ICES WORKING GROUP ON ELECTRICAL TRAWLING (WGELECTRA)

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International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H.C. Andersens Boulevard 44-46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

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Editors

Adriaan Rijnsdorp • Mattias van Opstal

Authors

Pim Boute • Julie Bremmer •.Clive Fox • Martin Lankheet • Pieke Molenaar • Hans Polet • Adriaan Rijnsdorp • Edward Schram • Arianna Servili • Daniel Stepputtis • Justin Tiano • Mattias van Opstal

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Contents

i Executive summary

The Working Group on Electrical Trawling (WGELECTRA) works on improving knowledge of the effects of electrical or pulse fishing on the marine environment. At the 2020 meeting, the working group considered the Scottish Ensis fishery, ongoing work on shrimp pulse fishery study and analysed the possible contribution of pulse trawling to reducing or increasing the ecosystem/environmental impacts of the North Sea sole fishery and its fuel consumption.

Substantial efforts were invested during the last 10 years to examine the effect of pulsed currents at the individual level on a range of species, species groups and life stages. Exposure to the pulsed bipolar current (PBC), used in pulse trawling for sole, does not result in direct mortality in fish and invertebrates, but may cause spinal injuries in fish. Pulse induced injury rate is low (<=1%) in the twelve fish species studied and population level effect will be negligible. Injury probability in cod is 36% and seems to decrease in small cod. The population level consequences are considered negligible. Adverse effect on electroreceptive species is unlikely because they are sensitive for low frequency direct current and not to high frequency PBC. Non-lethal effects are considered unlikely due to low exposure. No adverse effects (mortality or lesions) were found for the benthic invertebrate species exposed to the sole pulse, and animals returned to normal behaviour less than one hour after exposure. This made any long-term ecological effect unlikely. The low exposure probability and short duration implies no chronic exposure to pulse stimuli.

Pulse trawling has less mechanical impact on the benthic ecosystem than conventional beam trawling. The lower towing speed of pulse trawls led to reduced mobilization of sediments, and resulted in a smaller footprint and a reduced surface area swept when exploiting the sole quota. The replacement of tickler chains by electrodes reduced the depth of disturbance of the trawl and likely reduced the average mortality imposed on benthic invertebrates.

Although no specific experiments have been carried out on Natura 2000 species, the available knowledge suggests that the probability of exposure is likely to be (very) low. Natura 2000 habitats will have been exposed less by pulse trawls compared to conventional beam trawls.

CO_2 emissions of pulse trawlers are lower than those of conventional beam trawlers due to an estimated reduction in fuel consumption by ~50% per unit of sole quota and ~20% per unit of total landings.

Pulse trawls catch, per hour, more sole and less plaice and other species and can contribute to a reduction in the bycatch of undersized fish (discards) and benthic invertebrates. Pulse trawling does not impose a risk to the sustainable exploitation of sole if the stock is well managed, although an increase in local fishing pressure was observed in the southern North Sea following introduction of the pulse trawl.

ii Expert group information

Expert group name	Working Group on Electrical Trawling (WGELECTRA)
Expert group cycle	Multiannual fixed term
Year cycle started	2018
Reporting year in cycle	3/3
Chair(s)	Adriaan Rijnsdorp, The Netherlands
	Mattias van Opstal, Belgium
Meeting venue(s) and dates	17-19 April, WMR, Ijmuiden, The Netherlands (18 participants)
	11-13 June, Ghent, Belgium (28 participants)
	25-27 March, By Correspondence (12 participants)

1 Introduction

Investigations to use electricity in catching target species have a long history (Soetaert et al., 2015b). In the North Sea, the studies focused 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 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 jeopardized 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, called the fishery to improve its practises. In 2006, the EU allowed North Sea member states to issue pulse trawl licenses to up to 5% of their fleet. In 2011 and 2014, the Netherlands got permission from the EU to issue 20 and 42 additional licenses up to a total of 84 (Haasnoot et al., 2015).

The use of electricity to catch sole raised concerns about the possible increase mortality on 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 sublethal and reproductive effects on target and not-target species (ICES 2006, 2012, 2016). ICES (2012, 2016) recognized 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 "Impact Assessment Pulse Fishery (IAPF)" 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 licenses 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 organization, Bloom, campaigned against pulse fishing (Stokstad, 2018; Le Manach et al., 2019). In January 2018, the European Parliament voted against pulse trawling in the context of the revision of the technical measures. In 2018 to further inform and support the decision-making process, the Netherlands has requested ICES to compare the ecological and environmental effects of using traditional beam trawls or pulse trawls when exploiting the TAC of North Sea sole. Despite a favourable advice (ICES, 2018a), the EU decided to maintain the ban on pulse trawling in the Technical Management Regulations (CEC, 2019).

The current report reviews the available information to provide the science base for an advice on the request from the Netherlands to "Analyse the possible contribution of pulse trawling to reduce or increase the ecosystem/environmental impacts of the fishery for sole in the North Sea and reflect on the fuel consumption used in the fishery sole in the North Sea". WGELECTRA applied the assessment framework developed by WGELECTRA in 2018. Due to the Corona crisis, the working group worked by correspondence. A document summarizing the results of the IAPF project was made available to the participants two weeks before the meeting (Rijnsdorp et al., 2020c). To facilitate discussions a draft report including an assessment table was made available to the participants two days before the meeting. After the presentation and discussion of the results of recent research projects, the discussions focused on the assessment table summarizing the scientific knowledge of the effect of pulse trawling on individual organisms and biogeochemical processes and on the scaling up of these effects to the level of the population and ecosystem. The scientific knowledge was summarized by answering the following questions: (i) Does pulse exposure cause direct harm, or have long term adverse consequences, to marine organisms ?; (ii) Does pulse trawling impose a risk to the sustainable exploitation of sole?; (iii) Does pulse trawling affect the selectivity of the sole fishery and affect the discarding of fish and benthic invertebrates?; (iv) Does pulse trawling affect the impact on the benthic ecosystem of the sole fishery?; (v) Can pulse trawling reduce the impact on sensitive habitats and threatened species / ecosystems?; (vi) Does pulse trawling affect the CO_2 emissions of the sole fishery?

In addition the working group reviewed the recent update on the Scottish Ensis fishery and research on pulse fishing for brown shrimps.

2 Electric fishing for razor clams

Razor clams (Ensis sp.) have been collected for millenia at a low level for local consumption but commercial landings began to increase in the late 1990s. Clams begun to be collected using mainly hydraulic dredges from beds in Ireland and Scotland. At the time the main market was in Iberia, but this declined in the early 2000s but was replaced by new markets in the Far East. Reports that illegal electrofishing was taking place in Scotland began to emerge in the press with reports of high profits from the Far Eastern sales. In this approach, exposure to an electric field causes the razor clams to emerge from the sediment so that they can be collected by divers following behind the electrofishing rig. Because fishing with electricity is illegal under the Common Fisheries Policy these activities were of concern to the Scottish Government. In 2016, the Scottish Government consulted on whether electrofishing should become a permitted method for harvesting razor clams. Following this consultation, it was announced that controlled commercial research trials, which are permitted under the CFP, would commence in February 2018. The aims of these trials are to restrict the fishing activity to a controlled number of licenced vessels, to tightly control the electrofishing gear being deployed by the vessels, to control the spatial areas where electrofishing takes place, to gather further information about the impacts of electrofishing and to evaluate the potential for such fisheries to be managed within sustainable limits. It is important to realize that the electrofishing technique used in razor clam harvesting is different from that in the pulse-trawls used in the southern North Sea sole fishery. The technical specifications for the Ensis fishing gear are provided in Scottish (Government, 2017). There is little information on the abundance of razor clams in Scottish waters with only limited surveys being conducted historically. A major initiative in the trial fishery has been to begin surveys of the densities and sizes of razor clams in beds around Scotland. To achieve this, a new survey method using towed-video cameras combined with electrofishing rigs has been developed (Fox et al., 2019). These surveys are ongoing and will, over time, build up a much better understanding of the resource and how it is changing over time. Additional research is being planned to study the wider ecosytem impacts of this form of electrofishing including whether there are longer term impacts on non-target species. At present electrofishing for Ensis appears to be largely limited to Scotland although some illegal activity in England has been reported. The situation in Ireland differs in that collection of shellfish using SCUBA is banned - this means that all razor clams harvested in Irish waters are collected using hydraulic dredges. However, this approach leads to more damaged clams, is less selective than using electrofishing and may have larger impacts on the benthic habitat. Results from the Scottish electrofishing trial are thus likely to be of wider interest.

3 Pulse fishing for brown shrimps

All Dutch pulse trawlers targeting shrimp (HA31, ST24 and WR40 all year-round + TH10 in late summer) were involved in a 3 year project (2018-2020). The first goal was to gather 'reference data' of this fisheries in every season (per quarter) and in each of the N2000 areas (2018-2019). Data are gathered in 3 ways: (i) catch volume estimate + commercial catch are recorded for every haul and compared with a conventional fishing 'buddy', (ii) selfsampling while fishing with 1 conventional and 1 pulse trawl simultaneously (direct left right catch comparison) and (iii) an observer trip doing the same but onboard.

The first results indicate that on average the catches of commercial and small shrimp are ± 15% and 35% higher respectively, while the bycatch of roundfish, flatfish, benthos and rubble was reduced with ±5%, ±40%, ±50% and ±40% respectively. The increased catch rates for shrimp seem highest in summer and more shallow fishing grounds like the Waddensee. In 2019-2020 some innovations such as a different bobbin rope design or shorter electrodes are being evaluated. The final results of this project should be available by the end of 2020.

4 Assessment Framework

To assess the ecological and environmental impact of electrotrawling of North Sea sole the list of criteria and subcriteria defined by WGELECTRA in 2018 was adjusted and updated (Table 4.1). The criteria and subcriteria are relevant to address the request for advice (ToRe) but also 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; Quirijns et al., 2018). In the assessment, the effects of the pulse trawl were compared to the effects of the conventional tickler chain beam trawl which is the dominant gear being used.

The strength of the scientific support is assessed as high confidence, medium confidence and low confidence. High confidence is used when there is strong experimental or observational evidence available. Medium confidence is used when there is limited experimental or observational support. Low confidence 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.

The effects were scaled up to the level of the fleet, population and ecosystem by estimating the impact for each sub-criterion of the Dutch fleet of pulse license holders (PLH) fishing in the southern and central North Sea with 80 mm codends. The sole fishing area (SFA) is restricted to a northern boundary at 55oN west of 5oE and 56oN west of 5oE. The PLH increased their share of the sole landings by Dutch vessels to 95% after the transition to the pulse trawl. Hence, comparing the impact before and after the transition provides information on the change in impact of the transition from tickler chain beam trawling to pulse trawling.

A crucial step in the upscaling is the calculation of the exposure probability, which estimates the proportion of a population that is exposed to a pulse stimulus above a threshold field strength where exposure might result in an adverse effect. If an organism or certain life-history stage does not come into contact with a pulse stimulus, the impact of pulse fishing will be absent even if an electrical exposure may adversely impact an individual when exposed in an experiment. Along the same line, if the whole population is exposes and experiments have shown a modest adverse effect, the population level effect may still be important. Similar to the assessment of the direct effects on individuals, the confidence of the upscaled effect was classified as high, medium or low.

Table 4.1. List of criteria used to assess the ecological and environmental impact of the pulse fishery for sole.

Sustainable exploitation of the target species (sole)
- Catch efficiency target species (landings)
- Catch efficiency commercial bycatch (landings), such as plaice
- Size selectivity of sole, plaice
- Catch efficiency discards
- Bycatch invertebrates
- Discard survival
- Risk of overfishing sole
- Risk overfishing non target species

Adverse effects pulse stimulus on target and non-target teleost and Elasmobranchs that are exposed to the gear but not retained
- Mortality
- Injuries
- Mortality on egg and larval stages
- Feeding
- Reproduction
- Attraction / repulsion

5 Pulse Fishery for sole

5.1 Fishing gears

Although the beam trawl fishery catches a broad range of fish species and some invertebrate species, sole is the main target species because there are no alternative bottom-trawl gears that can effectively catch sole. The only alternative gear is a static gear - trammelnet - which is used seasonally when sole moves inshore to spawn (Appendix 3). Other fish species such as plaice that are caught with the beam trawl can be effectively caught by other bottom trawls, in particular twin trawls and seine nets, or trammelnets.

Sole is a difficult species to catch. The species spends most of its time on the seafloor to search for food, and may be buried in the sediment to hide for predators when inactive. Only since the introduction of the beam trawl in the 1960, which allowed fishers to tow a number of chains over the seabed that chase sole out of the sediment, the fishing pressure increased (Rijnsdorp et al., 2008). The beam trawl gear is also used in the fishery for sole in other sea areas such as the English Channel, Bristol Channel, Irish Sea and Bay of Biscay (Horwood, 1993; Polet and Depestele, 2010).

Since 2009 beam trawl vessels have switched to pulse trawling for sole. By January 2018, a total of 87 beam trawl vessels have been using pulse trawls to target sole (Table 5.1), most vessels flying the Dutch flag. Pulse trawl vessels operated under a (temporary) license (Haasnoot et al., 2016; ICES WGELECTRA Report 2018).

Table 5.1. Number of active pulse vessels targeting sole by country flag (1/1/2018). WGELECTRA Report 2018 (corrected).

Country	Sole fishery
Netherlands	76
Germany	8
United Kingdom	3

Figure 5.1 shows a schematic drawing of the frontal view and the bottom view of a conventional beam trawl and a pulse wing trawl. The horizontal net opening of a conventional beam trawl is fixed by an iron beam that rest on two shoes (de Groot and Lindeboom, 1994; Lindeboom and de Groot, 1998). The other type (Sumwing) uses a wing to fix the horizontal net opening. The wing improves the streamline and reduces both the hydrodynamic drag and fuel consumption (van Marlen et al., 2009; Taal and Klok, 2014). The nose of the wing, attached to the front side, follows the seafloor to maintain the position of the wing just above the seafloor (Polet and Depestele, 2010). The wing replaced the conventional beam trawl in the Dutch fleet since its introduction in 2008. In the Belgium fleet, vessels continued to use conventional beam trawls.

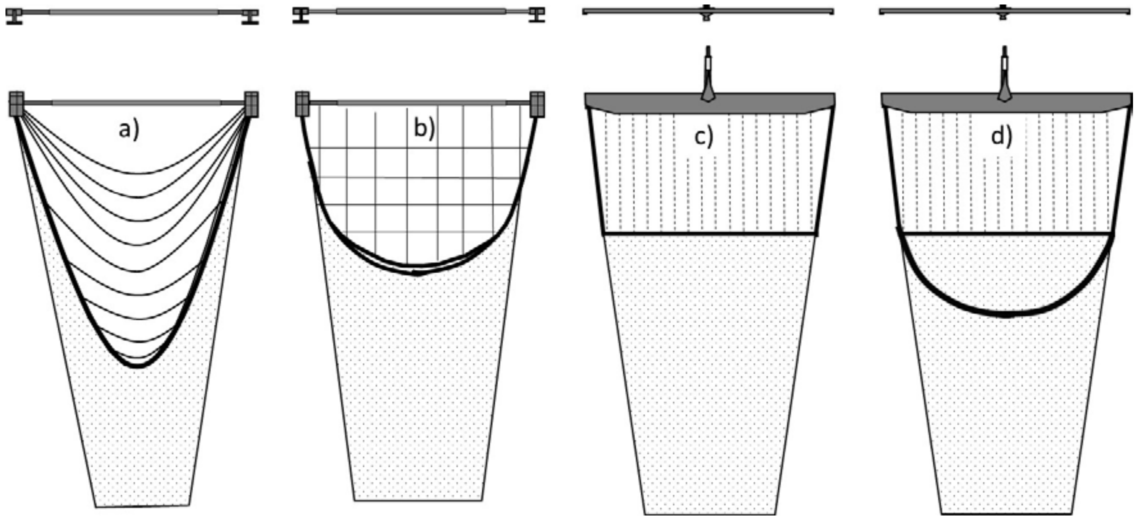

Figure 5.1. Schematic drawing of the frontal view (top) and bottom view (bottom) of beam trawl: (a) conventional tickler chain beam trawl with shoe-tickler chains and net-tickler chains (5); (b) a chain mat trawl with a double groundrope and a matrix of longitudinal and latitudinal chains; (c) Sumwing trawl with longitudinal electrode arrays and tension relief cords and rectangular groundrope; (d) Sumwing trawl with longitudinal electrode arrays and tension relief cords and U-shaped groundrope. Note that both tickler chains and longitudinal electrode arrays can be deployed on a beam and a Sumwing trawl (Rijnsdorp et al., under review).

The groundrope, netting and stimulation devices can be rigged in different manners. The conventional beam trawl deploys tickler chains attached to the shoes (shoe-ticklers) and the groundrope (net-ticklers) (Figure 5.1a). The ticklers chains are equally spaced over the net opening (Lindeboom and de Groot, 1998). The number of tickler chains deployed relates to the engine power of the vessel (Rijnsdorp et al., 2008) and varies across sediment types. A second type of beam trawl, the chain-mat trawl, is adapted to be used on hard grounds (Figure 5.1b). The array of longitudinal and latitudinal chains in the net opening prevent large stones from entering the net. Tickler chains can be added to improve the mechanical stimulation. The chain-mat beam trawl is used by the Dutch vessels fishing in the southern North Sea and by the Belgium beam trawler fleet fishing in the North Sea and other management areas such as the Channel, Irish Sea and Bay of Biscay. In pulse trawls the mechanical stimulation is replaced by electrical stimulation emitted by a matrix of electrode arrays running from the wing or beam to the groundrope (Figure 5.1c – d). In order to operate properly, the electrodes need to be of equal length. The electrodes are equally spaced over the full width of the trawl. To fit this rectangular array, a latitudinal (horizontal) groundrope is required. Different types of groundrope and net were developed to accommodate a latitudinal groundrope. Type 1 combines a rectangular shaped groundrope with either a trouser trawl (not shown) or a single trawl (Figure 5.1c). Some vessels may also use an additional latitudinal groundrope (‘sole rope’) and netting panel (‘sole panel’). Type 2 uses a U-shaped groundrope with an additional ‘sole rope’ and netting panel (‘sole panel’: Figure 5.1d). Tension relief cords are attached between the beam/wing and groundrope to support the rectangular groundrope shape and release the tension on the electrodes. In contrast to the electrode arrays, which have physical contact with the sea floor, tension relief cords are running above the seafloor and generally do not touch the sea floor (dr H. Polet, ILVO, Belgium. unpublished video).

5.2 Towing speed

Pulse trawl are be towed at a considerable lower speed than tickler chain beam trawls or chain mat beam trawls (Table 5.2). The towing speed was estimated from the speed recorded in the vessel monitoring by satellite (VMS) programme. The transition to pulse trawling coincides with a 23% reduction in towing speed in large vessels and 10% in small vessels.

Table 5.2. Towing speed (nautical miles.hour^{-1}): mean, standard deviation and number of observations by gear and engine class

	Small vessels (<221 kW)			Large vessels (>221 kW)		
	mean	sd	n	mean	sd	n
Gear						
Chain-mat	5.14	0.49	1087	6.02	0.25	2102
Tickler chain	5.17	0.74	3930	6.39	0.45	12483
Pulse trawl	4.64	0.31	4286	4.91	0.27	11387

5.3 Fuel consumption

Wageningen Economic Research (WEcR) collects economic data, including data on fuel consumption of a selection of Dutch fishing companies. Fuel consumption (liters per fishing hour) calculated by vessel and gear, and the fuel consumption relative to the conventional beam trawl are presented in Table 5.3. Vessels that switched from the conventional beam trawl to the Sumwing, a hydrodynamic foil replacing the beam but still using tickler chains, reduced their fuel consumption by 13%. After switching to the pulse trawl, allowing a lower towing speed, fuel consumption of the sampled vessels was reduced by 33% (pulse beam) and 46% (pulswing).

Table 5.3. Fuel consumption (liters per hour at sea) per vessel (large vessels) in the period 2009-2017 (data: WEcR).

	Fuel (liters/day) by vessel			Fuel consumption relative to conventional beam trawl by the same vessel		
	mean	sdev	n	mean	sdev	n
Beam trawl	312.5	47.2	30	-	-	-
Sumwing	264.7	34.0	19	-0.131	0.063	17
Pulsebeam	191.7	18.1	6	-0.333	0.148	4
Pulsewing	159.3	12.5	24	-0.465	0.095	19

Pulse licence holders (PLH) spent about 300 thousand hours each year trawling for sole in the SFA in the transition period (Figure 5.5). Applying the data from Table 5.3, the fuel consumption of the PLH can be estimated when exploiting the sole quota. For the conventional beam trawl, fuel consumption is estimated at 3.9 10^6 liters.year^{-1}. The hydrodynamic more efficient Sumwing with tickler chains reduced fuel consumption to 3.3 10^6 liters.year^{-1}, and the pulse trawl further reduced fuel consumption to 2.1 10^6 liters.year^{-1} (Table 5.4).

Pulse trawling thus can reduce the estimated annual fuel consumption by 37% when compared to the Sumwing and 47% when compared to the conventional beam trawl. The reduction is larger when expressed relative to the share of the sole quota. Since PLH increased their share of the sole quota from 73% to 95%, pulse trawling reduced the fuel consumption per unit of sole quotum by 52% when compared to the Sumwing and 59% when compared to the conventional beam trawl. If expressed relative to the total landed weight, which was estimated to be 22% reduced in pulse trawling, fuel consumption is reduced by 20% when compared with the Sumwing and by 32% when compared to the conventional beam trawl.

Table 5.4. Reduction in fuel consumption (litre) of the beam trawl fishery for sole when changing from conventional tickler chain beam trawl, or Sumwing tickler chain trawl, to pulse trawls.

Reference gear	%reduction fuel	%reduction / unit sole quota	%reduction / total landings
Conventional beam trawl	-47%	-59%	-32%
Sumwing	-37%	-52%	-20%

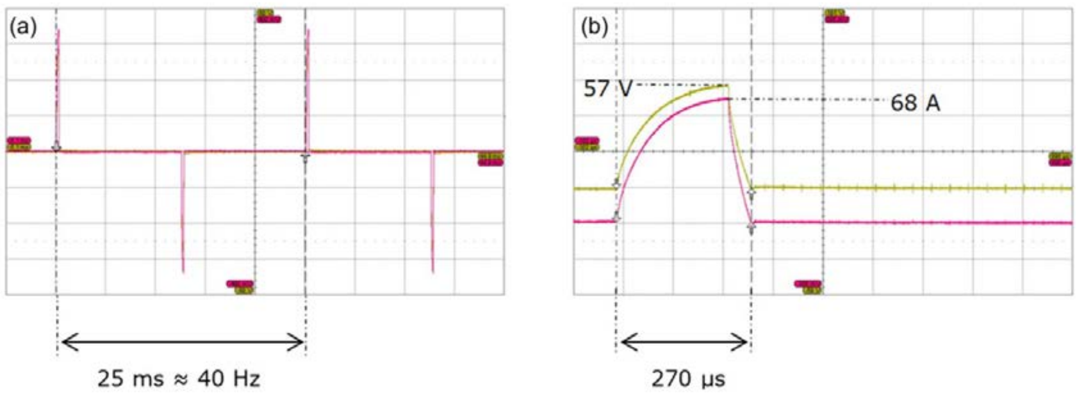

Figure 5.2. Schematic representation of a pulsed bipolar current (PBC) as used in the pulse fishery for sole (from de Haan et al., 2016).

5.4 Description of the electrical components and pulse stimulus

There are two commercial pulse systems available for the fishery for sole: the Delmeco system used by 12 vessels and the HFK system used by 64 vessels. Both systems use a pulsed bipolar current (Figure 5.2) emitted by longitudinal electrode arrays between the beam/wing and groundrope (Figure 5.3). A description of the electrode arrays is given in de Haan et al. (2016) and Soetaert et al. (2019). The number and configuration of the electrode arrays varies in relation to gear width and type of rigging of the net. The typical 4.5 m gear width used by Euro cutters within the 12 nm zone comprise of 10 electrode arrays. The typical 12 m gear, which is used outside the 12 nm zone, comprises between 24 to 28 electrode arrays.

Table 5.5 summarizes the main pulse characteristics and the legal restrictions. For inspection purposes vessels are equipped with an automatic computer management system, including a data logger, which registers the pulse settings that have been used and the peak voltage and effective power per minute for at least the last 100 tows and for at least the last 6 months (Ministry of Economic Affairs, January 2017). In addition, vessels are required to maintain a Technical Document (TD) comprising of a Technical on board Document and Manufacturers' Technical Dossier on the technical specifications of the gear and pulse equipment.

Data logger data of 39 vessels (6 Delmeco, 33 HFK) with one minute observations of pulse characteristics during fishing operations were available for analysis. Both pulse systems use a pulsed bipolar current (PBC). Delmeco uses a pulsewidth of 220-250 µs and frequency of 43-46 Hz. HFK uses a pulsewidth of 320-350 µs and frequency of 30 Hz. The peak voltage over the pairs of electrodes was set at a value close to 60 V. The peak voltage at the seafloor ranged between 54 – 58 V. Peak voltage at the seafloor varies among vessels and shows a seasonal pattern of lowest values observed in August when temperatures reach their seasonal high and largest values in March when temperatures reach their seasonal low (Figure 5.4). No seasonality is observed in the pulse frequency, pulsewidth and power. The number of Delmeco vessels was too small to analyse the seasonal patterns. The mean voltage (Vrms) was 8.3 and the duty cycle, e.g. the percentage time that the electric current flows between electrodes, was 2%. The power per meter gear width was 0.46 kW.m-1 and 0.56 kW.m-1. All pulse parameters were well within the boundaries set by regulatory authority.

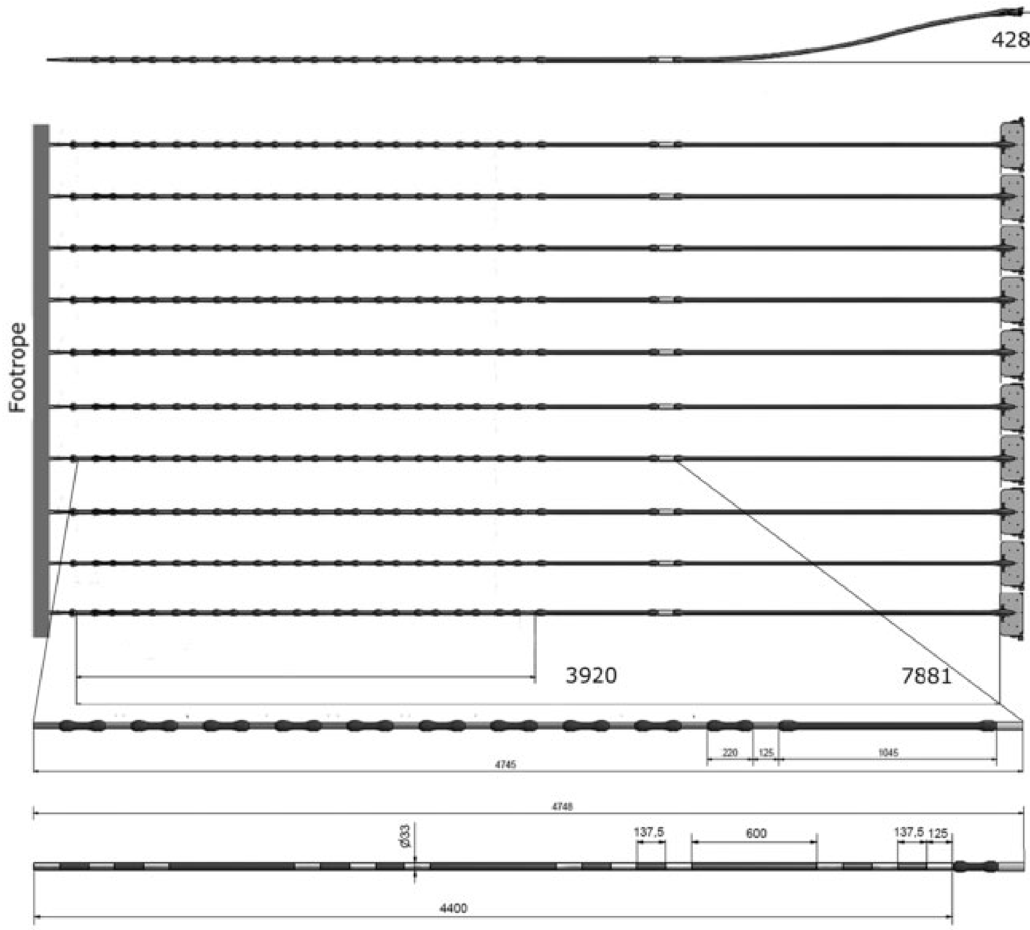

Figure 5.3. Schematic representation (in mm) of the ten 7.881 m long electrode arrays of a 4 m beam pulse wing used in electrotrawls targeting common sole with a close-up of two possible electrode array types (from HFK Engineering B.V.). The white or grey conductive parts are made of stainless steel or copper respectively and are called electrodes, whereas the longer black parts are non-conductive and called insulators or insulated parts. The entire structure consisting of electrodes and insulators through which the pulse generator releases its electrical current is called an "electrode array." (from Soetaert et al., 2019).

Table 5.5. Characteristics of the two pulse systems (mean, standard deviation) used in the fishery for sole. DL = data logger; TD = Technical Documentation

	Delmeco	HFK	Source	Restrictions
Pulse type	PBC	PBC		
Pulsewidth (microsec)	238.5 (8.5)	336 (23)	DL	
Frequency (Hz)	44.7 (1.8)	30 (2.2)	DL	20-180
Voltage (peak, V) setting		58.8 (0.9)	DL	<=60
Voltage (peak, V) seafloor	57.1 (2.6)	55.6 (1.8)	DL	<=60
Voltage (Vrms, V)	8.3 (0.4)	8.3 (0.2)	DL	<=15
Duty cycle (%time)	2.1 (0.09)	2.0 (0.09)	DL	<=3
Power per meter gear width (kW.m-1)	0.46 (0.03)	0.56 (0.04)	DL	<=1 kW.m-1
Distance between electrode arrays (cm)	42	41.5	TD	>=40

Frequency defined as the number of positive pulses per second. Duty cycle is defined as the product of pulsewidth and frequency.

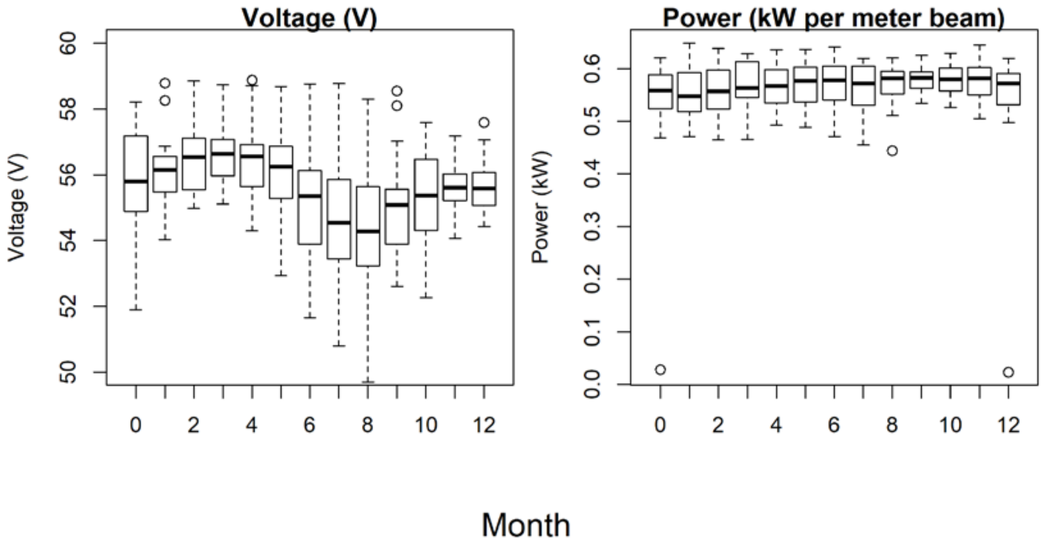

Figure 5.4. Distribution of the monthly mean pulse parameters. Horizontal bar shows the median value, box shows the 25th and 75th percentile, whiskers show the approximate range of the parameters, open dots show the individual extreme observations. Results from data loggers of 33 vessels using the HFK system.

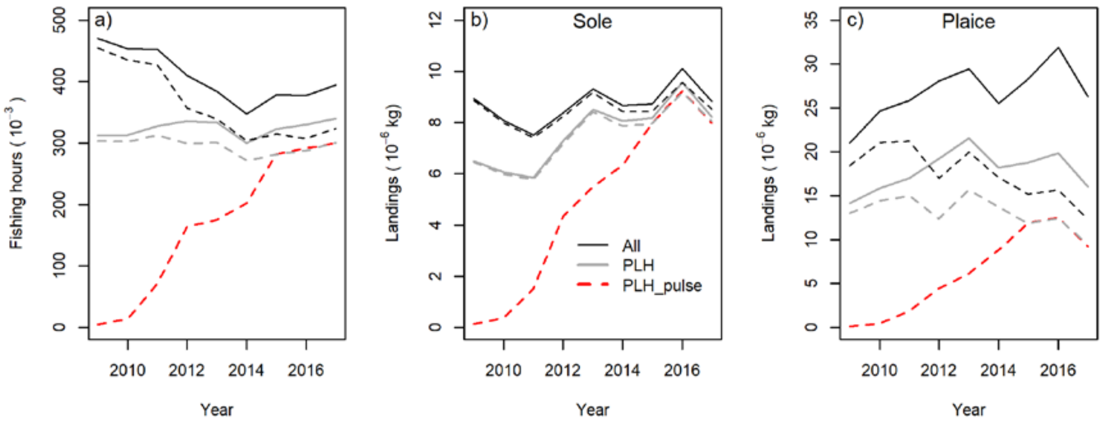

Figure 5.5. Evolution of fishing effort (a), sole landings (b) and plaice landings (c) of the total Dutch fleet of beam trawl vessels (ALL) and the subset of pulse license holders (PLH) in the North Sea areas IVc, IVb and Iva (full lines) and in the sole fishing area (SFA) between 51ºN and 55ºN west of 5ºE and 56ºN east of 5ºE (dashed lines). The grey dashed lines show the data for the PLH using the tickler chain or pulse trawl. The red dashed line shows the results for the pulse trawl, only (Rijnsdorp et al., 2020a).

5.5 Fishing effort and landings

Between 2009 and 2017, the total fishing effort of the Dutch beam trawl fleet decreased from about 480 to about 400 thousand hours (Figure 5.5a). In the sole fishing area south of the demarcation line running from west to east at 55ºN west of 5ºE and at 56ºN east of 5ºE fishing effort decreased from about 460 to just above 300 thousand hours. The decrease in effort is due to the reduction in the fleet size, and to the vessels switching to the twin trawl or flyshoot fishery.

The pulse license holders maintained their fishing effort in the sole fishing area and slightly increased their effort in the more northern waters. After the transition, more than 90% of the fishing effort in SFA was deployed by the PLH landing about 95% of the total Dutch landings of sole (Figure 5.5b). PLH increased their share of the Dutch sole landings from about 73% to 95% during the transition phase by leasing or buying sole fishing rights from other vessels. The share of PLH of the Dutch plaice landings decreased during the transition (Figure 5.5c).

