FISH and FISHERIES

Electrotrawling: a promising alternative fishing technique warranting further exploration

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Abstract

In trawl fisheries, beam trawls with tickler chains, chain mats or bobbin ropes are used to target flatfish or shrimp. High fuel consumption, seabed disturbance and high discard rates are well-known disadvantages of this fishing technique. These shortcomings are increasingly gaining international public and political attention, especially with the upcoming discard ban in Europe. The most promising alternative fishing technique meeting both the fisherman's aspirations, and the need for ecological progress is pulse fishing with electrotrawls. Here, the mechanical stimulation by tickler chains or bobbins is replaced by electrical stimulation resulting in reduced bottom contact, fuel costs and discards. Although a significant amount of research has been done on electrotrawls and their impact on marine organisms, most data were published in very diverse sources ranging from local non-peer-reviewed reports with a limited distribution to highly consulted international peer-reviewed journals. Therefore, there is a clear need for a comprehensive yet concise and critical overview, covering and summarizing all these data and making these available for the scientific community. This article aims to meet the above goals by discussing the working principle of electric fields, the history of electrotrawls and their current application in the North Sea and impact on marine organisms. It is concluded by elaborating on the opportunities and challenges for the further implementation of this alternative fishing technique.

Keywords Discard reduction, electrofishing, impact, North Sea, pulse trawling, seabed disturbance

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Received 14 Dec 2012
Accepted 10 Jun 2013

DOI: 10.1111/faf.12047

Introduction

Preoccupations on the potential negative effects of trawling on the seabed have existed almost as long as the fishing method itself, with early concerns being voiced by fishermen themselves dating back to the 14th century (Hovart 1985). These concerns are increasingly gaining international public and political attention (Linnane *et al.* 2000); especially, the beam trawl fishery with tickler chains targeting dover sole (*Solea solea*, Soleidae) and plaice (*Pleuronectes platessa*, Pleuronectidae) is an object of discussion due to its seafloor disturbance and the by-catch of benthic organisms (Lindeboom and de Groot 1998; Bergman and Van Santbrink 2000; Jennings *et al.* 2001; European Commission 2011). Apart from direct physical disruption such as scraping, ploughing or resuspension of the sediment (Jones 1992; Fonteyne *et al.* 1998), the bottom disturbance renders disturbed and damaged invertebrates susceptible to predation, while colonies rooted in the sand are dislodged (Rabaut *et al.* 2007).

Beam trawling is typically a mixed fishery, targeting different species at once and therefore often characterized by poor selectivity. This results in large amounts of by-catch, which is mainly discarded because it comprises undersized fish or non-marketable species. In its new policy for 2013, the European Commission has selected beam trawling as one of the first fisheries to implement the discard ban and for which unwanted by-catch should be reduced (European Commission 2011). The fact that, for example, shrimp beam trawling is carried out in vulnerable areas like coastal zones and estuaries, often important nurseries for a wide range of marine species, intensifies the problem. Discarding of young fish can have a significant influence on the commercial fish stocks because the limited survival rates results in a loss of potential growth and contribution to stock replacement (Van Beek *et al.* 1990; Van Beek 1998; Revill *et al.* 1999). The direct loss of potential income through the discarding of commercial species in the North Sea has been calculated for the Dutch beam trawl and UK roundfish fishery at 70% and 42% of the total value of the annual landings, respectively (Cappell 2001). Revill *et al.* (1999) estimated that the annual lost landings arising from discarding in the North Sea brown shrimp fisheries only had an estimated market value of over 25 million euro. This indicates very well the long-term economic potential of reducing discards. A third drawback of the traditional beam trawling is its high fuel consumption: 2.5 to 4 L of gasoil is consumed for each kg fish that is caught (Den Heijer and Keus 2001; Thrane 2004; Polet *et al.* 2010), resulting in 25–50% of the landing value needed for covering its fuel costs. Paschen *et al.* (2000) calculated that 65% of the gasoil is used to drag the gear over the seafloor and through the water and that 30% of the total towing resistance is caused by the tickler chains.

A promising alternative is electrotrawls, in which the mechanical stimulation by tickler chains or bobbins is replaced by electrical stimulation with electrodes, inducing electric pulses. The removal of the tickler chains or reduction in bobbins results in reduced bottom contact, discards and fuel costs. Despite the fact that this application has been under investigation since the 1960s, the huge technical challenge, the limited knowledge in this field and legal constraints put-off the commercial breakthrough of electrotrawls until 2009. Still, many questions about ecological impact and possible side effects remain unanswered. In this article, the rise of the marine electrical fishing in the North Sea is discussed with emphasis on the recently developed commercial systems, the effects of electric pulses on marine species and the environment, and the opportunities and challenges of this alternative fishing technique for the future.

Working hypothesis of electric fields

The physiological effect of electric fields on freshwater animals has been studied extensively. The data cited in this chapter concern freshwater organisms, as this might help to concede to the lack of knowledge on the effects in marine organisms. Additional information about the generation of electric fields and their different parameters and types can be found in the Data S1.

Largely, two different approaches are adopted to explain the reactions of freshwater fish to an electric field. First of all, different authors stated that direct nerve and/or muscle excitation is the major cause for the responses of the fishes in direct current (DC) fields (Bary 1956; Lamarque 1963; Vibert 1963; Blancheteau 1967). When the sensory nerves are being stimulated, the response is possibly of a reflex nature. If the motor nerves undergo stimulation, the response is probably due to their stimulation being transmitted directly to the muscles (Bary 1956). Danyulite and Malkevicius (1967) proved that locomotory activity and swimming are controlled by the spinal cord. When the spinal cord was cut, the reactions to electric fields stopped, while removal of skin receptors or the fish brain did not have any effect. Electric stimulation of the spinal cord can hence induce a muscle response in the fish. The reaction of organisms to pulsed direct current (PDC) is more complicated, as very complex physiological processes such as chronaxies, spatial and temporal summations, synaptic delays, excitatory post-synaptic potential (EPSP) and polarity are involved (Lamarque 1967). These neurological terms refer to the time gap between the onset of a pulse and the muscle contraction, the cumulative effect of stimulating multiple neurones at once or stimulating a neurone many times in succession and (de)polarization of the post-synaptic membranes, which affect the action potential of neurones.

