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Wageningen University &
Research report C037/20

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The multiannual programme Impact Assessment Pulse Fishery was funded under the EMFF, European Fund for Maritime Affairs by the Ministry of Agriculture, Nature and Food Quality and by funding from the Ministry of Agriculture, Nature and Food Quality for the purposes of Policy Support Research Theme Nature Inclusive Fisheries.

Project no. BO-43-023.02-004

IJmuiden, April 2020

Wageningen Marine Research report C037/20

Keywords: electro-fishing, pulse trawls, beam trawls, bottom-trawling, gear selectivity, discards, fish, benthos, geochemical functioning, footprint, impact indicators, fuel consumption.

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Wageningen Marine Research, an institute within the legal entity Stichting Wageningen Research (a foundation under Dutch private law) represented by Dr. M.C.Th. Scholten, Managing Director

KvK nr. 09098104,

WMR BTW nr. NL 8113.83.696.B16.

Code BIC/SWIFT address: RABONL2U

IBAN code: NL 73 RABO 0373599285

Contents

Summary

This report presents the results of a four year research project "Impact Assessment Pulse trawl Fishery (IAPF)" on the biological and ecological effects of electric pulse trawls used in the fishery for North Sea sole. The pulse trawl is an innovative fishing gear where the mechanical stimulation by tickler chains is replaced by electrical stimulation. Pulse trawls were introduced to reduce adverse ecological and environmental impacts of the beam trawl fishery and reduce fuel costs. In the Netherlands, 76 beam trawl vessels made the transition to pulse trawling under a (temporary) derogation from the EU legislation that prohibits the use of electricity to catch fish. In 2019, the EU decided to maintain the ban on pulse fishing.

The aim of the IAPF project (2016-2020) is to provide the scientific basis for the assessment of the consequences of a transition from conventional tickler chain beam trawls to pulse trawls for the sustainability of the beam trawl fishery for sole. The project was initiated in response to the extension of the number of licenses in 2014. The project comprised of four work packages which focused on the effect of pulse exposure on (1) marine organisms; (2) the benthic ecosystem; (3) fish stocks and the benthic ecosystem; and (4) a synthesis comparing the impact of pulse trawling with the impact of conventional beam trawling when catching the sole quota.

The research questions were tackled with a combination of (i) experimental studies in the laboratory and in the field; (ii) biological analysis of fish samples collected on board of commercial pulse and conventional beam trawlers; (iii) collection and analysis of fisheries dependent data (catch, effort, discards, Vessel Monitoring by Satellite); (iv) modelling studies. To assure the scientific quality and provide feedback on the workplan and progress of the research activities an international Scientific Advisory Committee (ISAC) was established. International Stakeholder Dialogue Meetings were organised by the Ministry of Agriculture, Nature and Food Quality (LNV) to discuss the concerns of stakeholders and inform them about the results of the research project.

The main findings of the project are the following:

- Biological relevant field strength are confined to the width of the pulse trawl. Field strength outside the pulse trawl is below the threshold level that invokes a response.
- Exposure to a pulse stimulus does not lead to additional mortality but may lead to spinal injuries in fish.
- Pulse-induced spinal injuries are low except in cod. Population level effects in cod are negligible in the North Sea stock and small in the southern North Sea stock because of the low exposure probability, and because the injury probability is lower in small cod.
- Electroreceptive fish like elasmobranchs are not specifically sensitive to the high frequency pulses used in the sole fishery
- The effects of pulse exposure, studied in selection of benthic invertebrate species, was found to be non-lethal and temporary.
- Pulse stimuli used in pulse trawling for sole do not affect geochemical processes
- Impact of pulse trawls on the benthic ecosystem is due to mechanical disturbance and not to electrical disturbance.
- The impact of mechanical disturbance of the pulse trawl is less than that of the conventional beam trawl.
- Pulse trawling improves the selectivity of the beam trawl fishery for sole and reduces the bycatch of undersized fish (discards) and benthic invertebrates.
- Survival of pulse trawl discards is estimated to be higher in plaice, turbot and brill, while no significant difference was found for sole and thornback ray.
- Pulse trawling allows fishers to catch their sole quota with a lower spatial footprint and a lower impact on the benthic ecosystem due to a lower penetration depth and sediment resuspension.
- Pulse trawling does not cause a chronic exposure to electric pulses because of the low frequency of exposure above the threshold field strength and low duration of a pulse stimulus.

- It is highly unlikely that pulse trawling will compromise the reproductive capacity of the target species by non-lethal exposure to pulse stimuli.
- It is highly unlikely that a possible adverse effect of pulse exposure of eggs and larvae will lead to adverse population level effects.
- The improved efficiency to catch sole in pulse trawls and the changes in spatial distribution may give rise to competition with other fisheries.
- Pulse trawls reduce the fuel consumption per kg landings by 20% and the fuel consumption per unit of sole quota by 52%.

Implications of assessment results in relation to the legislative framework of the EU on fisheries and the marine environment

The project provides strong support that pulse trawls can be used to sustainably exploit the quota of North Sea sole and at the same time substantially reduce the ecological and environmental cost. Pulse trawling therefore contributes to the objectives of the *Common Fisheries Policy* for sustainable exploitation. The improved selectivity further contributes to the objectives of the *Landing Obligation* to reduce the unintended bycatch.

The increased catch efficiency may lead to competition with other fisheries and may pose a problem for fisheries managers and stakeholders to find solutions to share out fishing opportunities fairly within a given legal framework.

The reduced spatial footprint and impact on the fish community and benthic ecosystem of pulse trawling will reduce the fishing pressure on the diversity, food web and the integrity of the sea floor. The lower footprint and towing speed likely reduce the wear on nets and engine and as a consequence will reduce the contaminants and marine litter. This will contribute to the objectives of the *Marine Strategy Framework Directive*.

Although no specific research has been carried out to study the impact of pulse trawling on *Natura 2000 species and habitats*, the available knowledge allows us to assess a possible adverse impact as highly unlikely, because exposure to electrical stimulation does not result in negative effects, probability of exposure is likely to be (very) low and the overall footprint of the pulse fishery has been reduced.

The reduction in fuel consumption will reduce CO2 emissions and contribute to the objectives of the *Paris agreement*.

Elaboration on the main findings

Effect of pulse stimulation on marine organisms

The wire-shaped electrodes of a pulse trawl generate a heterogeneous electric fields with the highest field strength close to the conductors. Field strength dissipate with increasing distance from the conductors. Within the trawl width the field strength ranges between ~ 5 and ~ 300 $V.m^{-1}$. Outside the trawl, the field strength is less than ~ 5 $V.m^{-1}$. Field strengths in the water column and in the sediment are similar. The duration of a pulse exposure is 1.5 seconds.

Muscle activation by electrical pulses is determined by the strength of internal electric fields inside the organism. Internal electric fields differ from the surrounding external fields due to conductivity differences of the body relative to seawater. Because the conductivity in sediment is less than in water, fish that are buried in the sediment experience a lower internal field strength than fish in the water. Internal electric fields in a typical 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 location between the pair of electrodes, or by the orientation of the fish. Susceptibility to electrical pulse decreases with fish size. At similar heights above the electrodes, field strengths in small fish are lower. In addition, the chance that small fish are exposed to high field strengths close to the electrodes is smaller.

Field strength thresholds were estimated in laboratory experiments for different responses. Thresholds provide information about the surface area where the field strength around a pulse trawl is exceeded and will affect the animals exposed. The threshold for a behavioural response is between 3 and 6

$V.m^{-1}$ (external field strength) and does not differ between electroreceptive and other fish species. Although electroreceptive fish like elasmobranchs are highly sensitive to low frequency electrical stimuli generated by their prey organisms, they are not specifically sensitive to high frequency pulses used in the pulse trawl fishery for sole. The muscle activation threshold was estimated at 15 $V.m^{-1}$ (internal field strength). A previous experiment showed that the external field strength threshold for spinal injury in cod was estimated at 37 $V.m^{-1}$, whereas 50% of the cod developed a spinal fracture when exposed at 80 $V.m^{-1}$.

Extensive sampling of fish caught by commercial vessels showed spinal injuries in most of the fish species sampled from pulse trawls and tickler chain beam trawls. Comparison of the injury probability of fish caught in a pulse trawl with the injury probability of fish caught in a conventional beam trawl or a pulse trawl where the pulse was switched off, indicated that injuries can be ascribed to mechanical damage inflicted during catching. Pulse-induced spinal injury probability was restricted to cod with an average injury probability of 36%. Spinal injury probability in cod seems to be related to fish size indicating that small cod are less sensitive to pulse exposure. Pulse-induced spinal injury probability was low (<=1%) in the other 11 fish species studied.

The effects of pulse exposure, studied in selection of benthic invertebrate species, was found to be non-lethal and temporary. Animals either did not respond (sea star, serpent star) or showed a cramp or squirming response (crabs, polychaetes), and showed an avoidance response after the stimulus.

The effect of pulse exposure on the geochemical processes was studied in both laboratory and field experiments. With the pulsed bipolar current (PBC) used in the pulse fishery for sole the potential effect of electrolysis is negligible. The studies carried out did not detect any measurable effect of pulse exposure on the biogeochemistry and the benthic disturbance by pulse trawling therefore will come from mechanical disturbance.

Scaling-up the impact to the level of the fleet and population

The pulse fishery for sole uses a pulsed bipolar current (PBC). The data logger installed, which stores the pulse parameters used during fishing, showed that the amplitude over the electrode ranged between 54 and 58V with lowest values recorded in summer and highest values recorded in winter. Average pulse frequency and pulse width was 89.4 Hz and 239 µs in the Delmeco system, and 60 Hz and 336 µs in the HFK system. The power supplied per meter gear width ranged between 0.5 – 0.6 $kW.m^{-1}$. Pulse parameters were within the boundaries set in the regulation.

To assess the consequences of a transition from conventional beam trawling to pulse trawling, the effects of mechanical and electrical stimulation during a trawling event needs to be scaled up to the level of the total fleet. The impact of both gears was compared by studying the impact of the Dutch pulse license holders (PLH) before and after the transition to pulse trawling. The PLH can be used as a proxy of the total fleet because they landed 95% of the Dutch sole landings after the transition to pulse trawling. This provides an under-estimate of the consequences of the transition by 23%, because PLH increased their share of the Dutch sole landings from 73%, when fishing with conventional beam trawls, to 95%, when fishing with pulse trawls.

During the transition period between 2009 and 2017, the PLH maintained their fishing effort (hours at sea) when fishing for sole with an 80mm mesh size in the sole fishing area (SFA), but reduced the surface area swept by the gear by 28%. The lower area impacted is due to the combined effect of a lower towing speed (-10% small vessels, -23% large vessels) and improved catch efficiency and selectivity for the target species sole. Pulse trawls have a 17% (95% confidence limits: 14%-20%) higher catch rate (kg/hour) of marketable sole and a 21% (19%-23%) lower catch rate of other flatfish and 35% (33%-38%) lower catch rate of marketable plaice.

Due to the improved selectivity, pulse trawls caught 27% (17%-36%) less discards (all fish) than conventional beam trawls. The catch rate of plaice discards was reduced by 30% (19%-40%), but the catch rate of sole discards was increased by 65% (16% - 137%). The reduction in discarding is supported by modelling the fishing mortality of the discard size classes imposed by the PLH. The partial fishing mortality decreased in flatfish except sole (33%), gadoids (16%), gurnards (10%) and other fish (16%), and increased for discard size classes of rays (44%) and sole (29%). The lower towing speed and lower catch volume in the pulse fishery resulted in a higher discard survival of plaice, turbot and brill, although no difference was found for sole and thornback ray.

The impact of pulse exposures by PLH was assessed by estimating the exposure frequency of a population to the lowest field strength where fish showed a behavioural response corresponding to the width of the pulse trawl. This is a precautionary assumption because the field strength threshold for injuries as observed in cod is substantially higher and occurs in only part of the trawl width. Based on the VMS (Vessel Monitoring System) recordings of the PLHs at a resolution of 1 minute latitude x 1 minute longitude grid cells (about 2 km^2), the exposure frequency was estimated for a population that is randomly distributed over the trawled grid cells: 21% of the population was exposed to a pulse stimulus 1 time year^{-1}; 6.6% was trawled 2 times year^{-1}; 2.4% was trawled 3 times year^{-1} , 0.3% was trawled 4 or more times year^{-1}, and 70% of the population was not exposed. This low exposure frequency and the short duration of a pulse exposure (1.5 sec) indicates that pulse trawling for sole does not cause a chronic exposure of marine organisms or the benthic ecosystem to pulse stimuli.

The population level consequences of potential pulse-induced mortality among cod that are too small to be retained in a pulse trawl, is estimated to be small (<2%) for cod in the southern North Sea and negligible (<0.5%) for the total North Sea. Adverse consequences of nonlethal exposure of sole on the reproductive output of the population is highly unlikely due to the short exposure duration (1.5 sec) and the low exposure probability of sole during the maturation year. A population level impact on the egg and larval stages of sole is highly unlikely due to the low exposure probability, the high natural rate of mortality of these stages and the density-dependent mortality that will occur later in life. The same conclusion applies to other fish with pelagic or demersal eggs.

The transition to pulse trawling reduced the impact on the seafloor and benthic ecosystem due to a reduction in the footprint (23%) and reduction in sediment resuspension (39%). The reduction in the depth of sediment disturbance will reduce the direct mortality of benthos. Indicators of the benthic impact of PLH decreased between 20% and 61%. Long-term geochemical effects of pulse trawling is reduced due to the lower mechanical disturbance. No additional effect of the pulse exposure is found. Although benthic invertebrates may respond to a pulse exposure by temporary slowing down their normal activities, the duration of this effect is short and will unlikely affect the macro-invertebrate food web.

The local increase in fishing effort of pulse trawlers in combination with the higher catch efficiency for sole may have resulted in increased competition with other fisheries. Competition between the pulse trawl fleet and the Belgium beam trawl fleet was found in the southwestern North Sea.

Pulse trawls allow fishers to tow their gears at a lower speed over the seafloor and reduce their fuel consumption and CO_2 emissions.

Samenvatting

In dit rapport worden de resultaten gepresenteerd van het vierjarig onderzoeksprogramma "Impact Assessment Pulse trawl Fishery" (IAPF) naar de effecten van pulsvisserij op de duurzame exploitatie van tong en de effecten op het ecosysteem. De pulskor is ontwikkeld om de schadelijke neveneffecten van de boomkorvisserij met wekkers te reduceren en het brandstofverbruik te verminderen. De pulskor is een innovatief vistuig waarbij de wekker kettingen waarmee tong uit de zeebodem wordt gejaagd zijn vervangen door elektrische stimulering, die de tong verkrampt en doet omkrullen zodat deze los komt van de zeebodem en makkelijker kan worden gevangen. In Nederland hebben 76 boomkorschepen gebruik gemaakt van de mogelijkheid een (tijdelijke) ontheffing te krijgen van het verbod pulsvisserij. In 2019 heeft de EU besloten om het verbod op pulsvisserij te handhaven.

Het doel van het IAPF was om wetenschappelijke kennis te vergaren waarmee de consequenties van een transitie in de Noordzee visserij op tong van de traditionele boomkor met wekkers naar de pulskor kan worden beoordeeld. Het onderzoeksproject, dat tot stand kwam na de uitbreiding van het aantal pulsvergunningen in 2014, omvatte 3 onderdelen (werkpaketten) die gericht waren op het onderzoek naar het effect van pulsstimulering op (1) zeedieren; (2) het functioneren van het zeebodem ecosysteem; (3) vispopulaties en het zeebodem ecosysteem; en (4) een werkpakket voor de synthese waarin de effecten van het gebruik van de pulskor wordt vergeleken met de effecten van het gebruik van de traditionele boomkor bij de exploitatie van de tong quota.

Voor het onderzoek is een brede verscheidenheid aan onderzoeksmethoden gebruikt: (i) blootstellingsexperimenten in het laboratorium en op zee; (ii) analyse van vismonsters verzameld aan boord van bedrijfsschepen die met de pulskor en met de traditionele boomkor visten; (iii) verzamelen en analyseren van visserijafhankelijke gegevens (vangst, visserijinspanning, bijvangst, VMS 'vessel monitoring by satellite'); (iv) model studies. Om de wetenschappelijke kwaliteit te borgen, en ervoor te zorgen dat het onderzoek goed aansloot bij de maatschappelijke vragen rond de pulsvisserij, is een International Wetenschappelijke Begeleidingsgroep ('International Scientific Advisory Committee') ingesteld. Daarnaast organiseerde het ministerie van Landbouw, Natuur en Voedselveiligheid jaarlijks een bijeenkomst ('International Stakeholder Dialogue Meeting') waarbij groepen belanghebbenden uit binnen- en buitenland de mogelijkheid werd geboden hun zorgen naar voren te brengen en de voortgang van het onderzoek te bespreken.

De belangrijkste resultaten van het project zijn de volgende:

- De biologisch relevante veldsterkte beperkt zich tot de breedte van het vistuig. Buiten het vistuig is de veldsterkte onder de drempelwaarde waarbij vissen op een pulsprikkel reageren.
- Experimentele blootstelling aan een pulsprikkel veroorzaakt geen extra sterfte maar kan wel resulteren in ruggengraatletsel.
- Vismonsters verzameld aan boord van pulsschepen laten zien dat, met uitzondering van kabeljauw, het percentage vis met ruggengraatletsel laag is. Het effect van ruggengraatletsel bij kabeljauw is verwaarloosbaar klein voor het bestand in de Noordzee en klein voor het bestand in de zuidelijke Noordzee omdat maar een klein deel van de populatie aan de puls wordt blootgesteld en kleine kabeljauw minder gevoelig is voor ruggengraatletsel.
- Electrogevoelige vissoorten zoals haaien en roggen zijn niet extra gevoelig voor de hoog frequente pulsen van de pulsvisserij op tong.
- Pulsblootstelling van een aantal ongewervelde diersoorten resulteert in een tijdelijke verandering van het gedrag en veroorzaakt geen extra sterfte.
- Pulsblootstelling heeft geen effect op de geochemische processen in de zeebodem
- De invloed van pulsvisserij op de zeebodem is een gevolg van de mechanische verstoring maar niet van het gebruik van elektrische stimulering.
- Het effect van mechanische verstoring door de pulskor is lager dan van de traditionele boomkor.
- Pulsvisserij vergroot de selectiviteit van de boomkorvisserij op tong en vermindert de bijvangst van ondermaatse vis en bodemdieren.

- Pulsvisserij verhoogt de overleving van discards van schol, tarbot en griet. Voor tong en stekelrog is er geen verandering in overleving.
- Het gebruik van de pulskor stelt de boomkorvisserij in staat haar tong quotum te exploiteren met een lagere impact op het bodemecosysteem als gevolg van een kleinere ruimtelijke voetafdruk, een verminderde diepte van bodemverstoring en een verminderde opwerveling van sediment.
- Pulsvisserij resulteert niet in een chronische blootstelling aan pulsprikkels omdat de kans op blootstelling laag is en de duur van een blootstelling kort.
- Het is zeer onwaarschijnlijk dat niet-lethale blootstelling aan pulsprikkels de voortplanting van tong negatief beïnvloedt.
- Het is zeer onwaarschijnlijk dat de pulsblootstelling van viseieren en larven een negatief effect heeft op vispopulaties.
- De hogere vangstefficiëntie van de pulskor en de veranderende verspreiding resulteert in verhoogde concurrentie met andere visserijen
- Het gebruik van de pulskor vermindert het brandstofverbruik met 20% per kg gevangen vis en met 52% per eenheid tong quotum. Brandstofbesparing leidt tot een evenredige reductie van de CO_2 emissie.

Implicaties van de resultaten voor het wettelijke kader van het visserijbeheer en het beheer van het zeemilieu in de EU

De onderzoeksresultaten tonen aan dat de pulskor een verantwoord alternatief is voor een duurzame exploitatie van Noordzee tong waarbij een aanzienlijke reductie van de ongewenste neveneffecten optreedt. Pulsvisserij draagt daarom bij aan de doelstellingen van het *Gemeenschappelijk Visserij Beleid (GVB)* voor een duurzame exploitatie. De lagere bijvangst (discards) draagt bij aan de doelstelling van de *Aanlandplicht*.

De hogere vangst efficiëntie kan mogelijk leiden tot een verhevigde competitie met andere visserijen en kan tot beheersproblemen leiden rond de eerlijke verdeling van vangstmogelijkheden binnen de bestaande wetgeving van het *GVB*.

De kleinere ruimtelijke voetafdruk van de pulsvisserij en de verminderde visserijdruk op de visgemeenschap en het bodemecosysteem vermindert het negatieve effect van de boomkorvisserij op de diversiteit, voedsel web en zeebodem integriteit. De lagere vissnelheid resulteert waarschijnlijk in een vermindering in de productie van vervuilende stoffen en afval (slijtage van netten). Dit draagt bij aan de doelstellingen van het *Kader Richtlijn Marien (KRM)*.

Alhoewel geen specifiek onderzoek is uitgevoerd naar de effecten van pulsvisserij op *Natura200 soorten en habitats*, is het onwaarschijnlijk dat de pulsvisserij tot negatieve effecten leidt in vergelijking met de traditionele boomkor: experimentele blootstelling aan elektrische prikkels gaf geen aanwijzing voor negatieve effecten; de kans op blootstelling aan de pulsprikkel is klein; de ruimtelijke voetafdruk van de pulsvisserij is verminderd.

De reductie in het brandstofverbruik draagt bij aan de doelstellingen van het klimaatbeleid (*Akkoord van Parijs*).

Toelichting op de belangrijkste conclusies

Effect van pulsstimulering of zeedieren

De electrode-kabels zoals gebruikt in de pulsvisserij op tong genereren een heterogeen elektrisch veld met de hoogste veldsterkte vlak naast de geleider. De veldsterkte neemt snel af met toenemende afstand van de geleider. Binnen het wekveld van een pulskor ligt de veldsterkte tussen de ~5 en ~300 V/m. Buiten het vistuig is de veldsterkte minder dan ~ 5 V/m. De sterkte van het elektrisch veld in de zeebodem verschilt niet of nauwelijks van de veldsterkte in het water.

Elektrische stimulering prikkelt de spieren. Spieractivatie wordt bepaald door de veldsterkte binnen het organisme. De veldsterkte in het organisme verschilt van de veldsterkte in het water als gevolg van de verschillen in geleidbaarheid van het water en het organisme. Omdat de geleidbaarheid in het sediment lager is dan in het water is de veldsterkte in b.v. een ingegraven platvis lager dan in b.v. een rondvis die zich in het water boven de zeebodem bevindt. De veldsterkte in een vis is afhankelijk van de grootte van de vis. De veldsterkte in een kleine vis is lager dan in een grotere vis die zich op een zelfde afstand van de electrode bevindt. De kans dat een kleine vis wordt blootgesteld aan een hoge veldsterkte is kleiner dan voor een grotere vis.

In laboratorium experimenten is de drempelwaarde vastgesteld waarbij vissoorten op een pulsprikkel reageren. Vissen reageerden op een pulsprikkel wanneer de externe veldsterkte van 3 tot 6 $V.m^{-1}$ werd overschreden. Electrogevoelige vissoorten zoals haaien en roggen bleken niet gevoeliger te zijn voor de tongpuls dan andere vissoorten. Electrogevoelige soorten zijn wel veel gevoeliger voor laag frequente elektrische pulsen die door hun prooidieren worden gegenereerd. De drempelwaarde voor spieractivatie werd vastgesteld op 15 $V.m^{-1}$ (interne veldsterkte). Uit de literatuur is bekend dat de drempelwaarde voor ruggengraatletsel bij kabeljauw ligt op 37 $V.m^{-1}$, en dat bij 80 $V.m^{-1}$ 50% van de blootgestelde kabeljauw ruggengraatletsel oploopt.

In de uitgebreide bemonstering van visvangsten van commerciële puls- en traditionele boomkorschepen schepen werd letsel aan de ruggengraat waargenomen bij veel van de bemonsterde vissoorten. Vergelijking van het voorkomen van ruggengraatletsel in vis die gevangen was met de pulskor en vis die gevangen was in een pulskor zonder elektrische stimulering of in de traditionele wekker tuig, liet zien dat ruggengraatletsel veelal een gevolg is van de mechanische verstoring tijdens het vangstproces. Het percentage ruggengraatletsel dat kon worden toegeschreven aan pulsstimulering was klein (<=1%) in twaalf vissoorten met uitzondering van kabeljauw waarbij 36% van de dieren ruggengraatletsel werd gevonden. Het voorkomen van ruggengraatletsel in kabeljauw lijkt verband te houden met de grootte van de vis waarbij kleine en grootte kabeljauw een kleinere kans hebben om ruggengraat letsel op te lopen.

Pulsblootstelling van ongewervelde bodemdieren veroorzaakte geen extra sterfte. De reactie op een tongpuls verschilde tussen soorten. Zeester en slangster reageerden niet. Krabben en wormen reageerden met een kramp of kronkel reactie. Na de pulsprikkel toonden de dieren een vermijdingsreactie. Kort na blootstelling hervatten de dieren hun normale gedrag.

Het effect van pulsblootstelling op de geochemische processen in de zeebodem is onderzocht in laboratorium en veldexperimenten. Met de gepulseerde bipolaire stroom (PBC) die wordt gebruikt in de pulsvisserij op tong is het potentiële effect van elektrolyse verwaarloosbaar. In geen van de experimenten leidde de pulsblootstelling tot een meetbaar effect op de geochemische processen. Het effect van de pulsvisserij op de zeebodem is daarom vooral een gevolg van de mechanische verstoring.

Opschaling van de effecten naar het niveau van de vloot en van de populatie

De pulsvisserij op tong maakt gebruik van een gepulseerde bipolaire stroom (PBC). De pulsgegevens, zoals die zijn geregistreerd in de 'data logger', laten zien dat het potentiaal verschil over de electroden varieerde tussen 54 en 58V. De laagste waardes werden geregistreerd in de zomer en de hoogste waardes in de winter. De gemiddelde puls frequentie en pusbreedte was 89.4 Hz en 239 µs voor het Delmeco system, en 60 Hz en 336 µs voor het HFK system. Het geleverde vermogen lag tussen 0.5 – 0.6 kW per meter tuigbreedte. De geregistreerde puls gegevens lagen binnen de grenswaardes van de regelgeving.