The analysis of the spatial distribution of fishing effort – expressed as the annual mean swept-area ratio by grid cell of 1x1 minute latitude and longitude - showed that before the transition tickler chain beam trawl activities were spread out over SFA with local hot spots along the boundaries of the plaice box in the German Bight and along the 12 nm zone in the southern North Sea (Figure 5.6). In offshore waters concentrations of beam trawl activity were observed in the area of the Nordfolk Banks and local areas in the southern North Sea (IVc). Beam trawling in coastal waters (plaice box or 12 nm zone) was mainly restricted to the Belgium and Dutch coastal waters. After the transition the reduced tickler chain beam trawl activities was recorded in off-shore areas from around the 53ºN towards the border with the Skagerrak. The tickler chain activities north of the SFA increased due to the recovery of the plaice stock which improved the profitability of the northern fishing grounds to target plaice with large meshed beam trawls or twin trawl.

The pulse trawl distribution shifted toward the southwest. Pulse trawl effort reduced substantially in the German Bight and remained the same in the southern part of the North Sea or even increased in local areas within the Belgium 12 nm zone and just off the coastal waters of England off the Thames.

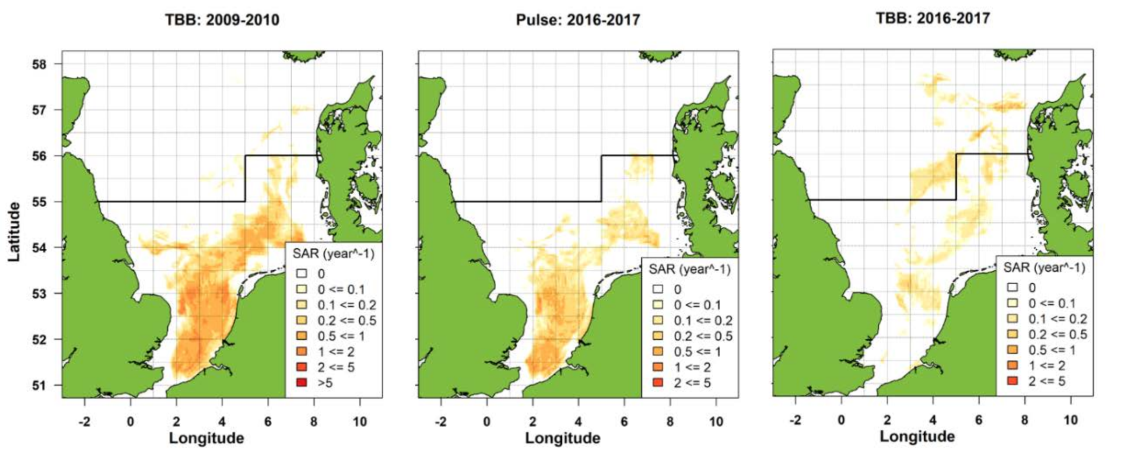

Figure 5.6. Annual trawling intensity by grid cell (SAR) of (a) the tickler chain beam trawl before the transition (2009-2010), and (b) the pulse trawl and (c) tickler chain beam trawl after the transition (2016-2017). The horizontal line at 55ºN west of 5ºE and 56ºN eats of 5ºE separate the sole fishing area (SFA) to the south (minimum codend mesh size = 80mm) and the plaice fishing area to the north (minimum codend mesh size = 100mm) (Rijnsdorp et al., 2020a).

5.6 Habitat association of pulse and tickler chain beam trawls

The analysis of the distribution of fishing effort (swept-area) over the EUNIS habitats showed that both tickler chain and pulse beam trawls were positively associated with sandy habitats (Table 5.6). More than 80% of their fishing effort was deployed on sand which only accounted for 61% of the surface area. Coarse, mixed and other habitats are trawled less than their proportional surface areas by both gears. Pulse trawling occurs slightly more in coarse habitats and less in mud than tickler chain beam trawls.

Table 5.6. Percentage fishing effort (swept-area) of the Dutch beam trawl fleet and percentage surface area by Eunis habitat in the sole fishing area (SFA) south of the demarcation line at 55°N and west of 5°E and 56°N east of 5°E. The analysis used a resolution of 1 minute longitude x 1 minute latitude grid cells (Rijnsdorp et al.2020a).

Habitat	2009-10	2016-17			Surface
	Tickler	Pulse	Tick-ler	Tickler + Pulse	
Coarse (A5.1)	10.2	15.2	3,2	12.7	20.8
Sand (A5.2)	83.0	81.9	84,5	82.4	60.8
Mud (A5.3)	6.6	2.7	12,2	4.7	6.8
Mixed (A5.4)	0.1	0.1	0.1	0.1	4.0
Other	0.1	0.0	0.0	0.0	7.7

To further investigate the habitat association Hintzen et al (submitted) analysed the habitat association of the VMS fishing positions of both gears in further detail by including continuous sediment characteristics (%sand, %mud, %gravel, %rock), bed shear stress and two BPI indices as well as distance to harbour into a statistical model. The bathymetric position index (BPI) metric represents the depth of the grid cell relative to the depth of the surrounding grid cells within a radius of 5km (BPI 5) and 75km (BPI 75), thus describing whether the grid cell is located in a valley or on a top of the hill, or on a relatively flat area. (van der Reijden et al., 2018) showed that the BPI is an important habitat variable to explain the habitat association of fishing activities. The analysis of Hintzen corroborated that pulse fishing is significantly more active in areas with higher gravel content, and showed that pulse fishing is more active in more elevated areas compared to its wider surroundings (BPI 75) and in areas with higher natural disturbance (bedstress). Tickler chain fishers fish in areas with lower gravel content, on less elevated patches compared to its wider surroundings (BPI 75) and in areas with lower natural disturbance (bedstress). The above analysis was conducted using the pooled data of each gear in the period 2009-2017 at a spatial resolution of 1x1 minute (about 2km^2) for which the habitat information was available.

These results are not in line with the slight reduction of pulse trawling in muddy habitats (Table 5.6) and the results of the habitat association model do not support the anecdotal information from the fishing industry suggesting that pulse trawls moved into previously unfished muddy grounds in the southern North Sea (ICES, 2018c). It is possible that the spatial scale used in the present study (1.8 km latitude * 1.1 km longitude at 52°N) is too coarse and may confound habitat differences that occur at smaller scale, such as the pattern of trough's and ridges which differ in grain size and benthic community (van Dijk et al., 2012; van der Reijden et al., 2019).

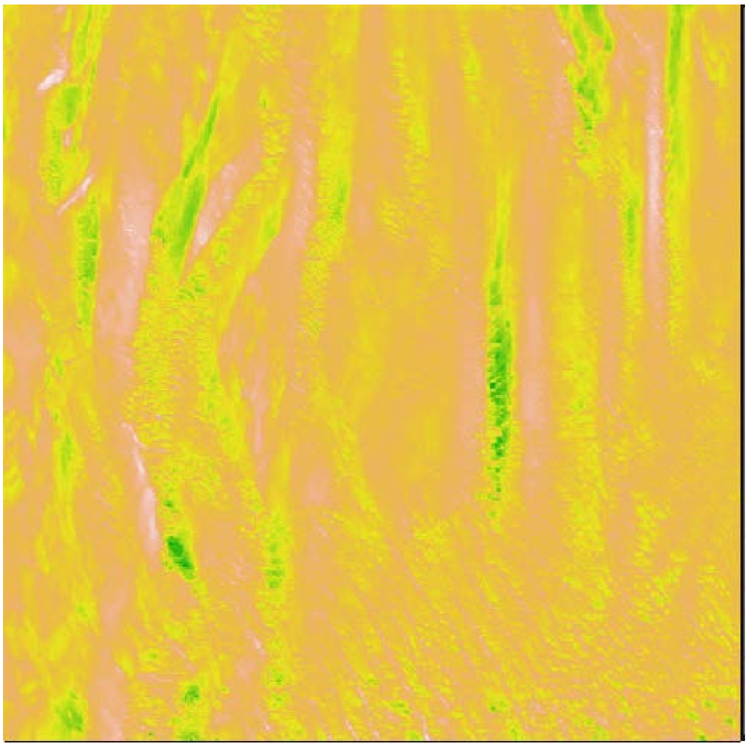

Figure 5.7. Map of the bathymetric index BPI5 of ICES rectangle 33F2 showing the depth relative the average depth in a circle with a radius of 5km. BPI5 colours range between green (shallow) to lilac (deep). (Hintzen et al. in prep)

Hintzen et al. therefore analysed the habitat association of pulse and tickler chain beam trawls at a fine spatial scale (150x150m). At this resolution, only bathymetric data were available and the BPI5 index was calculated for this resolution (Figure 5.7). The habitat association analysis was carried out for individual ICES rectangles to both avoid the influence of variation in the BPI15 index between ICES rectangles as well as numerical constraints to obtain results within a reasonable time-span (several hours per rectangle). The results are consistent between rectangles and can be interpreted to reflect the habitat preference of the gear. Figure 5.8 shows the results for two ICES rectangles in the southwestern North Sea which have been particularly attractive for pulse fishing. Both gears have a preference to fish in grid cells with a relative high BPI5, e.g. areas which are deeper than the mean depth of the surroundings within a radius of 5 km. No significant difference between tickler chain and pulse trawl in the preferred areas.

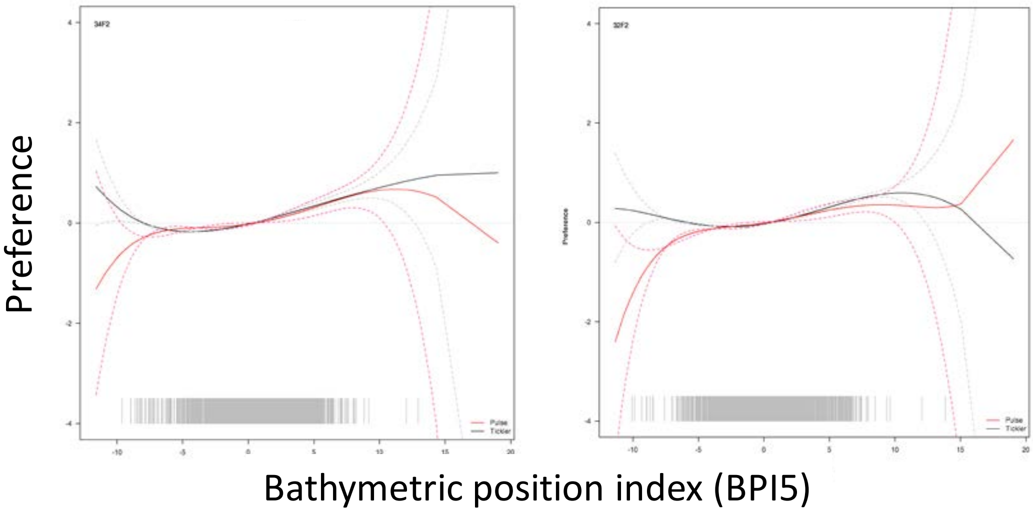

Figure 5.8. Habitat preference of pulse and conventional beam trawl vessels for relative depth (BPI5) in two ICES rectangels in the southern North Sea (left - 33F2; right - 34F2). The increase in preference with BPI5 shows that beam trawling for sole prefers areas that are relatively deeper than the average depth of the surounding 5km. The preference does not differ between pulse (red) and tickler chain beam trawl (black). Grey lines at the bottom indicate a sample of the BPI of the grid cells (Hintzen et al., in prep)

Table 5.7. Landings: log catch (per hour) ratio of the pulse trawl relative to the tickler chain trawl (estimate, SE) as estimated for a number of species and species groups with a mixed effect model. Nobs gives the number of observations and Ngroups gives the number of week*rectangle groups.

Species/group	Estimate	SE	Nobs	Ngroups
Sole	0.158	0.014	6483	1413
Plaice	-0.438	0.020	6483	1413
Whiting	0.380	0.102	3205	614
Rays	-0.082	0.079	4628	974
All flatfish	-0.227	0.012	6483	1413
All gadidae	-0.176	0.058	6483	1413
All fish	-0.236	0.012	6483	1413

Mixed effect model: log(catch rate) ~ as.factor(pulse) + as.factor(year) + (1|area_time) + (1|vessel). Weeks when trip limits were imposed were excluded from the analysis. This applied to turbot and brill since October 2016.

5.7 Selectivity and catch efficiency

5.7.1 Landings and discards

The difference in catch efficiency of the pulse and tickler chain vessels was estimated for the landings and discards fraction of the catch separately. Catch efficiency of the landings fraction was estimated by comparing the landings per hour at sea of vessels fishing in the same ICES rectangle during the same week. The relative catch efficiency was estimated for the main commercial fish species and species groups using a mixed effect model with gear type and year as fixed effect and week*rectangle group and vessel as random effects. The results are presented in Table 5.7. Pulse trawls caught on average 17% (95% confidence limits: 14%-20%) more sole than conventional beam trawlers, whereas the catch rate of plaice and flatfish – important bycatch species in the beam trawl fishery for sole - is reduced by 35% (33%-38%) and 20% (18%-22%), respectively. For all fish species catch rate is reduced by 21% (19%-23%). Only for whiting an increase of 46% in catch rate is observed (20%-79%).

Differences in catch efficiency of pulse and conventional beam trawlers of discard size classes per fishing hour was estimated using data form the discard monitoring programme of the Dutch beam trawl fleet carried out by WMR. Table 5.8 gives an overview of the species composition showing that the discards are dominated by flatfish. Although a total of 905 fishing trips were sampled, the number of observations in the same area and the same week was much too small. Therefore, the gear effect was estimated in a statistical analysis where the temporal evolution in catch rate was modelled for four areas. Parameter estimates are given in Table 5.9. Pulse trawls caught 27% (17%-36%) less discards than conventional beam trawls. The catch rate of plaice discards was reduced by 30% (19%-40%). In line with the higher catch rate of pulse trawls of marketable sized sole and whiting, pulse trawls caught 65% (16% - 137%) and 95% (56%-145%) more discards of sole and whiting, respectively.

Table 5.8. Discards. Species composition (numbers) of discards in the Dutch beam trawl fishery for sole (80mm mesh size) between 2009-2017 in the self-sampling and observer trip monitoring programmes

	Self sampling	Observer trips
Sole	2.6%	1.7%
Plaice	36.0%	35.7%
Other flatfish	50.1%	52.7%
Cod	0.1%	0.1%
Whiting	2.4%	3.6%
Other gadoids	0.3%	0.3%
Gurnards	2.3%	2.3%
Other bony fish	5.8%	3.4%
Elasmobranchs	0.4%	0.2%

The comparison of the catch rate per hour of pulse and conventional beam trawls is affected by the differences in towing speed. The catch rates were therefore also compared after correcting for the differences in towing speed (Figure 5.9). Estimated per unit of area swept, the analysis provides an estimate of the relative catchability to be used in the upscaling (section 10). Pulse trawls caught significantly more marketable sized sole and whiting per unit area swept, but significantly less plaice and all flatfish except sole. For the other species or species groups the catch was proportional to the area swept. Catch efficiency of discard sized fish, although more variable, similar differences were observed. Only for all gadoids, significantly more discards were caught in pulse trawls. This result is due to the contribution of whiting which dominates the gadoid discards (Table 5.8). Both landings and discards catch efficiency analysis indicated that pulse trawls caught more whiting than the conventional beam trawl.

The higher catch efficiency of pulse trawls for sole is likely related to the change in body shape of sole when exposed to a pulse stimulus. Sole bends into a U-shape when cramped and comes loose from the seabed increasing their accessible to the gear (van Stralen, 2005; Soetaert et al. 2015). Further, the penetration depth of the electric field into the sediment exceeds that of the tickler chains (section 6), and may increase the proportion of fish in the trawl path that will be available to the gear.

The higher catch efficiency suggested for both landings and discards of whiting are puzzling. The catch of whiting is rather variable in space and time and the landings may be affected by market conditions and the quota constraints. A higher catch efficiency for whiting is not supported by the catch comparison experiments (van Marlen et al., 2014). A higher catch efficiency of whiting, however, could be explained by the large mesh sized top panels used directly behind the beam/wing to reduce drag. It is well known that whiting tend to swim upward and may escape through the large meshed net panel located above the tickler chains. In a pulse trawl, whiting will be immobilized by the pulse stimulus and unlikely to be able to escape. The above considerations add caution to the interpretation of the estimated increase in catch efficiency of whiting.

Table 5.9. Discards: log catch (per hour) ratio of the pulse trawl relative to the tickler chain trawl (estimate, SE)

Species	Estimate	SE
Sole	0.503	0.183
Plaice	-0.358	0.078
Whiting	0.670	0.116
Flatfish	-0.396	0.073
All fish discards	-0.315	0.068

The lower catch efficiency observed for plaice, and flatfish (except sole), is likely due to the more rigid body shape when cramped, which may cause part of the plaice and other flatfish to pass underneath the groundrope.

Comparison of catch efficiency between discard and marketable size classes of sole and plaice do not support the results of the comparative fishing experiment between a conventional beam trawler and two pulse trawlers, which indicated that both undersize sole and plaice were caught less in the pulse trawls (van Marlen et al., 2014).

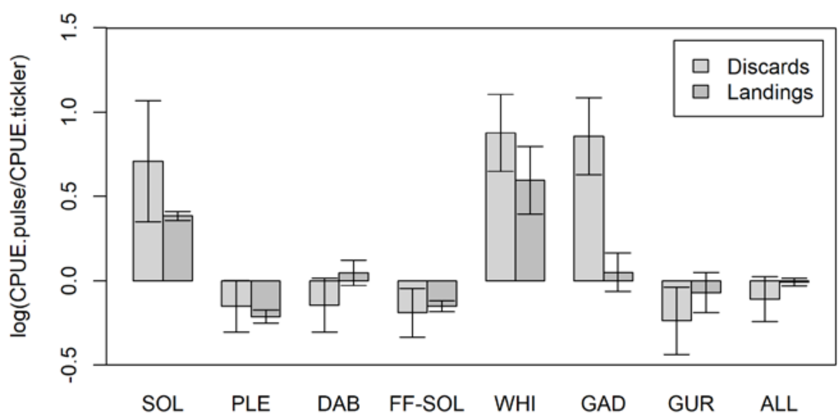

Figure 5.9. Landings and discards. Catch efficiency per swept-area differences and 95% confidence intervals between pulse and tickler chain beam trawl for discards and landings of sole (SOL), plaice (PLE), dab (DAB), all flatfish minus sole (FF-SOL), whiting (WHI), all gadoids (GAD), gurnards (GUR) and all fish (ALL).

5.7.2 Bycatch of benthos

The replacement of transversal tickler chains by longitudinal electrodes and the coinciding change in the groundrope will influence the catch of benthic invertebrates and debris from the sea floor. The catch rate (number per fishing hour) of benthic invertebrates of 646 commercial fishing trips with a pulse and conventional beam trawl (80mm mesh) were compared. Pulse trawls on average caught +6% and -62% of benthic invertebrates of conventional beam trawls of small (<= 221kW) and large (>221kW) vessels (ICES, 2018). Taking account of the number of small (n=19) and large vessels (n=57) in the pulse trawl fleet and correcting for the difference in towing speed, the change in the cpue of benthos per area swept by the total pulse trawl fleet is estimated at -33%.

The reduction in benthos caught by pulse trawls is supported by the decrease of 20% in the weight of benthos caught per area swept found in a comparative fishing experiment with one conventional beam trawl and two pulse trawl vessels (van Marlen et al., 2014). It is noted that the cpue of benthos of the conventional beam trawl is underestimated due to the damage caused by the tickler chains on fragile organisms such as sea urchins (ICES, 2018).

5.8 Discard survival

The consequence of a transition from tickler chain to pulse trawling on the survival of discards was studied by comparing the fish condition of undersized fish during on board sampling of the catch (Schram et al., 2020). Three trips of commercial vessels using a tickler chain were sampled as part of the IAPF project. Results were compared with the results of nine trips with commercial pulse beam trawlers (Schram and Molenaar, 2018). In both studies fish vitality was scored from good (A) to poor (D) according a standardized methodology (van der Reijden et al., 2017). Discards survival probabilities were predicted from the frequency distributions over vitality index scores in combination with species-specific survival probability by vitality score established for pulse beam trawl fisheries by Schram and Molenaar (2018).

The frequency distributions over vitality scores differed for the two gear types for brill, plaice and turbot, indicating that the overall condition of these species was affected by the gear type. Brill ($p = 0.001$), plaice ($p < 0.001$) and turbot ($p < 0.001$) discards have a higher probability of good condition (AB) in pulse beam trawl fisheries compared to tickler chain beam trawl fisheries. For sole, thornback ray and spotted ray no effect of gear type on fish condition could be detected (Figure 5.10). The estimated discard mortality rate for plaice, brill and turbot all lie below the lower limits of the 95% confidence intervals of the survival probabilities measured in pulse beam trawl fisheries. For sole and thornback ray discards survival appears more or less equal in both fisheries (Figure 5.11). It is noted that damage observed in sole discards is related to the mechanical injuries suffered when sole gets stuck in a mesh size.

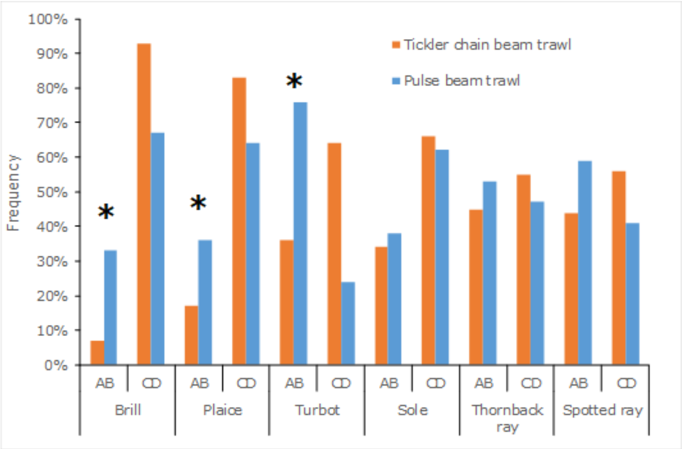

Figure 5.10. Frequency distributions per fish with good (AB) and poor (CD) vitality score in pulse and tickler chain beam trawl fisheries. Asterixis mark a significantly larger proportion of fish in good condition in pulse beam trawling compared to tickler chain beam trawling (Fisher's exact test right-sided p-value <0.05).

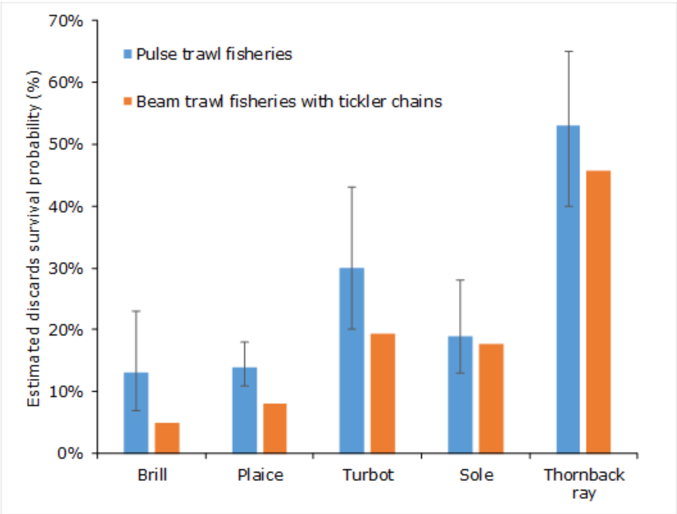

Figure 5.11. Discards survival probabilities per species for tickler chain and pulse beam trawl fisheries. Error bars represent the 95% confidence intervals for the survival probability estimates.

6 Field strength around a pulse trawl

The electrodes of a pulse gear create a heterogeneous electric field, with highest field strengths close to the electrodes. Field strength quantifies the gradient in voltage ($V.m^{-1}$) and determines the current for a specified conductivity of the medium. Field strength for a point-source electrical charge is proportional to the charge and inversely proportional to the square of the distance relative to the charge. The shape of the electrical field generated by a pair of electrodes in contact with seawater is a complex function of the size and shape of the electrodes, the conductivity of the medium and the spatial layout of the electrodes. The electrical field is also influenced by objects of different conductivity within the field – for example the presence of fish or other organisms will alter the field. Typical pulse gear electrodes consist of parallel chains of electrodes, with conducting parts of e.g. 12.5 length and 3 cm in diameter, separated by 22 cm insulators. Within a chain, all conductors are connected and have the same voltage. Two of these longitudinal chains act in pairs, one being the anode and the other the cathode. The electrical fields pulse at a frequency of about 30 Hz, with a unipolar pulse duration of about 0.3 ms. At any moment in time only a single pair of electrodes is activated; different pairs being activated in alternation. This implies that neighboring electrode pairs do not interact in generating the electrical field. However, since each chain of electrodes can participate in two pairs the actual frequency of pulsing can be doubled relative to the frequency setting for a single pair. In order to describe the electrical fields generated by pulse gear it suffices to simulate one pair of electrode chains. Also, electric fields around electrodes will be independent of movement of the gear, implying that the temporal profile for a location directly follows from the spatial profile in the direction of movement in combination with the towing speed.

The COMSOL Multiphysics package was used to simulate the electric fields generated by such a pair of electrodes (**Figure 6.1**). In all simulations the field strength was determined in the steady state, which corresponds to the maximum field strength during a brief pulse. Electrode voltages applied in pulse gear vary between about 52 and 58V (**Figure 5.4).** A comparable voltage of 60V was used to model the fields in the water column, and in the sediment, with the electrodes at the interface between water and sediment. Electrodes were 41.5 cm apart, similar to the electrode distance in commercial gear. Field strengths are very similar in the water column and in the sediment and are largely independent of the conductivity of the sediment, in agreement with electric field measurements undertaken at various field locations (de Haan & Burggraaf, 2018). Both in the sediment and in the water column, field strengths steeply decrease with distance from the electrode. Close to the electrode field strengths reach values of 200 $V.m^{-1}$ and show a strong modulation along the length of the chain, with high values close to the conductors and lower values near insulators. Field strengths drop below a value of 10 $V.m^{-1}$ at a distance of about 30 cm, this decline being slightly steeper in the lateral direction than in the vertical direction. At larger distances, modulations in the longitudinal directions vanish.

6.1 Effect of salinity and temperature on field strength

To assess the effects of temperature and salinity variations, the decline of the electric field with distance was estimated for different conductivities of the water. Salinity values in the southern North Sea vary between 28 and 35 psu (95%), depending on location and time-of year. Temperature varies between 1 and 19 deg Celsius (95%). These variations lead to differences in conductivity, ranging from about 2.5 $S.m^{-1}$ (1 deg C, salinity 28) to 4.7 $S.m^{-1}$ (19 deg C, salinity 35) (salinometry.com). Such variations in conductivity, however, did not noticeably affect the field strengths. Results presented in Figure 6.2 are similar for the range of conductivities encountered.

Whereas field strengths are, to a large extent, independent of the conductivity of the medium, higher conductivities allow for higher currents and thus the effects on organisms will be affected. Therefore, to assess the effects of electric fields generated by pulse gear the interaction of the gear with fish needs to be simulated. Most importantly, knowledge is required on the internal electric fields in the fish, because thresholds for the induction of muscle reactions are determined by local electric field strengths inside the animal, not in the surrounding water. Involuntary muscle cramps occur when internal neuronal or muscular thresholds for electrical stimulation are exceeded. To estimate susceptibility to electric fields for fish of different sizes and shapes, field strengths inside model fish were estimated by inserting idealized shapes into the COMSOL model.

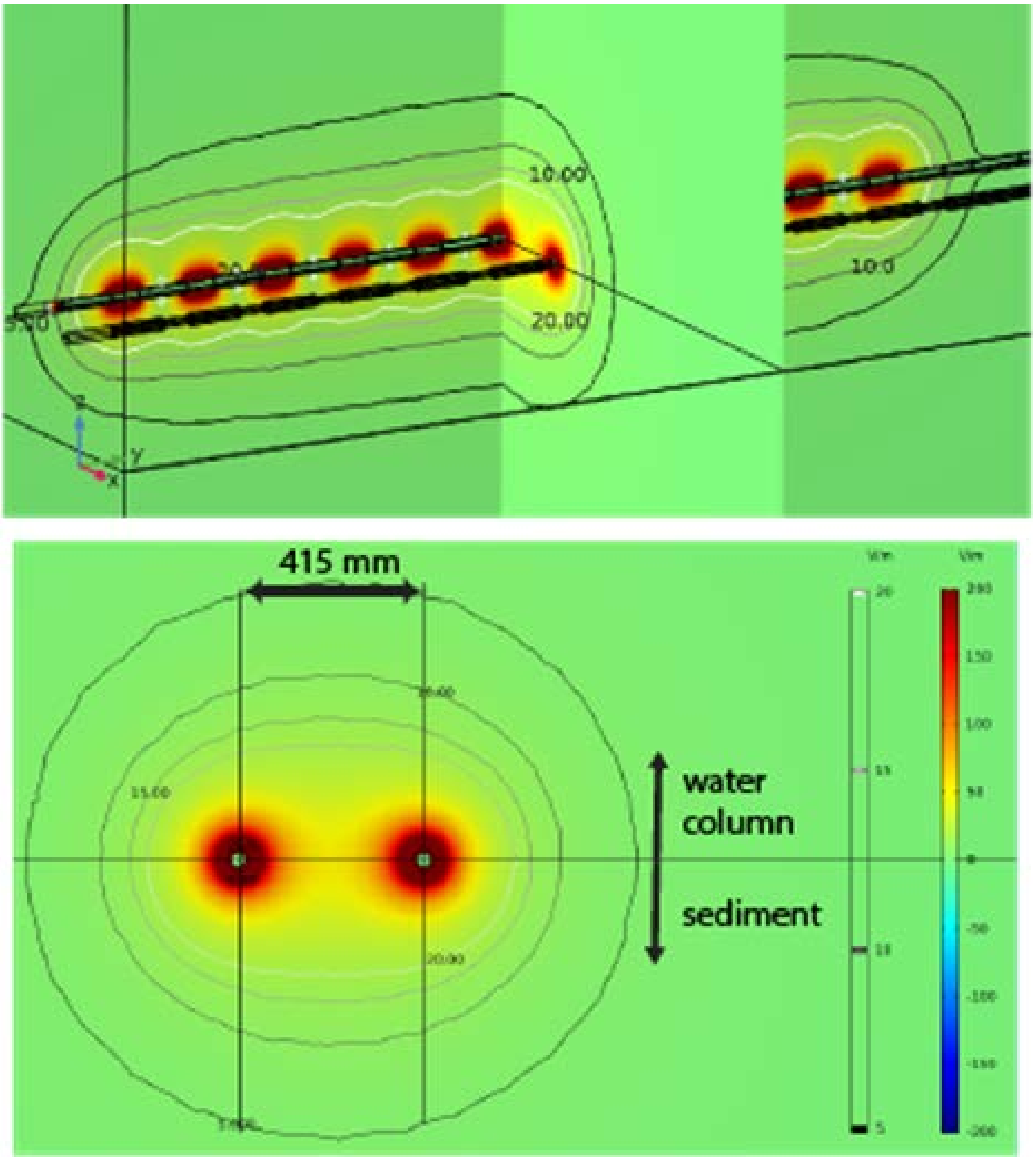

Figure 6.1. Contour plot of the field strength around a pair of electrode arrays. Top panel: three-dimensional view with transections in the vertical-longitudinal plane at the level of one of the chains, and in a vertical plane orthogonal to the two electrode chains. Bottom panel: field strengths in a cross section at the level of the conductors. Contour lines indicate

equal field strengths at 20, 15 , 10 and 5 V.m^{-1}. Conductivity for water was set at 5 S.m^{-1} and for the sediment at 0.5 S.m^{-1}. Conductors were 3cm in diameter, 12.5 cm in length and separated by 22 cm insulation.

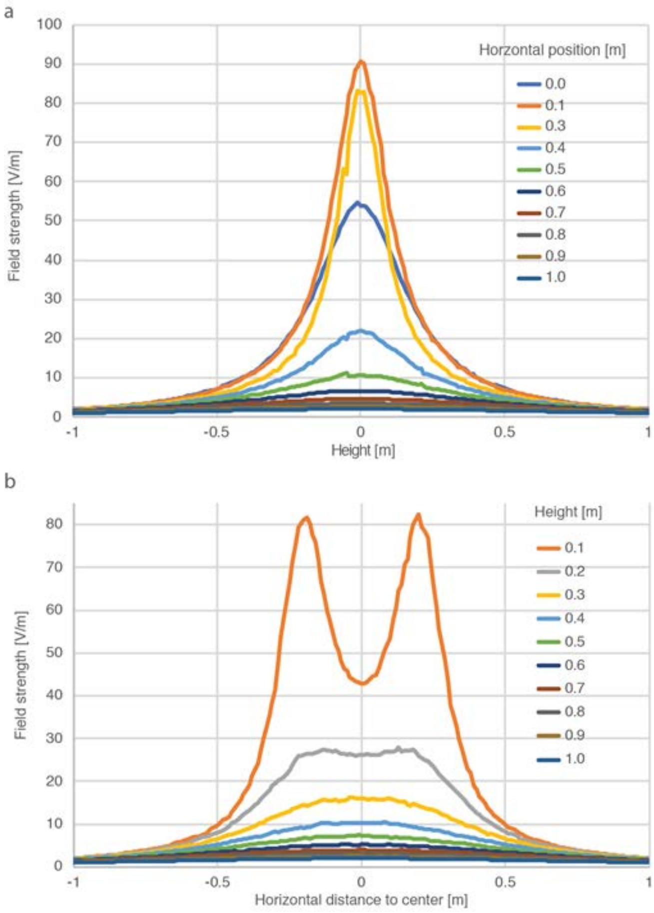

Figure 6.2. Field strengths as a function of height relative to the seabed and distance to the center of an electrode pair. The electrode pair is at the interface between water column and sediment (height 0, see Figure 6.1). A) Field strengths plotted as a function of height (z-dimension in Figure 6.1), for different positions relative to the electrode pair (along the x-dimension in Figure 6.1, as defined in the legend). B) Field strengths plotted as a function of horizontal distance to the electrode pair (x-dimension in Figure 6.1), for different heights above the electrodes (z-dimension in Figure 6.1, see legend). Horizontal distance is relative to the center of the pair of electrodes.

6.2 Exposure to electrical disturbance

Figure 6.3 shows simulation results for idealised roundfish in the water column. Electric fields inside the fish deviate substantially from those surrounding the fish (**Figure** 6.3**b**). Field strengths inside fish declined strongly with its height in the water column (**Figure** 6.3**c**). Larger fish also experience stronger internal electric fields than small fish, especially when close to the electrode. For all sizes of fish, internal field strengths dropped below 20 V.m^{-1} within about 50 cm. Maximum internal field strengths also occurred in fish directly above one of the electrode chains (**Figure** 6.3**d**), but dropped below the values for the location in between the electrodes at heights above about 20 cm..

The internal fields in idealized flatfish that were buried in the sediment, at different depths is shown in **Figure** 6.4**b**., and these values for a typical roundfish in the water column are shown in **Figure 6.4a**. Although external electric fields were similar in the water column and in the sediment, flatfish were somewhat protected in the sediment. Only at depths less than 5 cm were they stimulated above 50 V.m^{-1}. Internal fields strengths in both types of fish steeply decline with height and depth, and even more steeply as a function of distance to the electrode. Peak stimulations occur in both cases when the fish are immediately above or below an electrode.