Second, Sharber and Black (1999) emphasized the similarities with the responses of other animals and humans subjected to electroconvulsive therapy. They stipulated that the various reactions can be seen as stages of epilepsy. Their insight originated from Delgado-Escuata (1986), stating that epileptic events were describing the physiological response of animals, even at tissue and cellular levels, to a chemical, electrical or mechanical shock on the central nervous system. Once the central nervous system is overwhelmed by the stimulus, seizures occur (Penfield and Jasper 1954). The onset of such epileptic events is frequently accompanied by myoclonic jerks, that is, simultaneous contractions of the white muscle tissue on either side of the spine (Penfield and Jasper 1954). This is important in relation to the occurrence of injuries (Sharber *et al.* 1994) and will be discussed in more detail below.

Both approaches imply that minimal stimulus intensity is needed to exceed the threshold stimulation that causes a reaction of the fish, either to excite the nerve and muscle or to give rise to an epileptic seizure. This elicits that the greatest effect will be observed when the potential difference is largest, namely when the longitudinal head-to-tail axis of the fish body is parallel to the field lines, which is perpendicular to and between the electrodes, in case of plates that generate a uniform electric field (Fig. 1) (Snyder 2003). Therefore, it is generally accepted that larger fish, with a larger potential difference over its body as illustrated in Fig. 1, will show greater reaction (Adams *et al.* 1972; Stewart 1975a; Emery 1984; Dalbey and Mcmahon 1996; Dolan and Miranda 2003). Bary (1956) found that the relationship between fish length L and the voltage V required to produce a reaction was of the form $V = aL + b$, where a and b are constants. Therefore, large fish still respond to lower field strengths than small fish. However, the sensitivity varies greatly between different species (Halsband 1967).

At low frequencies, a PDC field will frighten the fish, which as a consequence will try to swim away (startle reaction). This principle is used nowadays to catch brown shrimp (Polet *et al.* 2005a, b). Once the frequency exceeds a certain threshold value, usually around 20 Hz, the jerking movements of the muscle, induced by the electrical pulses, are succeeding so fast that the muscles are continuously stimulated and remain contracted. This summation of many individual contractions

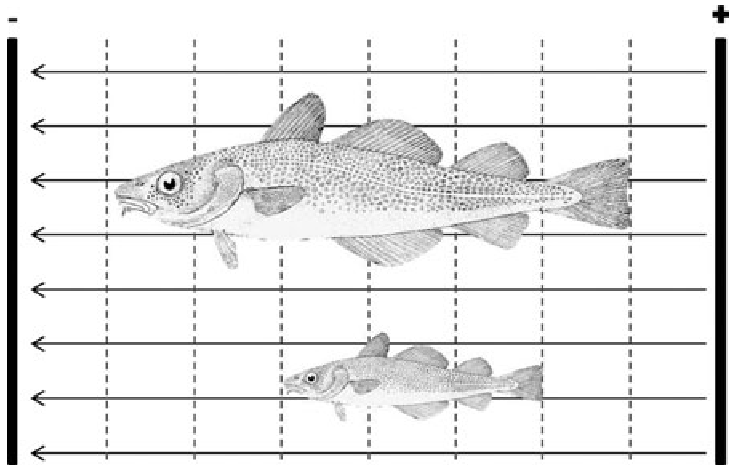

Figure 1 Draw of cod in a homogenous electric field. The heavy vertical lines represent 2 electrodes. The horizontal lines are the field lines, representing the current flow between the 2 electrodes. The dashed vertical lines are equipotentials, zones with the same potential. The larger the difference between 2 extremities of a fish (here: between head and tail), the higher the potential difference over its body and the stronger it is experiencing the electric field. For example, suppose an applied potential difference over the electrodes of 80 V that results in a potential difference between each equipotential of 10 V. In this case, the large fish will feel 60 V, whereas the small one will only feel 30 V. Note that the orientation of the fish has a marked influence on the potential difference over his body.

may lead to a cramp and immobility (Snyder 2003). This cramp reaction seems especially suitable for catching Dover sole and plaice because their powerful dorsal muscles make them bend in a U-form when going into cramp. This makes it easy to scoop the fish up with the ground rope (Van Stralen 2005).

Early developments in marine electrotrawls

Electricity has been used first time by humans to kill, anaesthetize, capture, drive, draw, tickle, guide, block or repel fish in the 1800s in freshwater (Hartley 1967; Vibert 1967; Halsband and Halsband 1984). Already in 1863, a British patent was granted to Isham Baggs for electrofishing, but the widespread development and use of electrofishing did not occur until the 1950s (Hartley 1967), when it became an important capture technique for population and community surveys in freshwater systems. Even today, it is still a common technique due to its high sampling efficiency (Growns *et al.* 1996). The first record of the use of electricity for seawater applications dates back to 1765 when the Dutchman Job Baster wrote 'Would the electricity, which shocks are so similar to those produced by the electric eel, have no effects on shrimp? To my opinion, it's worth to investigate that' (De Groot and Boonstra 1974). However, it took until 1949 before the interest in marine electrofishing was really stimulated by the successful introduction of electrofishing techniques in freshwater and experiments carried out in Germany, as reported by Houston (1949). In the subsequent years, the response of tropical marine fish (*Kuhlia sandvicensis*, Kuhliidae) (Morgan 1951; Tester 1952), sardines (*Sardinops sagax*, Clupeidae) (Groody 1952) and the pink grooved shrimp (*Penaeus duorarum*, Peneidae) (Highman 1956) to electric pulses was investigated, but also the potential application of electrified hooks for tuna, electrified harpoons for whales, electric fences with fish magnets and spherical anodes with lights and fish pumps was subjects of research (Sternin *et al.* 1976 [1972]). At that time, the aim was most often to attract the animals to the anode as is the case in freshwater, but this gradually changed when Bary (1956) stipulated that the theories used for freshwater could not be extrapolated to seawater. Additionally, pulsed current had to be used instead of DC, because of the high power demand needed due to the high conductivity of the seawater. From then on, the focus was put on a startle reaction of the target species, to make them leave the seafloor and enter the net. This would make it feasible to replace the heavy tickler chains or bobbins on conventional beam trawls with electrodes without loss in efficiency (De Groot and Boonstra 1970).

