Request from the Netherlands regarding the impacts of pulse trawling on the ecosystem and environment from the sole (*Solea solea*) fishery in the North Sea

Advice summary

ICES advises that the change from conventional beam trawling to pulse trawling when exploiting the total allowable catch of North Sea sole contributes to reducing the ecosystem/environmental impacts of the sole fishery.

ICES advice analyses the ecosystem/environmental effects of the pulse trawl sole fishery on North Sea ecosystems. However, the advice does not consider other forms of electrical fishing, such as those for brown shrimp (*Crangon crangon*) or razorshells (*Ensis arcuatus*), nor does it consider pulse fisheries in other ecosystems.

Provided that the sole stock is well-managed, ICES advises that pulse trawling does not impose any increased risk to its sustainable exploitation.

ICES advises that the direct impact of the electrical pulse on marine organisms does not increase mortality compared to that of conventional beam trawling (other than being caught in a fishery). Cod (*Gadus morhua*) is known to be an exception; however, the increase in overall mortality due to pulse trawling is negligible for the North Sea cod stock, and small (< 2%) for the cod stock components in the southern North Sea. Despite the uncertainty regarding the physiological impacts to marine organisms not caught in the fishery, pulse trawling is not expected to affect the reproductive potential of these populations, given the low probability of exposure to pulse stimuli.

ICES advises that pulse fishing reduces the bycatch of most undersized fish and of benthic invertebrates, and reduces the disturbance of the seafloor and the impact on the benthic ecosystem. It also reduces use of fuel and associated CO2 emissions as compared to conventional beam trawling.

ICES further advises that the documented effects of pulse trawling on the benthic ecosystem are consequences of mechanical disturbance rather than electrical pulses. Furthermore, the effect of mechanical disturbance is less pronounced because of the smaller area that is trawled by the pulse gear, the reduced penetration into the seabed, and the reduced resuspension of sediments as compared to conventional beam trawling.

ICES advises that the change from conventional beam trawling to pulse trawling does not increase, and in some cases may reduce pressure on Natura 2000 habitats and species.

Request

ICES is requested to provide advice on the possible contribution of pulse trawling to reduce or increase the ecosystem/environmental impacts of the fishery for sole in the North Sea in light of the elements listed in article 31(1) of regulation (EU)2019/1241 of 20 June 2019, namely: marine ecosystems (including the long-term effects on), sensitive habitats and selectivity.

Furthermore, ICES is requested to reflect on the fuel consumption used in the fishery for sole in the North Sea, taking into consideration the discussions within the FAO[1] *on the issue of CO_2 emissions in fisheries*.

[1] The issue of fuel consumption in fisheries and its impact on climate change has been discussed in multiple sessions of the Committee on Fisheries (FAO) and addressed in the 2009 FAO Climate Change Technical Paper (FAO Fisheries and Aquaculture Technical Paper No. 530) and its subsequent update 2018 FAO Climate Change Technical Paper. See http://www.fao.org/3/i9705en/i9705en.pdf, in particular chapter 27

Elaboration on the advice

The present advice analyses the ecosystem/environmental effects of the pulse trawl sole fishery on soft sediment North Sea ecosystems, it does not consider other forms of electrical fishing, such as for brown shrimp or razorshells.

The sole fishery in the North Sea comprises directed mobile gear (90% beam trawl, including pulse gear), 8% static gear (gill and trammel nets) and 2% other gears. In 2018, at least 75% of the total sole landings were caught by pulse gear.

In response to this request, ICES evaluated the contribution of pulse trawling in the sole fishery to either reduce or increase the ecosystem/environmental impacts of the sole fishery in the North Sea by comparing it to conventional beam trawling with tickler chains or chain mats, which, prior to the changeover, was the dominant gear used to exploit the sole quota in the North Sea. The advice does not consider other gears such as gill and trammel nets, which have smaller impacts on benthic ecosystems. This approach follows the comparison made by ICES in its previous advice on pulse fishing (ICES, 2018a). The phrase 'sole fishery' is used in the remainder of this advice to refer to the mobile gears used for fishing sole, such as conventional beam trawl and pulse trawl.

The ecosystem / environmental impacts are assessed by considering: the target stock(s), the bycatch, the impact on the seafloor (and life within), and ongoing developments with both conventional and pulse gear (see Additional information in the Methods section below). Owing to the lack of long-term field experiments, the direct possible harm, consequences, and long-term implications of pulse trawling in the North Sea are evaluated based on data and information covering the past ten years of pulse trawling.

Fuel consumption is used as a proxy for CO2 emissions and the reduction percentages provide an estimate of the reduction in CO2 emissions that can be achieved when using the pulse trawl as opposed to conventional beam trawl in the sole fishery.
ICES notes that field and laboratory studies have focused on those dominant components of the demersal and benthic ecosystem that are most likely to be impacted. Not all species or ecosystem components have been studied for pulse gear impacts. However, serious impacts on population or ecosystem components are considered unlikely to be larger than any impacts reported below.

1) Direct harm and long-term adverse consequences to marine organisms caused by exposure to a commercial pulse stimulus.

Exposure to the pulse stimuli used in the North Sea sole fishery may cause spinal injuries in a small percentage of exposed animals. For most fish species, the probability of injury is low (≤ 1%), except for cod (in size range 15–90 cm), where approximately 35% of the animals sampled show spinal injuries.