De consequenties van de overgang van de wekker naar de pulsvisserij is onderzocht aan de hand van de gegevens van de pulslicentie houders (PLH). Deze PLH zijn in de studieperiode overgestapt van de traditionele boomkor naar de pulskor en zijn verantwoordelijk voor bijna de gehele Nederlandse tongvangst. Hun aandeel in de Nederlandse tongvangst nam toe van 73% in 2009 tot 95% vanaf 2015.

De visserijinspanning (uur op zee) van de PLH in het tongvisgebied (SFA) waar de vloot met 80mm kuilen vist bleef gedurende de studieperiode gelijk. Het beviste oppervlakte nam echter af met 28% als gevolg van de lagere vissnelheid (-10% voor euro kotters, -23% voor grote schepen) en de hogere vangstefficiëntie voor tong. De pulskor had een 17% (95% betrouwbaarheidsinterval: 14%-20%) hogere vangstefficiëntie (kg/uur) van marktwaardige tong en een 21% (19%-23%) lagere vangstefficiëntie van andere platvis en 35% (33%-38%) lagere vangstefficiëntie van marktwaardige schol.

Door de verbeterde selectiviteit ving de pulskor 27% (17%-36%) minder discards (kg/uur van alle vis) dan de traditionele boomkor. De vangst van schol discards was 30% (19%-40%) lager, maar de vangst van tong discards was 65% hoger (16%-137%). De consequenties van de transitie op de visserijdruk op discards is ook onderzocht door de partiele visserijsterfte die PLH veroorzaken te berekenen. De analyse bevestigt dat de overgang naar pulsvisserij een vermindering van de visserijdruk op ondermaatste vis geeft voor platvis exclusief tong (33%), kabeljauwachtigen (16%), ponen (10%) en andere vis (16%), en een verhoging voor tong (29%) en roggen (44%). De lagere vissnelheid en het kleinere vangstvolume van de pulskor resulteert in een betere conditie van de ondermaatste vis en een verhoogde overlevingskans van discards voor schol, tarbot en griet. Voor tong en stekelrog werd geen significant verschil in overleving gevonden.

Om de impact van pulsblootstellingen door PLH te schatten op het niveau van de populatie is de blootstellingsfrequentie geschat aan de minimale veldsterkte waarbij vissen een gedragsreactie vertoonden. Dit is een voorzichtige schatting omdat de veldsterktedrempel voor verwondingen zoals waargenomen bij kabeljauw aanzienlijk hoger is. Op basis van de VMS-gegevens (Vessel Monitoring by Satellite) van de PLH's werd de blootstellingsfrequentie geschat voor een populatie die willekeurig is verdeeld over de rastercellen van 1 minuut breedte x 1 minuut lengte (ongeveer 2 km2): 21% van de bevolking werd 1 keer jaar-1 blootgesteld aan een pulsprikkel; 6,6% werd 2 keer per jaar blootgesteld; 2,4% werd driemaal met jaar 1 blootgesteld, 0,3% werd 4 keer of meer per jaar blootgesteld en 70% werd niet blootgesteld. Deze lage blootstellingsfrequentie en de korte duur van een pulsprikkel (1,5 sec) laat zien dat er in de pulsvisserij op tong geen sprake is van een chronische blootstelling aan pulsprikkels.

Het gevolg op populatieniveau van de mogelijk door pulsvisserij veroorzaakte sterfte onder kleine kabeljauw die door de mazen van het net kan ontsnappen is naar schatting klein (<2%) voor kabeljauw in de zuidelijke Noordzee en verwaarloosbaar (<0,5%) voor de totale Noordzee. Nadelige gevolgen van mogelijk niet-dodelijke blootstelling van tong op de voortplanting van de tongpopulatie zijn hoogst onwaarschijnlijk vanwege de korte blootstellingsduur (1,5 sec) en de lage blootstellingskans tijdens het rijpingsjaar. Een impact op populatieniveau op de ei- en larvale stadia van tong is hoogst onwaarschijnlijk vanwege de lage blootstellingskans, het hoge natuurlijke sterftecijfer van deze stadia en de dichtheid-afhankelijke sterfte die later in het leven zal optreden. Dezelfde conclusie geldt voor andere vissen met pelagische of demersale eieren.

De overgang naar pulsvisserij heeft geleid tot een reductie van de impact van de tongvisserij op de zeebodem en het bodemecosysteem. Deze reductie is een gevolg van de verkleining van de voetafdruk (23%) en een vermindering van de opwerveling van sediment achter het vistuig (39%). Ook zal de vermindering van de diepte van sedimentverstoring tot een reductie van de directe sterfte van benthos leiden. Indicatoren voor de benthische impact van PLH daalden met 20% tot 61%. De geochemische effecten is verminderd door de lagere mechanische verstoring en het ontbreken van een negatief effect van de pulsblootstelling. Hoewel bentische ongewervelde dieren kunnen reageren op blootstelling aan een puls door hun normale activiteiten tijdelijk te verminderen, zal dit geen effect hebben op het voedselweb van macro-ongewervelde dieren.

In combinatie met de verhoogde vangstefficiëntie van tong kan de lokale toename van de pulsvisserij geleid hebben tot een toename van de concurrentie met andere visserijen, zoals is aangetoond in de zuidwestelijke Noordzee voor de Belgische boomkorvloot.

Omdat de pulskor met een lagere vissnelheid wordt gebruikt, geeft de overgang naar de pulskor een aanzienlijke verlaging van het brandstofverbruik en de CO_2 emissie ten opzichte van de traditionele boomkor.

1 Introduction

Ecosystem effects of bottom trawl fisheries are a major concern (Dayton et al., 1995; Jennings and Kaiser, 1998; Martín et al. 2014). Bottom trawling takes place over large parts of the continental shelves and is responsible for about 25% of the wild marine landings (Eigaard et al., 2017; Amoroso et al., 2018). Bottom trawling generally requires heavy fishing gears and powerful engines with a high fuel consumption and CO_2 emission (Turenhout et al., 2016). Bottom trawling homogenises sea floor texture, disturbs the sorting of sediment generated by natural or biological processes (Watling and Norse, 1998; Thrush et al., 2006; Hewitt et al., 2010), mobilises fine sediments into the water phase (Lucchetti and Sala, 2012; Puig et al., 2012), and may cause sediment systems to become unstable (Kaiser et al., 2002). Bottom trawls impact benthic communities by damaging habitats and by imposing direct mortality among animals that come into contact with the gear (reviews in Clark et al., 2016; Hiddink et al., 2017; Sciberras et al., 2018). All these impacts also affect bio-geochemical processes in the sea floor – water interface and food webs (Duplisea et al., 2001; Puig et al., 2012; Collie et al., 2017). Finally bottom trawls are generally unselective and catch a broad range of bottom dwelling species, part of which is discarded because they are of no commercial interest or are too small to be landed (Kelleher, 2005; Uhlmann et al., 2014).

Beam trawls used to target flatfish species, in particular sole (*Solea solea*), are considered to be among the fishing gears with the largest ecological impact on the benthic ecosystem (Hiddink et al., 2017). The tickler chains dragged over the sea floor to chase sole into the net, penetrate the sediment and disturb the top layer of the sea bed down to a depth of 4 - 8 cm (Paschen et al., 2000; Depestele et al., 2016; Depestele et al., 2018). The relatively small cod-end mesh size required to retain the slender soles, results in large bycatches of undersized plaice and other fish species (van Beek, 1998; Catchpole et al., 2008; Uhlmann et al., 2014). Since the introduction of the beam trawl in the 1960s, fishers have invested in larger vessels to increase gear size, towing speed, and the number of tickler chains (Rijnsdorp et al., 2008). This increase in fishing capacity fuelled concern about the environmental impacts of this fishery (Lindeboom and de Groot, 1998).

Already in the 1970s, research started to investigate the possibility to replace mechanical stimulation using tickler chains by electrical stimulation in the beam trawl fishery for flatfish and in the fishery for brown shrimps (Soetaert et al., 2015b). It was shown that electrical stimulation can be successfully deployed in the sole fishery to immobilise fish, preventing them to escape from the approaching gear. In the shrimp fishery, it can be used successfully to reduce the large bycatch of fish and benthic invertebrates (Polet et al., 2005; Verschueren et al., 2019).

In the 1980s, when the flatfish stocks in the North Sea were severely over-exploited, the EU added the use of electrical stimulation to the list of prohibited gears. Research on pulse trawling and the effects on marine life continued. The interest in the application of electrical stimulation in the sole fishery revived in the 2000s due to the low economic profitability of the beam trawl fishery caused by the high price of fuel and low stock size, and to the growing concern about the ecosystem impacts (van Balsfoort et al., 2006) culminated in a successful year-round trial with a commercial prototype in 2004 (van Stralen, 2005). To study the possible contribution to mitigate the adverse ecosystem effects of beam trawling, the EU allowed a derogation in 2006 to use the pulse trawls for a maximum of 5% of the beam trawl fleet. The first vessels switched to pulse trawling for sole in 2009. Their success resulted in a growing interest among fishers exceeding the number of available licenses. The Dutch government negotiated with the EU to increase the number of derogations by 20 in 2010 and by another 42 temporary derogations in 2014 under the conditions that the vessels would contribute to the research of the consequences of the use of the pulse trawl to the sustainable exploitation and the ecosystem effects (Haasnoot et al., 2016).

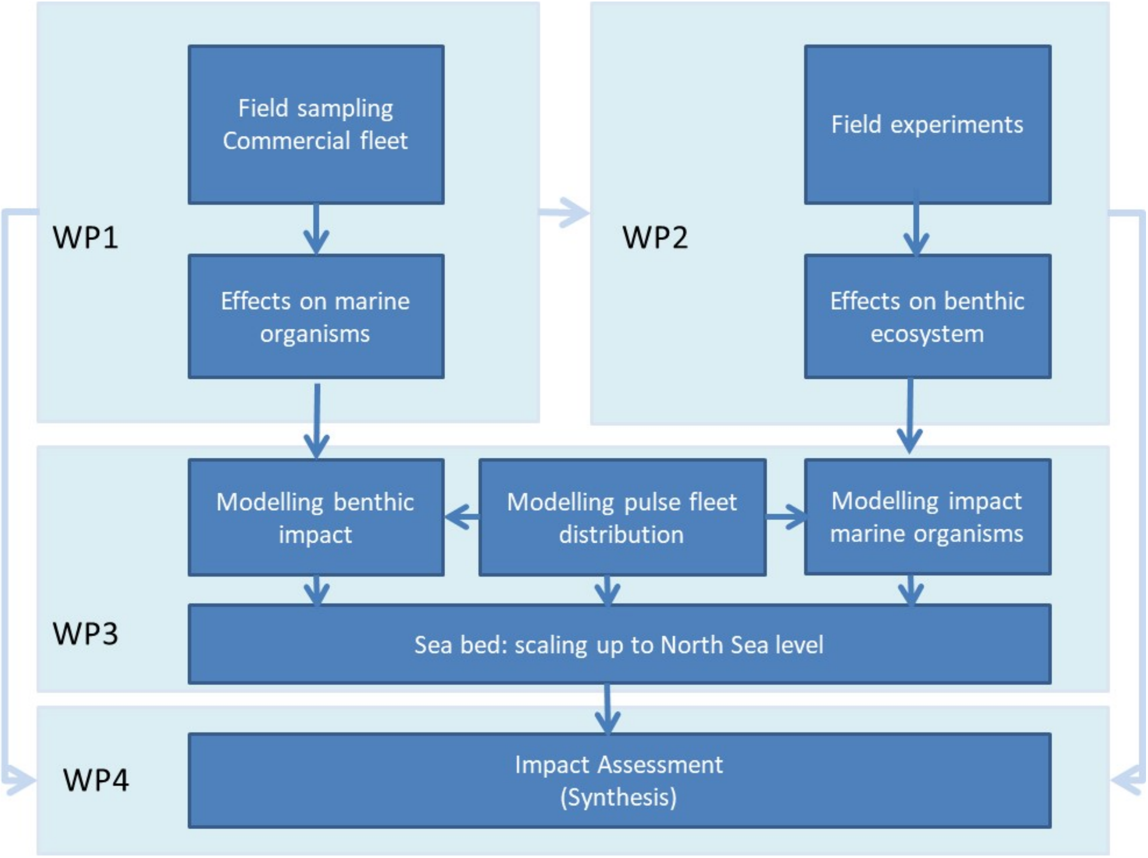

Figure 1.1 Work package structure of the Impact Assessment Pulse trawl Fishery (IAPF) project.

1.1 Impact Assessment Pulse trawl Fishery project

The current report presents the results of the Impact Assessment Pulse trawl Fishery project (IAPF), a research project (2016-2020) conducted by a research consortium comprising of Wageningen Marine Research (WMR), the Experimental Zoology Group of Wageningen University, the Netherlands Institute of Sea Research (NIOZ) and the Belgian Fisheries Research Institute (ILVO). The IAPF project was funded by the ministry of LNV to address the knowledge gaps (ICES 2012, 2016) and the concerns among stakeholders (fishing industry, NGO's) and EU member states raised by the growing application of pulse trawls in the fishery for sole (Kraan et al., 2015). The concerns are related to the lack of knowledge about the ecological effects of electrical pulses on the marine organisms and the ecosystem, the risk that an increase in catch efficiency could lead to overexploitation of the sole stock, and the consequences for other fisheries. The concerns were aggravated by the increasing number of temporary licences to 84 in 2014, as part of a Dutch pilot project in preparation of the introduction of the landing obligation under the reformed European Common Fisheries Policy.

The objective of the IAPF project is to study the effect of pulse trawling on marine organisms and the ecosystem in order to provide the scientific basis for the assessment of the consequences of a transition in the flatfish fishery from using traditional tickler chain beam trawls to pulse trawls. The project comprises of four work packages, each centred around a single topic (Figure 1.1), and a number of research questions:

1. Marine organisms: what is the response of selected marine organisms representing different groups of fish and invertebrate species (such as roundfish, flatfish, rays and sharks, bivalves, crustaceans, polychaetes) to the exposure by a range of pulse parameters representative for the commercial pulse trawls?

2. Benthic ecosystem: what is the effect of pulse trawling on the functioning and biogeochemistry of benthic ecosystems (short-term and long-term effects)?

3. Sea bed: what is the effect of pulse trawling on the fish stocks and the benthic ecosystem at the scale of the North Sea? Does a transition in the flatfish fishery from conventional beam trawling to pulse trawling contribute to a reduction in bycatch and adverse impact on the benthic ecosystem?

4. Synthesis: what is the effect of the transition of the tickler chain beam trawl fleet to a pulse trawl fleet on the bycatch of undersized fish and on the adverse effects on the benthic ecosystem?

The research topics were tackled with a combination of (i) experimental studies in the laboratory and in the field; (ii) biological analysis of fish samples collected on board of commercial pulse and conventional beam trawlers; (iii) collection and analysis of fisheries dependent data (catch, effort, discards, Vessel Monitoring by Satellite); (iv) modelling studies. The animal experiments were conducted with approval of the Animal Welfare Commission.

In addition to the research projects of the IAPF, other complementary research projects were conducted such as the discard monitoring of pulse trawl vessels (Rasenberg et al., 2013), study of the effect of pulse exposure on the development of ulcers in dab (de Haan et al., 20015), monitoring on the catch and effort by individual tow of the pulse fleet (Rijnsdorp et al., 2018), in situ measurements of the electric field (de Haan and Burggraaf, 2018).

To examine the research process and the assure the quality of science produced (by peer review) and to assist both the scientists involved and the government to identify and address knowledge gaps in innovative ways an International Science Advisory Committee (ISAC) was established (Kraan and Schadeberg, 2018).

International Stakeholder Dialogue Meetings were organised by the Dutch Ministry of Agriculture, Nature and Food Quality to engage in a more transparent and inclusive process concerning the benefits, questions and concerns about the development of pulse fisheries (Steins et al., 2017; Kraan and Schadeberg, 2018).

The results of the IAPF and accompanying studies are presented in such a way that they address the objectives of the fisheries management under the Common Fisheries Policy (CFP) and the objectives to protect the marine environment and safeguard biodiversity under the Birds and Habitats Directives (BHD) and the Marine Strategy Framework Directive (MSFD). The results of the project will be summarised in the light of the scientific literature by addressing the following questions:

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

2 Reading guide

The report starts with a description of the beam trawl fishery for sole.

- Chapter 3 presents a description of the conventional and pulse trawl beam trawl, data on trends in effort and landings of sole and plaice, data on the spatial and seasonal distribution of effort, the habitat association of the conventional beam trawling and pulse trawling, towing speed and fuel consumption, and the developments in the sole and plaice stock in the North Sea.
- Chapter 4 analyses the differences in selectivity and catch efficiency between conventional beam trawls and pulse trawls, and provides information on the discard rates between both gears and the discard survival rate.

The report continues with chapters related to the effects of pulse stimulation on fish.

- Chapter 5 presents the technical characteristics of the pulse stimulation, describes how the strength of the electric field around a pulse trawl attenuates with distance from the electrodes and shows how the internal electric field is affected by the size, shape and position of the fish in the water or sediment.
- Chapter 6 presents results from tank experiments conducted to determine the threshold level of a behavioural response and involuntary muscle contraction in a selection of fish species, presents information on the threshold for spinal injuries and explains how electrosensitive species responds to a pulse stimulus.
- Chapter 7 presents the results on injury probabilities observed in a broad range of fish species sampled from commercial pulse trawls and conventional beam trawls are presented and provides the results of an exposure experiment to test the sensitivity of sandeel to the sole pulse stimulus.

The focus then shifts to the effect of pulse trawling on benthic invertebrates and the benthic ecosystem

- Chapter 8 presents the results of exposure experiments with a selection of invertebrate species and of an experiment on the effect on the functioning of benthic organisms
- Chapter 9 presents the results of the studies of the effect of pulse trawling on the functioning of the benthic ecosystem distinguishing between the effect of mechanical disturbance and electrical disturbance.

The following chapters focus on the upscaling of the effects to the level of the population and total fleet.

- Chapter 10 describes how the effect of pulse exposure on the level of the individual organism is scaled up to the impact of the fleet on the population or habitat.
- Chapter 11 presents the result of the upscaling on fish populations. Specific attention is given to the consequences of possible pulse-induced mortality of small cod that escape the net on North Sea cod, possible population level effect of non-lethal exposure on the reproduction of sole, and the population level effect of a possible pulse-induced mortality on pelagic egg or larval stages.
- Chapter 12 presents the results of the analysis of the impact on the seafloor and benthic community, as well as on the long-term geochemical effects and on the food web.

The final chapters present the synthesis and discuss the results in a broader context (chapters 13, 14)

- Chapter 13 presents a synthesis of the assessment in the context of the EU legislation on fisheries and the marine environment and answers the six questions mentioned in the introduction.
- Chapter 14 discusses the results of the impact assessment in the context of the broader societal debate about pulse trawling.

3 North Sea sole fishery

3.1 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 - trammel net - which is used seasonally when sole moves inshore to spawn. 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.

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 sea bed 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).

Figure 3.1 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 (Turenhout et al., 2016). In the Belgium fleet, vessels continued to use conventional beam trawls.

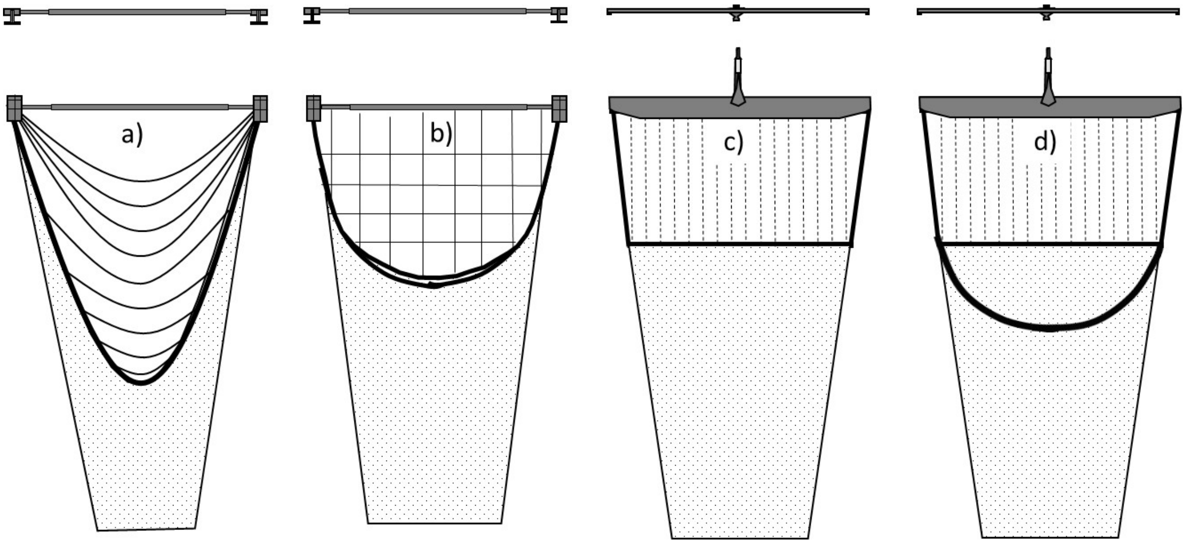

Figure 3.1. *Schematic drawing of the frontal view (top) and bottom view (bottom) of beam trawl: (a) conventional tickler chain beam trawl with 4 shoe-tickler chains and 5 net-tickler chains; (b) a chain mat trawl with a double ground rope and a matrix of longitudinal and latitudinal chains; (c) Sumwing trawl with longitudinal electrode arrays and tension relief cords and rectangular ground rope; (d) Sumwing trawl with longitudinal electrode arrays and tension relief cords and U-shaped ground rope. Note that both tickler chains and longitudinal electrode arrays can be deployed on a beam (a,b) and a Sumwing trawl (c,d).(from Rijnsdorp et al., 2020a).*

The ground rope, 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 ground rope (net-ticklers) (Figure 3.1a). 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 3.1b). 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 ground rope (Figure 3.1c – 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) ground rope is required. Different types of ground rope and net were developed to accommodate a latitudinal ground rope. Type 1 combines a rectangular shaped ground rope with either a trouser trawl (not shown) or a single trawl (Figure 3.1c). Some vessels may also use an additional latitudinal ground rope ('sole rope') and netting panel ('sole panel'). Type 2 uses a U-shaped ground rope with an additional 'sole rope' and netting panel ('sole panel': Figure 3.1d). Tension relief cords are attached between the beam/wing and ground rope to support the rectangular ground rope 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).

3.2 Towing speed

Pulse trawl are be towed at a considerable lower speed than tickler chain beam trawls or chain mat beam trawls (Table 3.1). 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 3.1. Towing speed (nautical miles.hour^{-1}): mean, standard deviation and number of observations by gear and engine class (Rijnsdorp et al. 2020b).

	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

3.3 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 3.2. The introduction of the Sumwing, a hydrodynamic foil replacing the beam but still using tickler chains, reduced the fuel consumption by 13%. The introduction of the pulse trawl, allowing a slower towing speed, reduced fuel consumption by 33% (pulse beam) and 46% (pulswing).

Table 3.2. Fuel consumption (liters per hour at sea) per vessel (large vessels) in the period 2009-2017 (data: WEcR).

	Fuel (liters/hour) by vessel			Fuel consumption relative to fuel consumption when using the conventional beam trawl by the same vessel		
	mean	sdev	n	mean	sdev	n
Beamtrawl	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

A total of 76 beam trawl vessels made the transition to pulse trawling. These pulse licence holders (PLH) spent about 300 thousand hours each year trawling for sole in the sole fishing area (SFA) in the transition period (Figure 3.2). Applying the data from Table 3.2, 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 3.3).

Table 3.3. Reduction in fuel consumption (liter) when pulse trawls replace conventional tickler chain beam trawl, or Sumwing tickler chain trawl in the beam trawl fishery for sole (PLH in SFA).

Reference gear	%reduction fuel.hour^{-1}	%reduction / unit sole quota	%reduction / total landings
Conventional beam trawl	-47%	-59%	-32%
Sumwing	-37%	-52%	-20%

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.

3.4 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 3.2a). In the sole fishing area south of the demarcation line running from west to east at 55^{o}N west of 5^{o}E and at 56^{o}N east of 5^{o}E 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 3.2b). 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 3.2c).

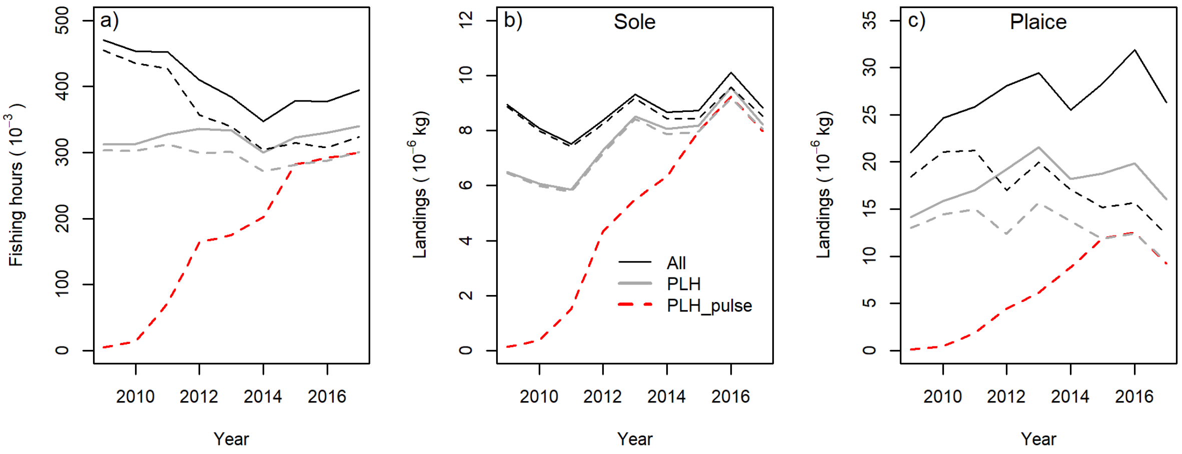

Figure 3.2. Evolution of fishing effort (a), sole landings (b) and plaice landings (c) of the total Dutch fleet of beam trawl vessels (ALL) and the subset of pulse license holders (PLH) in the North Sea areas IVc, IVb and IVa (full lines) and in the sole fishing area (SFA) between 51°N and 55°N west of 5°E and 56°N east of 5°E (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 PLH using the pulse trawl, only.

