other behavioural traits, such as the response to stimuli or swimming activity, were evaluated.

8.4 Reproduction

No studies examining the effect on early life stages of the sole pulse have been carried out so far, but two experiments with the shrimp pulse have been conducted. Desender *et al* (2017b) exposed young life stages of cod to the shrimp pulse. A reduced survival was observed in larval stages exposed 2 and 26 days post hatching, but not in 2 other larval stages, 3 embryonic (egg) stages and 1 juvenile stages. One embryonic stage exposed for 3 days before hatching (18 days post fertilisation) showed a slightly delayed developmental rate during the hatching process. In a follow up experiment, Desender *et al* (2018) could not detect reduced survival or other side-effects in sole larvae exposed to the shrimp pulse at the same developmental stages. No negative impact on morphometrics was observed (Desender *et al*., 2018). Additional evaluations of potential effects of early-life exposition should be undertaken at metamorphosing and post-metamorphosis stages.

Soetaert *et al*. (2016c) studied the effect of pulse exposure on shrimp by exposing them in a tank experiment 20 times in 4 days. The experiment did not reveal a difference in mortality, egg loss or number of moults between shrimp exposed to the sole pulse and shrimp exposed to a mechanical stimulus.

8.5 Effect of chronic exposure to sub lethal effects

A few studies have tried to examine sub-lethal effects. The results indicate that sub lethal effects are not easy to determine because they can more easily be overlooked, it is difficult to judge their significance and their presence may be more variable. The latter was illustrated by increase in the abundance of intranuclear baculoform viruses observed in shrimp exposed to a 200 V/m pulse stimulus by Soetaert *et al*. (2014) which was not seen in shrimp exposed four times to the same stimulus at 150 V/m during the same experiment neither in shrimp exposed 20 times in 4 days in an experimental set-up with commercial electrodes and settings.

Similarly, the study of Desender *et al*. (2016) found a significant increase in the number of melanomacrophage centres in the spleen of cod exposed to the startle pulse from shrimp 24h after exposure. The studies of Soetaert *et al*. (2016b) on the other hand did not observe this increase in cod 24h post exposure to the stronger sole pulse. Furthermore, this rise in in number of melanomacrophage centres was not found 14 days after exposure in cod exposed to a variety of electric pulses, amongst which the shrimp and sole pulse (Soetaert *et al*., 2016a). The reasons for these differences in findings between these studies are not known.

9 Mechanical disturbances of sea bed

9.1 Penetration in sea bed

The mechanical disturbance of the sea bed by pulse and traditional beam trawls was studied in the FP7-project BENTHIS (2012-2017). Two controlled fishing experiments were carried out in a coastal sandy habitat and an offshore area with fine sediment (Depestele *et al*., 2016; Depestele *et al*., submitted). The study used a range of complementary instruments such as a multibeam acoustic profiler, sediment profile image (SPI) camera, box corer, LISST 100X particle size analyser and numerical modelling of penetration depths and sediment mobilisation. The most complete data were obtained in the second experiment the results of which are summarised below. The results of the first fishing experiment were consistent with those of the second (Depestele *et al*., 2016).

Trawling impact on the seafloor comprises of changes to the topography and texture of the seafloor and the disturbance (mixing) of the top layer of the sediments.

Impacts on topography and texture of the seafloor were measured with multi-beam echosounder (MBES). Bathymetrical measurements using MBES showed that the traditional beam trawl tracks were consistently and uniformly deepened to 1.5 cm depth in contrast to the 0.7 cm deepening that followed pulse trawling. While the overall impact of the beam trawl was greater, due to the heterogenous impact of the pulse trawl (some parts of the pulse gear creates deeper furrows in the seafloor surface), a minority (20%) of the MBES measurements resulted in a deeper level of bathymetrical alteration than that of the traditional beam trawl. MBES backscatter strength analysis suggested that traditional beam trawls (3.11 dB) also flattened seabed roughness significantly more than pulse trawls (2.37 dB). The reduced pulse trawling impacts allowed a faster re-establishment of the oxygenated layer (based on SPI) and micro-topography in contrast to traditional beam trawling (based on MBES backscatter).

The penetration depth was estimated by measuring the depth of the disturbance layer (SPI) and by modelling the erosion of the surficial sediments due to sediment mobilisation in the wake of the gear (traditional beam = 0.6 cm; pulse trawl = 0.8 cm). The traditional beam trawl showed a deeper penetration depth (mean = 4 cm, SD= 0.9 cm) than the pulse trawls mean = 1.8 cm, SD = 0.8). Traditional beam trawls homogenized the sediment at a greater depth (3.4 cm, 0.9 cm) and removed a higher proportion of the oxygenated layer than pulse trawls (1 cm, 0.8 cm) (Figure 9.1). Particle size analysis suggested that pulse trawling caused a coarsening trend towards the top layers (winnowing effect), while traditional beam trawls exhibited this and additionally injected finer particles into the deeper sediment layers (~4 cm depth).

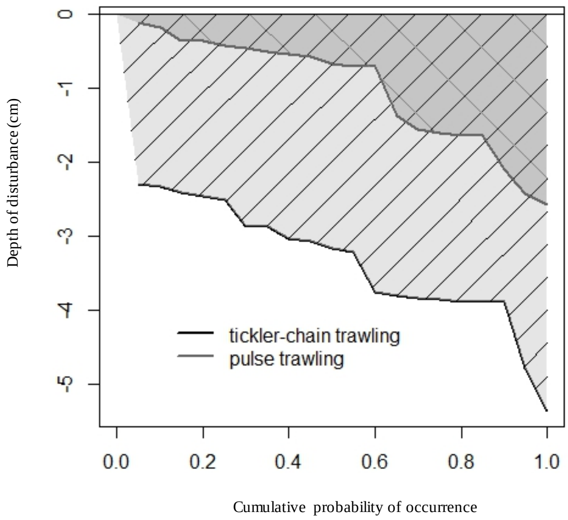


Figure 9.1. Depth of disturbance (cm) following traditional beam (tickler-chain) and pulse trawling based on the assessment SPI images. (/// = tickler chain; \\\\=pulse trawl). Depestele *et al* (submitted).

9.2 Conclusion

The experimental study of the mechanical disturbance of the seafloor by the traditional beam trawl and the pulse trawl showed that the replacement of tickler chains by electrodes reduce the average depth of mechanical disturbance (penetration) by more than 50% in sandy mud.

10 Structure and functioning of the benthic ecosystem

Bottom trawling disturbs the seafloor and may impact the species composition and the ecosystem functions such as bio-turbation, bio-irrigation, bentho-pelagic coupling and habitat provision. In this chapter the available scientific knowledge is presented about the impact on the benthic ecosystem of the mechanical disturbance of the seafloor by pulse trawls and traditional beam trawls. Additionally, the information on how electrical stimulation will affect the biogeochemical processes that influence the ecological functions of the benthic ecosystem is also reviewed.

10.1 Effects of mechanical disturbance on biomass and community composition

The impacts of mechanical disturbance of the sea bed and of the benthic ecosystem was studied in two parallel projects - FP7-project BENTHIS (2012-2017) and the Trawling Best Practice project (https://trawlingpractices.wordpress.com/). The methods developed were adopted by ICES to estimate the impact of trawling and to estimate indicators of sea bed integrity (ICES, 2017b).

Trawling damages and kills benthos and will reduce the benthic biomass and cause a shift in the community composition towards shorter lived species (Kaiser *et al*., 2006; van Denderen *et al*., 2015; Sciberras *et al*., 2018). Hiddink *et al*. (2017) performed a meta-analysis of all published studies that have measured the mortality imposed by a fishing gear on the benthos. They estimated that a passage of a traditional beam trawl imposed a mean mortality of 0.14 per year. Because the trawling mortality is related to the penetration depth of the gear (Hiddink *et al*., 2017) and the penetration depth of a pulse trawl is about 50% of the traditional beam trawl (section 9), the mortality induced by the mechanical disturbance of a pulse trawl is estimated at 0.07 assuming no added mortality from electrical stimulation.

The impact of traditional beam trawls and pulse trawls on the benthic community is estimated using the PD2 method based on Pitcher *et al* (2017) and used by ICES (2017b). This method estimates the decrease in benthic biomass given the level of fishing pressure and the recovery rate of the benthos. The latter is determined by the longevity composition of the benthos which differs between seafloor habitats (Rijnsdorp *et al*., in press).

The benthic impact of the fleet used by today's pulse licence holders was estimated from the annual trawling intensity in 1x1 minute grid cells, distinguishing between trips where the traditional beam trawl was used and those where the pulse trawl was used. Gear deployment by trip was determined based on the vessel speed during fishing from VMS recordings (section 6.5). Trawl tracks were interpolated between VMS fishing locations (Hintzen *et al*., 2010) and the swept area was assigned to 1x1 minute grid cells (Eigaard *et al*., 2017). The results show that the overall impact of the traditional beam trawl fleet that obtained a pulse licence and switched to pulse trawling reduced by about 50% between 2009 and 2017 (Figure 10.1). The impact score included fishing trips where the pulse licence holders returned to use the traditional beam trawl. This mostly happened for part of the year when some of the large vessels fished for plaice with a large mesh size (>100mm) in the central or northern North Sea. The impact caused by pulse trawling increased gradually over the transition period and reached a maximum impact in the most recent three years at less than 50% of the overall impact.

The change in impact is related to the footprint of the fleet, e.g. the surface area fished during a year at least once, which reduced by about 18% (Figure 10.2), and the reduction in the total area swept during fishing, which reduced by slightly more than 30% as compared to 2009.

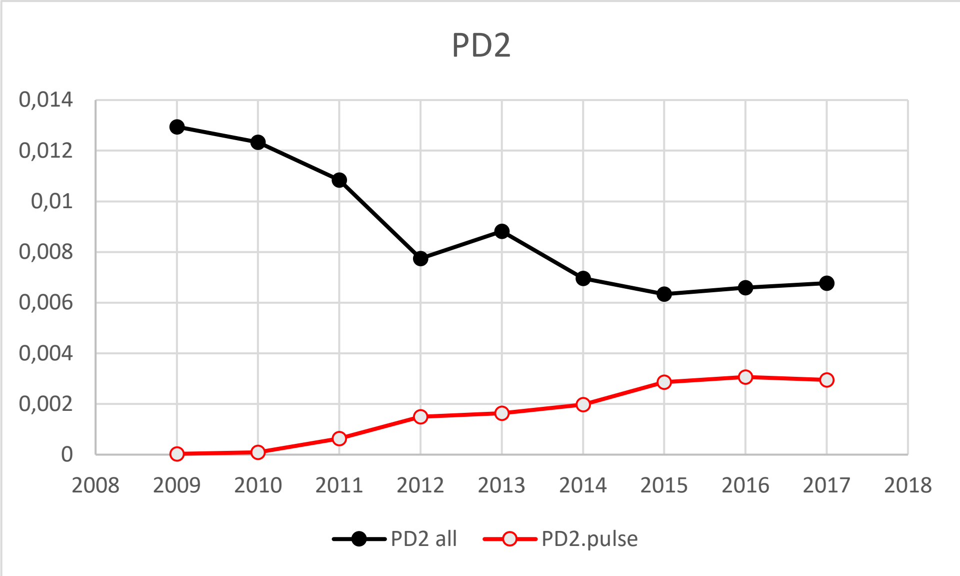


Figure 10.1. Mechanical impact of bottom trawling on the benthic community of the traditional beam trawl vessels that have switched to use the pulse trawl. The impact is estimated as the decrease in biomass relative to the carrying capacity of each grid cell. (BENTHIS: Rijnsdorp *et al.*, in prep).

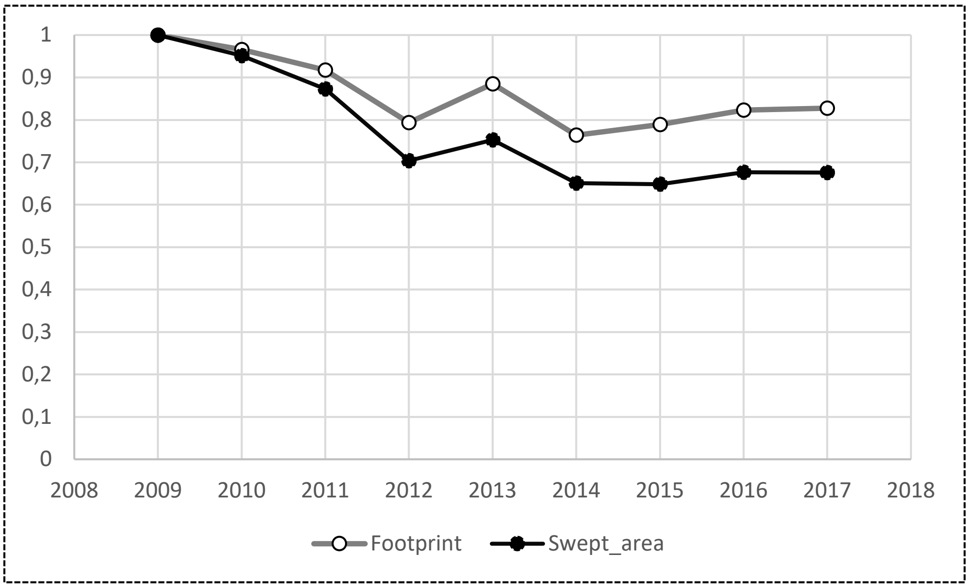


Figure 10.2. Relative footprint (grey) and swept area (black) of the traditional beam trawl vessels that have switched to use the pulse trawl. Swept area is the time spent fishing multiplied by the width of the gear multiplied by the towing speed. Footprint is estimated as the surface area fished at least once per year. Annual estimates were expressed relative to the value in 2009.

10.2 Bio-geochemistry

In order to fully assess the impact of pulse fishing on the benthic ecosystem, the potential consequences to biogeochemistry and to the functioning of benthic organisms need to be analysed. As changes to biogeochemical dynamics may affect benthic pelagic coupling and primary production in the water column, these effects may extend beyond the benthic region (Nedwell *et al*., 1993). In addition to the general release and consumption of nutrients and oxygen, the ability for organisms to facilitate changes to these processes through activities such as bioturbation can have a substantial effect on biogeochemical characteristics (Braeckman *et al.*, 2010). Therefore, the possible sub-lethal impacts of electrical stimulation on the functioning of benthic organisms is of particular importance. Possible chemical changes due to electrolysis is also a subject of concern due to the potentially harmful substances which may be released into marine habitats (Soetaert *et al*., 2015).

10.2.1 Field experiments

In June 2017, a field experiment assessing the biogeochemical effects of electric pulse fishing took place in the Frisian Front area of the North Sea (Tiano *et al*., in prep). The study compared the impact of both electric pulse fishing and traditional beam trawl methods with tickler chains. Benthic landers were deployed and box core sediment samples were collected to measure rates of oxygen consumption and nutrient fluxes in fished and unfished areas. Traditional beam trawling tended to produce a larger and more consistent impact on sediment oxygen consumption, oxygen micro-profiles and sediment surface chlorophyll levels. Pulse trawling, on average, had lower yet more variable effects for these measurements. Nutrient fluxes and porewater nutrients did not show many consistent patterns between either fishing method.

10.2.2 Ex-situ exposure experiments

Intact sediment samples were exposed to electrical or physical stimulation in order to measure potential changes to biogeochemical properties in laboratory conditions. Results suggest that while physical disturbance tends to cause an initial release of nutrients into the water column, exposure of sediment samples to electrical disturbance from sole pulses does not seem to have any consistent effect on nutrient concentrations (Tiano *et al*., in prep). Clear increases in oxygen consumption were found after physical disturbance, however, so far, there is no evidence of electrical stimulation (using stimulation equivalent to commercial sole pulses) having a significant impact on benthic oxygen dynamics.

10.2.3 Sub-lethal impacts on ecosystem functioning

Laboratory experiments are being carried out to analyse sub-lethal consequences of electrical stimulation on the functioning of benthic infauna (organisms living inside the sediment). Porewater pressure sensors are being used to characterise organism behaviour and bioirrigation (pumping water into the sediment) activity. Preliminary results suggest that lugworms *Arenicola marina* contract their bodies during electrical exposure, displaying a cramping response. Planar optodes will be used to visualise oxygen dynamics in the sediment and possible changes which may occur through infaunal responses to electrical stimulation.

10.2.4 Effects from electrolysis

Electrolysis can cause the formation of chlorine gas (Cl_2) in saltwater. To test if the commercial sole pulse causes this reaction to occur, concentrations of chlorine ions (Cl^-) in the overlying water of incubation cores with intact sediment were measured before and after exposure to electrical pulses. Preliminary results did not show noticeable differences between control samples and samples exposed to electricity. Additional laboratory experiments were carried out to see if the release of Cl_2 gas led to the formation of hydrochlorous acid and subsequent changes in pH. After 10+ minutes of constant pulsing, no changes in pH occurred when using commercial sole or shrimp pulse parameters. When parameters were adjusted to exhibit a pulsed direct current (PDC) at a high frequency (90 pulses per second), visual formation of Cl_2 gas bubbles was observed along with a corresponding drop in pH confirming the potential for electrical pulses to exhibit electrochemical reactions under certain conditions. Nevertheless, there is currently no evidence showing that commercial pulse parameters lead to effects related to electrolysis.

10.2.5 Discussion

Research on biological fuel cells and "cable bacteria" show that electrical currents in the sediment have the ability to create a significant impact on sediment biogeochemistry (Nielsen *et al.*, 2010). A unidirectional current can cause the mobilization of porewater ions and can facilitate the consumption of oxygen in marine sediments (Risgaard-Petersen *et al.*, 2012). There is currently no evidence, however, linking electrical pulses used in the flatfish fishery to changes in biogeochemical characteristics. This may be due to the bi-directional flow of electrons limiting impacts from chemical reactions or electrolysis. Moreover, the current research suggests that the mechanical impact from both pulse trawling and traditional beam trawling may have a much greater influence on biogeochemical dynamics than effects from electricity (Tiano *et al*. in prep).

10.3 Conclusion

The transition from the traditional beam trawl to the pulse trawl resulted in a reduced mechanical impact on the seafloor which will have reduced the impact on the benthic ecosystem due to the smaller footprint (surface are trawled), lower trawling intensity, and lower penetration depth (depth of disturbance). According to a population dynamic model PD2, this will reduce the impact on the equilibrium benthic biomass by 50%. Relatively little is known about the potential adverse effect of electrical stimulation on the benthos and functioning of the benthic ecosystem. The preliminary results of the laboratory and field experiments do not reveal any consistent impact of electrical stimulation on benthic biogeochemical functioning in contrast to the mechanical disturbance related to sediment mixing and sediment resuspension.

11 Comparing ecosystem impacts of using pulse trawls or traditional beam trawls in exploiting North Sea sole

The performance of the pulse trawl relative to the traditional beam trawl when exploiting the sole quota is assessed according to a number of criteria and sub-criteria. The assessment results are summarised in Table 11.1 and are described below.

11.1 Sustainable exploitation of the target species

11.1.1 Catch efficiency and Species selectivity (landings)

The analysis of the catch rate of pulse and traditional beam trawl vessels convincingly showed that the catch efficiency (landings kg per hour) of pulse trawls for the main target species sole is 30% greater than that of traditional beam trawls (section 6). The higher catch efficiency was observed despite the 20-25% reduction in towing speed. For the other target species, plaice, pulse trawls have a 40% lower catch efficiency. Analysis of the fishing effort of pulse trawl vessels showed that a number of the vessels switch back (seasonally) to traditional beam trawling to target plaice. The comparative fishing experiments showed a higher catch efficiency of the pulse trawl to catch sole than for plaice and other demersal species (van Marlen *et al.*, 2014; van der Reijden *et al.*, in prep; ICES, 2017a). The higher efficiency can be related to the cramp response of sole which immobilises the fish into a U-shape which will enhance the probability of the fish being caught by the net. The higher catch efficiency of the pulse implies an improved selectivity of the gear.

11.1.2 Size selectivity sole and plaice

There is conflicting evidence whether pulse trawls have a lower efficiency in catching undersized fish (improved size selection). The first comparative fishing experiment suggested that pulse trawls caught less undersized sole and plaice as compared to the traditional beam trawl (van Marlen *et al.*, 2014), but this result was not be supported by a second comparative fishing experiment (van der Reijden *et al.*, in prep; ICES, 2017a).

11.1.3 Discards

The analysis of the catch rate of discards shows a lower absolute catch efficiency of the pulse trawl targeting sole. When evaluating the catch of all fish species together or the catch of all flatfish species, the absolute catch rate of pulse trawl trips was less than the catch rate of traditional beam trawl trips. The absolute catch rate of non-flatfish species, however, was higher in pulse trawl trips. Because the catch rate of sole discards in the pulse trawl trips was higher than in the traditional beam trawl trips, in line with the higher catch efficiency of pulse trawls catching sole, the catch rate of non-flatfish species relative to the catch rate of sole, was lower in pulse trawl trips than in the traditional beam trawl trips. We, therefore, conclude that the available evidence suggests a reduced catch efficiency of pulse trawls for discards. Because the statistical analysis did not take account of the effect of the seasonal and spatial effects, further analysis is required.

11.1.4 Bycatch invertebrates

The comparative fishing experiments with the pulse trawl and the traditional beam trawl (- 38% van Marlen *et al.*, 2014; –72% van der Reijden *et al.*, in prep), as well as the on board monitoring during commercial fishing trips (- 62% for vessels >221 kW), provided convincing evidence for a substantial reduction in the bycatch rate ($N.hour^{-1}$) of benthic invertebrates in pulse trawls as compared to traditional beam trawls. In those trips of small Eurocutters a small (6%) increase in benthic invertebrate bycatch was observed.

11.1.5 Discard survival

An improved survival can also be inferred from the lower towing speed and the cleaner catch of pulse trawls compared with traditional beam trawls. No comparative survival experiments have been carried out on pulse and beam trawl caught fish. The survival experiments carried out on board commercial pulse trawlers showed a mean survival rate of 24% and 14% in sole and plaice, respectively. Mean survival rates of other fish ranged between 13% and 31%, and between 45% and 53% for flatfish and rays, respectively. Results of experiments carried out around 1980 cannot be compared because of changes in the rigging of the gears. However, one study compared the reflex-impairment of discard flatfish, showing a greater impairment in traditional beam trawl caught flatfish as compared to pulse trawl caught flatfish (Uhlmann *et al.*, 2016) supporting the inferred improved survival.

11.1.6 Risk of overfishing

The fishing effort in the sole fishery is regulated by the TACs for the main commercial fish species. Although the pulse trawl has a higher landing efficiency than traditional beam trawls, this does not increase the risk of overexploitation of the North Sea stock because the vessels are constraint by their sole quota. Because the TAC is set for the total North Sea, which may comprise of several sub-stocks, the TAC management cannot prevent the overexploitation of sub-stocks.

11.1.7 Fishing effort

In the study period 2009-2017, the total fishing effort (kW hours) of Dutch beam trawl vessels decreased, while vessels switched from traditional beam trawl to Sumwings with tickler chains or to pulse trawls (Figure 5.2.2).

Fishing effort (fishing hours) of the fleet of pulse licence holders varied without a trend (Figure 6.2.1). Coinciding with the transition to pulse trawling, their share of the total sole landings increased from 75% to 95% (+27%) (Figure 6.2.2), while their fishing effort in the sole fishery decreased by 9% (vessels >221kW) or remained stable (Eurocutters <=221kW). Pulse trawlers increased their fishing effort using traditional beam trawl gear with large mesh size to target plaice in the central North Sea.

Due to the lower towing speed of pulse trawling, fishing effort measured as the surface area swept by the gear has reduced by 32% (Figure 10.2).

11.1.8 Spatial distribution

The fleet of pulse licence holders changed their spatial distribution towards southern and western fishing grounds when switching from beam trawls to pulse trawls. Absolute fishing effort increased on local fishing grounds along the Belgian coast (within 12 nm zone) and off the Thames. In most other fishing areas, representing by far the largest proportion of the area fished, fishing hours decreased or remained stable.

11.2 Adverse effects pulse stimulus on target and non-target teleost and Elasmobranch fish species that are exposed to the gear but not retained

11.2.1 Injuries

There is experimental evidence that the cramp response induced by the sole pulse may result in spinal fractures and associated haemorrhages in cod, but not in flatfish (sole, plaice, dab), seabass and small-spotted catshark. Tank experiments further indicated that small cod did not develop fractures when exposed to a strong pulse stimulus, although the dome-shaped relationship suggested by the preliminary analysis of the field samples was not statistically significant (P=0.055). X-ray analysis of cod sampled from commercial pulse catches showed that 18% of the cod showed a spinal fracture and another 24% showed smaller vertebral abnormalities.

The cod (18% - 42%) and whiting (2%), that may develop spinal injuries when exposed to the pulse, comprise only a very small fraction of the fish numbers caught in pulse trawls (<1% and <10%, respectively), while the available experimental evidence suggest that flatfish, that contribute around 80% of all fish caught, do not develop spinal injuries when exposed to the pulse. Further studies are required to estimate pulse related damage in a broader range of fish species caught in pulse trawl, and to establish whether the fracture probability differs for size classes that are small enough to escape through the codend mesh.

11.2.2 Mortality

Based on the currently available research, there is no evidence that the exposure to a pulse results in a direct mortality of fish passing along the array of electrodes, although it seems likely that injured fish may have a higher risk of dying. As the proportion of fish species developing fractures is small (<1%, see 11.2.1), the additional mortality caused will be small. The inferred mortality rates due to exposure to a pulse stimulus can be compared to the mortality rate imposed during the catching process which is generally substantial (>10%; section 6.9).

There is no information available on the survival of early life history stages after exposure to the sole pulse. Experiments with exposure to the shrimp pulse suggest that exposure to a pulse may reduce the survivorship in certain larval stages when exposed to field strengths occurring at close range to the conductor. The results for cod were not corroborated in an experiment with sole.

The population level effects of a reduced survivorship of eggs or larvae due to pulse exposure will depend on the proportion of early life stages that are exposed to the pulse and by density-dependent processes that may affect survivorship later in life. Although no formal attempt to estimate the potential impact was made, we can infer that the proportion of the population that will be exposed to the high field strengths that occur close to the conductor will be relatively small for species that produce pelagic eggs. For species that produce demersal eggs, the exposure rate will be higher, and will depend on the spatial overlap between the pulse trawl fishery and the spawning areas of the species of concern. For species, where density-dependent regulation occurs after the egg and larval stage, such as flatfish (van der Veer *et al.*, 2000), even a reduced survivorship in the egg and larval phase will be unlikely to reduce the recruitment to the adult population.

11.2.3 Feeding

There is limited information available on the effect of pulse stimulation on the feeding of fish and invertebrate species. Most studies qualitatively reported that feeding was resumed normally after exposure, but none studied the effect quantitatively per individual (section 8.3). The possible adverse effect on electro sensitive species has been studied in small-spotted catshark. In a tank experiment it was shown that the ability of small-spotted catshark to detect prey using their electro sensitive sensory system was not significantly affected after being exposed to a sole pulse stimulus, although the experiment did not examine the possibility that the detection threshold was affected (Desender *et al*., 2017). Small-spotted catshark are renowned for their robustness to disturbance and it is unknown how other electro sensitive species will respond.

11.2.4 Reproduction

There is limited information available on the effect of pulse stimulation on reproduction of fish. In one tank experiment, small-spotted catshark were exposed to the sole pulse stimulus and followed over a nine month period. The small-spotted catshark showed normal feeding behaviour from the first day after exposure and were observed to lay eggs. No studies have been conducted to study the possible adverse effects of sub-lethal exposure on the maturation process, the quality of gametes and the spawning behaviour.

