Pulse fishing and its effects on the marine ecosystem and fisheries

An update of the scientific knowledge

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Abstract

This report summarises the knowledge on the effects of pulse trawls used in the North Sea fishery for flatfish and brown shrimp. The report describes the electrical characteristics of the pulse trawl systems currently used (potential difference over electrode pairs, pulse frequency, pulse width, duty cycle and dimensions of the gear). The shrimp pulse applies a low frequency pulse that invokes a startle response (tailflip) in shrimps. The sole pulse applies a higher frequency that invokes a cramp response that immobilise the fish species facilitating the catching process.

Electrical stimulation changes the species selectivity of the trawl. The catch efficiency of the pulse trawl for sole is higher, and the catch efficiency for plaice and other fish species is lower, when expressed in terms of the catch rate per swept area. It is uncertain whether the pulse trawl has a better size selectivity (reduced bycatch of undersized fish), but all experiments show that the bycatch of benthic invertebrates is substantially reduced. Applying electrical stimulation in the fishery for brown shrimp, offers a promising innovation to reduce the bycatch of fish and benthic invertebrates, while maintaining the catch rate of marketable sized shrimps. The reduction in bycatch depends on the design of the net, in particular the specifics of the groundrope. In ecological terms, the replacement of the tickler chains with electrodes and a lower trawl footprint constitute a highly positive contribution to diminishing the impact of trawling on the North Sea benthic ecosystem.

A number of laboratory experiments have been carried out in which a selection of fish species and invertebrate species have been exposed to electrical stimuli to study possible adverse effects. The maximum pulse treatment applied exceeded the strength of the pulse used by the fishery. Electrical stimulation did not cause direct mortality during exposure. Exposure to the sole pulse stimuli invoked vertebral fractures and associated haemorrhages in roundfish species (cod), but not in flatfish species (sole, plaice, dab) or seabass. Shrimp pulse exposure did not invoke fractures in roundfish or flatfish species. The results suggest that fractures are restricted to the larger size classes of cod that are retained in the net, whereas smaller cod that can escape through the 80mm meshes did not develop fractures even when exposed to high field strength. The fracture incidence in cod increases with field strength and decreases with pulse frequency. Fracture incidence varied between experiments.

Samples of cod and whiting taken on board of commercial pulse trawlers fishing for sole showed vertebral fractures and associated haemorrhages similar to those observed in the laboratory experiments and suggest incidence rates of around 10% and 2% in cod and whiting, respectively. Further studies are required to study the relationship between the fractures and the body size and determine the differences in fractures across fish species.

Histological examination of fish exposed to pulse stimuli in laboratory experiments, did not reveal other abnormalities in species examined, except for a small haemorrhage in 2 of the 25 exposed plaice, and a significant increase in melanomacrophage centres in the spleen of cod exposed to the shrimp pulse. No adverse effect could be detected on the electro-sense organ used in food detection behaviour of small-spotted catshark. In an experiment exposing brown shrimp and ragworms to a sole pulse showed no consistent adverse effects, but shrimps that were exposed 20 times during a 4 day period to a sole pulse showed an increased mortality.

No studies have been done on the effect of pulse stimulation on the functioning of the benthic ecosystem. Although the laboratory experiments suggest that fish and invertebrates resume their normal behaviour after exposure, no information is available on for instance the threshold levels at which the functioning of species is being adversely affected. Also little is known on the effects of electrical stimulation on the development of eggs and larvae. One experiment exposing early life stages of cod (egg, larvae, early juveniles) to a pulse stimulus exceeding the pulse used in the fisheries did not find an increase in developmental abnormalities in exposed animals, but observed a reduced hatching rate and an increased mortality in 2 out of the 8 experiments. No adverse effects were observed in sole eggs and larvae.

For the consistent interpretation of the experimental results, a mechanistic framework is required which is built on fundamental knowledge about how electricity affects the physiology of the organism. Such a framework should provide an explanation why for instance species and size classes differ in

their sensitivity for developing vertebral fractures, and should explain how electrical stimulation affects the species- and size-selectivity of the pulse trawl. In 2016, a 4-year research programme commissioned by the Dutch ministry of Economic Affairs has started with the aim to develop such a framework and provide the scientific basis to assess the long term impact of the commercial application of pulse trawls in the North Sea. This project will also tackle the knowledge gaps concerning the effects of electrical stimulation on the functioning of the benthic ecosystem.

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 invoke 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 shrimps 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.

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. The report incorporates the available peer reviewed publications and grey literature summarised by Quirijns et al (2015). This report describes the electrical characteristics of the flatfish and brown shrimp pulse system, reviews the effects of pulse stimulation on marine organisms, reviews the effect on the marine ecosystem, reviews the catch efficiency and selectivity of the gear and finally discusses the management implications.

2 Pulse systems used in the Netherlands

Three different pulse gears are being used in the Dutch fishery. The flatfish fishery either use the pulse trawl produced by HFK engineering (79%) or Delmeco BV (15%) (Figure 1). The shrimp fishery uses the pulse trawl developed by Marelec (6%) for shrimp pulse gear (Turenhout et al., 2016). Under the temporary derogation a total of 84 licenses were given: 27 to cutters <=300 hp (flatfish and/or shrimps) and 57 to cutters >300 hp of which six were not used in 2015. Seventy-four cutters use the pulse technique to catch flatfish and four cutters use the pulse technique to catch common shrimp.

Figure 1. Photo of a traditional tickler chain beam trawl (top left), HFK pulse wing (top centre), Delmeco pulse trawl (top right). From Quirijns et al (2015).