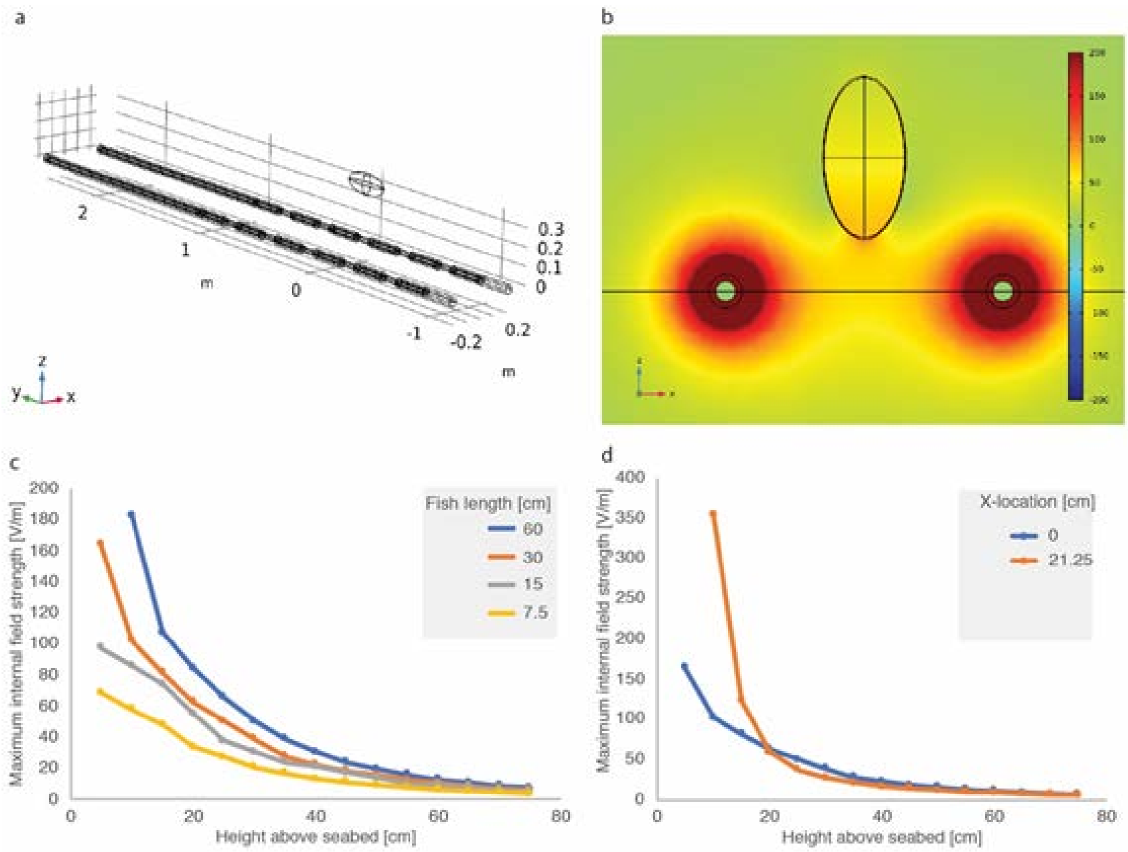

Figure 6.3. Simulations of electric fields inside fish. (a) Simulation setup, with two electrode chains, 41,5cm apart and a fish in the water column. Fish were simulated as ellipsoids, with 2mm skin at 0.1 $S.m^{-1}$, and the fish body at 0.5 $S.m^{-1}$. (b) Example of simulation result in a cross section through the center of the fish, orthogonal to the electrodes. (c) Maximum field strengths inside the fish as a function of distance above the electrode, for different fish sizes and for an x-position

of 0 (in between the electrodes) Fish width, height and length were isometrically scaled in a ratio of 1:5:2. (d) Results for a fish of 30cm length, at locations x = 0 and x = 21.25 (above one of the electrode chains).

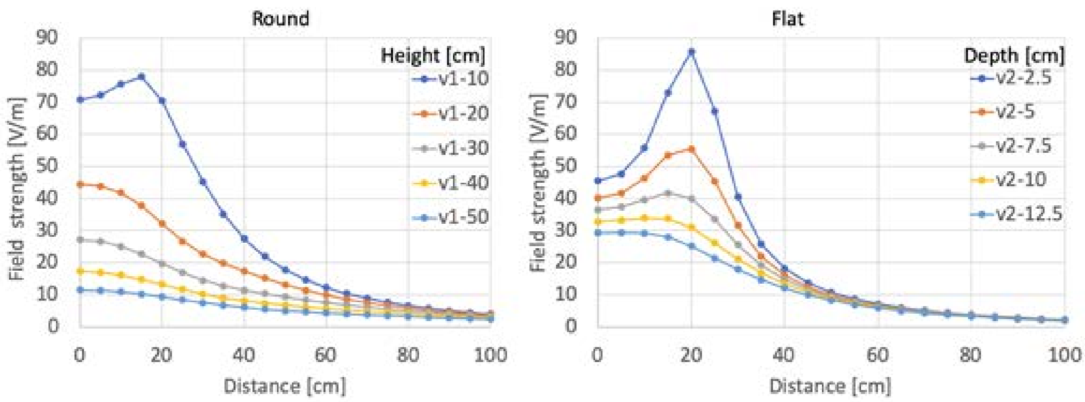

Figure 6.4. Simulated field strengths in roundfish in the water column and flatfish in the sediment. Distances are indicated relative to the midpoint between two chains of electrodes, in a horizontal plane.

6.3 Electric field modelling conclusions

- For homogeneous media the field strengths do not vary noticeably with conductivity. Field strengths in the water column and in the sediment are also similar. This corroborates field measurements undertaken by de Haan (de Haan and Burggraaf, 2019).
- Electric fields for multiple pairs of electrodes in pulse gear are not additive, because they are actuated alternately in time.
- If an electrode chain participates in two electrode pairs then the effective frequency of pulsing is doubled.
- Muscle activations in organisms in response to the electrical pulsing are determined by the strength of internal electric fields in the organism.
- Internal electric fields differ from the surrounding external fields, due to conductivity differences of the organism body relative to seawater.
- Internal electric fields (in a typical idealized roundfish) drop below a value of about 20 $V.m^{-1}$ at a distance of about 50 cm. This value is only weakly affected by the x,y location between the pair of electrodes, or by the orientation of the fish.
- At similar heights, internal field strengths in smaller fish are lower compared with larger fish. Smaller fish are therefore likely less affected by a given external field strength. Moreover, due to their smaller size, the chance that smaller fish are exposed to high field strengths closer to the electrodes is smaller.
- Salinity and temperature variations do not affect field strengths in a homogeneous medium (e.g. in the water column). Lower temperatures and lower salinity levels, however, do reduce conductivity, and thereby reduce the difference in conductivity between seawater and fish in the water column. This results in lower internal field strengths, and therefore less susceptibility to electrical pulses at lower temperatures or salinities.
- Flatfish buried in the sediment are less susceptible to electrical pulses.

7 Threshold levels to electrical pulses

Exposure to pulsed electric fields may result in different responses of the fish (Soetaert et al., 2015b). Fish may detect an electric field sensorially and respond by changing their behaviour. An electrical stimulus may also trigger involuntary muscle twitches that could provoke a response. When exposed to higher electric field strengths, the stimulus will result in whole-body muscle cramps (i.e. electrical-pulse induced tetanus), or even lead to an epileptic seizure. The muscle cramp may result in spinal injuries and rupture of blood vessels. Knowledge of the threshold level of the different responses allows us to quantify the width over which the pulsed electric field may impact marine organisms.

7.1 Fish behavioural thresholds

Concerns exist that the electric fields extend well beyond the netting, potentially affecting fish outside the trawl track. To address these concerns Boute et al., (in prep) measured the amplitude thresholds for behavioural responses and compared these response thresholds to the field strengths around the fishing gear. For behavioural threshold measurements, both electroreceptive and non-electroreceptive fish were placed in a large circular tank (⌀ 2.5 m) with seven, individually controlled, evenly spaced electrode pairs, spanning the tank's diameter. The electrical stimulus was a 3 second square-shaped Pulsed Bipolar Current at a frequency of 45 Hz and pulsewidth of 0.3 ms. Pulse amplitude was varied during the experiment and was changed according to a staircase procedure. Pulse waveform is described as 45 Hz PBC (*PW* = 0.3 ms, *PB* = 10.81 ms) (Soetaert *et al.*, 2019). We used 10 small-spotted catshark (*Scyliorhinus canicula*), 10 thornback ray (*Raja clavata*), and 7 turbot (*Scophthalmus maximus*). Behavioural responses of the fish were assessed from high-speed video camera recordings for different pulse amplitudes and for different positions of the fish relative to the stimulating electrodes.

The response of the fish was scored as no visible response (0) or a change in behaviour (1), such as movement of a body part. Computer simulations of the electric field, verified with measurements in the experimental setup, were subsequently used to determine the electric field strength at the animal's location. The electric field strength at the location of the animal used, relates to the field strength when no object was present other than the water in the computer simulation. The behavioural events (no response vs. response) were scored during the 3 second electrical stimulation period. A response is expected when the stimulus is above threshold level (true positive), however, a response during this period could also be coincidental (false positive). The threshold field strengths for a behavioural response were calculated per species with a receiver operating characteristic (ROC) curve by comparing the distributions of the binary classifier (**Figure 7.1**). Hereto, the true positive rate (sensitivity) is plotted against the false positive rate (1-specificity) from which, at a certain probability (area under the curve), the maximal true positive rate with minimal false positives can be found with a corresponding electric field strength in a lookup table (not shown).

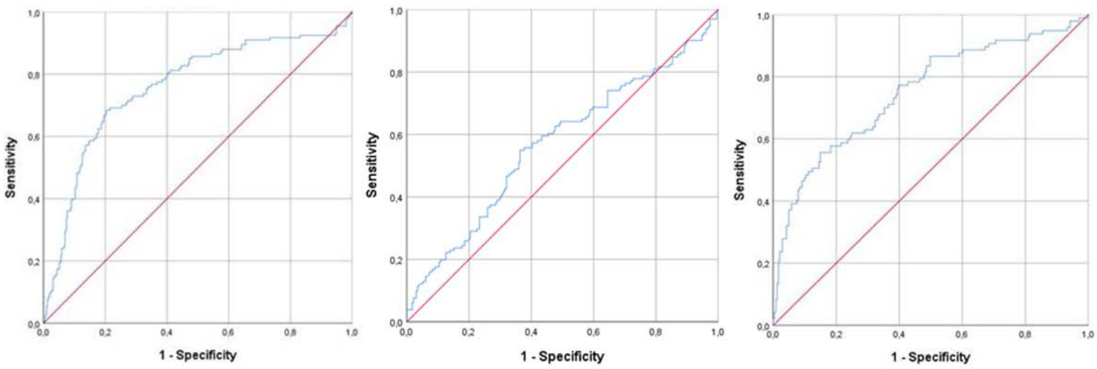

Figure 7.1. Receiver operating characteristic curves for (a) small-spotted catshark (*Scyliorhinus canicula*) ($n_{total\_stimulations}$ = 537), (b) thornback ray (*Raja clavata*) ($n_{total\_stimulations}$ = 419), and (c) turbot (*Scophthalmus maximus*) ($n_{total\_stimulations}$ = 348).

In small-spotted catshark, an electric field strength of at least 5.7 V m^{-1} is 76% likely to induce a change in behaviour. In thornback ray, an electric field strength of at least 3.1 V m^{-1} is 57% likely to induce a change in behaviour. In turbot, an electric field strength of at least 3.75 V m^{-1} is 75% likely to induce a change in behaviour.

7.2 Sensitivity of electroreceptive species

Elasmobranchs use a sense organ – the ampullae of Lorenzini - to detect electric fields in the water. These electroreceptors detect the potential difference between the opening of the pore in the skin and at the base of the receptor cell. Elasmobranchs use the electroreceptors to detect e.g. prey and thus, in line with emanated bio-electric fields are particularly sensitive for field strengths as low as $1*10^{-7}$ V m^{-1} (Kalmijn, 1966; Tricas and New, 1997) and a pulse frequency < 0.1 – 25 Hz (Peters and Evers, 1985; Collin, 2010; Rivera-Vicente et al., 2011).

The high sensitivity for low field strength of direct current (DC) was corroborated in studies on the potential effect of electromagnetic field (induced by transportation of electric current in cables) in the context of the potential impact of windfarms. WGELECTRA 2018 reviewed the studies of small-spotted catsharks of (Gill and Taylor, 2001; Gill et al., 2005) showing that elasmobranchs are attracted by electric fields generated by DC between 0.005 and 1 μV cm^{-1}, and repelled by electric fields of approximately 10 μV cm^{-1} and higher (ICES, 2018).

The behavioural threshold of the two electroreceptive fish (catshark and ray) tested were not substantially lower than in non-electroreceptive fish (turbot). This apparent discrepancy can be explained by the sensitivity for low frequencies in electroreceptive fish and the high frequency content of the electrical pulses emitted by pulse trawls. The frequency content, of a 3 second square-shaped PBC stimulus, pulsed at a frequency of 30 Hz and with pulsewidth of 0.3 ms was computed using a Fast Fourier transform (Figure 7.2a). Pulse waveform is described as 30 Hz PBC (*PW* = 0.3 ms, *PB* = 16.37 ms) (Soetaert *et al.*, 2019). This example is used in pulse fishing and consists mainly of high frequencies which are outside the detection range of the ampullae (Figure 7.2b). In addition, the highest energy content of the stimulus is within the higher frequency range (≥30 Hz; Figure 7.2b).

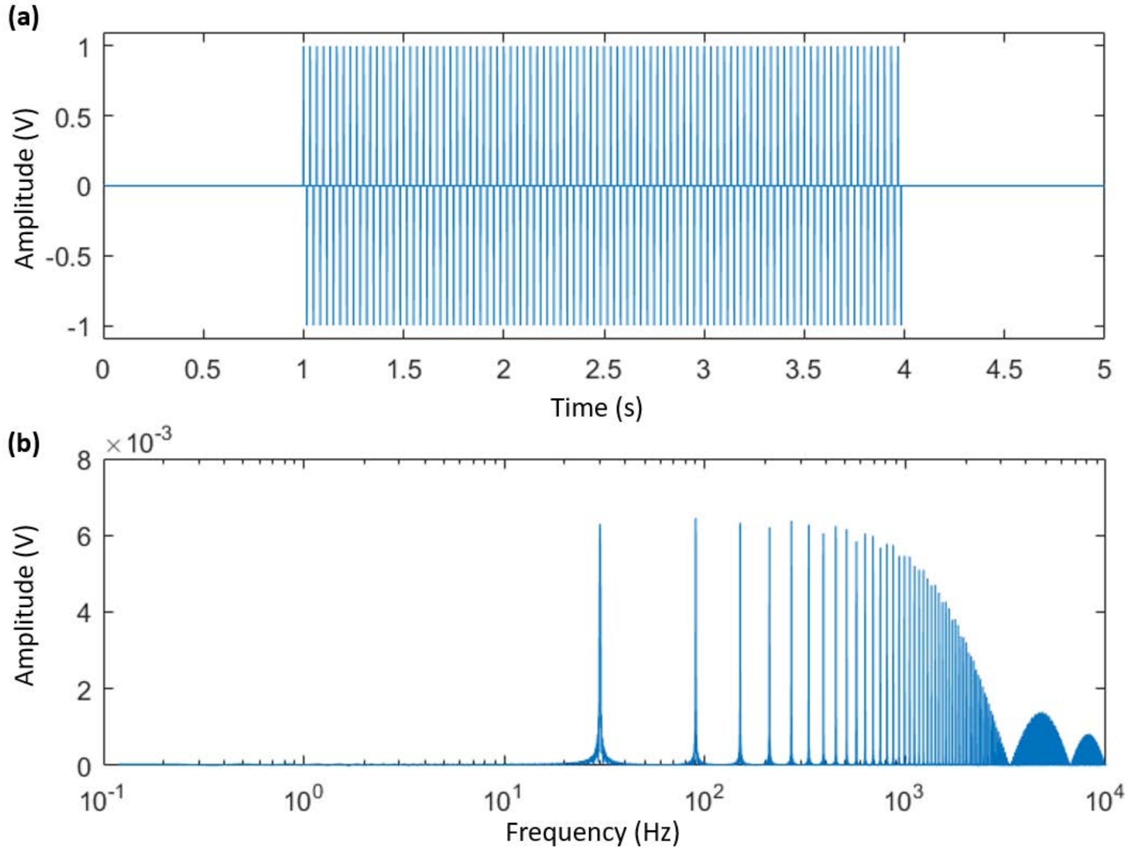

Figure 7.2. (a) A PBC waveform used in pulse trawling. (b) Fast Fourier transform spectrum of the pulse waveform in (a).

If the electroreceptive fish could detect the electric field with the ampullae of Lorenzini, then the electric field strength over the skin is relevant since this triggers the ampullae. Otherwise, if the fish could not detect the pulsed electric field with the ampullae, the internal electric field strength is relevant since this will either stimulate the nerves (e.g. which could result in a tingling feeling), or cause muscle activation to which the animal will respond.

7.3 Fish muscle activation thresholds

Apart from behavioural response thresholds, fish may also experience involuntary muscle contractions in response to the electrical pulse stimulus of the fishing gear. Such involuntary muscle contractions could hamper an escape of the fish or lead to injuries, even though it is not inside the netting.

Boute et al (in prep) measured amplitude thresholds for involuntary muscle contraction in 4 small Atlantic salmon (*Salmo salar*) (mean = 26.2 cm, sdev = 2.7 cm), and 5 large specimens (mean = 45.0 cm, sdev = 1.5 cm) . . For measurements of involuntary muscle contractions, fish were anaesthetized (i.e. to immobilize) and placed in a tank with electrode pairs at different locations along the anteroposterior axis of the fish (i.e. head, abdominal, and caudal region). In addition, the electrode pairs were placed at 20 cm and 40 cm apart (Figure 7.3). Each fish was placed in-between the electrode pair. Muscle activation thresholds were established by increasing the pulse amplitude until a visible muscle twitch on the outside part of the skin was observed. Subsequently, computer simulations of the electric field, in both the tank and an idealised fish, were used to determine the internal electric field strength corresponding to the potential difference over the electrode pair that triggered muscle activation (Figure 7.3).

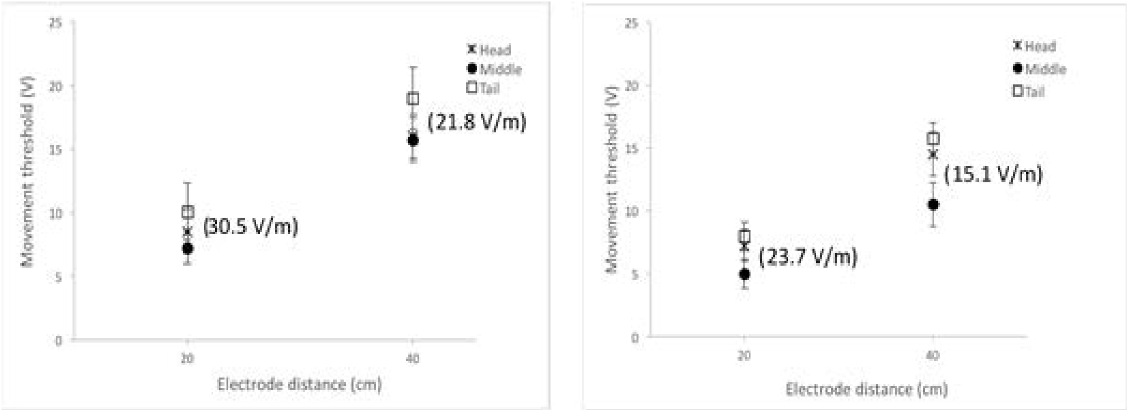

Figure 7.3. Muscle activation thresholds in anaesthetized (a) small and (b) large Atlantic salmon (*Salmo salar*) between an electrode pair spaced at 20 and 40 cm apart. Thresholds were determined by skin movement of the fish in the head, abdominal, and caudal region where the electrode pairs were placed respectively. Pulse amplitudes provided by the pulse generator, as shown on the y-axis, were used to calculate the internal field strength in the fish by a computer simulation of the experimental setup. The internal field strengths that correspond to the muscle activation threshold are provided in parentheses next to the whisker plots.

Larger fish appear to have a lower muscle activation threshold than small specimens, which is also concluded based on modelling shown chapter 4 where internal field strengths are higher in larger fish. The lowest muscle activation threshold, estimated as the internal field strength, was 15.1 V m^{-1} as found in the large Atlantic salmon class where the electrode pair was spaced at 40 cm. This threshold field strength can be compared to the internal field strength shown in Figure 6.4.

7.4 Thresholds for spinal injuries

Finally, muscle cramps/tetanus may occur if exposed to higher field strengths. The muscle cramps can cause spinal injuries and haemorrhages. Field strength thresholds for inducing spinal injuries have been reported to be >37 V m^{-1} in large Atlantic cod (*Gadus morhua*), whilst the field strength at which the probability is 50% is 80 V.m^{-1} (95% cl: 60 - 110 V.m^{-1}: de Haan et al., 2016). This threshold field strength can be compared to the electric field strength around an electrode pair when no fish is present.

Apart from pulse amplitude (field strength), the pulse frequency, pulsewidth (which are combined in the duty cycle), and pulse shape may affect susceptibility of fish to electrical-pulse induced injuries (de Haan *et al.*, 2016; Soetaert *et al.*, 2019). Muscle cramp / tetanus does not seem to occur if lower pulse frequencies area used. For example, pulse systems as used in the fishery for brown shrimp use a lower frequency of ~5 Hz which elicits an involuntary escape response whereby the shrimp jump into the water column whilst fish respond more variably, from no response to fast swimming, depending on the species (Desender *et al.*, 2016; Soetaert *et al.*, 2019). The low-frequency shrimp pulse did not cause spinal injuries in European plaice, common sole, Atlantic cod, bull-rout (*Myoxocephalus scorpius*), and armed bullhead (*Agonus cataphractus*) (Desender *et al.*, 2016). However, higher pulse frequencies could reduce the occurrence of spinal injuries, since de Haan *et al.* (2016) did not find injuries in large Atlantic cod exposed to 180 Hz.

8 Effect of pulse stimulation on marine organisms

8.1 Introduction

The pulsed bipolar (PBC) and pulse alternating current (PAC) used in pulse trawls that target common sole can affect organisms variably (Soetaert *et al.* 2015a, 2019). Exposure experiments with fish did not reveal injuries or mortality in sole (Soetaert et al., 2016a), European sea bass (Soetaert et al., 2018), small-spotted catshark (de Haan et al., 2009; Desender et al., 2017b), while no effect on ulcers was detected in dab (de Haan et al., 2015). Spinal injuries and heamorrhages were observed in exposure experiments with cod, but the frequency of occurrence varied substantially (de Haan et al., 2016; Soetaert et al., 2016b). Two preliminary studies, that explored the effect of worst-case exposure of 20 different benthic invertebrate species, did variable effects due to small number of animals tested (Smaal and Brummelhuis, 2005; van Marlen et al., 2009). A more elaborate study with shrimp and ragworm did not reveal any mortality or injuries (Soetaert et al., 2015a). A follow-up experiment exposed shrimp for 20 times during 4 days to electrical and mechanical exposure did not show consistent impacts (Soetaert et al., 2016c). ICES (2018, 2019) provides a review of the previous studies. The current report presents new data.

8.2 Laboratory experiment on the effect of pulse exposure on sandeel

Sandeels sampled from pulse trawls showed a relatively high incidence of spinal injuries (section 8.4). The observed incidence rate, however, may be biased due to a higher retention of injured sandeel in pulse trawls compared to undamaged sandeels. It is expected that due to their slender shape only few animals may be caught and most will pass through the net and escape through the codend meshes. In addition, spinal injuries may also be caused during the catching process. Hence the incidence rate estimated from sandeel retained in commercial nets is an unreliable indicator of the potential damage inflicted by pulse stimulation.

A laboratory experiment with two species of sandeels - lesser sandeel (*Ammodytus tobianus*) and greater sandeel (*Hyperoplus lanceolatus*) was conducted to further investigate the sensitivity of sandeel for pulse exposure. The sandeels were collected with a small-meshed shrimp trawl in the coastal waters off the Netherlands and kept in the laboratory for 3 days before the experiments. In the experiment, sandeels were exposed to a single bipolar pulse stimulus with a pulse frequency and pulsewidth corresponding to the pulse stimuli generated by the Delmeco and HFK system used in the commercial fishery (**Table 8.1**). Pulse exposure was 2 sec which is slightly higher than the 1.5 sec exposure in the commercial fisheries. Fish were exposed in groups of 10 fish. After exposure, each group was euthanized and stored for later investigation of spinal injuries by Rontgen photography and autopsy. Control treatments were included to distinguish between spinal injuries resulting from electrical stimulation and fish handling associated to the experimental procedures. Handling of control groups was identical with treatment groups except for the absence of electrical stimulation. The experimental set up is shown in **Figure 8.1**. Fish were put into a cage of 40*35cm placed between a pair of electrodes (conductor length = 18 cm; diameter = 26.4mm) and filled with a layer of sand of 5cm. Cage was constructed of nylon wired with a mesh size of 4 mm. The field strength was measured after the experiment using the methodology of (de Haan and Burggraaf, 2018). Since field strength is a function of the potential difference U over the electrodes and the distance r1 and r2 to the electrodes (U ~ V/(r1*r2): Sternin et al., 1976), the field strength was modelled for the surface of the sediment and the bottom of the cage. At the level of the sediment, field strength ranged between 28 V.m-1 close to the isolators to 800 V.m-1 close to the conductor. Median field strength was between 41 and 54 V.m-1. At the bottom of the cage at 5cm into the sediment, field strength is less variable and ranged between 27 and 90 V.m-1. Median field strength in the three experiments was between 38 and 49 V.m-1.

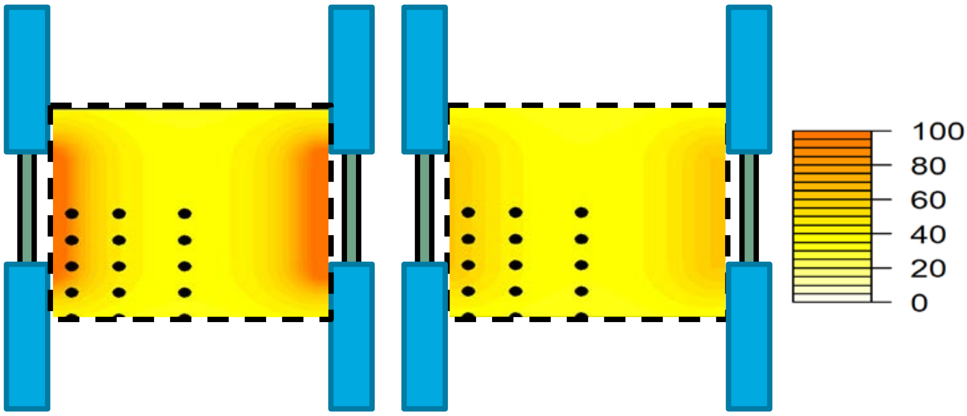

Figure 8.1. Field strength (V.m-1) in the experimental tank at the level of the sediment (left) and at the bottom of the cage at 5cm in the sediment (right). Black dots indicate the locations of the field strength measurements.

Three experiments were carried out with 253 lesser sandeel exposed to either the Delmeco pulse (pulse 1) or the HFK pulse (pulse 2 and pulse 3) and one experiment with 49 greater sandeel exposed to the Delmeco pulse. Spinal injuries were scored using the same methodology used to score the samples from commercial vessels. In two of the 230 sandeel exposed to a pulse stimulus a spinal injury was recorded against none in the 211 sandeel that were handled but not exposed (**Table 8.2**). Haemorrhages, as can observed in cod with spinal injuries due to electrical stimulation (de Haan et al., 2016), were not observed. Given the low injury rate of exposed sandeel in our experiment, we conclude that the high injury rate observed sandeel sampled from commercial pulse and tickler chain beam trawlers are likely due to mechanical damage inflicted during the catch process and subsequent processing of the catch on deck. The injury rate observed in commercial pulse and beam trawls may also be raised due to a higher retention probability of injured sandeel. The current results suggest the same for great sandeel but number of observations is too low for final conclusions.

Table 8.1 Pulse parameters used in the sandeel experiments and the field strength measured in the cage at the surface of the sediment and at 10cm into the sediment. Note that the maximum burying depth in the cage was restricted to 5cm.

Treatment	Pulse frequency (Hz)	Pulse-width (µs)	Voltage (V)	Field strength (V.m-1) at sediment			Field strength (V.m-1) at bottom of cage (5cm in sediment)		
				min	median	max	min	median	max
Pulse 1	40	263	43.5	28.5	40.8	607	27.3	37.5	68.6
Pulse 2	30	330	52.5	37.4	53.5	796	35.8	49.1	89.9
Pulse 3	30	330	43.5	28.5	40.8	607	27.3	37.5	68.6

Table 8.2 Spinal injury rate (%) per species and treatment.

Experiment	Species	Treatment	Total no. of tests	No. fish / test	Total no. of fish	Injury rate (%)
1	Lesser sandeel	Pulse 1	10	10	103	1.0
		Control	10	10	100	0

2	Lesser sandeel	Pulse 2	10	10	101	1.0
		Control	10	10	101	0
3	Greater sandeel	Pulse 1	4	5	17[1]	0
		Control	2	5	10	0
4	Lesser sandeel	Pulse 3	4	10[2]	49	0
		Control	0	0	0	No data

1) In one test 3 fish were used. 2) In one test 9 fish were used.

8.3 Laboratory experiment with benthic invertebrates

8.3.1 Response of benthic invertebrates to pulse exposure

Concerns exist regarding possible negative impacts of the electrical stimulus on benthic invertebrates (ICES, 2018c; Quirijns et al., 2018). Invertebrates are exposed to high electric field strengths between the electrodes arrays (de Haan *et al.*, 2016; de Haan and Burggraaf, 2018). This may lead to direct mortality but also indirect mortality due to injuries and increased predation risk related to behavioural changes (e.g. (Kaiser and Spencer, 1994; Hiddink et al., 2017; Sciberras et al., 2018). Effect of electrical stimulation on locomotor performance was studied in six benthic invertebrate species from four different phyla: common starfish (*Asterias rubens*; $n_{control} = 44$, $n_{treatment} = 41$), serpent star (*Ophiura ophiura*; $n_{control} = 21$, $n_{treatment} = 21$), common whelk (*Buccinum undatum*; $n_{control} = 46$, $n_{treatment} = 41$), sea mouse (*Aphrodita aculeata*; $n_{control} = 45$, $n_{treatment} = 43$), common hermit crab (*Pagurus bernhardus*; $n_{control} = 43$, $n_{treatment} = 43$), and flying crab (*Liocarcinus holsatus*; $n_{control} = 46$, $n_{treatment} = 44$) (Boute *et al.*, under review).

Species-specific acute behaviour was described during and immediately after a worst-case electrical stimulation. In addition, the effect of electrical stimulation on species-specific behaviours was quantified that may indicate prolonged changes to predation risk, including righting reflexes and locomotor activity such as walking and burying. These behaviours were quantified before and after electrical stimulation and compared to the behaviour of animals in a non-exposed control group. Finally, animal survival was monitored up to 14 days after exposure. The electrical stimulus was a 3 second square-shaped Pulsed Bipolar Current at a frequency of 30 Hz and pulsewidth of 0.33 ms. The field strength was 200 $V\ m^{-1}$ (V_{pk} on plate electrodes = 86 V) which is similar to the field strength directly adjacent to a commercial electrode (de Haan *et al.*, 2016). Pulse waveform is described as 30 Hz PBC (*PW* = 0.33 ms, *PB* = 16.34 ms) (Soetaert *et al.*, 2019).

Responses during stimulation varied from no effect (starfish and serpent star) to moderate squirming (sea mouse) and fast retractions (whelk, hermit crab, flying crab). Within 30 s after stimulation, all animals resumed normal behavioural patterns, without signs of lasting immobilization. About two-thirds of the whelk (63%) ejected a white substance during or immediately after stimulation, presumably related to reproduction. No indications were found for compromising changes in righting reflexes and locomotor activity, except for significantly increased righting reflex duration after electrical stimulation in hermit crab due to increased retraction times. Animal survival was not negatively affected. These findings suggest that electrical pulses as used in pulse trawling are unlikely to substantially affect the behaviour and survival of the investigated species.

8.3.2 Laboratory experiment on the effects of burrowing organisms

The effect of electrical exposure on non-target burrowing organisms was of particular interest. Animals residing in greater sediment depths may escape the mechanical effects of bottom-trawl gears but can still be affected by the electrical fields which has been shown to penetrate the seabed (de Haan and Burggraaf, 2018). These organisms also carry out important functions such as bioirrigation (pumping water into the sediment) and bioturbation (sediment mixing) which strongly influence benthic habitat characteristics (Volkenborn and Reise, 2006; Volkenborn et al., 2007).

Experiments were conducted to investigate the effect of electrical exposure on bioirrigation behavior and movement of a common ecosystem engineer, *Arenicola marina*. Animals were left to burrow in the sediment inside narrow aquariums. Sediment oxygen levels and organism activity was monitored before and after exposure to electrical pulses using a planar optode oxygen sensor and high resolution pressure sensors. Twenty-six individuals were exposed to a homogenous electrical field (200 V/m) using a square shaped pulsed bipolar current (PBC) with a pulsewidth (PW) of 0.33 μs and a frequency of 30 Hz in order to simulate the electrical exposure of an animal found directly next to an electrode (worst case scenario) used in the sole flatfish electrofishery. After a 3 day acclimatization period, measurements were started for one day without electrical exposure. For the following 3 days, organisms were subject to one 3 second PBC exposure per day. Respiration measurements were taken for an additional 80 individuals which were either exposed to 3 seconds of PBC or used as controls.

A muscle cramping response from *A. marina* was observed upon electrical stimulation, however, the vast majority of these animals resumed burrowing and pumping activity within a 5-10 minutes (Figure 8.2). Electrical exposure temporarily halted bioirrigation activity which led to a momentary decrease in oxygen levels inside the macrofauna burrows before pumping behaviour resumed (Figure 8.3). Respiration rates per unit biomass for individuals exposed to PBC compared to controls were not significantly different.

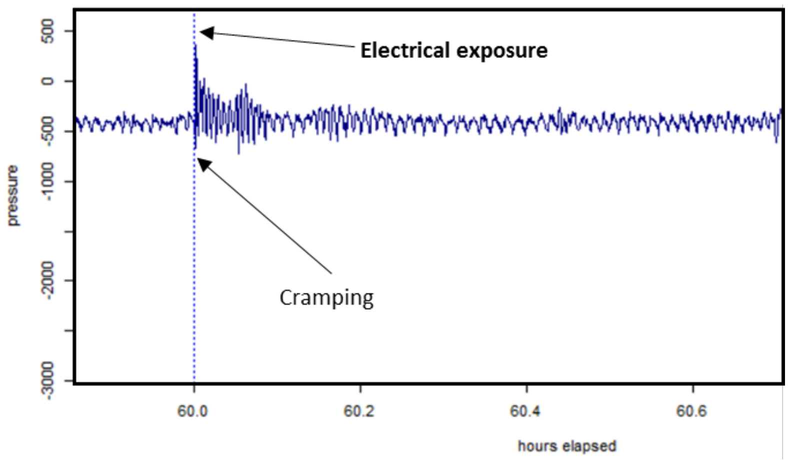

Figure 8.2. Example of *A. marina* activity and response to electrical exposure as observed through high resolution pressure sensors in the sediment.