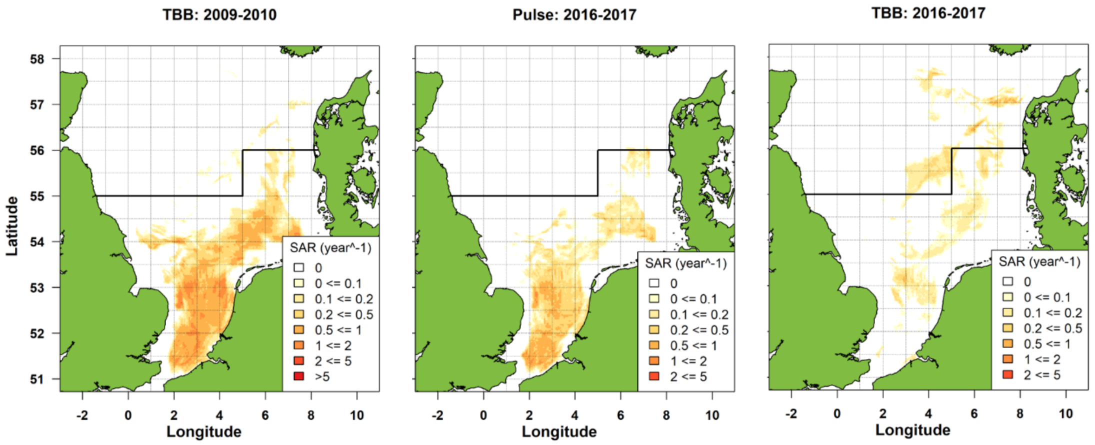

Figure 3.3. Annual trawling intensity by grid cell (SAR) of (a) the tickler chain beam trawl before the transition (2009-2010), and (b) the pulse trawl and (c) tickler chain beam trawl after the transition (2016-2017). The horizontal line at 55°N west of 5°E and 56°N eats of 5°E separate the sole fishing area (SFA) to the south (minimum cod-end mesh size = 80mm) and the plaice fishing area to the north (minimum cod-end mesh size = 100mm). (from Rijnsdorp et al., 2020b)

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 hotspots along the boundaries of the plaice box in the German Bight and along the 12 nm zone in the southern North Sea (Figure 3.3). 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 offshore areas from around the 53°N 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 and increased in local areas within the Belgium 12 nm zone and areas off the coast of England.

Table 3.4. 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 (from Rijnsdorp et al., 2020b).

Habitat	2009-10	2016-17			Surface%
	Tickler	Pulse	Tickler	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

3.5 Habitat association of pulse and tickler chain beam trawls

The analysis of the distribution of fishing effort (swept area) over the seafloor habitats showed that both tickler chain and pulse beam trawls were positively associated with sandy habitats (Table 3.4). 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.

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 bathymetric position indices (BPI) as well as distance to harbour into a statistical model. The 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 3.4) 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, 2018). 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).

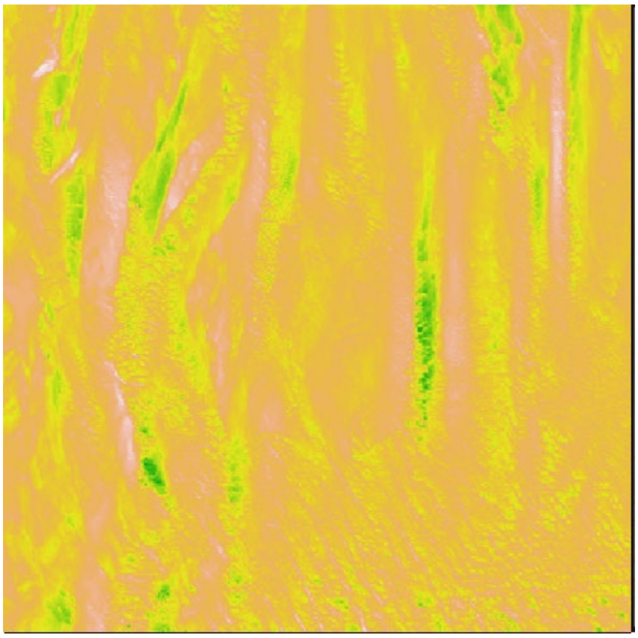

Figure 3.4. Map of the bathymetric index BPI5 of ICES rectangle 33F2 showing the depth relative the average depth in a circle with a radius of 5km. Green areas are relative shallow, lilac areas are relative deep.

We 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 3.4). 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 3.5 shows the results for two ICES rectangles in the south-western 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.

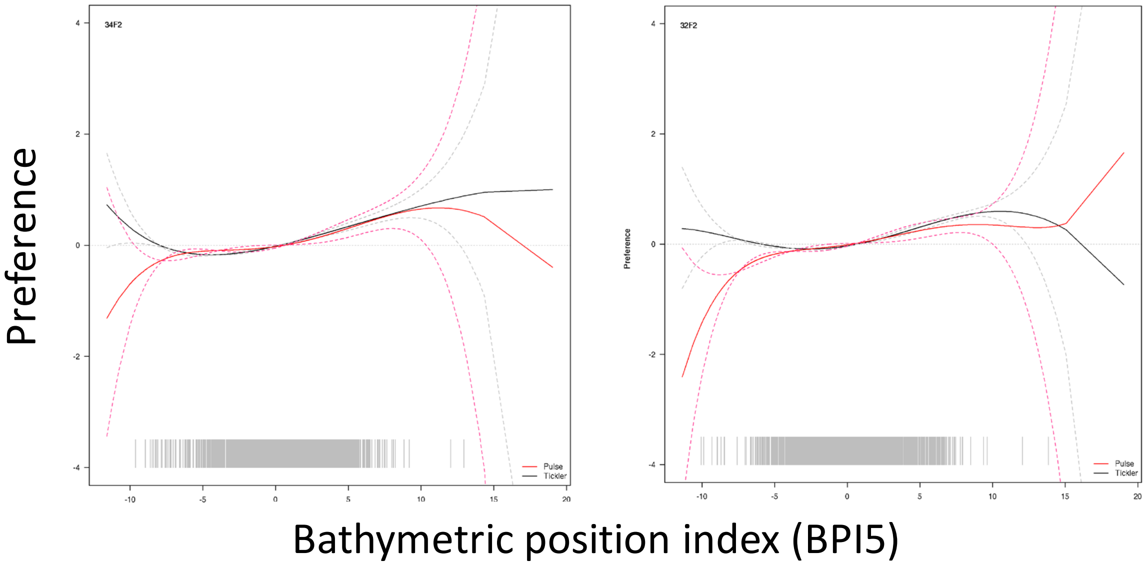

Figure 3.5. Habitat preference of pulse and conventional beam trawl vessels for relative depth (BPI5) in two ICES rectangels in the southern North Sea (left - 34F2; right - 33F2). The increase in preference with BPI5 shows that beam trawling for sole prefers areas that are relatively deeper than the 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 the distribution of BPI5 values (Hintzen et al., in prep).

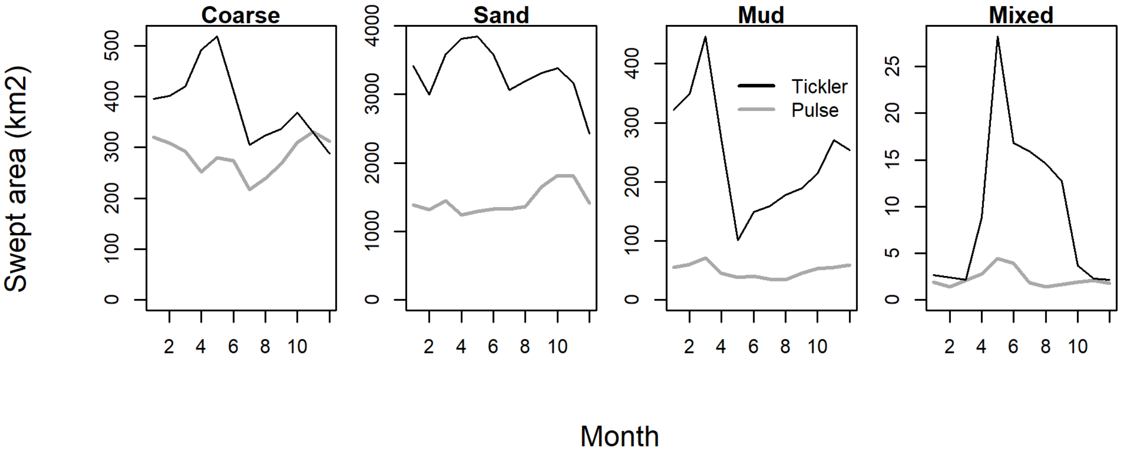

Figure 3.6 Seasonal pattern in fishing effort (annual mean area swept between 2009-2017) of tickler chain beam trawls and pulse trawls by Eunis habitats (based on VMS data 2009-2017).

3.6 Seasonality in fishing effort

Pulse and tickler chain beam trawls show a similar seasonality in effort allocation. Sandy sediments are trawled throughout the year. Coarse and muddy sediments are predominantly trawled between the autumn and spring, and mixed sediments during summer (Figure 3.6). During spring, both gears increase their fishing effort in coastal waters, such as in area 2 and 1, following the inshore migration towards the spawning area of sole (Figure 3.7).

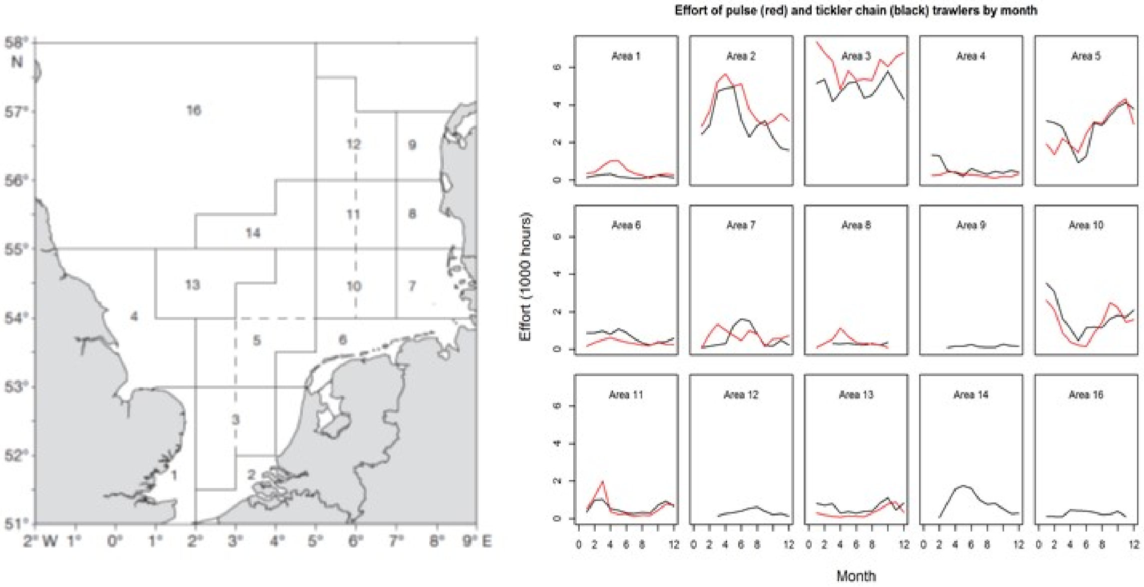

Figure 3.7. Seasonality in the distribution of fishing effort of pulse and tickler chain beam trawling (2009-2017). Results based on VISSTAT logbook data.

3.7 Fishing patterns pulse and conventional beam trawlers

Knowledge on how fishers exploit their fisheries resources is important for understanding how fishing affect the population dynamics of the exploited species and how the fishery may affect the ecosystem. The introduction of a new gear may affect the way fishers deploy their gear in space and time. The spatial dynamics of pulse trawl vessels when exploiting local aggregations of sole was investigated using catch and effort data recorded for individual tows of pulse vessels collected. The behaviour of pulse trawl vessels is compared to the behaviour of conventional beam trawl vessels. Results of the analysis has been presented in Rijnsdorp et al. (2019). The logbook data analysed comprised catch and effort information per tow collected between 1 January 2017 and 30 September 2018 (Table 3.5). The results were compared with an analysis of comparable logbook data of traditional beam trawl vessels collected between 2000 – 2005 (Rijnsdorp et al., 2011).

Table 3.5. Overview of the coverage of the Dutch[1)] pulse trawl fleet targeting sole for which detailed logbook data have been collected in the period between 1-1-2017 and 30-9-2018 (from Rijnsdorp et al., 2019).

		Logbook data per tow			
	Number of vessels	Number of vessels		Number of tows	
	2017-2018	2017	2018	2017	2018
Vessel class					
Euro cutters	19	16	13	17239	12301
Large vessels	58	52	53	61409	46941

1) Including two flag vessels

The study showed that pulse trawl (PT) and conventional beam trawl (BT) vessels had similar fishing patterns with alternating periods of searching, or sampling, for fishing grounds and exploitation of fishing grounds. The catch rate of sole during exploitation of a fishing ground was on average 22% (PT) and 23% (BT) higher than while searching for fishing grounds. PT deploy 73% of their tows while exploiting a fishing ground and 27% while searching or sampling, as compared to 69% and 31% in BT. The number of tows taken on a fishing ground by PT (large vessels: median = 16.4; small vessels: median = 18.8) was higher than by BT (median = 13.0). During an exploitation event – the period of successive tows made at a fishing ground – the sole catch rate declined over successive tows. Although the rate of decline varied substantially among different fishing grounds, the statistical analysis showed that on average the rate of decline was faster for BT than for PT. Of the pulse fishing grounds distinguished during the study period 61% were exploited by a single vessel and 39% were exploited by two or more vessels. Vessels differ in the proportion of fishing grounds shared with other vessels. Fishing effort on shared fishing grounds is higher than on the fishing grounds exploited by a single vessel only.

The logbook data provide detailed information on what happens on the local fishing grounds which is fundamental to assess the impact of the pulse trawl fishery and beam trawl fishery on the fisheries resources and on the benthic ecosystem. The study of the total pulse fleet provides a unique data set to study not only the dynamics of the whole fleet, including the interactions among pulse vessels, but also provides a solid basis to study competitive interactions with other fisheries.

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.

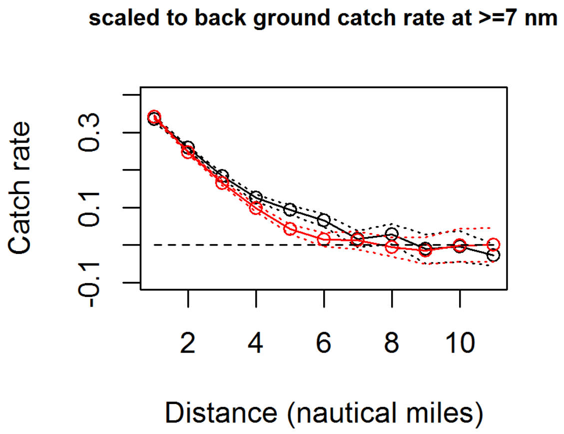

Figure 3.8. Mean and 95% confidence interval of the catch rate of sole of tows by pulse trawlers (red) and beam trawlers (black) at an increasing distance to the core fishing ground. The core fishing ground was defined by the tows that were clustered at a distance criterion of h=1 nautical mile. The horizontal dashed line shows the background catch rate in the tows that were not clust

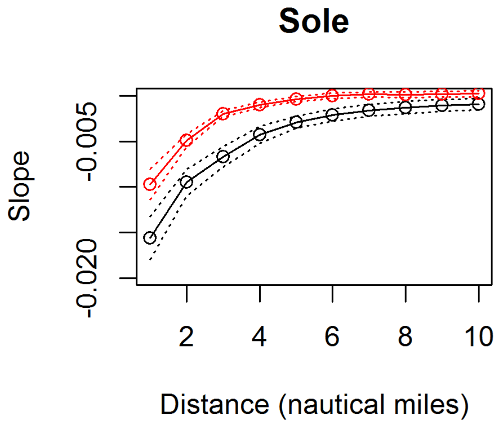

Figure 3.8. Relationship between the estimated rate of decline (h^{-1}) in catch rate of sole during an exploitation event for exploitation events determined with a distance criterion ranging between h=1 and h=10 nautical miles for pulse trawlers (red) and beam trawlers (black) (from Rijnsdorp et al., 2019).ers at a distance <7 nautical miles

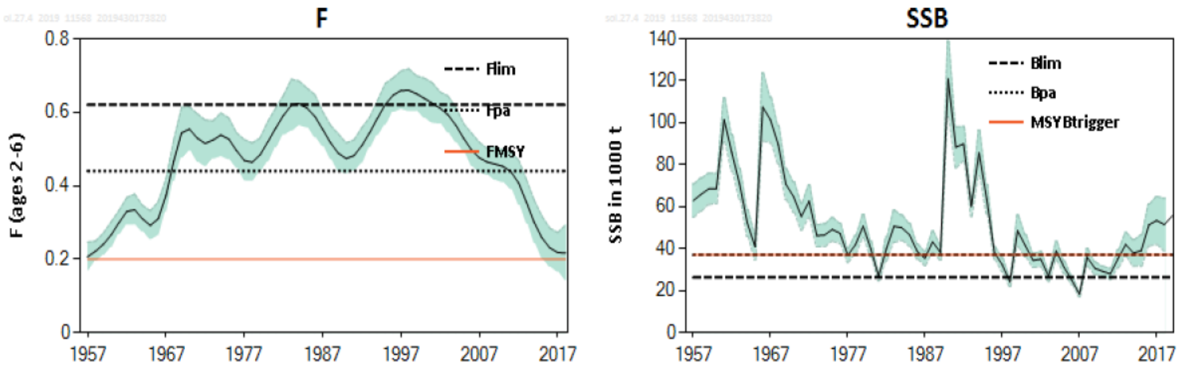

Figure 3.9. Temporal changes in the fishing mortality (F2-6) and spawning stock biomass of North Sea sole as estimated by ICES (ICES, 2019).

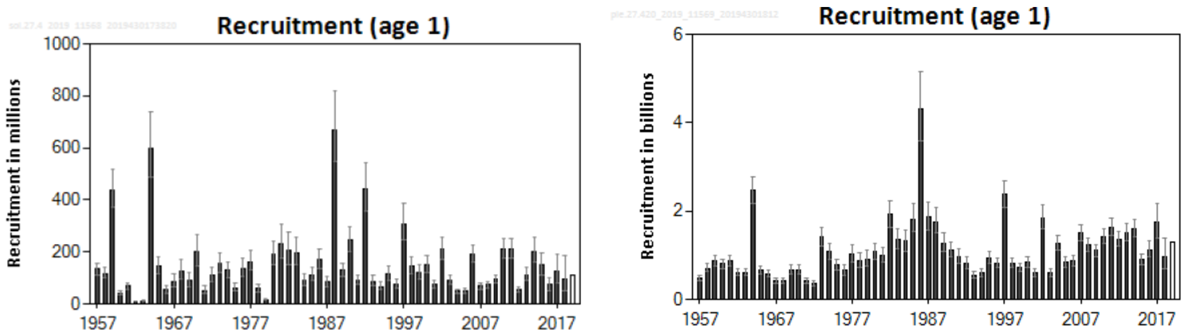

Figure 3.10 Recruitment to the stock of North Sea sole (left) and plaice (right) estimated by ICES (ICES, 2019).

3.8 Developments in the exploitation rate and stock biomass of sole and plaice

The developments in the fishing pressure and stock biomass are assessed annually by ICES. Figure 3.9 presents the history of the stocks showing the period of over-exploitation in the 1970s till mid 2000s and the subsequent decrease in fishing mortality and recovery of the stock coinciding with the reduction in fleet capacity. Sole and plaice are currently exploited sustainably. Spawning stock biomass is above biomass reference points for both stocks, whereas fishing mortality is just above F_{msy} in sole and just below F_{msy} in plaice.

During the transition to pulse trawling between 2009 and 2015 fishing mortality of sole decreased by about 50%, while the fishing mortality rate of plaice remained stable. Annual recruitment of 1 year olds is variable but does not indicate a decrease since 2010. Above average recruitment of sole is observed in 2010, 2011, 2014 and 2015, whereas plaice recruitment was relatively high between 2007-2014 and in 2017 (Figure 3.10).

Decadal changes in the distribution of North Sea sole as reflected in the catch per unit of effort (CPUE) by British trawlers showed a southern displacement of the centre of gravity (Engelhard et al., 2011). A southwestern shift in the distribution is also shown by the catch rate of sole in the international beam trawl survey carried out in the third quarter (Brunel and Verkempynck, 2018), which showed a decrease in abundance in the German Bight and an increase in abundance off the coast of England (Figure 3.11).

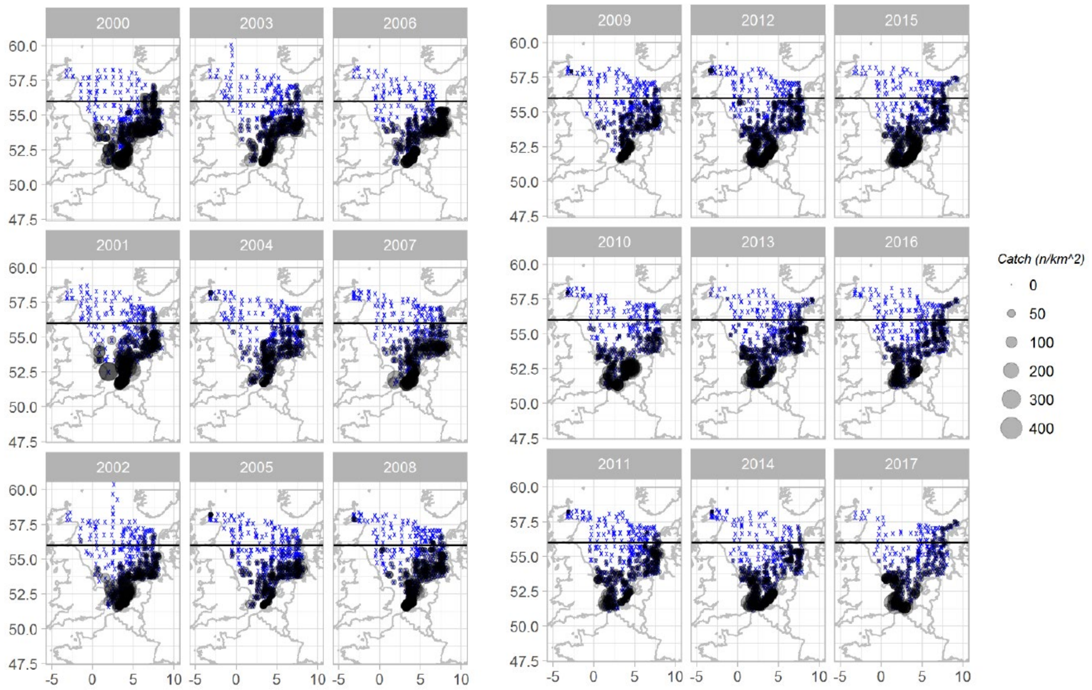

Figure 3.11. Survey stations (blue crosses) and catch rate (number/km^2) of sole in the beam trawl survey (BTS) (Brunel and Verkempynck, 2018).

3.9 Conclusions

- During the transition to pulse trawling, fishing effort (hours at sea) of the total Dutch beam trawl fleet in the sole fishing area decreased by 29%. Fishing effort of pulse license holders (PLH) increased by 9% due to an increase in conventional beam trawling with a mesh size of >=100mm targeting plaice in the fishing area north of the SFA. Fishing effort of PLH in the SFA targeting sole reduced slightly (-1%). The share of PLH of the Dutch sole landings increased from 73% to 95%.
- Pulse trawlers reduced their towing speed by 10% in small vessels and 23% in large vessels as compared to tickler chain beam trawlers.
- When pulse trawling for sole PLH reduce their fuel consumption by 20% per kg landings and by 52% per unit of sole quota.
- Pulse trawlers concentrated their fishing effort in the southern North Sea coinciding with a decrease in the sole abundance in the German Bight and high abundance in the southern North Sea.
- Pulse trawl and tickler chain beam trawls preferred to fish in sandy habitats and in areas that are deeper than the immediate surroundings. The relative proportion of pulse trawl effort decreased in muddy habitats and increased in coarse sediments in comparison with tickler chain beam trawls.
- Pulse trawlers and tickler chain beam trawlers show a similar fishing patterns. Tows are aggregated on local concentrations of sole. During the exploitation of a local aggregation the catch rate decrease. The decrease in catch rate is steeper in conventional beam trawls than in pulse trawls. Pulse trawls remain on a local aggregation for a longer time than conventional tickler chain beam trawlers.

4 Selectivity and catch efficiency

4.1 Landings

The difference in catch efficiency of the pulse and tickler chain vessels was estimated for the landings and discard 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 number of week*rectangle groups is shown in Figure 4.1. 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 4.1. 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%).

*Table 4.1. 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).

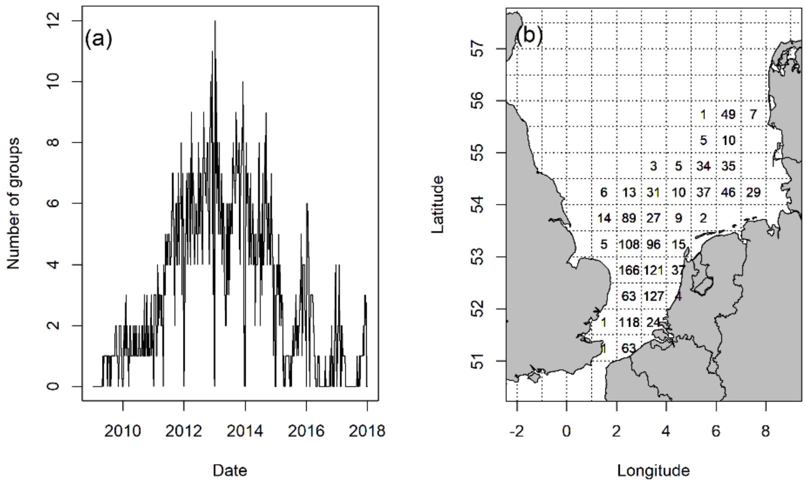

*Figure 4.1. Distribution of the number of week*rectangle groups with catch rate data of both pulse and conventional beam trawlers in time and space.*

Table 4.2. 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%

4.2 Discards

Differences in catch efficiency of discard size classes was estimated using data from the discard monitoring programme of the Dutch beam trawl fleet carried out by WMR. Table 4.2 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 (Table 4.3). Data of Euro cutters (vessels with engine capacity <=221kW) were excluded because of the low number of observations due to the relatively short period of overlap of both gears.