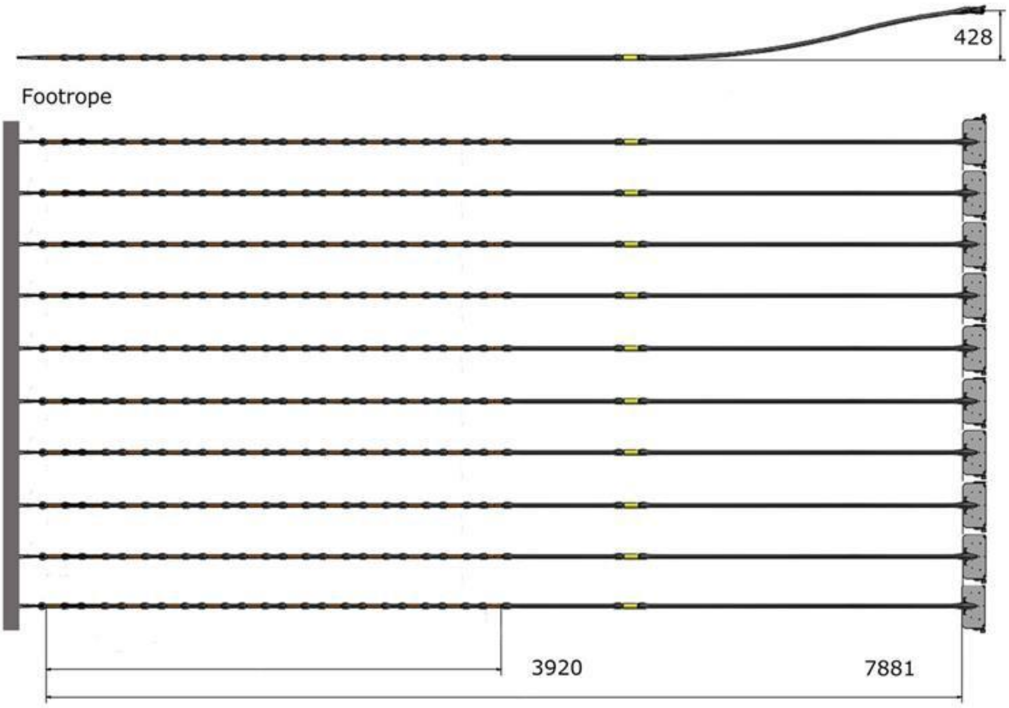


Figure 2. Array of electrodes of a 4m pulse wing of an Euro cutter. From: de Haan et al. (2016).

2.1 Electrical characteristics

The main characters of the three pulse systems is summarised in Table 1. The electrical pulses are characterised by the maximum voltage, frequency, pulse width and pulse shape. The product of the pulse weight and the 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 marginally in their electrical characteristics and in the number and the design of the electrodes.

Table 1 1. Characteristics of the tow flatfish pulse systems and the shrimp pulse system

	Flatfish pulse (Euro cutter)		**Flatfish pulse (Large vessels)**		**Shrimp pulse**
	Delmeco	**HFK**	**Delmeco**	**HFK**	**Maralec**
Width of the trawl (m)	4.5	4.5	12	12	9
Towing speed (knots)	~5	~5	~5	~5	2.5-3.5
Length of electrodes (m)	Max 4.75	Max 4.75	Max 4.75	Max 4.75	2.5-3
Length of conductor elements (cm)	18	12	18	12.5	150
Number of conductor elements	6-12	6-12	6-12	6-12	-
Diameter of conductor elements (mm)	28	28	28	28	12
Distance between electrodes (cm)	42	42.5	42	42.5	60-70
Voltage between conductors (Vpeak)	50	50	50	50	65
Pulse frequency (Hz)	38-42	40-80	38-42	40-80	5
Pulse width (μs)	210-230	100-270	210-230	100-270	500
Duty cycle (%time)	2.5	2.5	2.5	2.5	0.03

All pulse systems use wired electrodes. The sole pulse electrodes comprise of alternating conductor and isolator elements (Figure 2). The heterogeneous electrical field that is generated shows highest field strength close to the conductor. The field strength decreases at increasing distance from the conductor in the horizontal and vertical plane (Figure 3) (de Haan et al., 2016). 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

The physical boundaries of the sole pulse 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 latest version 1.3 is the final result of coordinated meetings chaired by NVWA (The Netherlands Food and Consumer Product Safety Authority), pulse gear manufacturers and fishing industry. Wageningen Marine Research was involved during earlier meetings and performed an advisory role.

For flatfish gears the main derogations are:

- A maximum power consumption of 1 kW per meter beam length;
- A pulse amplitude of 60 V $_{0\text{ to peak}}$ 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