In Mc Rae and French 1965 started experimenting with electric fields as an addition to the conventional stimulation in otter trawl nets, using the field to shock the fish upon their arrival at the net so that they would be immobilized and swept easily into the trawl. This multiplied the fishing effectiveness by a factor 1.5, 1.5, 2 and 4.4 for cod (*Gadus morhua*, Gadidae), haddock (*Melanogrammus aeglefinus*, Gadidae), flatfish and whiting (*Merlangius merlangus*, Gadidae), respectively. In the USA, Pease and Seider (1967) developed a small electrotrawl (<3 V, 4–5 Hz) to catch shrimp during daylight and in clear water, when catching efficiency is normally very low. Depending on the substrate, the catches were 95–109% (muddy) to 50% (calcareous sand-shell) of the normal quantity caught at night. In Europe, this knowledge was adopted by a German group reporting a 30% catch increase (Anonymous 1969). In 1970, experiments were set up in the Netherlands with electrified nets (60 V, 2 ms, <5 Hz, 0.5 m) intended for brown shrimp (*Crangon crangon*, Crangonidae). Besides the increase in catching efficiency at daytime, another advantage became apparent, namely the reduction in damage to immature flat fish by fishing with a less heavy gear (Boonstra and de Groot 1970). In Belgium, Vanden Broucke (1973) obtained good results by means of a pulse generator (100 V, 2 Hz), dredging up 44% more shrimp and 250% more sole (on a small number of 39 individuals). In his quest to find suitable stimulations for other species, Stewart also investigated the effect on Norway lobsters (*Nephrops norvegicus*, Homaridae) (Stewart 1972, 1974). He found that electric pulses (1–5 Hz, 20–40 V m^{-1}) could stimulate emergence of these animals from their burrows in <5 s. Meanwhile, the research on brown shrimp had continued as well, and De Groot and Boonstra (1974) found almost equal catch ratios for the electrified (60 V, 0.2 ms, 5 Hz) and the normal trawl. From then onwards, driven by the energy crises in the 1970s, priority was given to reducing the drag and consequently the fuel consumption of the more fuel intensive flatfish fishery.

The high sole catches obtained by Vanden Broucke (1973), triggered research on the adoption of electric pulses for sole to reduce the damage on immature flatfish and to economize the exploitation costs of the heavy tickler chains by replacing them by light electrical ticklers (De Groot and Boonstra 1970). The first experiments (Stewart 1975b,c) suggested that the most efficient stimulation pattern for flatfish (Pleuronectidae) was a 1 s long burst of DC pulses at 20 Hz (50–60 V with electrodes 1 m apart), with 1 s delay between bursts. At higher frequencies a greater percentage of the flatfish remained tetanized on the bottom. It was also found that the 20 Hz PDC tended to preferentially stimulate larger flatfish, which was promising for a better selectivity. In the following years, studies with 3 to 4 m beams in the UK (Stewart 1977, 1978; Horton and Tumilty 1983), Germany (Horn 1976, 1977), the Netherlands (Van Marlen 1997) and Belgium (Vanden Broucke and Van Hee 1976, 1977) indicated indeed that light electrodes are an effective alternative for heavy tickler chains.

Despite the good progress that was made in the first decades, the challenge, especially on the technical side, was still enormous (Anonymous 1970; Stewart 1971). It was very difficult to reproduce the results made with the small beam trawls in larger commercial 9-m-beam trawls, as more electrodes and thus more power was required. The increased power demand, the water resistance of the voluminous pulse generators, the electrode connections in the water, the electrode material and the electrical efficiency were all leading to an accumulation of technical difficulties and frequent malfunctioning (Boonstra 1979). The low fishing speed and the lack of electrical power, making it impossible to sufficiently stimulate sole, resulted in poor catch results of 1:2 (Boonstra 1978). This hurdle was difficult to overcome at that time and hence markedly slowed down the further study and development of marine electrofishing. Half a decade later, a new generation of pulse generators enabled sufficiently high voltage peaks (Agricola 1985). An increase in catch weight of 114% combined with a reduction in by-catch and benthos to almost 50% was achieved in Germany (Horn 1982, 1985). A decade later, in the Netherlands, 45% and 65% more sole were caught during the day and during the night, respectively (Van Marlen 1997). In Belgium, higher sole catches with an electrified otter trawl with less undersized fish and more fish above the minimum landing size were achieved (Delanghe 1983; Delanghe and Vanden Broucke 1983). The first commercial electric beam trawls were already commercially available in the Netherlands (Anonymous 1988a,b), when the German authorities did not allow electrical fishing on a commercial basis in 1987 and the

Dutch government followed their footsteps one year later. Later on 30 March 1988, the European Commission prohibited the use of electricity to catch marine organisms (EC nr 850/98, article 31: non-conventional fishery techniques). The main reason for this ban was likely the fear of further increasing catch efficiency in the beam trawling fleet, which was under severe international criticism back then (Van Marlen 1997). Moreover, it became more and more difficult to obtain a cost-effective system with the falling prices of fuel (Anonymous 1988c). Additional hurdles were safety issues, malfunctioning or system breakdowns. This vulnerability, combined with the large investment and maintenance costs of an electrofishing device, hampered a successful introduction.

The reticence to electric fishing gradually changed when oil prices were sharply rising again some 20 years later, traditional beam trawls became less profitable, making the investment more economically feasible. At the same time, the environmental impact issue became increasingly important. In the early 90s, new initiatives were taken in the Netherlands leading to a revival of the electrotrawls.