11.3 Adverse effects mechanical disturbance on benthic invertebrates

11.3.1 Impact on benthic invertebrates

There is a robust body of scientific information about how bottom trawling inflicts mortality on benthic organisms and on how this affects the community composition (review in Sciberras *et al*., 2018). There are only three studies which have attempted to examine the direct mortality imposed by pulse trawls. One study in the REDUCE project suggested that pulse trawls cause less mortality than traditional beam trawls (van Marlen *et al*., 2001). In two experiments, carried out in the BENTHIS project, no significant difference in mortality was found. Power analysis, however, showed that a larger number of samples would be required to statistically show a significant mortality rate inflicted by the pulse trawl as compared to the traditional beam trawl, supporting the qualitative difference in mortality rate between pulse and traditional beam trawls. Hiddink *et al* (2017) showed that the trawling-induced mortality is related to the depth of disturbance (penetration depth) of the gear. Hence, the reduced depth of disturbance of the pulse trawl (section 9) implies up to a 50% lower mortality rate.

11.4 Adverse effects pulse stimulus on benthic invertebrates

11.4.1 Mortality of benthic invertebrates

Few experiments are available that studied the effect of pulse stimulation on benthic invertebrates. One study found variable effects due to the small number of animals tested. Experiments with ragworm and shrimps using larger number of animals exposed to both the shrimp and sole pulse were unable to find an increase in mortality in exposed animals. Only a third experiment where shrimps were exposed to an extreme stimulus, 20 exposures over a 4 day period, observed a higher mortality in the pulse exposed group compared to one reference group but not to a second reference group. These studies do not provide support that exposure to a pulse stimulus during one event will result in measurable additional mortality in the species studied. The limited number of studies means that possible adverse effect cannot yet be excluded.

11.4.2 Sub-lethal effects on benthic invertebrates

It can be hypothesized that exposure to a pulse stimulus may affect the behaviour and physiology of benthic invertebrates, which may enhance mortality due to, for instance, predation or impaired immune system. The few studies that investigated the effect of pulse stimulation on benthic invertebrate species over a period of 14 days after exposure do not provide clear support for sub-lethal effects. The increase in baculoform inclusions in shrimps, which could be due to a suppressed immune system after pulse exposure, was observed in only one treatment with a worst case exposure between plate electrodes to the sole pulse but was not observed in other treatments with lower amplitudes and multiple exposures nor in a follow-up experiment in which shrimp was exposed 20 times to the commercial sole pulse between commercial electrodes.

The limited evidence does not provide support that exposure to a pulse stimulus adversely affect growth or increase the risk of disease reflecting an impaired immune system. The limited number of studies means that possible adverse effect cannot yet be excluded.

11.4.3 Reproduction

Only one experiment has been carried out to study the effect of pulse exposure on adult shrimps. The number of animals carrying eggs was not affected after exposure to pulse stimulation. The limited number of studies means that possible adverse effect cannot be excluded.

11.5 Exposure

11.5.1 Electric field around a pair of electrodes

Pulse trawls generate a heterogeneous electric field. The field strength at which an animal will be exposed is determined by the position of the animal relative to the conductors of the electrodes. Tank and in-situ measurements showed that field strength is highest close to the electrode and declines exponentially with increasing distance from the conductor. In-situ measurements showed that the sediments typical for the fishing grounds of pulse trawlers (sand or sandy-mud) hardly affect the field strength within the sediment compared to the water column.

11.5.2 Frequency of exposure

The frequency of exposure to a pulse stimulus is determined by the annual trawling frequency and the sensitivity of the animal for the field strength. The surface area of the seafloor (proportion of 1x1 minute grid cells) with a mean annual trawling intensity of >1 $year^{-1}$ is estimated at around 17% of the grid cells trawled by the pulse trawl fleet during a year (Figure 7.1).

As the electric field of the pulse trawl is heterogeneous, the actual strength of the pulse will depend on the position of the organism in the electric field. Under the assumption that animals will be sensitive for pulse stimuli within the width of the trawl, the trawling intensity can be used to estimate the frequency of exposure to a pulse stimulus. If the sensitivity threshold is below the minimum field strength within the width of the trawl, the exposure frequency will be higher. If organisms have a low threshold, the exposure frequency will be higher.

11.5.3 Repetitive exposure

Repetitive exposure at intervals of less than one week are very rare, assuming that animals are sessile. In the most intensively fished ICES rectangles, less than 0.3% of the seabed may encounter a repetitive exposure with intervals of less than one week.

11.6 Mechanical disturbance of sea bed

11.6.1 Depth of disturbance

The depth of disturbance of pulse and beam trawls have been studied in two study sites in the North Sea. Results show that pulse trawls reduce the average depth of disturbance by approximately 50% as compared to the traditional beam trawl.

11.6.2 Resuspension of sediment

The quantity of fine sediment that is resuspended in the wake of a bottom trawl is proportional to the drag of the gear components towed over the seafloor (netting, groundrope, beam shoes, nose of the sumwing and pulsewing). Because of the lower towing speed, it is inferred that pulse trawls reduce the resuspension of sediments. However, this reduction in resuspension will be lessened by the shift towards muddier habitats.

11.7 Structure and functioning of the benthic ecosystem

11.7.1 Benthos biomass

Bottom trawling will reduce the biomass of the benthos relative to the carrying capacity of the location. Taking account of the habitat specific recovery rates of the benthic community and the gear specific mortality induced by trawling, the mechanical impact of pulse trawls and traditional beam trawls on the benthic biomass was estimated using a model approach (Pitcher *et al*., 2016; ICES, 2017b). The analysis suggested that the mechanical impact of the pulse trawl relative to that of the traditional beam trawl on the benthic ecosystem is reduced by about 50%. The reduction is due to the reduced towing speed and the corresponding footprint, taking account of the changes in spatial distribution.

11.7.2 Bio-geochemistry

The preliminary results of a 4-year study on the effects of pulse and traditional beam trawl fishing on the functioning of the benthic ecosystem has shown that in a controlled fishing experiment, traditional beam trawling tended to produce a larger and more consistent impact on sediment oxygen consumption, oxygen micro-profiles and surface chlorophyll levels. Pulse trawling, on average, had lower yet more variable effects for these measurements. Nutrient fluxes and porewater nutrients did not show many consistent patterns between either fishing method. Tank experiments have, so far, not found evidence of electrical stimulation (using commercial sole pulse parameters) having a significant impact on benthic oxygen dynamics.

11.8 Environment

11.8.1 CO_2 emission

The 22% reduction in the towing speed of large vessels and the 14% reduction in towing speed of smaller vessels will be responsible for a reduction in fuel consumption and CO_2 emissions. The fuel saving for the larger vessels (>221 kW) is estimated at 46% (Turenhout *et al*., 2017). The reduction in CO_2 emissions will be even larger when expressed relative to the landings of sole as the catch efficiency of sole increased by about 30%.

11.8.2 Litter

It can be inferred that the reduction in towing speed and the reduction in bycatch of benthos and debris, will reduce the wear of netting material and so reduce the volume of material lost during fishing operations.

11.8.3 Electrolysis

No effect of electrolysis was found in a tank experiment using the sole pulse. Although temperature and salinity will influence the rate of electrolysis, the much longer exposure time used in the experiment and the rather small volume of water of the experimental tank, make it highly unlikely that the pulse stimuli used on gears that are towed through the water at a speed of around 5 knots will cause a significant effect.

Table 11.1. Assessment of the change in the performance of the pulse trawl relative to the beam trawl according a number of criteria.

Criterion / sub-criteria	Pulse/Traditional	Strength of support	Comment	Source
Sustainable exploitation of the target species				
Catch efficiency and Species selectivity (landings)	Increased catch efficiency of for sole, reduced efficiency for plaice and other fish species	Proven	About 30% more sole and 40% less plaice (landings in kg per hour fishing)	Section 6.6
Size selectivity sole and plaice	The lower catch efficiency for undersized sole and plaice reported in one experiment could not be confirmed in a follow up experiment	Unknown	Contradictory results of two comparative fishing experiments for sole and plaice.	Van Marlen *et al* (2014); van der Reijden *et al* (in prep).
Discards	Lower catch rate of discard size classes of all flatfish, but not for sole and other fish.	Iindicativ e	Discard catch rates (number per hour) of trips sampled over different years and different areas. For example, for plaice, discards are 25% less. Discards are still substantial for pulse trawls.	Section 6.5
Bycatch invertebrates	Reduced bycatch of benthic invertebrates over the whole fleet	Proven	Bycatch of benthos is reduced between 38%-72% although this is not supported by discard rate of small vessels (<=221 kW)	Van Marlen *et al* 2014; van der Reijden

				et al (in prep); Section 6.7
Discard survival	Improved survival of discarded fish	Inferred	Reduced towing speed, cleaner catch, smaller catch volume, less damage. Discard survival rates are estimated at 29% for sole and 14% for plaice in pulse trawls.	Section 6.9
Risk of overfishing	No increased risk	Proven	Conclusion applies to the total North Sea stock which is managed by an annual TAC. The conclusion is conditional on the enforcement of the quota regulation. Local sub-stocks within the North Sea may be overexploited.	Section 11.1.6
Fishing effort	Reduction of fishing effort in the sole fishery	Proven	Reduction of fishing effort in the sole fishery (70mm mesh) by 9% for large vessels (>221kW). Constant fishing effort targeting sole of smaller vessels (<=221kW). Relative share of sole landings by current pulse licence holders has increased from 75% to 95% between 2009 and 2017.	Section 6.2.
Spatial distribution	Pulse trawl can be deployed on softer grounds.	Proven	Shift in fishing effort to southern part of North Sea. Increase in fishing effort (hours) on some grounds (off Thames Estuary, Belgium coast). Fishers tell they can fish on softer grounds with the pulse trawl Changes in effort distribution need to be taken into account when assessing the ecological consequences of switching from traditional beam trawls to pulse trawls.	Section 6.4.
Adverse effects pulse stimulus on target and non-target teleost and Elasmobranch fish species that are exposed to the gear but not retained				

Injuries	Fractures and haemorrhages due to cramp observed in cod and whiting, but not in flatfish, seabass and small-spotted catshark.	Proven for cod, indicative for others	Low impact on ecosystem because only a small fraction of the fish community seems to be affected. No evidence that flatfish, which is the bulk of the catch, are affected.	Section 8.2.
	Fracture probability shows a dome-shaped relationship with body size with a lower incidence rate in small and large cod.	Indicative	Large variability in injury rate between studies. Indications of a possible lower sensitivity in small cod which need further study. Low impact on ecosystem as above.	Section 8.2.
Mortality	No direct mortality found in lab experiments. Fish with spinal fractures may have an increased mortality risk.	Indicative	Low because only a small fraction of the fish caught will be affected. No evidence that flatfish, which is the bulk of the catch, are affected. .	Section 8.2..
	Early life stages of cod exposed to shrimp pulse stimulus did show increased mortality in 2 out of 4 larval stages, but not in 3 embryonic and one juvenile stage. This adverse effect could not be corroborated in an experiment with sole larvae.	Indicative	Exposure experiment with shrimp pulse. Exposure of egg and larval stages of cod and sole to pulse stimulus will be very low because the eggs and larvae are distributed in the water column. Exposure of egg stages of demersal spawning fish such as herring or sandeel may be larger. Population effect will be modulated by the possible density-dependent regulation later in the life cycle	Section 8.4.
Feeding	No effect of pulse exposure on the food detection ability observed in an electro-sensitive fish species (small-spotted catshark).	Indicative	Electro-sensitive species contribute only a minor component of the fish biomass. From conservation perspective, the species are of particular interest as they are among the species most vulnerable for trawling imposed mortality. No in depth studies on effect on feeding	Section 8.5

			behaviour has been conducted	
Reproduction	Small-spotted catshark exposed to pulse stimulus were observed to lay eggs when kept for several month in the lab.	Inferred	One observation only	Section 8.3
Adverse effects mechanical disturbance on benthic invertebrates				
Impact on benthic invertebrates	Pulse trawls inflict less mortality on benthic invertebrates through mechanical disturbance.	Indicative	Sound scientific basis that beam trawls cause significant mortality among benthic invertebrates and that mortality scales with the penetration depth of the gear. Penetration depth of pulse trawls is 50% of beam trawl, hence mortality imposed by pulse is 50% lower. Three field studies on impact of pulse trawls suggesting lower mortality as compared to beam trawls	Sciberras *et al* 2018 Hiddink *et al*., 2017 Section 11.3.1.
Adverse effects pulse stimulus on benthic invertebrates				
Impact on benthic invertebrates	Few incidences of pulse induced mortality found in tank experiments.	Indicative	Individual effects studied in tank experiments on a small number of species do not provide support that exposure to a pulse stimulus during one event will result in measurable additional mortality in the species studied. The limited number of studies, however, implies that the possible adverse effect cannot be excluded.	Section 8.2.2.
Sub-lethal effects	Electrical exposure may impact the immune system, affect growth, or increased predation risk.	Inferred	The few experimental studies available do not provide show that exposure to a pulse stimulus adversely affect growth or increase the risk of disease reflecting an impaired immune system. However, the limited number of studies implies that the possible adverse effect cannot be excluded.	

Reproduction	Number of shrimps carrying eggs was not affected.	Inferred	One lab experiment. Overlap in distribution of shrimp and sole pulse fishing between April – November is low.	Section 8.4..
Exposure				
Exposure frequency	Proportion of the seafloor (grid cells) exposed at least once per year is 17% of the grid cells trawled	Inferred	Exposure frequency is determined by the combination of trawling intensity (known) and the field strength sensitivity threshold of organisms (unknown). For mobile species it may be influenced by their behaviour (attracted or repelled). Species that are sensitive to (very) low field strength outside the path of the pulse trawl will be exposed more often.	Section 7
Frequency distribution of repetitive exposure	Proportion of the seafloor that is exposed multiple times over a short (day) or medium long (week) time period is negligible.	Inferred	The conclusion is based on the estimated exposure interval under the assumption that organisms are insensitive to the low field strength generated outside of the width of the trawl. For mobile species it may be influenced by the behaviour. Species that are sensitive to (very) low field strength outside the path of the pulse trawl will be exposed more often. If the trawling hotspots coincide with rare habitats, repetitive exposure probability will be higher.	Section 7 Van Dendere n *et al* (2015)
Mechanical disturbance of sea bed				
Depth of disturbance	Average penetration depth of pulse trawl <50% of traditional beam trawl	Proven	Shallower overall penetration shown on sand and fine sand (measured at 4.0 cm average depth for beam trawl; 1.8 cm average depth for pulse trawling.	Section 9.1
Resuspension of sediment	Lower towing speed will reduce hydrodynamic drag and hence reduce sediment	Inferred	Prediction from model of O'Neill and Summerbell; O'Neill and Ivanovich (2016)	Section 11.6.2.

	resuspension. A shift in fishing grounds to muddier sediments will increase the resuspension.			
Penetration of electric field in sediment				
Exposure to electric field	Electric field measurements above and below the seafloor show that the depth of penetration is comparable	Proven	Two experiments done in sand and sandy mud habitats. From one study, the field strength at 20cm above and 20cm below the seafloor is 30% of the seafloor source.	Section 5.4
Structure and functioning of the benthic ecosystem				
Benthos biomass	Reduced impact of pulse trawls on benthic biomass due to lower footprint and reduced mechanical penetration.	Inferred	The reduced impact is predicted by a mechanistic model that is parameterised on all available experimental data on trawling impact on benthos including beam trawl, otter trawl and dredges. Two experiments conducted to estimate trawl mortality imposed by the traditional and pulse trawls support the conclusion that pulse trawl impose a lower mortality. Potential mortality induced by electrical stimulation is assumed zero	Section 10.1
Bio-geochemistry	Average effect (chlorophyll and oxygen dynamics) of pulse fishing is lower but more variable	Indicative	Few experiments. No effect for nutrients	Section 10.2
Environment				
CO2 emission	Reduction by about 50% due to lower fuel consumption compared to traditional beam trawl.	Proven	Fuel savings are largest for large vessels. Sumwing in isolation reduces fuel consumption by 10%	Section 11.8
Litter	Lower towing speed will reduce the wear of the gear	Inferred		Section 11.8

Electrolysis	No electrolysis observed in tank experiments.	Indicative	Lab experiment showed that commercial pulses in sole and shrimp fishery did not result in electrolysis.	Section 10.2.4.

12 WGECO input

WGECO provided a list of questions to be considered by WGELECTRA. The questions were according to the topics mentioned in the request for advice. A summary of WGELECTRA's responses to each statement/question is provided.

12.1 The sustainable exploitation of the target and bycatch species (species and size selectivity)

1. Species and size selectivity: there is a need for formal selectivity study for a standard pulse-trawl configuration (Wieman *et al*. 1996).

   WGELECTRA: results of a mesh selection experiment is presented in section 6.8.

2. The spatial distribution of the fishing effort of the Dutch tickler-chain [traditional] trawls has changed when pulse trawling was introduced What are the consequences of this shift? Possible research questions are:

   a) How has the CPUE of sole (and bycatch species) changed in space and what are possible consequences of this shift in species and size catch composition on populations?

   b) Pulse trawls can be used in softer sediments compared to [traditional] beam trawling. Does this have consequences on refugia for sole?

   c) How has CPUE of sole (and bycatch of other fish species) changed over time since the introduction of the pulse trawl? Has catch efficiency increased due to pulse trawling, i.e. are pulse trawls able to catch more and/or larger sole as opposed to conventional [traditional] beam trawls? Do pulse trawls maintain catch rates of larger sole since their introduction? A time series of CPUE by size class and species could indicate how CPUE changes since the introduction of pulse trawling.

   WGELECTRA: changes in the distribution of the fishery for sole after switching to the pulse is presented in section 6.4. No quantitative analysis has yet been done to study the consequences on the issues mentioned in the possible research question proposed by WGECO, except for the studies of the change in catch (landing efficiency) and of the size selectivity.

12.2 Target and non-target species that are exposed to the gear but are not retained (injuries and mortality)

1. Laboratory experiments have been conducted to test for the effects of electricity on several species and life stages. How comprehensive and representative are these experiments with respect to evaluating the impacts on different life stages of marine organisms? Should the effects on more species or size classes or life history stages be examined? Are there critical life stages that are at risk, such as metamorphosis of flatfish or the period of gametogenesis?

   WGELECTRA: the results of the laboratory experiments available today are restricted to a number of fish and benthic invertebrate species. The on-going research project Impact Assessment Pulse Fisheries (2016-2019) has the objective to derive a mechanistic theory to describe how electrical pulses may harm marine organisms. In particular, the project will develop a mechanistic basis to explain the differences in lesions observed between fish species and between different size classes.

2. The effects of electric pulses were studied for Atlantic cod (*Gadus morhua*), showing significant effects (De Haan *et al*., 2016; Soetaert *et al*., 2016). What are the potential risks of these injuries to cod populations?

   WGELECTRA: The potential risk will be determined by the overlap in distribution of the size classes of cod that are too small to be retained in the pulse trawl fishery and the effect of body size on the probability that a cod will develop a spinal injury when exposed to the pulse trawl. If cod that escape through the meshes of a pulse trawl are injured, this may increase their mortality risk and may ultimately influence recruitment. Whether cod that are retained in the net develop a fracture has no population consequences but may affect the price of the fish and will have implications for the assessment of animal welfare. The Impact Assessment Pulse Fisheries project (2016-2019) is currently studying the effect of body size on the sensitivity to develop spinal fractures. Results are expected to be available in 2019.

3. Can the results from laboratory experiments be extrapolated to field settings? Are there delayed effects (e.g. on growth, reproduction, etc.)?

   WGELECTRA: As for all laboratory experiments, extrapolation to the field is difficult due to the broad range of (often unknown) different environmental variables, especially since all laboratory studies were performed with a non-moving electric field. However, all studies used commercial settings or mimicked worst-case scenario exposures to evaluate possible side effects. For example, the longer exposures durations, closer electrode distances or high voltage homogenous exposures will all result in a potentially more harmful exposure (which has been evidenced in freshwater experiments as reviewed by Snyder, 2003). Furthermore, the detailed measurements of the electric field strength made by de Haan *et al*. (2011 & 2016) in the laboratory experiments with commercial wire-shaped electrodes corresponded with the those measured in set-ups at sea with different sediment types, confirming that electric settings tested were truthful.

   When it comes to possible delayed effect, the results of the limited laboratory experiments carried out so far do not provide any information. No studies have been done on the effect on maturing fish.

4. Investigate in more detail the impacts of effects of pulse fishing on electrosensitive species. While no effects of pulse trawling have been shown for lesser spotted catshark, the effects of pulse fishing on electrosensitive species (e.g. sharks, skates and rays) in the sole directed fishery are still poorly understood.

   WGELECTRA: point taken.

12.3 The mechanical disturbance of the seabed

1. Local reduction of mechanical disturbance by replacing tickler-chain trawls with pulse trawls is expected (Depestele *et al*., 2016). Were the sediment, habitat and hydrographic conditions investigated representative of the main areas where the fleet operates? Which aspects were (not) covered? What can be said on seabed impact at the fleet level (e.g. taking into consideration the change in gear use and effort as well as the displacement of effort)?

WGELECTRA: The habitat conditions in the study areas of Depestele (2016, submitted) are representative for the soft sediments fished by pulse trawlers but do not cover the full range of habitat conditions of the pulse trawl fishing grounds. Further studies on the mechanical impact of bottom trawls taking account of the differences in seafloor characteristics are needed. The FP7-BENTHIS project has embarked on an approach to model the gear – seabed interactions to provide a mechanistic tool to use in trawl impact assessment studies.

2. What are the effects of pulse trawling on the geochemistry (e.g. redox potential) and sediment properties in areas where fishing can be carried out by these pulse trawls but not beam trawls?

   WGELECTRA: these questions are being addressed by in-situ and ex-situ experiments within the IAPF project.

12.4 The structure and functioning of the benthic ecosystem

1. It is important to obtain comprehensive information on the effects of pulse trawling on benthic communities in the field. Can we extrapolate the effects of electricity derived from laboratory studies to field settings?

   The approach taken in the IAPF project is to combine laboratory experiments with field experiments and data collection on board commercial pulse and beam trawl vessels. Quantitative models will be developed to scale up the effects from experiments to the scale of the North Sea and the fleet.

2. There is a need for a trawling experiment that will compare the effects of both pulse trawl and [traditional] beam trawl on benthic invertebrates simultaneously, using rigorous replicated design (e.g. BACI) and including estimates of the benthos bycatch from these experimental fisheries. Conduct a power analysis to estimate the effect size that could be detected.

   WGELECTRA: these questions are being addresses by the IAPF project.

3. What is the fate of the non-target species in the path of the trawl but not retained? Direct sampling in the tracks of traditional beam and pulse trawls can be conducted with divers or with directed grab sampling.

   WGELECTRA: point taken.

4. Evaluate the behavioural responses of infauna to electrical stimulation. Is infauna stimulated with electricity more prone to come to the surface where it is more likely to be predated upon?

   WGELECTRA: exposure experiments planned in the IAPF project will provide information on the behavioural response on a selection of benthic invertebrates to pulse stimulation.

12.5 The impact of repetitive exposure to the two gear types on marine organisms

There is some concern over the longer-term impacts of repetitive sublethal exposure of benthic organisms to electric pulses. Cumulative effects of electric stimulation over longer time periods differ from the cumulative effects of physical disturbance that result in mortality. The evaluation of cumulative risk could involve dose-response experiments in the laboratory (e.g. growth rates, stress) and spatial distribution modelling to estimate the probability of encounter. Given the patchiness of trawling in time and space, there will be a need to define repetitive exposure with a time scale relevant for the stress variables studied to establish the magnitude of any effect.

WGELECTRA: The approach taken here is to estimate the exposure and the repetitive exposures from the available VMS data. This information, in combination with information on the threshold levels at which organisms are affected by the pulse, has allowed us to assess the potential impact.

13 General discussion

The impact of a fishery on the ecosystem is determined by the surface area exposed to the fishing gear, the intensity of the exposure and the sensitivity of the ecosystem and its components to the exposure. The comparison of the traditional beam trawl and its electric alternative is therefore complex and inherently subjective since different aspects such bottom-impact, bycatch, animal welfare, spinal injuries, fishing effort, have to be considered in relation to each other.

13.1 Comparing the footprint and catch efficiencies

The lower towing speed and the higher catch efficiency result in a decrease in the footprint of the sole fishery. The reduced seabed penetration of the pulse trawl as compared to the traditional beam trawl will likely result in a lower mortality imposed on invertebrates, and hence in a reduced impact on the benthic community and benthic biomass. According to the PD2 method, which was adopted by ICES as a method to quantify the impact of bottom trawling on the seafloor and which combines the mortality and recovery of the benthos, the impact of pulse trawls is less than 50% of that of the traditional beam trawl, despite the fact that the pulse trawlers have increased their trawling intensity in areas with a softer seafloor. No studies are available that have addressed the potential sensitivity of the benthic community in the areas of increased pulse trawl fishing or effects on the functioning of benthic organisms.

The reduction in the surface area trawled will reduce the impact on other marine organisms that occur in the trawl path. The reduced catch efficiency of the pulse trawl for species other than sole, may imply that this gear will reduce the catch of undersized fish (discards). The total amount of discards caught in a fishery, however, is not only determined by the catch efficiency of the gear, but also by the spatial distribution of the fishery relative to the areas with high abundance of fish that would be discarded if caught, and where the effect of management regulations affect the choice of gear and the spatial distribution of the fishery. Additionally, shifts in fleet composition or the use of different gears throughout the year should be taken into account. Indeed, the fleet of pulse licence holders reduced their fishing effort on sole and increased fishing for plaice using a large mesh size. The increase in beam trawling for plaice of the pulse licence holders may counteract to some extent the reduction in benthic impacts of using a pulse trawl in the sole fishery, although we expect that the large meshed plaice fishery will further contribute to a reduced impact in terms of discards.

13.2 Impact on seafloor and benthic ecosystem

The exposure to the mechanical disturbance can be readily estimated from the swept area of a gear (Eigaard *et al*., 2016). The exposure to the electrical field of a pulse trawl differs as the electric field extends beyond the trawl track. Field strength at the lateral edges of the trawl track was estimated to be < 17 $V.m^{-1}$, below the strength that inflicts injuries to cod, and quickly dissipates with distance from the gear (de Haan *et al*., 2016). Without information on the critical threshold levels of potential adverse effects of electrical stimulation, we have assumed that the effect of the pulse stimulation was restricted to the width of the gear. When fuller information becomes available, a more precise analysis can be carried out on the exposure to electrical stimuli.

Due to the reduced towing speed and the improved catch efficiency for the target species, the surface area of the seafloor exposed by the pulse trawl vessels is substantially less than the surface area of the same vessels deploying the traditional beam trawl. The impact is even further reduced as the pulse trawl licence holders have increased their share of the sole quota from 75% to 95% and consequently other vessels have reduced their fishing effort on sole by switching to other fisheries or ending their fishing operations (Turenhout *et al*. 2016).

The reduction in the surface area trawled and the reduction in the trawling intensity resulting from the switch to pulse fishing was particularly pronounced in the German Bight. In the southern North Sea, the trawling intensity remained more or less stable. Within the southern North Sea, two notable areas of high fishing intensity by pulse trawlers are apparent: one off the Norfolk banks and one off the Thames estuary. Although the area off the Thames was not fished by the Dutch beam trawl fleet before they switched to pulse trawling, the area was an important fishing ground for Belgium beam trawlers using heavy chain mat gears (Sys *et al*., 2016) which will cause a substantial impact on the seafloor and the benthic ecosystem. The potential adverse impact of pulse trawling in this area therefore needs to be compared to the impact of the Belgium beam trawlers.

It can be concluded that the transition from traditional beam trawl to pulse trawl has reduced the mechanical impact on the seafloor and the benthic ecosystem. The shift in the spatial distribution has resulted in an increase in the trawling intensity in a few ICES rectangles. At least some of the areas where the trawling intensity has increased were already fished by Belgium beam trawlers using traditional beam trawls (Sys *et al*., 2016). The current analysis at the ICES rectangle resolution is too coarse to fully quantify the changes in relation to seafloor habitat type. There is also insufficient evidence yet to understand the impact of electrical pulse on the benthic ecosystems across the North Sea, although the few experimental studies available do not suggest a major adverse impact.