The absolute weight of discards by species (plaice, sole, whiting) and species group (all fish discards, flatfish (excluding sole), roundfish and gadoids) in each haul was modeled as a function of haul duration, gear (i.e. tickler chain and pulse), area, sampling programme (i.e. self-sampling and observer programme), and smoothing functions for seasonal and annual variability by area using a Generalized Additive Mixed Model (GAMM). In order to account for temporal autocorrelation trip number was included as a random effect in the model. When there was still a structure left in residuals of the model, an autocorrelation model was included to reduce any structure. By including such an autocorrelation model, the GAMM takes into account the structure in the residuals and reduces the confidence in the predictors accordingly (https://cran.r-project.org). The response variables were depending on the discards weight converted into 10 kg (plaice, flatfish (excluding sole), all fish discards) or 0.5 kg (sole, whiting) bins. The Aikaike's Information Criterion (AIC) was used to determine the optimal model fit.

Parameter estimates of the models are given in Table 4.4. 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 4.3. Number of discard observations in four study areas by gear (large vessels). Area codes are shown in Figure 3.7.

Area	Tickler chain trawl	Pulse trawl
#2	97	181
#3	395	514
#5	371	153
#10	191	127

Table 4.4. Discards: log catch (per hour) ratio of the pulse trawl relative to the tickler chain trawl (estimate, SE). Data analysed for large vessels only.

	Catch per hour	
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

4.3 Development of gear efficiency after the transition to the pulse trawl

Poos et al. (2020) studied the transition process from tickler to pulse and showed that the switch to pulse did not immediately resulted in an increase in catch efficiency for sole. The vessels that switched first experienced a decrease in catch rate after switching to the pulse gear. Catch efficiency gradually increased after the transition and after about one year the full gain in catch efficiency was achieved. Vessels switching later to pulse almost immediately experienced the gain in catch efficiency. The drop in catch efficiency of plaice was experienced by all vessels immediately after switching to pulse gear. The gradual improvement of the catch efficiency of the first group of pulse vessels can be explained by the technical improvements in rigging and construction of the gear, and the increase in experience of the skippers using the new gear.

The analysis of Poos et al (2020) estimated an increase in catch efficiency per fishing hour for sole of 74% and 17% for small and large vessels, and a decrease in catch efficiency for plaice of -31% and -32%.

4.4 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).

4.5 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 and Molenaar, 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 4.2). 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 4.3). It is noted that damage observed in sole discards is related to the mechanical injuries suffered when sole gets stuck in a mesh size.

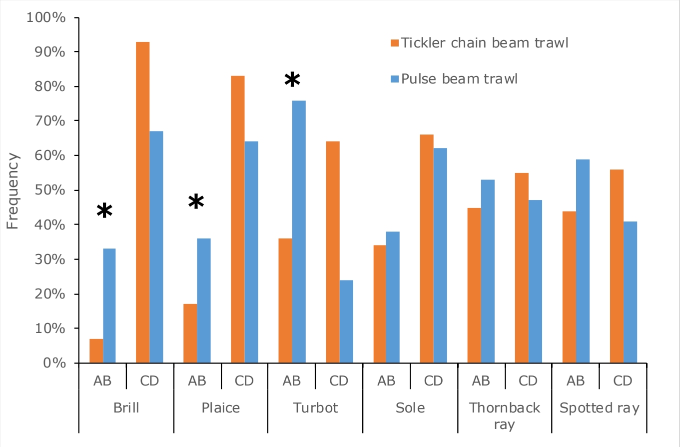

Figure 4.2. Frequency distributions per fish with good (AB) and poor (CD) vitality score in pulse and tickler chain beam trawl fisheries. Asterixis mark a significantly higher proportion of fish in good condition in pulse beam trawling compared to tickler chain beam trawling (Fisher's exact test right-sided p-value <0.05).

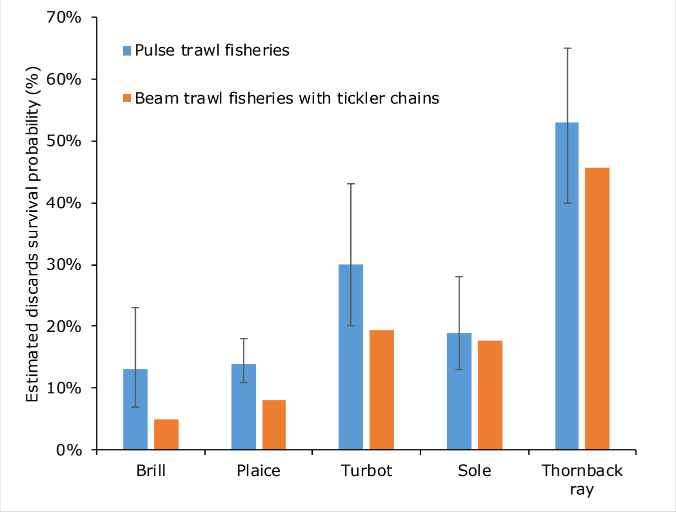

Figure 4.3. Discards survival probabilities per species for tickler chain and pulse beam trawl fisheries. Error bars represent the 95% confidence intervals for the survival probability estimates.

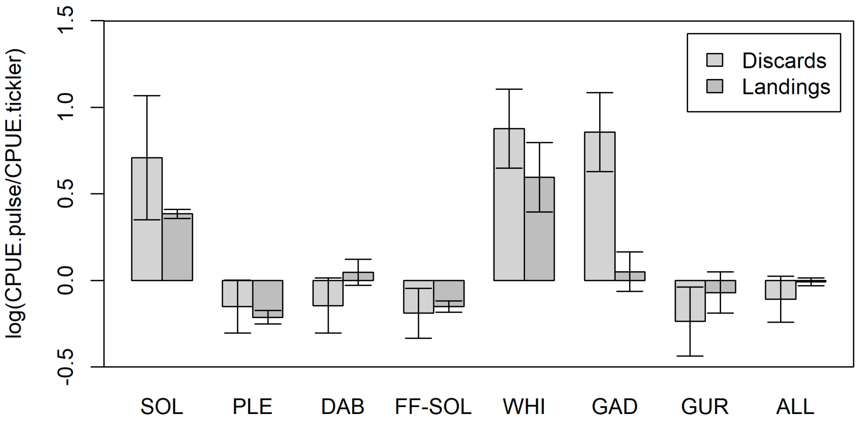

Figure 4.4. Catch efficiency and 95% confidence intervals (per area swept) difference between pulse and tickler chain beam trawl for discards and landings of sole (SOL), plaice (PLE), dab (DAB), all flatfish minus sole (FF-SOL), whiting (WHI), all gadoids including whiting (GAD), gurnards (GUR) and all fish (ALL).

4.6 Discussion

The catch efficiency was estimated for the landing and discard fractions separately. Landing observations represented the landings and effort of the whole trip, whereas discard observations represented single tows. The difference in the nature of the data is reflected in the width of the confidence intervals (Figure 4.4). Comparison of the catch efficiency of discards and landings does not support the improved size selectivity reported by van Marlen et al (2014). Confidence intervals of the catch efficiencies overlapped for most species. Only for gadoids, the catch efficiency of discards was significantly higher than for landings. This discrepancy is due to the dominance of whiting in the gadoid discards (Table 4.2).

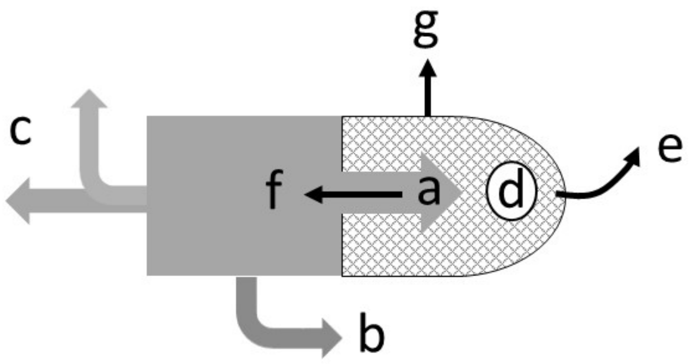

Figure 4.5. Schematic representation of the catch process. The grey box represents fish in the trawl path. Fish may enter the net (a), escape underneath of the ground rope (b) or swim away before entering the net (c). The fish that enter the net may be retained (d), escape through the cod-end meshes (e), or swim back in the net and escape through the front (f) or through the large meshed top panel (g).

Differences in species selectivity can be related the processes illustrated in Figure 4.5. The increase in catch efficiency of sole can be explained by the specific response of sole 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. 2015bc). The deeper penetration of the electric field into the sediment may further increase the proportion of fish available to the gear. In other flatfish, such as plaice, dab, turbot and brill, the skeleton is more rigid and will not allow the body to bend in a U-shape. Plaice will remain flat when exposed (Molenaar, pers comm) and may pass underneath the ground rope as suggested by the reduced catch efficiency of the pulse trawl. This may also apply to other species that are tightly linked to the seabed and with low swimming ability, such as gurnards.

The higher catch efficiency suggested for both landings and discards of whiting is puzzling. Although a reduced catch efficiency of whiting in a conventional beam trawl could be explained by the large mesh sized top panels used directly behind the beam/wing to reduce drag, a higher catch efficiency for whiting in pulse trawls is not supported by catch comparison experiments (van Marlen et al., 2014). The catch of whiting is rather variable in space and time and the landings may be affected by market conditions and the quota constraints. The above considerations add caution to the interpretation of the estimated higher catch efficiency of whiting.

Electrical stimulation could improve the size selectivity of a trawl because a larger fish will experience a higher field strength over its body than a smaller sized fish (Soetaert et al., 2015b and references therein). This expectation is supported by the results of a comparative fishing experiment with a conventional tickler chain beam trawl vessel and two pulse trawl vessels showing that the pulse trawl caught less undersized plaice and sole (van Marlen et al., 2014). The improved size selectivity (Figure 4.6), however, was not be supported by a catch comparison experiment carried out in 2016 by van der Reijden (pers comm), although the results are uncertain because of differences in the cod-end mesh size used by the pulse and tickler chain vessel. The catch efficiency analysis of pulse and conventional beam trawls for discards and landings did not support a reduced catch efficiency of small fish either, hence we conclude that it is uncertain whether the pulse trawls used in the current fishery improve the size selectivity of the beam trawl fishery for sole.

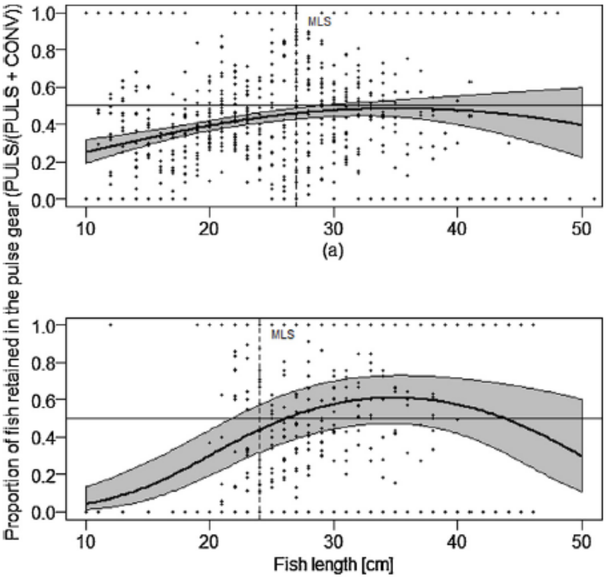

Figure 4.6. Proportion of fish retained in the pulse gear (=PULS/(PULS + CONV)) vs. length for plaice (a) and sole (b). The value of 0.5 means both gears catch equal numbers. The solid line gives the mean and the grey band gives the 95% confidence limit. The sampling ratios were corrected by fished area. Data points are given in black dots. MLS is Minimum Landing Size (plaice: 27 cm, sole: 24 cm) (van Marlen et al., 2014).

4.7 Conclusions

- Pulse trawls are more selective in catching sole and catch on average 17% (95%cl: 14% - 20%) more sole per hour than conventional beam trawlers and 20% (18%-22%) less other flatfish (except sole). Catch rate of plaice is 35% (33%-38%) lower.
- Pulse trawls caught 27% (17%-36%) less discards than conventional beam trawls. The catch rate of plaice discards was 30% lower (19%-40%), whereas the catch rate of sole discards was 65% higher (16% - 137%).
- Pulse trawls caught a higher proportion of soles per area of seafloor swept and a lower proportion of plaice and all flatfish except sole. For other fish species, the proportion was proportional to the area swept, but the catch of benthic invertebrates was reduced by 33%. Survival of pulse trawl discards is estimated to be higher in plaice, turbot and brill, while no significant difference was found for sole and thornback ray.

5 Pulse stimulation

5.1 Pulse systems used by the fleet

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 5.1) emitted by longitudinal electrode arrays between the beam/wing and ground rope. 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 of the 12 nm zone, comprises between 24 to 28 electrode arrays.

Table 5.1 summarises 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) of 1 minute observations of pulse characteristics during fishing operations were available for analysis. Both pulse systems use a pulsed bipolar current (PBC) with a different pulse width and frequency. Delmeco uses a pulse width of 220-250 µs and frequency of 43-45.5 Hz (number of positive (or negative) pulses per second as defined by Soetaert et al., 2019). HFK uses a pulse width of 320-350 µs and frequency of 30 Hz. The other pulse parameters are quite similar. The peak voltage over a pair of electrodes during fishing ranged between 54 – 58 V. Peak voltage 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 5.2). No seasonality is observed in the pulse frequency, pulse width and power. The number of Delmeco vessels was too small to analyse the seasonal patterns.

Table 5.1. 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 (Annex 3)
Pulse type	PBC	PBC		
Pulse width (microsec)	238.5 (8.5)	336 (23)	DL	
Frequency (Hz)	89.4 (3.6)	60 (4.4)	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 is defined here as the number of positive and negative pulses per second. Duty cycle is defined as the product of pulse width and frequency.

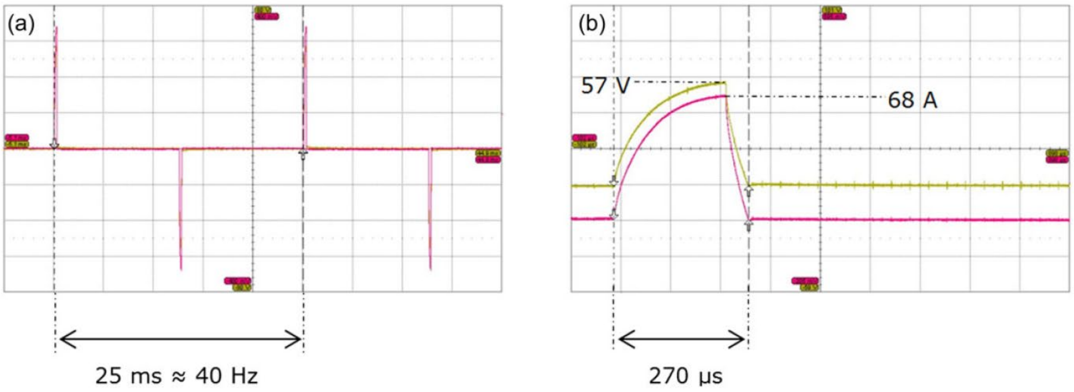

Figure 5.1. Schematic representation of a pulsed bipolar current (PBC) (from de Haan et al., 2016).

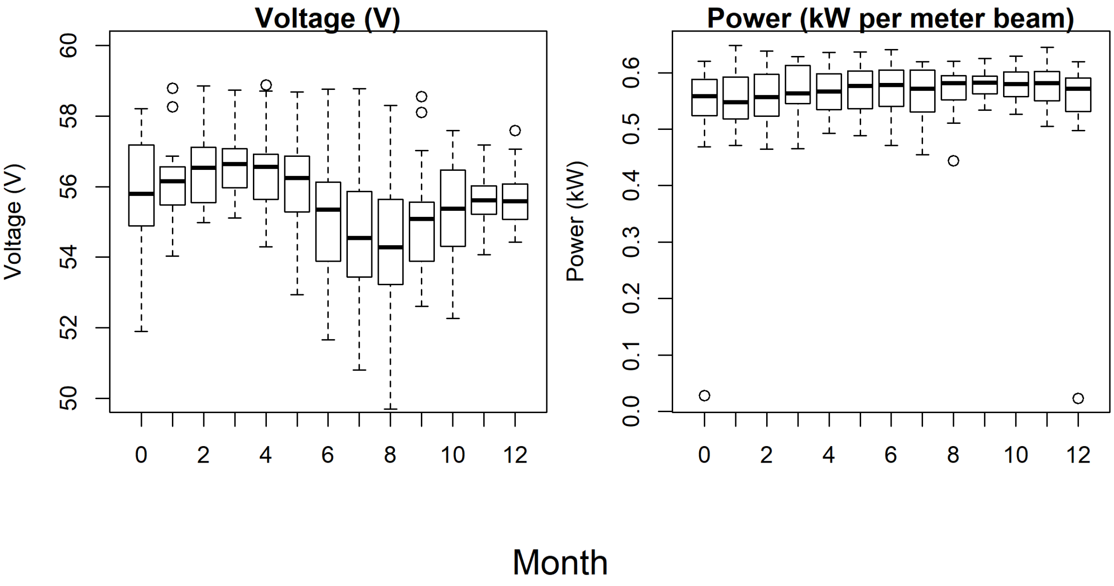

Figure 5.2. Monthly amplitude (V) over electrode pairs and power (kW per meter beam width) recorded during trawling. Horizontal bar shows the median value, box shows the 25th and 75th percentile, whiskers show the approximate range of the parameters, open dots show the individual extreme observations. Results of 33 vessels using the HFK system.

5.2 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 60 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.

We used the COMSOL Multiphysics package to simulate the electric fields generated by such a pair of electrodes (Figure 5.3). In all simulations we determined field strengths 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 5.2), we used a comparable voltage of 60V, and we modelled the resulting 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.

5.3 Effect of salinity and temperature on field strength

To assess the effects of temperature and salinity variations, we quantified the decline of the electric field with distance, 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 5.4 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 we need to simulate the interaction of the gear with fish. Most importantly, we also need to assess 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 we therefore calculated field strengths inside model fish by inserting idealized shapes into the COMSOL model.

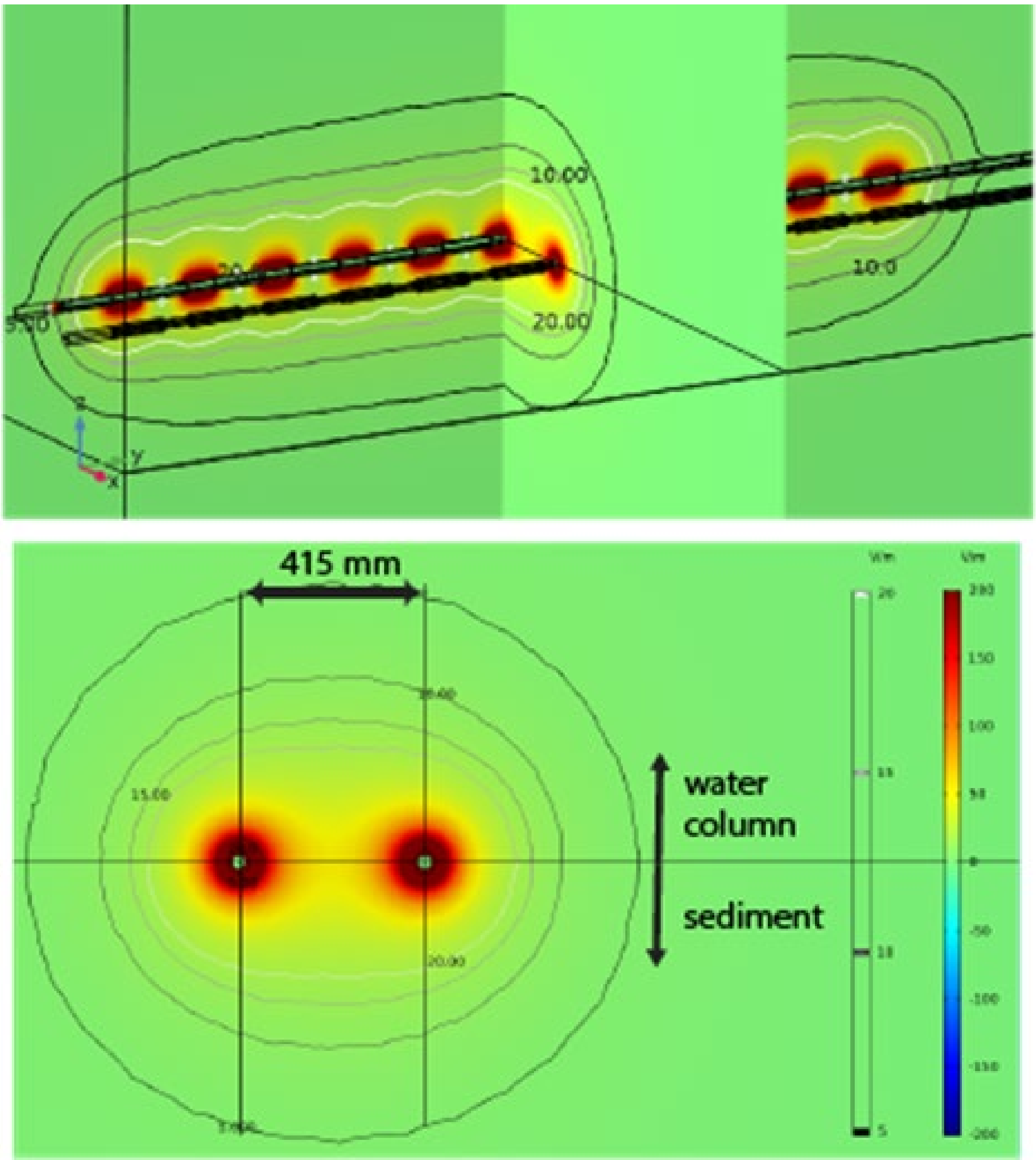

Figure 5.3. Contour plot of the field strength around a pair of electrode arrays. Top panel: three-dimensional view with transections in the vertical-longitudinal plane at the level of one of the chains, and in a vertical plane orthogonal to the two electrode chains. Bottom panel: field strengths in 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.

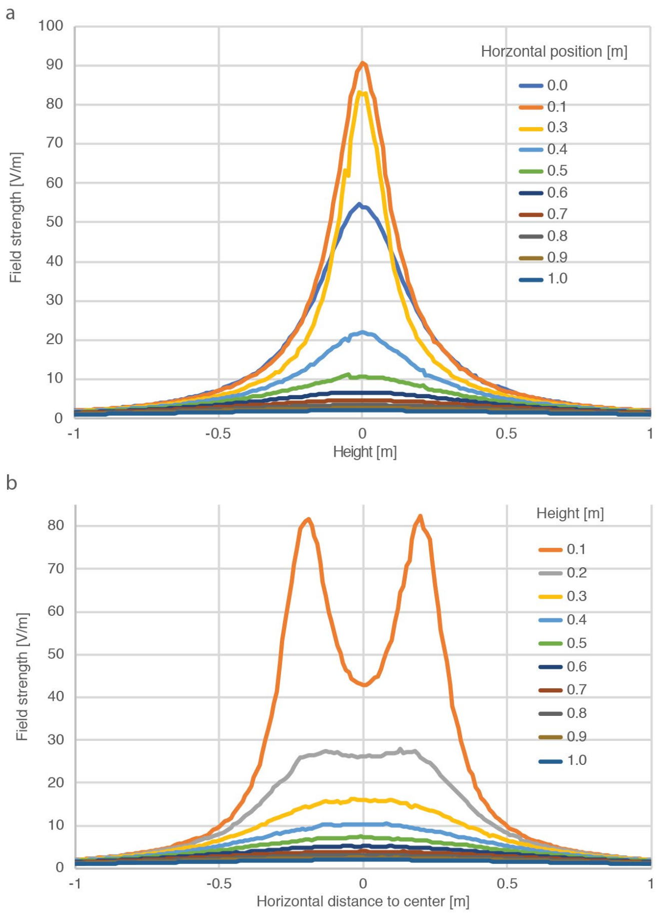

Figure 5.4. Field strengths as a function of height relative to the seabed and distance to the center of an electrode pair. The electrode pair is at the interface between water column and sediment (height 0, see Figure 5.3). A) Field strengths plotted as a function of height (z-dimension in Figure 5.3), for different positions relative to the electrode pair (along the x-dimension in Figure 5.3, as defined in the legend). B) Field strengths plotted as a function of horizontal distance to the electrode pair (x-dimension in Figure 5.3), for different heights above the electrodes (z-dimension in Figure 5.3, see legend). Horizontal distance is relative to the center of the pair of electrodes.

5.4 Exposure to electrical disturbance

Figure 5.6 shows simulation results for a model roundfish in the water column. Electric fields inside the fish deviate substantially from those surrounding the fish (Figure 5.6b). Field strengths inside fish declined strongly with its height in the water column (Figure 5.6c). 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 5.6d), but dropped below the values for the location in between the electrodes at heights above about 20 cm..

We also simulated the internal fields in model flatfish that were buried in the sediment, at different depths (Figure 5.7b), and we compared these values to data for a typical roundfish in the water column (Figure 5.7a). 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 fishes 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.