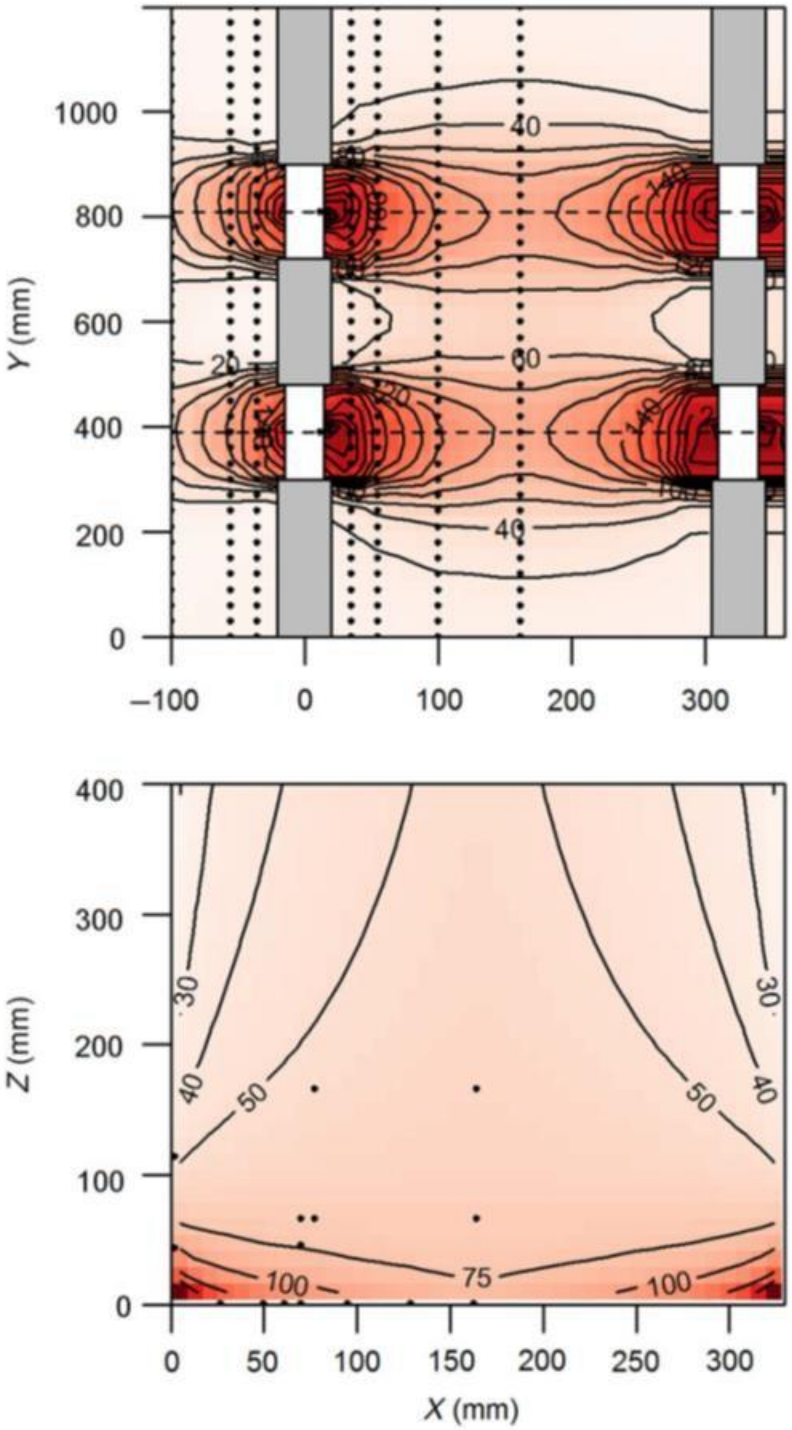


Figure 3. Contour plot of peak field strength (V/m) around a pair of Delmeco electrodes positioned at X=0 mm and X = 325 mm. The field strength is shown in the horizontal plane (a) and the vertical plane (b). Locations of measurements are indicated by black dots. White parts show the conductor elements. The grey parts show the isolator elements. From de Haan et al (2016).

3 Pulse trawl selectivity and catch efficiency

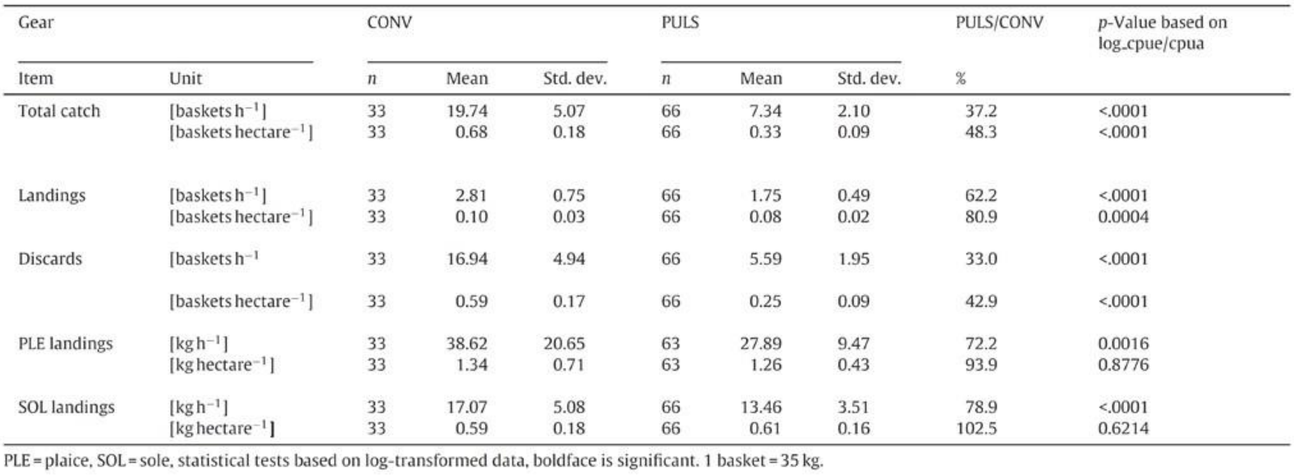
3.1 Flatfish pulse

During the developmental phase of the pulse trawl between 1998 - 2011, a series of catch comparison experiments between a 7 m and 12 m prototype ‘pulse’ trawls and a conventional beam trawl were conducted on board of research vessel Tridens (summary in Quirijns et al., 2015). The results showed that the pulse trawl catch rate of sole matched those of conventional tickler chain beam trawls, while the catch rate of plaice was generally reduced and the bycatch of benthic invertebrates was substantially reduced.

These results are in line with the expectations based on the response of the target species to the electrical stimulus. The flatfish pulse invokes a cramp response which immobilise the fish and prevent the fish to escape from the approaching gear. The contraction of the body muscles during exposure raises the head and the tail of the flatfish by which it comes lose from the seafloor. This is particularly pronounced in sole, which bends its body in a U-shape where the tail and nose are almost touching one another (van Stralen, 2005). The U-shape of a cramped sole makes it easier to catch in a bottom trawl. This effect is less pronounced in other flatfish which show a much shallower U-shape.

In 2011, after the successful implementation of the pulse trawl technique in the Dutch flatfish fishery, the selectivity and catch efficiency was compared between a HFK-pulse, a Delmeco-pulse and a conventional vessel using a tickler chain beam trawl. The data have been reanalysed and published in the scientific literature substituting earlier reports (van Marlen et al., 2014). The catch rate per hour fishing in the pulse trawl was reduced by 21% and 28% for marketable sized sole and plaice, respectively (Table 2). The lower catch rate was mainly due to the lower towing speed, and hence the smaller surface area covered per hour fishing. For discarded bycatch, the catch rate of the pulse trawl was reduced by 67%. The size selectivity for the two main target species sole and plaice suggests that the pulse trawl is more selective in catching marketable sized flatfish (Figure 4).