Current status of implementation

Flatfish

Verburg Holland B.V. (taken over by Delmeco Group B.V. since 2010) started in 1992 with the development of an electrified pulse beam trawl for flatfish, using a pulse to induce a cramp reaction instead of a startle reaction. In 1995, the first 4-m-beam prototype was built, and in 1997 a 7-m prototype was tested at sea. The results were to such an extent fortifying that the project was continued in cooperation with the Dutch ministry and fishery sector, leading to the up scaling to an

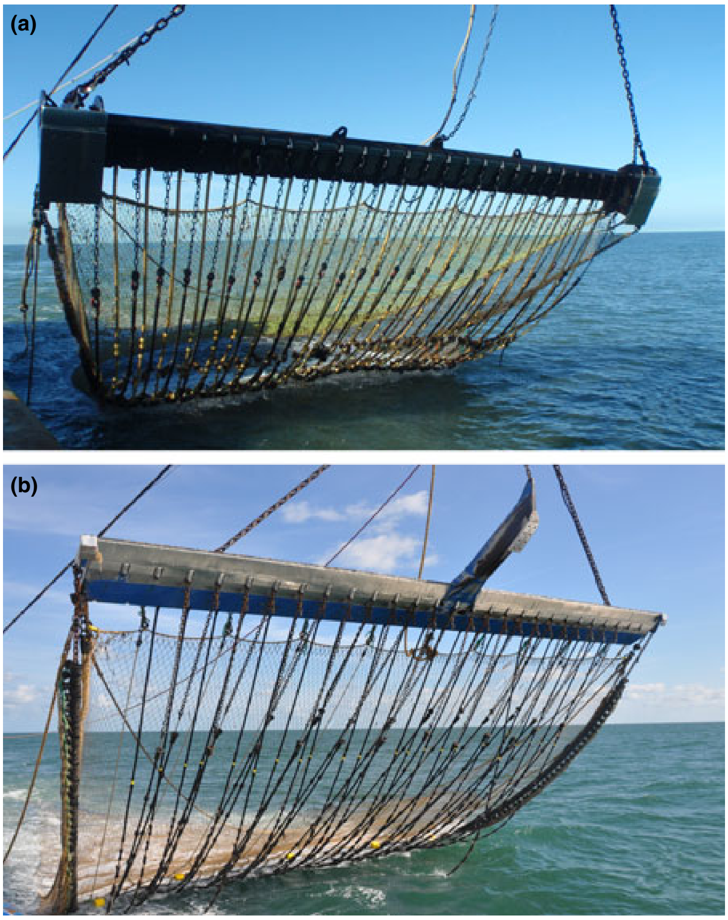

Figure 2 The Delmeco pulse beam with beam and trawl shoes (a) and the HFK PulseWing with the wing and the runner in the centre (b).

operational 12-m-beam fishing gear that could be used on commercial vessels in 2004 (Fig. 2a) (Van Stralen 2005). Meanwhile, another Dutch company, HFK engineering, had started its own developments, applying the pulse system on a new type of beam trawl, the so-called SumWing trawl. In this gear, the cylindrical beam with trawl shoes is replaced by a wing-shaped foil with a runner at the centre (Fig. 2b). This SumWing itself has less bottom contact compared with the conventional beam and due to its hydrodynamic wing shape, it reduces the fuel consumption by some 10% (Van Marlen *et al.* 2009). The implementation of the pulse system to the 'SumWing' trawl is called 'PulseWing' and has a larger potential for the reduction in gear drag (50%), bottom impact and fuel consumption (Van Marlen *et al.* 2011). The beam trawler TX-36 was the first commercial vessel using this system at the end of 2009. The price is similar for both systems: approximately € 300 000 for a large beam trawl and € 200 000 for a eurocutter.

The pulse systems receive electric power from the vessel by an additional cable that also provides communication between controls on board and the pulse generator on the fishing gear. Each electrode has a module that generates pulses independent of the other electrodes. This makes it possible to replace just one electrode module instead of the entire generator in case of malfunctioning. The pulse generator of the Delmeco electrotrawls fires the 25 electrodes attached to the beam with ±0.42 m spacing. An electrode itself consists of 6 different copper conductors (ø26 mm, 0.18 m length) alternated with isolators and the total length of the electrode measures about 6 m (Van Marlen *et al.* 2011). The pulse wing on the other side is rigged with 28 parallel 6-m-long electrodes, at a mutual distance of ±0.415 m. Each electrode is composed by 12 copper conductors (ø33 mm, 0.125 m length) alternated with polyurethane isolators (Van Marlen *et al.* 2011). A detailed construction design of both systems can be found in Van Marlen *et al.* (2011).

The pulse characteristics are similar for both systems. They have a bipolar sinus and block pattern for the pulse beam and the pulse wing, respectively. The basic nominal design characteristics of the pulse systems are listed in Table 1. Note that the characteristics of more recent pulse trawls can be slightly different. The electric parameter settings can also be adapted to the environmental conditions such as seawater temperature and salinity. These conditions may influence the conductivity or flatfish behaviour and thus the response to the electrical pulse field (De Haan *et al.* 2011).

The movement of heavy tickler chains over and through the seabed is normally responsible for 30% of the resistance of a trawl and they can penetrate up to 8 cm in the bottom (Paschen *et al.* 2000). Replacing these tickler chains by electrodes hence greatly reduces the fuel costs and physical disruption of the seafloor. This less invasive impact on the seafloor means also a reduced stimulation of the fish, which means a reduction in unwanted by-catch (Van Marlen *et al.* 2011). This is clearly illustrated by the most recent catch comparisons (Van Marlen *et al.* 2011). The net earnings (gross earnings – fuel costs) showed almost a duplication of efficiency for the TX-36 (186%) and large increase for the TX-68 (155%). However, the large investment and high maintenance costs of the electric gears are hereby not taken into account. This increase was mainly because of the large savings in fuel consumption, as the catches of the main target species were lower (65–69%) compared with conventional beam trawls with tickler chains. This was accompanied by less fish (30–50%) and benthos (48–73%) discards. Other nonsignificant trends were the reduced catch of undersized sole and cod. Obviously, these data

Table 1 Pulse characteristics of the pulse beam on the TX-68 (Delmeco Group B.V.) and pulse wing on the TX-36 (HFK engineering), both targeting flatfish (De Haan *et al.* 2011), and the Hovercran system (Marelec NV) targeting shrimp (Verschueren *et al.* 2012).

Pulse system (company)	Electrical power (kW m^{-1})	Electrode distance (m)	Peak voltage (V)	Frequency (Hz)	Duration (μs)
Delmeco	0.46	0.42	50	40	220
HFK	0.58	0.41	45	45	380
Marelec	0.13	0.67	60	4.5	250

depend on amongst others the type of net and ground rope (Van Marlen *et al.* 2011).