13.3 Potential side-effects of electric pulses on animals

13.3.1 Effects on behaviour

Fish as well as some invertebrates show a cramp reaction when exposed to the sole pulse. The reaction immediately after exposure varied from absent with immediate resettling to a vigorous escape response. No prolonged adverse effects on the behaviour of invertebrate or fish species have been reported after exposure to the electric pulses used in pulse trawls. However, most studies described the behaviour only in qualitative terms and it is questionable to what extent reaction during lab experiments can be extrapolated to field exposures in the natural habitat of the animals.

13.3.2 Effects on adult commercial fish species

Pulse trawls reduce risk of mechanical impact by replacing mechanical stimuli by electrical ones. Therefore, a major aspect is the potential additional electric-induced side-effects of pulse trawls. The available evidence for damage caused by electrical stimulation on marine organisms is restricted to cod and whiting. Recent preliminary data consisting of samples collected on board commercial pulse vessels showed an average rate of spinal damage of 18% (spinal fracture and dislocations) and 24% smaller spinal abnormalities in cod. This confirms laboratory experiments where 0-70% of the cod exposed near the electrodes showed electric-induced spinal injuries and associated paravertebral haemorrhages, depending on the cohort of cod used (de Haan *et al*., 2016; Soetaert *et al*., 2016b). The data on the effect on juvenile and undersized cod remains inconclusive and requires further study. The laboratory experiments suggested that undersized cod, in particular the smallest size classes that may enter the net but can escape through the meshes, are less vulnerable to spinal damage (de Haan *et al*., 2016). Interestingly, spinal injuries were not observed in the non-gadoid round fish (seabass) which indicates inter-round fish variability. Further studies are required to investigate which other species and size classes may be prone to electric-induced spinal injuries and what the average injury rate is that might be expected in the field. The traditional beam trawl fishery for sole, however, catches only a small percentage of the total landings of this species in the North Sea. As most of the cod are retained in the net and landed for commercial purposes, the damage has most likely no ecological consequences but will affect the price of the fish. Nevertheless, these fractures pose an animal welfare problem and might be avoided or reduced by means of technical modifications in the gear.

Although more research is currently being conducted to investigate the vulnerability of the broad variety of fish species that may come into contact with the pulse gear, observations made in other studies evaluating the effect of the cramp pulse for sole, revealed no damage to non-gadoid round fish, cartilaginous fish such as small-spotted catshark or flatfish, which contribute to over 80% of the fish numbers caught in this fishery. Hence, we draw the preliminary conclusion that the available evidence suggests that the possible damage inflicted by pulse trawling on marine fish is restricted to only a small part of the fish community that is exposed to the pulse stimulus.

13.3.3 Effects on invertebrates

Preliminary studies with the sole pulse by Smaal and Brummelhuis (2005) and Van Marlen *et al*. (2009) exposing over 20 different species of benthic invertebrates to worst-case pulse conditions showed no consistent negative effects. The variable results suggest that insufficient animals were tested to exclude the variability due to natural mortality, which should be taken into consideration in future experiments. A more elaborate study in which shrimp and ragworm were exposed up to four times did not reveal any mortality or injuries after 14 days (Soetaert *et al*., 2014). A follow-up study (Soetaert *et al*., 2016c) exposing shrimp 20 times in 4 days could not reveal a difference in mortality, egg loss or number of moults between shrimp exposed to the cramp pulse for sole or shrimps exposed to a mechanical stimulus.

Any mortality imposed by the exposure to pulse stimulation should be compared to the mechanical impact caused by pulse trawling, estimated at 7% per trawl pass (section 10.1) and by traditional beam trawling which is estimated to kill on average 14% of the benthos (Hiddink *et al*., 2017).

Further research should broaden the number of species examined, including more endobenthos because the measurements by de Haan *et al*. (2018) showed that the electric field can penetrate over 30 cm in the sediment which is potentially an additional risk compared to the traditional beam trawl which penetrate on average 4cm (Depestele *et al*., submitted) with a maximum of about 8 cm (Paschen *et al*., 2000).

The survival of the benthic invertebrates might also be affected by electric-induced changes in the sediments biochemistry or oxygen dynamics. These effects were investigated by Tiano *et al*. but so far there is no evidence of electrical stimulation (using commercial sole pulse parameters) having a significant impact on benthic oxygen dynamics, although the exposure of sediment samples to electrical stimulation or mechanical disturbance showed clear increases in oxygen consumption after physical disturbance. Besides, the preliminary results of a field experiment in which an experimental site was disturbed by a traditional beam trawl and by a pulse trawl suggested smaller impacts on sediment oxygen consumption, oxygen micro-profiles and surface chlorophyll levels from the latter trawl. Porewater nutrient profiles from this study suggest that the traditional trawls reallocate the top layer of sediment compared to no conclusive changes associated with the pulse trawl (Tiano, pers comm).

13.3.4 Impact on reproduction, sub-lethal and long term effects

No studies have examined the effect of the cramp pulse for sole on the reproduction of fish or invertebrates. Two studies, conducted using the sole pulse, showed a potential risk for larval stages of cod whereas no problems were observed for the embryonic and juvenile stages of cod or for early live stages of sole (although the metamorphosis stage was not investigated). Further studies examining the effect of the cramp pulse for sole on reproduction are warranted. Special attention should be given to species which deposit their eggs on or in the sediment and/or which have demersal early life stages, as these have the highest likelihood of being exposed (repetitively).

The best studied sub-lethal effect is that on the electro-sensitive organs of small-spotted catshark (Desender *et al*., 2016). No adverse effect on their prey detection could be observed. Some other studies included histological research examining sub-lethal microscopic effects of electric exposures on the organs or immune system by counting melanomacrophage aggregates or viral inclusions (shrimp). Although in two treatments a potential sub-lethal effect was revealed, it is unclear what the long-term implications for the animal may be and how this might be affected by chronic, repetitive exposures.

Although the present report showed that the chance of being exposed repetitively is limited, concerns regarding the impact of sub-lethal or long-term effects are often raised. Animals which are not caught by the net or which survive discarding, such as certain invertebrate species and undersized fish, have the highest likelihood of being exposed chronically. Unfortunately, long term studies also face a lot of practical constrains such as housing facilities or the knowledge and expertise to control the life cycle of a species when studying reproduction. These elements make it difficult to design a conservative but realistic experimental set-up and explain why no studies so far have examined the effect of chronic/repetitive exposure to electric pulse (trawling) for a longer period and why most laboratory studies published to date were evaluating the effect of a single exposure within a 1 to 21 day period. Some exceptions exist, such as the study of de Haan monitoring small-spotted catshark up to nine months or the study of Soetaert *et al*. (2016c) exposing shrimp up to 20 times. This makes it difficult to properly assess the impact of chronic exposure to sub-lethal effects and it is questionable if laboratory set-ups can deliver a reliable answer since they will inherently miss environmental factors and interactions which may have a decisive influence on the result. This is particularly relevant if the results are to be compared to those of traditional beam trawling.

13.4 Prospects of application of electricity to improve the sustainability of capture fisheries

The use of electrical pulse as a stimulator in fisheries has mainly been limited so far to the area in front of the footrope to replace conventional mechanical stimulation by tickler chains in the sole fishery or bobbins in the fishery for shrimps, or to replace the hydraulic dredge to catch *Ensis*. However, it is clear that electric pulses offer a much wider range of possible application to enhance the selectivity of trawls, for example to separate fish or steer behaviour in the aft side of the net. This was successfully tried and described by Soetaert *et al* (2016d & 2018in prep) who used an electric cramp stimulus to avoid the escape of sole through a benthos release panel. This allowed for significant +-35% reductions of benthos, debris and certain undersized fish species without any loss of marketable fish. Other new applications may be to combine startle pulses with separation panels to induce a behavioural reaction of certain fish species or in combination with escape windows to promote the escape response of unwanted (choke) or undersized species.

14 Synthesis

Summarising the available evidence shows that the replacement of the traditional beam trawls by pulse trawls results in a reduction in environmental impacts: catch rate of fish discards (-16% to -24%), catch rate of benthos (-62% in large vessels and +6% in small vessels), trawling footprint (-18%), mechanical impact on seafloor and benthos (–50%) and CO_2 emissions (-46%). There is insufficient evidence to fully understand the impact of electrical pulse on marine organisms and the benthic ecosystems across the North Sea.

Clear adverse effects of electrical stimulation are the occurrence of spinal injuries and associated haemorrhages observed in gadoid roundfish, in particular in cod, when exposed near the electrodes. These injuries were not observed when the fish was exposed at distances of 30 cm above or 40 cm alongside of the electrodes. Electric-induced spinal injuries seem to be restricted to a few fish species that comprise a small percentage of the fish species caught in beam trawls. No injuries were observed so far in flatfish, non-gadoid roundfish or small-spotted catshark. A broader range of species is currently being investigated. Since flatfish dominate the fish community of the pulse fishing grounds (Daan *et al*., 1990; Heessen *et al*., 2015), the impact on the ecosystem level is expected to be modest. For cod, the population level effect of the fractures induced by the pulse stimulation of small cod passing through the pulse gear is expected to be modest because of the low overlap in the spatial distribution. The impact will further be determined by the size dependency of the injury rate. The preliminary results indicate a lower injury rate in cod smaller than a 20cm. Ongoing research will improve the basis to assess the population level consequences. If pulse trawling should increase the mortality of small cod in the southern North Sea, this may have consequences for the population recovery of this stock component. Further studies are required to address this question.

The laboratory experiments examining the effect of the more gentle startle pulse used in shrimp fisheries on reproduction suggested that electrical stimulation may result in mortality of particular larval stages of fish. Whether this will have a population level consequence (e.g. reduce recruitment) will depend on the proportion of the larvae that are exposed, and the occurrence of density-dependent processes later in life. The probability of exposure will be quite small as many larvae are pelagic and may be in a sensitive developmental stage only during a rather short time period. Future research on the potential effect on early life stages should focus on the effect of the sole pulse on species with demersal eggs or larvae such as sandeel or herring as these species are likely to have the highest contact rate with pulse fishing activities.

Potential adverse effects of pulse stimulation on benthic invertebrates will have to be compared to the physical effects of beam trawling. It is known that the passage of a traditional beam trawl imposes a mortality of 14% on average (Hiddink *et al.* (2017). Although no estimate of the mortality imposed by pulse trawls is available, the available experiments support a lower mortality rate. Based on the empirical relationship between penetration depth and benthic invertebrate mortality of Hiddink *et al*. (2017), it can be predicted that a 50% reduction in the penetration depth of the pulse trawl equates to a 50% reduction in the mortality rate.

Laboratory experiments carried out to date have provided little evidence for other (sub-lethal) effects in the fish and invertebrate species studied. However, the sometimes contradictory results, as well as the lack of mechanistic understanding of how electrical stimuli disrupt biological processes or biological structures, hamper the interpretation of the results. In addition, no quantitative study has yet been carried out to scale up the possible adverse effects of the exposure to pulses on marine organisms, but we can infer the possible order of magnitude of the effect by causal reasoning. The population level impact will be determined by the proportion of the population that is exposed to the pulse stimuli, the frequency of exposure, the strength of the pulse stimuli and the sensitivity of the different life stages.

Overall, the available evidence supports the potential of electrical stimulation to reduce the ecological and environmental impacts of beam trawl fishing. For some of the criteria, such as the possibility of sublethal effects and the uncertainty about the sensitivity of organisms to develop lesions when exposed to the sole pulse, our knowledge is still meagre. Hence, the above conclusions are still tentative. The in-depth studies being carried out within the IAPF project, are expected to provide a deeper understanding of the effects of the pulse exposure on the survivorship and behaviour of marine organisms and the functioning of the benthic ecosystem. The improved understanding will reduce the uncertainty attached to some of the tentative conclusions made in the current report.

15 Knowledge gaps

When assessing the impact of the transition from traditional beam trawling to pulse trawling ingwhen catch the TAC for North Sea sole, it became apparent that the scientific base to address the different criteria and sub-criteria varied. For the topics where we assessed the evidence to be indicative or inferred, further studies are required to reduce the uncertainty in the assessment.

The on-going research in the pulse impact assessment project that is currently being conducted in the Netherlands (https://www.pulsefishing.eu/research-agenda/impact-assessment-of-the-pulse-trawl-fishery) is expected to strengthen this scientific basis in particular with regard to (i) the study of pulse-induced injuries in fish, the effect on the threshold levels of the muscle activity, response of fish and invertebrates; (ii) the effect of pulse stimulation on biogeochemical processes in the benthic ecosystem; (iii) scaling up of local impacts to the level of the North Sea.

Below is a list of topics that were considered knowledge gaps by WGELECTRA.

15.1 Extrapolating results from laboratory experiments to the field.

Extrapolating laboratory results to the field introduces uncertainty as there are may be more factors affecting the interaction of a fishing gear with the marine organism or the ecosystem that can be realistically studied in the lab. Confidence in any extrapolations can be greatly enhanced once a mechanistic understanding exists of how an electrical stimulus may affect certain processes or structures in the organisms. Further research should be focussed on advancing the mechanistic understanding of how electrical stimuli affect marine life. This will be relevant for instance to understand the differences between species in their sensitivity to spinal injuries but will also be important to understand potential sub-lethal and/or long-term effects.

Field experiments

Field studies remain important because effects that are not visible during laboratory experiments might still appear in the dynamic environment of the sea where multiple, variable and complex interactions may arise. To date, there have been no large-scale, long-term field experiments to investigate the effects of pulse trawling, and the potential to design and conduct such an experiment should be explored, alongside the utility of enhanced on going monitoring that may detect the effect of pulse trawling.

15.2 Sub-lethal effects

15.2.1 Young life stages and reproductive phase

During the larval phase various complex morphological and physiological changes occur, rendering the larvae very sensitive to stressors. The precautionary approach hence is still warranted when making statements on the impact of electrical pulses on young life stages. When assessing these effects, not only mortality, but also parameters including growth and development, behaviour, stress and disease resistance need to be taken into account. Fish species producing demersal eggs should be given special consideration, including the eggs of elasmobranchs.

Research is warranted on the impact of the electrical pulses on the reproduction of adult brood stock and fertility success of exposed gametes.

15.2.2 Disease

One might hypothesise that exposure to electrical pulses may weaken an organism's physiological condition or immune system or alter its morphology, rendering it more susceptible to infections or noxious agents.

15.3 Behaviour

The knowledge of the effect of pulse stimulation on behaviour of fish and invertebrates is limited to descriptions of behaviour during and immediately after exposure, although this is mainly qualitative. Although some studies report normal feeding responses and swimming behaviour in the days following exposure, however, these responses were not quantified and the reports are anecdotal. None of the existing studies examined long time effects on the behaviour or interaction of exposed animals nor potential attraction or repulsion to repetitive electric pulse stimulus.

15.4 Long term effects on development, reproduction, growth, behaviour

Both acute and chronic stressors can induce responses that last into the later life of an organism and these long-term effects on individual fitness may translate into population-level impacts. The research on pulse trawling has thus far investigated only short-term effects and little is known about the long-term impacts on organism fitness for either fishes or benthic invertebrates. Particular gaps include:

- Whether exposure to the pulse impacts reproductive capacity
- Whether any injuries occurring in early life stages could cause developmental problems in juvenile and adult invertebrates and fish
- Whether pulse trawling affects growth
- Whether short term behavioural responses to pulse trawling translate into longer-term effects on energetics and fitness

15.5 Population and Ecosystem consequences

15.5.1 Ecosystem functioning

It is considered that the mechanical disturbance and average penetration in the seabed by a pulse trawl is less than the caused by a conventional beam trawl (Depestele *et al*., 2016). Electric fields, however, may penetrate into the sediment potentially affecting benthos that live below the penetration depth of tickler chains. The effects of pulse exposure are not yet fully understood and the combined effects have not been studied yet.

Trawling will impact different functional groups. However, there are still a number of evidence gaps on effects of pulse stimulus on the biogeochemistry of the benthic ecosystem, which will need further study. There are no studies on the impact of pulse trawling on broader ecosystem functioning such as bentho-pelagic coupling, trophic function, habitat provisioning or ecological connectivity.

15.5.2 Population movement

There is currently no information on the potential for changes in the distribution of species populations caused by the fishing activity of pulse trawlers. There is the possibility for movements of populations based either on their avoidance of, or attraction to pulse trawling activity, and this should be investigated.

15.5.3 Effect on sole stock of change in effort distribution

A change in the distribution of fishing effort with the transition from traditional beam to pulse trawling has been identified (section 6.4). There has been an intensification of fishing activity in some small areas in the southern North Sea, in areas most profitable for pulse trawls, i.e. with highest sole catches. The impact of the changed distribution in fishing effort on the population dynamics of sole should be investigated, taking account of the stock structure and the connectivity between nursery and spawning grounds.

15.6 Welfare

In the present report, the implications of the pulse, or the traditional beam trawl, fishery on the welfare of target and non-target marine organisms were not taken into account. However, WGELECTRA acknowledges that this remains an issue that needs to be considered in future research.

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Annex 1: List of participants

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Annex 2: Repetitive exposure for pulse trawl and traditional beam trawl

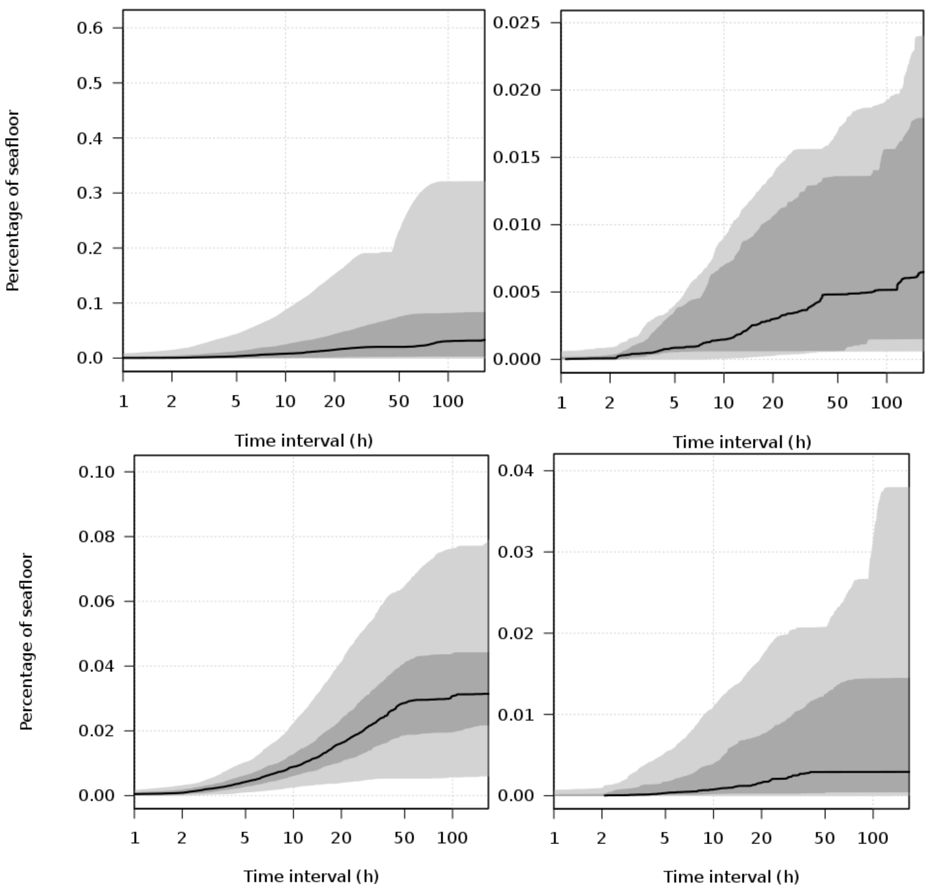


Figure A.1: Percentage of seafloor being trawled with a specific time-interval for ICES rectangle 37F7, 33F3, 32F2, 34F2 with Pulse gear. Black solid line presents the median interval-percentage relationship out of 2-years * 52-weeks combinations. The dark-grey area represents the 50% CI while the light-grey area represents the 95% CI.

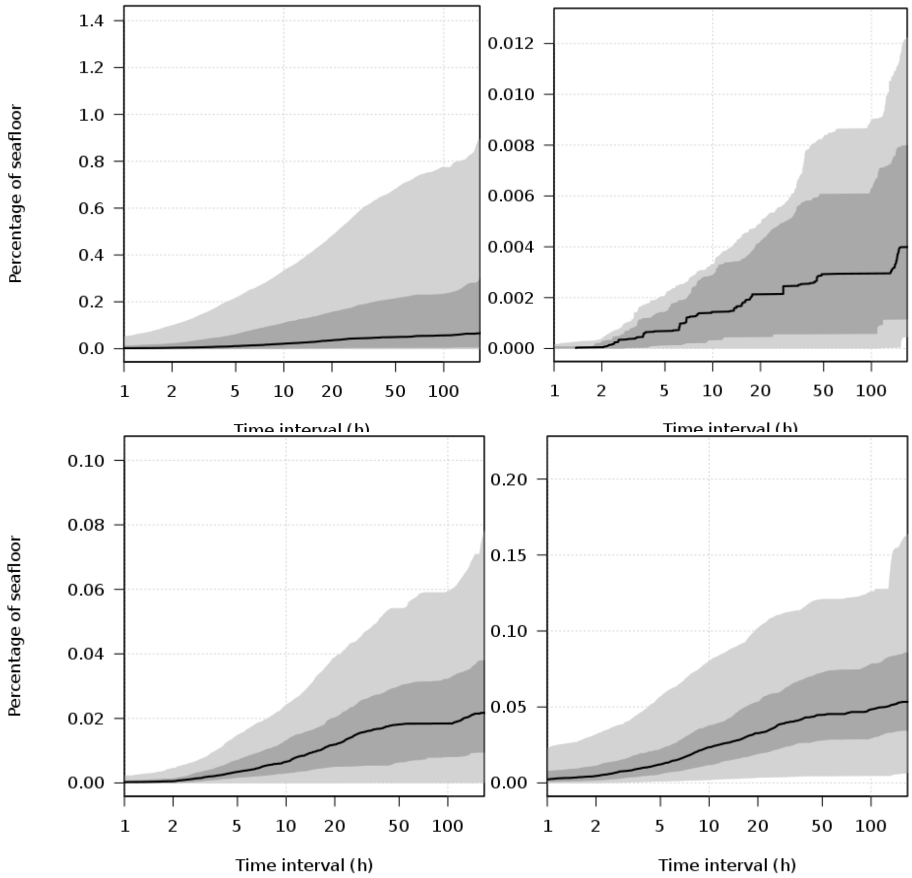


Figure A.2: Percentage of seafloor being trawled with a specific time-interval for ICES rectangle 37F7, 33F3, 32F2, 34F2 with beam-trawl gear. Black solid line presents the median interval-percentage relationship out of 2-years * 52-weeks combinations. The dark-grey area represents the 50% CI while the light-grey area represents the 95% CI.

Annex 3: Terms of reference

WGELECTRA - Working Group on Electrical Trawling

2016/2/SSGIEOM22

A **Working Group on Electrical Trawling (WGELECTRA)**, chaired by Maarten Soetaert, Belgium, and Adriaan Rijnsdorp, the Netherlands, will work on ToRs and generate deliverables as listed in the Table below.

	Meeting dates	Venue	Reporting details	Comments (change in Chair, etc.)
Year 2018	17-19 April	WMR Ijmuiden, the Netherlands	Interim report by 31 of May 2018 to ACOM-SCICOM	
Year 2019			Interim report by end of April 2019 to ACOM-SCICOM	Change in chair (Adriaan Rijnsdorp will step back)
Year 2020			Final report by end of June 2020 to ACOM-SCICOM	

ToR descriptors

ToR	Description	Background	Science Plan topics addressed	Duration	Expected Deliverables
a	Produce a state-of-the-art review of all relevant studies on marine electrofishing. Yearly update it by evaluating and incorporating new research to it.	a) Science Requirements b) Advisory Requirements	14,19,20,27,29	Yearly update	Review report to SCICOM
b	Supply required information to answer on request of member states concerning electrotrawling	b) Advisory Requirements	14,20,26,29,30	Upon request	Advice documents Responses to requests of member states
c	Discuss and prioritise knowledge gaps, and discuss ongoing and upcoming research projects in the light of these knowledge gaps, including the experimental set up	a) Science Requirements b) Advisory Requirements	11,12,14,17,19, 20,27	Year 1, 2 & 3	Scientific research adressing knowledge gaps or questions from management
d	Create a platform for the application for supra-national joint research projects on electrotrawling and scientific publication of the obtained results	a) Science Requirements b) Advisory Requirements	17,29	Year 1, 2 & 3	Joint projects and publications among participants and others Collaboration with other related WG's such as WGNSSK, WGCRAN

Summary of the Work Plan

Year 1	- Initiating the review document - Discussing & evaluating ongoing & recently completed research - Brainstorm & application of a joint research project - Answering possible requests
Year 2	- Updating the review document - Discussing & evaluating ongoing& recently completed research - Evaluating and presenting results from joint research projects - Answering possible requests
Year 3	- Finalizing the review document - Discussing & evaluating performed research - Presentation achievements and further goals joint research projects - Answering possible requests - Writing the final 3year report

Supporting information

Priority	The current activities of this Group will lead ICES into issues related to the ecosystem effects of fisheries, especially with regard to the application of the Precautionary Approach. Current pulse derogations in the sole fishery will expire in 2019 and a request for scientific advice is expected to assess the impact of pulse trawling on the ecosystem. Consequently, these activities are considered to have a very high priority.
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.
Participants	The Group is normally attended by some 10–15 members and guests. In 2016 two PhD students started working on the ecosystem effects of pulse trawling in the Netherlands.
Secretariat facilities	None.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	There is a close working relationship with the Assessment Working groups (WGNSSK) dealing with the target species of the pulse fisheries (sole, plaice) and WGCRAN. It is also very relevant to the Working Group on Ecosystem Effects of Fishing.
Linkages to other committees or groups	
Linkages to other organizations	/

Annex 4: Living document on principles and effects of pulse trawling

See the attached document below.

Pulse fishing in marine fisheries

Review of the technology, research and research agenda

Last revised and updated by WG Electra April 27th 2018.

Previous versions published in: \

This overview was initially merged and completed by Maarten Soetaert (2017) based on:

(1) Verschueren, B. and Polet, H. September 2016. Pulse fishing in marine fisheries – Review of the technology, research and research agenda. Institute of Agricultural and Fisheries Research (ILVO) internal document: 70 p.

(2) Rijnsdorp, A., De Haan, D., Smith, S. and Strietman, W. J.. December 2016. Pulse fishing and its effects on the marine ecosystem and fisheries. Wageningen Marine Research (WMR) confidential report C117/16: 32p.

(3) WG Electra, 2017. Final report of the working group on electric trawling. ICES CM 2017/SSGIEOM:20; 40 p.

Contents

1 Introduction

The North Sea flatfish fishery is mainly carried out with vessels that tow double beam trawls over the sea bed to target sole and plaice (Rijnsdorp et al., 2008). This beam trawl fishery, in particular the one targeting sole, is characterised by a substantial bycatch of undersized fish, benthic invertebrates and debris. In addition, beam trawls have an adverse impact on the structure of sea bed habitats and impose an additional mortality on invertebrate animals in the path of the trawl (Lindeboom and de Groot, 1998; Bergman and Santbrink, 2000; Kaiser et al., 2006). In terms of benthic impacts, flatfish beam trawls together with shellfish dredges are considered to be the most detrimental fishing gears in the North Sea (Polet and Depestele, 2010). These benthic impacts are related to tickler chains that are used to chase sole out of the sea bed. These tickler chains dig into the sea bed to a depth of 8cm or more (Paschen et al., 2000).