The ecological and population level consequences are assessed to be negligible because of low exposure rates. Pulse trawling is unlikely to affect electroreceptive species, because the pulse frequency used in pulse trawling is outside the range electroreceptive species are sensitive to. Following exposure to pulse-trawl stimuli, no adverse effects (mortality or lesions) were found in the ten benthic invertebrate species studied. These animals exhibited normal behaviour less than one hour after exposure, making any ecological effect unlikely.

The low probability of exposure and the short duration (1.5 seconds) implies that there is no chronic exposure to pulse trawl stimuli. Population level consequences of non-lethal exposures were negligible for the studied species. Similar or higher injury rates were observed in fish encountering conventional beam trawl.

2) Risk to the sustainable exploitation of sole from pulse trawling.

Provided the stock is well managed, pulse trawling does not impose any additional risk to the sustainable exploitation of sole in the North Sea. It is highly unlikely that pulse trawl stimuli will inflict additional mortality (other than being caught in a fishery) or compromise the reproductive capacity of sole that are exposed to pulse trawling, but escape capture. Fishing effort redistribution (Figure 1) has occurred in the sole fishing area in the North Sea, and there are no indications of a reduction in recruitment. ICES provides advice for fishing opportunities under the assumption that there is a single sole stock in the North Sea, and this advice is consistent with that approach.

3) The effect of pulse trawling on the selectivity of the sole fishery, discarding of fish, and on benthic invertebrates.

Pulse trawling improves the selectivity of the sole fishery by reducing the proportion of other fish species that are caught, and by reducing the bycatch of undersized fish for most fish species (discards, prior to implementation of the

EU landing obligation) and benthic invertebrates. The possible exceptions are sole and whiting (*Merlangius merlangus*), where some discard data suggest catch efficiency may be higher than with conventional beam trawl.

4) The effect of pulse trawling on the benthic ecosystem of the sole fishery.

Pulse trawling substantially reduces the impact on the benthic ecosystem in comparison to conventional beam trawling. The impact of pulse trawling on the benthic ecosystem is limited to the mechanical disturbance, which is reduced because less surface area is trawled at least once per year, reduced penetration into the seabed and reduced resuspension of sediments.

5) The impact of pulse trawling on sensitive habitats and threatened species / ecosystems.

Pulse trawling takes place along with beam trawling and other bottom trawling activities in the southern North Sea. Although no specific experiments have been carried out to study the impact of pulse trawling on Natura 2000 protected species, the available knowledge indicates that adverse impacts are unlikely and are reduced compared to conventional beaming trawling. This is because the probability of exposure is likely to be (very) low, and the overall area trawled at least once per year by the pulse fishery has been reduced compared to conventional beam trawling. Therefore, if sensitive seafloor habitats are trawled, then the expected impact from pulse trawling will be smaller compared to conventional beam trawling.

6) The effect of pulse trawling on CO_2 emissions of the sole fishery.

Pulse trawling reduced the estimated fuel consumption by at least 37% compared to the conventional beam trawling setup using a sumwing (for information on sumwing see Additional information in the Methods section below). Under the assumption that CO_2 emissions are proportional to fuel consumption, the reduced percentages provide an estimate of the reduction in CO_2 emissions that can be achieved when using pulse trawl in the beam trawl fishery for sole.

Basis of the advice

The available scientific knowledge on the effect of pulse trawling for sole on a range of marine organisms and ecosystem components in the North Sea is summarised and assessed in the 2020 WGELECTRA report (ICES, 2020). The confidence classifications are explained in the Methods section.

1) Direct harm and long-term adverse consequences to marine organisms caused by exposure to a commercial pulse stimulus

Experiments exposing sole, plaice (*Pleuronectes platessa*), sea bass (*Dicentarchus labrax*), and small-spotted catshark (*Scyliorhinus canicula*) to a commercial pulse stimulus did not show evidence of direct mortality. Concerns regarding high ulcer rates in dab (*Limanda limanda*) in the southern North Sea led to experiments exposing dab to pulses; no evidence of ulcer development was found in these experiments. In a sampling of fish catches on commercial pulse vessels approximately 35% of the sampled cod showed fractures in the spine, haemal, or neural arches or associated haemorrhages, consistent with fractures observed in tank experiments. From retained cod, which ranged in size between 15 and 90 cm, the injury rate was highest in cod of around 40 cm.

A tank experiment showed a low (1%) injury rate among lesser (*Ammodytes tobianus*) and greater sandeel (*Hyperoplus lanceolatus*) exposed to pulse stimuli. In the field, higher rates of injury were recorded in samples from pulse trawl catches but injury rates were lower than in catches with conventional beam trawls and consequently unlikely to be due to pulse exposure. For other fish species, the injury rate in fish caught by pulse trawling was not higher than recorded when the pulse stimulus was switched off and often lower than in fish caught with conventional beam trawls, and never exceeded 2%

This indicates that the incidence rate of pulse-induced injuries as distinct from mechanical injuries is low (≤ 1%), (high confidence).