Shrimp

Encouraged by the rumours of successful application of electrotrawls in China and helped by the import of a Chinese prototype by the Belgian shipowner Willy Versluys, the Belgian Institute for Agricultural and Fisheries Research (ILVO) started the development of an electrotrawl for brown shrimp in the late 1990s. The research of Polet *et al.* (2005a,b) revealed that a half-sine square pulse with a frequency of 5 Hz, a pulse duration of 0.25 ms and an electric field strength of approximately 30 V m^{-1} gave the best result to startle brown shrimps (Fig. 3). The low frequency and pulse duration make it possible to operate with a very low energy input of only 1 kWh per trawl (Verschueren and Polet 2009).

Based on these findings, a commercial 8-m-electrified shrimp beam trawl, the 'Hovercran', was developed in 2008 in cooperation with the Belgian company Marelec NV, and the University of Ghent (Fig. 4). This electrotrawl consists of an on-board main control unit, connected with the pulley block at the top of the outrigger via a supply cable, which is hauled along with the fishing gear cable. The 12 electrodes (6 cathodes + 6 anodes) form 11 electrode pairs and are fired alternatively by the pulse generator. The electrodes are 12 stainless steel cables (ø 12 mm, 3 m length) in which the central strand is replaced with a 10 mm^2 cupper conductor. The front 1.5 m is isolated, the last 1.5 m which is hanging horizontally above the seafloor is an uninterrupted conductor, this in contrast with the previous systems, where the electrodes were composed of alternating conductor and isolated parts (Verschueren *et al.* 2012). The basic nominal design settings and pulse characteristics of the Hovercran are listed in Table 1.

In the original Hovercran concept, the trawl is meant to hover above the seafloor. Therefore, the replacement of the bobbins by electrodes and an increased footrope make it possible for non-target species to escape underneath the trawl. The tar-

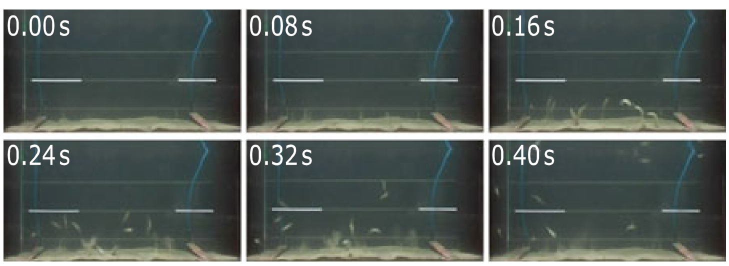

Figure 3 Exposure of brown shrimps to an electric field in the laboratory, the electric field is switched on at 0.08 s. The different points show startling reaction of the shrimp, which is forcing them to jump out of the sand (Verschueren and Polet 2009).

Figure 4 The Hovercran with 9-m beam and trawl shoes. The cylinder fixed on the middle of the beam is the pulse generator.

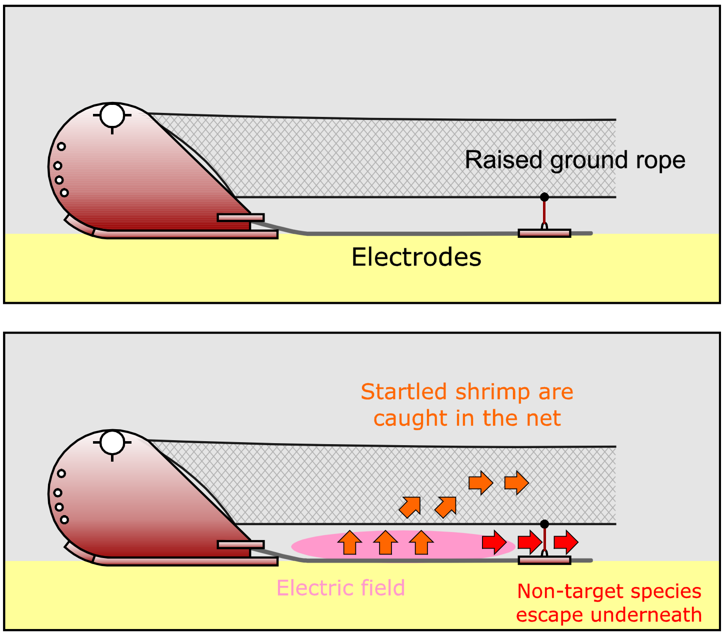

Figure 5 Schematic side view illustrating the basic principle of the HOVERCRAN (below) in comparison with the traditional catching technique (above); the bobbin rope has been replaced with electrodes, generating a specific electric field (Verschueren and Polet 2009).

geted shrimp that are stimulated by the electric field to jump up in the water column are caught by the hovering trawl (Fig. 5). With this set-up, a similar catch weight of shrimp can be obtained and at the same time, bottom contact is reduced by 75%. An overall by-catch reduction of 35% results in cleaner catches, hereby improving the sieving process, the quality of the shrimp and reduce the workload of the crew. Moreover, the catch efficiency is less dependent on light and turbidity conditions. This contrasts with the traditional shrimp trawl where catch efficiency varies strongly with light intensity and turbidity of the seawater (Verschueren and Polet 2009; Verschueren *et al.* 2012). Only a minor reduction in fuel consumption of 10% was obtained with the Hovercran, because the drag resistance of this gear is mainly caused by the small mesh-sized net (Verschueren *et al.* 2012).

In contrast to the original Hovercran configuration, rewarded with runner-up prize of the WWF International Smart Gear Competition in 2009, the commercial vessels using this system in 2012 still use a bobbin rope. However, the number of bobbins is reduced from 32 to maximum 12 and the bobbin rope is straightened (Verschueren *et al.* 2012). This way, the gain in selectivity and reduced bottom contact is less extreme, but the amount of shrimp caught has increased substantially. When electrodes are used in combination with a conventional trawl with 36 bobbins, 50% more shrimp can be caught in clear-water conditions (Verschueren *et al.* 2012). The conversion of a conventional trawler to the Hovercran system costs approximately € 70 000.