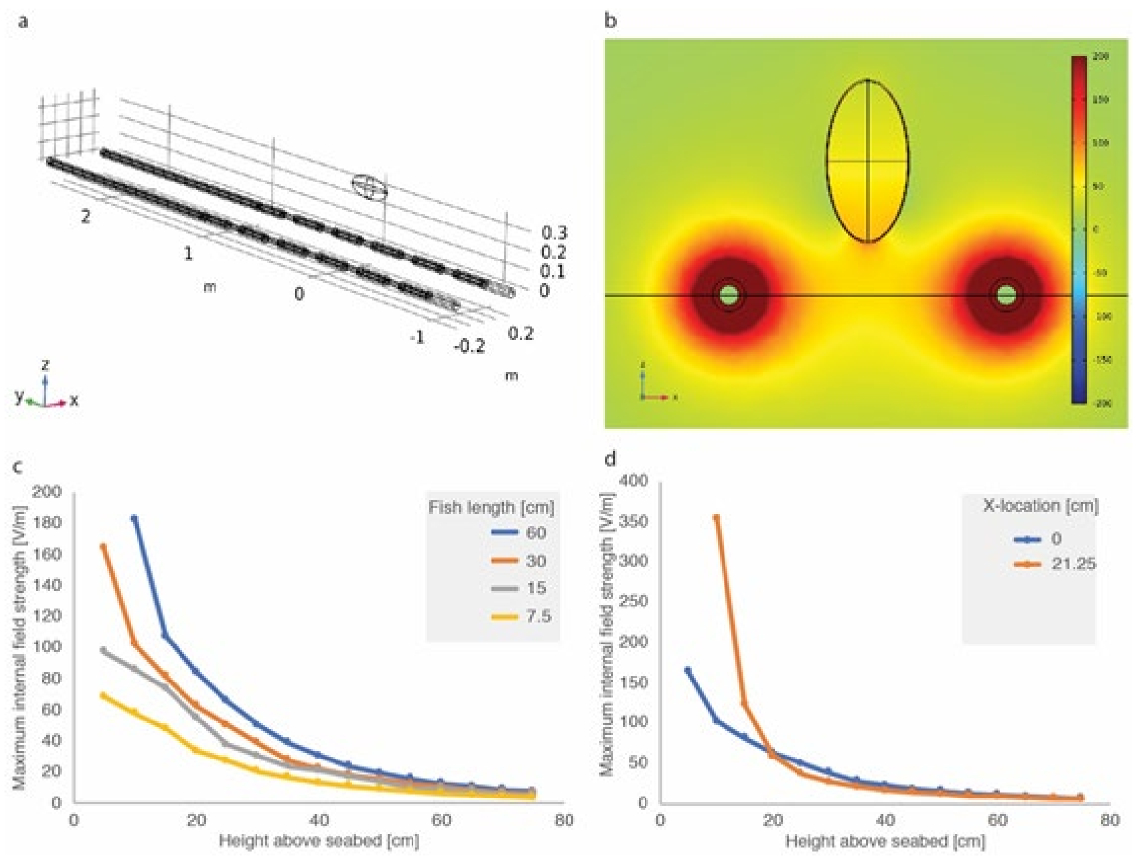

Figure 5.6. Simulations of electric fields inside fish. (a) Simulation setup, with two electrode chains, 41.5cm apart and a fish in the water column. Fish were simulated as ellipsoids, with 2mm skin at 0.1 S.m^{-1}, and the fish body at 0.5 S.m^{-1}. (b) Example of simulation result in a cross section 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).

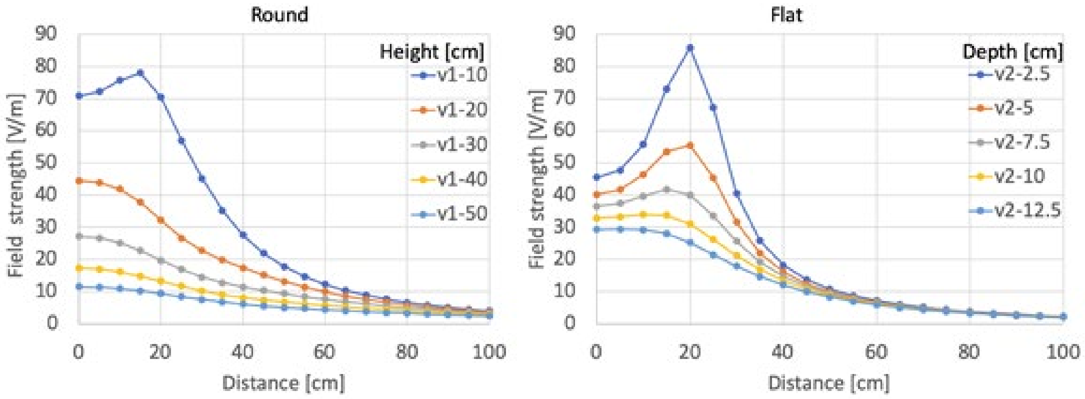

Figure 5.7. Simulated field strengths in a model roundfish in the water column and a model flatfish in the sediment. Distances are indicated relative to the midpoint between two chains of electrodes, in a horizontal plane.

5.5 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 model 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.

6 Threshold levels to electrical pulses

Exposure to pulsed electric fields may result in different responses in the animal (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 on the threshold level of the different responses allows us to quantify the width over which the pulsed electric field may impact marine organisms.

6.1 Fish behavioural thresholds

Concerns exist that the electric fields extend well beyond the netting, potentially affecting fishes outside the trawl track. Here, we address these concerns by measuring amplitude thresholds for behavioral responses and compare these response thresholds to the field strengths around the fishing gear (Boute et al., in prep). 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 (PBC) at a frequency of 45 Hz and pulse width 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, pulse break time *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 6.1). 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).

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.

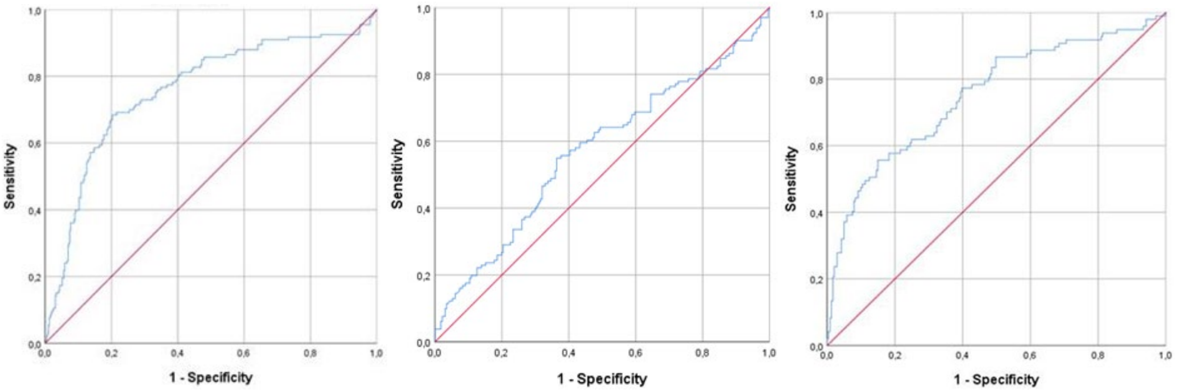

Figure 6.1. Receiver operating characteristic curves for (a) small-spotted catshark (Scyliorhinus canicula) ($n_{total\_stimulations}$ = 537), (b) thornback ray (Raja clavata) ($n_{total\_stimulations}$ = 419), and (c) turbot (Scophthalmus maximus) ($n_{total\_stimulations}$ = 348).

6.2 Sensitivity of electro-receptive 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, 2018a).

In our experiments, 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 a pulse width of 0.3 ms was computed using a Fast Fourier transform (Figure 6.2a). 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. In addition, the highest energy content of the stimulus is within the higher frequency range (≥30 Hz) (Figure 6.2b).

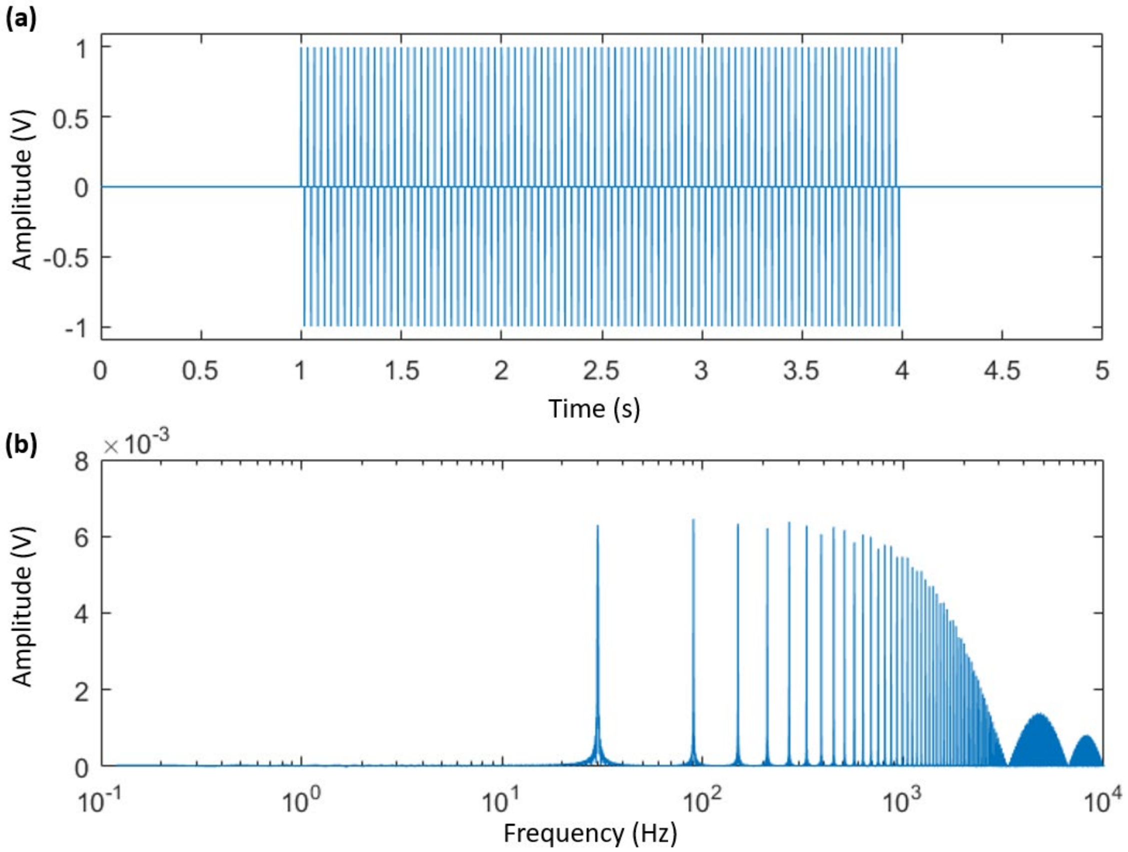

Figure 6.2. (a) A PBC waveform used in pulse trawling. (b) Fast Fourier transform spectrum of the pulse waveform in (a).

If the electroreceptive fishes 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 fishes 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.

6.3 Fish muscle activation thresholds

Apart from behavioural response thresholds, fish could also involuntary respond to the electrical pulse stimulus of the fishing gear by means of muscle contractions. Involuntary muscle contractions could hamper an escape of the fish from the fishing gear.

Here, we address these concerns by measuring amplitude thresholds for involuntary muscle contraction and compare these response thresholds to the field strengths around the fishing gear (Boute *et al.*, in prep). We used 4 Atlantic salmon (*Salmo salar*) categorised in a small length class (26.2 cm, ±2.7 cm; mean, ±SD), and 5 specimens categorised in a large length class (45.0 cm, ±1.5 cm; mean, ±SD). 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 6.3). This 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 the artificial fish, were used to determine the internal electric field strength corresponding to the potential difference over the electrode pair that triggered muscle activation (Figure 6.3).

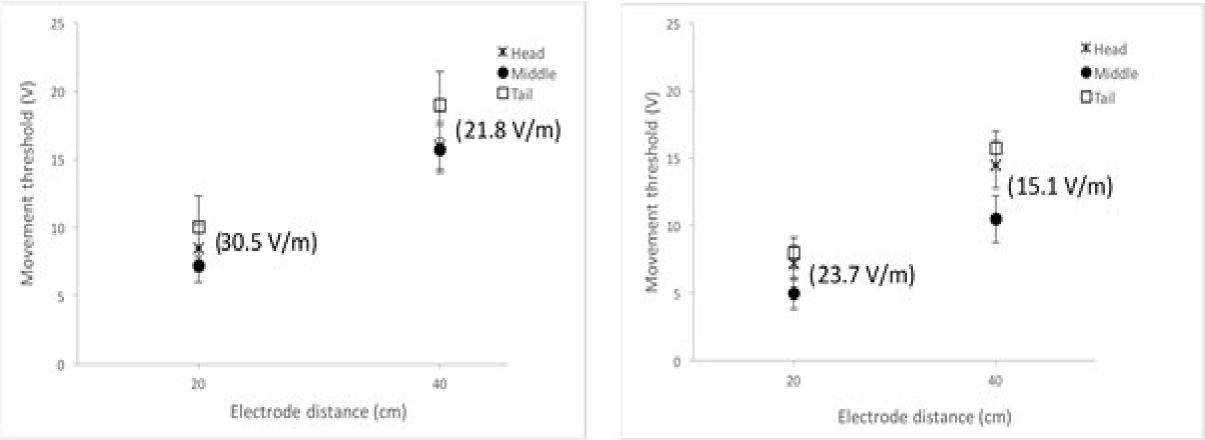

Figure 6.3. Muscle activation thresholds in anaesthetized (a) small and (b) large Atlantic salmon (Salmo salar) between an electrode pair spaced at 20 and 40 cm apart. Thresholds were determined by skin movement of the fish in the head, abdominal, and caudal region where the electrode pairs were placed 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 5.4.

Preliminary results show that muscle activation thresholds were not substantially lower in electro-receptive fish than in non-electro-receptive fish. Moreover, the behavioural field strength thresholds were similar to those for involuntary muscle activations.

6.4 Thresholds for spinal injuries

Finally, muscle cramps/tetanus may affect the fish if they are situated in the higher field strengths. The muscle cramps can cause spinal injuries and haemorrhages. Field strength thresholds for inducing spinal injuries are reported to be >37 V m^{-1} in large Atlantic cod (*Gadus morhua*). 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), pulse frequency and pulse width (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 induced by the high frequency sole pulse does not seem to occur if lower pulse frequencies area used. 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 fishes 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.

6.5 Conclusions

- The response of animals to a pulse exposure is determined by the field strength and frequency.
- Electro-sensitive elasmobranchs are highly sensitive to low frequency pulses. Their sensitivity does not differ from other fish species for the high frequency pulses used in the pulse fisheries for sole.
- External field strength thresholds for a behavioural response to a sole pulse is between 3 and 6 V.m^{-1}
- Lowest muscle activation threshold was estimated at 15 V. m^{-1} (internal field strength)
- External field strength thresholds for spinal injury was estimated at 37 V.m^{-1}, whereas of the cod exposed developed a spinal fracture at 80 V.m^{-1}.

7 Pulse-induced injuries in fish

7.1 Injury rate in fish caught in commercial pulse and tickler chain trawls

The electric field near to the electrode array, within the surrounding nets, 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, 2018). Internal injuries, however, 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 fishes' body (e.g. components of the fishing gear, debris in the netting, towing speed, and hauling on deck).

To assess the occurrence of internal injuries that are likely induced by electrical pulse stimulation , we extensively sampled target and non-target species from catches of commercial pulse trawlers (n=9). To distinguish electrical-pulse induced injuries from injuries inflicted by the catch process, we also sampled the catch of pulse trawls with the pulse stimulation switched off from 5 hauls of 3 vessels, and from conventional beam trawlers (n=2) using tickler chains (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. In addition to heavy injuries, also minor deformations and abnormalities were found in the fishes. However, since these have not been related to electrical-pulse induced injuries in laboratory exposure studies (Sharber et al., 1994; Soetaert et al., 2018), we excluded these here.

The percentage of fish with at least one spinal injury are provided in Table 7.1 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 cod-end 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 7.1). In the graph the two sandeel species were pooled and only species with more than 100 animals sampled were included.

Table 7.1. Percentage of fish with at least one spinal injury by species and catch method. The number of fish sampled is indicated between parenthesis.

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 seabass	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)

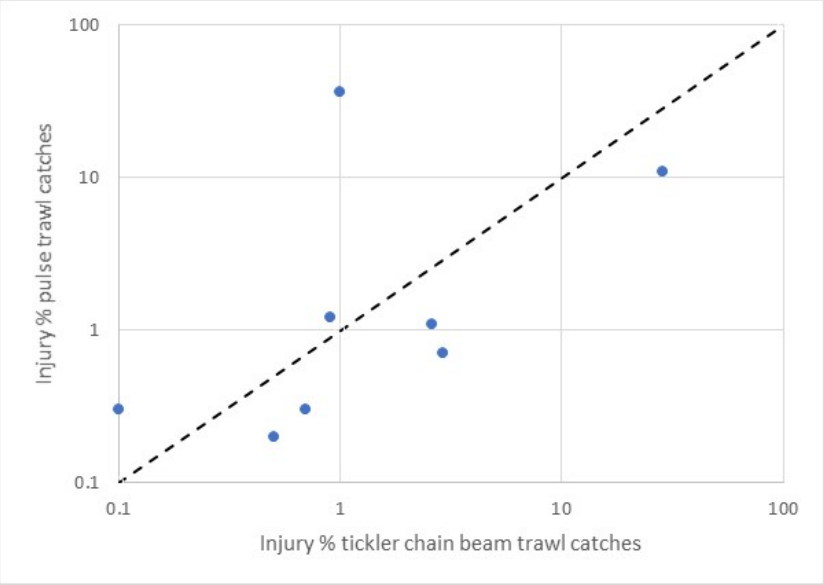

Figure 7.1. Comparison of the injury rate (% of fish sampled) in different fish species in tickler chain beam trawl catches and pulse trawl catches (pulse-on). Species plotted if the sample size was >100 fish per gear. Data of lesser and greater sandeel were combined. Data from Table 7.1

7.2 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 generalised 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 7.2 shows that the injury probability is highest for intermediate sized cod and decrease for smaller and larger sized cod.

The size dependence of the occurrence of spinal injuries is in line with the experimental results of de Haan et al., (2016).

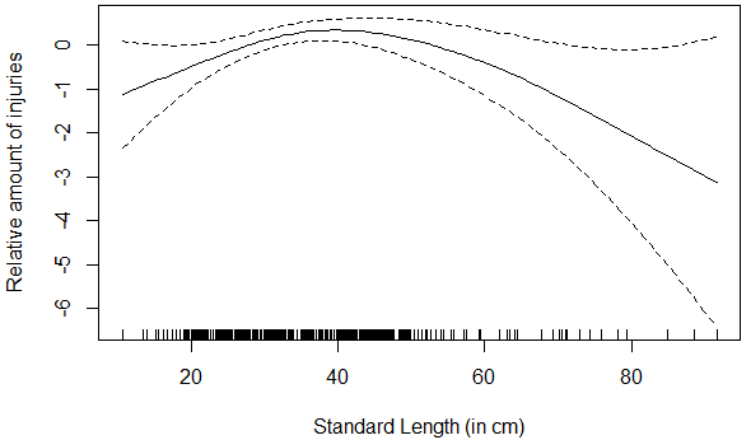

Figure 7.2. Generalized additive model showing the relationship of incidence rate of spinal injuries in relation to standard length in Atlantic cod (Gadus morhua) (n=475). These Atlantic cod were caught by pulse trawlers using the electrical stimulus.

7.3 Effect of pulse exposure on sandeel

Sandeels sampled from pulse trawls showed a relatively high incidence of spinal injuries (section 7.1). The observed incidence rate, however, may be biased due to a higher retention of injured sand eel in pulse trawls compared to undamaged sandeels. We expect that due to their slender shape only few animals may be caught and most will pass through the net and escape through the cod-end 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.

We therefore conducted a laboratory experiment with two species of sandeels - lesser sandeel (*Ammodytus tobianus*) and greater sandeel (*Hyperoplus lanceolatus*). 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 pulse width corresponding to the pulse stimuli generated by the Delmeco and HFK system used in the commercial fishery (Table 7.2). 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 to treatment groups except for the absence of electrical stimulation. The experimental set up is shown in Figure 7.3. 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}.

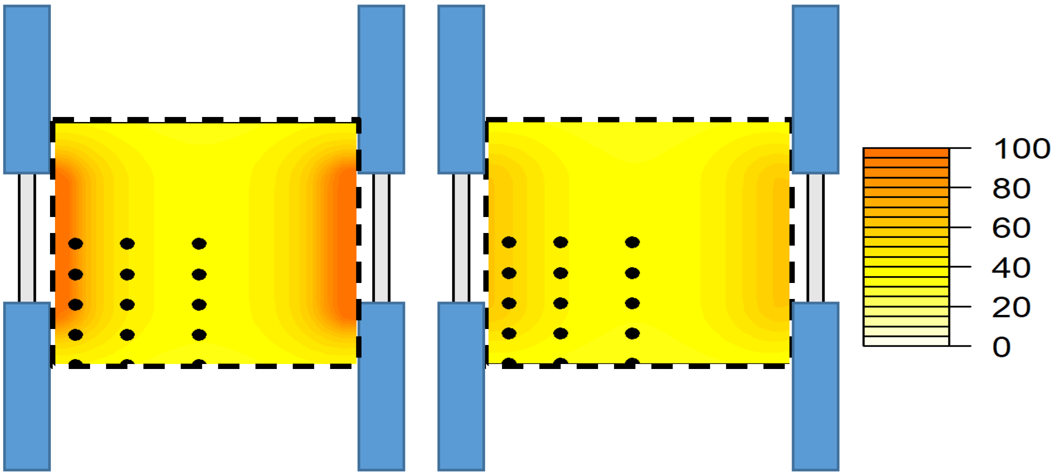

Figure 7.3. Field strength (V.m^{-1}) in the experimental tank in between the electrode pair at the level of the sediment (left) and at the bottom of the cage at 5cm in sediment (right). Black dots show the locations of the measurements.

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 7.3). 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 7.2 Pulse parameters used in the sandeel experiments and the modelled field strength at the surface of the sediment and at bottom of the cage at 5cm into the sediment.

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		
				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 7.3 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.

7.4 Conclusions

- Extensive sampling of fish caught by commercial vessels showed spinal injuries in most species caught in pulse trawls and tickler chain beam trawls.
- Most injuries can be ascribed to the mechanical damage inflicted during catching.
- Pulse-induced spinal injury probabilities is estimated at 36% in cod and <=1% in the other 11 fish species studied.
- Spinal injury probability in cod is related with fish size indicating that small cod and large cod will be less sensitive to pulse exposure.
- An exposure experiment with sandeel showed a pulse-induced injury probability of 1%.

8 Effect of pulse exposure on benthic invertebrates

Concerns exist regarding possible negative impacts of the electrical stimulus on benthic invertebrates (ICES, 2018; 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). The benthic community comprise a large number of species of different taxonomic groups. Because it is impossible to study all individual species that occur in the fishing area of the beam trawl fleet, a selection of typical species were selected that are representative for the biodiversity of benthic invertebrates (sea stars, crabs, polychaetas, bivalves and gastropods) and can be kept in the laboratory.

8.1 Response of benthic invertebrates to pulse exposure

To assess the effect of electrical stimulation on locomotor performance in benthic invertebrates, we studied the effects in six benthic invertebrate species from four different phyla: common starfish (*Asterias rubens*; $n_{\text{control}} = 44$, $n_{\text{treatment}} = 41$), serpent star (*Ophiura ophiura*; $n_{\text{control}} = 21$, $n_{\text{treatment}} = 21$), common whelk (*Buccinum undatum*; $n_{\text{control}} = 46$, $n_{\text{treatment}} = 41$), sea mouse (*Aphrodita aculeata*; $n_{\text{control}} = 45$, $n_{\text{treatment}} = 43$), common hermit crab (*Pagurus bernhardus*; $n_{\text{control}} = 43$, $n_{\text{treatment}} = 43$), and flying crab (*Liocarcinus holsatus*; $n_{\text{control}} = 46$, $n_{\text{treatment}} = 44$) (Boute *et al.*, under review).

We described species-specific acute behaviour during and immediately after a worst-case-scenario electrical stimulation. In addition, we quantified the effect of electrical stimulation on several, species-specific behaviours that may indicate prolonged changes to predation risk, including righting reflexes and locomotor activity such as walking and burying. We measured these behaviours before and after electrical stimulation and we compared these results to animals in a non-exposed control group. Finally, we monitored animal survival up to 14 days after the behavioural assessment. The electrical stimulus was a 3 second square-shaped Pulsed Bipolar Current (PBC) at a frequency of 30 Hz and pulse width 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. We found no indications 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.

8.2 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 bio irrigation (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 bio irrigation behaviour 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 pulse width (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 8.1). Electrical exposure temporarily halted bio irrigation activity which led to a momentary decrease in oxygen levels inside the macrofauna burrows before pumping behaviour resumed (Figure 8.2). Respiration rates per unit biomass for individuals exposed to PBC compared to controls were not significantly different.

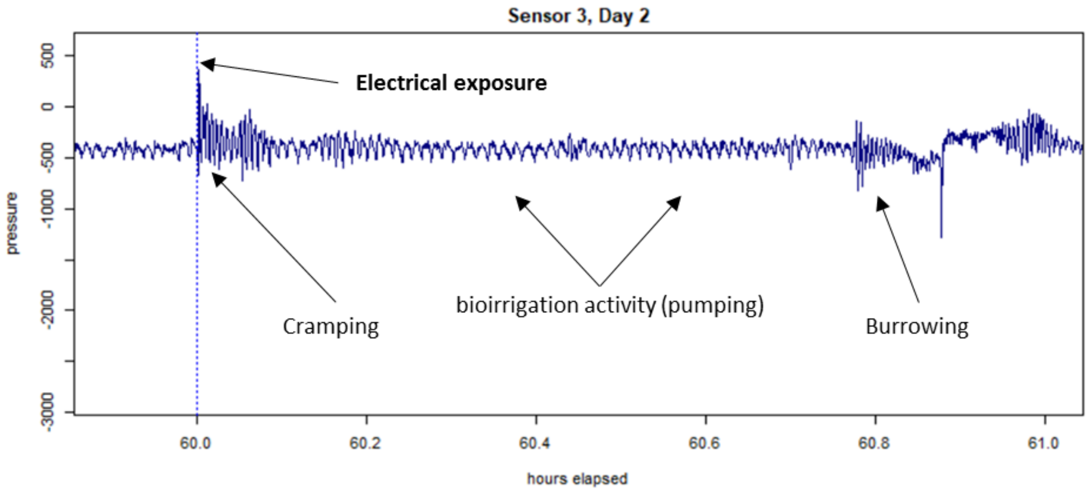

Figure 8.1. Example of Arenicola marina activity and response to electrical exposure as observed through high resolution pressure sensors in the sediment.