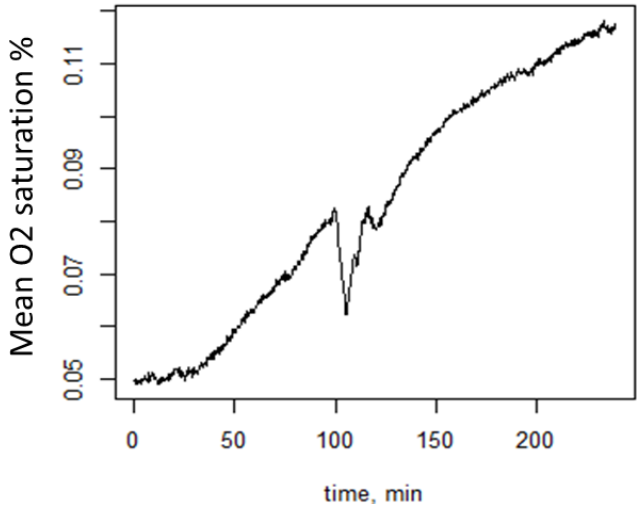

Figure 8.3. Oxygen saturation levels inside an *A. marina* burrow. The temporary decrease in oxygen saturation occurred directly after electrical stimulation.

An experiment examining the response of *Arctica islandica* to electrical stimuli (6 exposures over 2 months; 200 V/m, PBC, PW = 0.33 μs, 40 Hz, 3 s exposure time), measured the opening and closing activity of the bivalves using valve gape sensors. Individuals with open valves (shells) immediately shut their valves upon electric exposure. Some individuals remained closed for several days, however, other individuals opened their valves within minutes after exposure. As this long lived species may remain dormant for several weeks in natural conditions (Ballesta-Artero et al., 2017), it is not clear if electrical exposure led to prolonged inactivity. There were, however, some instances when electrical exposure appeared to cause the valve opening of previously inactive individuals. No mortalities were recorded and at the time of writing, all experimental organisms (8) are currently alive in an animal housing facility one year after the commencement of the study.

Conclusion

The fact that no mortalities were observed from direct electrical stimuli, indicates that electrical impacts on non-target species are non-lethal. Claims of burrowing organisms coming out of the sediment in response to electrical exposure are not supported by these studies though some evidence of increased burrowing behaviour was observed with *A. marina*. The results suggest that non-lethal effects and possible biogeochemical consequences (i.e. declines in sediment oxygen levels) due to changing behaviour are temporary. Compared to trawl-induced mechanical impacts, the effects of electrical exposure to macrofaunal functioning seem to be minor.

8.4 Field study on injury probability in fish caught in pulse and tickler chain trawls

The electric field near to the electrode array, within the trawl track, induces muscle cramps in the fish (Soetaert *et al.*, 2019). These muscle cramps may consequently lead to spinal injuries and haemorrhages (van Marlen *et al.*, 2014; de Haan *et al.*, 2016; Soetaert *et al.*, 2016a, 2016b, 2016c, 2019). In addition to pulse-induced injuries, internal injuries may also be caused by an external mechanical load acting on the body of the fish. Various parts of the catch process can cause mechanical loads to act on the fish body (e.g. components of the fishing gear, debris in the netting, towing speed, and hauling on deck). Especially injuries in small specimens, which may not be retained in the netting, may lead to indirect mortality after a trawling event due to sustained injuries and increased predation risk (Kaiser and Spencer, 1994; Kaiser and Spencer, 1995; Kaiser and Spencer, 1996). Direct and indirect mortality can, in turn, change species population dynamics and foodweb structure (Kaiser et al., 2002; Collie et al., 2017). To model direct and indirect mortality in population and foodweb models, it is essential to quantify internal injuries in fish resulting from capture methods, especially in small specimens.

The occurrence of internal injuries in target and non-target species was determined from samples collected on board of commercial pulse trawlers (9 vessels) and compared to internal injuries in fish collected from pulse trawls with the pulse stimulation switched off (5 hauls of 3 vessels), and from conventional beam trawlers using tickler chains (2 vessels) (Boute *et al.*, in prep). To detect spinal injuries, all fish were X-rayed laterally and, in the case of roundish, dorsoventrally. Hereafter, the fish were filleted to reveal internal haemorrhages. Spinal abnormalities were categorized on a 5-point scale as described in ICES (2018). Spinal abnormalities in category 1 and 2 were excluded from further analysis, since these have not been related to electrical-pulse induced injuries in laboratory exposure studies (Sharber et al., 1994; Soetaert et al., 2018).

The percentage of fish with at least one spinal injury of categories 3 to 5 are provided in **Table 8.3** per species and catch method (Boute *et al.* in prep). These spinal injuries correspond to those previously reported in experimental studies (van Marlen *et al.*, 2014; de Haan *et al.*, 2016; Soetaert *et al.*, 2016b, 2016a). Our results corroborate that Atlantic cod (*Godus morhua*) is sensitive to pulse-induced injuries, as has previously been found in laboratory studies (de Haan *et al.*, 2016; Soetaert *et al.*, 2016b, 2016a), and field studies (van Marlen *et al.*, 2014; Soetaert *et al.*, 2016c). Atlantic cod do not appear highly sensitive to mechanically induced injuries.

In most other species, both roundfish and flatfish, relatively low spinal injury probabilities were found. No clear difference was found in the injury probability between pulse-on and pulse-off caught fish for dab, plaice, grey gurnard and whiting. For tub gurnard a spinal injury was observed in 3 out of 249 tub gurnards caught with the pulse-on, but none in 67 tub gurnards caught without the electrical pulse stimulus. The sample size is too low to draw any firm conclusion. The probability of spinal injuries observed in conventional beam trawl catches was at the same level as observed in pulse trawl caught fish, or slightly higher. In lesser sandeel (*Ammodytes tobianus*) and greater sandeel (*Hyperoplus lanceolatus*), however, injury probability in both the pulses on and tickler chain catches are elevated. Since injury probability in the tickler chain catches are highest, we expect that these injuries are likely caused by mechanical stimulation. As these species are relatively slender and elongated, a potential selection bias of injured specimens in the 80 mm meshes of the codend could result in an overestimation of the injury probability.

The injury probability of fish sampled from pulse trawls and conventional beam trawls shows that injury probability is higher in conventional beam trawls in five species (Figure 8.4). In the graph the two sandeel species were pooled and only species with more than 100 animals sampled were included.

Table 8.3. Percentage of fish with at least one spinal injury by species and catch method. The spinal injuries taken into account correspond to injuries previously reported in studies focusing on pulsed-induced injuries in marine electrotrawling (van Marlen *et al.*, 2014; de Haan *et al.*, 2016; Soetaert *et al.*, 2016b, 2016a). The number of fish sampled is indicated between parentheses.

Species	Pulses on	Pulses off	Tickler chain beam trawl
Atlantic cod	36.4 (475)	0 (1)	1.0 (100)
Bull-rout	0 (17)	No data	0 (1)
Callionymus spp.	0 (147)	No data	0 (27)
Common sole	0.7 (824)	No data	2.9 (349)
Dab	0.3 (765)	0.6 (637)	0.7 (812)
European plaice	0.2 (1684)	0.2 (1629)	0.5 (1006)
European sea bass	1.0 (102)	No data	No data

Greater sandeel	11.0 (539)	No data	42.4 (33)
Grey gurnard	0.3 (1009)	1.8 (56)	0.1 (765)
Lesser sandeel	8.3 (48)	No data	24.2 (99)
Lesser weever	1.0 (98)	No data	No data
Pouting	0.6 (352)	No data	0 (5)
Solenette	0 (14)	0 (3)	0 (8)
Surmullet	0 (21)	No data	0 (9)
Tub gurnard	1.2 (249)	0 (67)	0.9 (224)
Whiting	1.1 (2629)	1.0 (586)	2.6 (1148)

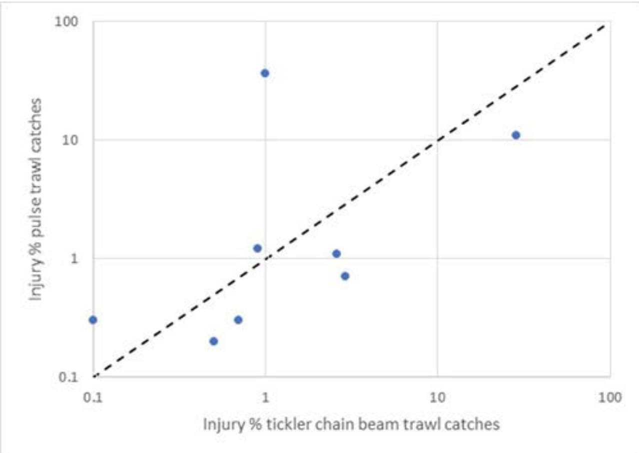

Figure 8.4. Comparison of the injury rate (% of fish sampled) in different fish species in tickler chain beam trawl catches and pulse trawl catches (pulse-on). Species plotted if the sample size was >100 fish per gear. Data of lesser and greater sandeel were combined. Data from Table 8.3

8.5 Size dependence of spinal injuries in cod

In Atlantic cod, the spinal injuries are likely caused by the pulsed electric field that elicits muscle cramps. These injuries may occur on top of mechanically induced injuries in pulse trawls. If these pulse-induced injuries occur in small specimens that could escape the net after exposure, this could have implications for the population dynamics. Hence, it is relevant to check whether injury probability is fish-length dependent. The effect of standard length (SL) on the spinal injury probability (P) was analysed using a generalized additive model:

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

Where s(SL) is the smoother for standard length SL, B is the factor representing the different pulse trawlers ($n = 7$), and ϵ is the binomial distributed error term (model choice based on lowest AIC). The model explains 7.54% of the deviance in the data. The effect of pulse vessel was significant as well as the effect of fish length ($p < 0.01$). **Figure 8.5** shows that the injury probability is highest for intermediate sized cod and decrease for smaller and larger sized cod.

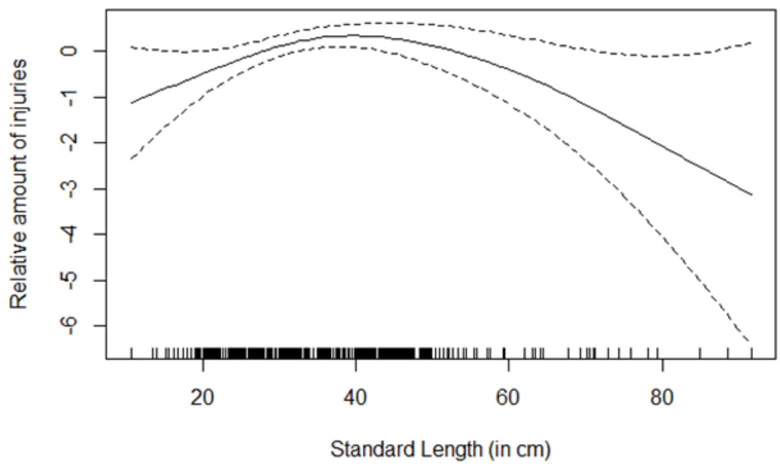

Figure 8.5. Generalized additive model showing the relationship of incidence rate of spinal injuries in relation to standard length in Atlantic cod (*Gadus morhua*) (n=475). These Atlantic cod were caught by pulse trawlers using the electrical stimulus.

8.6 Field sampling in the track of a pulse trawler

Concerns have been expressed that pulse trawling may cause direct, mass mortality among benthic organisms, resulting in a 'graveyard' in the wake of a pulse trawler (Quirijns et al., 2018). Schram and Molenaar (2019) conducted a field experiment to investigate this concern by sampling the track of a pulse trawl vessel with a small mesh shrimp trawl within 15 to 30 minutes after passage of the trawl. Two type of pulse tracks were created: a complete pulse trawl (electrical and mechanical exposure) and a pulse trawl with its netting and groundrope removed (electrical exposure and minimal mechanical exposure). Control samples were collected for each treatment outside the trawl track. The condition of three fish species and three species of invertebrates was assessed. Fish species included plaice (*Pleuronectus platessa*), dab (*Limanda limanda*) and solenette (*Buglossidium luteum*). Invertebrate species included flying crab (*Liocarcinus holsatus*), hermit crabs (*Paguroidea spp.*) and brittlestars (*Ophiuroidea spp.*). Direct survival ranged from 91-100% among treatments for the fish and 88-100% for the invertebrates. No significant differences in survival were detected between the two treatments and their respective controls for any of the species.

Underwater video observations confirmed deployment of the sampling trawl inside the pulse trawl tracks, although part of swept-area was outside the pulse trawl tracks. However, also when correcting the observed direct mortality for this, no differences between treatments and controls were detected.

The study shows that with the right equipment, skilled skippers and a calm sea, it is possible to collect biota samples from a trawl track within one hour after trawling. However, it is very difficult to sample exclusively from a pulse trawl track; it is inevitable that part of the area swept by a sampling tow lies outside the pulse trawl track aimed for. Despite these limitations, any direct mass mortality caused by a passing pulse trawler would have been recorded in the current study, not only for the systematically observed species but also for other species in the samples.

9 Effect of pulse trawling on benthic ecosystem functioning

Bottom trawling disturbs the seabed and affects biogeochemical processes. As changes to biogeochemical dynamics on the seafloor may affect benthic pelagic coupling and primary production in the water column, these effects may extend well beyond the benthic region (Nedwell et al., 1993). Possible chemical changes due to electrolysis by pulse trawling was also topic of concern due to the potentially harmful substances which may be released into marine habitats (Soetaert et al., 2015).

9.1 Effect of electricity

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 movement of porewater ions, facilitate the consumption of oxygen and can alter the nutrient dynamics in marine sediments (Risgaard-Petersen et al., 2012; Rao et al., 2016). Marine electrofishing features different combinations of electric parameters (pulse type, length, duration etc.; Soetaert et al., 2019). The longer a given piece of seafloor is subjected to a unidirectional current, the more likely it is to experience electricity-induced biogeochemical changes.

A study was conducted to experimentally isolate the biogeochemical consequences of the effects of electricity and mechanical disturbance (Tiano et al., in prep). Sediment was collected from 11 locations in the North Sea (9) and Dutch Eastern Scheldt (2) and were subjected to electrical or mechanical stressors. Electric treatments included short (3 seconds) and long (120 seconds) term exposures using PBC (PW = 0.33 μs, 40 Hz) and PDC (PW = 0.33 μs, 80 Hz). This study did not find evidence linking electrical pulses used in the pulse trawling for sole (3 s exposure time, PBC) to changes in biogeochemical characteristics (Figure 9.1; left). Even with 1+ minute PBC exposure times, no changes to pH or nutrient dynamics could be detected. This due to the bi-directional flow of electrons limiting impacts from chemical reactions or electrolysis and short pulse duration (average 1.5 sec, section 6). Prolonged (1+ min) exposure to high frequency (80 Hz) pulsed direct currents (PDC), however, caused decreases in water column pH, phosphates and the formation or iron oxides (Tiano et al. *in prep*). Sole pulse trawling does not seem to induce significant electrochemical reactions (using PBC), though, the 1+ minute exposure times seen in razor clam electrofishing will cause some electrolysis if a continuous direct current (DC) or high frequency (> 40 Hz) PDC is used.

9.2 Effect of resuspension

Mechanically induced sediment resuspension in the previously mentioned study, showed a rapid release of ammonium, phosphates, and silica from the seabed after physical mixing (Figure 9.1). Resuspension also led to declines in O_2 concentrations and pH in the water column. The magnitude of these changes are related to grain size and concentrations of fresh organic material (i.e. chlorophyll-a) in the sediments (Tiano et al. *in prep*). The results suggest that the trawl-induced release of nutrients may be consistent and conspicuous but relatively short lived (< 8 h) as most of the longer term solute flux rates after disturbance did not show significant alterations (Figure 9.1; Tiano et al. *in prep*). These results also imply that mechanical impact from pulse trawling (and traditional beam trawling) has a much greater influence on biogeochemical dynamics than effects from electricity.

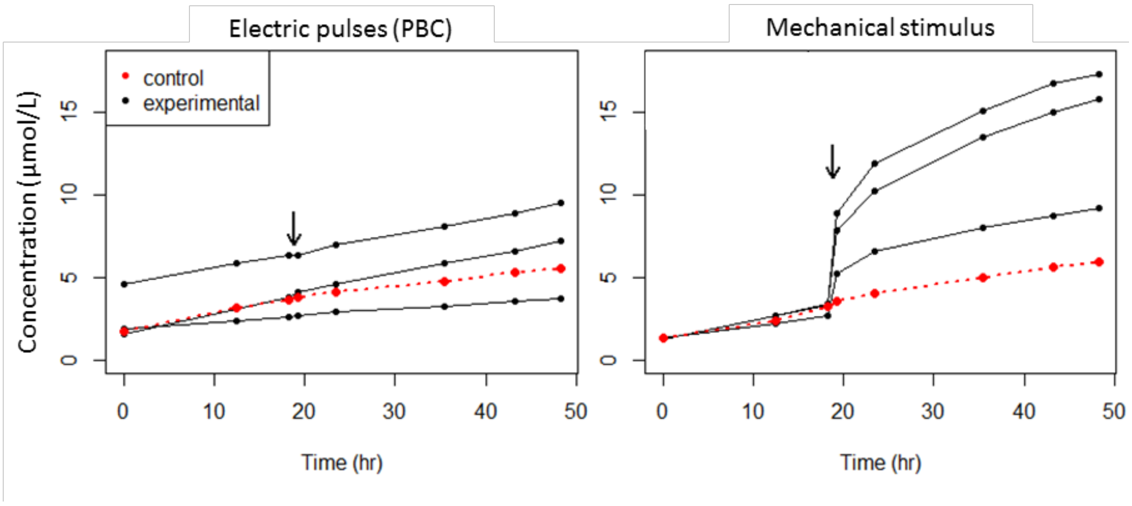

Figure 9.1. Comparing electrical (left) and mechanical (right) stressors on the release of silica concentrations from the sediment.

9.3 Effect of mechanical disturbance

It is well known that bottom trawling can cause direct mortality of biota which will affect the biomass and species composition of the benthic community. Trawling will shift benthic community composition to shorter lived taxa (van Denderen et al., 2014; van Denderen et al., 2015). The sensitivity of benthic communities differs among habitats and is related to the degree of natural disturbance with communities in stable environments being more sensitive than communities living in shallow waters exposed to high bed shear stress (Rijnsdorp et al., 2018a; Hiddink et al., 2019). Several studies have attempted to estimate the mortality imposed by a trawling event with a beam trawl (Bergman and Hup, 1992; Bergman and van Santbrink, 2000). Direct mortality estimates are quite variable between studies due to the huge variability in abundance of benthos and differences in the sensitivity of trawling among species.

Meta-analysis of published literature showed that the mortality rate differed between fishing gears and was related to the depth of penetration of the gear into the sediment (Hiddink et al., 2017; Sciberras et al., 2018). The median mortality rate imposed by a tickler chain beam trawl was estimated at 0.14 (95%range: 0.07 – 0.25; Hiddink et al., 2017). Since the penetration depth of the pulse trawl gear is less than 50% of the penetration of the conventional beam trawl (Depestele et al., 2018), it is expected that the mortality imposed by the mechanical disturbance of the pulse trawl will be 50% lower.

9.4 Field studies of impact pulse trawls

Bergman and Meesters (2020) studied the direct mortality of three different beam trawls, including a conventionally rigged beam trawl with tickler chains, a beam trawl rigged with longitudinal tickler chains and a pulse trawl rigged with longitudinal electrodes. Mortality differed significantly between the three gear types, with the lowest mortality found for the pulse trawl and the highest for the longitudinal rigged beam trawl. The mortality imposed by the pulse trawl was 43% less than the conventional rigged beam trawl, close to the expected 50%, although the difference was not significant. Another study looking at smaller infaunal taxa in the Frisian Front found significant impacts from both pulse trawls (PulseWing) and tickler chain rigged beam trawls with no discernible differences between the fishing methods (Tiano et al., 2020). A study comparing epifauna in inshore (no pulse trawling) and offshore (pulse trawling) zones of the English coast found some differences in diversity and benthic community composition though due to the fishing history of the region it is difficult to attribute this to the effects of pulse trawling or other bottom-trawling activities (Ford et al., 2019).

9.5 Field experiments on biogeochemical effects

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., 2019). The study compared the impact of both electric pulse fishing and traditional beam trawl methods with tickler chains. Benthic landers were deployed and boxcore sediment samples were collected to measure rates of oxygen consumption and nutrient fluxes in fished and unfished areas. On average, traditional beam trawling produced larger and more consistent impacts on sediment oxygen consumption, oxygen micro-profiles and sediment chlorophyll levels. Pulse trawling had lower yet more variable effects for these measurements. Both fishing gears significantly reduced the total benthic metabolism from the sediments as caused from the decrease in chlorophyll-a (proxy for fresh organic material; Figure 9.2). This led to lower biological activity in the sediment as evidenced with the greater sediment oxic layer found after trawling activity (Figure 9.3; Tiano et al., 2019).

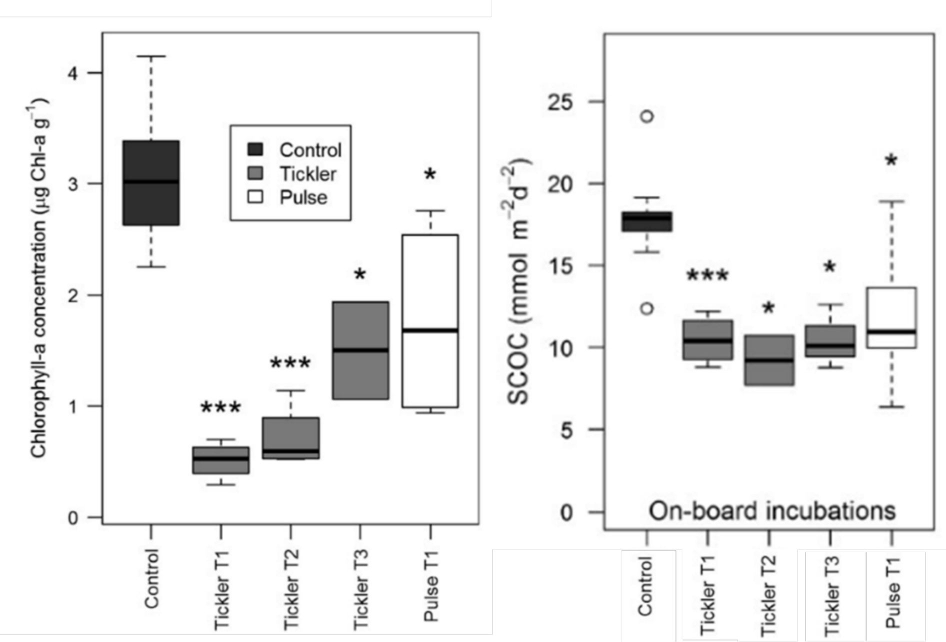

Figure 9.2 Biogeochemical impact from tickler chain beam trawls vs. electric pulse trawls for chlorophyll-a (left) and sediment community oxygen consumption (SCOC; right). ***Figure adapted from Tiano et al. 2019***

In June 2018, an extensive field campaign in a nearshore area (Vlakte van De Raan) was carried out to determine the effects of pulse fishing and beam trawling in a high energy habitat. Multiple trawled areas were fished with a beam trawler (3x areas) and a pulse trawler (3x areas with the electricity turned on, 3x with the electricity turned off). Information was collected with multibeam sonar, SPI camera and benthic samples (incubation cores/macrofauna data). In addition to this, samples were taken from three nearby transects passing through areas of high and low fishing intensity. Results in this dynamic habitat showed high variability within the experimental locations and only some evidence of fishing effects were found for both gears. Information from fishing intensity transects suggest that trawlers prefer to fish in biogeochemically active areas (Tiano et al. *in prep*).

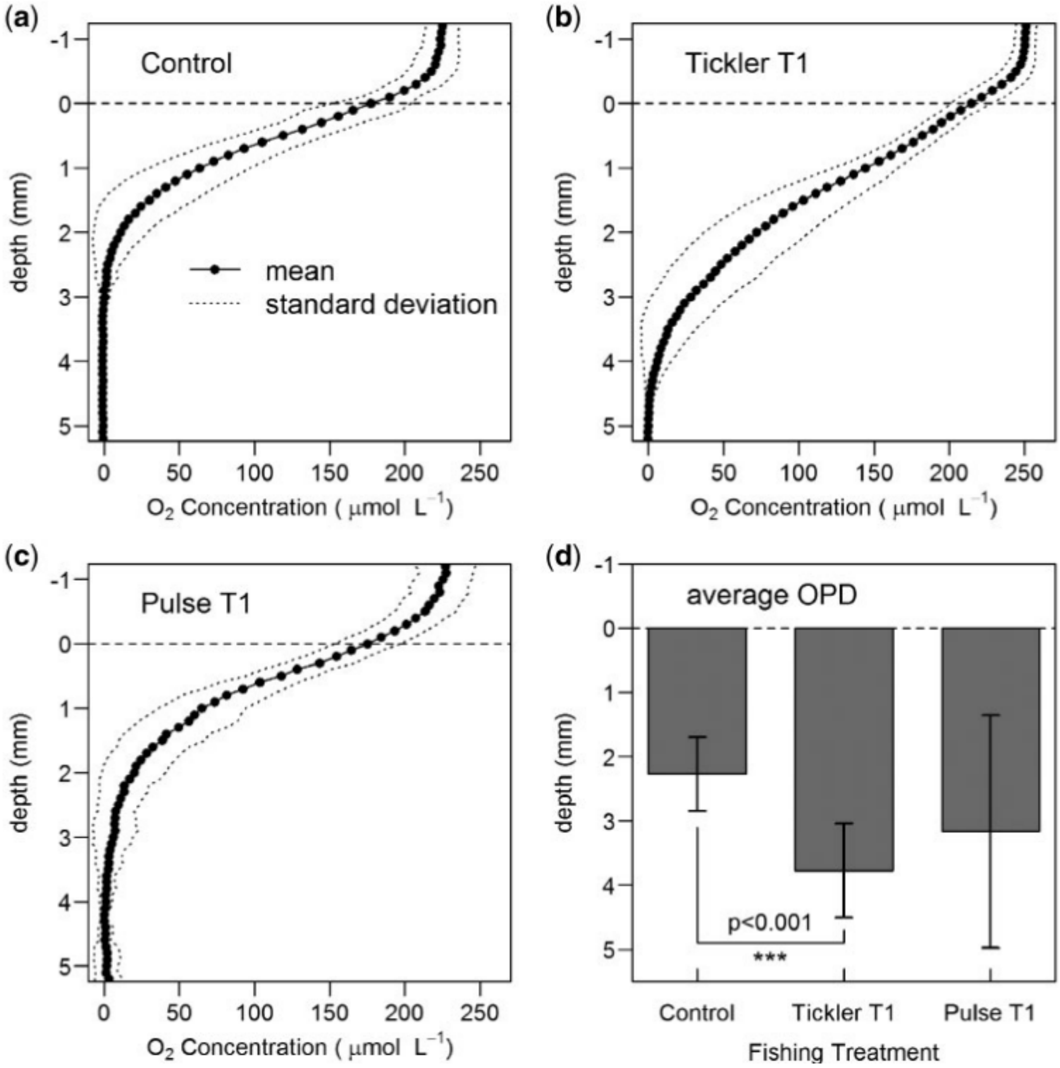

Figure 9.3. Oxygen microprofiles for (a) control, (b) tickler T1, and (c) pulse T1 areas. (d) Average O2 penetration depth (mm) and standard deviation from each treatment. *Figure from Tiano et al. 2019.*

9.6 Conclusion

Bipolar and AC pulse stimulation does not seem to affect the biogeochemical processes

Bidirectional pulses seen in PBC and PAC seem to limit biogeochemical reactions from occurring. In addition, electrolysis is also limited when using low frequency (5 Hz) PDC parameters, as seen in the shrimp pulse fishery (Tiano unpublished research). Only high frequency pulse DC (40+ Hz) or continuous DC have the potential to create electrochemical changes. It is not clear, however, if these changes are likely to be harmful. Electrolysis in the marine environment is used to "grow" calcium carbonate structures for reef restoration (Goreau, 2012). Though potentially harmful chlorine gas is formed in this process, it seems to be neutralized quickly in the marine environment and several observations have been made of organisms residing in close proximity to where the chlorine is produced on these structures (Goreau, 2012). Because the sole fishery uses a PBC the potential effect of electrolysis is negligible.

Effects of pulse trawling are only related to mechanical disturbance

Since our studies did not detect any measurable effect of pulse exposure, it is likely that the benthic disturbance caused by pulse trawling comes from mechanical disturbance. As pulse trawls exert a lower mechanical impact compared to beam trawls (Depestele et al., 2018, 2016; Rijnsdorp et al., 2020a), its effects on benthic biogeochemistry will also be reduced on average but not eliminated (Tiano et al., 2019).

What are the main impacts on ecological functions of the benthic ecosystem?

Benthic macrofauna (sediment inhabiting animals larger than 1 mm) support demersal fisheries by supplying the main food supply (Amara et al., 2001). The feeding, respiration and movement of these animals also mixes and pumps oxygen into the sediment, which facilitates important biogeochemical functions such as nutrient release via benthic-pelagic coupling(Mermillod-Blondin and Rosenberg, 2006). The sedimentary release of nutrients fuels pelagic primary production and thus has an important impact on the system's productivity. Within the marine realm, sediments are also the main sites where reactive nitrogen (Soetaert and Middelburg, 2009) and phosphorus (Slomp et al., 1996) are removed, thus buffering marine habitats against eutrophication. Removal of nutrients from the marine system also prevents or reduces the extent of low oxygen zones, which often result from nutrient overloading. As their occurrence is predicted to increase in the North Sea (Weston et al., 2008), the buffering ability from the sediment is becoming increasingly important.

Pulse trawling like other fisheries using bottom-trawls, dredges or seines (Eigaard et al., 2016), and other forms of anthropogenic activities that cause the mechanical disturbance to the seabed, have the potential to disrupt the natural cycling of nutrients. By removing and resuspending the organic material from the seabed, the benthic metabolism and denitrification is reduced (Ferguson et al.; Tiano et al., 2019). This lessens the nutrient cycling capacity of the sediments and can leave an ecosystem more vulnerable to eutrophication.

10 Scaling up the effect of pulse stimulation to the fleet

In order to compare the ecosystem effects of the conventional beam trawl and the pulse trawl, the effects of mechanical stimulation and electrical stimulation need to be scaled up to the total fleet. The impact of both gears was compared by studying the impact of the Dutch pulse license holders before and after the transition to pulse trawling (Rijnsdorp et al., 2020c). The PLH can be used as a proxy of the total fleet because they landed 95% of the Dutch sole landings after the transition. The study area is confined to the part of the North Sea where the beam trawl fishery is allowed to use 80mm codend mesh: e.g. between 51oN and the demarcation line running from west to east at 55oN, west of 5oE, and 56oN, east of 5oE.

The impact of the two gears is assessed for a selection of marine organisms and habitats. Sole is included as it is the main target species of the fishery. Plaice is included because it is an important commercial bycatch species. Plaice and dab are both an important component of the discard fraction. Special attention is given to cod because of the poor status of the stock in the North Sea and the possible sensitivity for pulse stimulation that may pose an additional source of mortality on early life stages that may be exposed to the pulse but that are not retained in the gear. A particular concern has been raised about the possible adverse effects of non-lethal exposure on the reproductive capacity of sole. Rays and sharks are included because they may be sensitive for electric pulses due to their dependence on their electro-sense organs for finding food and navigation. The thornback ray *Raja clavata* is included because it is the dominant ray species in the southern North Sea. The main soft sediment habitats (Eunis level 3 habitats: A5.1 coarse sediment; A5.2 sandy sediment; A5.3 muddy sediment; A5.4 mixed sediment) are used to assess the impact on the seafloor and benthic habitats. The selected species and species groups represent different ecosystem components and habitats that are relevant with regard to the management under the Common Fisheries Policy (CFP), the Landing obligation (LO), the Marine Strategy Framework Directive (MSFD) and the Birds and Habitat Directive (BHD). The species are also related to specific concerns that have been raised about possible adverse effects of pulse fishing (Kraan et al., 2015; Quirijns et al., 2018).

10.1 Methods

The impact of trawling (I) is determined by the probability that an organism/habitat will encounter a trawl (p) and the effect of an encounter event on the organism/habitat (m).

$$I = pm \qquad [1]$$

The impact of a trawling event occurs at the scale of the gear. In order to scale up the effect of the impact of a single event to the level of the study area, we estimated the encounter probability (p) from the overlap in the distribution of the organism/habitat and the fishery. If b_i is the biomass proportion in grid cell i, f_i is the fishing effort in grid cell i, p is given by:

$$p = \sum_{i=1}^{n} b_i f_i / \sum_{i=1}^{n} f_i \qquad [2]$$

The trawling intensity t_i is estimated as the ratio of the swept-area over the surface area of the grid cell (s_i) where the swept-area is estimated as the product of the effective width of the trawl (w), the towing speed (u) and the number of fishing hours (h).

$$t_i = wuh_i / s_i \qquad [3]$$

The effective width is equal to the gear width when dealing with mechanical disturbance. In case of pulse exposure, the effective width of the gear is equal to the width of the electric field above the sensitivity threshold. If n is the number of electrodes, d is the distance between the electrodes and e is the distance to the nearest conductor where the field strength exceeds the sensitivity threshold, the effective width for pulse exposure is given by

$w = 2ne$ if e< half the distance between electrodes [4]

$w = (n-1)d + 2e$ if e>= half the distance between electrodes [5]

The fishing mortality (F) imposed by a fishery on a population in a study area comprising of n grid cells is calculated from the biomass proportion (b_i), trawling intensity (t_i), effective gear width (w), physical gear width (W) and the catchability coefficient (q) of the gear

$$F = \sum_i^n \left(qb_it_i\frac{w}{W}\right) \quad [6]$$

10.1.1 Spatial scale of the analysis

The spatial scale used in the upscaling differed between the analysis. For the impact assessment on the fish and discards, we used the spatial resolution of the ICES rectangle (0.5 degrees latitude, 1 degree longitude). For the analysis of the impact on the seafloor and benthic ecosystem, a resolution of 1 minute latitude x 1 minute longitude is used.

10.1.2 Cohort analysis

The population dynamic consequences of pulse exposure was investigated by applying a length based cohort analysis. The length based cohort methodology (Jennings et al., 2001) describes how the numbers and biomass of a cohort changes due to body growth and natural and fishing mortality. Body growth is described by the von Bertalanffy growth equation and modelled in steps of 1 cm. With information on the size selectivity of the fishing gears and the minimum landing size, the proportion of each size class retained in the codend can be estimated and allocated to the discard or landing fractions. Different fishing mortality scenarios were compared using spawning-stock biomass and yield as indicators assuming constant recruitment.

10.1.3 Data

To assess the impact of the transition on the exposure probability of the fleet to the species / species group, the relative biomass distribution of the species / species groups was estimated from the BTS survey data (downloaded on 4 August 2019 from ICES DATRAS database) by ICES rectangle and corrected for the dependence of the survey gear efficiency on body size (Walker et al., 2017). Catch rate (weight per km^2) was estimated by ICES rectangle and year, and the relative biomass distribution was then calculated for the study period 2009-2017. The rationale for using an average distribution pattern is that we are interested to quantify the consequences of the gear transition independent of possible changes in the fish distribution during the transition period.

IBTS survey data were analysed to estimate winter and summer distribution of 10cm size classes of cod. Mean cpue (weight per hour) was estimated by ICES rectangle by year and season, and averaged over the years to obtain an average distribution in the study period.