Razor clam

Woolmer *et al.* (2011) experimentally designed and trialled methods to harvest razor clam (*Ensis spp.*, Pharidae) using electrical stimuli. This research group used 3 mild steel flat bar electrodes (30 x 8 x 3000 mm) on a separation distance of 0.6 m to produce maximal DC field strength of approximately 50 V m^{-1}. They demonstrated that electrofishing gear generating relatively low DC can be effectively used to stimulate the emergence of Ensis spp. from their burrows. No serious negative effects on the epifaunal and macrofaunal benthic community were detected during the month after a single pass of the electrodes. Therefore, this is potentially a more environmentally benign alternative to existing hydraulic and toothed dredges (Breen *et al.* 2011; Woolmer *et al.* 2011).

Changing political climate

The growing interest in the flatfish pulse trawl in the North Sea is mainly driven by the average reduction of 50% in fuel consumption. The significant reduction in discards and seafloor disturbance is extra commercial assets in the light of an increasing market demand for fish caught in a sustainable manner. These three characteristics are equally important benefits in terms of ecological sustainability. Altogether, these are convincing advantages compared with the traditional beam trawl fishery that is collapsing under the pressure of rising fuel prices and public and political criticism. These were valid arguments to question the ban on electrofishing (EC Reg nr 850/98, article 31: not-conventional fishery techniques).

Following its assessment, ICES (2009) advised that while there were many positive aspects to the pulse trawl, several concerns about possible side effects on target and non-target species needed to be addressed before final conclusions could be drawn on the likely ecosystem effects of electrogears. The European Commission subsequently granted Member States a derogation of 5% of the fleet to use the pulse trawl on a restricted basis, provided attempts were made to address the concerns expressed by ICES. This permission however, only counts for the Southern part of the North Sea (ICES subarea IVb & IVc). This derogation has been renewed annually since 2007 and in the Netherlands all available licences are being used, providing a total of 42 vessels: 39 targeting flatfish and 3 targeting brown shrimp (Rijksoverheid Nederland 2012). By the end of 2012, the council of the European Union proposed to extend the derogation from 5 to 10% of the fleet, which means that the number of Dutch licences may increase to 85 when the new integrated maritime policy come into force in 2014 (European Council 2012).

Side effects of electric fields

Snyder (2003) pointed out that electrofishing involves a very dynamic, complex and often misunderstood mix of physics, physiology and behaviour. The determination of possible harmful effects on fish is therefore a giant task. Because most fundamental research about the harmful effects on fish was done in freshwater species, a selection was made by the author, with the intention to give an image of the harmful effects that can possibly, but not necessarily, be expected for saltwater species exposed to the PDC used in electrotrawls.

Although the freshwater research offers a lot of data, one always has to remember that it is incorrect to extrapolate the findings observed in freshwater research to seawater because there are large differences in sensitivity amongst different species (Halsband 1967; Emery 1984), and the distribution of the electric field in and around the fish is completely different in freshwater compared with seawater. This is reflected in the applied exposure time that is at least 10 times longer in freshwater than in seawater (only 1–2 s), the applied voltage that is often 2–6 times higher in freshwater, and the pulse type chosen. Indeed, alternating current (AC) is sometimes used in seawater, which is more harmful to fish than PDC (Snyder 2003). Nevertheless, the data generated from studies involving freshwater fish species may give a better insight into certain trends of possible effects in case information on marine species is lacking.

Harmful effects on freshwater fish species

The most reported harmful effects of PDC are spinal injuries and associated haemorrhages as observed in rainbow trout (*Oncorhynchus mykiss*, Salmonidae), documented in up to 50% of fish examined internally (Sharber and Carothers 1988). In some cases, 29–100% of the exposed fish are affected, with even the lowest voltages and frequencies causing a substantial amount of internal haemorrhages (Schreer *et al.* 2004). These injuries are most probably induced by myoclonic jerks (Fink 1979; Sharber *et al.* 1994) provoked by pulsating changes in field intensity, for example when the current is switched on and off. As each pulse can be seen as such an on–off switch, the frequency of PDC appears to be a primary factor affecting the incidence of spinal injuries and may be a significant factor in electrofishing mortalities (Sharber *et al.* 1994; Snyder 2003). The link between spinal injuries and mortality was contradicted for warmwater species such as centrarchids. Crappies showed spinal injuries at 5, 60 and 110 Hz but haemorrhaging was higher at 60 and 110 Hz, and mortality was only seen at 5 Hz (Dolan 2002). This was confirmed by Miranda and Kidwell (2010), who concluded that the mortality of the warm freshwater non-game test species was not related to gross-scale injuries because similar or worse haemorrhages and spinal injury were seen in fish that survived electroshock and those that died. This finding suggests that the mechanisms causing physical injuries are not the same as the mechanisms that cause immediate mortality. Besides, Dolan and Miranda (2004) found higher injury and mortality when pulses with a lower duty cycle, that is, energy content, were used in other centrarchids like bluegill sunfish (*Lepomis macrochirus)* and largemouth bass (*Micropterus salmoides)*, which is the opposite of the observations made in trout. Obviously, there appears to be a fundamental difference in the effects on salmonids such as trout and warmwater species such as centrarchids, which might possibly be due to their physiological or morphological differences: several warmwater fish species have fewer and larger vertebrae, which are more resistant to injury and sometimes also compressed bodies with less musculature, whereas trout have many small vertebrae surrounded by a rather large muscle mass. Consequently, trout are highly susceptible to vertebral injury caused by pulsating electrical current compared with centrarchids.

Electric shocks also have some effect on cardiac functions. Although Kolz and Reynolds (1990) stated that cardiac arrest is seldom a factor in fish mortality, Schreer *et al.* (2004) observed cardiac arrest in rainbow trout. This lasted for the duration of the shock, immediately followed by a period of arrhythmia of a few seconds to several minutes after the shock. An exposure (2 ms, 30 Hz, 100 V) of rainbow trout during 2 s, which is comparable to the pulses used in electrotrawls, resulted in a cardiac arrest of 6 s, a cardiac recovery time of 40 min for the heart rate (108% intensity), a cardiac recovery time of 120 min for the cardiac output (165% intensity) and stroke volume (193%), while the behavioural recovery time was only a couple of minutes. With regard to cardiac functions, shock duration appeared to be the major factor, while higher voltages and frequencies result in longer recovery times (Schreer *et al.* 2004). These values are in the same range as the results Emery (1984) obtained when recording physiological changes during exposure to electrical current. An increase in oxygen consumption ranging from 110 to 150% depending on the current was observed, with a recovery time of 30–120 min. According to Emery (1984), this is possibly the result of lactic acid accumulation due to the rapid muscular contractions induced by the electricity. While most fish will recover from this build-up of lactic acid within 4–12 h, some fish will never recover resulting in delayed mortality.