Pulse injured fish that are retained in the net and landed do not result in additional unaccounted mortality. Fish that pass through the electric field without being retained in the net, or are retained but subsequently discarded, contribute to unaccounted mortality. However, for all fish species studied except for cod, the injury rate is low (≤ 1%); therefore, the population level effect of pulse-induced injuries is negligible (high confidence).

For cod that pass through the gear without being retained, the exploration of the potential consequences of mortality imposed by pulse trawling indicates that the population-level effects are negligible for the North Sea population (high confidence) and, at most, the effects are small for the southern North Sea stock component (medium confidence).

Pelagic eggs and larvae have a very low probability of exposure to pulses. If there was any pulse-induced effect on pelagic eggs and larvae, the low exposure probability would mean that the population-level consequences are negligible (high confidence). Demersal eggs have a higher exposure probability than pelagic eggs, but the potential mortality imposed by pulse trawling is much lower than the rates of natural mortality, and will therefore have a negligible population-level impact (medium confidence).

Elasmobranchs lay demersal egg capsules that potentially are exposed to pulse trawls. The three species of rays inhabiting the southern North Sea are increasing in abundance and spawn in shallow waters off the English coast, where pulse trawlers are not active (medium confidence). Elasmobranchs are electroreceptive and may be particularly sensitive to pulse stimuli. However, the pulse frequency used in pulse trawling is outside the range of the sensitivity of the electroreceptors. In tank experiments, the electroreceptive small-spotted catshark did not show an impaired ability for food detection when exposed to pulse stimuli at frequencies used by pulse trawls (high confidence).

Pulse exposure with a field strength of 150–200 $V.m^{-1}$ did not result in additional mortality among ten representative species of the benthic invertebrate fauna of the southern North Sea. The species represented different ecological groups and body plans. Most animals responded to the pulse stimulus and showed an avoidance response or remained inactive for a short period after exposure. Consequently, for the species studied, the possible population level and food web effects of pulse trawling are negligible (high confidence). Because benthic invertebrates are a diverse group of species, not all body plans have been studied experimentally. Thus, these results have medium confidence for species similar to those tested. However, some groups, such as sponges and cephalopods, have not been tested.

The electric field strength quickly dissipates at increasing distance from the conductors (Figure 6). Consequently, animals located outside the path of a pulse trawl are only exposed to a low field strength (significantly lower than 5 $V.m^{-1}$). Experimental evidence shows that fish do not respond to field strength this low making it very unlikely that these animals are adversely affected (high confidence). Animals located within the trawl path are exposed to higher field strength. The field strength used in the experiments with benthic invertebrates (150–200 $V.m^{-1}$) in practice occurs only within a few centimetres of the conductor and was found to cause only non-lethal effects, such as avoidance behaviour. Since this area of higher field strength comprises only a part of the total trawl width, the probability of a single 1.5 second exposure to high field strength is lower than in the total trawl path. The low exposure probability and the short duration (1.5 s) implies that there is no chronic exposure of individual organisms to pulse stimuli. This implies that at the current level of pulse trawling, the risk of possible adverse effects later in life is very low (medium confidence).

2) Risk to the sustainable exploitation of sole from pulse trawling

Sole cramps into a U-shape when exposed to a pulse trawling stimulus, but as demonstrated above does not experience elevated rates of injury or mortality, and the proportion of sole eggs and larvae exposed to pulses is negligible at the population scale. Sole discards caught in the pulse fishery and conventional beam trawl fishery show similar mortality rates (around 73%), supporting the conclusion that the injuries and mortality are related to the mechanical catching process, rather than to the pulses.

Pulse trawls are more efficient at catching sole and are towed at a reduced speed. The 76 Dutch pulse licence holders in 2017 harvested 11 832 tonnes of sole, whereas in 2009 the same fishers caught 8016 tonnes using conventional beam trawls. The fishing effort (swept area) of these pulse licence holders, required to catch their share of the quota decreased from 2009 to 2017 by 35%.

The sole fishery is managed by a total allowable catch. During the past decade, 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 level for the North Sea stock (ICES, 2019). There is no indication of reduced recruitment after the change to pulse trawling. Recruitment is variable, with above average year classes in 2013, 2014, and 2016. Therefore, the changeover to pulse trawling has not resulted in overfishing of North Sea sole (high confidence).

The increase in fishing effort on sole in areas such as the Belgian coast and off the coast of England coincided with an increase in local abundance of sole, as shown in fishery-independent surveys. 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 from the sole fishery in this area. This localised increase in fishing effort has shown no indications of reduced recruitment, but may have consequences for competition among fleets and for fishing pressure on different sole-stock components within the North Sea.

There is no existing experimental evidence of non-lethal effects on the reproductive capacity of individual fish. However, age-structured population model estimated that about 10% of the sole that survive until the reproduction phase could pass through the electric field once without being retained in the net during the year leading up to it reaching its reproductive phase. Passing through the electric field will result in the sole being exposed for about 1.5 seconds to a field strength of > 5 $V.m^{-1}$. Repeat spawners are either retained in the gear or pass outside the trawl and are exposed to a field strength significantly lower than 5 $V.m^{-1}$. Consequently, it is unlikely that a single exposure will compromise the reproductive capacity of the stock, and the analyses indicate that multiple exposures are unlikely (medium confidence).