10.2 Results

10.2.1 Exposure

To estimate the proportion of a population that is exposed to a pulse or conventional beam trawl information is required on the intensity and distribution of trawling. Under the assumption of an effective width is equal to the physical width of the trawl, the information is captured in the trawling intensity profile that shows the cumulative proportion of the grid cells trawled at a certain minimum trawling intensity. Figure 10.1 shows that in 2009 the PLH trawled 60% of the grid cells in the SFA. In 10% of the grid cells trawling intensity was higher than 1 $year^{-1}$, whereas in 50% of the grid cells trawling intensity ranged between 10^{-2} and 10^{0} $year^{-1}$. After the transition to pulse trawling in 2017, the PLH trawled fewer grid cells (about 54%) and reduced the trawling intensity throughout the trawled grid cells. The analysis was carried out using a resolution of 1 minute latitude x 1 minute longitude (2.1 km^2 at 52^oN). At this resolution, beam trawl effort is randomly distributed when assessed annually in most of the grid cells, but will tend towards a uniform distribution when assessed over longer time periods (Rijnsdorp et al., 1998; Ellis et al., 2014; Eigaard et al., 2017).

Under the assumption of a random distribution of trawling activities within a grid cell, the probability that an organism is exposed to a trawl can be estimated with the poisson distribution and mean trawling intensity. Given the observed trawling intensity by grid cell, the frequency distribution of the number of trawling events was estimated for each grid cell and the number of trawling events was summed over all grid cells trawled by PLH in 2017. The calculations showed that 30% of the surface area of the trawled grid cells was trawled at least once in a year. Within this trawled area, 67% was trawled 1 $year^{-1}$, 22% was trawled 2 $year^{-1}$, 8% was trawled 3 $year^{-1}$ and 1% was trawled 4 or more times $year^{-1}$ (Figure 10.2).

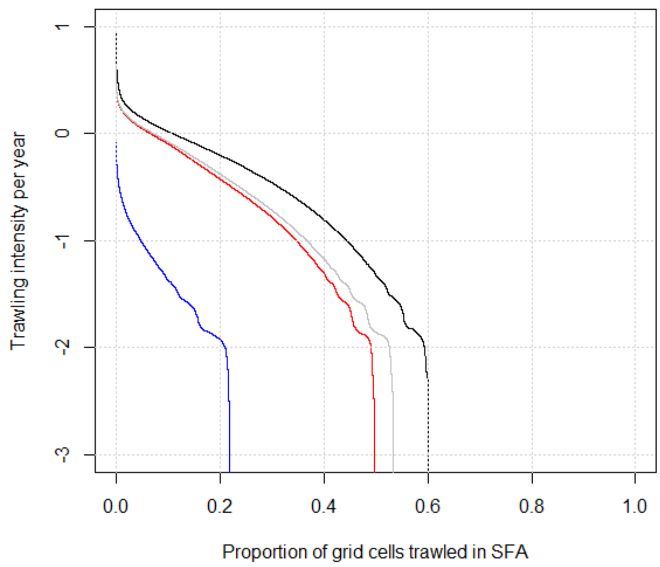

Figure 10.1 Trawling intensity (log10) profile of pulse license holders (PLH) in the sole fishing area (SFA) when fishing with the tickler chain beam trawl in 2009 (black) and with the tickler chain beam trawl (blue) or pulse trawl (red) in 2017. The

grey line shows the profile in 2017 when tickler and pulse effort is summed. Grid cells were sorted from high to low trawling intensity.

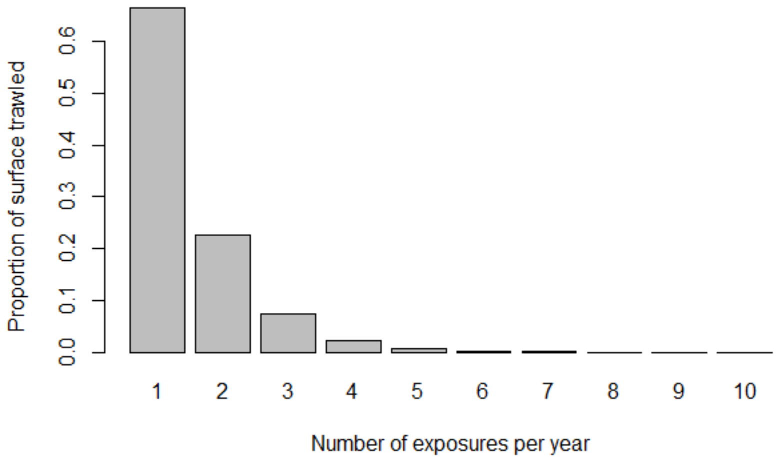

Figure 10.2 Proportion of the trawled surface area that is exposed 1 to 10 times during a year to a pulse stimulus of 1.5 seconds and field strength >5 V.m^{-1}

The above analysis shows that only animals that live in the most intensively trawled grid cells will have a chance of being exposed several times during a year, whereas animals living in most of the trawled grid cells will be not be exposed to a pulse or exposed only once in a year. A pulse exposure involves an exposure to a field strength of >5 V.m-1 for the duration of 1.5 sec. The short duration and the low exposure frequency suggest that there is no chronic exposure to pulse stimuli used in the pulse trawl fishery for sole.

WGELECTRA 2018 explored the time interval between successive pulse exposures for the most intensively trawled ICES rectangles. The analysis showed that even in the most intensively trawled rectangles the part of the seabed (pixels at the size of the gear) that is exposed repetitively within a week is very small. Only up to 0.3% of the pixels may be exposed for a second time during a week. These percentages further drop if a shorter time interval is considered. For instance, less than 0.16% of the grid cells are trawled for a second time within a day.

10.2.2 Impacts on fish populations

Changes in the partial fishing mortality imposed by beam trawling of PLH during the transition is estimated with equation [6] with a spatial resolution of ICES rectangles, annual time-step, and species-specific catchability coefficients for pulse trawl (Table 10.1). The estimated partial fishing mortality differs between species and species groups reflecting the spatial overlap and the estimated catchability coefficients (Figure 10.3). With the exception of cod (0%), sole (+27%) and rays (+20%), partial fishing mortality of the PLH decreases between 2009 and 2017 by 10%-31% (**Table 10.1**) coinciding with the decrease in the swept-area. The change in partial fishing mortality of rays and cod, will reflect an increase in overlap in species distribution with the trawling activities of the PLH.

The increase in partial fishing mortality of sole by PLH can be explained by the increase in catchability during the gear transition. For the total Dutch beam trawl fleet a 9% reduction is estimated from 0.31 in 2009 to 0.28 in 2017. These estimates can be compared to the partial fishing mortalities of the Dutch fleet in the stock assessment (ICES, 2019), which decreased from 0.40 in 2009 to 0.16 in 2017 (ICES, 2019).

Combination of the change in partial fishing mortality with the injury rate estimated for catches in both gears will provide insight in the population level effects of injuries. Since injury rate is generally higher in conventional beam trawls than in pulse trawl (Figure 8.4), a decrease in the partial fishing mortality after the transition to pulse trawling implies a reduction in injuries imposed. For cod, however, the injury rate observed in pulse trawls exceeds the injury rate in conventional beam trawls and the change in fishing mortality rate was estimated at 0%, hence the transition to pulse trawling will increase the number of fish with injuries.

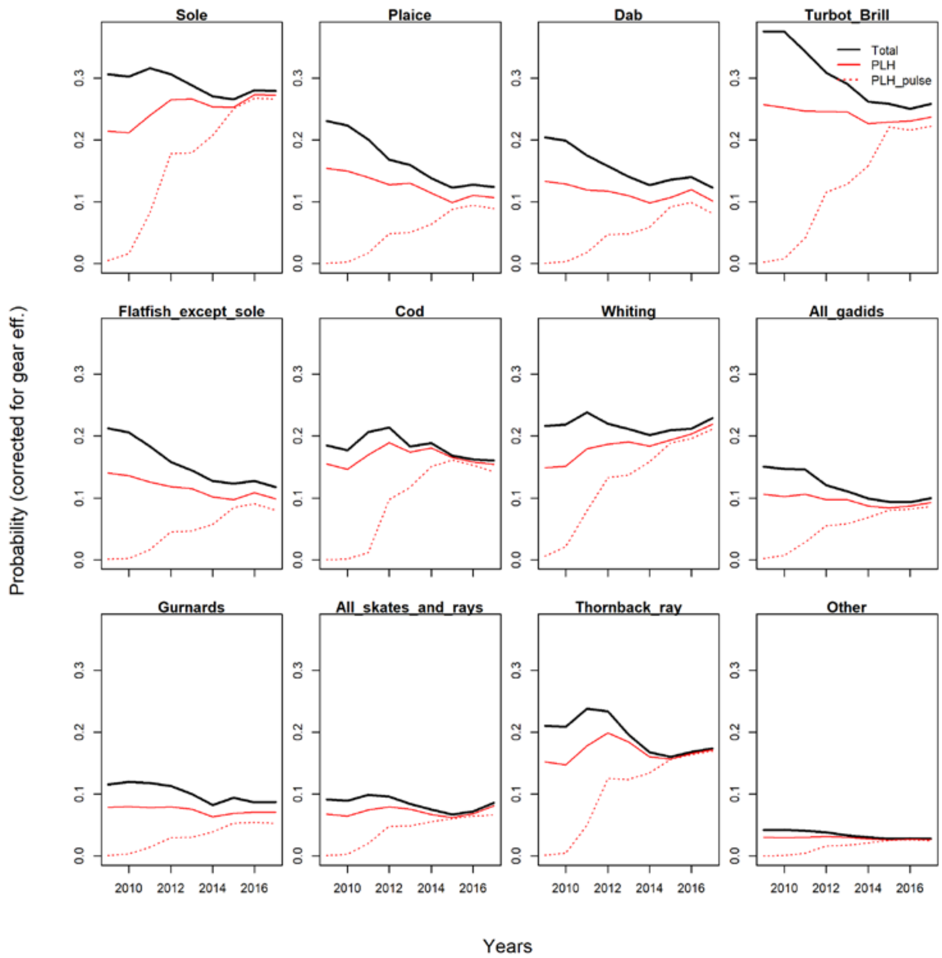

Figure 10.3. Total population: Change in partial fishing mortality imposed by the total Dutch beam trawl fleet (heavy black line) and the pulse license holders (PLH, red line). The red dotted line shows the exposure probability to the pulse trawl (analysis 1 with species-specific q from Table 3).

Table 10.1. Total population: Change in the partial fishing mortality between 2009 and 2017 imposed by the total Dutch beam trawl fleet (TBB_all) and the subset of pulse license holders (PLH) by species and species groups. The catchability coefficient of the conventional beam trawl is set at 1. The catchability coefficient of the pulse trawl (q.pulse) reflect the differences in catch efficiency between the gears estimated in section 5.7

		2009	2017		2009	2017	
Species group	q.pulse	TBB_all	TBB_all	%change	PLH	PLH	%change
Sole	1.47	0.3060	0.2788	-9%	0.2143	0.2723	27%
Plaice	0.81	0.2305	0.1242	-46%	0.1541	0.1066	-31%
Flatfish_except_sole	0.86	0.2122	0.1178	-45%	0.1401	0.0988	-29%
Cod	1	0.1850	0.1604	-13%	0.1549	0.1545	0%
All_gadids	1	0.1505	0.0998	-34%	0.1056	0.0927	-12%
Gurnards	1	0.1154	0.0873	-24%	0.0786	0.0706	-10%
Other	1	0.0420	0.0278	-34%	0.0303	0.0265	-13%

All_skates_and_rays	1	0.0916	0.0860	-6%	0.0676	0.0813	20%
All_fish	1	0.1813	0.1150	-37%	0.1222	0.1011	-17%

10.2.3 Impact on discarding

The analysis of the discard samples collected from pulse trawl vessels and conventional beam trawl vessels showed a significant differences between the gears (Table 5.8). To further investigate the possible effect of a gear transition on the discarding, the partial fishing mortality of the discard size classes due to fishing activities of the PLH was estimated (Figure 10.4). During the transition period the estimated partial fishing mortality imposed by pulse license holders (PLH) decreased by 33% for flatfish and 37% plaice, and increased with 29% for sole (Table 10.2). For other species and species groups the partial fishing mortality decreased between 9% and 21%. Only for rays an increase of 44% was estimated. When all fish were considered, a decrease in the partial fishing mortality was estimated of 21%. Assessed for the total Dutch beam trawl fleet, the decrease is discard fishing mortality was stronger.

For rays, the partial fishing mortality rate on discard size classes increased by 44% after the transition to pulse trawling. The increase is consistent with the shift in spatial distribution to the southwestern North Sea where rays have their highest abundances. The higher catch of rays may possibly be compensated to some extent by a better survival. Survival experiments with thornback rays shows a rather high survival rate of around 50%. Survival rate of pulse trawl caught rays is slightly higher than rays caught in the conventional tickler chain beam trawl, although not statistically significantly (Figure 5.11).

Table 10.2. Discard size classes: Change in the partial fishing mortality between 2009 and 2017 imposed by the total Dutch beam trawl fleet (TBB_all) and the subset of pulse license holders (PLH) by species and species groups. The catchability coefficient of the conventional beam trawl is set at 1. The catchability coefficient of the pulse trawl (q.pulse) reflect the differences in catch efficiency between the gears estimated in section 5.7

		2009	2017		2009	2017	
Species group	q.pulse	TBB_all	TBB_all	%change	PLH	PLH	%change
Sole	1.47	0.2874	0.2606	-9%	0.1991	0.2565	29%
Plaice	0.81	0.2952	0.1383	-53%	0.1951	0.1231	-37%
Flatfish_except_sole	0.86	0.2320	0.1206	-48%	0.1520	0.1021	-33%
Cod	1	0.0487	0.0357	-27%	0.0358	0.0325	-9%
All_gadids	1	0.1970	0.1238	-37%	0.1353	0.1142	-16%
Gurnards	1	0.1016	0.0785	-23%	0.0685	0.0618	-10%
Other	1	0.0436	0.0276	-37%	0.0315	0.0266	-16%
All_skates_and_rays	1	0.0501	0.0588	17%	0.0369	0.0531	44%
All_fish	1	0.2055	0.1229	-40%	0.1368	0.1083	-21%

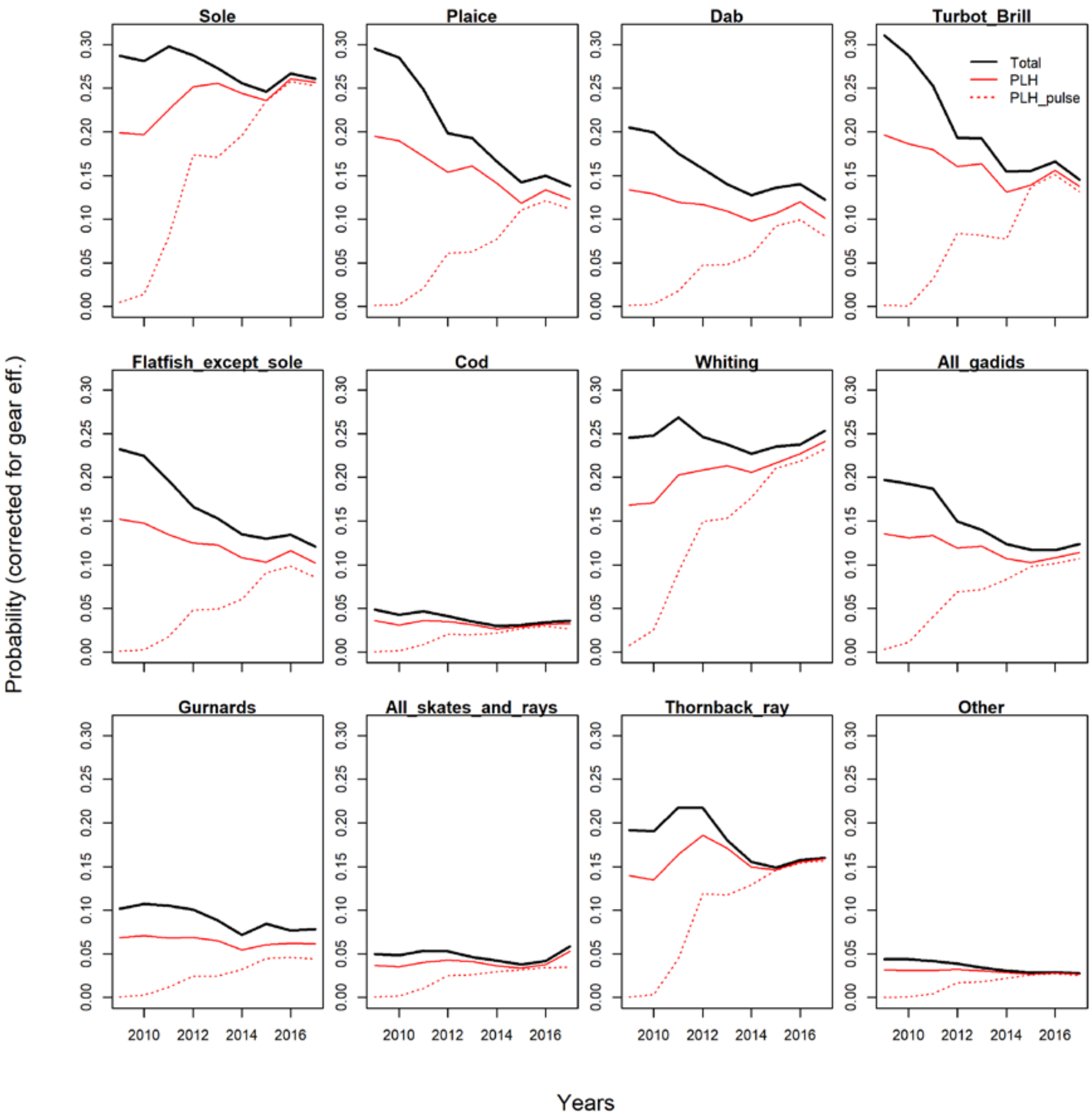

Figure 10.4. Discard size classes: Changes in the partial fishing mortality of undersized fish due to beam trawling activities of the total Dutch fleet (TBB) and beam trawl activities of pulse license holders (PLH) using the tickler chain beam trawl or pulse trawl. The red dashed line shows the fishing mortality due to pulse trawling.

10.2.4 Population dynamic consequences

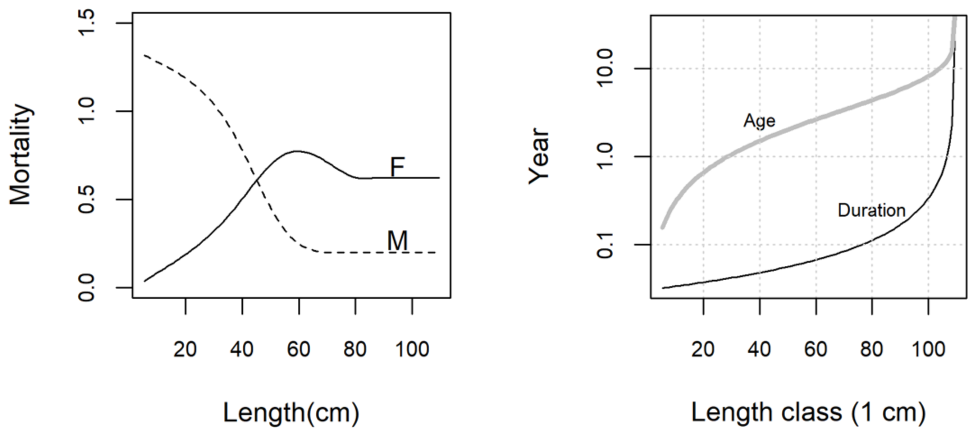

Figure 10.5 North Sea cod: rate of fishing (F) and natural (M) mortality (year-1) in relation to body size (left panel) and stage duration and cumulative stage duration (age) in relation the 1 cm length class used in the cohort analysis (right panel).

10.2.4.1 Cod population level impact

There is convincing evidence that the pulse stimulus may invoke fractures and haemorrhages in cod, but there is some uncertainty whether this also applies to small cod. Small cod of around 17cm, that are small enough to escape through a 80mm codend, did not develop fractures when exposed to the high field strength close to the conductor (de Haan et al., 2016). A lower sensitivity of small cod is supported by the analysis of cod collected on board commercial pulse trawlers which suggests a dome-shaped relationship with body size. In addition, the fracture probability in the field samples may be overestimated due to a likely lower escape probability of injured cod (Boute et al., in prep; see section 8.4).

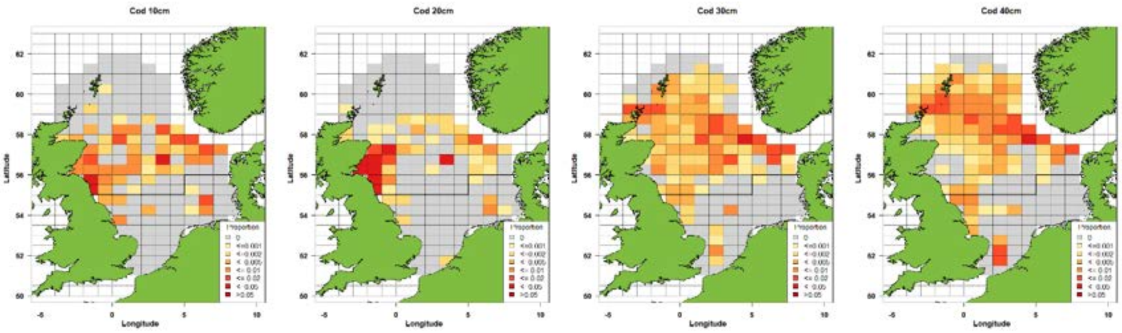

Figure 10.6. Cod. Relative distribution of size classes (<10cm, 11-20cm, 21-30cm, 31-40cm) based on 1st and 3rd quarter IBTS data (2009-2017). The horizontal line at 55°N and 56°N shows the northern limit of the sole fishing area (SFA)

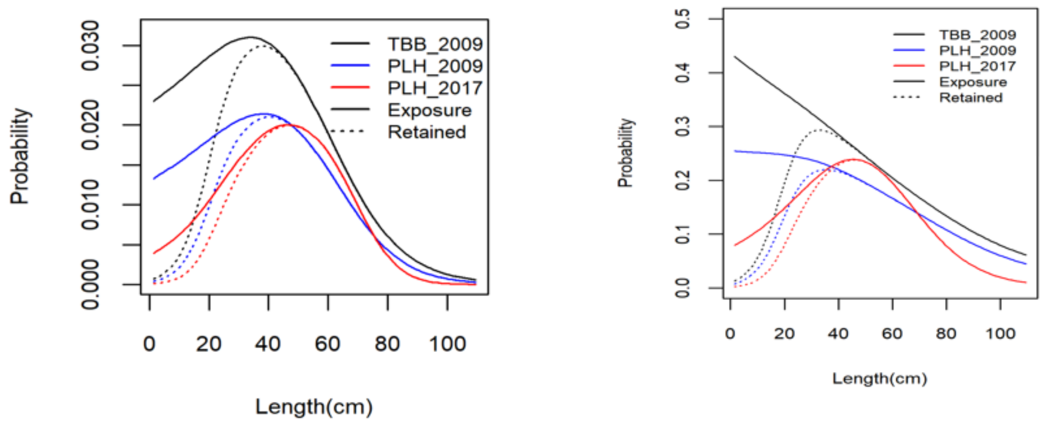

Figure 10.7. Cod. Encounter probability with the Dutch beam trawl fleet. Left: total North Sea. Right: sole fishing area SFA. Dashed lines refer to the probability of being retained in the mesh. Encounter probability curves were estimated for the pulse licence holders (PLH_2009) fishing with the conventional beam trawl in 2009 before, and the pulse license holders fishing with the pulse trawl in 2017 (PLH_2017) after the transition to pulse trawling and the total Dutch beam trawl fleet (TBB_2009)

To explore the effect of a possible additional mortality induced by pulse exposure of small cod that escape through the codend meshes a length based cohort analysis was conducted. The cohort model was parameterized based on literature data (Table 10.3). Fishing and natural mortality were obtained from the 2019 stock assessment (ICES, 2019) and assigned to the mean length-at-age estimated from the von Bertalanffy Growth Equation. Figure 10.5 shows the relationship of the fishing and natural mortality rates, and the stage duration and age with body size.

The encounter probability with different size classes of cod was estimated by calculating the weighted mean trawling intensity by ICES rectangle over the relative abundance of each cod size class. The spatial distribution of cod was estimated from IBTS survey data by 10cm size class averaging over the Q1 and Q3 surveys in the period 2009-2017 (Figure 10.6). A smooth relationship between the encounter probability and length was calculated by fitting a generalized additive model (Figure 10.7). The shift from conventional beam trawling to pulse trawling resulted in a decrease in the encounter probability in line with the reduction in swept-area and towing speed. The encounter probability differed greatly when calculated for the total North Sea cod population and when calculated for the SFA.

Most cod that encounter a beam trawl will be retained but smaller cod may escape through the meshes shown by the difference between the full line (probability of encounter) and dashed line (probability of being retained) in Figure 10.7. The consequences of the potential mortality imposed by pulse trawls on these cod was investigated by estimating the yield and spawning-stock biomass for different spinal injury scenarios of additional mortality imposed by pulse exposure. The simulations assume that all cod retained will die and that the cod that escape through the meshes will have a mortality varying between 0% and 40% (Table 10.4). The 40% corresponds to the maximum proportion of cod with a spinal injury. Fishing mortality was set as the sum of Fvpa (Figure 10.5 left) and the partial fishing mortality imposed by the PLH in 2017 (Figure 10.7).

Table 10.3. Cod. Input parameters used in the cohort analysis

Von Bertalanffy growth equation (Daan, 1974a)	
K	0.3
L_{inf}	110.0
t0	0.7
Length (cm) - weight (kg) (Daan, 1974a)	
a	0.0000068
b	3.1
Maturity ogive (Oosthuizen and Daan, 1974)	
a_{mat}	-33
b_{mat}	0.6
Mesh selectivity (Reeves et al., 1992)	
sf	2.4
sr	1.4
Mesh size (mm)	80
Minimum landing size (cm)	35

The yield and spawning-stock biomass was calculated for each of the spinal injury scenarios and compared the results of a reference run with the fishing mortality set at the sum of the Fvap and the partial fishing mortality imposed by the PLH in 2009. For the total North Sea population, the population level effect of pulse-induced mortality among small cod that escape through the meshed is negligible (<<1%). When assessed for the SFA, the maximum population level effect is a 2% reduction in SSB when 40% of the cod dies when exposed to a pulse trawl (Table 10.4). This reduction is lower that the difference between the estimated effect between a 40% and a 0% mortality for PLH_2017 which was estimated at 2.9% for the Yield and 3% for the SSB, because the transition to pulse trawling coincides with a reduction in discarding (Figure 10.7 right panel).

Table 10.4. Cod. Changes in spawning-stock biomass and yield due to a hypothetical range of mortalities of small cod that are exposed to the pulse stimulation but pass through the net and escape through the mesh. Changes are expressed relative to a simulation of pulse license holders in 2009 (F_{PLH_2009}) fishing with the conventional beam trawl before the transition to pulse trawling.

	Cod in total North Sea		Cod population in SFA	
Scenario	Yield	SSB	Yield	SSB
$F_{vpa} + F_{PLH\_2017}$ + 0% / $F_{vpa} + F_{PLH\_2009}$	0.9993	0.9972	1.019	1.010
$F_{vpa} + F_{PLH\_2017}$ + 10% / $F_{vpa} + F_{PLH\_2009}$	0.9989	0.9968	1.012	1.003
$F_{vpa} + F_{PLH\_2017}$ + 20% / $F_{vpa} + F_{PLH\_2009}$	0.9985	0.9964	1.005	0.995
$F_{vpa} + F_{PLH\_2017}$ + 30% / $F_{vpa} + F_{PLH\_2009}$	0.9980	0.9959	0.998	0.987
$F_{vpa} + F_{PLH\_2017}$ + 40% / $F_{vpa} + F_{PLH\_2009}$	0.9976	0.9955	0.990	0.980

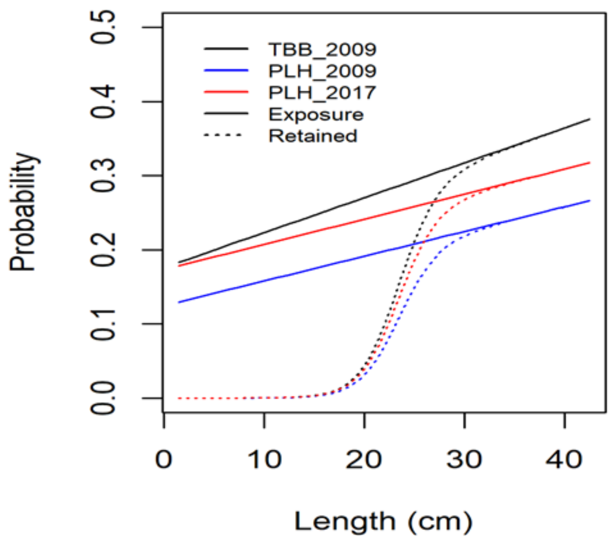

Figure 10.7. Sole. Encounter probability at length of sole with the Dutch beam trawl fleet. Dashed lines refer to the probability of being retained in the mesh. Encounter probability curves were estimated for the total Dutch beam trawl fleet (TBB_2009) and subset of pulse licence holders (PLH_2009) fishing with the conventional beam trawl in 2009 before, and the pulse license holders fishing with the pulse trawl in 2017 (PLH_2017) after the transition to pulse trawling. The PLH_2017 took account of the improved catchability of the pulse trawl for sole.

10.2.4.2 Sole population level impact

For sole, concern has been raised about the possible adverse effects of non-lethal exposure on the reproductive capacity. The potential impact has been investigated for soles that are exposed to the field strength generated in front of the pulse trawl but that are not retained in the net because they pass through the net and escape through the codend meshes. Soles that are outside the track of the trawl will be exposed to a field strength that is too low to induce a behavioural response (section 7). Although no experimental studies have been carried out, it is unlikely that such an exposure will adversely affect the reproductive physiology of the fish.

Table 10.5. Sole. Input parameters used in the cohort analysis

Von Bertalanffy growth equation (Daan, 1974a; Rijnsdorp et al., 2012)	
K	0.263
L_{inf}	42.9
t0	0.03
Length (cm) - weight (kg) (Rijnsdorp et al., 2012)	
a	0.003224
b	3.293
Maturity ogive	
a_{mat}	-22.194
b_{mat}	0.925
Mesh selectivity (WGELECTRA Report, 2018)	
sf	2.9
sr	4.2
Mesh size (mm)	80
Minimum landing size (cm)	35

The cohort model was used to estimate the size and stage durations required to estimate the exposure probability. The cohort model was parameterized based on literature (Table 10.5). The encounter probability of different size classes of sole with the beam trawl gear was estimated by calculating the weighted mean trawling intensity by ICES rectangle over the relative abundance of sole for each of the 5cm size classes up to 40cm in the BTS survey in quarter 3. The size classes up to 15cm were pooled because sole smaller than 10cm are not well covered in the BTS survey. A gam model was fitted to obtain a smooth relationship. The encounter probability for the PLH_2017 was raised for the increase in catchability of the pulse trawl. The encounter probability shows a linear increase with body size and increased between 2009 and 2017 (**Figure 10.7**). The dashed lines show the proportions of the sole that is retained in the net. The difference between the dashed and full lines show the proportion of sole that will escape through the codend mesh.

The probability that a sole will encounter a pulse trawl but escape through the codend mesh and survive is given by the cumulative sum of the encounter probability*stage duration. **Figure 10.8a** shows how this probability increase with size to about 0.6 at a size of 30 cm. Above this size almost all sole are retained in the gear and the cumulative probability to be exposed but escape no longer increases. Assuming that the exposure events are occurring at random, the frequency distribution of exposure events is given by the poisson distribution. **Figure 10.8b** shows that about 53% of the sole surviving for 4.5 years upto a size of 30cm will not be exposed to a pulse stimulus. About 34% of the sole will be exposed once in their life time, while the percentage sole that will be exposed 2 times or more is about 13%.

A similar analysis was carried out for the exposure during the maturation phase between 20 cm (age = 2.5) and 25cm (age = 3.5), the analysis showed that about 12% of sole will be exposed during the maturation year once. Multiple exposures are rare (about 1%: **Figure 10.8c**). Although no experiments have been conducted to study the possible physiological consequences of multiple exposures, the short exposure duration (1.5 sec) and the low exposure probability makes it highly unlikely that pulse trawling will impair the reproductive capacity of the stock.

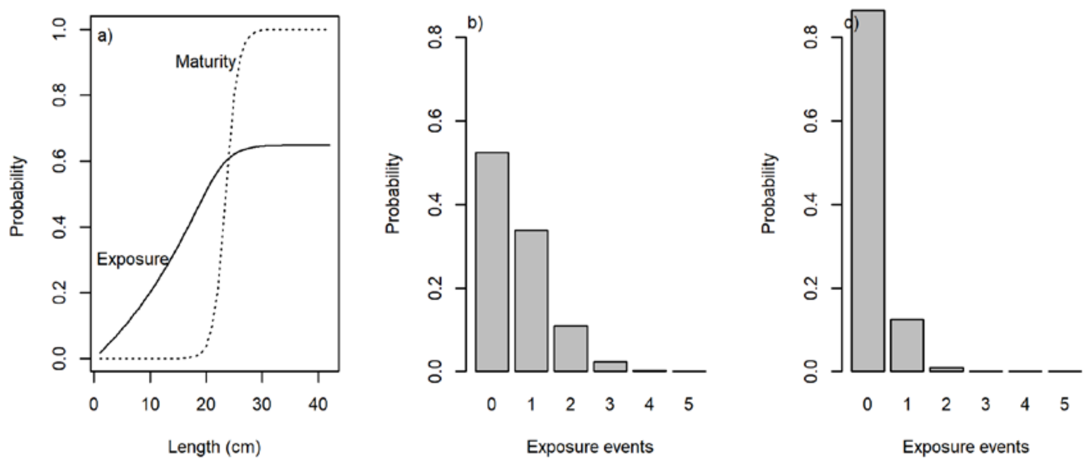

Figure 10.8. Sole. (a) Cumulative probability that a sole surviving to a particular length is exposed to a pulse stimulus but not caught; (b) probability distribution of the number exposure events for a 30 cm sole that survived 4.8 years; (c) probability distribution of the number exposure events during the year of sexual maturation prior to spawning at 25 cm.

10.2.5 Impact on egg and larval stages

Pelagic eggs and larvae

The potential mortality imposed by pulse trawling on the eggs and larvae depends on the proportion of the population that is exposed to a pulse stimulus. This proportion can be estimated from the exposure distance to the electrodes where the field strength exceeds the threshold level, the fishing intensity and the overlap in distribution of the fisheries and egg and larval stages. The early life stages of cod and sole live in the water column and will be exposed during the hauling and shooting of the gear and, when in the bottom-water layers during the towing of the trawl. The proportion of the water volume exposed during fishing is given by the sum of the volume of water exposed during towing the gear over the seafloor (Vt) and the volume of water exposed during the shooting and hauling of the gear (Vs). The probability of exposure during a fishing event (swept-area ratio = 1) is then given by the sum of the water volume exposed divided by the volume of water above the sea floor trawled.