Long-term effects of electrofishing on rainbow trout were examined by Dalbey and Mcmahon (1996) with some remarkable results: fish with intermediate or severe injuries (28% of total) showed a significantly reduced growth and condition, and one year after exposure (10 ms, 60 Hz, 200–400 V), the initial spinal injuries had increased with 60%. This was in contrast with the rapid physiological and behavioural recovery. Moreover, no proof was found that the pulse form or the initial injury had an effect on the long-term survival of the fish.

Finally, the impact on early life stages is also of major concern. Despite several investigators reporting no evidence of harmful effects (Halsband 1967; Halsband and Halsband 1984; Walker *et al.* 1994), others showed that exposure of egg carrying fish to electric fields can cause significant damage or premature expulsion of gametes and sometimes reduced viability of subsequently fertilized eggs (Marriott 1973; Muth and Ruppert 1996; Roach 1996). The survival of embryos on or in the substrate was also affected, particularly when exposure happened between pre-cleavage stages and eyed-egg stages (Godfrey 1957; Lamarque 1990). This early stage of development was also most vulnerable when exposed to mechanical shocks (Kolz and Reynolds 1990). Exposure of recently hatched larvae might not cause significant mortality but can reduce growth rates for at least a few weeks, although significant differences in growth were not detected until 21 days after treatment (Muth and Ruppert 1997). According to Maxfield *et al.* (1971), there was no long-term effect on survival and growth of yearling rainbow trout. The most critical parameters affecting embryos and larvae appear to be the field intensity and duration of exposure (Dwyer and Fredenberg 1991; Dwyer *et al.* 1993). This data set seems to indicate that the sensitivity of early life stages is decreasing as their development proceeds.

Harmful effects on saltwater fish species

The knowledge of possible negative or harmful effects on marine organisms is scarce. Cod is encountered most frequently in research, because this species appeared sensitive during sea trials with 4 of 45 fish caught suffering from spinal fractures (Van Marlen *et al.* 2011). Small juvenile cod fish (0.12–0.16 m), exposed to high field strengths of 250–300 V m^{-1}, all survived with post-mortem examination not revealing vertebral injury nor haemorrhage (De Haan *et al.* 2011). On the contrary, 50–70% of large cod (0.41–0.55 m) exposed to field strengths of 40–100 V m^{-1} showed vertebral injuries. A reduction in injuries was noted when using increasing pulse frequencies higher than 80 Hz (De Haan *et al.* 2011). De Haan *et al.* (2009b) demonstrated clearly that the position of the fish relative to the conductors of the electrode was a decisive factor towards the effects noted. Indeed, cod exposed outside the distance range of 0.4 m from the electrodes, representing fish in the region just outside the trawl, did not react to the exposure and exhibited normal feeding behaviour. However, negative effects occurred when the fish were located in the near distance range of 0.1–0.2 m from the electrode: about 20% died shortly after exposure and 30% by day 14 following exposure. In total, 45% of the fish exposed to the near field had injuries, while no lesions were found in fish exposed at more than 0.2 m of the electrode. The bone fractures were located ventral to the third dorsal fin, which was explained by the authors as due to strong muscle contractions during exposure. Fish exposed at 0.2–0.3 m from the electrodes, displayed milder contractions without getting injured and responded well to feeding cycles. The high peaks in field intensity near the electrodes proved to be a major factor determining possible harmful effects. A reduction in the pulse amplitude by 15% of the nominal setting would reduce the effects and vertebral injuries (De Haan *et al.* 2009b).

Besides cod, dogfish (*Scyliorhinus canicula,* Scyliorhinidae), was included in the study. This electrosensitive fish uses electroreceptors to locate its prey, based on the very low bioelectrical fields produced by every living organism (Kalmijn 1966, 1982; Tricas 2001). This might render these animals vulnerable to electric pulses. De Haan *et al.* (2009a) exposed three groups of 16 dogfishes with similar lengths (0.3–0.65 m) in the same experimental set-up as described for cod, but each fish was exposed four times in a row for a duration of 1 s each time. No mortality, macroscopic lesions or aberrant feeding behaviour were observed in the first 9 months after exposure.

A first series of experiments to examine the effect of electric pulses on benthic invertebrates was carried out by Smaal and Brummelhuis (2005). They exposed 19 different species belonging to molluscs, echinoderms, crustaceans and polychaetes to electrical pulses with amplitude that was 2 times higher and an exposure of 8 times longer than the settings used in practice on commercial vessels. Reactions during exposure were minor or negligible and the survival after 3 weeks did not deviate from the control group. Van Marlen *et al.* (2009) exposed a selection of 6 benthic invertebrates to 3 subsequent 1 s bursts at different distances from the electrode, ranging from 0.1 to 0.4 m. For the ragworm, European green crab and the razor clam, a lower survival of maximum 7% was observed, while for common prawn, subtruncate surf clam and common starfish, no significant effects on survival were found. The food intake was only significantly lower (10–13%) for the European green crab. All other species did not deviate from the control group in food intake or behaviour after exposure. This made the authors conclude that ‘it is therefore plausible that the effects of pulse beam trawling, as stimulated in this study, are far smaller than the effects of conventional beam trawling’.

Challenges and opportunities for the future

Electrotrawls may constitute a substantial improvement towards sustainability compared with the traditional beam trawls used to target flatfish and shrimp. The most promising step forward for the flatfish fishery is undoubtedly the large savings in fuel consumption, up to 60% (Van Marlen *et al.* 2011), leading to a substantial increase in profit. Regarding environmental impact, all pulse trawls obtain significant discard reductions. Additionally, the impact on the seabed may be markedly reduced. The Hovercran has the potential to reduce the bottom contact with 75%, provided all bobbins are removed (Verschueren and Polet 2009). In practice, not all bobbins are removed, but still the bottom contact is reduced by at least 30%. Still, this constitutes a marked improvement, and further optimization aimed at further reducing seabed contact is ongoing and should be a major focus point. It should be stated that in the case of the flatfish electrotrawls, the reduction in bottom contact is limited, because the footrope is still towed over the complete width of the trawl. However, the intensity of the seafloor impact is lowered as the tickler chains, which can normally penetrate up to 0.08 m in the sediment (Paschen *et al.* 2000), are removed. Moreover, the innovation has not stopped with the introduction of the pulse trawl. The wider commercial application in the North Sea will undoubtedly boost innovation, and its selectivity can be improved even more in combination with escape windows and sorting grids.