3) The effect of pulse trawling on the selectivity of the sole fishery, discarding of fish, and on benthic invertebrates

Pulse trawls catch more sole and fewer other total fish per fishing hour. The bycatch of most undersized fish and benthic invertebrates, in pulse trawls is estimated to be lower with the possible exception of sole and whiting. Per unit of area swept, pulse trawls have a higher catch rate of sole, a lower catch rate of plaice, and catch of other species is in proportion to the area swept (high confidence). There is conflicting information from different sources regarding catch efficiency for whiting, but some discard data suggest that catch efficiency for whiting may be higher with pulse trawl than with conventional beam trawl.

The physical condition of the plaice, turbot (*Scophthalmus maximus*), and brill (*Scophthalmus rhombus*) bycatch is generally better in pulse fisheries due to the lower towing speed and cleaner catch composition, resulting in a higher survival potential for discards compared to conventional beam trawling (medium confidence). No difference in survival potential was estimated for sole.

4) The effect on the benthic ecosystem of pulse trawling in the sole fishery

The change from conventional beam trawling to pulse trawling reduced the area trawled by the sole fishery. The replacement of tickler chains by electrodes reduced the depth of seabed disturbance of the trawl and likely reduced the mortality imposed on benthic invertebrates. The lower towing speed of the pulse trawls reduced the mobilization of sediments, and resulted in less area fished and a reduced surface area swept (high confidence).

The change to pulse trawling reduced the benthic impact by 62%, with a decrease ranging between 54% for coarse sediments to 72% for muddy sediments (high confidence). The estimated decrease in impact in muddy areas (72%) may be an overestimate, as it does not reflect anecdotal information that pulse trawling has increased in muddy parts of individual grid cells (medium confidence).

Field and laboratory experiments show that electrical pulses used in the fishery for sole had no measurable effect on geochemical processes and electrolysis. The observed geochemical effects were due to the mechanical disturbance of the sediment by the gear. Sediment mobilisation is estimated to have decreased by 39% for the total annual sole fishery, with a patchy, but on average reduced disturbance of geochemical processes. With the reduction in trawled area and fishing intensity, the geochemical impacts are less after the changeover to pulse trawling (high confidence).

5) The impact of pulse trawling on sensitive habitats and threatened species/ecosystems

Natura 2000 habitats that occur within the area fished by conventional beam-trawl and pulse-trawl fishery include sandbanks permanently covered by seawater, reefs, submarine structures leaking gases, and estuaries. Natura 2000 protected species include fish, such as sea lampreys (*Petromyzon marinus*), allis shad (*Alosa alosa*), twaite shad (*Alosa fallax*), and Atlantic salmon (*Salmo salar*); marine mammals, such as the harbour porpoise (*Phocoena phocoena*), common seal (*Phoca vitulina*), and the grey seal (*Halichoerus grypus*); and piscivorous and molluscivorous seabirds and coastal birds, such as the red-throated diver (*Gavia stellata*) and the little tern (*Sternula albifrons*). The European eel (*Anguilla anguilla)* is protected under the Eel Regulation 2007/1100/EC (EU, 2007) and its habitats must be managed in accordance with the Habitats Directive. Sharks, skates, and rays are also protected from fishing under EU 2015/104 (EU, 2015).

Adverse impacts of the changeover to pulse trawling for Natura 2000 protected mammals are considered highly unlikely (high confidence). None of the protected marine mammals are at risk of being caught in a conventional beam trawl or pulse trawl because of the low vertical net openings of approximately 70 cm and 40 cm, respectively. The low field strength outside the trawl makes any adverse effect of pulse exposure highly unlikely. Pulse trawling is more selective than beam trawls in catching sole and will therefore result in a reduced, or similar fishing pressure on other fish species (with the possible exception of whiting). No negative effect is expected on the food base of Natura 2000 protected species, given the evidence from directed studies that found negligible impacts on sand eel, one of the potentially most vulnerable prey species (medium confidence).

The same reasoning applies to the Natura 2000 protected seabirds. Many seabirds rely on pelagic fish, but the probability of exposure of pelagic fish species to pulse trawling is expected to be low, further reducing the probability of exposure to the electric field (medium confidence). This is supported by very low bycatch numbers for pelagic fish species.

Given the reduction in mechanical impact on the benthos, no or only reduced effect on the food base of mollusc-eating birds is expected. A reduction in discards may diminish the food base of scavenging species (medium confidence).

Adverse impacts of the changeover to pulse trawling on Natura 2000 protected fish species are unlikely because of the low overlap in distribution of those with the pulse trawl fishery for sole, although some may be caught incidentally (medium confidence). All anadromous Natura 2000 protected fish species are not typically found near the seabed during the marine phase of their life histories; they are therefore unlikely to encounter pulse fishing gears. Shads are pelagic fish, which reduces the probability of this species being caught in a beam or pulse trawl towed on the seafloor.

European eels and sturgeon *(Acipenser sturio)* pass through parts of the southern North Sea and along with lampreys, are demersal. None of these species have been reported in the monitoring of pulse trawl catches.