Table 2. Catch rate per fishing hour and catch rate per area swept for different components of the catch of a conventional tickler chain beam trawl (CONV) and in a pulse trawl (PULS). From van Marlen et al. (2014)



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

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

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.

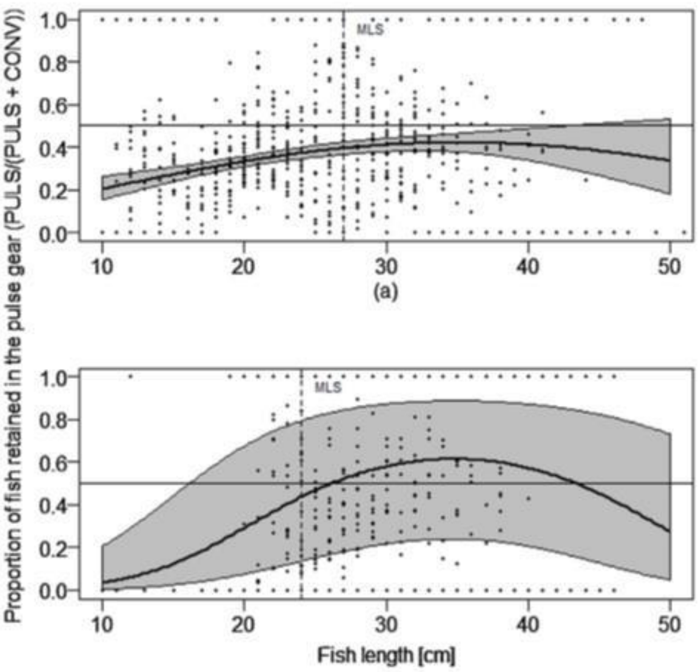


Figure 4. Size selection of the pulse trawl relative to the conventional tickler chain beam trawl for plaice (a) and sole (b). The heavy line shows the proportion of fish retained caught per hour fishing in pulse gear vs. length The value of 0.5 means both gears catch equal numbers (> 0.5 means pulse 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 2016, a mesh selection experiment was conducted studying the effect of pulse stimulation on the probability of sole and plaice to escape through the meshes. The study was carried out in the context of the FP7-BENTHIS project on board of the sumwing pulse vessel TX43. The vessel was fishing with her normal gear and a small-meshed cover to collect the fish that had escaped through the cod-end mesh. During the experiment the electrical stimulation of the starboard and port-side net was alternately switched on and off. The preliminary analysis indicated that the electrical stimulation had a small but significant effect on the slope of the selection ogive. Plaice and sole had a higher chance to escape through a cod-end mesh after being exposed to an electrical stimulus than when caught without electrical stimulation (3rd Periodic Activity and Management Report BENTHIS).

3.2 Shrimp pulse

The low frequency shrimp pulse invokes a tail flip response by which shrimp jumps up from the seafloor. The tail flip response is dependent on the field strength and the size of the shrimp. Exposure to a field strength of 4 V/m is already sufficient to invoke a response in large (> 6 cm) shrimps, whereas small shrimps (3 cm) require a field strength of 6 V/m. These values refer to shrimps that have a perpendicular orientation to the electrodes. For shrimps with a parallel orientation, the critical field strength to invoke a tail flip response are higher, e.g. 18 and 24 V/m, respectively (Verschueren et al, 2014).

The catch efficiency of a pulse shrimp trawl was compared with a conventional shrimp beam trawl during four trips on board of a commercial shrimp trawler fishing in the Wadden Sea (Verschueren et al, 2014). The pulse trawl caught more market sized shrimp in summer (June: +16%; September: +9.4%), whereas in October and December, no significant difference was observed. In three of the trips, the bycatch of undersized shrimps was 19% to 33% lower. The bycatch of fish and benthos in the pulse trawl was reduced by 50% to 76%.

3.3 Conclusion

The available evidence shows that the sole pulse has a higher catch efficiency for sole and the lower catch efficiency for plaice and other fish species when expressed in terms of the catch rate per swept area. 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, 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.

For the beam trawl fishery for brown shrimp, electrical stimulation offers a promising innovation to reduce the bycatch of fish and benthic invertebrates other than shrimps, while maintaining the catch rate of marketable sized shrimps. The reduction in bycatch depends on the design of the net, in particular the specifics of the groundrope.

4 Effects on marine organisms

Various adverse effects of electrical stimulation on fish have been reported. Electro-fishing in freshwater has been well studied and there is ample evidence for vertebral fractures and associated haemorrhages (review in Soetaert et al., 2015). Electrofishing in the marine environment is less well studied. Laboratory experiments related to the sole pulse have been reviewed by Quirijns et al (2015). Table 3 presents an updated overview of the relevant studies. Below we will summarise and synthesize the available information and distinguish between the effects on the physiology, behaviour, egg and larval stages, fractures in fish, invertebrates and ecosystem.

4.1 Physiology

The effect of electricity will primarily be related to the activation of nerve cells and muscles (Soetaert et al., 2015). Muscles contract if the stimulus exceeds a threshold value. Muscle contractions may also be due to the activation of nerve cells responding to an electrical stimulation. The effect of electricity is dependent on the conductivity and isolating properties of the body relative to the conductivity of the water.

4.2 Behaviour

The effect of electrical stimulation on the behaviour will depend on the strength and characteristics of the stimulus (such as frequency, pulse shape) as well as the duration of the exposure. A fish may respond to an electrical stimulus of increasing strength by showing a flight response (startle), a cramp response, and epileptic seizures. The strength of the stimulus depends on the orientation and size of the fish in the electrical field.

Sole exposed to a 5Hz pulse showed a flight response and muscle contractions similar to the normal fin fluttering. Pulse frequencies of 40 Hz or higher invoked a cramp response during which the fish bended in a U-shape. After exposure, all soles showed normal behaviour (Soetaert et al., 2016).