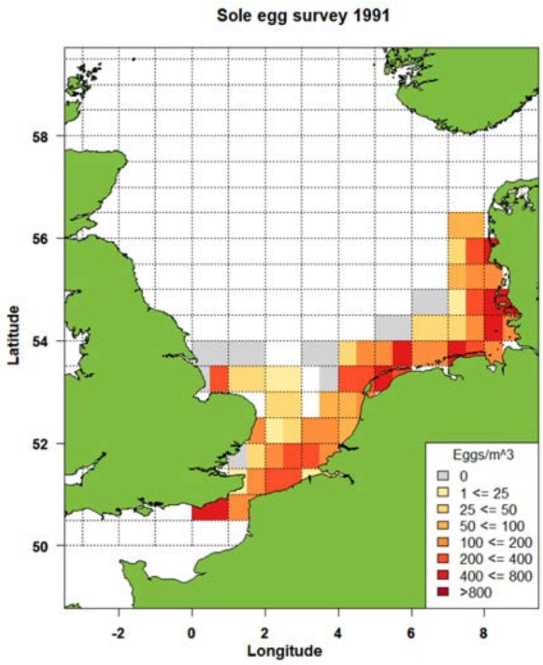

Figure 10.9. Sole. Maximum daily egg production observed in the sole egg surveys conducted in 1991 (data WMR).

The proportion of the pelagic stages of sole in the North Sea that are exposed to a pulse stimulus assuming a sensitivity threshold of 5 $V.m^{-1}$ corresponding to the field strength observed at the borders of the trawl (e ~ 0.5m). The distribution of the maximum daily egg production in the spawning season of 1991 was estimated from the primary observations (**Figure 10.9**) and overlaid with the effort distribution of pulse trawl effort observed in 2017. To estimate the volume of water exposed to pulse stimulation during the hauling and shooting of the gear, the number of hauls was estimated for each ICES rectangle from the recorded total area swept assuming a typical haul duration of 2 hours at the average towing speed. The swept-area was adjusted to spawning period of 20% of the year. Given the water depth in each rectangle, the ratio of the total volume of water exposed over the total volume of water for each rectangle was calculated. The mean ratio, weighted over the relative egg production in the rectangle, gives an estimate of the proportion of eggs that is exposed to a pulse. The calculation shows that only 0.02% of the sole eggs will be exposed >5V.m-1 during a pulse exposure of about 1.5 sec. The proportion of eggs exposed is very low in particular compared with the known mortality rates during the pelagic phase which are generally higher than 30% per day (see review in (Horwood, 1993).

A population level effect of pulse exposure on the reproductive success is also highly unlikely because many marine fish populations are regulated by density-dependent processes occurring after the pelagic phase (Leggett and Deblois, 1994). Mortality during the pelagic phase is highly variable and generate the variability observed in year class strength. Variability damping mortality are thought to occur after the egg and larval stages. In cod, predation mortality on juvenile cod by older cod is an important mechanism that reduce recruitment at high stock biomass levels

(Daan, 1974b; Neuenfeldt and Köster, 2000). In flatfish, density-dependent mortality and density-dependent growth occur in the juvenile stage after settlement in the nursery areas (van der Veer et al., 2000).

It can be concluded that given the decay of the electric field strength, the intensity and distribution of pulse trawling and the distribution of the pelagic stages and spawning duration of sole, it is highly unlikely that pulse trawling will have an adverse effect on the survival of eggs and larvae.

Demersal eggs

A small number of North Sea fish species, such as herring and sandeel, lay their eggs on the seafloor. The probability that demersal eggs will be exposed to a pulse stimulus will be larger than pelagic eggs. The exposure probability will depend on the trawling intensity of the spawning site and the duration of the egg stage. Given maximum trawling intensities in a 1x1 minute grid cell, the worst case mortality rate imposed is 4/365 = 0.01% day^{-1}., much lower than a typical daily mortality rate of fish eggs of about 60% (range: 2%-97%; (Bunn et al., 2000). Sandeel eggs, for example, are slightly sticky and adhere to sand grains (Gauld and Hutcheon, 1990). With an incubation time of sandeel eggs of up to 36 days at 6 °C (Régnier et al., 2018), the maximum cumulative mortality is estimated at 0.4%, low compared to the estimates of the proportion of demersal eggs removed by predators of 7% to 50% (Bunn et al., 2000). Demersal eggs will not only be exposed to a pulse stimulus but also to the mechanical disturbance of the bottom trawl. The population level effects of pulse trawling on demersal eggs, therefore, will be negligible.

Although experiments have been done to study the effect of pulse stimulation on the survival and viability of egg capsules of Elasmobranchs, the population impact may be higher because the incubation time is much longer and the natural mortality rate lower. The thornback, blonde and spotted rays are the most abundant ray species in the southern North Sea which overlap in distribution with pulse trawling. These three species show an increase in stock development in recent years (ICES, 2018b). Nursery areas of these species are typically in shallow waters (Ellis et al., 2005). Egg-laying and nursery areas for thornback ray are the Outer Thames Estuary and the Wash (Heessen et al., 2015); Ellis et al., 2005, ICES, 2018b). The pulse fishery is not active in these shallow egg-laying and nursery areas.

Based on the increase in stock development in combination with the lack of overlap between the pulse fishery and the early life stages of ray species in the North Sea, it can be inferred that it is unlikely that the introduction of the pulse fisheries impacted the survival of egg capsules of the ray stocks that are abundant in the southern North Sea.

10.2.6 Impact on seafloor and benthic ecosystem

Footprint

The annual footprint of the beam trawl fisheries, defined as the surface area of the sea floor that is trawled at least once in a year, decreased during the transition by 19% from about 62 thousand km2 in 2009 to 50 thousand km2 in 2017 (Figure 10.10b). The decrease was less than the decrease in swept-area. The footprint of the PLH, including pulse and tickler chain trawling, decreased by 15% from 48 thousand km2 in 2009 to 41 thousand km2 in 2017. After the transition, the footprint of the pulse trawl varied around 34 thousand km2. The number of 1x1 minute grid cells with trawling activities varied without a clear trend (Figure 10.10c), although the number of grid cells in 2017 was 7% higher in the total fishing area and 10% lower in SFA than in 2009. The number of grid cells with pulse trawl activities reached a stable level in 2012 when the swept-area only reached about half of its final level in 2015 and later years (Figure 10.10a).

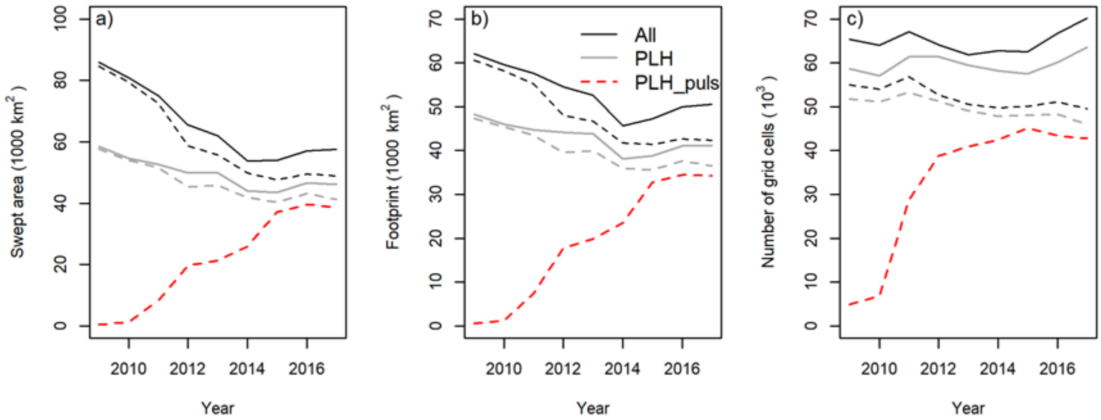

Figure 10.10. Changes in the area swept (a), the surface of the sea floor which is trawled at least once per year (b, footprint) and the number of 1x1 minute grid cells with trawling activities (c) recorded for the total Dutch beam trawl fleet (ALL) and for the subset of pulse license holders fishing with a tickler chain trawl or a pulse trawl (PLH) or with a pulse trawl (PLH-pulse). Full lines refer to the total fishing area. Hatched lines refer to the sole fishing area (SFA) with 80mm mesh size south of the demarcation line. (from Rijnsdorp et al. 2020a)

Sediment mobilization

Bottom trawls disturb the seafloor by mobilizing sediment in the turbulent wake of the trawl affecting the biogeochemical processes and functioning of the benthic ecosystem (Lucchetti and Sala, 2012; Puig et al., 2012). The amount of sediment mobilized is a determined by the hydrodynamic drag of the gear and the silt fraction of the sediment (O'Neill and Ivanović, 2016; O'Neill and Summerbell, 2016). Based on a quantitative inventory of the dimensions of the major gear elements of various types of beam and pulse trawls and their towing speed, the hydrodynamic drag of a representative trawl was estimated for large vessels at tickler chain beam trawl = 6.2 kN.m^{-1} and pulse trawl = 3.8 kN.m^{-1} (small vessels: tickler chain beam trawl = 2.8 and pulse trawl = 2.9 kN.m^{-1})(Rijnsdorp et al., under review).

The estimated amount of sediment that is mobilized in the wake of the beam trawls decreased during the transition period (Figure 10.11). For the PLH the estimated amount of sediment mobilized in 2017 in SFA is 39% of the amount that was mobilized in 2009 (total North Sea 33%). For the total fleet the decrease is 66% in the SFA (Total North Sea 59%) (Table 10.4).

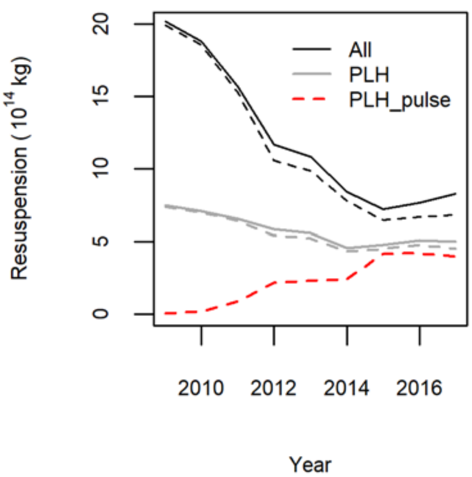

Figure 10.11. Time-trends in the amount of sediments mobilized by the Dutch beam trawl fisheries (ALL: thick black), the subset of pulse license holders fishing with a tickler chain trawl or pulse trawl (PLH: thin black) or fishing with a pulse

trawl (PLH-pulse: red). Full lines refer to the total fishing area. Hatched lines refer to the sole fishing area (SFA) with 80mm mesh size south of the demarcation line. (from Rijnsdorp et al. 2020)

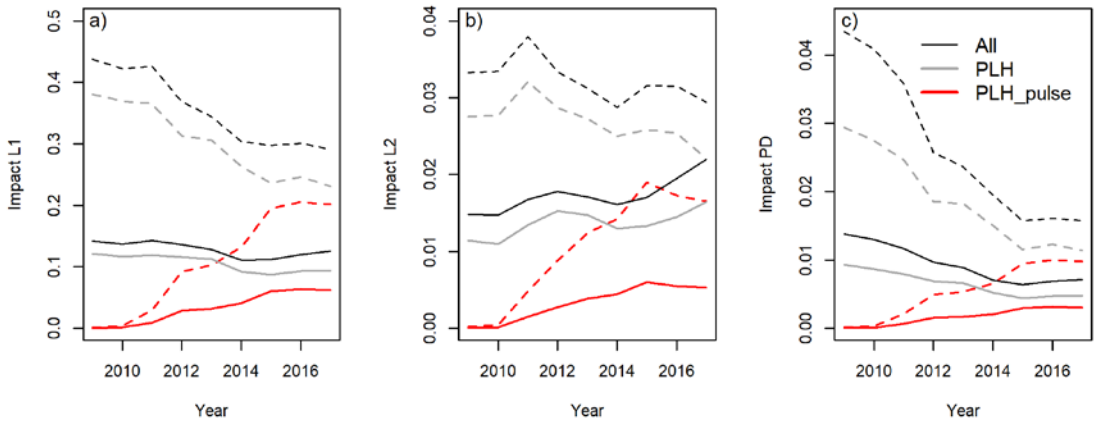

Figure 10.12. Time-trends in the impact indicators of the total Dutch beam trawl fleet (ALL) and for the subset of pulse license holders fishing with a tickler chain trawl or pulse trawl (PLH) or with a pulse trawl (PLH-pulse). Full lines refer to the total fishing area. Hatched lines refer to the sole fishing area (SFA) with 80mm mesh size south of the demarcation line. (from Rijnsdorp et al. 2020)

Impact on benthic community

The benthic impact was assessed using a set of three indicators recently developed in the BENTHIS and Trawling Best Practice projects (review in Rijnsdorp et al.2020b; Kaiser, 2019). L1 is a precautionary indicator that estimates the proportion of the biomass of the benthic community that is potentially impacted by trawling (Rijnsdorp et al., 2016). It assumes that benthic taxa with a longevity exceeding the average interval between two successive trawling events will be potentially affected by bottom trawling. L2 estimates the decrease in median longevity due to trawling relative to the median longevity of the untrawled community and is based on a statistical model of the effect of beam trawling on the median longevity of the benthic community (Rijnsdorp et al., 2018a). PD estimates the impact of bottom trawling in terms of the reduction in the benthic biomass (B) relative to the carrying capacity (K) of the habitat (Pitcher et al., 2017; Hiddink et al., 2019).

Table 10.4. Summary of the change in impact on the sea floor following the transition from tickler chain beam trawling to pulse trawling. The change in impact is expressed as the impact ratio between 2017 and 2009 (I_{2017}/I_{2009}) of the pulse license holders (PLH) and the total Dutch beam trawl fleet in the sole fishing area (SFA) and the total North Sea. Values >1 indicate and increase in impact by pulse trawling (from Rijnsdorp et al. 2020a).

	Pulse license holders (PLH)		Total fleet	
Indicator	Total fishing area	Sole fishing area (SFA)	Total fishing area	Sole fishing area (SFA)
Swept-area	0.79	0.72	0.67	0.58
Footprint	0.85	0.77	0.81	0.70
Number grid cells	1.08	0.89	1.07	0.90
Impact L1	0.77	0.61	0.88	0.66
Impact L2	1.44	0.80	1.49	0.89
Impact PD	0.51	0.39	0.52	0.36
Sediment mobilization	0.67	0.61	0.41	0.34

All three indicators showed a decline in impact during the transition to pulse trawling (Figure 10.12). For the PLH in the SFA the L1 indicator decreased by 39%, L2 by 20%, and PD by 60%. For the total North Sea area, L1 decreased by 20% and PD decreased by 60% but L2 increased by

49%. The increase in L2 is due to the increase in the beam trawling with the tickler chain trawl targeting plaice north of SFA following the recovery of the plaice stock. The L2 indicator takes account of the effect of natural disturbance on the sensitivity of the benthic community for trawling. In the SFA, the natural disturbance is relatively high to the high bed shear stress. On the plaice fishing grounds north of SFA, the benthic community is in this area is more sensitive for trawling and the increase in beam trawl effort of PLH north of the SFA overrides the impact reduction due to the transition to pulse trawling in the SFA.

A reduction in trawling impact due to the transition to pulse trawling is observed in all soft sediment habitats (Figure 10.13).

The impact metrics estimate the effect of the mechanical disturbance by the pulse and conventional beam trawl gear. As the studies on the effect of electrical exposure did not provide evidence of adverse effects, the results can also be seen as a proxy for the reduction in overall impact.

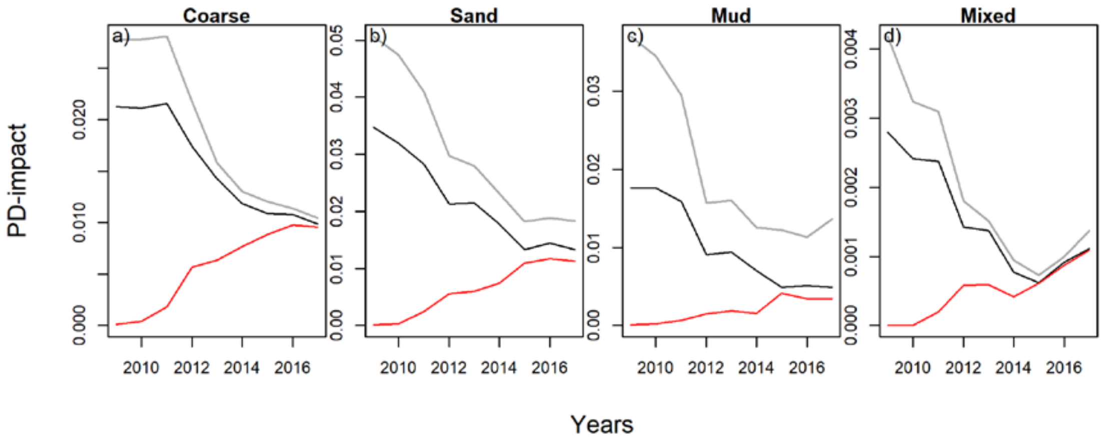

Figure 10.13. Changes in benthic impact by habitat type in sole fishing area (grey = total beam trawl fleet, black = pulse license holders; red = pulse license holders with pulse trawl)

10.2.7 Impact on biogeochemical functioning

In order to predict long term impacts of bottom-trawl disturbance on biogeochemical parameters and benthic pelagic coupling, the OXYMEDIA model was expanded upon to run simulations for pulse trawl and tickler chain beam trawl gears (Soetaert et al., 1996). For this, data from previous studies on gear penetration depth and mobilization were used with pulse trawls exhibiting 0.5 of the mixed layer depth and 0.7 of the total sediment mobilized compared to beam trawls (Depestele et al., 2018, 2016; Rijnsdorp et al., 2020a, under review). As the geochemical impact of electricity in pulse trawls is negligible (Tiano et al., *in prep.*), the model only uses the mechanical effects of the gears on the seafloor. Model projections ran for 10 years at a frequency of 0 to 5 trawl events per year at 5 different North Sea habitats: 1) coarse sand/low nutrients, 2) fine sand/low nutrients, 3) fine sand high nutrients, 4) mud/low nutrients and 5) mud/high nutrients.

The impact of a single trawl event per year on oxic mineralization (recycling of organic matter when oxygen is present) and denitrification (reduction of nitrate to N_2 gas) had the greatest effect at the coarse sand/low nutrient habitat. Trawl induced disturbance of the relatively large oxic layer in coarse sediment habitats may cause the disruption of these processes (Ferguson et al., 2020). The effects of trawling on anoxic mineralization (recycling of organic matter without oxygen) were strongest in high nutrient habitats (fine sand/mud) where sedimentary oxygen is less available.

In many cases, the average impact of pulse trawling on biogeochemical characteristics was lower than beam trawling, however, this pattern was not significantly different nor consistently lower than that of beam trawls (Figure 10.14). This is because both fishing methods have an effect on the fresh organic material found on the sediment surface. Fresh organic material, most of which originates as phytoplankton and settles from the water column, acts as the driving force for benthic biogeochemical processes.

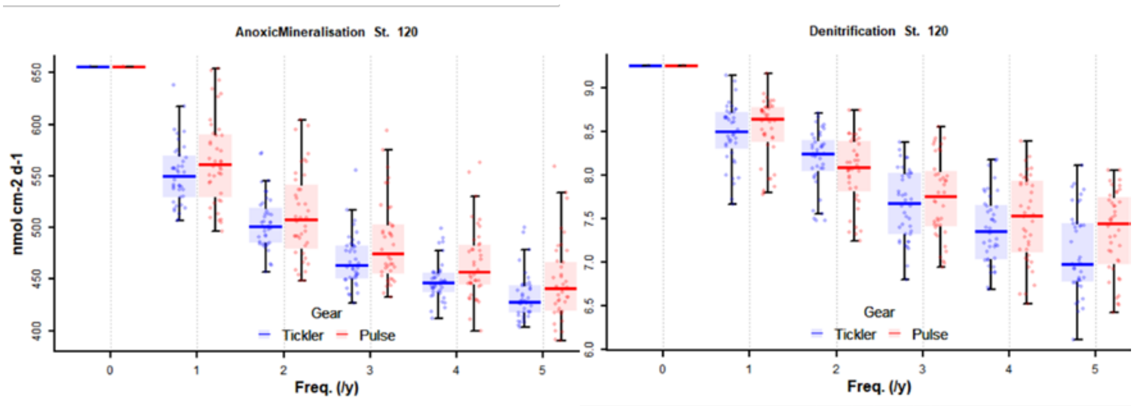

Figure 10.14. Example of model results showing the effects of tickler chain beam trawled vs. pulse trawled sediments on anoxic mineralization (left) and denitrification (right). Simulations show how this effect is worsened over the course of multiple trawling events per year.

10.2.7.1 Discussion

To place these results into context, it is important to note that the switch from pulse trawls to beam trawls reduced the total fishing effort, swept-areas and estimated amount of mobilized sediment (Rijnsdorp et al., 2020a). Though the modelled effects of both gears may be similar, the decreased fishing effort under pulse trawling (lower trawl frequencies/year) would have led to a lower net geochemical impact. The model results suggest that more trawling will reduce sedimentary nutrient cycling through the slowing down of mineralization and denitrification processes. With the removal capacity of reactive nitrogen (Soetaert & Middelburg, 2009) and phosphorus (Slomp et al., 1996) weakened in the southern North Sea, these nutrients may follow the prevailing northerly current and can affect primary production and potentially eutrophication in other regions.

11 Synthesis

11.1 Assessment table

The available scientific knowledge of the effect of pulse trawling on a range of marine organisms and ecosystem components is summarized in Table 11.1. The table updates a similar table compiled in the 2018 WGELECTRA Report. The strength of the scientific evidence is assessed as being High confidence, Medium confidence, Low confidence. High confidence is used when there is strong experimental or observational evidence available. Medium confidence is used when there is limited experimental or observational support. Low confidence is used when there is no empirical evidence but when there is a mechanistic understanding about a causal chain of steps that lead to a conclusion.

We further scale up the possible effect of pulse exposures to the level of the population, taking account of the distribution and intensity of the pulse and conventional beam trawl fleet and the distribution of the species or ecosystem component considered. In the upscaling, a possible adverse effect may be assessed to be negligible if there the probability of exposure to the pulse fishery is very low. The assessment of the upscaling is presented in the column Population level consequences. The Strength of support for population level consequences is assessed as High confidence, Medium confidence, Low confidence.

Table 11.1. Criteria and subcriteria used to assess the effect of pulse trawling relative to the conventional tickler chain beam trawl and the population-level consequences. Extended and updated from the WGELECTRA Report 2018.

		Individual level effect				Up-scaling to population / ecosystem		
Criterion / subcriteria		Effect pulse trawling	Strength of support for effect	Data	Comment	Population level consequences	Strength of support for population consequences	Source
Sustainable exploitation of the target species								
Catch efficiency target species (landings)		Increased catch efficiency for sole (per hour)	High confidence	Catch and effort statistics of fishing trips total fleet	Pulse trawl improves the species selectivity because it is more efficient for sole and less for bycatch commercial species	Increased landings/h for sole (+17%) and reduced landings/h of other species (-22%) implies that the sole quota can be caught with less effort	High confidence	Sections 5.7.1
Catch efficiency commercial bycatch (landings)		Reduced efficiency for commercial bycatch (per hour)	High confidence	Catch and effort statistics of fishing trips total fleet				
					Higher catch efficiency whiting contrast with results comparative fishing experiments		Low confidence	
Size selectivity of sole, plaice		Reduced efficiency per swept-area of undersized sole, plaice	Low confidence	Catch and effort statistics of fishing trips total fleet Discard monitoring database	Improved size selection observed in comparative fishing experiment for sole and plaice is not supported by catch	Catch efficiency pulse for undersized flatfish equals catch efficiency of marketable size classes	Low confidence	Section 5.7.1

				(observer trips, self-sampling trips)	efficiency analysis discard monitoring data			
Catch efficiency discards		Catch rate of discard size classes (per hour) reduced	High confidence	Discard monitoring database (observer trips, self-sampling trips)	Discard catch efficiency analysis show reduced efficiency except for sole and whiting (per hour). Higher efficiency sole in pulse trawl consistent with cramp response to pulse.	Pulse trawling catch about 27% less discards, but more undersized sole.	High confidence	Section 5.7.1. Table 5.8
					Higher catch efficiency of whiting contrast to results of comparative fishing experiment		Low confidence	Fig 5.9
Bycatch invertebrates		Reduced bycatch of benthic invertebrates (per swept-area)	High confidence	Discard monitoring database (observer trips, self-sampling trips)	Discard rate of benthos (numbers per area) Comparative fish experiments	Pulse trawling reduce bycatch of benthic invertebrates (20-33%)	High confidence	Section 5.7.2
Discard survival		Improved survival of discarded fish in pulse trawl	Medium confidence	Dedicated experiments	Discard survival rates in pulse trawls of plaice, brill, turbot are estimated to be higher than in	Pulse trawling improve discard survival by 6% - 15% in plaice and rays. No change in survival for sole.	Medium confidence	Section 5.8

					conventional beam trawls. No difference estimated for sole.			
Risk of overfishing sole		No increased risk	High confidence		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.	Pulse trawling does not increase the risk of overfishing of North Sea sole.	High confidence	ICES NSSK; ICES Advice 2019 Section 11.3
						Exploitation rate of local stocks may vary over time. Possible refugia in southern North Sea may have become exploited by pulse trawl which may have increased fishing mortality on local stock	Low confidence	
Risk overfishing non target species		No increased risk	High confidence		Pulse trawls catch less by-catch species	Modelled fishing mortality discarded species decreased except for rays.	High confidence	Table 10.2 Fig 10.4

						Rays are managed. Discard survival rays probably higher than tickler beam trawl	Medium confidence	Section 11.7
Adverse effects pulse stimulus on target and non-target teleost and Elasmobranchs that are exposed to the gear								
Additional mortality		No additional mortality	High confidence	Tank experiments	Exposure experiments to sole pulse: cod, sole, dab, sea bass, sandeel, cat-sharks	Spinal injuries may increase mortality probability. Only relevant in small cod escaping through codend meshes (see 2 rows below).	High confidence	Section 8.1; 8.2
Injuries		Fractures and haemorrhages due to cramp in cod retained in 80mm trawl	High confidence	Fish sampling from commercial fishing trips of pulse trawlers and conventional beam trawlers	Experimental proof of fractures in cod >30 cm. Fleet sampling indicate an average spinal injury rate of ~36%	Fracture rate in cod retained in the net will not lead to additional mortality because they will be landed or die from baratrauma if discarded.	High confidence	Section 8.4; 8.5
Injuries		Fractures and haemorrhages due to cramp in cod that escape through 80mm mesh	Medium confidence	Fish sampling from commercial fishing trips of pulse trawlers and conventional beam trawlers	Likely lower sensitivity in small cod because: (i) no fractures cod ~17cm when exposed in tank experiment; (ii) Fleet sampling indicate a	Potential adverse effect pulse stimulation on small cod that escape through meshes negligible when upscaled to North Sea stocks	High confidence	Section 8.4; 8.5

					reduced injury rate of small cod.	Potential effect on local stock in southern North Sea will be small. Poor state of this stock may be due to other factors as well Potential adverse effect pulse stimulation on small cod that can escape through meshes is max2%	Medium confidence	Section 10.2.4 ICES cod assessment
		Fractures and haemorrhages due to cramp in other fish species	High confidence	Fish samples taken from commercial fishing trips of pulse trawlers and conventional beam trawlers	(i) Similar injury rate in fish sampled from commercial pulse trawl with pulse-on and pulse-off. (ii)Injury rate pulse trawl catches similar or lower than injury rate conventional beam trawl catches. (iii)No fractures inflicted in experiments with dab, sole, sea bass. (iv)Low incidence rate in sandeel experiment.	Proportion of fish caught with spinal injuries inflicted by pulse exposure less than 1 percent.	High confidence	Section 8.1; 8.2; 8.4
Mortality on pelagic egg and larval stages			Medium confidence		Exposure experiment with	Potential pulse-induced mortality	High confidence	Section 10.2.5

		Early life stages exposed to pulse stimulus show increased mortality		Two lab experiments (cod, sole)	low frequency shrimp pulse but with a field strength representative for sole pulse showed an increased mortality in 2 out of 8 early life stages in cod, but no effect on sole early life stages.	will have negligible population level consequences due to low exposure probability		
Mortality on demersal egg and larval stages						Exposure demersal eggs higher but still low compared to rate of natural mortality due to short duration of egg stage in teleost (sandeel, herring)	Medium confidence	Section 10.2.5.
			Low confidence	No experiments with eggs Elasmobranchs		For rays, spawning is in shallow water with little pulse trawling. Reduced exposure to mechanical disturbance	Medium confidence	Section 10.2.5
Feeding electroreceptive species		No effect of pulse exposure on the food detection ability observed in an electrosensitive fish species (small-spotted catshark).	High confidence	One tank experiment	Food detection ability of the electro-sensitive catshark was not affected by pulse exposure. Electroreceptivity catshark comparable for food detection other elasmobranchs Electrophysiology predict frequency of the	No effect expected on population level because of low field strength outside net and low exposure probability	High confidence	Section 7.2

					pulse stimulus outside sensitivity range Elasmobranchs. Low field strength outside net and low exposure probability			
Reproduction		Non-lethal pulse exposure of fish does not adversely affect the reproduction later in life.	Low confidence one species; viability of oocytes not studied	One tank experiment	Small-spotted catshark exposed to pulse stimulus were observed to lay eggs when kept in the tanks for several month. Low field strength outside net and low exposure probability	No effects expected on population level because of low field strength outside net and low exposure probability	Medium confidence	Section 11.3; 10.2.4
Attraction / repulsion		Pulsed electric fields will not attract or repel fish	High confidence	Tank experiment with two electrosensitive fish and one non-electrosensitive fish species	Threshold for behavioural response not exceeded outside the trawl. Towing speed high compared to swimming speed fish	No effect expected	High confidence	Section 7.1, 7.2
Effects of pulse stimulus on benthic invertebrates								

Additional mortality		No additional mortality observed among benthic invertebrates on exposure to sole pulse	High confidence	Tank experiments	Experiments: crustaceans, bivalves, polychaetes, starfish, gastropods	No effect on populations expected	High confidence	Section 8.3
					No experiments available on other species groups (body plans)	No effects on populations expected	Low confidence	
Non lethal effects (applies to animals that are exposed but not killed after contact with the trawl).		Pulse stimulation affects the behaviour	High confidence	Tank experiments	Most benthic invertebrates species investigated react to a pulse stimulus by an avoidance response. Exposed animals in lab studies resumed typical behaviour within one hour after pulse stimulus Whelk ejects white substance on exposure (sperm,	No effects on populations expected of species studied	High confidence	Section 8.3
						No effects on populations expected of other taxa	Medium confidence	Section 8.3

					mucus, stomach?)			
		Electrical exposure do not impact the immune system, growth, reproduction	Medium confidence	Tank experiment	Few experimental studies available do not show that exposure to a pulse stimulus adversely affect growth or increase the risk of disease reflecting an impaired immune system. Limited number of studies implies that possible adverse effect cannot be excluded.	No population effects expected because (i) electric field dissipates quickly; (ii) high field strength limited to area close to conductor; (iii) probability of exposure low; (iv) probability of multiple exposures very low.	Medium confidence	Wgelectra2018 Section 11.2., 11.3
Effects of mechanical disturbance on benthic invertebrates								
Mortality		Pulse trawling impose mortality that is lower than tickler chain beam trawls	Medium confidence	Field experiments (BACI) Field measurements penetration depth	Field experiments contrasting results. Lower mortality expected given reduced penetration depth.	Reduced mortality expected	Medium confidence	Section 9.3

				Literature data on relation penetration depth and direct mortality				
Structure and functioning of the benthic ecosystem								
Mechanical disturbance seabed		Mechanical disturbance seabed by pulse trawl smaller than tickler chain beam trawl	High confidence	Field measurements penetration depth	Bottom trawl homogenizes surface layers of the seafloor Mean penetration depth pulse trawl shallower than tickler beam trawl on sand and fine sand.	Mechanical disturbance reduced due to smaller footprint and reduced penetration depth	High confidence	Section 9.3
Resuspension of sediment		Lower towing speed reduce hydrodynamic drag and sediment resuspension	Medium confidence	Technical data on dimensions of trawl gear Towing speed data from VMS	Prediction from model hydrodynamic drag estimated for beam and pulse trawls and applied to the observed distribution of the fleets	Modelled resuspension decreased,	High confidence	Section 10.2.6; 10.2.7
						Locally an increase in resuspension may occur due to an increase in pulse trawling	Medium confidence	Section 11.6
Benthic community composition		Bottom trawling shift longevity community composition towards shorter lived species	Medium confidence	Literature data on relation trawling intensity and longevity	Reduced impact of pulse trawls due to lower footprint and reduced mechanical penetration.	Trawling impact indicators (L1, L2) show reduced impact on species composition (mechanical impact)	Medium confidence	Section 10.2.6

				com position benthos Trawling intensity maps from VMS / logbook data total fleet				
Benthic biomass		Bottom trawling reduces benthic biomass	Medium confidence	Literature data on direct mortality beam trawl and pulse trawl Trawling intensity maps from VMS / logbook data total fleet	Reduced impact of pulse trawls due to lower footprint and reduced mechanical penetration / mortality.	Trawling impact indicators (PD) show reduced impact (mechanical impact)	Medium confidence	Section 10.2.6
Biogeochemistry		Average effect (chlorophyll and oxygen dynamics) of pulse fishing is lower but more variable	High confidence	Lab experiments Biogeochemical model	No evidence of electric induced chemical reactions from lab studies using bi-polar pulse exposure. Biogeochemical effects reflect patterns of mechanical disturbance showing a reduced but more variable impact.	Mechanical disturbance reduced due to smaller footprint and reduced penetration depth	High confidence	Section 10.2.7
Other impacts								

Electrolysis		No detectable electrochemical effects observed in microcosm experiments.	High confidence	Laboratory experiment	Lab experiments on water and sediment showed that the sole (bi-polar) pulse did not result in detectable electrolysis from 3 seconds to 2 minutes of exposure.	Electrochemical effects will be negligible.	High confidence	Section 9.1
CO2 emissions		Lower emissions	High confidence	Data on fuel consumption per trip of sample of beam and pulse trawl vessels	Pulse trawls reduce fuel consumption by 40-50% per hour at sea.	Fuel consumption to catch sole quotum reduced 52%, and 20% by total landed weight	High confidence	Section 5.3

The results of the assessment can be summarized by answering the following questions:

- Does pulse exposure cause direct harm, or have long term adverse consequences, to marine organisms ?
- Does pulse trawling impose a risk to the sustainable exploitation of sole?
- Does pulse trawling affect the selectivity of the sole fishery and affect the discarding of fish and benthic invertebrates?
- Does pulse trawling affect the impact on the benthic ecosystem of the sole fishery?
- Can pulse trawling reduce the impact on sensitive habitats and threatened species / ecosystems
- Does pulse trawling affect the CO_2 emissions of the sole fishery?

11.2 Does pulse exposure cause direct harm or have long term adverse consequences to marine organisms

Exposure experiments with sole, plaice, sea bass, small-spotted catshark did not find evidence of direct mortality of fish exposed to a commercial pulse stimulus (Soetaert et al., 2016a; Desender et al., 2017b; Molenaar, pers comm), nor caused ulcers in dab (de Haan et al., 2015),

Extensive sampling of fish catches on board of commercial pulse vessels and pulse exposure experiments in tanks showed pulse-induced lesions in cod. About 35% of the sampled cod showed injuries that corresponded to pulse-induced injuries (luxation or fractures in the spine, heamal or neural arches and associated haemorrhages) observed in tank experiments. The injury rate showed a domeshaped relationship with fish size with highest incidence rate in cod of around 40 cm.