All North Sea ray and skate stocks are managed through a generic multi-species TAC, together with additional measures for depleted species (ICES, 2018a). The thornback (*Raja clavata*), blonde (*Raja brachyuran*), and spotted (*Aetobatus narinari*) rays are the most abundant ray species in the southern North Sea, and their distribution overlaps with pulse trawling. These three species show an increase in stock development in recent years (ICES, 2018b). The nursery areas of these species are typically in shallow waters, outside the pulse trawl fishery area and therefore, any adverse effect of pulse trawling on these species is unlikely (medium confidence).

There are multiple Special Areas of Conservation (SAC) within the pulse trawling zone, designated for a number of reasons, including protected habitats. No adverse effect of electrical stimulation was found on geochemical processes in sediments, and in the area trawled, benthic impacts and sediment mobilisation are all reduced. Although a change in the spatial distribution of effort and catches was observed during the changeover period, the decrease in benthic impact was found for the main seafloor 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 (medium confidence).

6) The effect of pulse trawling on CO_2 emissions of the sole fishery

Pulse trawling reduced the estimated fuel consumption by at least 37% compared to conventional beam trawling setup using a sumwing. The reduction is higher (52%) when expressed relative to the share of the sole quota, and lower (22%) when expressed relative to the weight of all fish landings. The reduction is also higher when compared to conventional beam trawl with shoes (47%). Under the assumption that CO_2 emissions are proportional to fuel consumption, the reduction percentages provide an estimate of the decrease in CO_2 emissions that can be achieved when using pulse trawl in the beam trawl fishery for sole (medium confidence).

Methods

The ecological and environmental impact of pulse trawling in the North Sea sole fishery is assessed using a quantitative approach that takes into account the effects of electrical stimulation and mechanical disturbance. The effects of pulse trawling are compared to the effect of conventional beam trawling, which is the dominant gear used to exploit the sole quota. The effects are assessed for a number of properties (Table 1) that are relevant to address the request for the present advice. It addresses concerns related to the potential adverse effects of pulse fishing on the marine environment and general concerns about the adverse effects of bottom trawls.

The scientific knowledge on the effect of pulse exposure on marine organisms and the benthic ecosystem is reviewed, and the validity of the scientific support is assessed as high confidence, medium confidence, and low confidence. The scientific knowledge is classified high confidence when strong experimental and/or observational evidence is available. It is classified as medium confidence when only limited experimental and/or observational support exist. The scientific evidence is classified as low confidence when little empirical evidence exists, but there is a mechanistic understanding about a causal chain of steps that suggests a conclusion.

The effects are scaled up from the level of the individual trawls to the level of the fleet, population and ecosystem by estimating the effect of the pulse license holders fishing for sole in the sole fishing area of the North Sea. The sole fishing area is in the southern and central North Sea 51°N in the south and 55°N west of 5°E, or 56°N west of 5°E in the north (Figure 1). In this area, fishing for sole is permitted with 80 mm codends. Dutch pulse license holders harvested 95% of all Dutch sole landings in 2017 after their switch to pulse trawling, as compared to 73% in 2009, when fishing was carried out with conventional beam trawls. Hence, comparing the ecological and environmental impact in 2009 and 2017 provides information on the change in impact of the switch from tickler chain beam trawling to pulse trawling at the level of the total fleet.

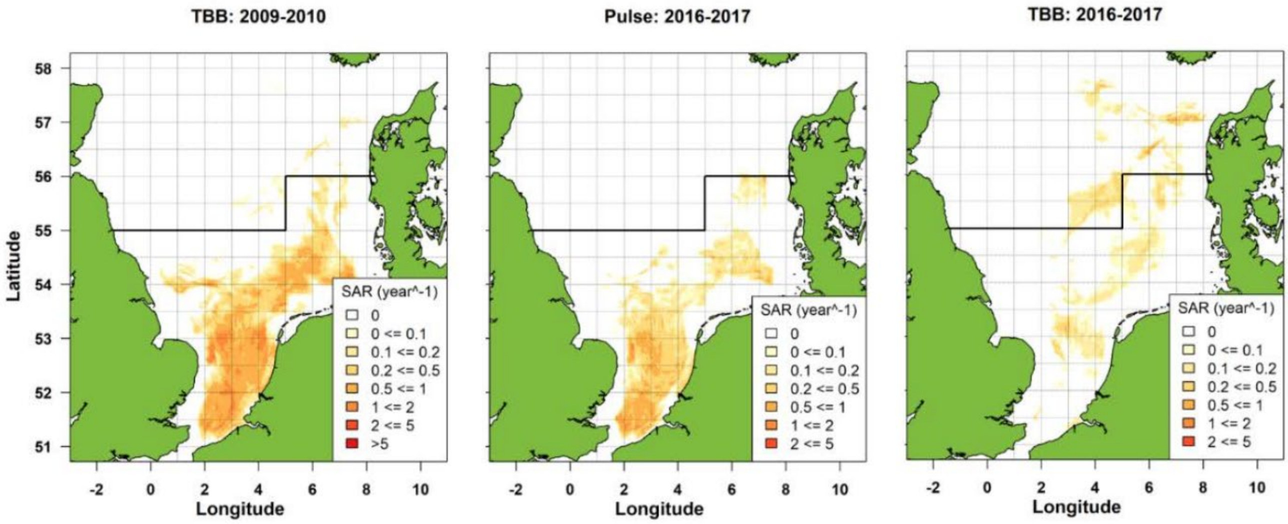

Figure 1 Annual swept-area ratio (SAR) by grid cell of (left) the tickler chain beam trawl before the changeover (2009–2010), (middle) the pulse trawl, and (right) the tickler chain beam trawl after the changeover (2016–2017). The horizontal line at 55°N west of 5°E and 56°N east of 5°E separates the sole fishing area to the south (minimum codend mesh size = 80 mm) and the plaice fishing area to the north (minimum codend mesh size = 100 mm).