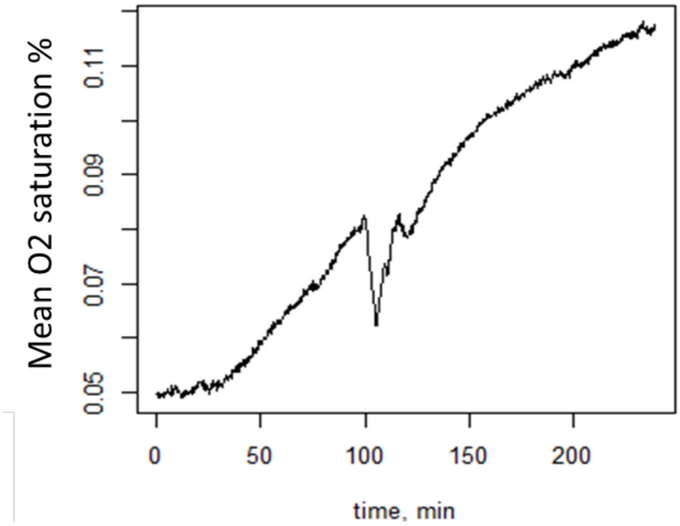

Figure 8.2. Oxygen saturation levels inside an Arenicol marina burrow. The temporary decrease in oxygen saturation occurred directly after electrical stimulation.

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.

8.3 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 *Arenicol 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.

9 Effects 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. 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 pulsed direct currents (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 is due to the bi-directional flow of electrons limiting impacts from chemical reactions or electrolysis and short pulse duration (average 1.5 sec). Prolonged (1+ min) exposure to high frequency (80 Hz) 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.

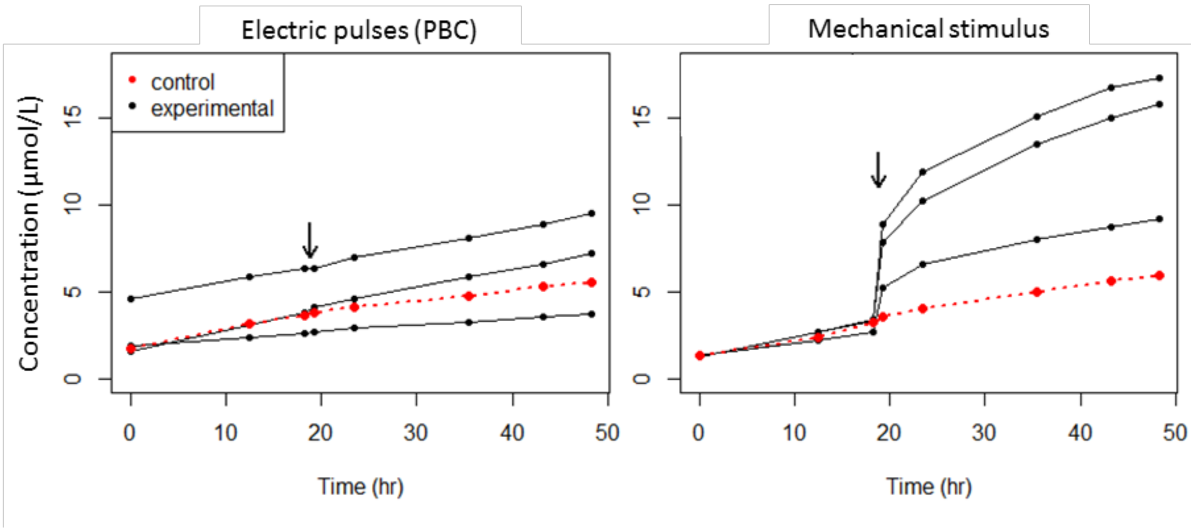

Figure 9.1. Comparing electrical (left) and mechanical (right) stressors on the release of silica concentrations from the sediment. The arrow indicates the experimental treatment.

9.2 Effect of sediment 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 oxygen (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.

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 (reviews in Hiddink et al., 2017; Sciberras et al., 2018). 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), we expect that the mortality imposed by the mechanical disturbance of the pulse trawl will be 50% lower.

This prediction can be compared to the results of Bergman and Meesters (2020) who 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).

9.4 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 box core sediment samples were collected to measure rates of oxygen consumption and nutrient fluxes in fished and unfished areas. Traditional beam trawling produced on average larger and more consistent impacts on sediment oxygen consumption, oxygen micro-profiles and sediment chlorophyll levels, while 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 9.2b). 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)

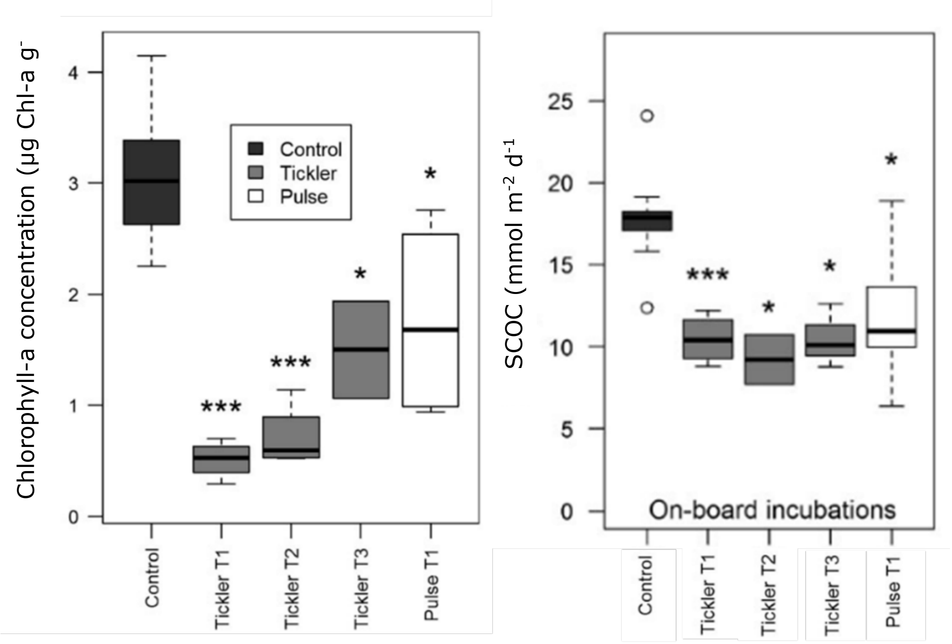

Figure 9.2 Biogeochemical impact from tickler chain beam trawls vs. electric pulse trawls for chlorophyll-a (left) and sediment community oxygen consumption (SCOC; right). Figure adapted from Tiano et al. 2019

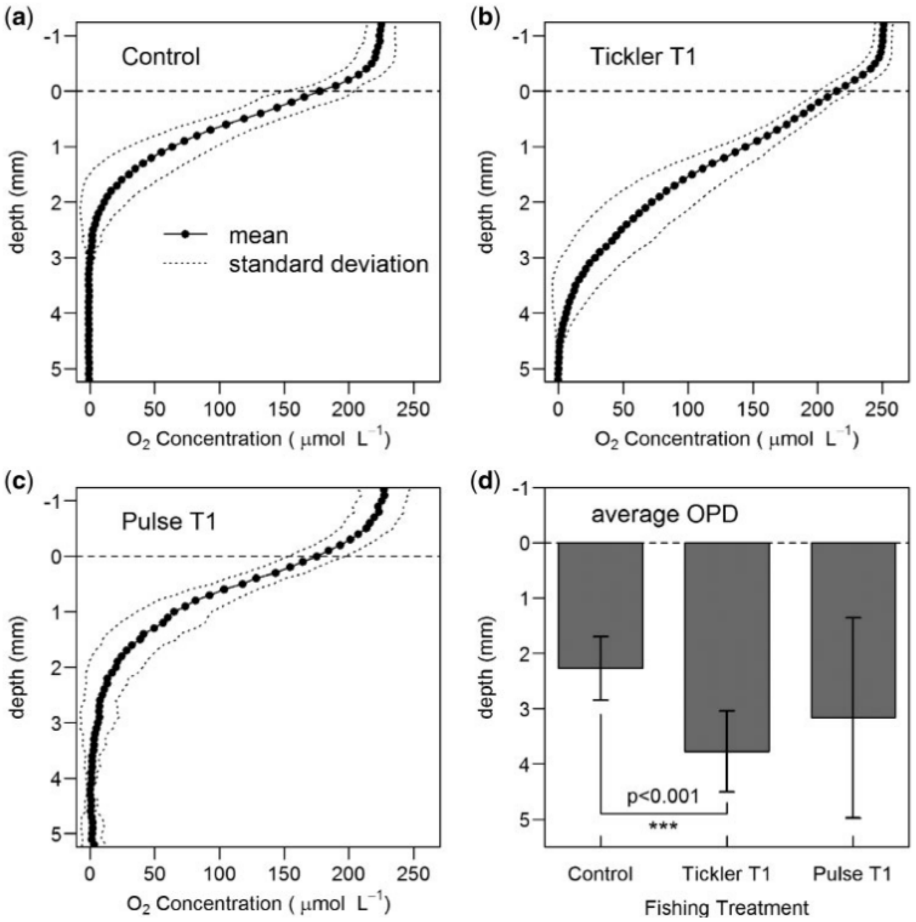

Figure 9.3. Oxygen microprofiles for (a) control, (b) tickler T1, and (c) pulse T1 areas. (d) Average O2 penetration depth (mm) and standard deviation from each treatment. Figure from Tiano et al. 2019.

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 multi-beam 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*).

9.5 Discussion

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.

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, 2020ab), its effects on benthic biogeochemistry will also be reduced on average but not eliminated (Tiano et al., 2019).

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., 2016a), 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.

9.6 Conclusions

PBC and PAC pulse stimulation used in pulse fisheries for sole does not seem to affect the biogeochemical processes

Effects of pulse trawling are related to mechanical disturbance and will be lower than in conventional beam trawling but not eliminated

Mechanical disturbance to the seabed has 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

10 Scaling up impact to the population level and fleet level

10.1 Introduction

In order to compare the ecosystem effects of the conventional beam trawl and the pulse trawl, we need to scale up the knowledge on the effects of mechanical stimulation and electrical stimulation 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. The PLH can be used as a proxy of the total fleet because they landed 95% of the Dutch sole landings after the transition to pulse trawling. 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 55°N, west of 5°E, and 56°N, east of 5°E.

10.2 Exposure to a pulse trawl

The impact of a fishery on a population, ecosystem component or habitat is determined by the proportion of the population and the number of exposure events to the fishing gear or pulse stimulus and the effect of the exposure. To estimate the proportion of a population and the number of exposure events to a pulse or conventional beam trawl information is required on the intensity and distribution of trawling. Under the assumption of an effective width that 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°N). At this resolution, the number of exposure events 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; Amoroso et al., 2018).

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 and 70% was not trawled. Within this trawled area (footprint), 67% was trawled 1 year^{-1}, 22% was trawled 2 year^{-1}, 8% was trawled 3 year^{-1} and 3% was trawled 4 or more times year^{-1} (Figure 10.2). For population occurring in all of the trawled grid cells by the PLH, the proportion of the population that is exposed at a certain frequency can be calculated as the product 0.3 * number of trawling events (Figure 10.2): 20.1% of the population was trawled 1 year^{-1}; 6.6% was trawled 2 year^{-1}; 2.4% was trawled 3 year^{-1} and 0.9% was trawled 4 or more times year^{-1}.

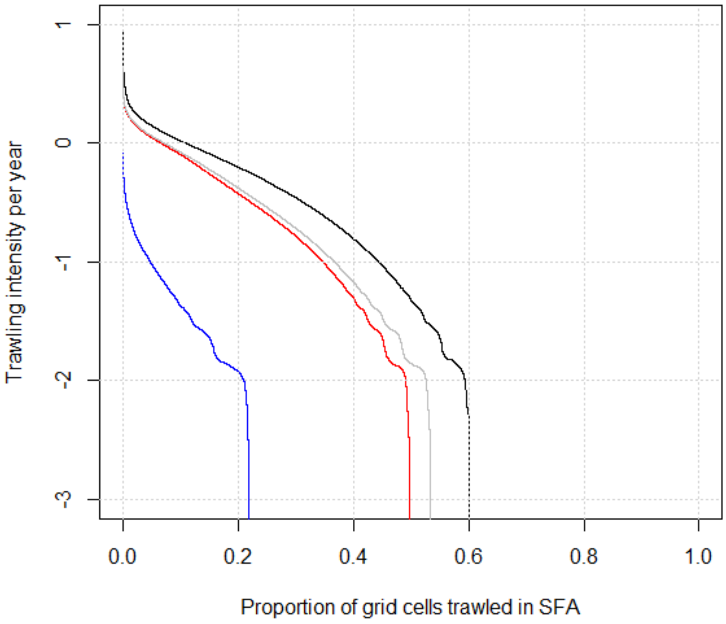

Figure 10.1 Trawling intensity (log10) profile of pulse license holders (PLH) in the sole fishing area (SFA) when fishing with the tickler chain beam trawl in 2009 (black) and with the tickler chain beam trawl (blue) or pulse trawl (red) in 2017. The grey line shows the profile in 2017 when tickler and pulse effort is summed. Grid cells (1 minute latitude x 1 minute longitude) were sorted from high to low trawling intensity.

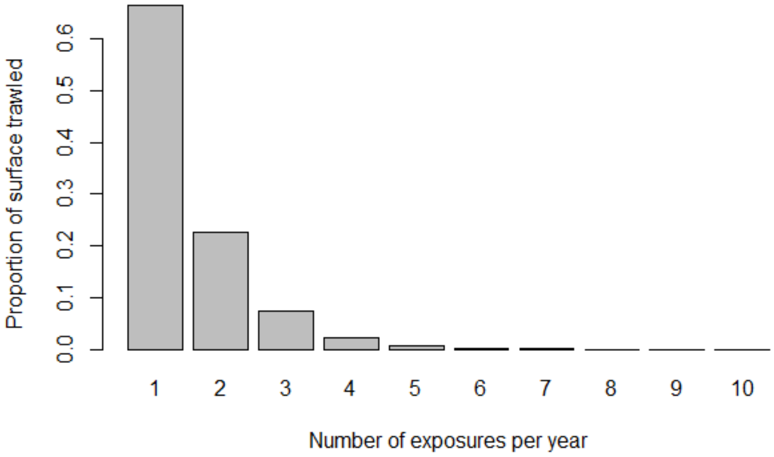

Figure 10.2 Proportion of the trawled surface area that is exposed 1 to 10 times during a year to a pulse stimulus of 1.5 seconds and field strength >5 V.m^{-1}

The above analysis shows that 10% of animals that live in the most intensively trawled grid cells will have a chance of being exposed >=2 times during 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.

10.3 Conclusions

For a population that is randomly distributed in the fishing area of the beam trawl fleet targeting sole, 30% of the population was exposed to one or more pulse stimuli per year (exposure probability).

Only 10% of the animals will be exposed 2 or more times per year. The low exposure frequency and the short duration (1.5 sec per exposure) suggest that the pulse trawl fishery for sole does not impose a chronic exposure to marine organisms.

11 Impact on fish populations

The impact of the transition from conventional beam trawling to pulse trawling is assessed by estimating the changes in the fishing mortality imposed by a fishery (partial fishing mortality) on a fish population. The methods and data used in the analysis is described in Appendix 2.

The impact is assessed for a selection of marine organisms. 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).

11.1 Partial fishing mortality imposed by beam trawl fleet

Changes in the partial fishing mortality imposed by beam trawling of PLH during the transition is estimated with equation [A6 in Appendix 2] with a spatial resolution of ICES rectangles, annual time step, and species specific catchability coefficients for pulse trawl and assuming that all fish caught will die (Table 11.1). The estimated partial fishing mortality differs between species and species groups reflecting the spatial overlap and the estimated catchability coefficients (Figure 11.1 left). 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 11.1) 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 (or equal) in conventional beam trawls than in pulse trawl (Table 7.3), 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.

Table 11.1. Total population: Change in the partial fishing mortality between 2009 and 2017 imposed by the total Dutch beam trawl fleet 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 estimated in section 4.2 and converted to catch rate per unit area swept.

Species group	q.pulse	Total beam trawl fleet			Pulse license holders (PLH)		
		2009	2017	%change	2009	2017	%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%

11.2 Partial fishing mortality of discard size classes

The analysis of the discard samples collected from pulse trawl vessels and conventional beam trawl vessels showed a significant difference in catch rate per hour between the gears. To further investigate the possible effect of a gear transition on the discarding, we estimated the partial fishing mortality of the discard size classes due to fishing activities of the PLH during the transition period (Figure 11.1 right). 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 11.2). 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. Survival experiments with discards of thornback rays shows a rather high survival rate of around 50% and suggest that the survival in pulse trawls may be higher than rays caught in the conventional tickler chain beam trawl, although not statistically significantly (Figure 4.3).

Table 11.2. Discard size classes: Change in the partial fishing mortality between 2009 and 2017 imposed by the total Dutch beam trawl fleet 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 4.2 and converted to catch rate per unit area swept.

Species group	q.pulse	Total beam trawl fleet			Pulse license holders (PLH)		
		2009	2017	%change	2009	2017	%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%

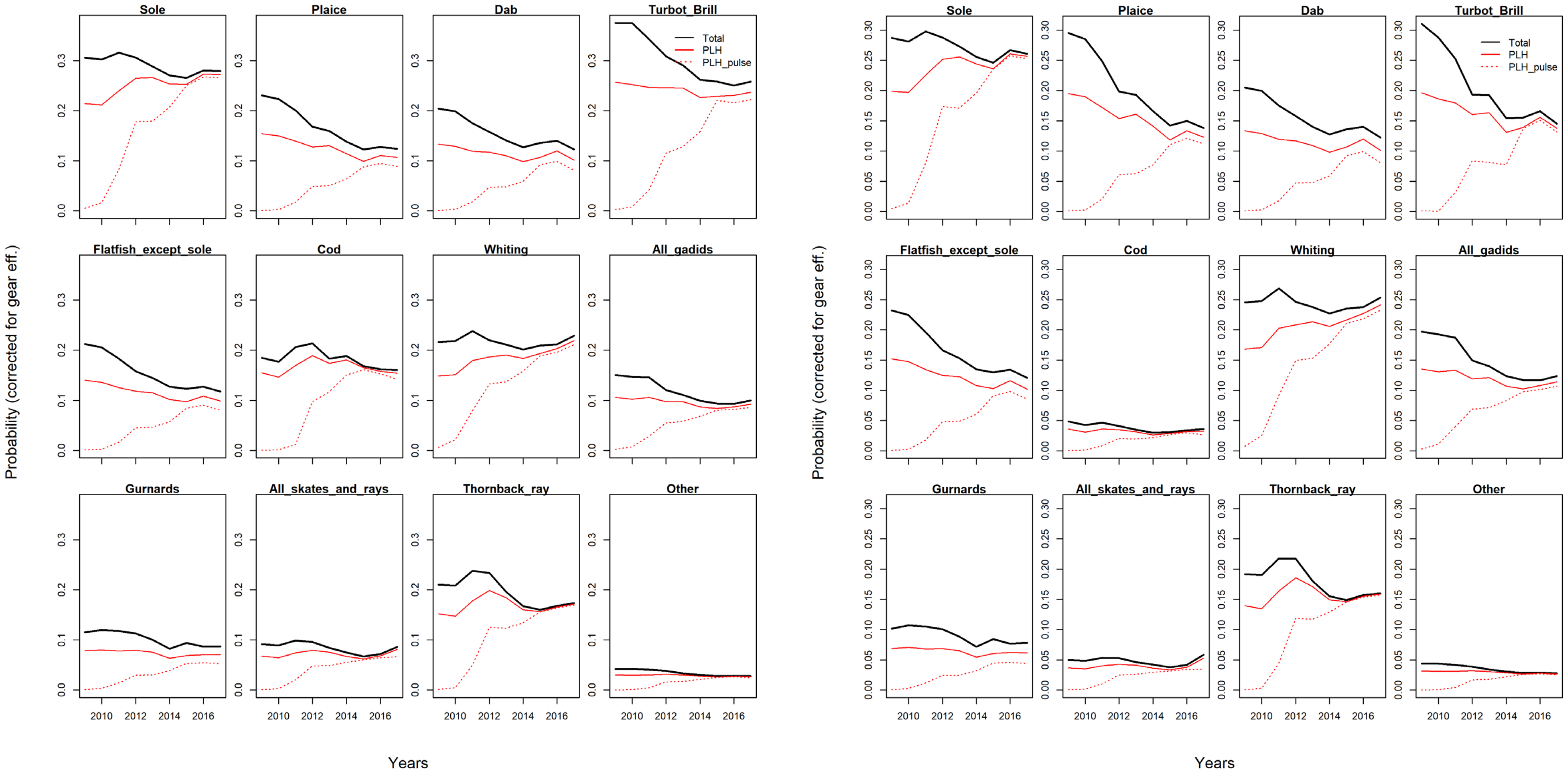

Figure 11.1. Total population (left panels) and discard size classes (right panels): change in partial fishing mortality imposed by the total Dutch beam trawl fleet (heavy black line) and the pulse license holders (PLH, red line). The red dotted line shows the exposure probability to the pulse trawl.

11.3 Impact on cod population

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 17 cm, that are small enough to escape through a 80mm cod-end, 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 7).

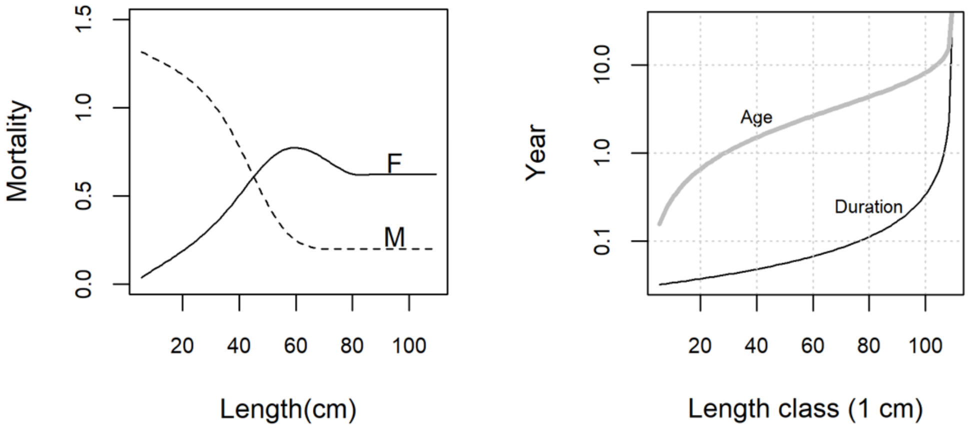

Figure 11.2 North Sea cod: rate of fishing (F) and natural (M) mortality (year-1) in relation to body size (left panel) and stage duration and cumulative stage duration (age) in relation the 1 cm length class used in the cohort analysis (right panel).

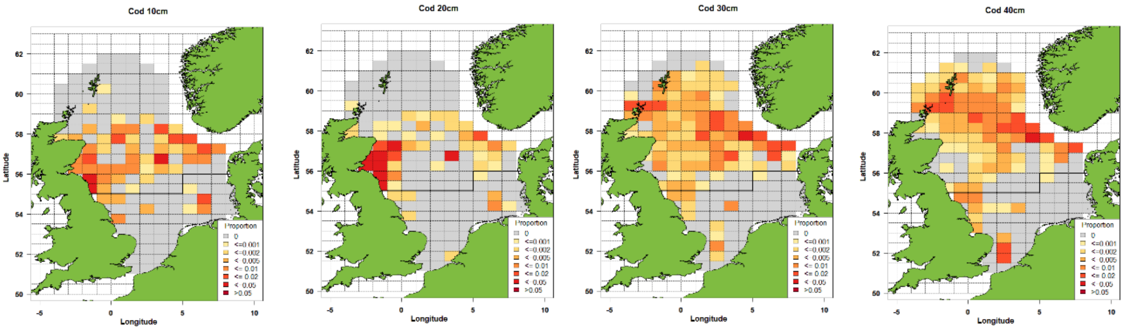

Figure 11.3. Cod. Relative distribution of size classes (<10cm, 11-20cm, 21-30cm, 31-40cm) based on 1st and 3rd quarter international bottom-trawl survey (IBTS) data (2009-2017). The horizontal line at 55oN and 56oN shows the northern limit of the sole fishing area (SFA)

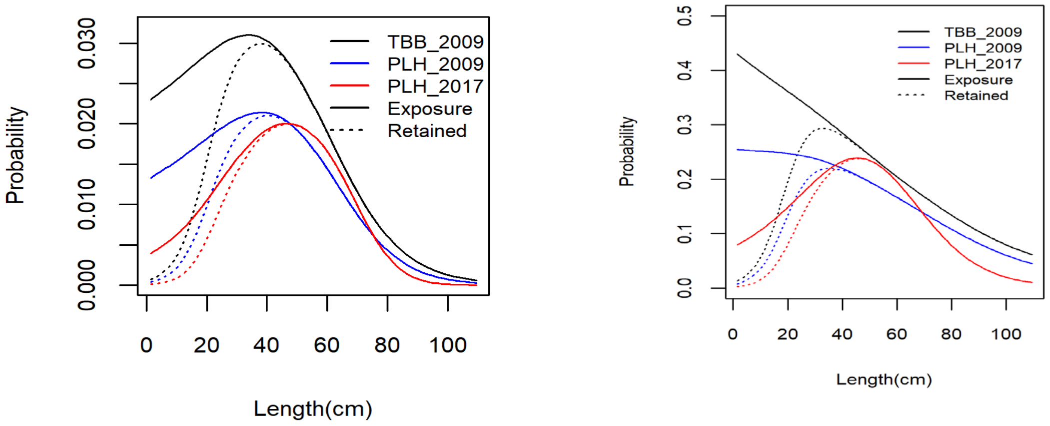

Figure 11.4. Cod. Encounter probability with the Dutch beam trawl fleet. Left: total North Sea. Right: sole fishing area SFA. Dashed lines refer to the probability of being retained in the mesh. Encounter probability curves were estimated for the pulse licence holders (PLH_2009) fishing with the conventional 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 cod-end meshes a length based cohort analysis was conducted. The cohort model was parameterised based on literature data (Appendix 2). 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 11.2 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 11.3). A smooth relationship between the encounter probability and length was calculated by fitting a generalised additive model (Figure 11.4). 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 11.4. 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 11.3). The 40% corresponds to the maximum proportion of cod with a spinal injury. Fishing mortality was set as the sum of fishing mortality (Fvpa) estimated by ICES (Figure 11.2 left) and the partial fishing mortality imposed by the PLH estimated for 2017 (Figure 11.4).