Research into alternative methods to catch sole has been conducted since the 1970s to increase the selectivity for sole. This research focussed on the use of electrical pulses that led to a contraction of the body muscles (cramp response) during exposure which prevented the sole to dig into the sediment. The U-shaped form of a cramped sole makes it easier to catch in a bottom trawl. After successful commercial trials since 2005, an increasing number of vessels has switched from the traditional tickler chain beam trawls to pulse trawls. These vessels operate under a temporary licence, because use of electricity in catching marine fish is not allowed in EU waters (EC nr 850/98, article 31: non-conventional fishery techniques).

In addition to the deployment of pulse trawls in the flatfish fishery, pulse trawls have adopted in the fishery for brown shrimps in the Netherlands although the number of vessels is small (4) and the vessels are not allowed to use the gear in the Natura2000 areas. The shrimp pulse invokes a startle response in shrimps which allows the fishers to reduce the weight of the gear and subsequent bottom contact. Experiments have shown that the application of electrical stimulation in the fishery for brown shrimp may reduce the bycatch of other species (Polet et al., 2005a, 2005b.

The introduction of pulse fishing in the North Sea has raised serious concerns among stakeholders (fishing industry, NGO's) and EU member states. Fishing trials and laboratory experiments reported spinal fractures in cod (van Marlen et al., 2007; de Haan et al., 2008). Kraan et al. (2015) made an inventory of the concerns which were discussed at a pulse dialogue meeting organised in July 2015. The concerns are related to the lack of knowledge about (i) the ecological effects of electrical pulses on the marine ecosystem and (ii) the risk of an increase in catch efficiency and the consequences for other fisheries. The concerns were aggravated by the increasing number of temporary licences to 84 in 2014, as part of a Dutch pilot project in preparation of the introduction of the landing obligation under the reformed European Common Fisheries Policy[1].

[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32013R1380

The objective of the current report is to provide a synthesis of the studies on pulse fishing that have been conducted so far in the light of the major concerns raised. This report describes the electrical characteristics of the flatfish and brown shrimp pulse system and reviews the catch efficiency and selectivity of the gear , the effects of pulse stimulation on marine organisms, the effect on the marine ecosystem and the effects on viability and survival.

2 Electrotrawl technology

2.1 Basic working principle

Electrical fishing works by using electrical currents to induce a desired response in the target species, which either compromises the target's ability to evade capture or makes it available for capture by stimulating it to move into the net opening of the fishing gear (Breen et al., 2011). A less obvious, but nonetheless promising application is to enhance escape behaviour of unwanted species in selective devices.

The form and dimensions of the electric field generated in the water and the underlying substrate and its effect on the target will be dependent upon many factors, i.e. the characteristics of the electrical power source and the electrodes, the properties of target species and habitats in the fished area.

2.1.1 Some explanatory physics

A good understanding of the operation of electric fields in water is essential to fully comprehend the working principles and the effects of electrotrawling. An electric field is generated by an electrical power supply that charges one electrode positive (anode) and one electrode negative (cathode). This creates a potential difference (voltage [V]) over the 2 electrodes, spaced at a certain distance. Charged ions in the water will be attracted to the oppositely charged electrode and induce a flow of charge in the water between the electrodes that is called the current (I, [A]). It is analogous with the flow of water down a river or through a pipe and is a measure of the amount of electrical charge moving through a point over a period of time. One ampere is equivalent to $6{,}2 \times 10^{18}$ electrons passing a given point in one second.

The more ions in the water, the higher its conductivity and the better its capacity to conduct electric current. Conductivity varies considerably, depending on the temperature, the salinity and the organic matter content of the water (Soetaert et al., 2013). The capacity of the power source to create a potential difference over 2 electrodes (power, [W]) is limited and depends on the conductivity, because it is in permanent competition with the ion flow in the water, which will continuously neutralize the charge on the electrodes. Therefore, the potential difference over the 2 electrodes will be inversely proportional to the conductivity of the water, which is illustrated by the formula of electrical power: $P = V^2/R$, with P the power, V the potential difference and R the resistance, which is the inverse of conductivity. Indeed, when the conductivity is high as in sea water, the charge on the electrodes supplied by the power source will be easily neutralized and the potential difference will be small. Each potential difference over 2 electrodes induces an electric field in the water. This field is characterized by the field strength ([V/m]) which indicates the voltage gradient at a certain location in the medium between the electrodes.

In most natural situations, the lines of force/flux within an electric field radiate out from the electrode and thus do not run parallel to each other (Polet, 2010). These heterogeneous electrical fields differ from homogeneous electrical fields, where the force/flux lines run in parallel to each other. An (almost) homogeneous electrical field can easily be created by placing two plate-shaped electrodes parallel, providing a constant voltage gradient, current density, and power density. A homogeneous field simplifies experimental conditions and is ideal for lab experiments, but it may be difficult to extrapolate to commercial electrofishing operations, during which the electric fields will always be heterogeneous.

The distribution and strength of an electrical field is strongly influenced by a complex relationship between the shape and size of the electrodes (anodes and cathodes), as well as the mutual distance (Novotny, 1990).

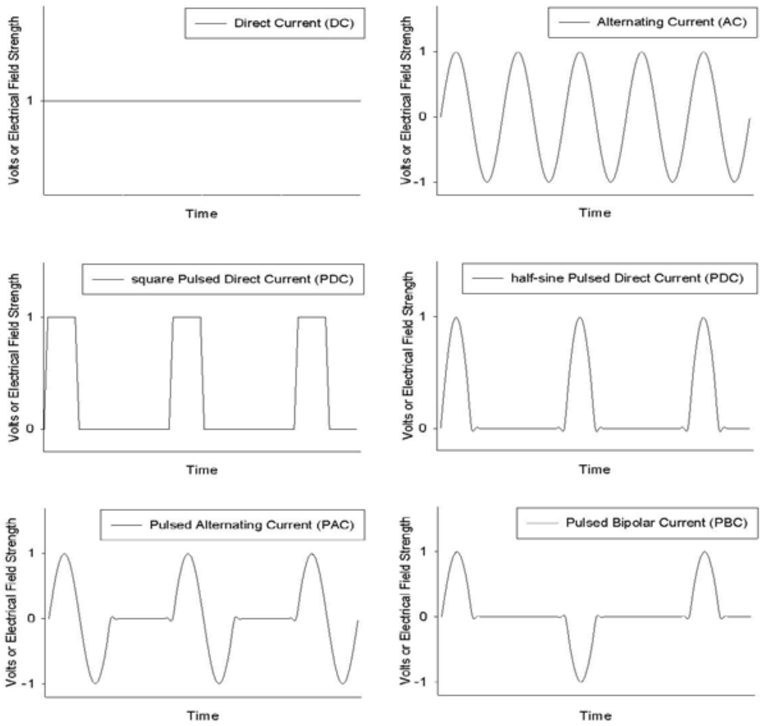


Fig. 2-1 – Different types of waveforms used in electrofishing

Power sources can produce different types of current as is illustrated in Fig. 2-1. Basically these can be divided into two types: Direct Current (DC) which is the movement of electric charges in one direction and Alternating Current (AC), which is a bipolar current flow. Both types can be applied with intervals and hence will generate pulses. In case of DC this results in Pulsed Direct Current (PDC). In case of AC this results in either Pulsed Alternating Current (PAC) if 1 pulse consist of a positive and negative part, or in Pulsed Bipolar Current (PBC) if 1 pulse is successively positive or negative.

Pulsed currents are characterized by the number of pulses per second (Hz), pulse duration (ms), pulse shape and amplitude (V). The higher the potential difference on the electrode, the higher the amplitude and the field strength will be. In highly conductive seawater, the preferred use of pulsed current instead of continuous current is obvious. It allows to reach acceptable, i.e. sufficiently low, electrical power demand, while maintaining desired electrical field intensity. The pulses can be generated by producing large bursts of peak power that are short in duration and intercalated with recovery periods in which the transformer and capacitor components store the energy required for the next burst (Novotny, 1990). A more exhaustive list of pulse parameters and their definitions are defined in Soetaert *et al.* (2018).

2.1.2 Animal responses

A wide range of responses of aquatic animals to electric fields, ranging from initial startle reactions to death, has been observed (Snyder, 2003). However, for the practical purposes of marine electrofishing these can be broadly summarised into four main responses (Polet, 2010): 1) Fright, minimum response which may include undirected movement; 2) Electro-taxis, induced directed movement; 3) Electro-narcosis, immobilisation of the target specimen through an induced narcosis and 4) Electro-tetanus, paralysis of the target specimen through an induced muscle contraction.

Given a fixed field strength, the level of response from an exposed specimen will be determined primarily the specimen's orientation in the field and its relative size, by its distance from the electrode and by the form of the electrical signal. Distance from the electrode will determine the current and/or power density that the specimen is exposed to, while its orientation in the field and its relative size will determine the potential voltage difference that it experiences across its body. Therefore, it is generally accepted that larger fish, with a larger potential difference over its body as illustrated in Fig. 2-2, will show greater reaction. However, the sensitivity varies greatly between different species.

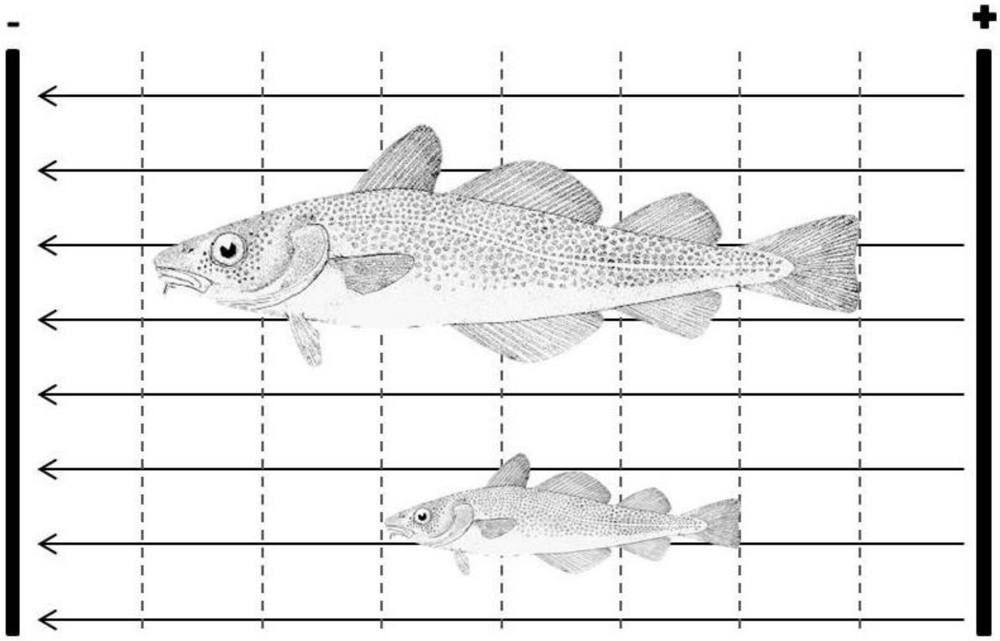


Fig. 2-2 - illustration of cod in a homogenous electrical field between 2 parallel electrodes. The horizontal lines are the electrical field lines, representing the current flow between the electrodes. The dashed vertical lines are equipotentials, zones with the same potential. The larger the difference between 2 extremities of a fish, in this case head and tail, the higher the potential difference over its body and the stronger it is experiencing the electrical field. E.g.: Suppose an applied potential difference over the electrodes of 80 V which results in a potential difference between each equipotential of 10 V. In this case the large fish will experience 60 V, whereas the small fish only 30 V. Consequently, the orientation of the fish has a marked influence on the potential difference over his body. Reproduced from Soetaert et al., 2013.

At low frequencies, a PDC field will frighten the fish, which as a consequence will try to swim away (startle reaction). Once the frequency exceeds a certain threshold value, usually around 20 Hz, the jerking movements of the muscle, induced by the electrical pulses, are succeeding so fast that the muscles are continuously stimulated and remain contracted. This summation of many individual contractions may lead to a cramp and immobility (Snyder, 2003).

Due to the electro-chemical nature of nerve impulse and muscle stimulation, the presence of a sufficiently intense electric field can stimulate both nerves (neurones) and muscle cells to induce a range of behavioural responses including: inhibition of movement, enforced directional movement towards electrodes (electro-taxis) and uncoordinated and severe muscular contractions (electro-tetanus). However, the precise role of varying electric field strength on the central nervous system and the many different manifestations in observed responses is less clear. In the scientific literature, most work on this topic has focused on teleost fish and this was comprehensively reviewed by Snyder (2003).

2.1.3 Differences with freshwater electrofishing

Electrofishing has been used frequently since the 1950's as sampling technique for fish in freshwater whereby electric energy is passed into the water. In case direct current (DC) is used, fish intercepting this energy will show forced swimming toward the source of electricity, which is called galvano-taxis. As reviewed by Snyder (2003a), freshwater electrofishing is a very effective sampling method but it has the disadvantage that it may inflict harm to fish. Salmoninae are known to be susceptible to spinal injuries, associated haemorrhages, whereas it can be lethal for burbot and sculpins under some conditions. Freshwater electrofishing is also reported to result in cardiac arrests, long behavioural and physiological recovery times and doubtful effects on early life stages. Unfortunately, many questions remain unanswered, the interpretation of some results is often difficult to understand or questionable and a lot of variation and contradictions are reported.

This is not surprising since application of electric pulses comprises many different factors: electrode shape and set-up, different pulse parameters used, differences in conductivity, temperature and surrounding medium, size of the animal, species-dependent reactions and side-effects,… Freshwater electrotrawling differs from pulse trawling electrofishing in almost every characteristic, as overviewed in Table 2.1. Note that this table does not include marine electrofishing on *Ensis* spp. because it is poorly documented and the pulse settings (continues current, not pulsed) are more similar to freshwater electrofishing because it aims for a similar slow behavioural response in *Ensis* spp. and subsequently requires exposure times around 1 minutes.

Table 2.1: Overview of major differences between freshwater and marine electrofishing. (taken from Soetaert et al., 2015)

	Freshwater electrofishing	Marine pulse fishing
Application	sampling of river or lakes	commercial trawling
Goal	sampling all fish species of all size	increase marketable catch
Working principle	inducing galvano-taxis to anode	upwards startle reaction
	or immobilization on the seafloor	or immobilization on the seafloor
Gear	static	dynamic/moving
Electrodes	2 (hemi)sphere, ring or cylinder	multiple wire-shaped electrodes
Electrode distance	> 1 m	0,3 - 0,6 m
Water conductivity	0,01-0,1 S m^{-1}	4,2 S m^{-1} (North Sea, 15°C)
Electric dispersion	current = or > in fish than in water	current < in water than in fish
Exposure duration	0,5-3 minutes	0,5-3 seconds
Duty cycle	always >10%, often 60-100%	<3%
Frequency	15-120 Hz (and up to 500 Hz)	5-80 Hz
Potential difference	100-400 V	60-100 V
Pulse type	DC, PDC or PAC	always pulsed
Pulse shape	exponential, sinus, quartersinus, square, triangular,…	rounded shape caused by impedance of long electrodes

How electric current interferes with the fish physiology is not yet elucidated. Fish can be considered to be an electrical network composed of resistors and capacitors. The membrane and tissues act as the dielectric of a capacitor with the ability to by-pass frequencies as well as frequency attributes expressed in the leading and trailing edges of the pulse (Sternin *et al.*, 1976; Sharber *et al.*, 1999). Given the differences in the anatomy of fish species, the response to an electric stimulus will differ across species (Halsband, 1967; Emery, 1984). The interaction with the electric field is also affected by the pulse settings and the environment. In addition, other pulse parameters can affect the impedance of tissues (Finlay *et al.*, 1978), resulting in different electric doses and effects. The conductivity of the surrounding medium is also decisive. Whereas in fresh water high amounts of current may flow through the fish' body as it conduct current better than the surrounding water, this will not occur in fish surrounded by seawater with a much higher conductivity (Lines and Kestin, 2004). On the other hand, much higher field strengths will be found in the immediate surrounding of a fish in seawater, which might indirectly affect the flow of ions in the fish' body, the charge on neurons, the polarity of membranes and tissues,…. The long list of differences and poorly understood phenomena stress that prudence is warranted when extrapolating freshwater results.

2.2 History of pulse trawling

Interest in marine electrofishing was stimulated by the successful introduction of electrofishing techniques in freshwater and experiments carried out in Germany, as reported by Houston (1949). Attracting fish to an anode, as is the case in freshwater, was the main focus back then. This gradually changed when Bary (1956) stipulated that the theories used for freshwater could not be extrapolated to seawater. Inducing a startle reaction in the target species, to make it leave the seafloor and enter the trawl, became the primary objective. This would possibly allow the replacement of traditional tickler chain or bobbin rope stimulation with electrodes, without loss in efficiency (De Groot and Boonstra, 1970). Successful experiments with electric fields in otter trawls targeting demersal fish (Mc Rae and French, 1965) and shrimp (Pease and Seider, 1967) showed increased catch efficiency. In 1970, experiments were set up in the Netherlands with lightweight electrotrawls intended to target brown shrimp. Besides higher catch rates at daytime, another advantage became apparent, as for example, the reduction in trawl induced injury of juvenile flatfish (Boonstra and de Groot, 1970). In Belgium, Vanden Broucke (1973) obtained good indicative results with increased shrimp and Dover sole catches. In search of alternative stimulation mechanisms for other species, Stewart also investigated the effect on Norway lobster (Stewart, 1972, 1974). He found that electric pulses could stimulate emergence of these animals from their burrows in less than 5 seconds.

In those years '70-80 European fisheries institutes in The Netherlands, UK, Belgium, France and Germany carried out research and development in the use of electrofishing in marine fisheries, in some cases in collaboration with private companies. The main motivation for this work was to develop gears which saved fuel, particularly during the post 1974 'oil shock' period when the price of oil rose rapidly and electrofishing, which was perceived as being more energy efficient than conventional towed gears, offered the opportunity to save fuel. Despite the good progress that was made, the challenge, especially on the technical side, was still enormous (Stewart, 1971). It was very difficult to reproduce the results made with the small beam trawls in larger commercial trawls, as more electrodes and thus more power was required. The increased power demand, the drag resistance of the voluminous pulse generators, the electrode connections in the water, the electrode material and the electrical efficiency were all leading to an accumulation of technical difficulties, safety issues and frequent malfunctioning (Boonstra, 1979). This hurdle was difficult to overcome at that time and hence markedly slowed down the further study and development of marine electrofishing. This vulnerability, combined with the large investment and maintenance costs of an electrofishing device, hampered a successful introduction.

Half a decade later, a new generation of pulse generators enabled sufficiently high voltage peaks (Agricola, 1985). From then on various experiments proved very successful in increasing catch efficiency (Horn, 1982, 1985; Delanghe and Vanden Broucke, 1983). The first commercial pulse beam trawls were already commercially available, when the method was banned in 1988 in the Netherlands. Development in the other European nations also ceased around that time. Later the European Commission prohibited the use of electricity to catch marine organisms (EC nr 850/98, article 31: non-conventional fishery techniques). The main reason for these bans were likely the fear of further increasing catch efficiency in the beam trawling fleet, which was under severe international criticism back then (Van Marlen, 1997).

Since then all legal electric fishing in European waters has taken place under an agreed derogation from these regulations. Since the 1990s there has been an increased focus on reducing the environmental impact of trawling, particularly beam trawling. Electrofishing techniques have the potential to reduce this impact because of the reduced gear weight, lower towing speed and higher selectivity. This led to a revival of interest in electrofishing and a high level of collaboration between public and private sectors. In the Netherlands this has lead to the redevelopment of the flatfish pulse trawl and in Belgium the brown shrimp (*Crangon crangon*) pulse beam trawl was optimised. In a separate development in the early 2000s, it was discovered that razor clams (*Ensis sp.*) could be induced to emerge from the seabed through electrical stimulation.

2.3 Electrotrawls and pulse trawls today

2.3.1 The *Crangon* pulse trawl

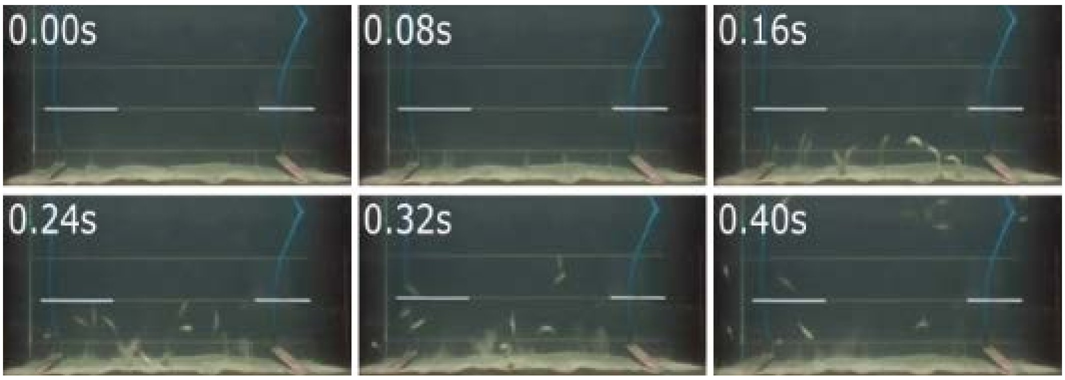


Fig. 2-3 – Pulse stimulation of brown shrimp (Crangon crangon). The shrimp are buried in the sand (top left), when the electrical pulse field is switched on. After only 0,16 s all shrimp have left their buried position in a vertically upward direction.

Based on successful application of shrimp electrotrawls in China, the Belgian Institute for Agricultural and Fisheries Research (ILVO) started investigating the potential of pulse trawling for brown shrimp in the late 1990s. The research of Polet et al. (2005a,b) revealed that a half-sine square pulse (PDC) with a frequency of 5 Hz, a pulse duration of 0,5 ms and an electric field strength of approximately 30 V/m gave the best result to startle brown shrimp successfully. By stimulating the body musculature involuntary, these shrimp are forced to leave there buried position in the seabed in a vertically upward direction, as is illustrated in Fig. 2-3.

Based on these findings, a commercial pulse beam trawl system for *Crangon* (Fig. 2-4), was first developed and tested by ILVO in 2008 in cooperation with the Belgian company Marelec and the University of Ghent (Verschueren and Polet, 2009). The pulse beam trawl is equipped with a pulse generator on top of the beam. The pulse generator connects to 12 stainless steel electrodes (6 cathodes + 6 anodes) that are rigged in the net opening of the trawl. They form 11 electrode pairs that are fired alternatively by the pulse generator. The gear is connected to the vessel via an electrical supply cable, which is hauled along with the fishing line. The low frequency and short pulse duration of the applied electrical field allows the system to operate with a very low energy input of about 1 kWh per trawl (Table 2.2).

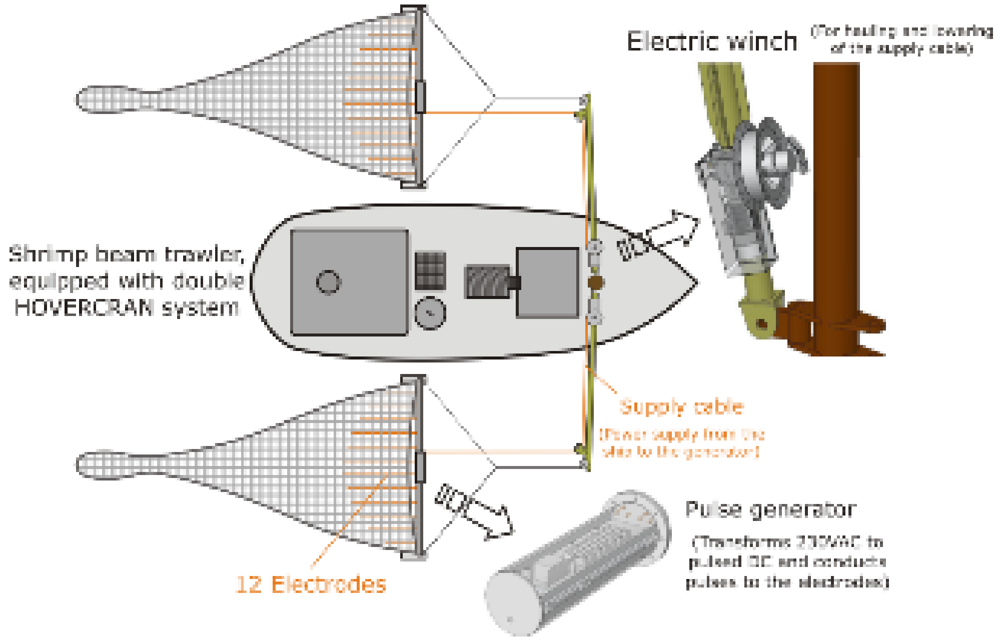


Fig. 2-4 – Illustration of the pulse trawl system for brown shrimp as it was developed in Belgium by Marelec, ILVO and UGent in 2008.

In the original ILVO concept the pulse trawl was meant to hover above the seafloor, in order to minimise seafloor contact. Therefore, the entire bobbin rope was removed and replaced by electrodes. Combined with a raised footrope this allowed non-target species to escape underneath the trawl (Fig. 2-5). Stimulated shrimp are forced to leave the seafloor high enough, so they can be caught by the hovering trawl. This setup was called the Hovercran configuration (= the HOVERing pulse trawl for a selective CRANgon fishery) and it was rewarded with the runner-up prize of the WWF International Smart Gear Competition in 2009. The gear (without a sieve net) was successfully tested on the Belgian coast. Normal catch rates were preserved, seafloor contact was reduced by 75% and an overall by-catch reduction of 35% resulted in cleaner catches. Moreover, the catch efficiency seemed less dependent on light and turbidity conditions. This contrasts with traditional shrimp beam trawling, where catch quantity varies strongly with light intensity and turbidity of the seawater (Verschueren and Polet, 2009).

Table 2.2 – Overview of pulse characteristics applied in the brown shrimp pulse fishery. Modified from Verschueren et al. (2014).

Pulse characteristics	
Pulse type	DC, between square and half-sine
Average power supplied per m beam width	0,125 kW
Maximum conductor voltage*	65 V
Pulse frequency	5 Hz
Pulse width**	500 µs

Electrode characteristics	
Number of electrodes	12
Distance between electrodes	600 – 700 mm
Total electrode length (isolator + conductor)	2750 – 3200 mm
Number and dimensions (length and diameter) of conductor elements	1 (1500 mm x 12 mm)

* Voltage ratings refer to the peak voltage measured (zero to peak).
** The pulse duration refers to a single pulse period.

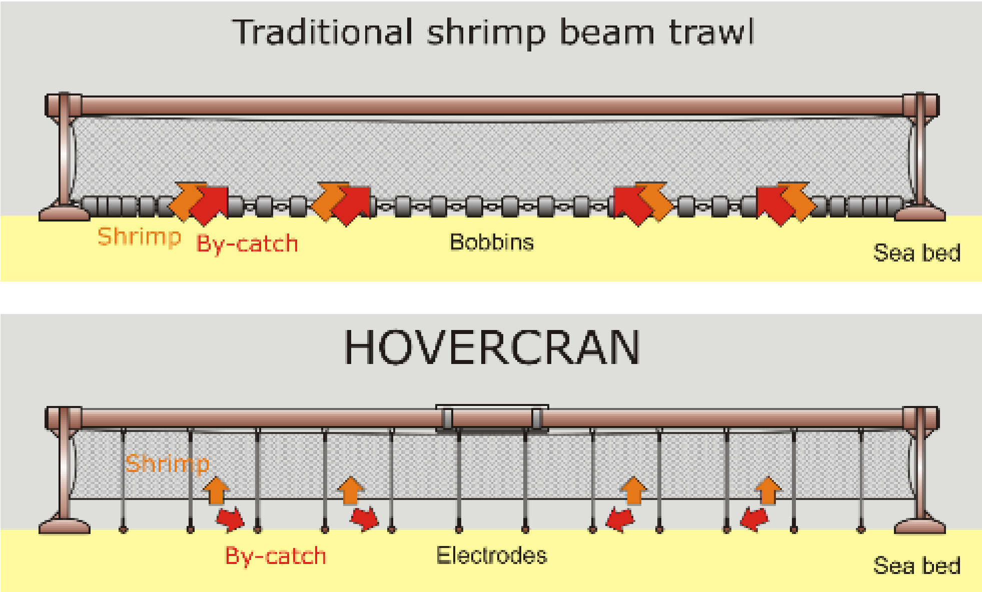


Fig. 2-5 - Illustration (frontview) of the original HOVERCRAN concept (how it was conceived by ILVO in 2008). The traditional bobbin rope is removed in order to reduce seafloor contact and create opening for non-target species to escape. In its place, the electrodes stimulate the shrimp to leave their buried positions.