A crucial step in the upscaling is the calculation of the exposure probability, which estimates the proportion of a population that is exposed to a pulse stimulus above the threshold field strength where exposure might result in an adverse effect. If an organism at a certain life history stage does not encounter a pulse stimulus, the impact of pulse fishing will be absent. If the whole population is exposed, the population-level effect may still be important, even though experiments have shown only a modest adverse effect. Similar to the assessment of the direct effects on individuals, the confidence of the upscaled effect is classified as high, medium, or low.

The exposure probability of the population is estimated by overlaying the map of the estimated trawling intensity of the pulse license holders with the map of the distribution of the marine organism or benthic habitat. The effective width of the electric field used in the estimation is taken as the physical width of the gear, which was found to coincide with the threshold field strength of approximately 5 $V.m^{-1}$ (the field strength at which fish were found to respond). Animals located within the trawl path are exposed to higher field strength (Figure 6), and are also at risk of mechanical impacts.

Given the observed pulse-trawling intensities in 2017 at a resolution of 1-minute latitude × 1-minute longitude grid cells (about 2 km^2), and assuming a random distribution of trawling events within each grid cell, the surface area trawled at least once per year by the pulse trawl was estimated to be 34 000 km^2 of the seafloor. Of the proportion of the sole fishing areas actually exposed to pulse trawling, Figure 2 shows the proportion that is exposed 1 to 10 times during a year to a pulse stimulus of 1.5 seconds and field strength >5 $V.m^{-1}$.

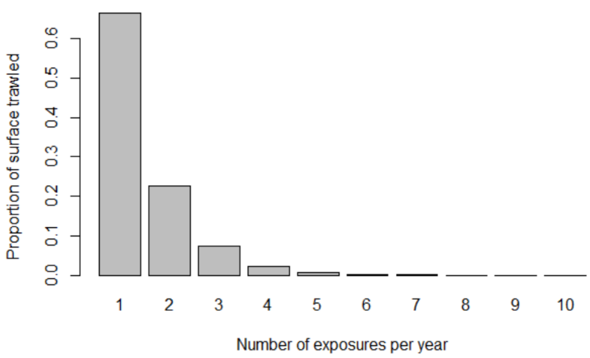

Figure 2 The proportion of the sole fishing area with pulse trawling that is exposed 1 to 10 times per year to a pulse stimulus lasting 1.5 s and with a field strength of > 5 $V.m^{-1}$.

The consequences on the benthic ecosystem from the change to pulse trawling were assessed using an impact assessment methodology adopted by ICES (ICES, 2017). The impact was assessed at the scale of 1-minute longitude × 1-minute latitude (grid cell of approximately 2 km^2).

Table 1 List of properties used to assess the ecological and environmental impact of the pulse fishery for sole.

Ecological and environmental impact	List of properties for assessing the impact
Sustainable exploitation of the target species (sole)	Catch efficiency of the target species (landings)
	Catch efficiency of commercial bycatch (landings), such as plaice
	Size selectivity of sole and plaice
	Catch efficiency discards
	Bycatch (invertebrates)
	Discard survival
	Risk of overfishing sole
	Risk of overfishing non-target species
Adverse effects of the pulse stimulus on target and non-target teleost and elasmobranchs that are exposed to the gear, but not retained	Mortality
	Injuries
	Mortality on egg and larval stages
	Feeding
	Reproduction
	Attraction/repulsion
Effects of pulse stimulus on benthic invertebrates	Mortality
	Non-lethal effects
Effects of mechanical disturbance on benthic invertebrates	Mortality
	Structure and functioning of the benthic ecosystem
	Mechanical disturbance in the seabed
	Resuspension of the sediment
	Benthic community composition
	Benthic biomass
	Biogeochemistry
Other impacts	Electrolysis
	CO_2 emissions

Additional information

Conventional beam trawls for flatfish

A beam trawl is a demersal trawl whose horizontal spread during trawling is maintained by a horizontal beam across the net mouth, supported at both sides by beam trawl shoes, maintaining the vertical spread. To this steel structure, a conical net is attached to V-shaped net opening, rigged with tickler chains or a chain matrix to startle the target species (Figure 3).