Cod showed a flight response to pulse frequency of 5 Hz. A cramp response was induced in cod exposed to pulse frequencies of 40Hz or higher (Soetaert et al. 2016) and in cod exposed to a field strength of 37 V/m and higher (de Haan et al., 2016). High field strength invoked an epileptic response. Within 10 minutes after exposure, most of the fish were breathing normally but showed little swimming activity and weak reactivity to tactile stimuli. All fish survived and showed normal behaviour 24 h post exposure (Soetaert et al., 2016). Cod resumed feeding after exposure although their appetite was related to the field strength. Cod exposed to a field strength that invoked vertebral fractures (82 V/m) were passive and did not resume feeding (de Haan et al., 2016).

Seabass showed a cramp response when exposed to a pulsed bipolar current of 80 Hz, pulse width of 250 μs, duty cycle of 2% and exposure duration of 2 s of wire-shaped electrode. Directly after exposure, the fish showed a strong flight response swimming away from the point of exposure. When removed to their housing tank, all fish resumed normal swimming behaviour. During the 2 week observation period after exposure, all fish showed normal feeding behaviour.

Catsharks, also known as the lesser spotted dogfish. Elasmobranchs possess electro-sense organs to detect food, which may make them particularly sensitive for pulse fishing. Two experiments have been conducted with the small-spotted catshark, *Scyliorhinus canicula* as model organism.

In the 1st study, de Haan et al. (2009) exposed three groups of 16 fish to a series of 4 pulse bursts at maximum amplitude at three different distances from a conductor pair, in a set-up similar to the experiments of de Haan et al. (2016), while a fourth group was used as a control. Fish in all tested groups started feeding normally directly after the exposures. Fish were kept in husbandry for 9 months after the exposure and produced eggs in numbers varying between 5-39 per group. Surprisingly the control group did not produce eggs.

In the 2^{nd} study, Desender et al (2017) studied the role of pulsed direct current (PDC) used in pulse trawls on the electro-detection ability. The electro-response of the sharks to an artificially created prey-simulating electrical field was tested before and after exposure to the pulsed electrical field 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 electro-response 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 bio-electrical field of a prey following exposure to PDC used in pulse trawls.

Brown shrimps responded with tail flips when exposed to a pulse stimulus of 5 Hz. When exposed to a frequency of 60 Hz or 200 Hz, a cramp response was observed that made them jump 0.1 – 0.15 m out of the sediment. This cramp persisted during the entire exposure. Within 0.25 s after the exposure, all shrimp showed tail flip escape behaviour. During the week after exposure, the exposed shrimps showed active food searching behaviour and ate all food provided (Soetaert et al. (2014).

Ragworms. During and immediately after exposure, ragworms showed squirming behaviour irrespective of the pulse frequency. The intensity of the squirming behaviour increased with duty cycle and field strength. No cramp response was observed. Control animals showed minor squirming in response to mechanical stimulation (Soetaert et al., 2014).

4.3 Egg and larval stages

There is one study that investigated whether pulse stimuli may affect the egg and larval stages of fish (Desender et al., in prep). Preliminary results presented in WGELECTRA showed no detectable effects in 6 out of 8 experiments with egg, larval and juvenile stages of cod. In one of the three egg stages exposed a reduced hatching rate was observed and in one larval stage of the four larval stages exposed a reduced survival was observed. In an experiment in which sole eggs and larvae were exposed no adverse effects could be detected. No increase in developmental deformities were recorded in both cod and sole.

4.4 Fractures in fish

4.4.1 Field observations

There is compelling evidence that roundfish, such as cod and whiting, caught in a flatfish pulse trawl may develop injuries related to the cramp invoked by the pulse stimulus. 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.

4.4.2 Laboratory experiments

Vertebral injuries were studied in laboratory experiments in cod, sea bass and dab exposed to commercial pulse stimuli.

Cod. de Haan et al (2016) reported on experiments conducted over a number of years with aquaculture cod. None of the cod of a size class that can escape through the 80 mm meshes of the sole fishery, that were exposed to the highest field strength close to the conductor did develop fractures, whereas almost 70% of the marketable sized cod exposed to the highest field strength close to the conductor developed a fracture in the spine, haemal and/or neural arches. Vertebral fractures were associated with a haemorrhage and a discoloration of the body. The probability to develop a fracture (or haemorrhage) increased with field strength and decreases with frequency. In the marketable sized cod, the fracture probability decreased with body size in marketable sized cod. In another experiments with cod with similar pulse settings and similar location of the cod next to the conductor, much fewer fractures were observed, suggesting that body condition may influence the sensitivity for injuries (Soetaert et al., 2016a). Cod exposed to a homogeneous electric field with a range of pulse settings, including those of the commercial fisheries, did not show any abnormalities when examined histologically, except for 1 cod showing a spinal fracture (Soetaert et al., 2015). Cod exposed to a shrimp pulse did not develop fractures (Desender et al., 2016).

Seabass. None of the small and large seabass exposed to a sole pulse stimulus developed a vertebral fracture or any other lesion and survived the 14 days after exposure, although the number of fish tested (31 tested, 13 control) was relatively small (Soetaert, 2015).

Sole. None of the sole exposed to a homogeneous electric field with a range of pulse settings, including those of the commercial fisheries, died and histological examination did not show any abnormalities (Soetaert et al., 2016; Desender et al., 2016).

Dab. In an experiment in which 100 wild caught dab were exposed to commercial pulse stimuli, no fractures or haemorrhages were observed (de Haan et al., 2015).

Bull-rout and armed bullhead exposed to a shrimp pulse did not develop fractures (Desender et al., 2016).

4.4.3 Conclusion vertebral fractures

The available evidence shows that electrical stimulation by the flatfish pulse settings may lead to fractures and haemorrhages in fish. No fractures 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 insensitive and do not develop 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 of 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 80mm meshes of the cod-end, 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. Because the occurrence of vertebral fractures is restricted to the cod that are retained in the net, it will not result in additional mortality affecting the population.

4.5 Other lesions in fish

In response to reports on an increase in the incidence rate of ulcers in dab off the Belgium coast coinciding with the start of the pulse trawling, a laboratory experiment was conducted in which 100 wild caught dab were exposed close to the conductor generating a commercial pulse trawl stimulus and 50 dab were used as control. The fish were kept for 2 weeks in the lab and euthanized for post-mortem analysis. After exposure, all fish showed normal behaviour and resumed feeding. One dab died on day 13 without any visible injury and likely unrelated to the pulse stimulus. No difference in the incidence rate of lesions of the exposed dab with the control fish was observed (de Haan et al., 2015).