In 2007, the Foundation for the Sustainability of the Crangon Fishery was established by the Dutch producers organisations with the aim of promoting new research that focuses on improving the sustainability of the brown shrimp fishery. The positive Hovercran results were picked up by this foundation and new study trials with the Hovercran on the Dutch Wadden Sea with commercial shrimp cutters were setup. These tests were carried out with the vessels TX 25 and HA 31, and in first instance focused on the technical improvement of the technique. It soon became clear that the risk of trawl damage, during fishing on rougher and more uneven fishing grounds, increased in absence of the bobbin rope. For such fishing grounds, like the Wadden Sea with its many tidal trenches, a solution had to be found in the form of a straight bobbin- and footrope (Verschueren et al., 2012 and Verschueren et al., 2014). However, the gain in better selectivity and reduced seafloor contact with the Hovercran design is counteracted by adding bobbins to the ground gear. On the other hand, the shrimp capture efficiency increases with the number of bobbins.

Fig. 2-6 - Image of a pulse trawl design that is being used today on the Dutch Wadden Sea by HA 31. The gear is characterised by the use of a straight, lightweight bobbin rope with 11 ellipsoidal bobbins (instead of 36 bobbins in the previous traditional beam trawls). The pulse generator (central) and the 12 electrodes are attached to the beam.

In order to avoid abuses, the Dutch ministry of economic affairs has implemented limiting technical measures where the *Crangon* pulse fishermen have to adapt to, if they want to continue pulse trawling. Herein, among other things, the number of bobbins was reduced in a way that a minimum mutual distance of 60 cm between two adjacent bobbins has to be ensured. In current practice this has led to a shrimp pulse trawl design that is illustrated below.

Meanwhile research and development on shrimp pulse trawling continues. ILVO is currently testing a complete new modular pulse system with all electronics (11 pulse modules) built-in a hydrodynamic efficient wing (figure 2-7). During 2016 and 2017 new trials on RV's and commercial shrimp cutters will be carried out. Another Dutch novelty is the cable-less 'Jack Wing' pulse gear. The idea is to partly generate the electrical energy underwater on the gear during towing. The energy is stored in battery packs inside the gear. This would make the use of an electrical supply cable and its necessary winch redundant.

Fig. 2-7 - ILVO's modular pulse fishing system with all electronics built-in a wing

2.3.2 The flatfish pulse trawl

In the pulse trawling technique targeting flatfish, a cramp inducing electrical field is applied. At least a ten times higher frequency is used compared to *Crangon* pulse trawling, stimulating the fish musculature in a cramp (Figure 2.6). As a consequence the fish are immobilised on the seafloor during the exposure, making it easy to scoop them with the ground gear of the pulse trawl.

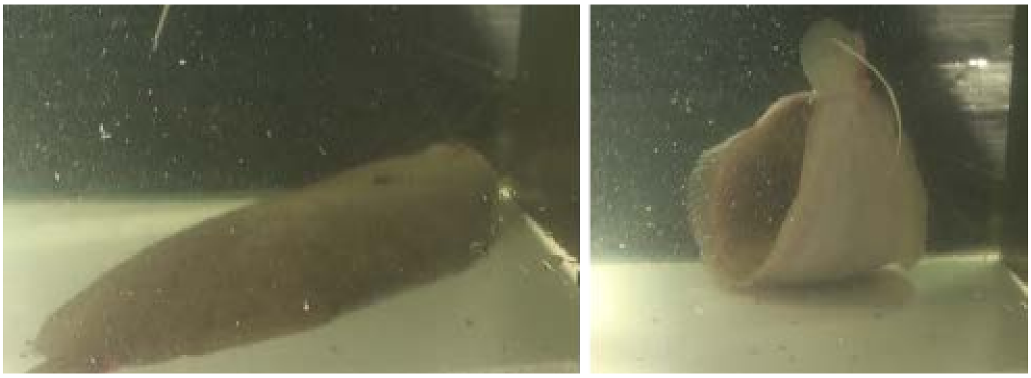


Fig. 2-8 – Dover sole (Solea solea) exposed in an aquarium to a pulsed electrical field. As long as the exposure lasts, the muscles are stimulated resulting in continuous spasms. Pulses are bipolar and the pulse frequency varies between 40 and 80 Hz.

In 1992 Verburg Holland, taken over by the Delmeco Group in 2010, started with the development of a pulse beam trawl for flatfish (Van Stralen, 2005). This fishing gear can be considered as the first in a series of prototypes that has led to 30% of the currently used electrotrawls (Figure 2.9, on the right). From 2007 on, another Dutch company, HFK engineering, had started its own developments in parallel. HFK applied the pulse system on a new type of beam trawl, the so-called SumWing trawl. In this gear, the cylindrical beam with trawl shoes is replaced by a wing-shaped foil with a runner at the centre. The SumWing itself reduces fuel consumption by some 10% (van Marlen et al., 2009). The integration of the pulse system into the SumWing has a larger potential in reducing gear drag, seafloor impact and fuel consumption (van Marlen et al., 2011), as a consequence it soon became the most popular pulse trawl in the Netherlands. Meanwhile also other combinations are in use, in which HFK pulse modules are incorporated into other beam trawl alternatives, such as the SeeWing and the Aquaplanning gear. The number of vessels using HFK pulse modules is about 5 times that using the Delmeco design (Turenhout et al., 2016).

Fig. 2-9 - Pulse SumWing by HFK Engineering (left) and Delmeco Multiwing (right). Both gears are used today in the Dutch flatfish pulse fishery. Around 90 vessels are equipped by either Delmeco or HFK according to a ratio of approximately 1 to 5 respectively.

Pulse trawls receive electric power from the vessel by an additional cable that also provides communication between the wheelhouse and the fishing gear. In both Delmeco and HFK systems the electrodes are connected to pulse modules, i.e. small ceiled units with electronics, built-in the beam or wing. The number and the configuration of the electrodes may vary according to the gear width and the manufacturer, although physical boundaries of the gear are described in a directive issued by the Dutch Ministry of Economic Affairs on 18 November 2016 (01. 20161111 "Nieuwe Voorschriften Pulstoestemming Platvis version 1.3") and refers to the conditions of electric gear application as described in article 31bis, lid 2 of the European reference for Technical Measures (EU 850/98). The main derogations for flatfish gears are:

- A maximum power consumption of 1 kW per meter beam length;
- A pulse amplitude of 60 V 0 to peak maximum;
- An electrode length of max 4.75 m, (the section that has bottom contact);
- Conductor length 125 to 200 mm with a maximum of 12 per electrode;
- Electrode distance not smaller than 0.4 m;
- Number of electrodes adapted to the width of the licenced gear (4 or 12 m);
- Operational conditions of the Delmeco system are registered on a computer as part of the pulse equipment. The HFK system does not record the electrode voltage and current real-time but operates with a pulse hardware certificate which assures the equipment will operate within the licensed bands. The Delmeco system stores information of:
  - the electric power discharged over the electrodes;
  - over at least 100 fishing hauls;
  - any access to the data storage;
  - the date, times and positions of pulse operation;
- Groundrope rigging will not contain additional tickler chains

The basic characteristics of the pulse systems as used in practice are listed in Table 2.3. An electrode itself measures around 6 m and consists of an alternating series of isolated parts (isolators) and conductive parts (conductors). A detailed construction design of both systems can be found in van Marlen et al. (2014) and de Haan et al. (2016). The pulse characteristics are similar for both systems. The electric parameter settings can also be adapted to the environmental conditions such as seawater temperature and salinity. These conditions may influence the conductivity or flatfish behaviour and thus the response to the electrical pulse field (de Haan et al., 2016).

Table 2.3 – Pulse and electrode characteristics applied in the Dutch flatfish fishery. Modified from de Haan et al. (2016).

Pulse characteristics	
Pulse type	Bipolar
Average power supplied per m beam width	0,6 – 0,7 kW
Conductor voltage*	45 – 50 V
Pulse frequency	45 – 80 Hz
Pulse width**	100 – 270 μs
Duty cycle	0,9 – 2,2%
Electrode characteristics	
Number of electrodes	10 (≤221 kW) or 25 – 28 (>221 kW)
Distance between electrodes	415 – 425 mm
Number and dimensions (length and diameter) of conductor elements	Delmeco: 6 (180 mm x 26 mm) HFK: 2 (125 mm x 27 mm) + 10 (125 mm x 33 mm)
* Voltage ratings refer to the peak voltage measured over the positive part of the pulse (zero to peak).	

** The pulse duration refers to a single pulse period.

In the first place, the large-scale conversion to pulse trawling in the Dutch beam trawl fishery, was based on economic motives. According to the comparison experiment of van Marlen et al. (2014), the net earnings (gross earnings – fuel costs), increased with 155 to 186% compared to conventional beam trawling with tickler chains. However, the rather large investment and relatively high maintenance costs related to pulse trawling, were not taken into account. This profit increase is mainly due to the large savings in fuel consumption. The relatively light design of the pulse trawls also allows operation on a wider range of sediments (Rasenberg et al., 2013). Additionally, the catch efficiency of Dover sole is clearly higher in pulse trawling (Rasenberg et al., 2013). As a result, the introduction of the commercial Dutch pulse trawler fleet caused a reallocation of fishing effort (Batsleer et al., 2016). Sys et al. (2016) studied the competitive interactions between the Dutch and the Belgian beam trawl fleets in the North Sea. The study showed that sole landings of traditional Belgian beam trawlers (>221 kW) from 2006 to 2013 were lower during weekdays than during weekends, when the Dutch fleet is in harbour. After pulse trawling was introduced in 2011, the negative weekday effect in the sole landing rates was much more pronounced in 2012 and 2013. This increased loss of efficiency during weekdays, as a result of increased competition with the Dutch trawler fleet, coincided with a reallocation of fishing effort by the Belgian beam trawler fleet.

2.3.3 The *Ensis* electrotrawl

According to Breen et al. (2011) electrical fishing techniques are certainly being used in the Scottish razor clam (*Ensis sp.*) fishery since 2004. Small inshore vessels fly-drag up to three pairs of electrodes slowly across the seabed, followed either by divers who collect emerging razor clams or less commonly by some kind of dredge that's drawn across the surface of the seabed. Because these practices are illegal, little detailed description of the gears is available. Murray et al. (2016) report that within the fishing community electrofishing is believed to be preferred over dredging, despite the risk of financial penalties if caught. This is due to the reduced fuel consumption required to drag the rig and to the lower incidence of damaged clams in the catch. Woolmer et al. (2011) experimentally designed and trialled methods to harvest razor clam using electrical stimuli. Three mild steel flat bar electrodes (30 x 8 x 3000 mm) were used on a separation distance of 0,6 m to produce maximal DC field strength of approximately 50 V/m. The study demonstrated that electrofishing gear generating relatively low DC can be effectively used to stimulate the emergence of razor clams from their burrows. Since no electrical pulses are used, it is recommended to use the more general name 'electrotrawl' instead of 'pulse trawl' for this fishing gear.

Fig. 2-10 - Two different prototypes of pulse dredges that were developed and tested in Irish (left) and Dutch (right) razor clam fisheries. Right picture modified from Breen et al. (2011) and left picture from Visserijnieuws (2015).

In Breen et al. (2011) it is mentioned that the development of a novel *Ensis* dredge employing electrical stimulus was being carried out in Ireland around 2010. Herein a skimming blade is used to pick up the razor clams (Figure 2.10 on the left). Preliminary results showed landings comparable to those achieved by hydraulic dredges and crucially, the condition of the razor clams seemed better with lower breakages and long survival. Similar prototypes were tested in the Netherlands (Figure 2.10 on the right). In general this technique is considered potentially more environmentally benign compared to existing hydraulic and toothed dredges (Breen et al. 2011; Woolmer et al. 2011).

2.3.4 Other applications in trawling

A less obvious, but nonetheless promising application of pulsed electrical fields is to enhance escape behaviour of unwanted species in selective devices. Soetaert et al. (2016d) studied the combination of a benthos release panel (BRP) provided with an electrical field. BRPs are known for their capacity to release large amounts of unwanted benthos, debris and to a lesser extent undersized fish. However, unacceptable commercial loss of Dover sole, due to escape through the BRP, is hampering a successful introduction in commercial beam trawl fisheries. To eliminate this drawback, the effect of electric stimulation at the height of the BRP to eliminate the loss of commercial sole was examined. This allowed for the release of 35-50% of the benthos and debris and significant parts of the undersized commercial fish without the loss of commercial fish in particular marketable sole. The results showing the promising potential of electrified BRPs (eBRPs) will be submitted in the summer of 2018.

3 Catch composition & effort of pulse trawls

3.1 General overview

When evaluating a new fishing method, gear selectivity with regard to target species and (unwanted) bycatch species is of major importance next to preservation of commercial catch rates. Comparative analysis between pulse and conventional trawling is therefore an essential approach. In recent years several experiments have been carried out at sea to determine catch compositions of *Crangon* and flatfish electrotrawls. Ideally both trawls, pulse and conventional, are simultaneously tested on the same vessel (port and starboard side), leading to paired observations. However, sometimes practical limitations, such as different optimal towing speeds, preclude direct catch comparison. Differences and variability between studies may also result from varying catch conditions (most importantly spatial or temporal variation), or by differences between the tested gears (e.g. arrangement of the ground gear, trawl design, dimensions, etc.).

So far, the data indicates that electrical stimulation offers a promising innovation to reduce the bycatch of fish and benthic invertebrates in **brown shrimp** fisheries, while maintaining the catch rate of marketable sized shrimps. However, this is only the case when a light bobbinrope with only 12 bobbins was used. When more bobbins and/or a more heave gear is used, the catch rates of marketable shrimp are up to 30% higher compared to a traditional trawl and the improvements in by-catch reductions are largely undone.

The available evidence for the **sole pulse** shows that it has a higher catch efficiency for sole and the lower catch efficiency for plaice and other fish and invertebrate species when expressed in catch rate per hour. The comparative fishing experiment in 2015 suggests that the catch efficiency of the pulse trawl may have improved. The better size selectivity of the pulse trawl indicated by the 2011 comparative fishing experiment (van Marlen et al., 2014), is not corroborated in later experiments. However, compared to the catch of marketable sized sole, the bycatch of undersized fish in the pulse trawl is lower than in the conventional beam trawl. All experiments carried out show that the bycatch of benthic invertebrates is substantially reduced. Therefore, the comparative fishing experiments suggest that the catch efficiency of the pulse trawl may have increased, but the available evidence, however, is too thin to draw a firm conclusion. It is well known that the catch efficiency of a fishing gear may increase over time due to technological developments and improved skills of the fishermen, in particular when new techniques are introduced (Eigaard et al., 2014). Additional comparative studies may shed light on this question. We expect that knowledge on the effect of fish size on the dose-effect relationship between pulse stimulation and the cramp response in sole and other flatfish species will allow us to give a mechanistic interpretation of the size selectivity of the pulse gears used in the commercial fishery.

When it comes to the catch rates of the ensis pulse trawl and selective innovations such as the electrified benthos release panel (eBRP), more data is required to draw reliable conclusions.

3.2 Catch composition of *Crangon* pulse trawls

Representative catch comparison experiments were executed recently on 6 commercial *Crangon* trawlers in Belgium, the Netherlands and Germany. An experiment was carried out by Verschueren et al. 2014 on the vessel HA 31. During four commercial trips on the Dutch Wadden Sea, a normal shrimp beam trawl, fitted with conventional ground gear with 36 bobbins and a sieve net, was directly compared with a lightweight pulse trawl (Figure 3.1). The pulse trawl was a combination of a classic beam with trawl shoes and a new 'square' net design with sieve net inside. In order to stimulate the shrimp to leave the sediment, an electrical pulse field (12 electrodes) was combined with a reduced bobbin rope (11 bobbins). The experimental setup is illustrated below.

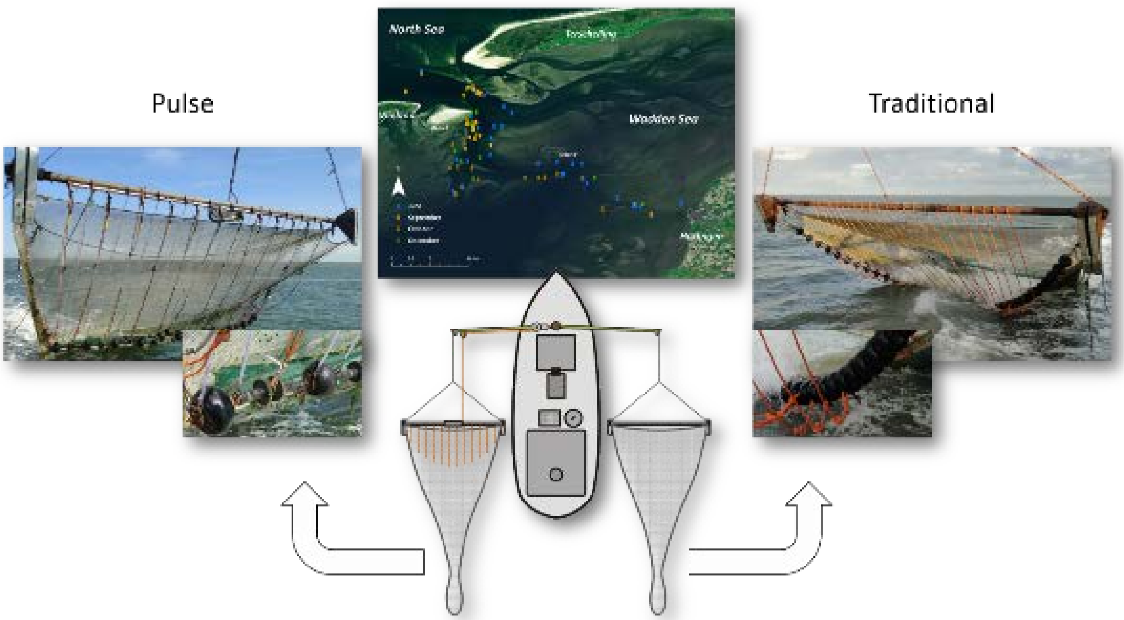


Figure 3.1: Schematic illustration of the paired catch comparison experiment carried out in the Dutch Wadden Sea. On the left (portside of the vessel) the pulse trawl with 12 electrodes and a lightweight bobbin rope (155kg) with 11 bobbins is shown. The conventional shrimp trawl (on the right – starboard side) was fitted with 36 bobbins (400kg). Modified from Verschueren et al. (2014).

Marketable shrimp catches were higher with the pulse trawl (16% in June and 9% in September). In October and December, no significant differences were observed in commercial shrimp. Bycatch of discarded, undersized shrimp was significantly lower with the pulse gear (-19 to -33%) during three of the four trips. Bycatch of benthic fish and invertebrates was significantly lower in volume (-50 to -76%) in the pulse gear for each trip. This reduction was particularly striking when looking at juvenile plaice (Figure 3.2) and to a lesser extent when considering juvenile dab, flounder, cod and whiting. Sieve nets are satisfactory effective in avoiding the bycatch of relatively large individuals of all species, but less so at reducing 0-group plaice and sole. The pulse trawl with the configuration described above, appeared to be very complementary with the sieve net.

Less mobile benthic invertebrates such as razor clams, winkles, anemones and starfish were less abundant in the pulse trawl catches. The bycatch of many mobile demersal organisms like armed bullhead, goby, shore crab, starfish and pipefish was also significantly lower with the pulse gear. The improved selectivity of the HA 31 pulse gear can be attributed to the use of the lightweight ground gear. With only 11 bobbins distributed over the full width of the gear, considerable escape opening is created between the footrope and the seabed.

Another catch comparison between a commercial beam trawl and a shrimp pulse trawl with a straight foot- and ground rope with 11 bobbins as well as a sieve net was carried out between the summer of 2012 and the summer of 2013 in the German Wadden Sea. Results of the first project phase between June and August 2012 are reported in Kratzer (2012). On average, total shrimp catches in pulse trawls were 10% higher than in conventional beam trawls. Catches of large marketable A-shrimp were 8% higher in the pulse trawl and catches of small non-marketable shrimp 14% higher. In some of the trials the pulse trawl caught smaller shrimp, in other trials there were no significant differences between the gears. Variations of towing speed between 2,5 and 3,5 kts had no marked effect on the catch rates of the pulse and the standard trawl. The same study demonstrated that a smaller number of bobbins in the modified ground rope allows fish to escape underneath the footrope and leads to lower bycatch. Bycatch rates were on average 15% lower in the pulse trawl. The median of the fish bycatch was 6% in the conventional trawl and 4% in the pulse trawl (maximum values 30% and 20% respectively). On species level, the pulse trawl primarily caught fewer juvenile flatfish: plaice (5–12 cm: -28%); sole (5.5–10 cm: -43%); dab (4–6 cm: -50%), but also bycatch of sand goby (4.5–8.5 cm: -75%) and hooknose (4–10 cm: -44%) was considerably reduced compared to conventional beam trawling.

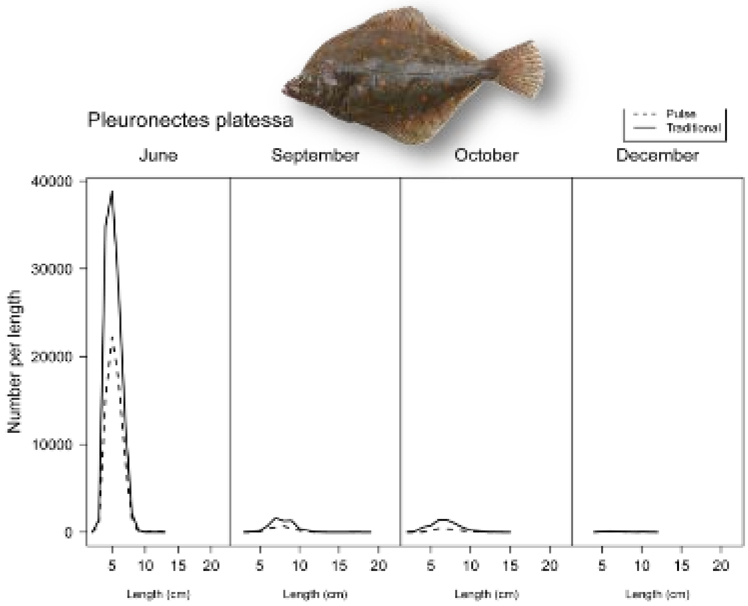


Figure 3.2: Length-frequency distribution of discarded plaice, one of the main by-catch species in Crangon fisheries. Separated in pulse (dotted) and traditional catch (solid) during seasonal sampling. In summer months the shortcomings of the sieve net as a selectivity-improving device are illustrated. Pulse stimulation and sieve net are clearly complementary. Modified from Verschueren et al. (2014).

The full project report by Stepputtis et al. (2014) extended these results. Total catch (+23%), discarded shrimp (+8%) and cooked shrimps (+9%) were significantly higher and bycatch (-9%) was significantly lower with the pulse beam trawl compared to the standard trawl. Further, there was a pronounced variability for all catch fractions over the course over the whole year and over the course of daytimes, indicating a clear seasonal effect and a clear daytime-effect on the catch composition. On average, the amount of bycatch per litre of cooked shrimp was reduced by 14% with the pulse beam trawl. Flatfish and benthic fish were significantly reduced in numbers of individuals with the pulse beam trawl (-13%, -29%, respectively) and in weight of individuals (-15%, -23%, respectively). To verify the effect of the electric field itself, the pulses of the pulse beam were switched off. Despite very small sample sizes, all catch fractions were significantly lower with in the pulse beam trawl without pulses, compared to the standard trawl. Taking into account results from the main experiment, high efficiency of the electric field was indicated.

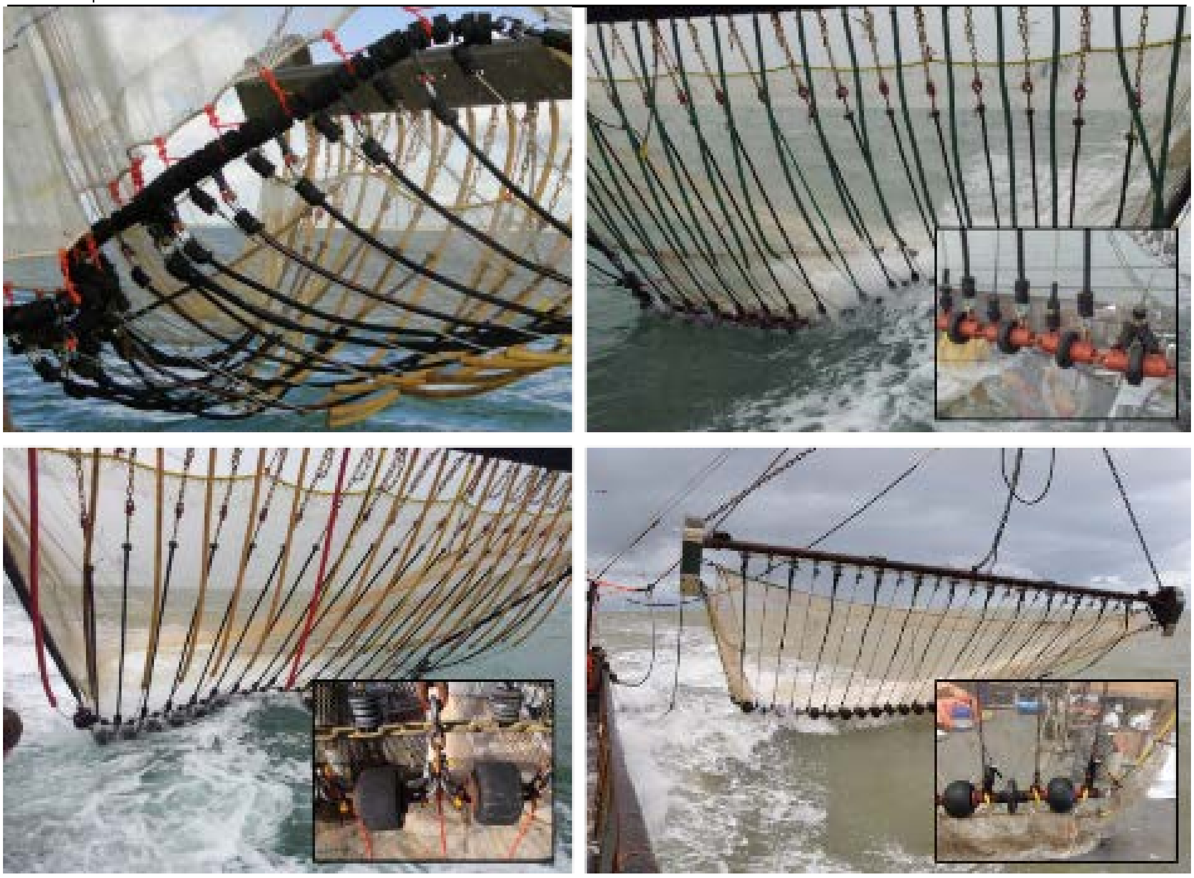


Figure 3.3: Four different ground gear designs tested in a pulse trawl on the Dutch eurocutter TH 10. Each design resulted in different bycatch rates when compared to a standard trawl. Bycatch reduction increased with the size of the escape opening between the seabed and the footrope. Modified from Verschueren et al. (2013).