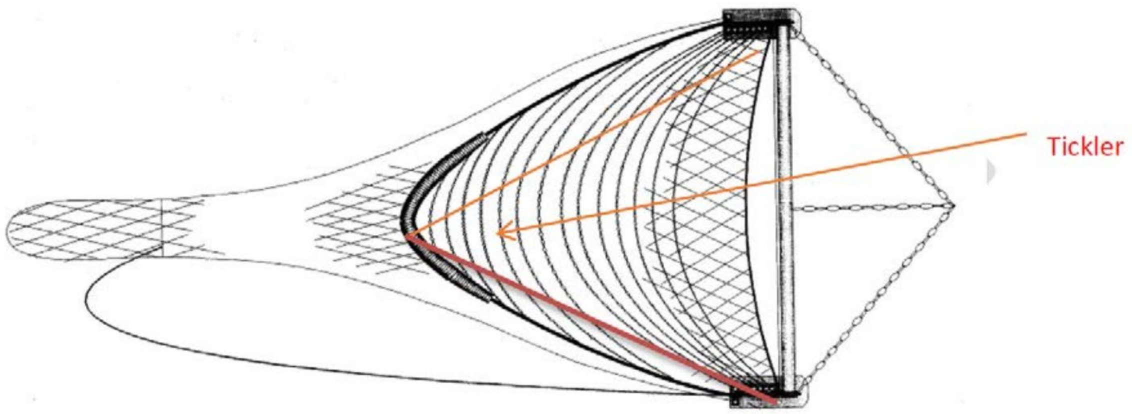

Figure 3 Schematic of conventional beam trawl with shoes.

Another type of conventional beam trawl (sumwing) uses a wing to fix the horizontal net opening, with the tickler chains attached to the tips of the wing. The wing improves the streamline and reduces fuel consumption. A nose is attached in the centre of the wing that follows the seafloor to maintain the position of the wing just above the seafloor. The sumwing has replaced the conventional beam trawl with shoes in the Dutch fleet since its introduction in 2008.

Pulse trawls used for fishing for sole

A pulse trawl is a demersal trawl with a net opening rigged with electrodes, generating an electric pulse field that causes a cramp response in the target species. The sole pulse trawl used in the North Sea is a demersal trawl, where the horizontal spread during trawling is maintained by a horizontal beam or wing across the net mouth. This is supported at both sides by beam-trawl shoes or centrally by a nose, maintaining the vertical spread. To this steel structure, a conical net is attached with a square net opening, rigged with electrodes, which stretch from the beam or wing to the ground rope and are spaced at regular intervals. A disc-protected rope is rigged alongside each electrode to take the tension during fishing.

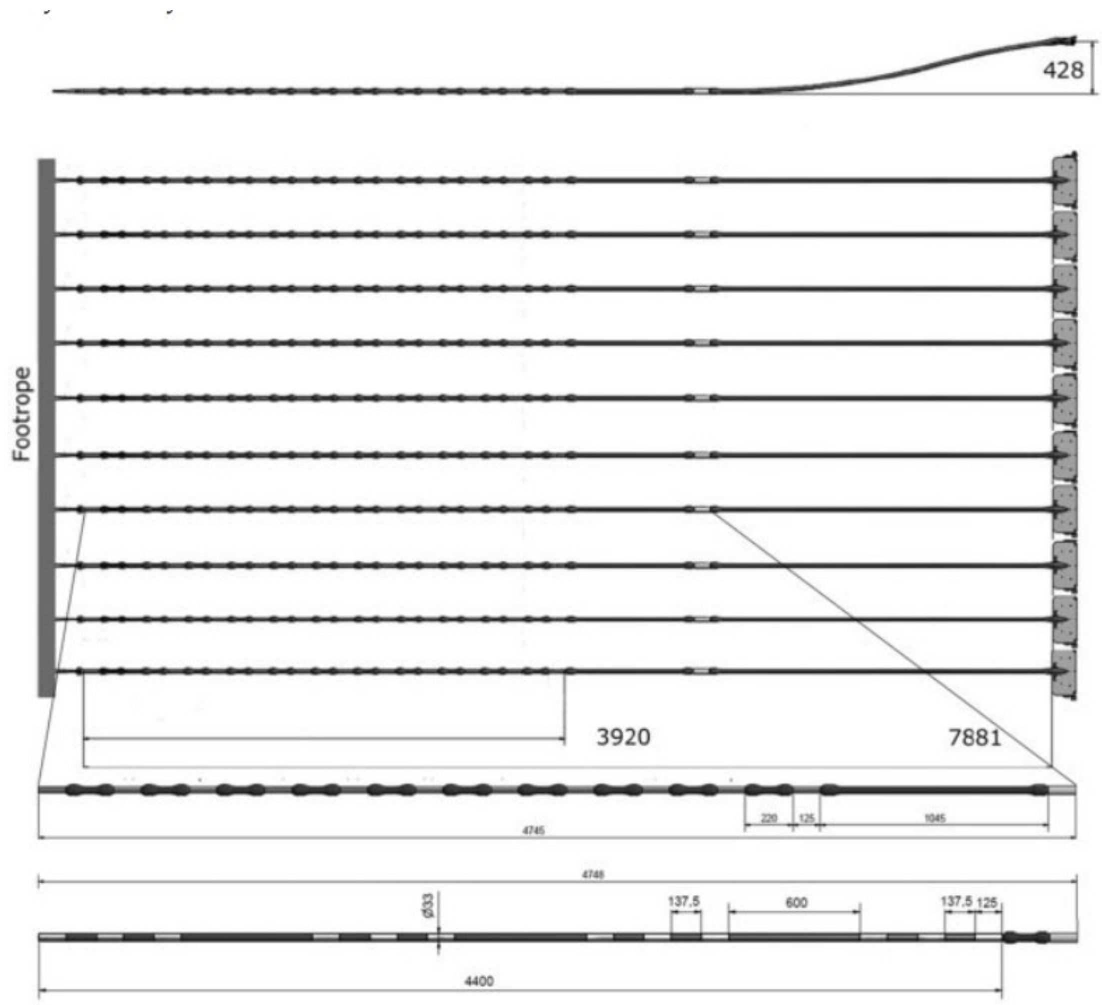

Figure 4 Schematic representation (in mm) of the ten 7.881 m long electrode arrays of a 4.5 m beam-pulse wing used in electrotrawls, targeting common sole with a close-up of two possible electrode array types (from HFK Engineering B.V.). The white or grey conductive parts are made of stainless steel or copper, respectively, and are called electrodes, whereas the longer black parts are non-conductive and called insulators or insulated parts.