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 Fvpa 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 spawning stock biomass (SSB) when 40% of the cod dies when exposed to a pulse trawl

(Table 11.3). This reduction is lower that the difference between the estimated effect for 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 11.4 right panel).

Table 11.3. 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

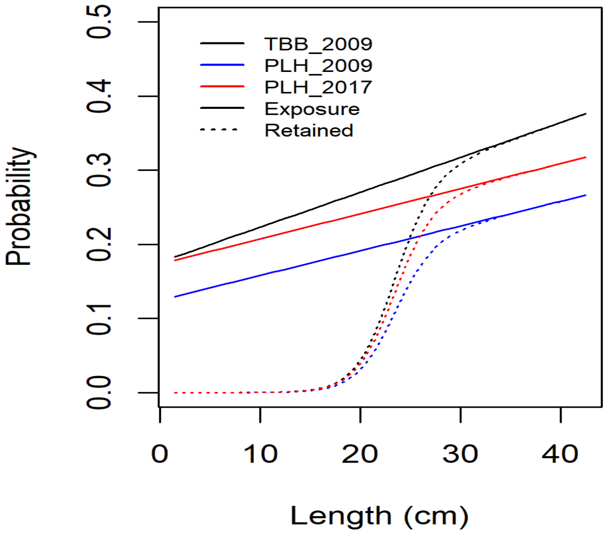

Figure 11.5. Sole. Encounter probability at length of sole with the Dutch beam trawl fleet. Dashed lines refer to the probability of being retained in the mesh. Encounter probability curves were estimated for the total Dutch beam trawl fleet (TBB_2009) and subset of pulse licence holders (PLH_2009) fishing 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.

11.4 Impact of non-lethal exposure on sole population

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 cod-end meshes. Soles that are outside of the track of the trawl will be exposed to a field strength that is too low to induce a behavioural response (section 6). Although no experimental studies have been carried out, it is unlikely that such an exposure will adversely affect the reproductive physiology of the fish.

The cohort model was used to estimate the size and stage durations required to estimate the exposure probability. The cohort model was parameterised based on literature (Appendix 2). 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 11.5). 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 cod-end mesh.

The probability that a sole will encounter a pulse trawl but escape through the cod-end mesh and survive is given by the cumulative sum of the encounter probability*stage duration. Figure 11.6a 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 11.6b shows that about 53% of the sole surviving for 4.5 years up to 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 11.6c). 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.

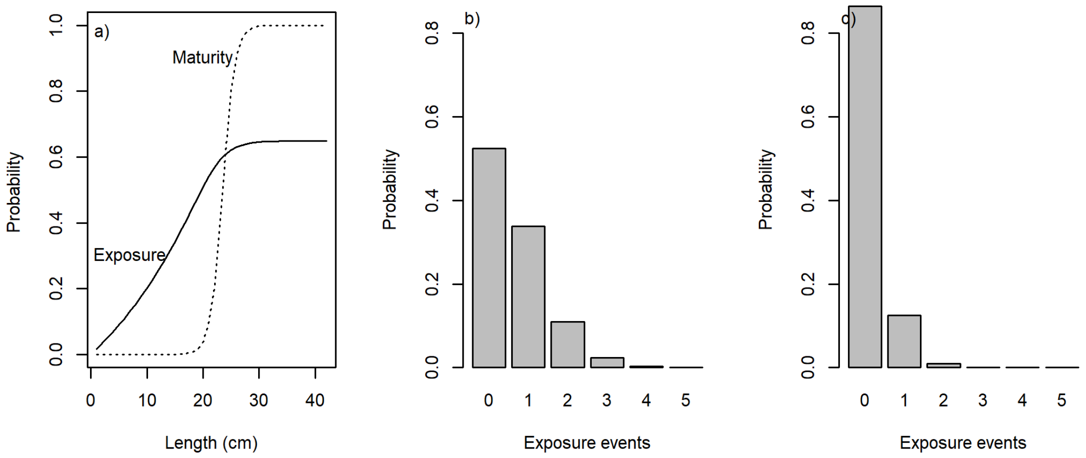

Figure 11.6. Sole. (a) Cumulative probability that a sole surviving to a particular length is exposed to a pulse stimulus but not caught; (b) probability distribution of the number exposure events for a 30 cm sole that survived 4.8 years; (c) probability distribution of the number exposure events during the year of sexual maturation prior to spawning at 25 cm.

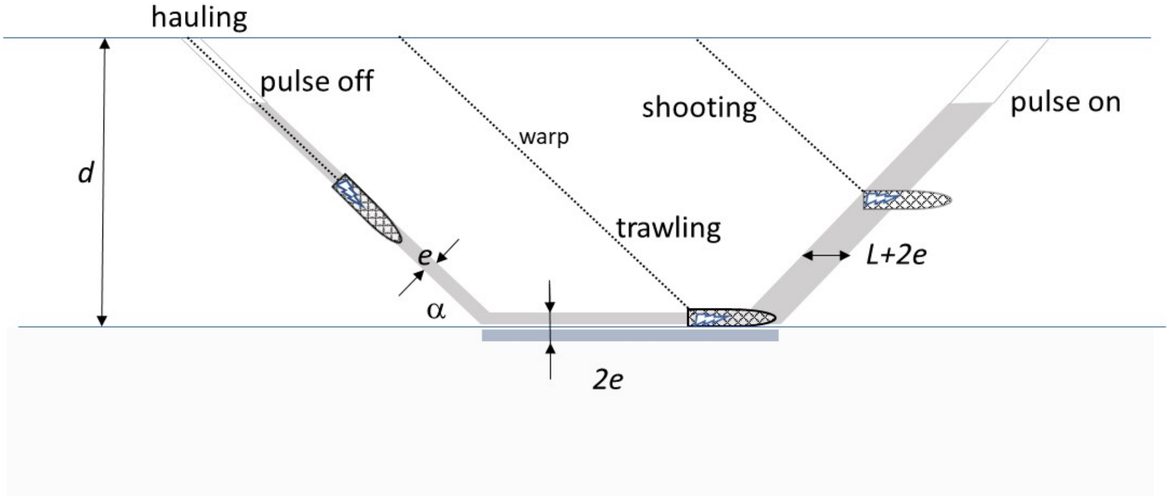

Figure 11.7 Schematic illustration of the pelagic (grey) and benthic (dark grey) zone exposed to electrical pulse stimulation during shooting, trawling and hauling of the pulse trawl. The pulse is automatically turned on and off when the warp is shot / hauled for a fixed length. e is the distance to the nearest electrode where the field strength exceeds the sensitivity threshold, L *is the length of the electrode (⚡),* d *is water depth and* α *is the angle corresponding to the warp ratio (length of the warp / water depth). The figure shows the cross section through the trawl. The width of exposure is given by the width between the two outermost electrodes* W *plus* $2e$*.*

11.5 Impact on egg and larval stages

11.5.1 Pelagic eggs and larvae

The potential mortality imposed by pulse trawling on the eggs and larvae is dependent 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 (Figure 11.7). 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.

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 11.8) 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, we estimated the number of hauls 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, we then calculated the ratio of the total volume of water exposed over the total volume of water for each rectangle, and calculated the weighted ratio over the relative egg production in the rectangle. 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 in comparison with the known mortality rates during the pelagic phase which are generally higher than 30% per day (see review in (Horwood, 1993).

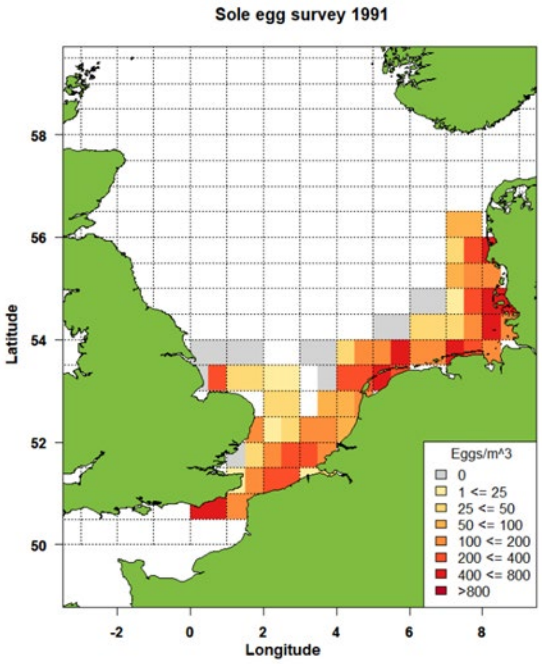

Figure 11.8. Sole. Maximum daily egg production observed in the sole egg surveys conducted in 1991 (data WMR).

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).

We conclude 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.

11.5.2 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. We therefore conclude that the population level effects of pulse trawling on demersal eggs 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, we infer 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.

11.6 Conclusions

- The estimated partial fishing mortality imposed by beam trawling of pulse license holders (PLH) on the total population decreased between 2009 and 2017 by 10%-31% but was stable for cod (0%) and increased for sole (+27%) and rays (+20%). The estimated partial fishing mortality of discard size classes decreased for all species combined (-21%). For individual species or species groups the partial fishing mortality decreased between -9% and -37%. Only for sole (+29%) and rays (+44%) an increase was estimated.
- The potential impact of pulse-induced mortality on small cod that are not retained was estimated to be negligible (<0.05%) for the North Sea and small (<=2%) for the cod stocks in the SFA.
- 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.
- A population level effect of pulse exposure of pelagic and demersal eggs is highly unlikely because of the low proportion of eggs that will be exposed to a pulse stimulus relative to the high rate of natural mortality and the density-dependent regulation of population numbers after the pelagic egg or larval phase.
- The increase in stock development in combination with the lack of overlap between the pulse fishery and the egg capsules of ray species makes it unlikely that the introduction of the pulse trawling negatively impacted the survival of egg capsules of the ray stocks in the southern North Sea.

12 Impact on the benthic ecosystem

The methods used to estimate the trawling impact is described in Appendix 1.

12.1 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 12.1b). 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 12.1c), 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 12.1a).

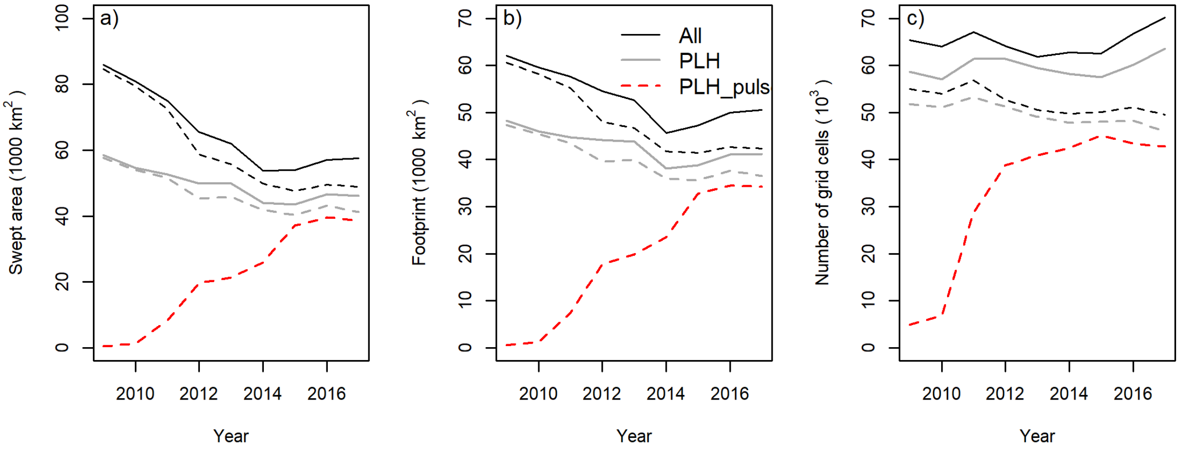

Figure 12.1. Changes in the area swept (a), the surface of the sea floor which is trawled at least once per year (b, footprint) and the number of 1x1 minute grid cells with trawling activities (c) recorded for the total Dutch beam trawl fleet (ALL) and for the subset of pulse license holders fishing 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. 2020b)

12.2 Sediment mobilisation

Bottom trawls disturb the seafloor by mobilising 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 mobilised 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., 2020a).

The estimated amount of sediment that is mobilized in the wake of the beam trawls decreased during the transition period (Figure 12.2). 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 12.1).

12.3 Impact on seafloor and benthic ecosystem

The benthic impact was assessed using a set of three indicators recently developed in the BENTHIS and Trawling Best Practice projects (Kaiser, 2019; Rijnsdorp et al., 2020c). 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., 2018). 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).

All three indicators showed a decline in impact during the transition to pulse trawling (Figure 12.3). 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 12.4).

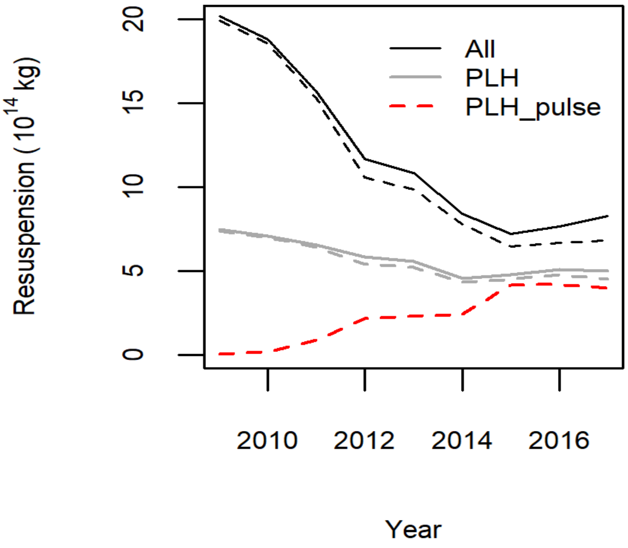

Figure 12.2. Time trends in the amount of sediments mobilised by the Dutch beam trawl fisheries (ALL: thick black), the subset of pulse license holders fishing with a tickler chain trawl or pulse trawl (PLH: thin black) or fishing with a pulse trawl (PLH-pulse: red). Full lines refer to the total fishing area. Hatched lines refer to the sole fishing area (SFA) with 80mm mesh size south of the demarcation line. (from Rijnsdorp et al. 2020b)

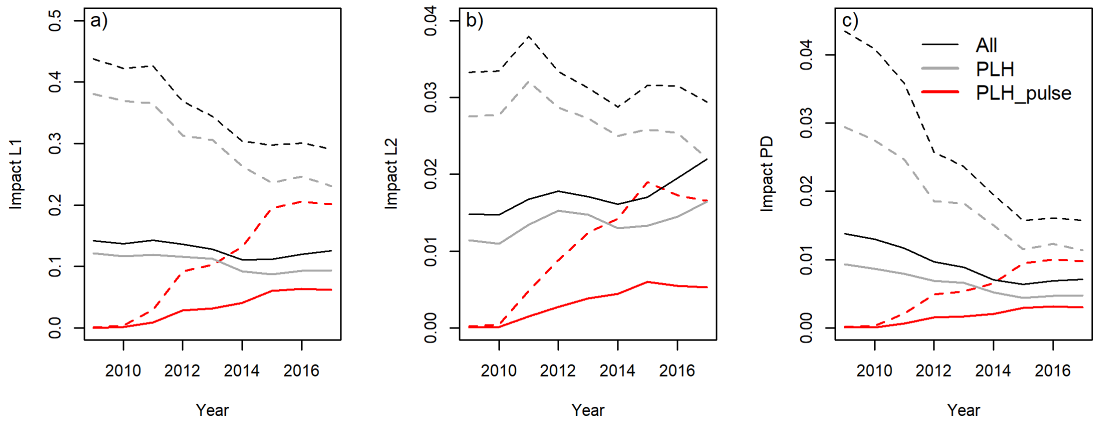

Figure 12.3. Time trends in the impact indicators of the total Dutch beam trawl fleet (ALL) and for the subset of pulse license holders fishing with a tickler chain trawl or pulse trawl (PLH) or with a pulse trawl (PLH-pulse). Full lines refer to the total fishing area. Hatched lines refer to the sole fishing area (SFA) with 80mm mesh size south of the demarcation line (from Rijnsdorp et al. 2020b)

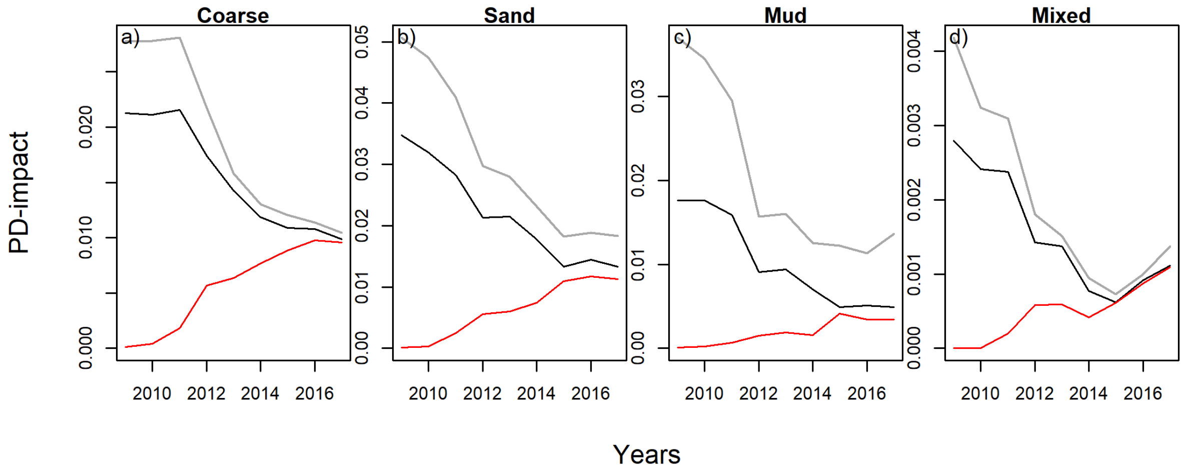

Figure 12.4. Changes in PD impact by habitat type in sole fishing area (grey = total beam trawl fleet, black = pulse license holders; red = pulse license holders with pulse trawl)

Table 12.1. 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. 2020b).

	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

12.4 Long-term geochemical effects

In order to predict long-term impacts of bottom trawl disturbance on biogeochemical parameters and benthic pelagic coupling, the OMEXDIA 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 mobilisation were used with pulse trawls exhibiting 0.5 of the mixed layer depth and 0.7 of the total sediment mobilised compared to beam trawls (Depestele et al., 2018, 2016; Rijnsdorp et al., 2020ab). 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 12.5). 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.

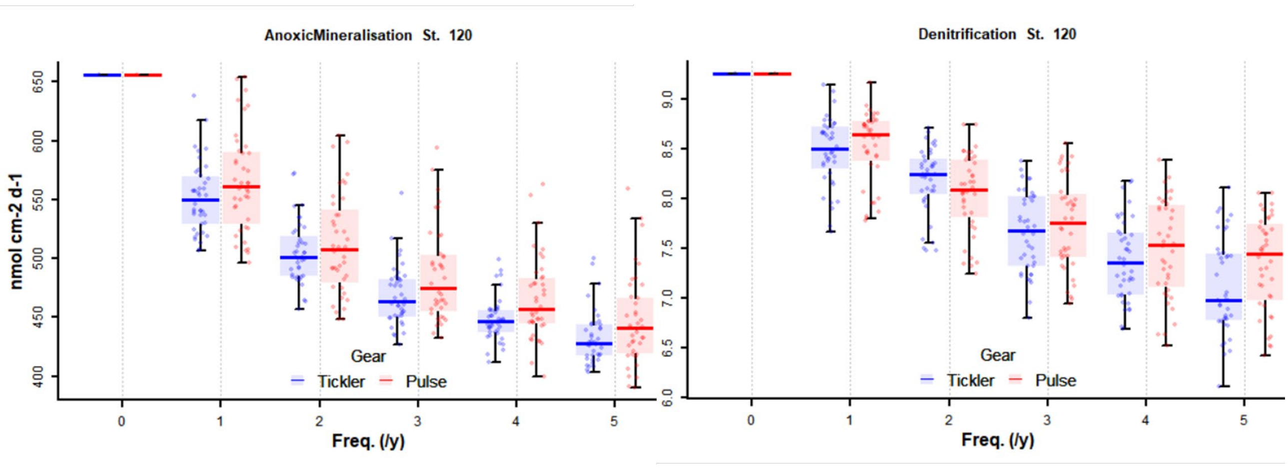

Figure 12.5. Example of model results showing the effects of tickler chain beam trawled vs. pulse trawled sediments on anoxic mineralisation (left) and denitrification (right). Simulations show how this effect is worsened over the course of multiple trawling events per year.

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 mobilised sediment (Rijnsdorp et al., 2020ab). 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 and 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.

12.5 Impact on food web

Experimental results of the electric field on individual benthic organisms and indicators to estimate the impact on the benthic ecosystem have been developed. However, the effects of electricity on the food web have hitherto not been addressed. This would of course be difficult in a field setting, although mesocosm experiments may provide opportunities for such studies. Nonetheless, impacts of non-lethal effects at food web level remain under addressed. To that end, a modelling approach was used which translates effects of trawling at individual level to into a food web context (van de Wolfshaar et al., 2020). These effects were modelled as direct, lethal effect and indirect, non-lethal effects of trawling, thereby mimicking effects of the traditional trawl with only lethal effects and the effects of the pulse trawl with both lethal and non-lethal effects. The model allows to for a simultaneous change in direct, lethal effect and indirect, non-lethal effects of trawling.

The model was used in particular to study how strong the non-lethal effect must be so that the pulse trawl has the same effect as the traditional trawl on the food web. In addition, the expected non-lethal effect of the pulse trawl on an individual was estimated, based on reported responses of benthic organisms to electric fields and trawl frequencies. Although these two measures (from model and field) cannot be directly linked, their relative strength does inform about the expected impact of the pulse trawl on the food web in a field setting.

The food web model used describes the benthic food web based on three species groups(van de Wolfshaar et al., 2020). These groups were defined based on a trait analysis (Bremner et al., 2006; Bolam et al., 2014; van Denderen et al., 2015a) and consist of predators/scavengers, filter/suspension feeders and deposit feeders. These three groups are general guilds that are present in the most, if not all, benthic ecosystems (Bolam et al., 2014). The group of predators consist of larger free-living species in fila such as annelids, cnidaria and crustaceans. The group of filter/suspension feeders is comprised of mostly sessile tube-dwelling species in fila such as molluscs, bryozoa and cnidaria. The group of deposit feeders consists of mostly burrowing species in fila such as annelids, crustaceans and molluscs and are mostly free living or tube-dwelling. The non-lethal effects were incorporated as a down-scaling of the intake rate of benthic invertebrates as suggested from experiments (van Marlen et al., 2009), (Tiano unpublished results).

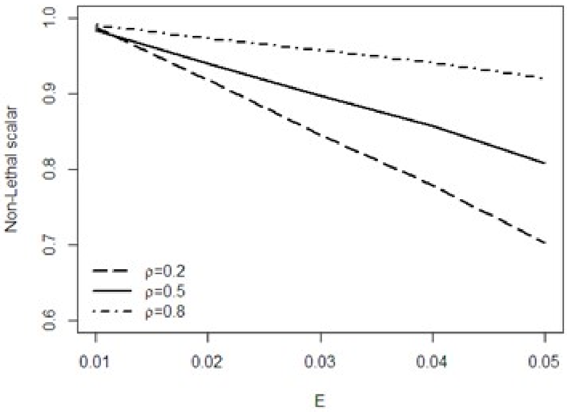

Figure 12.6. Non-lethal effect needed to maintain biomass at fishing intensity E, for different fractions of lethal effect (0.2, 0.5, 0.8). The solid lines represents the 0.5 reduction of lethal effect related to the transition in from tickler chain beam trawl to the pulse pulse trawl.

The results of the model exercise shows that a reduction in lethal effects can be compensated by non-lethal effects to maintain total food web biomass and that non-lethal effects need to be the same order of magnitude as the lethal effects. The strength of the non-lethal effects needed to compensate the loss of lethal effects depended on the trawling intensity (Figure 12.6). A higher trawling intensity resulted in a stronger required decrease of the intake rate; i.e. a strong impact needed more compensation.

Any gear with non-lethal effects smaller than those required to compensate for its reduced lethal effects, is predicted to have a smaller overall impact on the benthic ecosystem than the traditional beam trawl using tickler chains. Experiments show that after exposure to an electric field comparable to that of a single passing of a pulse trawl, benthic invertebrate individuals remain inactive for no more than 20 minutes (section 8). This implies a reduction in feeding time of 3%, given a 12 hour feeding activity per day, on the day of passing. Converted to the intake rate as used in the model this means a downscaling of the rate to 0.97 of its value on the day of passing. The food web consequences are further affected by the frequency of exposure (F) during the daily and seasonal activity period of the animals. Assuming an activity period of D hours per day and an activity period of N days/year for an individual animal, a fasting response of R hours to an electrical disturbance event during the activity period of the animal would represent a $F \cdot R / D \cdot N$ reduction in the food intake. Given a maximum exposure frequency to beam trawls of about 5 times per year (Eigaard et al., 2016b), a daily activity period D of 12 hours, a seasonal activity period of 9 months (Braeckman et al., 2010), and a fasting response time of 0.3 hours, the likely non-lethal effect will be about a 0.0004 decrease in intake rate in a year at individual level.

Although the results from the model study are hard to relate to quantitative measurements, it appears that the decrease in individual intake rate suggested by the information available (section 8; van Marlen et al. 2009) and as calculated above, is far less than what would be required to compensate for a 50% reduction in lethal effects at food web level, the difference in lethal effects between the traditional trawl and the pulse trawl. The model study demonstrated that the impact of the pulse trawl on the macro-invertebrate food web, taking non-lethal effects into account, will be less than that of the traditional beam trawl.

12.6 Conclusions

- The transition to pulse trawling reduces the swept area (28%), footprint (23%), and sediment resuspension (39%) of PLH in SFA
- Pulse trawling reduced the benthic impact due to a reduction in footprint and mechanical disturbance between 20% - 61% depending on the indicator used.
- Long-term geochemical effects of pulse trawling is reduced due to the reduced mechanical disturbance. No additional effect of the exposure to electric pulses is found.
- Although benthic invertebrates may respond to a pulse exposure by slowing down their normal activities, the duration of this effect is short and is unlikely to affect the macro-invertebrate food web.