Desender et al (2016) exposed plaice, sole, cod, bull-rout, armed bullhead to a shrimp pulse. Histological examination revealed a small haemorrhage in 2 of the 25 exposed plaice, and a significant increase in melanomacrophage centres in the spleen of cod exposed.

4.6 Effects on benthic invertebrates

Smaal and Brummelhuis (2005) exposed a variety of benthic invertebrates to a Delmeco sole pulse for 10s. Some species showed a response to the electrical stimulus by closing their shells (bivalves), withdrawing themselves in their shell (whelk, hermit crab) or showing a tail flip response (decapod shrimps), while other species (polychaetes, Echinodermata) did not show a visible response. The experiments did not suggest that electrical stimulation affected the filtration rate of bivalves or the mortality as compared to the control group. Because the company providing the pulse generator did not disclose the details of the pulse characteristics, the results are only indicative for the possible effects.

To detect the safe range of pulse parameters, Soetaert et al. (2014) exposed brown shrimps and ragworms to a homogeneous electric field for up to 5 s and studied their behaviour, 14-d mortality rate, gross and histology. Pulse setting included the commercially applied frequency and field strengths. No adverse effects were detected except for an increase in a virus infection (IBV) in the hepatopancreas in shrimps exposed to the maximum field strength (200 V/m). In a follow up experiment studying the effects of repetitive exposure in shrimps, however, this result could not be corroborated. In this experiment, brown shrimps were exposed 20 times during 4 days to either the sole pulse or the shrimp pulse. The survival, egg loss, moulting and the degree of IBV infection was compared shrimps exposed to electrical pulses, shrimps exposed to mechanical disturbance mimicking the conventional shrimp trawling and a control group. The sole pulse treatment gave a significant lower 14-day survival as compared to the control group, while moulting was reduced by mechanical disturbance.

Table 3. 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. V_{peak} refers to the potential difference over the pair of electrodes.

Species	Results	Pulse stimulus	Field strength (V/m)	Frequen-cy (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	Sole pulse	60-120 (Vpeak)	40-80	1-2	Soetaert et al (2016)

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[1] This publication includes earlier IMARES reports

Species	Results	Pulse stimulus	Field strength (V/m)	Frequen-cy (Hz)	Duration (sec)	Source
	in spinal fractures in 0-5% of the cod.					Marine Coastal Fisheries
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 (2016) 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 (2016) 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 C171/14.
Catshark N=23	No effect on the success rate of prey detection was observed after exposure to the pulse stimulus in catsharks trained to locate artificial prey buried in the sea bed with their electro-sense organs.	Sole pulse & Shrimp pulse	60 V (V_{peak})	5, 80	5	Desender et al (2017)
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	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)	Frequen-cy (Hz)	Duration (sec)	Source
	during 9 month post exposure.					
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	60 V_{peak}	5	5	Desender et al (2016) Fish Res
Cod 3 egg stages 4 larval stages 1 juvenile stage	Hatching rate reduced in 1/3 egg stage. Mortality increased in 1/4 larval stages No development deformities	homogeneous field	150		5	Desender in ICES (2016)
Sole 1 egg stage 1 larvael stage	No adverse effects or deformities recorded	homogeneous field	150		5	Desender in ICES (2016)
Helmet crab, Swimming crab	Freeze upon stimulation	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 2004.	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)	Frequency (Hz)	Duration (sec)	Source
	movements. When mechanically stimulated directly after exposure the animal moves normal.					Smaal and Brummelhuis (2005) RIVO Report: C089b/05
Hermit crab	Freeze or withdraw in shell upon stimulation.					
Echinodermata: Common sea star, Echinocardium, 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; homogeneous 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 injuries					
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 (2016) Marine Coastal Fisheries

5 Effects on the marine ecosystem

Bottom trawls impact the structure and functioning of the benthic ecosystem (Jennings and Kaiser, 1998). The impact is related to the mechanical effects of the gear components that either sweep or penetrate into the seafloor (Eigaard et al. 2016). Bottom trawls may homogenise the texture of the seafloor, disturb the sorting of the sediments and bring sediment into resuspension in the wake of the gear (O'Neill et al., 2016). Mechanical disturbance will also kill benthic invertebrates and may destroy biogenic structures (Kaiser et al., 2006). In addition to the mechanical impact, electrical stimuli may affect the ecological functioning of the benthos and may influence chemistry of the seabed.

5.1 Mechanical disturbance

Available evidence indicate that the mechanical disturbance of the seafloor by a pulse trawl is less than the disturbance by the tickler chains of a conventional beam trawl. In the FP7-BENTHIS project the sediment disturbance by a 4m Delmeco pulse trawl was compared to a conventional tickler chain beam trawl (Depestele et al., 2016). Results indicate that sediment disturbance of the pulse trawl is less than the conventional tickler chain beam trawl. No difference in the resuspension of sediments could be detected. A numerical model predicted that the tickler-chain trawl penetrates the seabed more deeply than the pulse gear.

The mechanical disturbance of benthos by a bottom trawl is determined by the weight of the gear components and the towing speed at which it collides with the benthos (Eigaard et al., 2016; Rijnsdorp et al., 2016). As a pulse trawl is lighter and is towed at a lower speed than a conventional tickler chain beam trawl, we expect that the energy at which it collides with benthos will be lower. This expectation was supported by the field study carried out in the REDUCE project (FAIR-CT97-3809, "Reduction of environmental impact of demersal trawls") which suggested that the mortality imposed by a pulse trawl was less than the mortality imposed by a tickler chain beam trawl (van Marlen et al., 2001). Preliminary results of FP7-BENTHIS could not detect a difference in mortality due to the large variability in benthic samples (Teal et al., 2014).

5.2 Effects of electricity

It is hypothesised that the electrical field may affect chemical reactions which might release pollutants that are bound to sediment particles (Soetaert et al., 2015). To our knowledge, no studies have addressed this question.