A third series of experiments was conducted on the Dutch eurocutter TH 10 (Verschueren et al. 2013 & Verschueren et al. 2016). Various types of straight bobbin ropes and a ground rope design with rubber discs, illustrated below, were compared mutually and with a conventional bobbin rope (Figure 3.3). Strongly varying results were demonstrated. Catch efficiency (commercial shrimp catches) and bycatch levels were different for each design.

As shown in most studies, the bobbin rope design has a large effect on the outcome in pulse trawling, as is confirmed by most studies. In all experiments it was found that bycatch reduction increases with the size of the escape opening between the seabed and the footrope. Consequently a lightweight bobbin rope design with significant spacing between adjacent bobbins delivers the best results in terms of bycatch reduction. Regulators and managers should consider gear specifications, i.e. number of bobbins and/or set-up of bobbins, when assessing the practical implementation of pulse fishing gear in the shrimp fishery.

3.3 Catch composition of flatfish pulse trawls

Development of pulse trawling systems for flatfish has proceeded without interruption in the Netherlands from 1998 to present. In 2007 a total of 5% of each European beam trawl fleet was allowed to use pulse beam trawls by derogation (Soetaert et al., 2013). All research and evaluations carried out before 2011 were based on the specifications of the pulse trawls developed by Verburg Holland (ICES, 2010). In 2011, the permits were doubled under the condition that information on the effects of the pulse trawl fishery on the ecosystem would be collected. As a consequence new manufacturers entered the market. Verburg Holland was acquired by the Delmeco Group and HFK Engineering introduced the 'PulseWing' in the

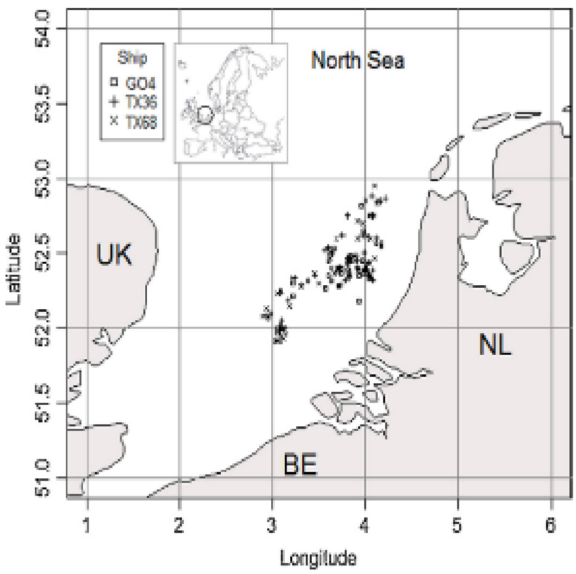
Dutch beam trawler fleet. From then on broadly two different types of the flatfish pulse trawl are being used on more than 90 beam trawlers in the Southern North Sea. As far as we know, only two studies on the catch composition of these gears were executed, since this large-scale implementation took place.

Van Marlen et al. (2014) reports on a one-time, 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. The three vessels fished 'side-by-side' as much as possible given the differences in optimal towing speeds. In total 93 hauls were sampled, sometimes partly, for sole, plaice and discards. The study area is shown on the map in Figure 3.4. The authors were particularly interested in finding out what the difference was between catches and bycatches of both gears, the fate of cod in the pulse trawl catches, and the fuel saving potential. In addition to this, (length-related) differences in landings and discards of the target species, plaice and sole, were studied.

The net earnings (gross earnings – fuel costs) showed a large increase for both pulse trawlers TX 36 (186%) and TX 68 (155%). However, the large investment and high maintenance costs of the pulse gears are hereby not taken into account. This increase is mainly due to their lower fuel consumption (on average 43%), as the catches of the target species were lower (plaice: 71% and sole: 86%), compared with conventional beam trawls with tickler chains (figure 6-5). The total catch in the pulse trawls was considerably lower, only 37% of the conventional trawl. Fewer discarded fish (57%) and benthic discards (80%) were caught by hectare fished, compared to the vessel fishing with conventional beam trawls during the experiment. The discards of the main target species were also lower, for plaice the ratio by hectare was 62%, and for sole 46%, which was confirmed by the analysis of the length effect (Figure 3.5).

Spinal damage in cod 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 was lower than with the traditional beam gear (31% in kg/h)

Figure 3.4: Fishing positions of the three vessels in the North Sea during the catch comparison of 2011. GO 4: Conventional beam trawler; TX 36: HFK SumWing with pulse and TX 68: Delmeco Multiwing with pulse. Modified from van Marlen et al. (2014).



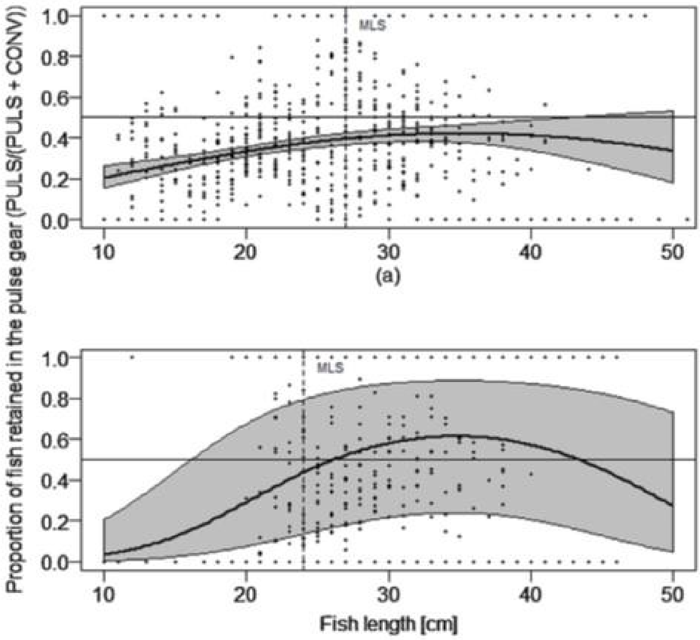


Figure 3.5: Size selection of the pulse trawl relative to the conventional tickler chain beam trawl for plaice (a) and sole (b). The heavy line shows the proportion of fish retained caught per hour fishing in pulse gear vs. length The value of 0.5 means both gears catch equal numbers (> 0.5 means pulse gear catches higher numbers; < 0.5 means pulse catches lower numbers). The grey band gives the 95% confidence limit. Data points are given in black dots. MLS is Minimum Landing Size (plaice: 27 cm, sole: 24 cm) (van Marlen et al., 2014)

In 2015 another comparative fishing experiment was conducted in conjunction with the fishing industry survey (van der Reijden *et al.*, in prep). A total of 38 parallel hauls were carried out. The results showed that the pulse trawl caught significantly more marketable sole per hectare and slightly less marketable plaice than the conventional beam trawl, but did not corroborate the results of van Marlen et al (2014) of a lower bycatch of undersized sole and plaice.

In order to meet the required conditions set by the EU, the Dutch Cooperative Fisheries Organisation (CFO) decided to set up a monitoring program in December 2011 that consisted of a combination of self-sampling and observer trips on 25 vessels. The outcome of this program is written down by Rasenberg et al. (2013). In what follows the main conclusions are highlighted.

First of all, the results from the two methods (self-sampling and observer trips) were compared to check the consistency of the self-sampling method. Three significant differences were observed: Both the bycatch of benthos & debris, sole discards and cod landings were significantly higher in the self-sampling program. This may be due to spatial and temporal differences.

Overall, more than 40% of the average pulse catches consisted of benthos and debris. In addition, the results show that there is variation in discards between quarters and between the five fishing areas that were defined in the analysis. However, no clear seasonal or spatial patterns were distinguished. The benthos catches of the observer program were compared with the benthos catches of the beam trawl fishery from the Data Collection Framework (DCF) program. The numbers of starfish and crab caught in the pulse trawl trips were lower than in the conventional beam trawl trips. The number of individuals caught by the pulse vessels was 84% lower for starfish and 58% lower for crabs compared conventional beam trawls. The amount of starfish and crabs in the bycatch is a good indicator of the benthos bycatch quantities in these fisheries. This is consistent with earlier research done in 2011 by Van Marlen et al. (2014).

Cod catches were very low as compared to the total catch in both the self-sampling and the observer program. The self-sampling program showed an average landing rate of 3 kg/hour and an average discard percentage of 7%. The observer program showed an average landing rate of 1 kg/hour and an average discard percentage of 12%. Cod catches are too low to make a reliable comparison with the DCF beam trawl data.

On average around 30% of the total pulse trawl catch consisted of marketable fish. The percentage of discarded commercial fish species varied between the self-sampling (17%) and the observer program (29%). Plaice and sole catches (landings and discards), both of the pulse self-sampling and the observer program, were compared with the beam trawl fishery samples from the DCF program, as is given in Table 3-1. The average amount of plaice caught in the pulse trawl fishery appeared to be lower than in the beam trawl fishery during the sampling period. The actual amount of plaice discards caught during the self-sampling (27 kg/hour) and the observer trips (66 kg/hour) was lower compared to the beam trawl fishery (87 kg/hour). This is consistent with the research done by van Marlen et al. (2014).

Table 3.1: Observed plaice and sole landings and discards (kg/hour), including standard deviation, and discard % for the self-sampling trips (>300hp), monitored observer trips (>300hp) and DCF beam trawl trips (>300hp) in 2012. Modified from Rasenberg et al. (2013).

Type of fishery and sampling method	**Plaice**			**Sole**		
	L	**DC**	**%DC**	**L**	**DC**	**%DC**
Pulse trawl, self-sampling	37 ±43	27 ±45	42%	35 ±19	6 ±26	15%
Pulse trawl, observers	61 ±44	66 ±66	52%	32 ±14	4 ±4	10%
Beam trawl, (DCF - observers)	90 ±86	87 ±71	49%	29 ±14	6 ±10	17%

The average sole discard percentage during the observer program (10%) seemed to be lower than the average calculated from the self-sampling trips (15%) and the DCR beam trawl trips (17%). The actual amount of sole discards was respectively 6 kg/hour, 4 kg/hour and 6 kg/hour for the three sampling methods and thus lie in the same range. Sole landings were clearly higher in the pulse fishery, according to the monitoring program. This is in contrast with the catch comparison by van Marlen et al. (2014), were both sole landings and discards were lower in the pulse fishery. This could be explained by the fact that in recent years, at the time of the CVO monitoring program, the fishermen got more experienced with the pulse trawl and learned to catch sole more efficiently. Apart from this van Marlen et al. (2014) only covered a small time period and a relatively small fishing area. However, since the difference in standard deviations in these results are relatively large, absolute correct comparison with the beam trawl fishery cannot be given.

3.4 Catch composition of *Ensis* electrotrawls

If the emerging razor clams are hand-picked by divers, it can be assumed that the selectivity is substantially 100%. This may not be the case when dredge-like devices are used. However, very little is known about (by)catch rates in these gears. In Breen et al. (2011) it is mentioned that the development of a novel *Ensis* dredge employing electrical stimulus was being carried out in Ireland around 2010. Preliminary results showed landings comparable to those achieved by hydraulic dredges and crucially, the condition of the razor clams seemed better with lower breakages and long survival. Similar prototypes were tested in the Netherlands. Nevertheless, we could find no documented studies that report catch comparisons between conventional *Ensis* dredges and pulse dredges.

3.5 Redistributing fishing effort

The transition from the conventional beam trawl to the pulse trawl, coinciding with an overall decrease in fishing effort, has resulted in a shift in the effort distribution. Relative fishing effort increased in areas off the Thames estuary, Norfolk banks and off the Belgian coast (Turenhout et al., 2016). Shifts in distribution of fishing effort of pulse trawlers may give rise to local competition between pulse vessels and traditional fishers. Sys et al. (2016) showed that the landing rates of sole by the Belgian beam trawlers (>=221 kW) from 2006 to 2013 were lower during weekdays than during weekends when the Dutch trawler fleet is in harbour, while no such an effect was found for plaice. After the development of a pulse trawler fleet, the negative weekday effect in the sole landing rates was much more pronounced in 2012 and 2013. This increased loss of efficiency during weekdays, as a result of increased competition with the Dutch pulse trawler fleet, coincided with a reallocation of fishing effort by the Belgian beam trawler fleet.

4 Effects of exposure to pulse fields

4.1 General overview

Introducing electrotrawling on a large scale without a sound knowledge of the interactions between electrical fields and the marine ecosystem would be against the principles of the precautionary approach and responsible fishing. Until recently, the effects of low frequency (<100Hz) pulses on marine organisms were largely unknown (Soetaert et al., 2013). The vast majority of studies on the harmful effects of electrofishing focuses on its use in freshwater, widely adopted as a sampling technique for fishery ecology and management purposes (Snyder, 2003; Polet, 2010). Snyder (2003) reported that, although often not externally obvious or fatal, spinal injuries and associated haemorrhages may be regularly present as a result of exposure to electricity, warranting the need for radiological and histological examination.

The principal cause of spinal injuries appears to be powerful convulsions of the body musculature induced by sudden changes in the electric potential. These sudden changes occur when the current is switched on and off or pulsed. In PDC, longer exposures subject the fish to more pulses and thereby increase the risk for spinal injury, with the incidence of injuries being lowest for low frequency (≤30Hz) PDC (Snyder, 2003). Besides minimizing frequency, results from several studies suggest that the field strengths should also be kept to a minimum to limit injuries (Schreer and Cooke, 2004).

An overview of all experimental studies in which marine organisms were exposed to a pulse trawl stimulus is given in Table 4.1. Thereafter, the specific effects of exposure to the 3 types of pulse stimulation that are applied today, are separately overviewed in detail per chapter.

Table 4.1. Overview of experimental studies in which marine organisms were exposed to a flatfish or shrimp pulse stimulus. N refers to the number of exposed animals. Vpeak refers to the potential difference over the pair of electrodes.

Species	Results	Pulse stimulus	Field strength (V/m)	Frequency (Hz)	Duration (sec)	Source
Cod (35-60cm) N=320	Maximal exposure close to conductor resulted in spinal fractures upto 70% of the cod. Fracture incidence increase with field strength and decrease with frequency	Sole pulse	4-103	30-180	1	De Haan et al (2016)[1]
Cod (<20cm) N=140	No injuries.	Sole pulse	76-370	30-180	1	
Cod (30-80 cm) N=180	Exposure of 180 cod close to conductor resulted in spinal fractures in 0-5% of the cod.	Sole pulse	60-120 (Vpeak)	40-80	1-2	Soetaert et al (2016a,b) Marine Coastal Fisheries

[1] This publication includes earlier IMARES reports

Species	Results	Pulse stimulus	Field strength (V/m)	Frequency (Hz)	Duration (sec)	Source
Cod (40- 70 cm) N=26	Exposure to a homogeneous field did not cause lesions except for a spinal fracture in 1 animal.	Square PDC, PBC	100-200	40-200	2	Soetaert et al (2016a) Fish. Res.
Sole (25-30cm) N=146	Exposure of 146 soles to a homogeneous field did not cause lesions. One sole died 13d after exposure but without any injuries. One sole showed minor gill haemorrhage during exposure.	Square PDC, various pulse types	150-200	5-200	2-5	Soetaert et al (2016a) Fish. Res.
Dab N=100	Cramp response. No lesions detected. No mortality observed related to exposure.	Sole pulse				De Haan, D. et al. (2015) IMARES Report number
Catshark N=23	No effect on the success rate and timing of artificial prey electric field detection was observed after exposure to the pulse trawl electrical fields	Sole pulse & Shrimp pulse heterogeneous field	60 V_{peak}	80 5	5	Desender et al., (2017a) Experimental Marine Biology and Ecology
Catshark N=48	No mortality and no visible injuries observed. Fish in all tested groups started feeding normally directly after the exposures. Fish of all pulse-exposed groups produced eggs in numbers varying between 5-39 per group during 9 month post exposure	Delmeco sole pulse	8, 48, 162	40	4 x 1 second	De Haan, D., et al. (2009) IMARES Report C105/09

Species	Results	Pulse stimulus	Field strength (V/m)	Frequency (Hz)	Duration (sec)	Source
Plaice (n=25) Sole (n=30) Cod (n=20) Bull-rout (n=19) Armed bullhead (n=20)	Flatfish: minor reactions in flatfish, 15% sole swam upwards. Roundfish: active swimming during exposure. No fractures detected. Histological examination showed small haemorrhage in 2 exposed plaice. Number of melanomacrophage centres in spleen of exposed cod was higher.	Shrimp pulse heterogeneous field	60 V_{peak}	5	5	Desender et al., (2016) Fish Res
Cod 3 egg stages 4 larval stages 1 juvenile stage	Hatching/developmental rate delayed in 1/3 egg stage. Mortality increased in 2/4 larval stages No altered development or deformities	Shrimp pulse homogeneous field	150	5	5	Desender et al., (2017b) Marine and Coastal Fisheries
Sole 1 egg stage 1 larval stage	No adverse effects or deformities recorded	Shrimp pulse homogeneous field	150	5	5	Desender et al., (2018) North American Journal of Fisheries Management

Helmet crab, Swimming crab	Freeze during stimulation and show escape reaction immediately afterwards	Delmeco sole pulse	Due to confidentiality, no details on the pulse characteristics were provided by the company. The potential difference over the electrodes was twice the potential difference of the Delmeco prototype of	1st group exposed 10 s; 2nd group exposed 10 s for 3 days in a row.	Smaal and Brummelhuis (2005) RIVO Report: C089b/05	
Decapode: brown shrimp, steurgarnaal	Tail flips and/or freeze. After 1 s resume to normal					

Species	Results	Pulse stimulus	Field strength (V/m)	Frequen-cy (Hz)	Duration (sec)	Source
	movements. When mechanically stimulated directly after exposure the animal moves					
Hermit crab	Freeze or withdraw in shell upon stimulation.					
Echinodermata: Common sea star, Echino- cardium, Ophiuroidea	No visible response.					
Polychaetes: Ragworm, sea mouse	No visible response.					
Bivalves: razor clam, cockle, *Acanthocardia echinata*	Closes shell, Ensis slightly extends its foot. No effect on filtration activity					
Whelk	(partly) withdraws in shell.					
Brown shrimp N=30-60 per group (tot=1730)	Tail flip response at 5 HZ. Cramp response at >=60 Hz. No increase in mortality or injuries. Increase in virus infection at highest exposure	Sole & shrimp pulse; homo-geneous field	150-200	5-200	1-5	Soetaert et al. (2014) ICES JMS
Ragworm N= 23-50 per group (tot=616)	Squirming response. No increase in mortality or					
Brown shrimp N=479 (pulse) N=178 (mechanical)	Sole pulse reduced survival. Mechanical stimulation gave reduced moulting rate. No increase in IBV infection.	Sole and shrimp pulse	60 V (Vpeak)	5 & 80	20 times 1 sec exposure during 4 days	Soetaert et al (2016c) Marine Coastal Fisheries

4.2 Effects of the *Crangon* pulse field

4.2.1 Effect of pulse parameters and temperature on pulse's efficacy

The masterthesis of Stappenpenbeck (2017) investigated the effect of pulse parameter settings and environment on the reaction of brown shrimp by using a high-speed camera and tracking the escape path of each shrimp. The parameters varied were:

- Number of pulses: 1 to 7
- Pulse duration: 0.1 ms, 0.3 ms and 0.5 ms
- The electrode shape: plate or wire
- Water temperature: 8°C or 16°C.

The results indicated that the pulse duration used in commercial trawls can be reduced from 0.5 ms to 0.3 ms. Additionally, shrimp showed much stronger responses when exposed to the threadlike wire electrodes compared to plate electrodes. Finally, it was shown that the shrimp achieved their highest position after 5 to 6 pulses in 16°C and after 8 pulses in water of 8°C. This illustrated that low water temperatures result in weaker responses of shrimp, which explains why the catches of a pulse trawl outperform that of a conventional trawl mainly during summer and autumn when the water is warmer (Verschueren et al., 2014). These results imply that it might be necessary to design more flexible systems, which can be easily adapted to actual water conditions in order to always get the minimal environmental impact for optimal catch rates and gradually decrease by-catch rates.

4.2.2 Effect on invertebrates

When conducting exploratory laboratory trials, Polet et al. (2005a,b) also assessed effects 9 invertebrate species after a single 15 second exposure to low frequency DC pulses including swimming crab (*Liocarcinus holsatus*), shore crab (*carcinus maenas*), hermit crabs (*Bernhardus pagurus*), starfish (*Asterias rubens*), *Spisula subtruncata*, brittle star (*Ophiurra* spp.) *Pandalus montagui* and brown shrimp. No adverse effect on survival was found. Similarly, ragworm (*Alitta virens*) and brown shrimp exposed up to 4 times to the shrimp pulse did not show a reduced 14 day survival (Soetaert et al. 2014). This result was confirmed in a follow up study in which brown shrimp was exposed 20 times to the shrimp pulse in a commercial setting without showing adverse effects on survival, moulting or the number of egg carrying females 14 days after the start of the experiment (Soetaert et al. 2016a).

4.2.3 Effect on adult fish

After the preliminary studies of Polet et al. (2005a) investigating survival and external injuries in sole, plaice, armed bullhead, cod, pogge, dab, turbot, dragonet, five-beard rockling and gobies, Desender et al. (2016) evaluated short-term effects on adult fish after exposure to the pulse stimulus which is used today in the *Crangon* electrotrawls. European plaice *(Pleuronectes platessa)*, Dover sole *(Solea solea)*, Atlantic cod *(Gadus morhua)*, Bull-rout (*Myoxocephalus scorpius*) and Armed bullhead (*Agonus cataphractus*) were once exposed during 5 seconds. Following characteristics were evaluated:

- behavioural reactions, observed 10′ before and 20′ after exposure

- short term mortality
- presence of macroscopic lesions by visual inspection
- presence of microscopic lesions in the dorsal muscle, gills, heart, liver, spleen, intestines and kidney, determined by means of histological examination
- Inspection of spinal damage by X-ray.

Roundfish species, Atlantic cod in particular, were displaying more active and agitated fast swimming activity during exposure. The majority of flatfish showed only minor reactions and remained close to the bottom throughout the observation period. During exposure,15% of sole swam upwards. There was no difference in number of movements before and after exposure between control and exposed organisms within the same species.

No mortality was observed, which corresponds to the findings of Polet et al. (2005a). No spinal damage was observed and macroscopic lesions did not differ significantly between control and exposed groups, Upon histological examination, in two exposed plaice, a small focal haemorrhage between muscle fibres was found, which was not encountered in control animals. In addition, the number of melanomacrophage centres (MMCs) in the spleen of exposed cod was significantly higher than in the non-exposed animals. No haemorrhages, MMCs or other lesions were observed in sole and cod 14 days after a 2 s exposure to the crangon pulse as well as other much stronger pulse stimuli between plate electrodes (Soetaert et al., 2016a). This indicates these histological deviations were reversible and healed after 14 days. The authors concluded the applied electrical field seemed to have only limited immediate impact on the exposed animals and no electric-induced irreversible injuries or mortality was observed.

Finally, possible impact of pulse trawling on electro-receptor organs, the Ampullae of Lorenzini, of elasmobranchs has been questioned by Desender et al. (2017a). This study aimed to examine the role of pulsed direct current (PDC) on the electro-detection ability of the small-spotted catshark, *Scyliorhinus canicula*. The response of the sharks to an artificially created prey-simulating electrical field was tested before and after exposure to the pulses used to catch flatfish and shrimp. No statistically significant differences were noted between control and exposed animals, both in terms of the number of sharks exhibiting an electroresponse prior to and following exposure as well as regarding the timing between onset of searching behaviour and biting at the prey simulating dipole. These results indicate that, under the laboratory circumstances as adopted in this study, the small-spotted catshark are still able to detect the bioelectrical field of a prey following exposure to PDC used in pulse trawls.

4.2.4 Effects on early life stages of Atlantic cod and Dover sole

Recently, concern was expressed about electrofishing over active spawning grounds and hereby affecting survival of sensitive embryos or juveniles that are present on or in the substrate (Polet, 2010). Brown shrimps are specifically caught in shallow coastal zones and estuaries, important nurseries or spawning areas for a wide range of marine species. Exposure of recently hatched larvae might reduce growth rates, induce malformations or cause mortality. The exposure of near-ripe or ripe broodstock fish to electric fields may also hamper natural reproduction (Snyder, 2003), an aspect that has not been investigated yet for pulse trawls.

In order to address this matter, experiments were carried out with different developmental stages of Atlantic cod (*Gadus morhua*) by Desender et al. (2017b). Three embryonic, four larval and one juvenile stage were exposed to a homogeneous electrical field of approximately 150 V/m during 5 seconds, mimicking a worst case scenario. In all embryos, no significant differences in mortality rate were found. However, in the embryonic stage exposed at 18 days post fertilization (DPF), the initial hatching/developmental rate was delayed. Larvae exposed at 2 and 26 days post hatching (DPH), exhibited a higher mortality rate. In the other larval and juvenile stages, no short-term impact of exposure on the survival was observed. Morphometric analysis of larvae and juveniles revealed no differences in yolk resorption, possible deformations and measurements of length, eye, head, and muscle height of the notochord. Although exposure to a worst case electrical field did not impact the survival or development of six out of eight young life stages of cod the observed delayed hatching/developmental rate and decreased survival for larvae are indicting an impact of electric pulses and warrant further research.

An analogous experiment was carried out by Desender et al. (2018) to investigate the effect on the development of Sole (*Solea solea*). Exposure of sole embryos at 2 days post fertilisation (DPF) and larvae at 11 days post hatching (DPH) did not result in lower survival eight days post exposure. Additionally, no differences in yolk resorption and morphometric length measurements of the notochord, muscle, eye, and head, were observed in the developing larvae at respectively 6 and 19 DPH. However, this study only included short term effects and was stopped before larvae metamorphosis.

4.3 Effects of the flatfish pulse field

4.3.1 On invertebrate species

Two exploratory studies evaluated the behaviour and survival of invertebrates exposed to the flatfish cramp pulse. Smaal and Brummelhuis (2005) exposed on average 10 individuals of 19 species of molluscs, echinoderms, crustaceans and polychaetes to pulse amplitudes and exposure times respectively two times higher and eight times longer than the settings used in the field. Reactions during exposure were minor or negligible and the survival after three weeks did not differ from control groups. Van Marlen et al. (2009) exposed six benthic invertebrate species to three subsequent 1 second bursts. For each species 20 animals were exposed at three different distances, ranging from 10 to 400 cm from the electrode. Compared to the control groups, they observed a significant reduction in the survival rate of exposed Ragworm (*Allita virens*) and European green crab (*Carcinus maenas*) of 3% and 5%, respectively. Atlantic razor clam (*Ensis directus*) displayed a significant 7% reduction in survival rate after exposure at 10 cm from the electrode, but higher survival rate at 20 cm from the electrode. Furthermore, food intake was significantly reduced by 10 to 13% in the European green crab. No significant effects were found for Common prawn (*Palaemon serratus*), Surf clam (*Spisula solidissima*) and Common starfish (*Asterias rubens*). Authors concluded that electrical stimulation in electrotrawls is less invasive than conventional beam trawling with mechanical stimulation. Both reports only examined the effect of the cramp stimulus and the variable results suggest that insufficient animals were included to exclude the variability due to natural mortality.

As an extension Soetaert et al. (2014) evaluated the survival, gross lesions and microscopic lesions of large numbers of Ragworm and Brown shrimp 14 days after exposure to various electrical pulses in a homogeneous electrical field. A series of single exposures to various pulses did not result in increased mortality, nor in the abundance of lesions (Soetaert et al. 2014). A fourfold exposure of Ragworm to a stimulus with maximal potential and duty cycle resulted in intense squirming during and especially after exposure, but none of the animals died or showed lesions in the 14 d after exposure. However, single exposure on brown shrimp to the highest electrical field strength showed an increase in the number and size of intranuclear bacilliform virus (IBV) infection in the hepatopancreas. In addition, no discernible negative effects were found in *Crangon*, 14 days after four repetitive exposures (Soetaert et al. 2014). However, indirect effects of pulse were not studied and cannot be completely dismissed. Therefore it was argued that additional experiments were warranted, evaluating the impact of repetitive exposure to commercial wire-shaped electrodes and pulses, as may occur in fishing practice.