Elevated injury probabilities were also recorded for lesser and greater sandeel in pulse trawl catches but it is unlikely that these are due to pulse exposure because (i) an even higher injury rate was observed in catches of tickler chain beam trawls and (ii) a tank experiment showed a low (1%) injury rate among sandeel exposed to a pulse stimulus. In other fish species, the injury rate in pulse trawl caught fish was less than 2% and was not higher than recorded when the pulse stimulus was switched off, and often even lower than in fish caught with conventional tickler chain beam trawls (Figure 10.1). This indicates that incidence rate of pulse-induced injuries will be low (<=1%).

Fish that are retained in the trawl will be landed and any pulse-induced injuries will not result in additional mortality. Injured fish may add to the unaccounted mortality if these are not landed. Ecological consequences of pulse-induced injuries will be limited to fish that pass through the electric field without being retained in the net or that are retained but subsequently discarded. The injury probability will have consequences for the consideration of fish welfare (section 12.2). For all fish species studied except cod, the injury rate is low (<=1%) and often less than the mechanical induced injuries inflicted during the catch process (section 8.4). Therefore, the population level effect of pulse-induced injuries will be negligible (high confidence).

Cod that pass through the electric field without being retained may become injured. The injury probability of small cod is uncertain and may be lower than in medium sized cod. An exploration of the population level consequences of different levels of mortality imposed by pulse trawling on cod that pass through the gear without being retained indicates that the population level effects will be negligible for the North Sea population (high confidence) and small for the southern North Sea stock component (section 10.6.1) (medium confidence).

A laboratory study found an increased mortality in early life stages (pelagic eggs, larvae) of cod that were exposed to a shrimp pulse with a comparable field strength but lower pulse frequency to a pulse trawl, but not for sole eggs and larvae (Desender et al., 2017a; Desender et al., 2018). Potential population level consequences of pulse induced mortality among pelagic eggs and larvae was explored by estimating the proportion of the eggs and larvae that are exposed to pulse trawling (high confidence). Demersal eggs will have a higher exposure probability then pelagic eggs, but the potential mortality imposed by pulse trawling is still much lower than the rates of natural mortality. The impact is considered negligible because of the low probability of exposure (medium confidence) (section 10.6.3).

Although Elasmobranchs lay demersal egg capsules that are potentially exposed to pulse trawls, the three species of rays in the southern North Sea are spawning in shallow waters off the English coast where pulse trawlers are not active (medium confidence) and have increased in abundance in recent years (section 10.6.3).

In a tank experiment the exposure to pulse stimulus did not affect the food detection ability of small-spotted catshark (Desender et al., 2017b). This is consistent with the results that elasmobranchs do respond to a same field strength threshold as a non-electroreceptive fish species, and with the electrophysiological knowledge of the insensitivity of the electrosense organs for high frequency pulses (section 7.2) (high confidence).

Pulse exposure did not result in additional mortality among six species of benthic invertebrates tested consistent with earlier studies (Soetaert et al., 2015a; Soetaert et al., 2016c; ICES, 2018c). The animals studied are a selection of different ecological groups and body plans of the invertebrates in the fishing area. Most animals responded to the pulse stimulus and showed an avoidance response or remained inactive for a short period after exposure. The population level effects on the studied species, and the potential foodweb consequences of pulse-induced change of behaviour, will be negligible (high confidence). Because benthic invertebrates are a diverse group of species, and not all body plans have been studied experimentally, the above conclusions have a low confidence for other taxa.

No experiments have been conducted where organisms have been exposed to non-lethal pulse stimuli to study potential effects later in life. Because the electric field strength quickly dissipate at increasing distance to the conductors, animals located outside the path of a pulse trawl will be exposed to a field strength <<5 $V.m^{-1}$. Although non-lethal effects of bipolar pulse stimulation used in the sole fishery have been only observed at much higher field strength (WGELECTRA, 2018), it is unlikely that animals located outside the path of the pulse trawl will be adversely affected. Animals located within the trawl path may be exposed to higher field strength. Exposure to a field strength which may cause a non-lethal effect may occur in the area close to the conductor. Since this area comprise only a part of the total trawl width, the probability of a single 1.5 sec exposure to a high field strength will be lower that the estimated exposure probabilities in section 10.5.1 (Figure 10.2). The low exposure probability and the short duration (1.5 sec) implies that there is no chronic exposure to pulse stimuli. The probability of multiple exposures will be even lower. This implies that at the current level of pulse trawling the risk of a possible adverse effect is very low. (section 10.5) (medium confidence).

Conclusion: Exposure to the sole pulse may cause spinal injuries in a small percentage of the exposed animals. In most fish species the injury probability is low (<=1%) except in cod where about 35% of the animals showed a spinal injury. The ecological and population level consequences are estimated to be negligible because of the low exposure rate. Pulse exposure is unlikely to affect electroreceptive species because of the difference between the high pulse frequency used in pulse trawling and the sensitivity range for low pulse frequency of the electroreceptors. No adverse effects (mortality or lesions) are found for the studied benthic invertebrate species exposed to the sole pulse. Animals will return to normal less than one hour after exposure making any ecological effect highly unlikely. The low exposure probability and the short duration (1.5 sec) implies that there is no chronic exposure to pulse stimuli. Population level consequences of non-lethal exposures will be negligible for the studied species. Similar or higher injury rates are observed in fish exposed to the conventional beam trawl.

11.3 Does pulse trawling impose a risk to the sustainable exploitation of sole?

Pulse exposure experiments show that sole cramps into a U-shape when exposed to a commercial pulse stimulus, but does not cause injuries or mortality. Survival of sole discards caught in the pulse fishery and the tickler chain beam trawl fishery suggest a similar mortality rate related to the injuries inflicted during the catch process. Although an exposure experiment with eggs and larvae indicated a possible adverse effect on larval cod but not on sole, the proportion of early life stages that are exposed to a pulse stimulus is much too low to have an adverse effect on the population of sole.

Pulse trawls are more efficient at catching sole and are towed at a reduced towing speed. It is uncertain whether pulse trawls catch fewer undersized sole. The beam trawl vessels that switched to pulse trawling (pulse license holders, PLH) increased their contribution to the Dutch landings from about 73% in 2009 before the transition to about 95% in 2017 after the transition. The fishing effort (swept-area) of the PLH needed to catch a fixed share of the quota reduced from 2009 to 2017 by 35% (59/0.73 in 2009 to 50/0.95 in 2017; Figure 10.10a).

Most of the sole that is caught in the North Sea is taken with beam trawls using a small-meshed codend. Only 8% is caught in a directed fishery in coastal waters using gillnets and trammelnets (ICES, 2019). The fishery is managed by a total allowable catch and during the transition period to pulse trawling the fishing mortality decreased from about F=0.4 in 2010 to just above the management target of F_{msy}=0.2 in 2018. Spawning stock size is above the reference levels for the stock (ICES, 2019). There is no indication for a reduced recruitment after the transition to pulse trawling. Recruitment is variable with above average recruitment born in 2013, 2014 and 2016.

The local increase in fishing pressure on sole in areas such as the Belgian coast and areas off the coast of England coincided with an increase in local abundance. The possibility for pulse trawlers to deploy their lighter pulse trawl in deeper gullies in the southern North Sea may have resulted in a loss of refugia for local stock in southern North Sea. Fishing pressure on the local stock in the southern North Sea may have increased but there are no indications for a reduction in local recruitment (section 11.4, 12.6.4). The local increase in fishing pressure may also have consequences for competition between fleets and the relative fishing pressure on different sole stocks within the North Sea.

Concern has been expressed that non-lethal exposure to pulse stimuli may compromise the reproductive capacity of the stock. Although no experimental evidence on non-lethal effects on reproductive capacity on an individual fish exist and potential adverse effects cannot be excluded, the quantitative analysis of the exposure probability makes it unlikely that non-lethal exposure to pulse stimuli will reduce the reproductive capacity of the stock. A cohort analysis showed that about 10% of the sole that survive till the reproduction phase will pass once through the electric field without being caught in the year before reproduction. During this event the sole is exposed for about 1.5 seconds to a field strength >5 $V.m^{-1}$. Repeat spawners will be either retained in the gear or outside the trawl and exposed to a field strength of <<5 $V.m^{-1}$. It is unlikely that a single exposure will compromise the reproductive capacity of the stock (medium confidence).

Conclusion. Pulse trawling does not impose a risk to the sustainable exploitation of sole if the stock is well managed. It is highly unlikely that pulse stimulation will inflict additional mortality in sole caught but escaping the catch process or compromise the reproductive capacity by non-lethal exposure to pulse stimuli. Fishing pressure on the local stock in the southern North Sea may have increased but there are no indications for a reduction in local recruitment.

11.4 Does pulse trawling affect the selectivity of the sole fishery and affect the discarding of fish and benthic vertebrates?

Pulse trawls catch more sole and less other total fish per fishing hour, hence improving the selectivity of the beam trawl fishery for sole. The bycatch of undersized fish and benthic invertebrates in pulse trawls is lower. Per unit of area swept, pulse trawls have a higher catch rate of sole, and a lower catch rate of plaice. Other species are caught in proportion to the area swept. Results of whiting are uncertain.

The condition of the flatfish bycatch in pulse fisheries is generally better due to the lower towing speed and cleaner catch composition, resulting in an higher survival of discards compared to conventional beam trawling.

A modelling study showed that the transition of conventional beam trawling to pulse trawling reduces the partial fishing mortality of the discard size classes.

Conclusion. Pulse trawling improve the selectivity of the sole fishery reducing the proportion of other fish species in the mixed bag, and reduce the bycatch of undersized fish for most fish species (discards) and benthic invertebrates (high confidence).

11.5 Does pulse trawling affect the impact on the benthic ecosystem of the sole fishery?

The transition of conventional beam trawling to pulse trawling reduced the footprint of the beam trawl fishery for sole. The replacement of tickler chains by electrodes reduced the depth of disturbance of the trawl and likely reduced the mortality imposed on benthic invertebrates. The lower towing speed of the pulse trawls coincided with a reduced mobilization of sediments, and resulted in a smaller footprint and a reduced surface area swept (high confidence).

The consequences of the transition to pulse trawling were assessed using a recently developed impact assessment methodology that has been adopted by ICES (ICES, 2017; Rijnsdorp et al., 2020b). The transition to pulse trawling reduced the benthic impact by 62%. The decrease ranged between -54% for coarse sediments to -72% for muddy sediments. The impact was assessed at the scale of 1 minute longitude x 1 minute latitude (grid cell ~ 2km^2). There is anecdotal information that in certain areas in the southwestern North Sea, pulse vessels have moved to more muddy parts of grid cells, which were not trawled with the conventional tickler chain beam trawl. The estimated decrease in impact in muddy areas of -72%, may be an overestimate as it does not reflect possible changes in local grounds (medium confidence).

Sediment mobilization is estimated to have decreased by -39%. The consequences on the biogeochemical processes were modelled and showed on average a reduced impact on the mineralization and denitrification per trawling event but not a consistent reduction. Due to the reduced footprint and trawling intensity, the reduction of the biogeochemical impacts of the transition to pulse trawling will be larger (high confidence).

The above conclusions apply to the reduction in mechanical disturbance. The field and laboratory experiments showed that electrical pulses used in the fishery for sole had no measurable effect of biogeochemical processes and that biogeochemical effects were due to the mechanical disturbance of the sediment by the gear. For the species studied we did not find an effect of pulse exposure. However, it is uncertain whether the lack of impact of electrical stimulation can be extrapolated to other taxonomic groups.

Conclusion. Pulse trawling substantially reduces the impact on the benthic ecosystem (medium confidence).

11.6 Can pulse trawling reduce the impact on sensitive habitats and threatened species/ecosystems?

Natura 2000 habitats that occur in the footprint of the conventional beam trawl and pulse trawl fishery include sandbanks covered by seawater all the time, reefs and submarine structures leaking gases and estuaries. Natura 2000 species include fish species, such as sea lampreys, allis shad, twaite shad and Atlantic salmon; marine mammals such as the harbour porpoise, common seal and the grey seal; and piscivorous and molluscivorous seabirds and coastal birds such as red throated diver and little tern. European eels are conserved under the Eel Regulation 2007/1100/EC and their habitats must be managed in the accordance to the Habitats Directive. Sharks, skates and rays (Rajidae) are also protected from landing under EU 2015/104. Common skate *Dipturus batis* (now *Dipturus flossada* and *intermedius*) particularly of concern.

We acknowledge reduced confidence around some of the conclusions in Table 10.1 on impacts on individual animals, particularly around benthic invertebrates and longer term sublethal impacts of pulse exposure, so here we take a logic-based approach using the evidence presented in section 10 on the likelihood of exposure to pulse trawls. Formal risk assessments for each species or habitat would be required to have high confidence but these are out of scope of the WG.

Adverse impact of the transition to pulse trawling for Natura 200 mammals are considered highly unlikely. None of the marine mammals included in Natura 2000 are at risk to be caught in a conventional beam trawl or pulse trawl because of the low vertical net opening of about 70cm and 40cm, respectively (discard monitoring programme). The low field strength outside the trawl makes an adverse effect of pulse exposure highly unlikely. Also no negative effect is expected on the food base of these species. Pulse trawling is more selective in catching sole and will result in a reduced, or similar fishing pressure on other fish species (Section 5.7, 10.4). The impact of pulse exposure on sandeel, an important food species for predator species, is considered negligible (Section 8.2).

The same reasoning applies to the Natura 2000 seabirds. Many seabirds rely on pelagic fish. Because the field strength that may cause involuntary muscle contractions is restricted to the width of the pulse trawl and extends into the water column for 50cm above the gear, the probability of exposure of pelagic fish species is expected to be low. Pelagic fish are known to respond to noise of fishing operations and swim away from the approaching gear reducing the probability of exposure to the electric field. Pelagic fish are reported in the catches of pulse and conventional beam trawls (Table 6.4.1 in ICES, 2018), but the low number show that these are an accidental bycatch.

Given the reduction in mechanical impact on the benthos, we expect that pulse trawling has no, or a positive, effect on the food base of mollusc eating birds. A reduction in discards may reduce the food base of scavenging species (Heath et al., 2014).

An adverse impact of the transition to pulse trawling on Natura 2000 fish species is unlikely because of the low overlap in distribution with the pulse trawl fishery for sole, although they may incidentally being caught. Allis shad was reported in the discard monitoring of the beam trawl fleet (ICES, 2018). All Natura 2000 species are anadromous that spawn in rivers and return to the sea as juveniles and adults. Shads spawn in rivers and reside in coastal waters and estuaries as adults and juveniles. Rather than overexploitation, the main causes for their decline lie in the reduced connectivity between, and deterioration of their freshwater habitats (Dickey-Collas et al., 2015). Shads are pelagic fish that live throughout the water column which reduce their probability of being caught in a beam or pulse trawl. Lampreys are parasitic and attach themselves to other pelagic and demersal fish species reducing the chance of being captured in a pulse trawl. Lampern (*Lampetra fluviatilis*) and sea lamprey (*Petromyzon marinus*) are mainly, but not exclusively caught in coastal waters (Kloppmann, 2015). Atlantic salmon (*Salmo salar*) travels widely over the northern Atlantic during their marine phase (Heessen and Daan, 2015) and is not typically attached to the seafloor which strongly reduce the probability of exposure to a pulse trawl. European eels *Anguilla anguilla* pass through parts of the southern North Sea as juveniles and adults and during these life stages they can use the demersal environment. Little is known with certainty about their movements in early life stages, but under the assumption that they are not residing in but passing through the pulse trawl fishing area, the exposure probability and potential impact will be small. Less is known about sturgeon in the area.

All North Sea rays and skates stocks are managed through a generic multispecies TAC together with additional measures for the depleted species (ICES, 2018; Ellis et al., 2008). The thornback, blonde and spotted rays are the most abundant ray species in the southern North Sea which overlap in distribution with pulse trawling. These three species show an increase in stock development in recent years (ICES, 2018b). Egg capsules are vulnerable for bottom trawling, in particular for the disturbance by tickler chains (Walker and Hislop, 1998). As the nursery areas of these species are typically in shallow waters (Ellis et al., 2005), outside the footprint of the pulse trawl fishery, and tickler chains have been replaced by longitudinal electrodes, an adverse effect of pulse trawling is unlikely.

There are multiple SAC within the pulse trawling zone, designated for a number of reasons including protected habitats. No adverse effect of electrical stimulation was found was found on biogeochemical processes in sediments, and both footprint, benthic impact and sediment mobilization is reduced. Although a change in the spatial distribution was observed during the transition period, the decrease in benthic impact was found for the main sea floor habitats (coarse sediment, sandy sediment, muddy sediment and mixed sediment). In terms of reef habitat (e.g. Sabellaria reef), no specific studies have been conducted. In the Dutch Brown Bank area, where conventional beam trawling has been largely replaced by pulse trawling, three *Sabelaria spinulosa* reefs were discovered within the sandbank troughs in August 2017 (van der Reijden et al., 2019).

Conclusion

Pulse trawling in the southern North Sea takes place against the background of beam trawling and other bottom-trawling activities. Although no specific experiments have been carried out to study the impact of pulse trawling on Natura 2000 species, the available knowledge allows us to assess a possible adverse impact as highly unlikely, because probability of exposure is likely to be (very) low and the overall footprint of the pulse fishery has been reduced compared to beam trawling (low confidence). Natura 2000 habitats will have been exposed less by pulse trawls compared to conventional beam trawls (medium confidence).

11.7 Does pulse trawling affect the CO_2 emissions of the sole fishery

Pulse trawling reduced the estimated fuel consumption of pulse trawling compared to the conventional beam trawling with a Sumwing by 37%. The reduction is larger (52%) when expressed relative to the share of the sole quota, and 22% when expressed relative to the total weight of the landings (Table 5.4).

Under the assumption that the CO2 emissions are proportional to fuel consumption, the reduction percentages provide an estimate of the reduction in CO2 emissions that can be achieved when using the pulse trawl in the beam trawl fishery for sole.

12 Discussion

The assessment summarized in Table 10.1 shows that a transition from conventional beam trawling to pulse trawling when exploiting the total allowable catch of North Sea sole will improve the ecological performance of the fishery by reducing the bycatch of undersized fish and benthic invertebrates, reducing the disturbance of the seafloor and impact on the benthic ecosystem, and reducing the fuel use and associated CO_2 emissions. The criteria used were restricted to the ecological and environmental domain and the comparison of pulse trawling with conventional beam trawling. In this final chapter, a number of other topics that were raised in the debate about pulse trawling will be briefly discussed.

12.1 Passive gear

Some stakeholders claim that static gears would be a more benign alternative to harvest sole (Bloom, 2018). Although passive gears will have a lower fuel use and CO_2 emissions, and will reduce the impact on the benthic ecosystem, the gear may catch substantial amounts of fish bycatch. Passive gillnets may also catch marine mammals and sea birds (Vinther, 1995; Vinther and Larsen, 2004; Žydelis et al., 2013).

In the North Sea sole fisheries only 8% of the total landings is caught with passive gears (ICES, 2019). The data collected about the sole fishery with passive gears (Appendix 3) shows that this fishery is mainly operated during the spawning season of sole when adults migrate towards coastal waters to spawn. During winter, sole leaves the coastal waters and adverse weather conditions preclude the deployment of passive gears to target sole. The available data from a few discard trips sampled suggests that gillnet fisheries for sole can have a substantial bycatch of fish (mainly dab). This information indicates that although gillnets may reduce some of the ecological and environmental effects, it may also have adverse side effects.

12.2 Animal welfare

The lab experiments conducted in this project show that the exposure of marine organisms to a Pulsed Bipolar Current as used in the pulse fishery for sole does not pose a risk of adverse effects, except for spinal injuries and associated haemorrhages in cod. Spinal injury rates estimated in 11 other fish species, representing >90% of the total pulse catch of fish, is low (<1%) and did not differ from the injury rates in pulse trawl tows where the pulse stimulus was switched off and similar or lower than in the catches of conventional beam trawlers. Although irrelevant from an ecological point of view, pulse-induced spinal injuries of fish are relevant from the point of view of animal welfare (Browman et al., 2018). For a balanced treatment of the problem the various steps in the catch process and deck processing need to be considered. Deck processing does not differ between pulse and conventional beam trawling, but the catch process differ. In conventional beam trawling fish are mechanically exposed to the tickler chains, whereas in pulse trawling fish are exposed to the electrical pulse stimulus and to the mechanical exposure to electrodes and tension relief cords. After passing the groundrope, fish either escape through the meshes or aggregate in the codend. In the codend, the fish are exposed to other components of the catch. Injuries are mainly due to the mechanical exposure during the catch process. The severity will relate to the exposure duration, towing speed and the composition and weight of the catch in the codend. Although a comprehensive analysis of the animal welfare aspects of the beam trawl fishery for sole is beyond the scope of our study, the above description of the different steps in the catch process highlight that the pulse exposure during 1.5 sec is only one of the many steps that may cause discomfort. The higher injury rate observed in fish caught in a conventional beam trawl for most species, except cod that comprise less than 5% of the numbers caught, suggests that the discomfort caused by a pulse exposure and the possible spinal injuries inflicted among a small number of fish caught, have to be compared to the generally higher injury rates observed in fish caught in conventional beam trawls.

12.3 Socio-economic consequences for other fisheries

The improved selectivity of the pulse trawl for the main target species sole, and the possibility that the lighter pulse trawls can be used on fishing grounds that were previously inaccessible to the conventional beam trawl gear, may give rise to an increased competition with other vessels fishing on the same fishing grounds. Indeed small-scale fishers loudly voiced their concern about falling catch rates which they attributed to pulse trawling. A report summarizing the complaints of a number of small-scale fishers voiced at a meeting on 1 September 2017 noted a general consensus on declining catches in recent years coinciding with the increase in pulse trawl activities in the area (Anon, 2017). In a meeting in March 2018 in IJmuiden similar concerns were expressed (Steijns, 2018) as they were by English fishers in meetings in Lowestoft and Ramsgate in 2017 (Bremner et al., 2019).

In a desk study, the catch rate of gillnet and handline fishers was compared to the catch rate of pulse trawlers in the southern North Sea. The study concluded that the decline in the gillnet catch of sole is likely due to the competition with pulse trawlers. The decline in cod catches in gillnet and handline fisheries matched the declining catch rate of beam trawlers between spring and autumn suggesting that the decline is related to a decline in stock size in the southern North Sea. For sea bass the decline in catch rates of the small-scale fishers is likely related to the decrease in stock size (Rijnsdorp et al., 2018b). The causes for these declines in stock size are unclear and may be climate change driven or due to high fishing pressure.

Local fishers in the Southern North Sea claim there is a deterrent effect of pulse fishing on these fish species. This is based on anecdotal information on their observations of fish movements in the vicinity of pulse trawls. However, the strength of the electric field declines sharply with distance from the electrode array. Results from a tank experiment to estimate the behavioural response to a pulse stimulus indicate response thresholds of about 3–6 $V.m^{-1}$ (section 7.1). This would mean that a behavioural response only occurs within 1 metre from the electrode array. Hence, the electric fields outside a pulse gear will be too low to elicit a response, although it is possible that other stimuli, such as vibrations, may lead to an avoidance response of the fish at a larger distance.

Strong support for the effect of increased competition among fleets comes from a study of the spatial distribution of the Belgian beam trawl fishery. Both the Belgian large (engine power >221 kW) and small fleet segment (engine power ≤ 221 kW) migrated out of the southern North Sea, while the effort of the Dutch small fleet segment increased in this area and more specifically in front of the Belgian coast (Vansteenbrugge et al., 2020). This change is likely due to competitive interaction as shown by (Sys et al., 2016), who showed that the catch rate of Belgian beam trawlers dropped when they were fishing together with Dutch pulse trawlers, whereas the catch rate increased during the weekend when the Dutch vessels were in port.

Competition may occur when different fishing gears are used on the same fishing ground, but may also occur for instance when a beam trawl catches sole during their onshore migration to the coastal spawning grounds within the 12 miles zone reducing the local availability of sole for the gillnet fishery. Gillnett fishers suggested another mechanism that may explain the decline in their catch rate. A mechanisms suggested by gillnet fishers that may explain the decline in their sole catch rate assumes that conventional beam trawling may chase away sole from a trawl track into the static gear located nearby. This will not occur if a pulse trawl is used because of the lower speed and larger proportion of the soles caught.

A special case in the issue on competition is the Belgian 12-miles zone. A Belgian study (Vansteenbrugge et al., 2020) demonstrated that the Dutch pulse trawler fleet <= 221kW shifted its fishing effort southward with a decrease in Dutch waters and an increase in the Belgian 12-miles zone. Over the same period, the (modelled) fishing mortality for sole decreased in the North Sea (4bc, 4c and Mouth of the Thames) while it increased in the Belgian 12-miles zone. Scientific survey data (BTS) for mature sole also showed a different trend in abundance in the North Sea (4bc, 4c and Mouth of the Thames) compared to the Belgian 12-miles zone. Whereas this has been quite stable for the former, there has been a peak abundance in the period 2012-2015 with a steep decrease from 2016-2019 for the latter. This difference was not at all present for young sole (<24cm). All this points at a high fishing intensity on sole in the Belgian 12-miles zone with an observable effect on the local stock that deviates from the rest of the North Sea. This confirms the observations and complaints by local recreational and coastal commercial fishers in Belgium.

EU fisheries management aims at a sustainable exploitation of fish stocks by setting limits to the annual catch to be taken (TAC) and by setting technical regulations to minimize the adverse effects on the marine ecosystem and the marine environment. In the socio-economic domain, management aims to lay the foundations for a profitable industry and to share out fishing opportunities fairly (https://ec.europa.eu/fisheries/cfp/fishing_rules_en). With the inception of the CFP, fishers of the member states were allowed to fish in the EU waters upto 3 nautical miles from the coastline, and the share of the annual catch of each species was fixed by country by species (relative stability). Member states were free to manage their fisheries as long as the catch would not overshoot their share of the TAC. Under this management system, fishing fleets improve their technologies within the constraints set by the Technical Regulations. As a result technical efficiency may increase (technological creep) (Eigaard et al., 2014) and give rise to conflicts among fishers, fleets and nations. Conflicts between fishers and between fishing gears are timeless (de Groot, 1984). It is the task of politicians, fisheries managers and stakeholders to find solutions within a given legal framework to share out fishing opportunities fairly.

12.4 Control and enforcement

Concern was voiced about the determination of the critical pulse characteristics (power, shape, frequency) and the control and enforcement (ICES, 2012). These concerns were taken up by the Dutch government and dimensions of the electrical equipment and pulse parameters were restricted (Appendix 4). As part of the regulation, pulse settings (voltage over electrode pairs, pulsewidth and pulse frequency) and pulse characteristics in sea (voltage, power) are recorded every minute and stored for at least half a year. Data extracted from the data loggers showed that the vessels were operating within the boundaries set (Rijnsdorp et l., 2020c).

12.5 Number of pulse licenses and contribution to scientific research

The number of licenses were granted under the following conditions and regulations:

- 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).

The increase in the number of licenses, negotiated by the Dutch government with the European Commission was there to accommodate the interest of the fleet (Haasnoot et al., 2016). This preceded the growth in the budget available for research to address the questions and concerns raised by ICES and STECF. The IAPF-project was initiated in response to the extension of the number of licenses in 2014 and an another multiyear project was funded in 2017 in which the detailed catch and effort data of all pulse trawl vessels is collected (Rijnsdorp et al., 2019).

Although unplanned, the growth of the number of active pulse trawlers led to a situation where almost the total Dutch share of the TAC of sole was caught by pulse trawlers. This created an unintended experiment on a gear transition at the scale of the whole fishery, although in an ideal experimental approach, half of the vessels would have been fishing with a pulse trawl and half with the conventional beam trawl.

12.6 Knowledge gaps

The current study provided a lot of new scientific knowledge of the effects of the exposure of marine organisms to a pulse stimulus used in the beam trawl fishery for sole which will close some of the knowledge gaps listed by WGELECTRA in 2018. In this paragraph we will discuss these gaps and describe the current status given the current knowledge.

12.6.1 Extrapolating results from the laboratory to the field

A mechanistic understanding of how an electric pulse affects spinal injury in different fish species and different size classes will reduce the uncertainty in the assessment of the population level effects. Although our project aims to develop such a mechanistic understanding, results are only partly available (effect of size and body shape on field strength in a fish). Nevertheless, the field samples of fish caught in pulse and conventional beam trawlers clearly showed that pulse-induced injuries are restricted to cod and may occur in other species in very low numbers. Hence, the assessment of its consequences on the ecology of marine fish populations is not hampered by the lack of mechanistic understanding.

For other effects of electrical pulses on marine organisms, such as sublethal effects on reproduction, mechanistic understanding will reduce the uncertainty in the impact assessment.

Field experiments

The lack of large-scale and long term field experiments on the effects of pulse trawling was noted. The situation has not changed since 2018.

12.6.2 Sublethal effects

Knowledge of the potential detrimental effects on larval development and survival, and reproduction of the adult broodstock and fertility success was noted as a knowledge gap. Although no experimental studies have been undertaken, the analysis in the current report of the probability of exposure makes it highly unlikely that the pulse trawl fleet has had a detrimental impact on the reproductive success of cod and sole. As the spawning areas of rays are located in shallow waters, this also apply to the rays.

12.6.3 Behaviour and long-term effects

WGELECTRA 2018 noted the lack of studies examining long time effects of exposure on the behaviour or interaction of exposed animals nor potential attraction or repulsion to repetitive electric pulse stimulus.

The analysis of the VMS fishing registrations showed that only animals that live in the most intensively trawled grid cells will have a chance of being exposed several times during a year, whereas animals living in most of the trawled grid cells will be exposed once in a year or not exposed at all to a field strength of >5 $V.m^{-1}$ for the duration of 1.5 sec. This suggests that there is no chronic exposure to pulse stimuli used in the pulse trawl fishery for sole making it highly unlikely that there will be long-term effects of non-lethal exposure to the electric stimulus of pulse trawling.

12.6.4 Population and ecosystem consequences

WGELECTRA 2018 noted lack of information on the effect of pulse exposure on the function-ing of benthic ecosystems and on the potential for changes in the distribution of populations caused by the fishing activity of pulse trawlers.

Ecosystem functioning

Substantial progress has been made in the study of the impact of pulse trawling on the ben-thic ecosystem functioning by the combination of laboratory experiments, field experiments and modelling. The results provide strong evidence that benthic ecosystem functioning is affected primarily by the mechanic disturbance and that the exposure to electrical pulses does not lead to a measurable effect.

Population movement

The laboratory experiments of the response of fish to an electrical pulse stimulus do not sug-gest that fish may respond to a pulsed electric field when they are outside the trawl track. Electro-physiological knowledge suggest that fish may be attracted or dispelled by an electric field. This response, however, is shown to pulse stimuli such as a direct current used in freshwater electro fishing, but not to the pulsed bipolar current applied in sole pulse trawling.

It is unknown whether other stimuli, that are related to the electrical fields, may have a biological effect.

Effect on sole stock of change in effort distribution

The shift in the distribution of the sole fishery during the transition period to the southwest-ern parts of the North Sea, coincides with the changes in distribution of sole observed in the beam trawl survey. Hence, it is unlikely that the change in distribution is due to the possibil-ity to deploy the lighter pulse trawls in softer sediments. On a smaller scale, the expansion of pulse fishing into certain throughs in the southern North Sea is confirmed by several pulse fishers although this was not supported by the detailed analysis of VMS fishing positions. Previous unfished grounds may have acted as refugia for the local sole stock but it is current-ly unknown how large these areas have been and how much effort has been involved.