It is unknown how chronic sub-lethal exposure will affect the functioning of the benthic invertebrates. Although the few experiments with benthic invertebrates seems to suggest that the exposed organisms resumed their normal behaviour soon after the pulse treatment, further studies are required.

6 Discussion

6.1 Direct mortality imposed by electrical stimulation

None of the experimental studies conducted showed that animals 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 fisheries anyhow. 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.

6.2 Sub-lethal 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.

6.3 Selectivity and catch efficiency

The empirical evidence clearly shows that the pulse trawl has a higher selectivity to catch sole as compared to the conventional tickler chain beam trawl. All comparative fishing experiments have shown a higher catch efficiency for sole than for plaice or other demersal species.

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).

The available data are also inconclusive whether pulse trawls may have a better size selectivity, e.g. catching fewer undersized fish. The promising results reported by van Marlen et al (2014) were not corroborated in a later study. 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.

A better understanding of the response of fish to electrical stimuli and the characteristic of the pulses used, could potentially guide us to improve the pulse stimuli to increase the length threshold for the cramp response.

6.4 Redistribution of 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.

6.5 Synthesis

In order to assess the ecological consequences of the use of pulse trawls in the sole fishery, the consequences should be assessed against the consequences of using the conventional tickler chain beam trawl.

6.5.1 Pulse trawl effects on the fish community

The available evidence indicates that roundfish species are sensitive for vertebral fractures due to the cramp response invoked by the sole pulse trawl, whereas flatfish species are insensitive. The experiments further suggest that the sensitivity may show a dome-shaped relationship with body size. It is unlikely that a similar effect will be caused by the shrimp trawl as the typical frequency of 5 Hz is below the critical threshold for the cramp response. A mechanistic understanding, that explains the differences in sensitivity between species and body size to the pulse stimuli applied, is required to quantitatively assess the consequences on the fish community level.

This mechanistic understanding may also help to interpret the contradictory information about the size-selectivity of the pulse trawls. To evaluate the consequences of the transition from the tickler chain beam trawl to the pulse trawl on the bycatch of undersized flatfish, we not only need information about the size-selectivity and species-selectivity, but we also need to understand why fishers change their fishing grounds.

An area of concern is the potential effect of pulse stimulation on the Elasmobranchs. The tank experiment with catsharks indicated that pulse stimulation did not impair their electro-sense organ to detect prey that is buried in the seabed. The observed shift in fishing effort distribution towards the western part of the southern North Sea, the area where the abundance of skates and rays is relatively high, has likely increased the bycatch. Information on differences in survival rate of skates and rays caught in the conventional beam trawl fishery and the pulse trawl fishery is needed.

The effect of pulse stimuli on eggs and larvae will be restricted to those species with demersal eggs and larvae. In the southern North Sea, only a few fish species produce demersal eggs, such as herring and some estuarine species. The contact rate of pulse trawls with the eggs and larvae of most fish species, which are dispersed in the water column, will be negligible. For the species that lay demersal eggs, the population consequences of possible adverse effects of pulse stimuli will likely be negligible because of the extreme high mortality rate of eggs and larvae.

6.5.2 Pulse trawl effects on the benthos

The impact of a bottom trawl on the benthos depends on the footprint of the gear used and the sensitivity of the benthic community. The great unknown in the assessment of the impact of pulse trawls is the lack of knowledge how the pulse stimulus affects the functioning of benthic organisms. The mechanical effects are probably lower because of the reduced mechanical disturbance. The replacement of tickler chains running across the net opening by electrodes running in longitudinal direction, has halved 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 constitute a highly positive contribution to diminishing 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 ultimate change in impact on the seafloor.

6.5.3 Future research

In order to assess the ecological consequences of a transition from the conventional beam trawl fleet exploiting North Sea sole with tickler chain trawls or chain mat trawls to a fleet using pulse trawls, we need to develop a predictive framework that can mechanistically explain the effects of electrical stimulation on marine organisms and their ecological functioning, which can be validated against empirical observations. Combined with information on the differences in distribution of the pulse fleet and the conventional beam trawl fleet, the consequences can be assessed on the scale of the ecosystem and of the North Sea. The 4-year research project on the pulse trawl impact assessment project commissioned by the Dutch ministry of Economic Affairs is designed to provide the scientific basis[2]. A summary of the project is given in Appendix 1.

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[2] https://pulsefishing.eu/sites/pulsefishing.eu/files/Pulse%20Trawl%20Impact%20Assessment%202016-2019.pdf

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Justification

Report number: C117/16
Project Number: 4318100036

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Pieke Molenaar
Researcher

Signature:

Date: 6 December 2016

Approved: drs. J. Asjes
Manager Integrations

Signature:

Date: 6 December 2016

Appendix: Impact assessment of the pulse trawl fishery (2016-2019)

Objective. The overall aim of this project is to assess the long term impact of the commercial application of pulse trawls in the North Sea flatfish fishery. In order to fulfil the overall aim, predictive models of the effect of electric pulses on organisms and on different ecosystem components will be developed and applied. The results will be integrated to assess the consequences of a transition in the flatfish fishery from using tickler chain beam trawls to pulse trawls on the bycatch of undersized fish (discards) and the adverse impact on the North Sea ecosystem.

The research project comprises of four inter-related work packages and use a variety of complementary approaches (Figure A1). In addition to these four work packages dedicated to the research, a fifth work package dedicated to project coordination and management will be included.

WP 1: Marine organisms.

WP 2: Benthic ecosystem.

WP 3: Sea bed (scaling up to the North Sea level).

WP 4: Impact assessment (synthesis).

The individual work packages are described in section 2 of this tender document. Here we give a summary of each WP and describe how the WPs are inter-related.