To evaluate the effect of repetitive exposure to electrical fields, Brown shrimp were exposed 20 times in 4 days to commercial electrodes and shrimp or flatfish pulse settings and monitored up to 14 days post first exposure (Soetaert et al., 2016c). Survival, egg loss, moulting and the degree of intranuclear bacilliform virus (IBV) infection were evaluated and compared to stressed but not-electrically-exposed (procedural control) and non-stressed non-exposed (control) shrimp as well as to shrimp, exposed to mechanical stimuli. The lowest survival at 14 days post first exposure was observed for the sole cramp pulse treatment (57%), which was significantly lower than the procedural control group with the highest survival (70%). However, no significant difference was found between the non-stressed control group (66%) or the shrimp exposed to mechanical stimulation (60%) or the shrimp pulse (65%). No effect of electrical stimulation on the severity of IBV infection was found this time, which illustrates that the observation in the previous study was most probably an anomaly. The lowest percentage of moults was observed for the repetitive mechanical stimulation treatment (14%), which was significantly lower than the procedural control group with the highest percentage of moults (21%). Additionally, the mechanically stimulated shrimp that died had a significantly larger size compared to the surviving individuals. Finally, no effect of the shrimp pulse was found. Therefore, it can be concluded that repetitive exposure to a cramp stimulus and mechanical stimulation may both have a negative effect on the growth and/or survival of *Crangon crangon*. However, there is no evidence that electrotrawl stimulation would have a more adverse impact on *Crangon* stocks than mechanical stimulation in conventional beam trawling.

Finally, the impact of a bottom trawl on the benthos depends also on the footprint of the gear used and the sensitivity of the benthic community. The mechanical effects of the pulse trawl are probably lower because of the reduced mechanical disturbance and by-catch rates which result in lower mortality rates. The replacement of tickler chains running across the net opening by electrodes running in longitudinal direction, has decreased by 50% the bycatch of benthic invertebrates. In addition, the trawling footprint, defined as the sea floor area swept per hour trawling, is 23% lower than the footprint of the conventional beam trawl due to the reduction in towing speed from about 6.5 to 5 knots. In ecological terms these two factors are important to decrease the impact of trawling on the North Sea benthic ecosystem. Because the pulse trawl vessels showed a change in their spatial distribution, differences in habitat sensitivity need to be taken into account on top of the additional impact of electrical stimulation to assess the changes in impact on the seafloor.

4.3.2 On adult fish species

4.3.2.1 Dover sole (Solea solea)

Soetaert et al. (2016a) exposed over 100 sole in a homogeneous electric field to a wide range of different electric pulses, including those of the commercial pulse trawlers targeting sole but also several ‘worst case’ exposures with much higher pulse durations, frequencies. No mortality was found in fish and neither macroscopic or histological lesions nor other abnormalities were observed.

4.3.2.2 Common dab (Limand limanda)

Recently concern has been raised about injuries and skin deformation observed in Common dab (*Limanda limanda*). Since the start of electrotrawling, the appearance of ulcers in fish was suggested in the media as a negative side-effect of pulse gears and became a debate in European fishing communities. De Haan et al. (2015) investigated whether electric stimuli could cause injuries in dab, and enhance the development of diseases, such as ulceration. The pulse treatment was given in the closest range of a conductor with a dose extending the commercially applied practice. The fish were kept in observation for five days after the treatment, after they were analysed for external and internal lesions, possibly attributable to pulse exposure. In case of lesions attributable to infections, bacteriological tests were conducted. It was concluded that lesions primarily related to pulse exposure were neither observed in the fish analysed directly after the treatment, nor in the fish that were kept in observation for a period of five days after the treatment.

4.3.2.3 Whiting (Merlangius merlangus)

van Marlen et al (2014) reported that 4 out of 45 cod (9%) caught in the comparative fishing experiment in 2011 showed a spinal fracture. In whiting, only 1 out of 57 fish examined showed a spinal fracture (2%). A similar result was obtained by Rost in her MSc thesis (2015) reporting a pulse related fracture in 5 out of 226 whiting collected on board of 4 pulse trawl vessels. No laboratory experiments have been performed yet because of the difficulty to get and keep whiting in captivity.

4.3.2.4 Atlantic cod (Gadus morhua)

Spinal injury in Atlantic cod induced by electrical pulses was first observed in catches from UK 153, the first commercial ship rigged with a pulse beam trawl, and in field research on board the TX 68 and TX 36 (van Marlen et al., 2014) and other pulse trawlers (Rasenberg et al., 2013), amongst which also undersized individuals (van Marlen et al., 2011).

An initial laboratory experiment performed by De Haan et al. (2008) with farmed cod in Norway revealed that the cod's position in relation to the electrode is critical: When a fish positioned next to a pair of electrodes at a distance of 40 cm was subjected to electrical pulses (i.e. with the fish next to the fishing gear), no reaction was observed. When a cod positioned above a pair of electrodes at a distance of 20 cm (half the height of the opening of the net) was subjected to the pulses, it would show strong spasms. Cod exposed in either of these positions exhibited normal behavior again immediately following the test. However, cod found closer to the conductors, in the hot-spots of the electric field located in the immediate 5-10 cm surrounding of the electrodes, exhibited spinal injuries as a result of the spasms in 50% of the cases. This initial trial showed that only those cod subjected to electric pulses close to an electrode are at risk of being injured. The answer to the question of what happens to the small cod that escape through the mesh in the fishing gear, was addressed by De Haan et al. in a follow-up study in 2010 published as a report in 2011 and a A1 paper in 2016. Two different groups of farmed cod were tested: small cod, on average 14 cm long, and mature cod, on average 47 cm long. The small cod was be exposed closer to the electrodes (at a distance of 1 to 3 cm) and were therefore subjected to pulses that were 3 to 5 times stronger, yet none of the 140 small cod showed injuries. This contrasts to the field trial of van Marlen et al. (2014) where the harmed fish were between 20 and 27 cm. The larger cod were exposed as close to the electrodes as possible (at a distance of some 6 cm). This time, 50 to 70% of the large fish incurred injuries, even after reducing the electrode charge by half. Injuries in the large fish decreased once the pulse frequency was increased to 100Hz; and at 180Hz, no injuries were observed. Increasing the pulse frequency may prove effective in reducing the incidence of injury, but then it is yet to be seen if sole can still be fished efficiently. Moreover, the strength of the electric field at sea has been reduced in comparison with the test conditions. The charge at sea is 17% lower, while the electrode distance is 30% greater, at 41 to 43 cm instead of 32.5 cm (UK153). Field strength measurements carried out by IMARES in 2010 on board the TH10 and OD17 with the fishing gear on the seabed, show that the cod were exposed in 2008 and 2010 under realistic conditions.

In 2013, ILVO also carried out tests on farmed cod in Norway, in partnership with Ghent University. The fish – 100 large fish (64-82 cm) and 50 smaller ones (42-49 cm) – were subjected to various pulses, including the same ones used by IMARES in 2008 and 2010. In addition, the same electrodes and configuration were used as those previously applied by IMARES. But this time, no injuries were observed (Soetaert et al., 2016a). There was also no mortality during the first two weeks following exposure, and no other injuries could be detected. The ILVO's results therefore deviated sharply from those of earlier experiments carried out by IMARES. In order to eliminate any effects which might be due to equipment, season, location, or treatment, a joint experiment was set up by the ILVO, IMARES, and Ghent University. The experiments were then recreated in late 2013 under identical conditions. A total of 80 cod (36-45 cm) were subjected to electric pulses, whereby only 2.5% effectively showed any such injuries. Even when the electric charge was doubled to 120V, only 13% of the fish were injured (Soetaert et al., 2016b). The comparative experiment demonstrated that differences in equipment could be eliminated as a cause of these results and that the cod themselves must hold the key to the variations in results. Possible parameters include body structure, muscle mass, response patterns, subtle differences in body position, genetic variation, and variation in skeletal strength.

In conclusion, it can be summarized that pulse trawl catches at sea exhibit signs of spinal injury in cod, and this is confirmed by the tank experiments. This research demonstrates that the size of the cod and its position with respect to the electrodes play a major role. Large cod positioned above or next to the field remained unharmed. Large cod exposed to electric pulses at the shortest possible distance from an electrode sustained an injury in 50 to 70% of the cases. Unlike the large fish, which were all caught, juvenile cod up to 16 cm were not harmed in laboratory studies. This however contrasts to the injuries observed in larger undersized cod of 20-27 cm in the field trials of van Marlen. Besides, the laboratory studies showed that cod's susceptibility to electric pulses can vary widely and would seem to depend on subtle differences in fish health. One of the recommendations is therefore to sample cod landings and/or discards so that the condition of round fish that have sustained injuries can be compared from one season to the next, in the hope of ultimately identifying the parameter responsible.

4.3.2.5 European Seabass (Dicentrarchus labrax)

Despite the spinal injuries observed in gadoid fish, especially cod, in previous studies (van Marlen et al., 2014; de Haan et al., 2016; Soetaert et al., 2016a&b) no spinal injuries were observed in two length groups of seabass (31.3 ± 2.2 cm and 42.1 ± 2.5 cm) after exposure to the same pulse stimulus and set-up as used in the experiments with cod. This difference in vulnerability may be due to natural variation as seen in cod by Soetaert et al. (2016b) but it seems more likely that it is linked to differences in vertebral morphology as was also seen in freshwater research (Soetaert et al. 2018).

4.3.2.6 Lesser spotted dogfish (Scyliorhinus canicula L.)

De Haan et al. (2009) exposed 3 groups of 16 dogfish with similar length (0.3-0.65 m) to the electric stimulus used in pulse trawling for sole, each on a different distance. One group was exposed in the 'far field' 0.4 m side ways of the conductor, another in the 'above field' or 0.1-0.3 m above the center of a conductor pair and the last one in the 'near field' which was closer than 0.1 m from the conductor element. A 4th control group was also included. Each fish was exposed four times in a row and feeding and behavioural responses were monitored during the stimulus and in the 14 days period following the stimulation. Afterwards, the fish were kept in husbandry for another 9 months.

Regarding other behavioural responses (mainly reflexes and muscle contractions, and post-reactions, such as a rapid body reverse, short-curled body rotations and acceleration towards the water surface), there were some clear differences between exposure groups. The responses of the fish exposed in the "far field" range, representing the fish just aside the fished area of the trawl, were minor and ignorable. However, the responses of the fish exposed in the "above field" range were more pronounced with contractions, rapid body reverses, short- curled body rotations and acceleration towards the water surface occurring.

No evidence was found on differences in feeding response or likelihood of injury or death between the exposure groups. There was no evidence that fish sustained injuries as a result of the exposures. Respectively 8 and 9 months after the experiment a single specimen of the "above field" category and "near field" category died. In the 14 days observation period after the exposures no aberrant feeding behaviour could be distinguished. Fish in all tested groups started feeding normally the same day directly after the exposures. In a period of 7 months after the exposures all exposed groups produced eggs in numbers varying between 5539 per group. Surprisingly the control group did not produce eggs.

4.3.2.7 On prey detection of electrosensitive cartilaginous fish (Scyliorhinus canicula L.)

Possible impact of electrotrawling on electro-receptor organs, the Ampullae of Lorenzini, of elasmobranchs has been questioned by Desender et al. (2017a) and investigated as described previously. Besides the effect of the 5 Hz startle pulse for shrimp, small-spotted catshark, *Scyliorhinus canicula*, was also exposed to a 60 Hz cramp pulse for flatfish. Again, no statistically significant differences were noted between control and exposed animals, indicating that, under the laboratory circumstances as adopted in this study, the small-spotted catshark are still able to detect the bioelectrical field of a prey following exposure to cramp pulse used in pulse trawls targeting flatfish.

4.3.2.8 Skin ulcerations

After one year of preliminary studies, Vercauteren started a PhD investigating the possible correlation between pulse fishing and (the rise) in skin ulceration in fish in 2016. A detailed project description can be found in Appendix 2 'ongoing and future research'.

The first workpackage of her PhD consists of sampling of wild dab and the construction of the monitoring database which will continue until the end of 2018. So far, an association of skin ulceration with temperature and salinity was found. This corresponds to different previously conducted studies. Furthermore, two bacterial species, *V. tapetis* and *A. salmonicida*, were isolated in virtually pure cultures from skin ulcers in dab. These findings indicate a potential involvement of these microorganisms in the development of skin ulcerations. The results of this campaign are already accepted for publication in a peer-reviewed journal (Vercauteren et al. 2017, Journal of Fish Diseases). Data of three years of monitoring will be thoroughly analysed at the end of 2018, when the planned monitoring campaigns are completed.

The goal of the 2nd workpackage was the development of a skin ulceration model and study the importance of previous trauma to the skin. Therefore these two previously discovered bacteria were used to set up an infection model to induce skin ulceration(s) under controlled laboratory circumstances. Two experiments in the laboratory using *V. tapetis* and *A. salmonicida,* were successfully completed. The first results indicate that ulcerations appeared to be worse in the area where scales were removed and this both on the pigmented and non-pigmented side, implying the facilitating role of previous skin damage in skin ulceration development. Furthermore, these descaled areas showed significantly more severe lesions in the group inoculated with one of the bacteria under study compared to the control group, pointing towards a contributing role of the inoculated microorganisms. Various confounding factors including sex, age, condition, length were analysed and proven to have no significant impact on the results. The manuscripts discussing the final results of these experiments will be submitted soon. Bacteriological examination of the ulcerations is ongoing to verify that the isolates retrieved from the skin ulcers belong to *V. tapetis* or *A. salmonicida*, including histological and immunohistochemical examination of the lesion to confirm that ulcerations are similar to those naturally occurring. The submission of the A1 publication reporting the final results is due this year. Futhermore, a study to evaluate the possibly contributing role of various environmental and anthropogenic factors in the development of skin ulcerations in dab and a final study of the impact of skin ulcerations on the general health status of dab are planned in the next year using the previously pinpointed experimental infection model.

4.4 Effects of the *Ensis* pulse field

4.4.1 Before-after-control impact study

An extensive study by Woolmer et al. (2011) summarises the results of experimental work carried out as part of "Design and Trials of Electrofishing System for Razorclams – FIFG 57437". The aim of the project was to design and trial methods of harvesting Ensis spp. using electrical stimulus with the intention of providing a more environmentally benign alternative to existing hydraulic and toothed dredges. The simple electrofishing gear used in this project (Figure 6.6) employed a voltage of 30 v DC with a current of 140 A. This produced a maximum electrical field strength of 50 vm-1 between the electrodes; a voltage at which guidelines consider it is safe for divers to come into direct contact with the electrodes.

A field experiment was developed and implemented to determine negative effects on non-target invertebrate macrofauna, and epifauna including fish species. A modified BACI (before-after-control-impact) design established a series of four 200 m x 100 m experimental areas containing 50 m x 100 m fished (treatment) or control sectors in Carmarthen Bay south Wales (Figure 6.7). The electrofising gear was used in the in the „treatment" areas by fly dragging in order to simulate a commercial fishing operation. In order to determine whether the electrofishing gear had negative effects on non-target macrofauna a series of macrofaunal grab samples were collected from each sample sub-sector before fishing, and then variously at intervals up to 28 days post-fishing. Epifaunal species were sampled by divers surveying transects before and after electrofishing treatments. Throughout the experimental work observations and video footage was reviewed for visual effects on species and changes in behaviour. The results of this study demonstrate that the effects of electrofishing gear employing relatively low DC voltage and amperage can be effectively used in the harvest of Ensis spp. without serious negative effects on the epifaunal and macrofaunal benthic community. Given the commonly reported negative effects of alternative approaches such as hydraulic and toothed dredges the results of this study suggest that further development work is warranted in order to develop less disturbing fishing gears, both for Ensis spp. and for other species.

4.4.2 Behaviour and survival.

In addition to this study, Murray et al. (2016) conducted a series of tank and in situ experiments with Ensis pulse fields. The authors state that species affected by the Ensis fishery will be exposed to an electric field for far longer than previous electrofishing studies have considered: continuously for over a minute, compared to several one second pulses in the Crangon fishery and 2 s exposures to the pulses used in sole fishery.

The experiments consisted of tank trials to determine the properties of the electric field generated by electrofishing equipment and to monitor the survival of individuals of the target species, *E. siliqua*, and three non-target species: the common starfish *Asterias rubens*, the hermit crab *Pagurus bernhardus* and the surf clam *Spisula solida*. Further direct observations were conducted using inshore fishing vessels to monitor recovery rates in situ of target species, non-target invertebrates and the sandeel, *Ammodytes marinus*. These were carried out using two commercial fishing vessels at two sites in Scotland: the FV Nicola Jane in Loch Nevis (Westcoast) and the FV Ensis in East Fife (East coast). An electrical stimulus was applied to the seabed, replicating commercial electrofishing practice. Video transects were also recorded to examine physical impacts of the electric rig on the seabed.

Electrofishing for Ensis spp. elicited a strong behavioural response from the target species and several non-target species, notably fish and crustaceans. The rapid and consistent emergent responses of razor clams both in tank and sea trials indicate that electrofishing is extremely efficient with little opportunity for marketable razor clams to escape capture once the track of a pair of electrodes passes them. Recovery time in the non-target species was shorter than for Ensis spp. in both sea trials and tanks trials, with individuals resuming apparently normal behavioural patterns after a maximum of 8 min8 s.

Overall, by-catch mortality was low, with only two incidences of mortality in the tank experiments. Tank trials involving *Ensis* and three other non-target species (Atlantic surf clam, *Spisula solida*; Sea star, *Asterias rubens* and Hermit crab, *Pagurus bernhardus*) were unable to reveal a significant difference in survival when comparing control against electrically fished individuals.

Whilst no direct observations of non-target species being predated were made, Ensis which were slow to recover and were observed being predated upon by fish (gobies) and crabs and in East Fife eider ducks (*Somateria mollissima*) have been observed following fishing vessels and diving between the electrodes to catch emerging Ensis. Predation will, however, be offset the by lack of by-catch, in comparison to the traditional alternative dredge methods with can result in 32 kg of by-catch, and 10 kg of displaced benthic invertebrates, to land 10 kg of razor clams.

Finally, there was no evidence of chemicals being released into the seawater, as chloride compounds were not found to evolve from the AC electrodes during the tank trials, nor was there any indication of erosion of the electrodes as has been reported in DC systems.

4.5 Conclusion

4.5.1 Direct mortality imposed by electrical stimulation

None of the experimental studies conducted showed that organisms exposed to pulse stimuli died from the exposure. The few incidences of mortality observed did not seem to be directly related to the electrical stimulation. The most severe effects observed are the spinal fractures and the internal bleeding through the rupture of the blood vessels. It seems likely that these lesions will impair their normal behaviour and will increase the risk of mortality for fish that are exposed to the pulse stimulus but escape from being caught. The experiment of de Haan et al (2016) showed that cod that are small enough to escape through the mesh did not develop vertebral fractures. The field strength generated outside of the path of a sole pulse trawl quickly reduces to values below 17 V/m, which is well below the critical field strength (37 V/m) above which fractures occur (de Haan et al., 2016). Although cod in the discard size range (17–35 cm) may develop vertebral injuries - spinal fractures were observed in cod of 20, 23, 27, and 55 cm in the catch of commercial pulse trawlers (van Marlen et al., 2014) - we do not expect that pulse trawling leads to additional mortality in discarded cod because the survival rate of cod discards in bottom trawl fisheries is low (Lindeboom and de Groot, 1998; Depestele et al., 2014). The fractures invoked by electrical stimulation do not contribute to the fishing mortality rate as they are restricted to the cod that are killed by any fisheries activity . The fractures invoked by electrical stimulation, however, will affect the economic revenue as the fractured cod will fetch a lower price, and may be relevant in terms of animal welfare.

In young life stages of cod exposed to the *Crangon* pulse, reduced survival was observed in two larval stages exposed 2 and 26 days post hatching. One embryonic stage exposed 3 days before hatching (18 days post fertilization) showed a slightly delayed developmental rate during the hatching process. This reduced survival was absent in sole larvae exposed at the same developmental stages (Desender et al., 2017b; 2018).

4.5.2 Electric-induced injuries

The only conclusively proven electrically-induced injuries so far are the spinal injuries observed (in gadoid species) after exposure to the cramp pulse for sole. No fractures or other major injuries have been observed in fish exposed to the shrimp pulse. The sensitivity to develop fractures in response to a pulse stimulus differ between fish species. Samples taken from the commercial fishery indicates that cod shows the highest incidence rate (about 10%), followed by whiting (about 2%). Sea bass and several flatfish species appear to be non-sensitive and do not developed vertebral fractures. These results are only indicative and needs further study as the number of observations is too low to draw any firm conclusion.

The experiments indicate that cod exposed to a field strength of less than 37 V/m, typical for the maximum field strength that is measured outside the array of electrodes, will unlikely develop a vertebral fracture. The experiments also indicate that small cod, that are small enough to escape through the 80 mm meshes of the codend, do not develop fractures. This indicates that only cod that are located within the trawl track run the risk of being exposed to a field strength that may invoke a vertebral fracture. In particular the cod that are located in close range to the electrodes are prone to develop a vertebral fracture. The size effect as well as the inter-stock variability on the fracture probability needs further investigation. It should be noted however that fewer cod are captured captured by pulse trawls compared to beam trawl (van Marlen et al., 2014) which can be attributed to the lower fishing speed, which will result in a lower total bycatch mortality for this species.

4.5.3 Sublethal effects

How the exposure of organisms to low field strength will affect their functioning is unknown and further research on the critical field strength at which the functioning is affected is required. We expect that the threshold levels for the sub-lethal effects will be species specific. The sub-lethal effects will further be affected by the frequency of exposure which can be estimated from the analysis of VMS and logbook information. A recent analysis of the trawling intensity at a resolution of 1x1 minute grid cells (about 2 km^2) showed trawling intensities between 0.1 and 5 times per year with a modal trawling intensity close to 1. Less than 5% of the surface area of the North Sea was trawled more than 5 times per year (Eigaard et al. 2017). These values refer to all bottom trawling fleet and are given as an upper level. The number of times that an organism will be exposed to an electrical stimulation per year is determined by the ratio of the width of the electric field exceeding the critical threshold level and the width of the pulse trawl and the annual trawling frequency. If low threshold levels apply, the exposure frequency will be higher.

5 Physical impact of pulse trawls

5.1 General

It is widely acknowledged that beam trawlers contribute extensively to the physical impact on the seabed in the southern North Sea (Jennings et al., 2012; ICES, 2014) and that beam trawling can affect benthic invertebrate and demersal fish communities (Lindeboom and de Groot, 1998; Kaiser et al., 2006; Polet and Depestele, 2010; van Denderen et al., 2014). The penetration into the seabed can be up to 8 cm, depending on beam trawl weight, towing speed, and sediment type (Paschen et al., 2000).

In recent years, some 80 Dutch flatfish directed beam trawlers have replaced tickler chains and their mechanical stimulus to raise fish into the path of the gear with electrodes and their electrical stimulus (Soetaert et al., 2013; van Marlen et al., 2014). These gears have greatly reduced fuel costs (van Marlen et al., 2014) and, it is claimed that, have also reduced benthic impacts (Soetaert et al., 2014).

Extensive studies have addressed the concern of seafloor disturbance by towed fishing gears, specifically of beam trawling. However, a few studies, have addressed the difference of seafloor disturbance between traditional trawls, such as beam trawls and dredges, and commercially used pulse gear targeting shrimps, sole and Ensis. An overview of the latter is given in the chapters below. Most of this work is still on-going or planned.

5.2 Physical impact of the shrimp pulse trawl

The opinions on the nature and consequences of the effects of shrimp trawls on the habitat are often very diverse and contradictory. Some studies indicate clear effects, while others regard this trawl as a relatively light gear with a limited impact (Rumohr et al. 1994; Vorberg 1997).

Disturbance of the seabed becomes important when it affects the habitat of the benthic population that supports it. Changes in epibenthic communities are usually most apparent when sessile epibenthic species decline or disappear (Riesen and Reise 1982). Also for the Wadden Sea, the shrimp fishing area par excellence, this is illustrated by the relatively sudden decline in a number of key species and habitats they form. The main species are the oyster (*Ostrea edulis*), seagrass beds (*Zostera marina*), the Sabellaria reefs (*Sabellaria spinulosa*) and the sea cypress fields (*Sertularia cupressina*). The effect of the shrimp fishery in the decline of these organisms in the Wadden Sea is under discussion.

The coastal zone where most of the shrimp fisheries in the North Sea is carried out, is characterized by a relatively dynamic environment. In addition to the fisheries there are also other processes that cause disturbance of the seafloor. The question is whether the fishing pressure causes effects that are distinguishable from other disturbance. As an analysis of the relationship between beam trawling and benthic fauna in the North Sea revealed (van Denderen et al. 2014), there was only a negative relationship with fishing effort in the relatively deeper areas further away from the coast with finer sediment and not in the shallower, closer to the coastal areas with coarser sediment. Even in the wind farm Egmond no effect could be demonstrated on the soil fauna after an absence of trawling for 5 years (Bergman et al. 2014).

Only one recent study has focused on the physical disturbance of the habitat by the shrimp beam trawl together with the shrimp pulse trawl. This study was carried out in the Benthis project by ILVO and IMARES in 2015. No report is available yet. However, studies have shown that the bottom impact of pulse trawlers targeting shrimp is smaller than using traditional beam trawl gear. Indeed, pulse trawls use a straight bobbin rope to enable a good rigging of the electrodes. On one hand this bobbin rope is much shorter and contains less bobbins (for example 12 for a pulse trawl vs 36 for a traditional trawl in the Netherlands) and on the other hand this guarantees a better orientation of the bobbins to allow them to roll properly over the seafloor instead of shearing over it as most bobbins close to the trawl shoes of a traditional gear do. This differences are illustrated below and will reduce the impact on both the amount of area touched by the fishing gear as well as the penetration depth.

Figure 5.1: Front view (top) and details of the bobbin rope (bottom) of a traditional trawl with 36 bobbins in a u-shaped bobbin rope (400 kg, left) and a pulse trawl with 11 bobbins in a straight configuration (150 kg inclusive of electrodes, right) illustrating the difference in mechanical stimulation and the size and orientation of escape opportunities between the bobbins for by-catch species

5.3 Physical impact of the flatfish pulse trawl

The physical effects of beam trawls rigged with tickler chains are expected to be high due the close contact with the seabed (Suuronen et al., 2012) and the infaunal benthic impact they cause (e.g. Lindeboom and de Groot, 1998; Kaiser et al., 2006). Surprisingly, only a few (grey literature) studies have quantified the *physical* effects of beam trawling. These studies focused on (i) changes in seabed bathymetry estimated from boxcore sampling or physical modelling of individual gear components (Paschen et al., 2000), and they also investigated (ii) compaction and (iii) changes in sediment composition by RoxAnn surveys, sidescan sonar imagery, and by estimating the pressure of individual gear components on the seabed (Fonteyne, 1994; Leth and Kuijpers, 1996; Lindeboom and de Groot, 1998; Fonteyne, 2000).

There is only one, recent, study (Depestele et al., 2015) available that presents a direct comparison in seafloor disturbance between the beam trawl fishing for flatfish and the pulse trawl fishing for flatfish. The sea trials have been carried out by in the FP7-BENTHIS project in 2013 on a fishing ground in the southern North Sea. A second series of sea trials have been carried out on another fishing ground in the Central North Sea in 2014. A report on this second series is expected by the end of 2018.