13 Synthesis

13.1 Introduction

Pulse trawls were introduced as a replacement of the tickler chain beam trawls in the fishery for sole to reduce the impact on the ecosystem and environment and improve its ecological and economic sustainability. Because the EU legislation prohibits the use of electricity to capture fish, the beam trawl vessels that switched to pulse trawling operated under a (temporary) derogation. Pulse trawling became a controversial fishery that was heavily criticised for its supposed detrimental impact on marine life and threatening the livelihood of other fisheries, in particular small scale fisheries (Haasnoot et al., 2016; Stokstad, 2018; Le Manach et al., 2019).

In absence of a comprehensive scientific advice, the public campaign against pulse fishing in 2017 culminated in a decision of the EU parliament for a ban on pulse trawling in January 2018. Despite of a positive advice of ICES (2018), the EU maintained its ban on pulse fishing in the revised regulation on technical measures (CEC, 2019)[1]. In this chapter we will synthesize the available information to answer the question whether pulse trawls provide an alternative for the traditional tickler chain beam trawl to improve the ecological sustainability of the fishery for sole, and quantify the gain in sustainability that can be achieved.

13.2 Approach

The consequences of the change in fishing gear will be assessed for a number of criteria covering the different ecosystem and habitat components that characterise the sole fishing area of the North Sea. The criteria are relevant for the EU to decide on the gears that are acceptable or unacceptable given the legislative framework of the EU[2]. The legislative framework includes the Common Fisheries Policy (CFP) that aims to ensure high long-term fishing yields and reduce unwanted catches and wasteful practices through the introduction of a landing obligation, and the Bird and Habitat Directive (BHD) and Marine Strategy Framework Directive (MSFD). The elements from the MSFD that are relevant to assess the consequences of the replacement of mechanical stimulation by electrical stimulation comprise biodiversity, commercial fish and shell fish, food webs, sea-floor integrity, contaminants, marine litter and energy including underwater noise.

Table 13.1 summarises the change in impact metrics that have been estimated in the present study. The metrics show the change in impact of the pulse license holders between 2009, before they switched to pulse trawling and were still using the conventional tickler chain beam trawl gear, and 2017 after the switch to pulse trawling. After the switch to pulse trawling, some vessels used the pulse trawl during part of the year only and temporarily used a shrimp trawl to harvest brown shrimps (Euro cutters, engine <= 221kW) or used a conventional beam trawl to harvest plaice north of the sole fishing area (SFA) (Poos et al., 2020). The impact comparison is done for the SFA in the North Sea where the PLH are allowed to use a 80mm cod-end mesh.

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[1] CEC. 2019. Regulation (EU) 2019/1241 of the European Parliament and of the Council of 20 June 2019 on the conservation of fisheries resources and the protection of marine ecosystems through technical measures, amending Council Regulations (EC) No 1967/2006, (EC) No 1224/2009 and Regulations (EU) No 1380/2013, (EU) 2016/1139, (EU) 2018/973, (EU) 2019/472 and (EU) 2019/1022 of the European Parliament and of the Council, and repealing Council Regulations (EC) No 894/97, (EC) No 850/98, (EC) No 2549/2000, (EC) No 254/2002, (EC) No 812/2004 and (EC) No 2187/2005.

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

Table 13.1. Impact metrics of the pulse license holders (PLH) before (2007) and after (2017) the transition from conventional beam trawling with tickler chain trawls to pulse trawling in the sole fishing area (SFA) below the 55°N west of 5°E and 56°N east of 5°E.

Species	Metric	Tickler before	Pulse after	%change
Sustainable exploitation of target species (CFP) and landing obligation (LO)				
Sole	Fishing hours PLH in SFA	303.4	300.6	-1%
	Swept area (10^3 km^2)	57.7	41.3	-28%
	% of total sole landings NL	73%	95%	+30%
	Change in catch rate per hour (landings)			+17%
	Change in catch rate per hour (discards)			+65%
	Partial fishing mortality discards	0.199	0.256	+29%
Plaice	Change in catch rate per hour (landings)			-35%
	Change in catch rate per hour (discards)			-30%
	% of total plaice landings NL	62%	36%	-42%
	Partial fishing mortality discards	0.190	0.121	-37%
Cod	Partial fishing mortality population	0.185	0.160	-13%
	Partial fishing mortality discards	0.036	0.032	-9%
	Effect pulse-induced injuries small cod on SSB			-2%
Marine strategy framework directive (MSFD): biodiversity, food webs				
Flatfish	Change in catch rate per hour (landings)			-20%
	Change in catch rate per hour (discards)			-33%
	Partial fishing mortality population	0.138	0.098	-29%
	exposure probability discards	0.150	0.101	-33%
Gadidae	Change in catch rate per hour (landings)			-16%
	Change in catch rate per hour (discards)			+93%
	Partial fishing mortality population	0.106	0.093	-12%
	Partial fishing mortality discards	0.135	0.114	-16%
All fish species	Catch rate per hour (discards)			-27%
	Partial fishing mortality population	0.121	0.100	-17%
	Partial fishing mortality discards	0.136	0.108	-21%
Marine strategy framework directive (MSFD): biodiversity, food webs, sensitive species				
Elasmobranchs	Partial fishing mortality population	0.068	0.081	20%
	Partial fishing mortality discards	0.037	0.053	44%
	discard mortality	55%	47%	-15%

Table 13.1 cntd. Impact metrics of the pulse license holders (PLH) before (2007) and after (2017) the transition from conventional beam trawling with tickler chain trawls to pulse trawling in the sole fishing area (SFA) below the 55oN west of 5oE and 56oN east of 5oE.

Marine strategy framework directive (MSFD): seafloor integrity and sensitive habitats				
Species	**Metric**	**Tickler before**	**Pulse after**	**%change**
Benthic impact	footprint (all habitats, 10^3 km^2)	47.3	36.5	-23%
	• coarse sediment (A5.1)	5.1	4.8	-15%
	• sand (A5.2)	50.0	34.9	-30%
	• mud (A5.3)	4.7	2.4	-50%
	• mixed sediment (A5.4)	0.1	0.07	-38%
	PD-Biomass reduction (all habitats):	0.029	0.011	-62%
	• coarse sediment (A5.1)	0.0212	0.0108	-54%
	• sand (A5.2)	0.0347	0.0133	-62%
	• mud (A5.3)	0.0176	0.0049	-72%
	• mixed sediment (A5.4)	0.0028	0.0011	-60%
	Sediment mobilisation (10^3)	7.4	4.5	-39%
Paris agreement on climate change to reduce CO2 emissions				
CO2 emissions	Fuel use per kg landings			-20%
	Fuel use per unit sole quota			-52%

The results of our study will be summarised in the light of the scientific literature by answering the following questions:

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

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

13.3.1 Fish

Exposure experiments with sole, plaice, sea bass, small-spotted cat shark did not find evidence for direct mortality of fish exposed to a commercial pulse stimulus (de Haan et al., 2015; 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. 36% of the sampled cod showed injuries that corresponded to pulse-induced injuries (fractures in the spine, heamal or neural arches and associated haemorrhages) observed in tank experiments. The injury probability was related with fish size with highest values in cod of around 40 cm and lower values for smaller and larger cod.

Elevated injury probabilities were also recorded for lesser and greater sandeel in pulse trawl catches. It is unlikely that these are due to pulse exposure because (i) an even higher injury probability was observed in catches of tickler chain beam trawls and (ii) a tank experiment showed a low (1%) injury probability among sandeel exposed to a pulse stimulus. In other fish species, the injury probability 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. This indicates that incidence probability 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 14.1). For all fish species studied except cod, the injury probability is low (<=1%) and often less than the mechanical induced injuries inflicted during the catch process (section 7.1). Therefore, the population level effect of pulse-induced injuries will be negligible.

Cod that pass through the electric field without being retained may become injured. The injury probability of small cod 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 (<0.5%) for the North Sea population and small (<2%) for the southern North Sea stock component (section 11.3).

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 (Desender et al., 2017a). A similar experiment with sole eggs and larvae did not find any adverse effects (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. The analysis showed that the exposure probability to be very low. 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 probability of exposure being much smaller than the rate of natural mortality and the density dependent mortality occurring later in life (section 11.5).

Although Elasmobranchs lay demersal egg capsules that are potentially sensitive 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 and have increased in abundance in recent years.

In a tank experiment the exposure to pulse stimulus did not affect the food detection ability of catshark (Desender et al., 2017b). This is consistent with our results that elasmobranchs do not have a higher sensitivity for the pulse stimulation used in the sole fishery, and the difference between the high frequency used in pulse trawling and the low frequency sensitivity range of the electro-receptors (section 6.2).

13.3.2 Benthic invertebrates

Pulse exposure did not resulted in mortality among six species of benthic invertebrates tested consistent with earlier studies (Soetaert et al., 2015a; Soetaert et al., 2016c; ICES, 2018b). The animals studied are a selection of different ecological groups and building 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 food web consequences of pulse-induced change of behaviour, will be negligible will be negligible. Because benthic invertebrates are a diverse group of species, and not all building 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 over 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} for 1.5 sec. Biological effects of bipolar pulse stimulation used in the sole fishery have been only observed at much higher field strength (WGELECTRA, 2018). It is therefore highly 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 much higher field strength. The observed distribution and intensity of pulse trawling shows that the probability of multiple exposures is very low. The low probability of exposure with a pulse stimulus implies that at the current level of pulse trawling only very few animals will be exposed multiple times, and the risk of a possible adverse effect of multiple exposures is very low. The low exposure probability and the short duration (1.5 sec) implies that there is no chronic exposure to pulse stimuli (section 10.2).

13.3.3 Conclusion

Exposure to the sole pulse may cause spinal injuries in a small percentage of the exposed fish. In most fish species the rate of injury is low (<=1%) except in cod where about 35% of the animals showed a spinal injury. The ecological and population level consequences are negligible because of the low exposure rate. Pulse exposure is unlikely to affect electrosensitive species because of the difference between the high pulse frequency used in pulse trawling and the sensitivity range for low pulse frequency of the electro-receptors. 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.

13.4 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.

Pulse trawls are more efficient in catching sole and are towed at a reduced towing speed. It is uncertain whether pulse trawls catch fewer undersized sole relative to marketable sized 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 12.1a).

Most of the sole that is caught in the North Sea is taken with beam trawls using a small meshed cod-end. Only 8% is caught in a directed fishery in coastal waters using gillnets and trammel nets (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.

During the transition to pulse trawling, a shift in the spatial distribution of PLH was observed which coincided with changes in distribution of sole. 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 3.7). 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 the 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 of a size to be retained in the gear, that are thought to contribute most to the reproductive output of a population, are unlikely to be affected since they are outside the track of the trawl and exposed to a field strength of <<5 V.m^{-1}.

Conclusion

Pulse trawling do 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.

13.5 Does pulse trawling affect the selectivity of the sole fishery and affect the discarding of fish and benthic invertebrates?

Pulse trawls catch more sole and less other 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. The higher catch of whiting is uncertain.

Per unit of area swept, pulse trawls have a higher catch efficiency of sole, and a lower catch efficiency of plaice. Other species are caught in proportion to the area swept. The higher catch efficiency of whiting suggested in the comparison of landings and discard data from both gears is 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.

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 improves the selectivity of the sole fishery reducing the proportion of other fish species in the mixed bag, and reduces the bycatch of undersized fish for most fish species (discards) and benthic invertebrates.

13.6 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.

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., 2020c). 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.

Sediment mobilisation is estimated to have decreased by 39%. The consequences on the biogeochemical processes were modelled and showed on average a reduced impact on the mineralisation 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.

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 bio-geochemical processes and that biogeochemical effects were due to the mechanical disturbance of the sediment by the gear. 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.

13.7 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 sea water 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 sea birds 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.

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 (Sections 4 and 11). The impact of pulse exposure on sandeel due to pulse-induced injuries, an important food species for predator species, is considered negligible (Section 7.3).

The same reasoning applies to the Natura 2000 sea birds. Many sea birds 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 probably 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 fresh water 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.

All North Sea rays and skates stocks are managed through a generic multi-species 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, 2018a). 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 Specific Areas of Concern 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 mobilisation 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

Although no specific experiments have been carried out to study the impact of pulse trawling on Natura 2000 species and habitats, 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.

13.8 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 3.4). Under the assumption that the CO_2 emissions are proportional to fuel consumption, the reduction percentages provide an estimate of the reduction in CO_2 emissions that can be achieved when using the pulse trawl in the beam trawl fishery for sole.

13.9 Relevance of the findings for the legislative framework

Sustainable exploitation of target species (CFP)

The results of our study provide strong support that the pulse trawl can be used to sustainably exploit the quota of North Sea sole at a substantially reduced environmental cost. The improved selectivity related to the increased catch efficiency for sole coinciding with a reduced footprint that reduced both the discarding of undersized fish and benthos. Pulse trawling therefore contribute to the objectives of the CFP for sustainable exploitation. The improved selectivity also contributes to the objectives of the landing obligation to reduce the unintended bycatch.

The use of a pulse trawl coincides with a reduced towing speed and a reduction in fishing costs, most notably the cost of fuel. The higher catch efficiency provides a competitive advantage the pulse trawl skipper when fishing with other fishers on the same fishing grounds. During the transition period, Dutch pulse trawl vessels replaced Belgian beam trawlers in the southwestern North Sea. The Belgian beam trawlers experienced a decrease in their catch rates during working days when they were fishing together with Dutch vessels, while their catch rates recovered during the weekend when Dutch vessels were in port (Sys et al., 2016). The competition among fishers is a socio-economic problem that can be tackled by managing access and fishing rights among fishers.

Marine strategy framework directive (MSFD): biodiversity, food webs, seafloor integrity

The reduced spatial footprint and impact on the fish community and benthic ecosystem will reduce the fishing pressure on the diversity, food web and the integrity of the sea floor, and thus contribute to the objectives of the MSFD when harvesting of the sole quota.

Marine strategy framework directive (MSFD): contaminants and marine litter

The lower footprint and towing speed of pulse trawling reduces the wear on the nets and engine. Although no quantitative information is available, we expect that the replacement of conventional beam trawling by pulse trawling will reduce the contaminants and marine litter produced when harvesting the sole quota.

Paris agreement on climate change to reduce CO2 emissions

The high fuel use in the beam trawl fishery has triggered the industry to explore technological solutions. A first step in to develop a more fuel efficient fishery was to replace the round metal beam with a wingshaped foil that reduced the fuel consumption by about 16% (Turenhout et al., 2016). The decrease in towing speed which was possible with the transition to electric stimulation further reduced the fuel consumption. The reduction in fuel consumption, when harvesting the sole quota with pulse trawls compared to Sumwing beam trawls, is estimated to be 52% (-22% per total landed weight). Because CO2 emissions are directly proportional to fuel consumption, the transition to pulse trawling will make a substantial contribution to the objectives of the Paris agreement.

14 Other considerations

The quantitative assessment summarised in Table 13.1 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 and reducing the disturbance of the seafloor and impact on the benthic ecosystem. However, there are a number of other concerns raised in the debate about pulse trawling that will be briefly discussed.

14.1 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 to accommodate the interest of the fleet (Haasnoot et al., 2016), preceded the growth in the budget available for research to address the questions and concerns raised by ICES (2012,2016) and STECF (2006). The current project was initiated in response to the extension of the number of licenses in 2014 and an another multi-year 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, where the impact could be assessed without the need to extrapolate from a sample of experimental vessels.

14.2 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 3). As part of the regulation, pulse settings (voltage over electrode pairs, pulse width 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 in this study showed that the vessels were operating within the boundaries set.

14.3 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 of 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.

14.4 Knowledge gaps

The current study provides a lot of new scientific knowledge on 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 ICES WGELECTRA in 2018. In this paragraph we will discuss these gaps and describe the current status given the current knowledge.

14.4.1 Extrapolating results from the laboratory to the field

A mechanistic understanding of how an electric pulse affects marine organisms, for instance how it causes a 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. The assessment of the consequences of pulse-induced injuries on the ecology of marine fish populations is not hampered by the lack of mechanistic understanding, because injuries in other species are rare (<=1%).

WGELECTRA 2018 noted the need for large-scale and long-term field experiments to investigate the effects of pulse trawling. The lack of clear evidence of adverse effects of the pulse stimulus used in the pulse fishery for sole in combination with the low exposure probability makes it unlikely that the exposure to electrical pulse of the pulse trawl fleet will have a measurable long-term effect on populations of fish and the functioning of the benthic ecosystem.

14.4.2 Sub-lethal effects

Knowledge on the potential detrimental effects on egg or larval phases on the reproductive success of the adult brood stock was noted as a knowledge gap. Although no additional experiments have been undertaken, the analysis of the probability of exposure presented in the current report 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.

The low exposure probability in combination with the short duration makes it unlikely that pulse exposure will weaken the physiological condition or immune system rendering the organisms more susceptible to infections or noxious agents.

14.4.3 Behaviour and long term effects

Although there are no experimental studies on the effect of long-term exposure, the low exposure frequency and short (1.5 s) duration of a pulse exposure suggest 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.

14.4.4 Population and ecosystem consequences

The knowledge gap of the impact of pulse trawling on the benthic ecosystem functioning has been closed 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 an additional measurable effect.

Population movement

The laboratory experiments of the response of fish to a pulse exposure do not suggest that fish may detect the pulse field when they are outside of the trawl track. Although electrophysiological knowledge learns that fish may be attracted or dispelled by an electric field, this response is observed when fish are exposed to a direct current, such as used in fresh water electro fishing, but not to the pulsed bipolar current applied in pulse trawling for sole.

Effect on sole stock of change in effort distribution

The shift in the distribution of the sole fishery during the transition period to the southwestern parts of the North Sea, coincides with the changes in distribution of sole observed in the beam trawl survey, and the increase in abundance during the study period. Hence, it is unlikely that the change in distribution is due to the possibility to deploy the lighter pulse trawls in softer sediments. The expansion of pulse fishing into certain throughs in the southern North Sea is not supported by the detailed analysis of VMS fishing positions although confirmed by several pulse fishers (Steins, 2020). It cannot be excluded, therefore, that previous unfished grounds may have acted as refugia for the local sole stock. It is currently unknown how large these areas have been and how much effort has been involved.

North Sea sole is composed of several sub-populations, each of them with a distinct spawning ground and nursery ground (Rijnsdorp et al., 1992; Diopere et al., 2018). The recruitment dynamics of the sub-populations is likely to be unrelated because of the relatively short distance over which the spawning grounds are connected to their nursery grounds. Above average recruitment to a sub-population may affect the local abundance which may temporarily increase or decrease (De Veen, 1996). We expect that the fishing fleet will follow changes in the availability of their target species. The increase in fishing pressure in the southern North Sea observed during the transition period is related to an above average recruitment of the sub-population spawning in the Thames estuary and off the Belgian coast. It is likely that the spatial distribution of the recruitment patterns will change in future.

14.5 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 summarising 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 (Steins, 2018). In a desk study, the catch rate of gill net and hand line 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 seabass the decline in catch rates of the small scale fishers is likely related to the decrease in stock size (Rijnsdorp et al., 2018).

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 gill net fishery. Gill nett fishers suggested another mechanism that may explain the decline in their catch rate. A mechanism suggested by gill net 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.

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 minimise 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 up to 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 of all times (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. For example, a conflict that arose when Dutch pulse fishers moved into a fishing ground of English fishers off the Thames estuary was solved by an agreement between the fisheries organisations that the Dutch pulse trawlers would voluntarily leave the area.

15 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2021. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

Furthermore, the chemical laboratory at IJmuiden has EN-ISO/IEC 17025:2017 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2021 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation. The chemical laboratory at IJmuiden has thus demonstrated its ability to provide valid results according a technically competent manner and to work according to the ISO 17025 standard. The scope (L097) of de accredited analytical methods can be found at the website of the Council for Accreditation (www.rva.nl).

On the basis of this accreditation, the quality characteristic Q is awarded to the results of those components which are incorporated in the scope, provided they comply with all quality requirements. The quality characteristic Q is stated in the tables with the results. If, the quality characteristic Q is not mentioned, the reason why is explained.

The quality of the test methods is ensured in various ways. The accuracy of the analysis is regularly assessed by participation in inter-laboratory performance studies including those organized by QUASIMEME. If no inter-laboratory study is available, a second-level control is performed. In addition, a first-level control is performed for each series of measurements.

In addition to the line controls the following general quality controls are carried out:

- Blank research.
- Recovery.
- Internal standard
- Injection standard.
- Sensitivity.

The above controls are described in Wageningen Marine Research working instruction ISW 2.10.2.105. If desired, information regarding the performance characteristics of the analytical methods is available at the chemical laboratory at IJmuiden.

If the quality cannot be guaranteed, appropriate measures are taken.

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Justification

Report C037/20

Project Number: 4314100010

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

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Appendix 1. Catch and effort data and methods applied

Catch and effort

Two data sets of catch and effort (landings by species, hours at sea, ICES rectangle, gear, mesh size, vessel ID, landing date) by fishing trip of Dutch flagged vessels were extracted from the VISSTAT data base of mandatory logbooks for the period 2009 – 2017. Set 1 comprises all fishing trips of vessels that have reported to use a beam trawl gear (TBB) targeting flatfish. Set 2 comprises the data from a subset of vessels referred to as the set of pulse license holders (PLH). A maximum of 74 pulse trawlers have been active at the same time. Because a separate code for pulse trawl fishing trips (PLH_pulse) was not available for the full study period, pulse fishing trips were identified based on the reported mesh size (70-99mm), mean towing speed during fishing, and the start date of the pulse license (data LNV).

VMS

Vessel speed and vessel positions of all beam trawl vessels were available from the Vessel Monitoring by Satellite (VMS) program. Vessel speeds typically show a three modal frequency distribution which allows us to distinguish the fishing positions from the positions during steaming or during floating (Hintzen et al., 2012; Poos et al., 2013). The swept area was estimated by 1 minute latitude x 1 minute longitude grid cells from interpolated fishing tracks given the VMS fishing positions (Hintzen et al., 2012).

Habitat variables

Habitat variables (%gravel, %mud) were obtained for 1x1 minute grid cells from (Wilson et al., 2018). Tidal bed shear stress (N.m-2) was obtained from a hydrodynamic model by John Aldridge (CEFAS) as used in (Hiddink et al., 2006) and (van Denderen et al., 2015b).

Footprint and trawling intensity

VMS fishing positions were interpolated to estimate the swept area by 1x1 minute grid cell longitude and latitude (Hintzen et al., 2010) and the trawling intensity is expressed by the swept area ratio. The grid cell resolution corresponds to approx. 1.9 km2 at 56° N with cell size gradually increasing/decreasing the further south/north it is located. At this resolution bottom trawling can be considered to be randomly distributed within a grid cell on an annual basis (Rijnsdorp et al., 1998; Lee et al., 2010; Amoroso et al., 2018) and to become uniform at longer time scales (Ellis et al., 2014).

Following (Eigaard et al., 2017), the trawling footprint was estimated as (i) the total surface area (km^2) trawled at least once a year under the assumption of a uniform distribution of trawling activities within a grid cell, and (ii) the proportion of grid cells with any trawling activity irrespective of the trawling intensity. The latter metric includes the untrawled part of fished grid cells.

Appendix 2. Scaling up to the population level and the fleet level

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 data base) 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 the 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.

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).

$$I = pm \qquad [A1]$$

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:

$$p = \sum_{i=1}^{n} b_i f_i / \sum_{i=1}^{n} f_i \qquad [A2]$$

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).

$$t_i = wuh_i / s_i \qquad [A3]$$

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 [A4]

$w = (n-1)d + 2e$ if e>= half the distance between electrodes [A5]

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 assuming that all fish will be retained. The same equation can be used to estimate the proportion of the population that will be exposed to a beam trawl.

$$F = \sum_{i}^{n} \left(q b_i t_i \frac{w}{W} \right) \qquad [A6]$$

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.

Cohort analysis

The population dynamic consequences of pulse exposure were investigated by applying a length based cohort analysis (Jennings et al., 2001). The length based cohort methodology describes how the numbers and biomass of a cohort changes due to natural and fishing mortality. The stage duration of each size class is given by the von Bertalanffy growth equation and modelled in steps of 1 cm. Duration of size class i with length L_i

$$d_i = \frac{1}{K} ln\left(\frac{Linf - Li}{Linf - L(i+1)}\right) \qquad [A7]$$

The proportion mature fish of size class i with length L_i is given by,

$$p_i = exp((a_{mat} + b_{mat}Li))/(1 + exp((a_{mat} + b_{mat}Li))\ ) \qquad [A8]$$

Weight is given by the length-weight relationship,

$$W = aL^b \qquad [A9]$$

The proportion of fish retained in the gear is given by

$$r \quad = \exp(a_m + b_m L)\ /(1 + \exp(a_m + b_m L)) \qquad [A10]$$

The minimum landing size (MLS) determines the size classes of the discards and landings.

The number of fish at each size class i is given by

$$N_{i+1} = N_i \exp(-(M_i + F_i)d_i) \qquad [A11]$$

where F_i and M_i are the fishing and natural mortality rates of size class i.

Given a vector of fishing and natural mortality rates and a number of recruits of 1, the corresponding yield and spawning stock biomass can be calculated

$$Y = \sum_i^n (r_i N_i W_i) \qquad [A12]$$

$$S = \sum_i^n (p_i N_i W_i) \qquad [A13]$$

Coefficients of the model parameters are presented in Table A1. 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.

Table A1. Input parameters for the cohort analysis

	Cod		Sole	
	Coefficient	Source	Coefficient	Source
Growth				
K	0.3	Daan (1974)	0.263	Rijnsdorp et al (2012)
Linf	110		42.9	
t0	0.7		0.03	
Weight-length relationship				
a	6.80E-06	Daan (1974)	3.22E-03	Rijnsdorp et al (2012)
b	3.1		3.293	
Maturity ogive				
a_{mat}	-33	Oosthuizen and Daan (1974)	-22.194	Rijnsdorp et al (2012)
b_{mat}	0.6		0.925	
Mesh selection				
sf	2.4	Reeves et al. (1992)	2.9	ICES (2018)
sr	1.4		4.2	
Minimum landing size				
MLS	35		24	

Appendix 3. 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

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