WP1 will carry out *laboratory experiments* and develop *predictive models*. Models will be developed of (i) the electrical fields generated by pulse trawls under different environmental conditions and (ii) the electrical fields inside marine organisms. Laboratory experiments will be conducted on the effect of electrical pulses on the behaviour and mortality of a selection of marine organisms. To cope with the diversity in species that will be exposed to pulse trawl fishing in the North Sea, species will be classified according to their building plan that determines their sensitivity to electrical stimulus. Fish samples of the various groups will be collected on board of pulse trawlers and analysed for injuries. Collected data will be compared to modelling results to optimize and fine-tune the boundary conditions and to estimate confidence intervals for model simulations.

WP2 will carry out *field and laboratory experiments* on the effect of electric pulses on the functioning of benthic ecosystems, and develop *predictive models* how ecosystem functioning is affected by pulse trawling. Field samples of the sea bed will be taken from stations before and after pulse trawling. The species composition and functional characteristics will be determined, and the samples will be exposed to electrical stimulation or mechanical disturbance to measure the effect on geochemical fluxes.

WP3 will develop the tools to integrate the results of WP1 and WP2 in a *spatialy explicit predictive model* of the distribution of fishing activities of pulse trawl fishers and its consequences for the catch, bycatch, and species that are not retained but come into contact with the electric field as well as the impact on the benthic ecosystem.

In WP4 the results obtained in WP1 – WP3 will be synthesised in an Impact Assessment that will quantify the consequences of a transition of the flatfish fleet from tickler chain beam trawls to pulse trawls. Consequences will be assessed in terms of the bycatch and the impact on the benthic ecosystem (fish and bentic invertebrates). In order to be able to respond to the topics raised in the stakeholder interactions the integration will be organised in a flexible manner.

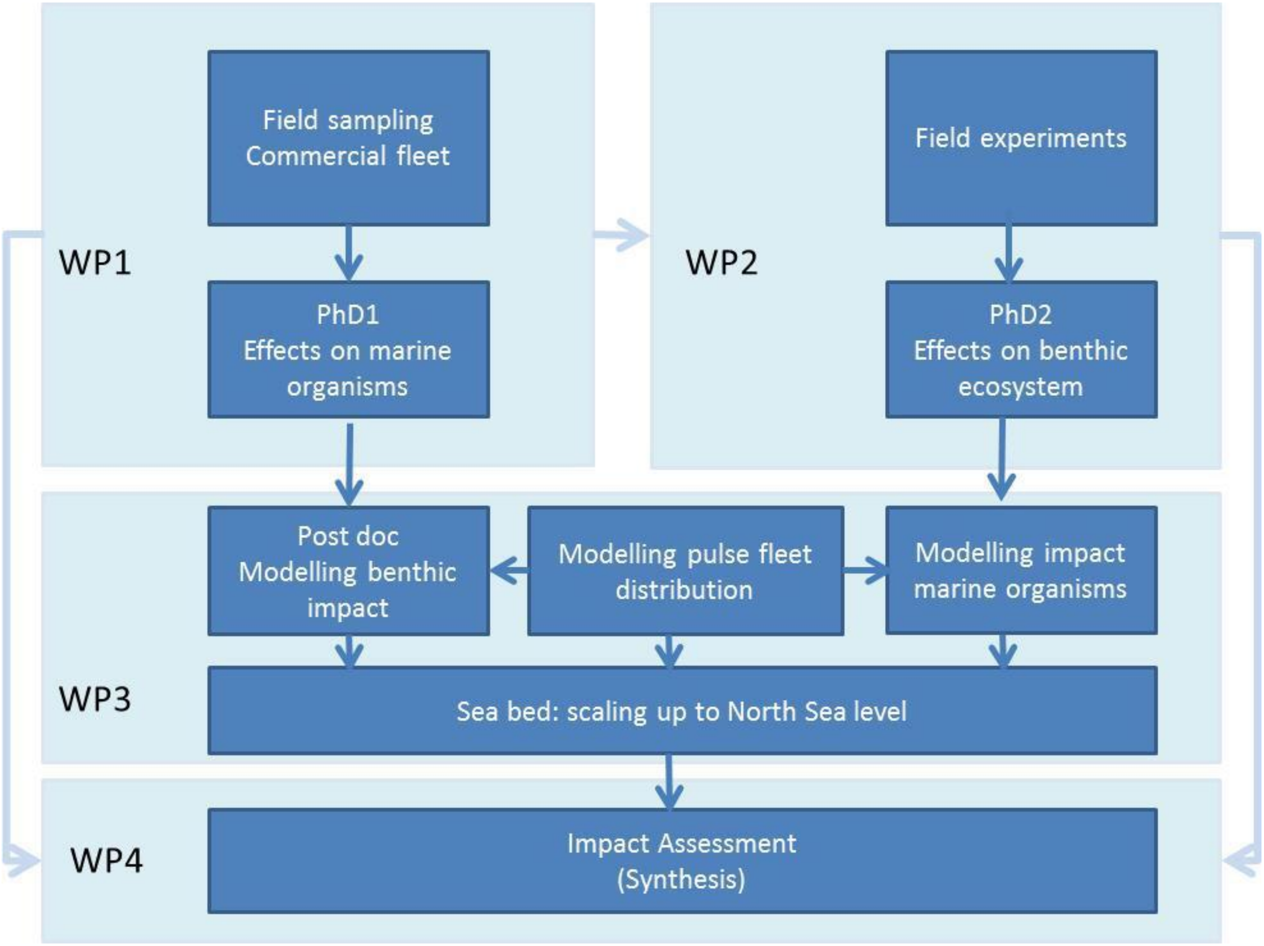

Figure A1. Diagram of the 4-year research programme commissioned by the Dutch ministry of Economic Affairs to provide the scientific basis for an assessment of the long term impact of the commercial application of pulse trawls in the North Sea flatfish fishery.

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Wageningen Marine Research is the Netherlands research institute established to provide the scientific support that is essential for developing policies and innovation in respect of the marine environment, fishery activities, aquaculture and the maritime sector.

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is specialised in the domain of healthy food and living environment.

The Wageningen Marine Research vision
'To explore the potential of marine nature to improve the quality of life'

The Wageningen Marine Research mission
- To conduct research with the aim of acquiring knowledge and offering advice on the sustainable management and use of marine and coastal areas.
- Wageningen Marine Research is an independent, leading scientific research institute

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