The first trials are described in Depestele et al. (2015) and investigated the geotechnical and hydrodynamic impact of a traditional tickler-chain beam trawl (hereafter called "tickler-chain trawl") and a "Delmeco" electrical pulse beam trawl (hereafter called "pulse trawl"). The geotechnical investigations focus on measuring the alteration to the seabed bathymetry using a Kongsberg EM2040 Multi-Beam EchoSounder (MBES) in conjunction with the fishing vessels' global positioning system (GPS). Not only does this approach permit the detection of trawl marks in a similar way to the study of Malik and Mayer (2007) but it also allows the quantification of vertical changes in sediment bathymetry before and after trawling. In particular, the alteration to seabed bathymetry is investigated for (i) a single pass of a tickler-chain beam trawl, (ii) multiple passages of a tickler-chain beam trawl, and (iii) pulse beam trawl.

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

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

Detailed materials, methods and results are given in Depestele et al. (2015). A view of the groundgear of both trawls is given in Figure 5.2.

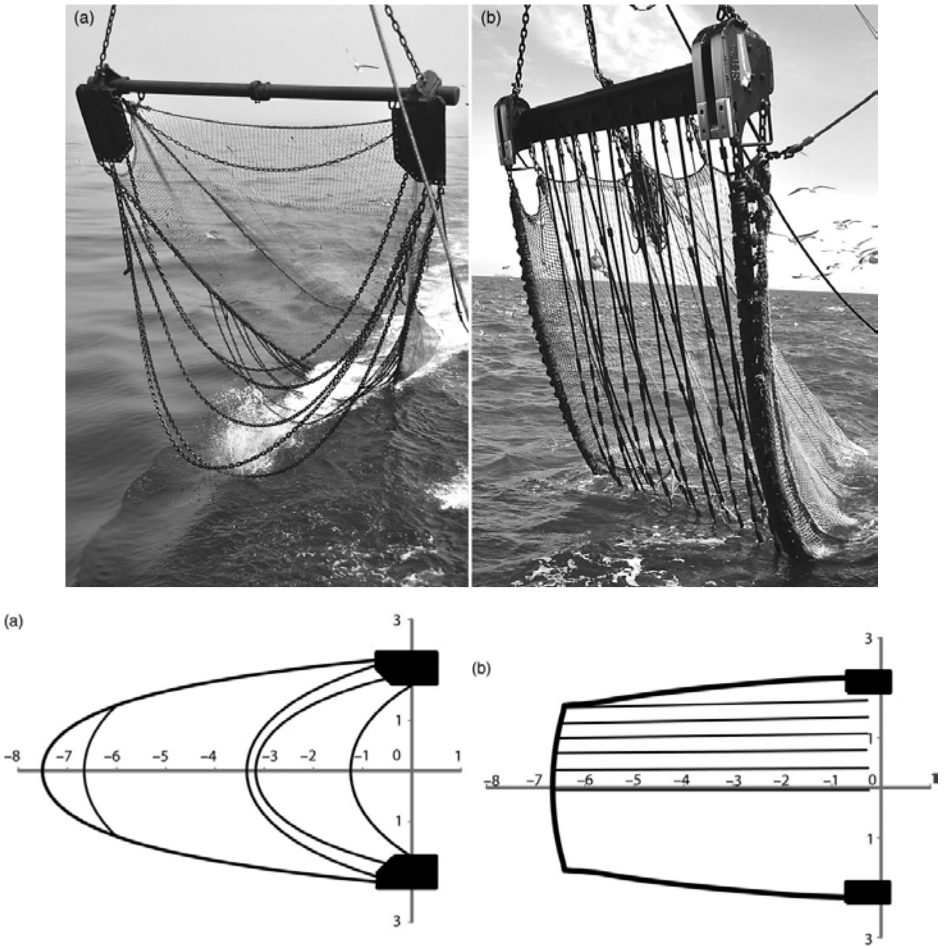


Figure 5.2: Gear components in contact with the seabed for the tickler-chain (a) and pulse (b) trawl. Tickler chains with a chain link diameter of 28 mmare attached to the trawl shoes, whereas the tickler chains of 11–16 mm are attached to the groundgear (only one is shown).

The results indicate that the seabed bathymetry changes between 1 and 2 cm after one passage of the trawl and that it is further increased by higher trawling frequencies. Furthermore, the results suggest that the alteration following the passage of the conventional trawl is greater than that following the pulse trawl passage. 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 likely to occur than with the pulse. There was no difference in the quantity of sediment mobilized in the wake of these two gears; however, the numerical model introduced in this study predicted that the tickler-chain trawl penetrates the seabed more deeply than the pulse gear. Hence, greater alteration to the seabed bathymetry by the tickler-chain beam trawl is likely to be a result of its greater penetration.

It has to be noted that the difference in seabed disturbance between the tickler and pulse gear is quite conservative. This is because the experimental tickler gear was a 'light type' (1.065 kg) in the group of tickler chain beam trawls and the experimental pulse gear was a 'heavy type' (2.500 kg) in the group of flatfish pulse trawls.

The differences in physical effect between a sumwing with tickler chains and electrodes (pulsewing) is illustrated in Figure X1 and X2 below on the basis of backscatter values, which reflect the intensity (strength) of the reflection of the acoustic signals on the seabed. The discrepancies in values inside and outside the trawl track are more pronounced for the trawl with tickler chains than those for the pulse trawl, but for both gears the discrepancies disappear within 3 days in muddy habitats. The changes in bathymetry have not been analysed but indicate an expected difference inside and outside the track of ~1-2 cm based on the analysis of randomly selected transects across the trawl track (Degrendele et al., 2015).

5.4 Physical impact of the Ensis pulse trawl

The study by Woolmer et al. (2011) does not address the issue of physical disturbance of the habitat but does state that the intense physical disturbance by the conventional harvesting gear for Ensis such as the hydraulic and toothed dredges makes further investigations in the less intrusive Ensis pulse gear worthwhile investigating. Murray et al. (2016) reported the physical impact of the fishing gear on the seabed was well within the range expected by natural disturbance and presented a visibly lower impact on the environment than current dredge methods.

5.5 Conclusion

Although the different types of pulse- and electrotrawls differ greatly in electric stimulation and rigging used, they all replace some part to almost all of the mechanical stimulation by electric stimulation which results each time in a reduction of the physical impact of the fishing gear. The pulse trawl targeting shrimp have less bobbins compared to traditional beam trawls reducing the area touched by the fishing gear. The pulse trawl targeting flatfish still has a ground rope covering the entire width of the trawl to scope up fish, however it was shown that the penetration depth of this ground rope and subsequent sediment resuspension are smaller than theconventional beam trawl with tickler chains. Moreover, these trawls fish slower which will also account for a ±10-30% decrease in the area swept by these trawls. Finally, the electrotrawls targeting *ensis* sp. with only flat steel bars touching the seafloor replace dredges which are considered to be amongst the fishing gears with the highest physical impact. Therefore, it can concluded that the physical impact of vessels using electric stimulation will be smaller than that of conventional fishing gears targeting the same species.

6 Viability and survival of the catch

6.1 Mechanical impact of pulse trawls

Although the primary stimulator are electric pulses, fish caught with pulse trawls still endure several mechanical impacts in a pulse trawl which, apart from the electric stimulus, will affect their viability and survival chances when escaping the net or after discarding. These mechanical impacts can be encountered in different stages of the process. It starts upon first contact with the fishing gear, where animals may be hit by those parts of the trawl making contact with the sediment such as the trawl shoes, the tickler chains, chain matrices or bobbin rope, the electrodes or the footrope (1). Afterwards, fish pass through the net and eventually end in the codend, where they will not only make direct and long lasting contact with the net material but also with fish, hard bodied invertebrates such as sea urchins and crabs, stones, litter and passing clouds of suspended sediment (2), all of which may cause external (scale loss, open wounds, loss of mucus layer, …) or internal (bruisings, bleedings…) lesions. Note that also fish escaping through the meshes may be exposed to these kinds of damage. Finally, the net is hauled to the surface, the catch will be emptied on deck and sorted by the crew (3) which exposes the fish to stressors such as barotrauma, thermotrauma and possible suffocation but also to additional mechanical impact before and during the sorting process causing more external and internal lesions. When comparing pulse trawling and conventional beam trawling, a lower physical impact on the animal is suggested in every stage of the process (excluding any electrical effect).

During the initial stimulation in front of the ground rope, the mechanical damage inflicted on animals will most likely be lower in a pulse trawl because the tickler chains are removed and the fishing speed is reduced up to 30% from 6-7 kn to 4-5 kn. Although this may result in less incidents of external damage, it is unclear how this relates to the potential impact of the additional electrical stimulus in a pulse trawl. When comparing the mechanical damage encountered in the net during the fishing process, it can be concluded that this will be lower for the pulse trawl. Firstly, the lower fishing speed as well as the reduced sediment re-suspension (Depestele et al., 2016) will favour selectivity and reduce the pressure on and possible sandblasting of the catch. Secondly, less organisms will be impacted since the smaller surface area fished and higher selectivity will reduce the bycatch. Thirdly, the lower volumes of benthos and stones (up to 80% according to van Marlen et al., 2014) will reduce external damage and crushing of the animals in the cod-end. For the same reason, the mechanical impact experienced in the last stage, the catch processing on deck, will also be smaller. Due to the smaller catch volumes, the catch in the hoppers will be less compacted and the processing will be faster resulting in a shorter air exposure which is also beneficial for the survival of the discards (Uhlmann et al., 2016; van der Reijden et al., 2017). Therefore, it may be concluded that it is most likely that the overall mechanical impact on the animal as caused by the fishing gear will be smaller when caught by a pulse trawl, which is confirmed by the higher reflex-impairment response in flatfish discards caught by beam trawls (Uhlman et al., 2016).

6.2 Discard survival in pulse trawls targeting sole

The EU landing obligation (LO)[2] requires fishers to land all marketable and undersized fish that are subjected to landing restrictions (quota). With scientific evidence for high survival after discarding fishers are allowed to discard those species, while other species under quota restrictions obligatory to land. This LO exemption chances of survival after discarding of several species were studied for multiple fisheries.

The aim of an elaborate survival study for pulse trawls (van Marlen et al., 2016) was to determine the average survival rate of sole, plaice and dab discards in commercial pulse trawl fishery of the Dutch fleet. This was executed by monitoring fish collected from catches for a certain period of time (21 days on average) to observe fisheries induced mortality. A second goal of this study was to investigate whether a vitality score can be used as a proxy of the survival chance. The vitality of each fish was assessed individually by scoring external damages and the impairment of reflexes, and related to the observed survival time. A third goal was to study the variation in discard survival estimates by looking into correlations between survival estimates and environmental or other potential factors.

In total eight experimental trips were carried out on board two pulse vessels in the North Sea in the period between November 2014 and October 2015, three of which were primarily dedicated to comparing techniques for improving survival. Live fish from the catch were collected from different locations in the processing line and at different times. All sampled fish were scored for external damages and reflex impairment, then tagged to enable individual monitoring over time. To observe and record the survival times, these fish were stored in a specially developed system of tanks filled with continuously refreshed sea water. Except for the first trip, all experimental trips were done with three of such tank systems. The tank systems were designed with restrictions in dimensions and weight to enable transport from the vessels to the IMARES laboratory in Yerseke, the Netherlands and monitor survival over an extended period of time. During storage on board fresh sea water was continuously supplied. During transportation the circulation of sea water was maintained and air supplied. Fish status was checked and dead fishes were removed daily during the monitoring period of some three weeks. To distinguish between fisheries induced mortality and handling induced mortality, control fish were used. These control fish were caught using a small vessel operating a shrimp trawl in short tows at low speed previous to the survival experiments and were treated in exactly the same way as fish from the catch.

[2] https://ec.europa.eu/fisheries/cfp/fishing_rules/discards_en

The result of the project showed that the average survival rates of discard sole (as determined after a monitoring period of 21 days on average) on the vessels fishing with a pulsewing (12 m width) and a commercial towing duration (~125 minutes) varied between 8% and 48% over 6 trips (n=226), with an average of 29% [95 CI: 11 - 19%] over all trips. For short hauls (~60 minutes) the overall survival rate was higher (24% - 59%) with an average of 41%. The overall survival rates of discard plaice on the pulse vessel taken from commercial hauls of ~2 hours was assessed 7 trips (n=349) and varied between 4% and 28% per trip with an average of 15% [95% CI: 11-19%]. Using a short tow duration (~60 minutes) increased this percentage, with an average of 39%. Dab was sampled during one trip on board a pulse vessel with an average survival of 15% (n=226).

Sole control fish showed good survival rates (~85%) in our experiment. Plaice controls suffered mortality a couple of days after arrival at the laboratory in Yerseke, around day 12. Mortality of control fish is undesirable and may lead to discussions about the accuracy and reliability of the observed survival rates. After trip eight, a Vibrio infection in the tank system affected mortality in the control and experimental fish. However, by right censuring these data, possible infection effects are excluded.

The results indicate that the overall discard survival rates are correlated with fish vitality. Vitality was measured in two distinct ways; by using a damage classification of A, B, C, and D, comparable with earlier survival research and as a summation of present damage scores and reflex impairment scores, divided by the total number scored damages and reflexes. Both showed a relation with the survival rate of discard plaice. Too few data were available for the species dab and sole to find a good correlation. However, the data suggests that a similar relation exists for sole discard survival. To confirm this a relation, more data should be collected, in which external factors are taken into account.

It was concluded (van Marlen et al., 2016) that the overall discard survival rate varied considerably between the trips, however, the conditions also varied to a great extent between trips. It should be noted that a full factorial design, in which all (potential) factors are tested individually was not made for this study. Such a design was practically not feasible, as multiple factors could not be controlled (such as weather), while other factors are very coherent (such as fishing location, and fishing depth), and because of limitations in resources only a relatively small number of trips could be carried out. As a result only a first explorative analysis was done to identify potential, influential factors. From this explorative analysis, it seems that water temperature, towing duration, fishing depth and vessel are factors that are highly correlated with discard survival rates, but a full predictive model was not tested so far. Such a model could lead to better knowledge of the various factors causing the mortality of the fish, and hence, give insight in adjustments that will increase discard survival rates.

Next to the study described above, a plaice discard survival study was performed in Belgium in 2015. Both the Dutch and Belgian datasets were merged and analyzed together. In total six different fishing vessels were included in the data, but for comparison with pulse trawls only three vessels were selected: two pulsewings (NL) and one sumwing using tickler chains (B). The width of the gear for those vessels was 12 m and engine power was around 1470kW (GO31, GO23, Z483). In comparison with survival estimates for plaice discards from pulse trawls, the merged dataset showed relatively lower survival estimates for comparable (in towing duration, fishing depth, vessel and gear size) conventional beam trawl fishing gear with thickler chains. Both damage class and vitality score appeared to be good proxies for survival. Haul duration was an important factor affecting survival rate, with shorter hauls having higher survival rates in general.

7 Overview Updates

Table 9.1: Updates made in 2018 version.

Topic	Description	Old section	New section

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Annex 5: Technical minutes by RGPULSE

Review of a Special Request from the Dutch Government

Review group: Jake Rice (chair), Stefán Áki Ragnarsson, Håkan Wennhage

The Special Request from the Dutch Government asks ICES for advice with regard to

"ICES is requested to compare the ecological and environmental effects of using traditional beam trawls or pulse trawls when exploiting the TAC of North Sea sole, on (i) the sustainable exploitation of the target species (species and size selectivity); (ii) target and non-target species that are exposed to the gear but are not retained (injuries and mortality); (iii) the mechanical disturbance of the seabed; (iv) the structure and functioning of the benthic ecosystem; and to assess (v) the impact of repetitive exposure to the two gear types on marine organisms."

This request was reflected explicitly in the Terms of Reference assigned to WGELECTRA, with ToR 2 being essentially a verbatim statement of the 5 components of the request. WGECO was also asked for information relative to the Dutch request, but since the conclusions and recommendations are summarized and incorporated in the WGELECTRA report, a review of only the WGELECTRA Report should be sufficient to evaluate the adequacy of the expert information available to ICES with regard to providing a response to the Government of the Netherlands.

The Special Request poses five subcomponents with regard the effects of pulse fishing on the North Sea - ecosystem: sustainability of exploitation of the target species when using pulse fishing gear; injuries and mortality to non-retained target and non-target species; mechanical damage of the seafloor; structure and function of the benthos; and the effects (assumed to be any of the four types of possible effects just listed) from repeated exposures to the gear.

General comments on Report and Request

The WGELECTRA report is clearly written, well structured, covers the relevant scientific literature from the region, including unpublished interim results in a few cases. The report does reference that a gear also using similar pulsed electric current was used in China a decade or so ago but does not include research results from that experience. The WG Report does note that the structure of the gear used in China was sufficiently different (much longer electrodes) that ecosystem consequences of that fisheries are very unlikely to be relevant to the fishery subject to the current request for advice. However, this conclusion also highlights that the conclusions drawn here are specific to the two commercial pulse fishing gears used in these studies, and gears with very similar operating parameters. If additional pulse gears with substantially different pulse features, electrode structure and configuration were considered for use, they may require additional testing. The differences with the largely anecdotal Chinese experiences also suggest that a description of the possibilities to change the electrical characteristics within the same gear would be useful to understand how general the conclusions of impacts will be for the future and what restrictions on the design that may be advisable. The review group did not have sufficient technical expertise to identify how different a pulse gear would have to be from those invested in the studies reviewed by WGELECTRA before additional testing would be necessary.

The Special request from the Dutch Government explicitly asks for advice on the effects of pulse fishing compared to the effects of fishing with traditional beam trawlers for the same stocks and fisheries. This is an important proviso, because the complete long terms effects on any fishing gear on any ecosystem are difficult or impossible to fully assess, particular for impacts of mobile bottom-contacting gears on benthic ecosystem structure and function. By making the request comparative, it becomes much more feasible to make statements about the performance of pulse fishing relative to fishing with traditional beam trawls, rather than comparisons of pulse fishing to a "natural system" which is always characterized by background variation on many scales. In that sense the report provides valuable information also on the effects of the conventional beam-trawl fishery on species, habitats and ecosystems.

Noting that the advice is specific to the pulse trawls used in the investigations, and some comparisons of gear impacts are relative to traditional beam trawls rather than absolute quantifications of impacts the WGELECTRA report is sufficient to allow ICES to respond to each of the five components of the Dutch request. In addition WGELECTRA also provides a useful review on i) changes in the beam trawl fishing fleet targeting sole during the introduction of the pulse trawl, ii) review of the effects of electrical stimulation and iii) disseminates findings from ongoing projects. The report notes, a few experiments gave different results, with some possible negative impacts in early studies not replicated in later, larger studies. A mechanistic framework built on fundamental knowledge about how electricity affects the physiology of the organisms would help interpret many of the research findings. This knowledge should assist the understanding of why species and size classes differ in their sensitivity, but has not been consolidated by the research community. Eventually this information should define the focus of future experiments and guide future regulations on the use of electricity in fishing.

i) sustainability of the gear for the target species:

The information is fully sufficient to inform a response on this point with regard to sole and plaice. The information on this point is of high quality and consistent across reports and sources. For sole catch rates per unit of effort are higher with pulse fishing than beam trawls whereas for plaice the opposite is true. The report shows that the amount of invertebrate bycatch caught by large pulse vessels was 62% less compared to large beam trawls, while no differences were noted when smaller pulse and beam trawls were compared, although the catch rates of individual taxonomic groups differs between the two gears (van Marlen et al., 2014).

WGELECTRA suggested that the differences among gears in invertebrate bycatch may be because the fishery of smaller pulse trawls take place in shallower water where starfish dominate. The spatial distribution of the pulse and beam trawl does differ (Figure 6.4.1), as pulse trawls can be towed in muddier substrates. However, as the effort by the two gears do largely overlap, it is difficult to comprehend these differences in the maps provided. In addition the expansion of the pulse fishery fleet to new areas may mean that some additional studies of invertebrate and fish discards in pulse fisheries are needed, to match the information available for the beam trawl fleet in the areas where both gears are used.

The expansion of the pulse fishery into new areas that were not fished previously by traditional beam trawls (shallow, muddy areas) does pose the potential for conflicts with completely different gears and fisheries, if any operate in those types of seafloor. However, no specific fisheries were mentioned as possible new sources of fleet interference or competition.

The overall sustainability of target fisheries is determined by compliance with the science-based TAC. Although the pulse fishing gear can produce higher CPUE for sole, as long as the fishery is limited by TAC and not effort, the pulse fishing gear does not make compliance harder, nor does it make jurisdictional monitoring of compliance any more difficult. The North Sea sole fishery has a total allowable catch, ITQs and a landing obligation, so exploitation rate is not expected to be governed by the efficiency of any gear.

ii) injury or mortality to non-retained catch:

The WG Report summarizes the results of several studies of this factor. Results of the studies are similar, and the report tabulates the results usefully. WGELECTRA convincingly argues that the mechanical damage of the pulse trawl is likely to be less than for the beam trawl, due to lower trawl speed and removal of the tickler chains. However, injuries other than mechanic damage are noted, and these vary both among species and among sizes of those species that may show injuries from exposure to pulse fishing gears. The species showing the greatest incidence of injury are cod, currently a high profile stock in the North Sea. It is noted that spinal fractures are largely constrained to intermediate sizes of cod. Due to the rapid drop in the field strength, only cod located in close distance (tens of centimetres) from the electrodes can be expected to suffer injury. With the landing retention requirement, these cod would be retained in any case, so the injuries would not be incremental to the takes by the fishery with other mobile net gears. Further studies could increase understanding of the relationship between the fractures and the body size and determine the differences in fractures across fish species especially for codfish. In addition some of the laboratory experiments performed show effects on eggs and larvae of fish, suggesting that additional studies on the effect of electric pulse on reproduction including gametogenesis, egg and larval stages, and metamorphosis might be informative, as would a wider selection of electrosensitive species to be tested in the future.

The report correctly acknowledged that not all species in the ecosystem have yet been assessed for impacts from the pulse fishing, but this is an extreme standard for any fishing gear. The selection of species to evaluate was reasonable, and included species of key concern, including cod, some other roundfish, and selected elasmobranchs. However, such studies have not been considered in field conditions for almost any fishery, so this will not be a serious limitation on this aspect of the advice.

iii) mechanical disturbance of the seabed:

For this aspect, the report summarizes the results of a number of laboratory and several field studies of the effects of the two gears. The studies are generally well designed, include both independent replication of key findings and address a range of environmental conditions. Overall, the penetration depth of the pulse trawl is roughly half of that of the beam trawl (on average 4 versus 1.8 cm respectively) in fine sand, although the shoe of the pulse trawl can actually create deep (~6 cm) furrows (Depestele *et al.*, 2016). The lesser penetration depth enables pulse trawlers to trawl in areas with finer sediments compared to the beam trawl. Although WGELECTRA and authors of the publications that the WG reviewed extrapolated (with appropriate cautions) that a 50% reduction in penetration depth of the gear could result in the 50% decrease in impact on benthic infauna. The 50% reduction is likely to be an optimistic upper bound on the degree of reduction in physical impact of the gear. Benthic infauna are not evenly distributed vertically in the substrate. Rather, density is highest near the surface of the seabed but declines with depth. Since both gears penetrate the surface, they are both penetrating the area with potentially highest infauna density with the areas only penetrated by the bean trawl having somewhat lower densities of benthos. However the density of infauna between 0.7 and 1.5 cm is still high enough that removing physical impacts of trawls from such areas can be expected to reduce the gear impact on benthic infauna.

In addition, the impact of trawling on a specific area of the seafloor is generally assumed to be greatest during the first trawling event and then diminish with repeated trawling (with substantial evidence to support this assumption in past ICES advice). Because pulse trawls are able to operate in a wider range of substrata/habitats than traditional beam trawls, it would be valuable to combine the evidence of reduced trawl penetration depth with possible effort displacement effects associated with the change in fishing practices. One of the more important concerns with introducing pulse-trawl may actually be the introduction of trawling in previously naturally untrawled areas of the sea to the extent that these changes have not already taken place.

The report notes that there are still some potential effects of the gear on the seabed that are not fully explored, but these are more second-order impacts, and for all the major factors usually addressed, the physical impacts of pulse fishing gears on the seabed are much lower than the physical effects of beam trawl gears in the same habitats.

iv) structure and function of the benthic ecosystem:

This is an open-ended aspects of the request for which no complete and definitive evidence-based response would be possible. The WGELECTRA report takes a largely indirect approach to this part of the request, but it is reasonable and well-explained. Several structural features of the benthic ecosystem that are possible to quantify, and even a couple indicators of functional processes, have been studied mostly in laboratory settings but to the extent feasible, also in the field. At the basic ecosystem function level pulse trawling has not been found to effect sediment oxygen consumption and profiles or surface chlorophyll levels.

Results that are summarized as generally consistent across studies, and all point to effects of both pulse fishing activities and traditional beam trawling as having effects on benthic structure and function. Although the medium term implications of these effects can only be incompletely known, in the very large majority of cases where evidence of impacts is available for both gears, the impacts of pulse fishing is less than the impact of beam trawling. The concerns that the 50% reduction in penetration of the pulse trawl gear compared to the traditional beam trawl gear is unlikely to translate fully to a 50% reduction in impact on benthos is highly relevant here. Moreover a few impacts of pulse fishing on specific benthic community members appear larger than those of beam trawling, at least in the short term. However, the types of benthic structural and functional properties likely to be impacted by larger or small amounts by pulse fishing relative to traditional beam trawls are characterized as well as possible in the report, and the remaining uncertainties are explained well. Until a set of rigorous trawl experiments that compare the effects of both pulse trawl and beam trawl on benthic invertebrates in the field simultaneously, are completed, the basis for advice on this aspect of the request can be strengthened further.

However, the information in the report, and particularly the comparative presentation of that information, means that ICES should be able to draft an up-to-date and useful response to this aspect of the request, highlighting that present knowledge is sufficient to infer that overall pulse trawling is likely to cause fewer and less detrimental impacts on the structure and function of benthic ecosystems than beam trawling for the same quota of sole, but not for the same quota of plaice.

v) effects of repeated exposure:

The report summarizes the results of several experimental studies of repeated exposures of both fish and invertebrates to simulated pulse fishing. The report was only able to find limited information on impact of repetitive exposure to the gears on the status of marine organisms, with very little data on sub-lethal and long-term effects of repeated exposures. The main focus chosen in the report is instead on establishing the percentage of the seafloor being exposed to repetitive exposure defined by the time interval between consecutive trawl events. Calculations indicate that 0.025 - 0.3% of the seabed may encounter a repetitive exposure with intervals of less than one week, dropping to 0.01- 0.15% for time intervals of one day. These calculations are used to argue that repeated exposure is a relatively minor problem, noting factors that could limit the generality of those estimates, and that also limit the ability to generalize laboratory results to field operations.

The experimental results showing no cumulative effects of repeated sub-lethal exposures of pulses are highly consistent and combined with the estimates of likelihood of repeated exposures given the data available on fishing behaviour of the fleet, provide a sound basis for ICES to prepare advice on this aspect of the special request, suggesting there is little evidence for concern about repeated exposures. The advice should have qualifications about the limited number of studies, and the intractability of sound field studies of this aspect of the effects of pulse trawls for all but highly sessile species. However the research included a reasonably selected range of species to study experimentally, and given the consistency of the results future experimental studies may rather be allocated towards new species and other life history stages than towards repeated exposure experiments for species having shown no response to a single exposure.

Other Comments and Conclusions

Overall, the WGELECTRA report is a clear and balanced summary of results from a fairly large body of experimental, and where feasible, field studies, comparing the impacts of pulse and traditional beam trawls. It is also clearly stated where results and conclusions are based on work still in progress, including ongoing research projects, where there are further experiments planned, and where there are knowledge gaps. The report should provide a sound basis for complete response to the Special Request from the Dutch Government. WGELECTRA has hence considered the questions posed and shown that new knowledge is under way to complement the picture concerning trawl effects. WGELECTRA should be commended for an excellent job.

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