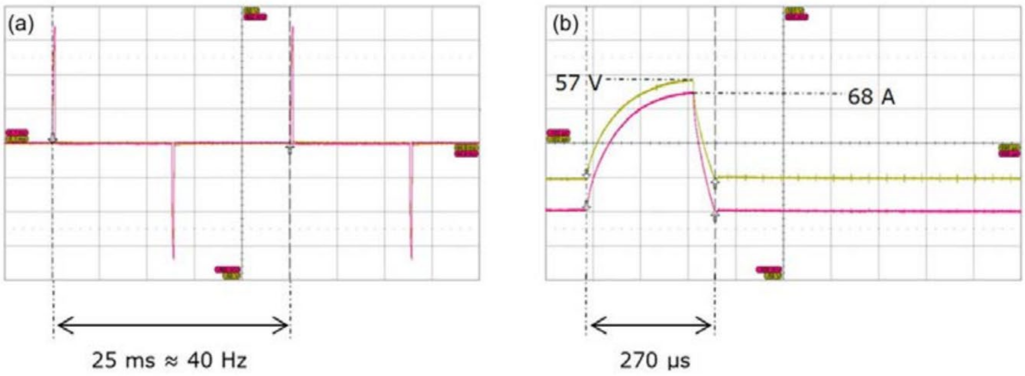

Figure 5 Schematic representation of a pulsed bipolar current (PBC) as used in the pulse fishery for sole (from de Haan *et al.*, 2016).

Pulse characteristics

Two commercial pulse systems are used in the fishery for sole, the Delmeco system and the HFK system. Both systems use a pulsed bipolar current (Figure 5), emitted by longitudinal electrode arrays between the beam/wing and ground rope (Figure 4). A description of the electrode arrays is given in the WGELECTRA report (ICES, 2020). The number and configuration of the electrode arrays varies in relation to gear width and the type of rigging of the net. The typical 4.5 m gear width used by Euro-cutters within the 12 nm zone comprises ten electrode arrays. The typical 12 m gear, which is used outside of the 12 nm zone, comprises between 24 and 28 electrode arrays. Further technical details are available in the WGELECTRA report (ICES, 2020).

The pulse trawl creates a heterogeneous field strength with the highest field strength observed close to the electrodes. 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 and the seabed 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 instance, the presence of fish or other organisms will alter the field. Electric fields inside the fish deviate substantially from those surrounding the fish (Figure 6). Flatfish buried in the sediment are less susceptible to electrical pulses because of reduced conductivity of the sediment.

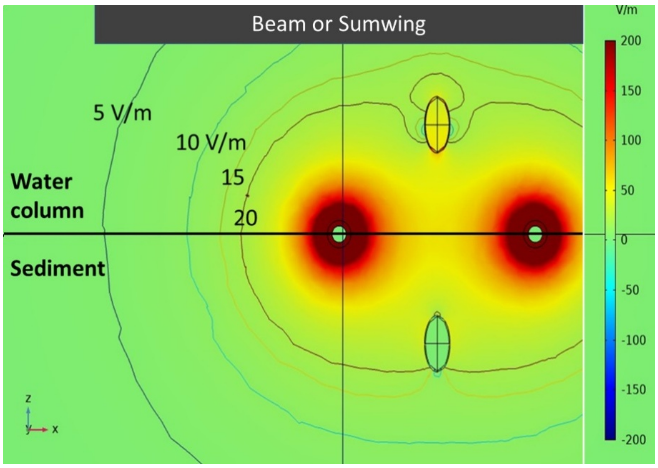

Figure 6 Cross section of the field strength (V.m^{-1}) around the outermost pair of electrodes of a pulse trawl in the vertical plane. Within the trawl path, indicated by the horizontal bar representing the beam or sumwing, the field strength ranges between approximately 5 V.m^{-1} to > 200 V.m^{-1}. Outside the trawl, the field strength is < 5 V.m^{-1}. The ellipsoids, drawn in between the electrodes, show the field strength inside a fish in the water column and in the sediment. The distance between the centre of the electrodes is 41.5 cm (enhanced from the WGELECTRA report [ICES, 2020], to indicate the fish in the water column and sediment).

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Recommended citation: ICES. 2020. Request of the Netherlands on the ecosystem and environmental impacts of pulse trawling for the sole (*Solea solea*) fishery in the North Sea. *In* Report of the ICES Advisory Committee, 2020. ICES Advice 2020, sr.2020.03. https://doi.org/10.17895/ices.advice.6020.