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Annex 1: List of participants

2020 Participants

Name	Institute	Country	E-mail
Adriaan Rijnsdorp	Wageningen Marine Research	The Netherlands	Adriaan.rijnsdorp@wur.nl
Arianna Servili	Ifremer	France	Arianna.servili@ifremer.fr
Clive Fox	Scottish Association for Marine Science (SAMS)	United Kingdom	Clive.Fox@sams.ac.uk
Daniel Stepputtis	Theunen Institute	Germany	daniel.stepputtis@thuenen.de
Edward Schram	Wageningen Marine Research	The Netherlands	Edward.schram@wur.nl
Hans Polet	ILVO	Belgium	hans.polet@ilvo.vlaanderen.be
Julie Bremmer	Cefas	United Kingdom	julie.bremner@cefas.co.uk
Justin Tiano	Netherlands Institute for Sea Research	The Netherlands	Justin.tiano@nioz.nl
Martin Lankheet	Experimental Zoology, Wageningen University	The Netherlands	Martin.lankheet@wur.nl
Mattias van Opstal	ILVO	Belgium	mattias.vanopstal@ilvo.vlaanderen.be
Pieke Molenaar	Wageningen Marine Research	The Netherlands	Pieke.molenaar@wur.nl
Pim Boute	Experimental Zoology, Wageningen University	The Netherlands	Pim.boute@wur.nl

2019 Participants

Name	Address	E-mail
Adriaan Rijnsdorp	Wageningen Marine Research, Haringkade 1, 1976 CP IJmuiden, Netherlands	Adriaan.rijnsdorp@wur.nl
Maarten Soetaert	ILVO, Ankerstraat 1, 8400 Oostende, Belgium	Maarten.soetaert@ilvo.vlaanderen.be
Pim Boute	Experimental Zoology, Wageningen University, Wageningen, Netherlands	Pim.boute@wur.nl
Justin Tiano	Netherlands Institute for Sea Research, Korringaweg 7, 4401 Yerseke, Nethernalds	Justin.tiano@nioz.nl
Pieke Molenaar	Wageningen Marine Research, Haringkade 1, 1976 CP IJmuiden, Netherlands	Pieke.molenaar@wur.nl
Koen Chiers	Gent University, Belgium	Koen.chiers@ugent.be
Marieke Desender	CEFAS, Lowestoft, England	Marieke.desender@cefas.co.uk

Julie Bremmer	CEFAS, Lowestoft, England	julie.bremner@cefas.co.uk
Clement Garcia	CEFAS, Lowestoft, England	Clement.garfcia@cefas.co.uk
Hans Polet	ILVO, Oostende, Belgium	Hans.polet@ilvo.vlaanderen.be
Mattias van Opstal	ILVO, Oostende, Belgium	Mattias.vanopstal@ilvo.vlaanderen.be
Lies Vansteenbrugge	ILVO, Oostende, Belgium	Lies.vansteenbrugge@ilvo.vlaanderen.Be

2018 Participants

Name	Address	E-mail
Adriaan Rijnsdorp	Wageningen Marine Research, Haringkade 1, 1976 CP Ijmuiden, Netherlands	Adriaan.rijnsdorp@wur.nl
Maarten Soetaert	ILVO, Ankerstraat 1, 8400 Oostende, Belgium	Maarten.soetaert@ilvo.vlaanderen.be
Daniel Stepputtis	Thunen Institute, Rostock, Germnay	daniel.stepputtis@thuenen.de
Phil Copland	Marine Scotland, Aberdeen, Scottland, UK	Phillip.Copland@gov.scot
Pim Boute	Experimental Zoology, Wageningen University, Wageningen, Netherlands	Pim.boute@wur.nl
Justin Tiano	Netherlands Institute for Sea Research, Korringaweg 7, 4401 NT Yerseke, Netherlands	Justin.tiano@nioz.nl
Pieke Molenaar	Wageningen Marine Research, Haringkade 1, 1976 CP Ijmuiden, Netherlands	Pieke.molenaar@wur.nl
Anthony Viera	CRPMEM Hauts-de-France, 12 rue de Solférino, 62 200 Boulogne-sur-Mer, France	antony.viera@copeche.org
Annemie Decostere	Gent University	Annemie.Decostere@UGent.be
Nicolas Desroy	IFREMER,	Nicolas.Desroy@ifremer.fr
Jose-Luis Zambonino	IFREMER	Jose.Luis.Zambonino@ifremer.fr
Tom Catchpole	CEFAS, Lowestoft	Tom.catchpole@cefas.co.uk
Julie Bremmer	CEFAS, Lowestoft	julie.bremner@cefas.co.uk
Ludvig Ahm Krag	DTU-Aqua	lak@aqua.dtu.dk
Yolanda Arjona	JNCC Inverdee House, Baxter Street Aberdeen, UK	Yolanda.Arjona@jncc.gov.uk
Dick de Haan	Wageningen Marine Research, Haringkade 1, 1976 CP Ijmuiden, Netherlands	Dick.dehaan@wur.nl
Niels Hintzen	Wageningen Marine Research, Haringkade 1, 1976 CP Ijmuiden, Netherlands	Niels.hintzen@wur.nl
Jan Jaap Poos	Wageningen Marine Research, Haringkade 1, 1976 CP Ijmuiden, Netherlands	Janjaap.poos@wur.nl

Annex 2: Resolutions

WGELECTRA - Working Group on Electrical Trawling

2016/2/SSGIEOM22 A **Working Group on Electrical Trawling (WGELECTRA)**, chaired by Mattias van Opstal, 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	11-13 June	Ghent, Belgium	Interim report by 11 of July 2019 to ACOM-SCICOM	
Year 2020	25-27 March	By correspondence	Final report by 24 April 2020 to ACOM-SCICOM	

ToR descriptors

ToR	Description	Background	Science plan codes	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	2.1, 6.1, 6.4	Yearly update	Review report to SCICOM
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..	b) Advisory Requirement as part of a response to request from the Dutch Ministry of Agriculture, Nature and Food Quality. s WGECO will provide some considerations for WGELECTRA to take account of when responding to this request.	2.1, 2.7, 6.4	Year 1	Relevant section of the WGELECTRA report must be made available for independent external review by 30 April 2018.
c	Discuss and prioritise knowledge gaps, and discuss ongoing and upcoming research projects in the light of these knowledge gaps,	a) Science Requirements b) Advisory Requirements	2.1, 2.7, 6.4, 6.6	Year 1, 2 & 3	Scientific research adressing knowledge gaps or questions from management

	including the experimental set up				
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	3.1, 6.6	Year 1, 2 & 3	Joint projects and publications among participants and others Collaboration with other related WG's such as WGNSSK, WGCRAN
e	Analyse the possible contribution of pulse trawling to reduce or increase the ecosystem/ environmental impacts of the fishery for sole in the North Sea and reflect on the fuel consumption used in the fishery sole in the North Sea.	Advisory Requirement as part of a response to request from the Dutch Ministry of Agriculture, Nature and Food Quality. Analysys must be developed taking into consideration: 1. The elements listed in article 31(1) of regulation (EU)2019/1241 of 20 June 2019 namely: marine ecosystems (including the long-term effects on), sensitive habitats and selectivity. 2. Discussions within FAO on the issue of CO2 emissions in fisheries and its impact on climate change. See http://www.fao.org/policy-support/resources/resources-details/en/c/1152846/ in particular chapter 27	2.1, 6.1, 6.4	Year 3	Relevant section of the WGELECTRA report must be made available for independent external review by 3 April 2020

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 special request from The Netherlands-Dutch Ministry of Agriculture, Nature and Food Quality.
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 enable ICES to respond to advice requests from member countries. Consequently these activities are considered to have a very high priority. It will also lead ICES into issues related to the ecosystem effects of pulse fisheries, especially with regard to the application of the Precautionary Approach. Current pulse derogations in the sole fishery will expire in 2019. 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 3: Sole gillnet fishery

Gillnet fishery in Belgium and the Netherlands

The Dutch and Belgian sole gillnet fishery mainly targets sole (*Solea Solea*) with minor marketable bycatch of other species. This fishery is a typical small-scale seasonal fishery with vessels with a length range from 6 to 12m with engines powers from 11 to 150kW. The fishing season ranges from February until November. Sole caches peak in February march during the annual migration to the coastal spawning grounds. Typical fishing grounds are the sandy coastal area's ranging from ~100m from the shore up to 20 miles offshore with a water depth from 2.5 – 24 m. Typical soaking time for this fishery is ~24 hours, but in the low water temperature moths this is sometimes extended to ~48 hours. Due to the limited vessel size this fishery is restricted to weather conditions that permit safe working conditions, therefore the gillnets are only deployed when there is a window with two consecutive days limited wind (0-6 bft) and waves (0-1.8 m).

In 2014-2016 there were ~210 Dutch gillnet licences. However the type of gillnet is not specified, those can use gillnets and trammelnets of various types targeting different species like sole, cod, sea bass and mullet. In 2015 there were 97 active gillnet vessels making a total of 2223 trips. Only 19 vessels made more than 40 trips in 2015, with 151 trips for the most active vessel. However this number does not specify what gear has been used but a large proportion have been sole gillnet trips. Those numbers indicate that gillnet fishing is only possible when weather conditions are favourable and sufficient fish is available in the area. The intensity of the Dutch gillnet fishery on sole is represented in Figure A3.1. The Belgian fleet has only 1 active gillnetter (2020), which mainly operates near the offshore sandbanks of the BPNS.

Gear characteristics

Single sole gillnets consists of a sinking and a floating line with (gill)netting in between made from monofilament, multi-monofilament and multifilament (Figure A3.2). Those have a stretched mesh opening of 92 to 100 mm, are 50 or 100 m long with an height of 1 but sometimes up to 2.2m. Individual sole nets are connected and deployed in strings with an length of 1000 up to 1500m with a double anchor and a boy marker on both ends of the string.

Catch composition

With the Dutch Visstat and DCF observer program data of 2014-2015 the catch composition for the sole gillnet fleet is extrapolated to a fleet level catch composition (van Helmond et al. 2016). Sole catches were 21% of the total catch of witch 85% was marketable sole. Except for large flounders and a small fraction of the dab (>25cm), almost all other caught species were undersized and discarded. It should be noted that those undersized fish are not removed from the gear, and are 'discarded from the gear' the next trip as the gears are deployed (Figure A3.3).

Depestele et al. (2011) conducted a one-year discard sampling programme for the BPNS in conjunction with trammelnet fishers. All four Belgian trammelnet fishers that were active in this period cooperated, which strongly reduced potential bias in selecting vessels. Adverse weather, or potential non-random selection of fishing trips was nevertheless a potential remaining source of bias. The observed discard rate, based on weights, were high to very high for dab (55.90 +-SD 44.79%), flounder (57.33 +- SD 47.78%) and plaice (70.23 +-SD 35.07%). The discard rate of sole was very low (2.19 +-SD 3.20%). The discard proportion of all fish species was estimated at 21.9%, which is low compared to the Dutch Visstat and DCF observer program.

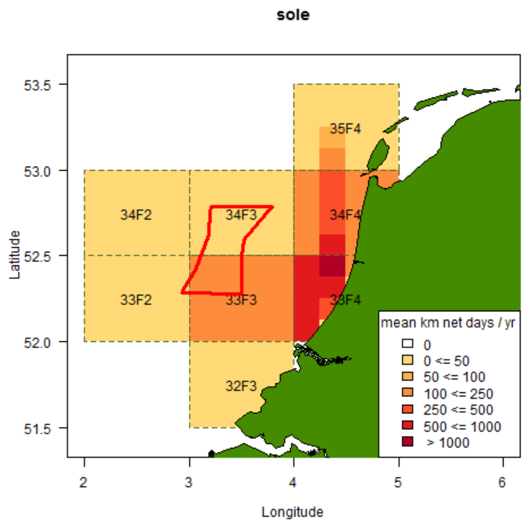

Figure A3.1 The intensity of gillnet fishery on sole in the Dutch coastal-zone, per 1/16 ICES square. Annual average for the period 2014 to 2017 expressed in number km-net-days per year (Jongbloed et al. 2019) . The red square is not relevant to this report.

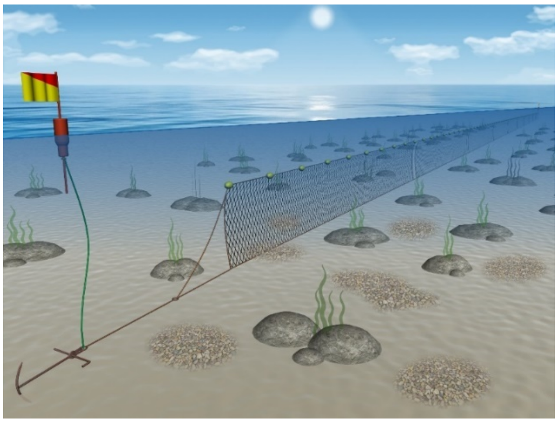

Figure A3.1. Gillnet gear set-up (seafish.org)

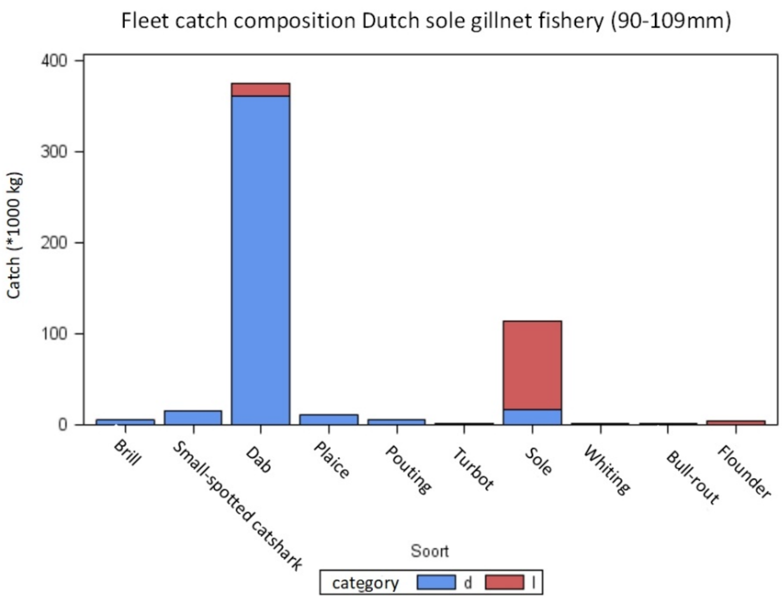

Figure A3.3. Total catch composition for the sole gillnet fleet based on VISSTAT. Blue bars represent discarded catch and red bars landed catch in weight for the 2014-2015 period (van Helmond et al. 2016)

References

Depestele J, Courtens W., Degraer S., Haelters J., Hostens K., Houziaux J-S., Merckx B., Polet H., Rabaut M., Stienen E.W.M., Vandendriessche S., Verfaillie E. & Vincx M. 2011. An integrated impact assessment of trammelnet and beam trawl fisheries. Final Report. Brussels : Belgian Science Policy 2009 (Research Programme for a Sustainable Development)

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van Helmond A.T.M., Steins N.A., 2016. Vangstsamenstelling per tuicategorie; Herziening contingentenstelsel in de Nederlandse visserij in het kader van de aanlandplicht. Wageningen Marine Research Wageningen UR (University & Research), Wageningen Marine Research Report C017/16. 62 blz.

Annex 4: Technical restrictions applicable to pulse trawl in the Netherlands

January 2017
Ministry of Economic Affairs
Translated Pulse requirements (voorschriften) - English

Updated pulse requirements:

1. Fishing with electric current using a beam trawl is only permitted in ICES zones IVc and IVb, south of the latitude 55^{0} N.
2. The Technical On-board Dossier (TOD), which must be prepared in accordance with Enclosure I, is present on board. Furthermore, a Manufacturers' Technical Dossier (MTD) must also be prepared for the pulse fishing gear in accordance with Enclosure II.
3. The fishing gear must comply with the following regulations:
    a. The peak voltage of the pulse must not exceed 60V, measured between the connections of the electrodes and pulse modules.
    b. The maximum effective output power must not exceed 1kW per metre of beam length, measured between the connections of the electrodes and pulse modules.
    c. The composition of the electrodes (item ix) of the fishing gear has been recorded in the MTD and the TOD by the manufacturer. The other specifications included below are included in both the MTD and the TOD:
        i. the overall length of the electrode
            - measured from the start of the first conductive part to the end of the last conductive part, not exceeding 4.75 metres;
        ii. the number of conductive parts per electrode
            - at least 6 parts and no more than 12 parts;
        iii. minimum and maximum thickness of the conductive part of the electrode (mm)
            - diameter (circular) no more than 40 mm (minimum dimensions due to limitation of maximum individual deviations in order to remain compliant with the conditions for testing in laboratory conditions);
        iv. minimum and maximum length of the conductive part of the electrode (mm)
            - at least 125 mm and no more than 200 mm;
        v. minimum and maximum length of the leading insulator (m)
            - at least two metres;
        vi. number and length of insulated parts per electrode;
        vii. The individual distance between the electrodes (mm) attached to the wing/beam
            - at least 400 mm centre to centre;
        viii. the diameter of the steel wire of the electrodes (mm)
            - no more than 20 mm;
        ix. the composition of the electrode (in MTD)
            - make-up and materials used.
    d. The pulse setting is between 20 and 180 pulses per second.
    e. The live part of the pulse period (the duty cycle) should not exceed 3.0%.
    f. The electrode pairs are not activated at the same time as the neighbouring electrodes to keep the generated field stable.
    g. The width of the whole field generated by the gear, measured as the horizontal distance between the two outermost electrodes perpendicular to the electrode direction, should not exceed the width of the fishing net, with a maximum of 12 metres.
4. The vessel is equipped with an automatic computer management system, including a data logger, which is described in the MTD by the manufacturer.
5. The data in the system cannot be manipulated. Apart from the enforcing authorities, or their mandatory, and the manufacturer, nobody has access to the computer management system to modify it. The system registers all the data stated below for at least the last 6 months and at least the last 100 tows.
    a. The system registers all the times when the data is read.
    b. The system registers whether the fishing gear has been powered up or down, linked to the exact time and position, in order to register if fishing has been carried out in the permitted zones.
    c. The system registers the peak voltage referred to under 3a and the effective power referred to under 3b, constructing a diagram per tow depicting the voltage on the

electrode pairs. Here, at least one sample/minute is used as the result of a moving average. This diagram is supplied in hard copy or digital form.

d. The instruction in 5c does not apply if the peak voltage referred to under 3a and the effective power referred to under 3b are automatically subjected to respective maximums of 60V and 1kW/metre. The units subjected to a maximum are certified by an accredited institution. This involves a type certification.

e. The system registers the pulse settings that have been used for fishing.

6. The diagram referred to under 5c is issued to the enforcing authorities at their request.
7. No tickler chains or other fish-stimulating facilities may be attached in front of the footrope.
8. A net with floating voltage is used on the vessel to supply power to the pulse system.
9. Assistance will be provided for the monitoring programme into the effects of pulse fishing that is being performed as a collaboration between the Ministry of Economic Affairs, the fisheries sector and the research institutes. This assistance may consist of financial contributions to the programme costs.
10. The following fishing gear codes are used in the log:

Name of fishing gear	**Code to be recorded in the log**
Pulse trawl	PUK
Pulse wing	PUL

11. The Sea Fishing Implementing Regulations are being met.

The following parts of the pulse fishing gear are subject to a transition period:

- Electrodes must comply with the above requirements by 1 March 2017 at the latest. Electrodes can be replaced with new ones in the interim.
- Modules must comply with the above requirements by 1 March 2018 at the latest.

The pulse permission may be suspended or withdrawn if a fisherman fails to comply with the requirements as set above.

This permission must be present on board the vessel for which the permission has been granted while fishing and must be presented immediately upon request by any official responsible for inspection.

Annex 5:

Messages from Review Group for WGELECTRA 2020 Report

The three members of the Review Group prepared separate reviews of the WGELECTRA 2020 Report, and then discussed the report and their reviews on April 27. Key points emerging from the discussion included:

- Although each of the three reviews makes slightly different points, reflecting, among other things, the different areas of specialization of the reviewers, there are no noteworthy differences of opinion among the reviewers regarding the points made in all three reviews and all three (attached) warrant consideration by the Advice Drafting Group
- Notwithstanding a number of minor points raised by each reviewer about the WG Report, all reviewers agree that the information in the report is scientifically sound, clearly presented, and is a sound basis for the ADG to work from in preparing the ICES advice.
- This support for the WGELECTRA report, and advice that would be based on it, is sound for the specific sole fishery currently using the specific pulse gear, in the southern North Sea. If the gear is considered for use in other fisheries, in other places, or with different operating parameters of pulse generation, all aspects of the results in the WG Report would need to be reviewed for applicability. There is a high likelihood that additional research would be needed on performance under the differing conditions with the nature of the additional necessary work depending on the operating conditions of these other fishery(ies).
- Although the ability to extrapolate the results reported in the WGELETRA 2020 Report to other conditions has not been established, and these results have uncertainties, the implications of the uncertainties are generally explained appropriately, and the Review Group noted that comparability quantity or quality of information has not been available for evaluating the performance of any other fishing gear, including some in wide use in the ICES area.
- As a result of the points above, objective, evidence-based decisions regarded environmental performance of the sole fishery using pulse gear can be made with less uncertainty than decisions about the environmental performance of all other gears known to the reviewers.
- The reviewers noted a couple of areas where, although the present WGELECTRA Report is a sufficient and sound basis for responding to the Special Request fro The Netherlands, the advice is likely to leave scope for public policy debate on a couple of issues. In particular:
    - With regard to the information on fuel efficiency and GHG emissions of the pulse gear fleet, it was difficult to make clear comparisons of the performance of this gear to gears with regard to these efficiency considerations. This is because there are no accepted metrics and standards for performance, so individual studies often report performance results in such different units that comparisons require a lot of additional calculations. The review group notes that discussions of fuel efficiency of different fishing methods and carbon footprint of different food sources are both escalating and become more contentious. ICES – possibly in partnership with FAO Fisheries – would be well placed to have an Expert initiative to compare metrics and standards for these features

of fishery performance, and provide advice on "best practices" for providing such information for fishing fleets and fisheries.

- The spatial distribution of both fishing effort and catches changed over the transition period to the pulse gear, with possible ecological, economic and social implications. Although this redistribution was discussed in the WGELECTRA Report in sufficient depth to respond to the Special Request, the review group noted there is a fair possibility that public policy debate about the causes and consequences of the spatial distribution of the fishery using various gears will continue. ICES might consider some targeted work on spatial aspects of the fisheries, anticipating that there will be calls for more advice on these issues in future and such advice would need information not available at the current spatial scales of most studies.

Review by Professor Reg Watson, Adj Professor of Fisheries and Ecological Modelling, Institute for Marine and Antarctic Studies, University of Tasmania, Australia

1. Evaluate the work performed by WGELECTRA on the possible contribution of pulse trawling to reduce or increase the ecosystem/environmental impacts of the fishery for sole in the North Sea

My review of the work performed by WGELECTRA suggests that it was comprehensive in coverage as relates to pulse fishing (PF) employed within ICES regulated waters and investigated many if not most of the possible interactions and impacts. Though the works are broad in scope at times they are somewhat shallow in depth, for example several important aspects were covered by comparatively few laboratory experiments.

I will evaluate the report as I would any scientific work:

Specific Comments

Though an area of only recent focus, an understanding of animal pain and suffering was only tangentially examined in this report. Admittedly, such considerations should naturally extend to all fishing methods but when a relatively new approach is considered this may be of wider concern. My read is, however, that the mechanical impacts of current non-PF fishing practises are at least as damaging and likely more pain inducing. It would be better if all injured individuals are retained and killed as quickly as possible but in all current fishing practises this has not been possible.

It remains to be seen whether long-term use of PF in an area will cause behavioural changes in some organisms or even drive some selection pressures. Indeed, these have not been well studied or documented even for traditional fishing practises.

The interaction between the electrical pulse and the muscular body frame of the target, working somewhat as in antennae, suggests a strong relationship with body length. This was observed here and was in previous work including mine with juvenile shrimp. Some sizes will be quite susceptible and some of those will undergo the strong body contractions required to allow their capture. There is a suggestion that different frequencies/waveforms can target different sizes - this can be an advantage but would have to be considered in assessments and quotas. It appears that there are currently only two major providers of the PF gear and little experimentation in wave profiles and frequencies other than very limited ones in the laboratory are discussed here.

Would the electrical pulse induce changes to the magnetic sensing that allows orientation and migration of target and non-target species, and if so, would these be only temporary? The findings suggest that the frequencies used do not impact the electric sensors used by some fishes (i.e. catsharks and rays).

How does the PF selectivity impact marine environments at an ecosystem level? Would there be new trophic cascades induced that have unexpected consequences? Will predators learn to follow the PF (with its slower speeds) and opportunistically take disorientated or injured animals (as happens somewhat with regular trawls)?

How do the electric fields impact the hulls of fishing vessels with regard corrosion, would any additional toxic materials be released into the environment? This seems unlikely unless the gear is operated in close proximity to the hull.

Electric fishing allows and indeed requires slower transit speeds over the bottom. How will winds and tides impact this? Currently the direction of trawl paths has to be selected for a number of reasons (including economy of motion) but will maximum effective bottom speed become more important?

It would seem obvious that salinity changes will impact the gears efficiency. Are there plans to use this gear in estuary areas?

Can whiting stocks take the extra fishing pressure of PF that is suggested by the report?

In 10.5.1 the modelling assumes a random distribution of trawling activities with a grid cell. Though this is convenient (and maybe unavoidable) it is usually not the case. Differing catch rates, sediments, depths, or just tradition may mean that some areas are fished hard and others seldom. How does this assumption impact the findings?

In 10.5.3 - my read is that more rays may be taken by PF but their survival is better – though not statistically significant. This may have to be investigated further. Uncertainty around the impact on vulnerable taxa must be minimised.

Minor Formatting

Colours used in 'Maps' such as Figure 5.7 are not very informative and not intuitive.

Units used in 10.5.1 and 10.6.4 are quite oddly and inconsistently expressed

2. Advise on the inclusion of the elements listed in article 31(1) of regulation (EU)2019/1241 of 20 June 2019 and reflections on fuel use consumption in the fishery for sole in the North Sea.

The background of electrical pulse fishing (PF) and the material presented in the report suggests that PF offers an opportunity to increase fishing efficiency (which was historically seen as a negative) in that both targeted catch per energy expended while reducing the degree of bottom disturbance and likely long-term impact. PF reportedly offers the opportunity to reduce bycatch and mortality of unwanted species. Technically it is possible that is can be tuned to be more size and species selective by varying frequency and waveform.

I have tried to confirm the fuel saving (-47% compared to conventional beam trawls) discussed in Chapter 5 but find this difficult. In 5.3 the authors discuss fuel consumption in l/hr @ sea (average) and this is also what is described in the caption for Table 5.3, however, the same table heading says l/day by vessel. I am therefore not sure what is shown. In other works, such as Parker et al. 2015[1], the best way to compare benefits to the fishery is l/t of landed product or to the environment (kg CO_2 per kg landed). Perhaps this might make comparisons easier, especially against other similar fisheries elsewhere.

With regard article 31(1), the disturbance of marine habitats will be reduced from conventional fishing and therefore sensitive habitats will be less impacted. There are no suggestions that PF will have negative long-term effects on marine ecosystems but rather it offers opportunities to reduce these effects. Selectivity is improved in most cases with the reduction in the catch of discarding species and even some types of bycatch. There may be possible to change the electrical pulses and increase the size and species selectivity in ways that conventional gear cannot do.

Specifically, with regard to the issues of CO_2 emissions in fisheries referred to in Chapter 27 of the FAO Technical Paper No. 530, the evidence strongly suggests that PF represents one of the 'significant opportunities to reduce fuel use and greenhouse gas (GHG) emissions in capture fisheries and aquaculture'. Future improvements to battery systems and low carbon electrical generation may even allow for some of PF's power needs to be met with low GHC emissions.

The energy saving of PF must be further studied and the technology enhanced. All of this must appear in peer reviewed publications which offer transparent and widely available information into the merits and challenges involved with this fishing method.

[1] Parker, R. W. R., K. Hartmann, B. S. Green, C. Gardner, and R. A. Watson. 2015. Environmental and economic dimensions of fuel use in Australian fisheries. Journal of Cleaner Production **87**:78-86.

3. Evaluate whether the work from WGELECTRA is suitable to be used for ICES advice.

I can see no compelling reason why the work completed by WGELECTRA cannot be used for ICES advice. It seems to meet at least the minimum scholarly standards and explores many aspects of the interaction of PF with the marine environment and marine species. Failure to include this broad scale information would require ICES to commission similar work to be undertaken by other groups. This delay would be inappropriate given the wide use of PF and some of the advantages that appeal both to fishers and some aspects of management. Several aspects of this report are apparently in review for publication in scientific journals and refinements such as some suggested here will likely be necessary. This additional review and scrutiny by experts in the various specialised area should ensure that the reported findings and conclusions can be adopted with greater confidence. The thin coverage of some subject areas (with limited experimentation) will perhaps be addressed in follow-on work and be necessitated for scientific publication. The use of the material for formal advice purposes could be delayed while that is underway, but it is my opinion that this delay is unnecessary.

Review by Dr. Jake Rice, Chief Scientist, Emeritus, Department of Fisheries and Oceans, Canada

This request from ICES for Review of this report in specifically in the context from a request for advice from The Netherlands regarding the evidence of diverse ecosystem effects of pulse fishing for sole in the North Sea, and the fuel consumption of the pulse trawl fleet. In terms of ecosystem effects the request calls specific attention to sensitive habitats and selectivity of the pulse fishery, but does not restrict the advice to solely those two aspects of the mangy possible aspects of fishing impacts. Although the request does not specify explicitly that the comparison be between the sole fishery using beam trawls, and the same fishery using pules gears, the reference to "to reduce or increase the ecosystem/environmental impacts of the fishery" strongly supports focusing on a comparative evaluation of the impacts of the two gears, although naturally there will be an interest in the absolute scale of impacts, even if comparatively the impacts of one gear are less using the other. The WGELECTRA report reports its finding primarily framed comparatively between the two gears. However it gives sufficient attention to measuring or estimating absolute impacts that the Report can provide an evidence basis for discussions of both whether the transition to a fishery largely prosecuted with pulse gears rather than beam trawls has deduced or increased various ecosystem impacts, and how large the impacts of the pulse fishery are.

Overall I found the WGELECTRA Report to be clear, well-written and consistent. There are editorial details that need attention before finalization, but for a Draft WG Report of a meeting only several weeks ago and prepared under the exceptional working conditions that have characterized the winter and spring of 2020, it is a fully acceptable basis for preparing a response to the Special Request from The Netherlands.

The structure of the Report contains many Sections and Subsections of the Report – enough that in my experience some experts and administrators ask for greater consolidation. Importantly, though this structure makes it relatively easy to extract the information need to respond to the Special report, and possible even go beyond a narrow interpretation of the request given the large number possible ecosystem impacts of the various gears that are considered in the Report. The pathways by which the pulse fishing gear – and usually the beam trawl – could impact the morphology, physiology and behaviour of the target species and key bycatch species are first examined individually. Next these results are rolled up to possible impacts on survivorship, growth and other aspects of fish well being. Those results are next aggregated to potential population level impacts. The same stepwise approach is then repeated for impacts on key bycatch species, seabed bio-geo-chemical features, and benthos. It is at the higher levels of integration of population-scale and habitat-scale impacts that impacts of ecosystem structure and functional properties are evaluated. This structure should make is relatively straightforward to identify the specific factors that make large contributions or negligible ones to overall performance of the gears in te context of an Ecosystem Approach to sustainable fishing, and to compare which features of which gears differ most in their performance.

Not only is the structure of the report useful, it allow the scientific soundness of the individual steps to each be evaluated. Without labouring over every single step for target species, bycatch, benthic community, habitat structure, and ecosystem properties, the individual pieces of scientific investigation are soundly done in essentially all cases. Conclusions from the early steps of the integrated approach rely heavily on laboratory-based research, with field validation to the extent possible – although such efforts at validation are often indirect. At the population and ecosystem scales of integration, the work is much more field based, with use of information from general monitoring and directed sampling of commercial fishing vessels and vessel-based experiments. Extrapolations from study results to population-scale impacts necessarily required modelling and extrapolation.

If one looks carefully minor details can be questioned at all scales. Why differences in sample sizes were used in various laboratory studies and some vessel-based sampling, when these resulted in different powers of detecting differences if they existed. Given it was obvious even before the laboratory and field experiments were done that it would be necessary to untangle the impacts of the pulse fishing gear itself from the electronic pulses the gear introduced to the environment, I was surprise the obvious control of the pulse fishing gear with the pulse turned off was not used more. Finally Table 11.1 is potentially very useful in preparing a consistent response to the Special Request. However, a critical examination of the individual cells makes it appear that the same amount of information can be considered a basis for "high confidence" in some cases and "low confidence". I made a point of tracking several of these cases back into the report and in each case the scientific reasoning for the differences or similarities in confidence was sound. However, in a number of cases one needs both a lot of experience as a scientist dealing with the various sources of uncertainty (incomplete information, inconsistent information, etc), and access to the fuller Report to understand why the individual judgements on confidence were made. When the advice is develop from this Report, if parts of Table 11.1 are used directly, effort should made to ensure the basis for each confidence statement would look sound to a bread readership. Overall, though, these are *extremely minor overall concerns, and the evidence from the studies reported comprise a sound basis for preparing a response to the request from The Netherlands.* In particular the methods used to extrapolate research results to population and ecosystem impacts are sound and well explained. Any extrapolation of research results to population or ecosystem scale inferences involve assumptions. In the case here the assumptions are generally quite standard for fisheries research, and most are well tested. The only place when there seemed to be some ad hoc explanations involved for patterned in the data themselves or the extrapolations from them are in the explanation of how the fleet and fishing effort has redistributed as the use of pulse fishing gears has increased the se of beam trawls decreased.

The overall strong endorsement of the WGELECTRA as a scientifically sound basis for a response to the Special Request from ICES does not mean more challenges are unlikely to arise - and this is aside from whether considerations like equity of access to opportunities to fish or competition among fleets or national interests have been addressed appropriately (or at all) during the transition. Among the next generation of concerns I foresee are

- whether the apparent ability of the pulse gears to fish in habitats like marine gullies where beam trawl did not fish will reduce the unquantified (in fact likely undocumented at all, but I don't know the full range of recent work on North Sea biodiversity conservation) benefits from may have been refugia with the mobile sole fleet used exclusively beam trawls;
- the actual population scale impacts of the apparent increased in mortality of some ages or sizes of cod and whiting in the North sea. The work reported in the WGELECTRA report on cod or whiting is good as far as it goes, but I suspect there is ample room for determined critics of pulse trawls to raise more questions about the long term sustainability of the southern North Sea cod and whiting
- a demand for more in-depth examination of the overall implications of the spatial redistribution of fishing effort in the southern North sea, as interest in spatial approaches to both fisheries management and conservation of biodiversity increase.

Review by Mark Tasker, Emeritus Principal Advisor at JNCC, United Kingdom

Specific evaluation of:

- The work performed by WGELECTRA on the possible contribution of pulse trawling to reduce or increase the ecosystem/environmental impacts of the fishery for sole in the North Sea
- The inclusion of the elements listed in article 31(1) of regulation (EU)2019/1241 of 20 June 2019 and reflections on fuel use consumption in the fishery for sole in the North Sea.
- Whether the work from WGELECTRA is suitable to be used for ICES advice.

I was supplied with a draft copy of the WGELECTRA 2020 report on 3 April 2020. I comment below on the bullet points listed above and other topics.

Draft report

Overall, I found the draft report very comprehensive and well written. It will provide a very solid basis for the provision of ICES advice on the ecosystem/environmental impacts of the fishery for sole in the North Sea. I particularly liked the use of a formal assessment framework, that can obviously be added to or amended should there be further scientific progress. I would note that this assessment goes far beyond that evcer assembled for other gear/fisheries in the region and perhaps sets a very good example. Similar work by other gears/fisheries might help to understand and potentially reduce their environmental impact.

It was evident that this draft still requires some copy-editing and correcting. In particular, some sections (e.g. Section 8.3) are written in the plural first person as if WGELECTRA had actually carried out the scientific work required, instead of assembling and describing the work. I suspect this is due to wholesale lifting of text from (draft?) reports. While this is an understandable response when assembling a report under the current "lock-down" pressures, I think that it would be very wise to change these sections before this is issued as otherwise a reader from outside might feel that WGELECTRA is carrying out the research and not critically evaluating and reporting it. Beware also of phrases like "this study found…" – better to state e.g. "WGELECTRA finds…".There are, of course, great overlaps between membership of ICES expert groups and the experts actually carrying out research, but the roles being conducted by individuals differ between these two circumstances. Some English could also be improved, but this is not essential. A cross-check between references cited in the text and those in the bibliography is required – especially for items "in press", "under review" etc. It is important that readers can refer independently back to sources. If these items are not publicly available, that should be indicated.

Technical points

I found a few inconsistencies. Pulse trawls are described as using "high frequency" pulses in a variety of places. First, no other science community would describe 100 Hz or less as being high frequency (e.g. 20 kHz is a commonly used threshold for "high" by sound researchers). I suggest removal of the adjective "high, just describe the frequency. Second in the summary, the frequency used by pulse trawls is described as 30-45 Hz, while on p11, two pulse sources are described, one around 86-91Hz and the other at 60 Hz. I assume the latter are correct and that the summary should be corrected – either way, consistency is important. There are other mentions of "high frequency" in the report that need to be made consistent.

On p8, the fuel consumption gain by the Sumwing is 16%, while on p10 it is 13%. It is not clear why these are different, or whether it is typographic mistake. Section 5.3 paragraph 3 says that pulse trawling thus can reduce the estimated annual fuel consumption by 37% when compared to the Sumwing, but I cannot see this from Table 5.3. I wonder if Table 5.3 might be converted into %ages (or have percentages added) to support the text. If these points are taken into account, WGELECTRA's text appears to be a suitable basis for provision of ICES advice on fuel use/consumption in the North Sea sole fisheries with the exception of the gill net fishery – I would add that I am not an expert in this area of work though.

I think the conclusion on p15 that pulse trawls have not moved into muddy habitats is important in debunking previous anecdotal evidence. It would be useful to have this (and other evidence on habitat impacts) included in the assessment framework/tables.

I was unclear where the evidence for frequency detection by ampullae (end of p28) comes from. Maybe the text could be expanded or some references cited for this.

In Table 8.3, I noted "surmullet" as a fish. I had not heard of this species before and find on Google that it is red mullet (or striped red mullet). I would perhaps recommend a table of species and scientific names might be included as an Annex (as done by other ICES expert groups).

Section 11.6 is understandably restricted to EU level protected species and habitats. I question whether "submarine structures caused by leaking gas" occur within the pulse trawl footprint in the North Sea. I presume the sentence at the end of paragraph 2 of Section 11.6 should read "out of scope…". It would be worth considering whether this section could be extended to include those species and habitats on the regional "threatened and declining" OSPAR list. There is some overlap, but I notice that work has already been carried out on *Arctica islandica*, which is on OSPAR's list. Some of the habitats on OSPAR's lists might well be described as "sensitive", hence would be well within the scope of the request from the European Commission.

WGELECTRA's report forms a good basis for advice to the European Commission on this innovative gear (sensu EU 2019/1241 Art 31(1)) in relation to marine ecosystems, sensitive habitats and selectivity.