These reasons indicate that electrotrawls may pose a valuable alternative for the conventional beam trawls. However, to be able to rectify the above statement, a vast amount research is still to be performed on the unwanted side effects and how these can be mitigated, and on the further reduction in the discards. The various research items in these areas that need to be addressed are discussed below.

Unwanted side effects

Impact of pulse parameters

In general, pulse frequency rather than high voltage gradients appears to be the primary cause of spinal injuries and haemorrhages. This is clearly demonstrated in freshwater by Sharber *et al.* (1994), showing only 3% of the exposed fish were injured at low frequency (15 Hz), but 24% and even 43% of the fish were injured at moderate frequencies of 30 and 60 Hz, respectively. Snyder (2003) added the comment that lower frequencies can still cause injuries if the voltage is raised above a certain threshold, which was confirmed by Schreer *et al.* (2004). This trend seems to be valid in seawater as well: while Verschueren *et al.* (2012) did not see spinal injuries in cod at low frequencies, 7 to 70% spinal injuries were reported at moderate frequencies, depending on the voltage gradients (De Haan *et al.* 2009b, 2011; Van Marlen *et al.* 2011). The reduction in injuries at frequencies >80 Hz, to no visible injuries at 180 Hz, as observed by De Haan *et al.* (2011), seems to disprove this. However, during these experiments the duty cycle (percentage of time the current is flowing) was kept constant. This means that the pulse duration decreased when the frequencies increased, resulting in very narrow peaks at high frequencies that were likely too short to induce muscle contraction. This phenomenon was also observed by Bird and Cowx (1993). These researchers demonstrated that the frequency and duty cycle of PDC had strong interactive effects and that threshold field strengths for perception and attraction responses increased with frequency at low (10%) duty cycles. As De Haan *et al.* (2011) kept the field strength constant, the amount of pulse energy might have become too low at higher frequencies and lower pulse durations to induce reactions and injuries. A possible alternative improvement to reduce the spinal injuries without losing catch efficiency was given by Sharber *et al.* (1994). It was determined that a pulse train of 15 Hz, 15 bursts of several quick successive pulses in 1 s, with the same energy content as pulses of 60 Hz induced similar effects on the fish but caused fewer injuries. Hence, the use of pulse trains might offer a promising alternative. However, the effect on other marine fishes should be examined thoroughly as well, because there might be large differences in reaction between species as proven in freshwater research with salmonids and centrarchids.

The field strength also seems to play a primary role in the amount of injury and mortality observed. The higher this parameter, the stronger the voltage gradient in the water, the larger the difference in electrical potential experienced by the fish en the risk of injuries. This was clearly illustrated by the experiments of De Haan *et al.* (2011). The majority of cod exposed to higher field strengths (i.e. near the electrode) showed injuries, whereas effects were absent at lower field strengths (0.4 m away from the electrode). Besides, large adult cod showed much more injuries than small juvenile cod, even though the juveniles were exposed to much higher field strengths. In both cases, a higher potential difference over the fish body elicits a stronger reaction of the fish. Another, additional, not experimentally tested hypothesis for this phenomenon was made by Stewart (1967), as cited by Lamarque 1990), who suggested that spawning fish, particularly salmon, may be especially susceptible to spinal injuries due to skeletal decalcification and weakened or brittle bones. To the author's opinion, another factor can play a role as well: different stages of calcification, from cartilage in yearlings to bone in old adult fish, can affect the sensitivity of spinal structures for the strong contractions during myoclonic jerks observed during exposure. Further research to clarify this effect is definitely needed.

The exposure time is mentioned by different authors (Emery 1984; Schreer *et al.* 2004) as determining parameter regarding cardiac arrests. Schreer *et al.* (2004) reported recovery times of

40 min and 120 min for the heart rate and cardiac recovery time, respectively, after a 2 s exposure, with a pulse duration that was 8 times longer than that applied in electrotrawls (2 ms vs. 0.250 ms). Similar recovery times are seen in other stress situations: 40 min after noise disturbance (Graham and Cooke 2008) and up to 210 min after angling (Schreer *et al.* 2001). Although this clearly indicates an effect, fish exposed to the capture process in beam trawls will also experience stress. Important to note though is the fact that the cardiac recovery time was 10–100 times longer than the behavioural recovery time of only a few minutes. The same was stated by Dalbey and Mcmahon (1996), who found that the rapid physiological and behavioural recovery contrasts with reduced long-term growth and condition and increasing injuries. This indicates that behaviour cannot be used as the only parameter when assessing the impact of electric pulses on an animal and that various parameters need to be included.

Finally, the pulse type and pulse form are 2 parameters that can influence the reaction of the fish to electric pulses. However, they have not yet been thoroughly examined. Concerning the pulse type, it is generally accepted that AC is the most and DC the least harmful, with PDC in between (Bary 1956; Sharber *et al.* 1994; Dalbey and Mcmahon 1996). This suggests that the pulsed alternating current (PAC) and the pulsed bipolar current (PBC) used in the electrotrawls for flatfish might be more harmful than PDC used in the Hovercran, but no direct comparison between bipolar pulses and PDC has been made yet. De Haan *et al.* (2011) found that a time delay between the positive and negative parts of the bipolar pulses seems to contribute to injury, although not in a significant way. Hitherto, the effect of the pulse form is still vague: although most authors agree that quarter sinus waves are the most harmful (Bird and Cowx 1993; Sharber *et al.* 1994), it is uncertain whether an exponential or a square bloc wave is the best one to use.

Effects on growth and development

Dalbey and Mcmahon (1996) observed reduced long-term effects on growth and conditions and an increasing number of injuries in rainbow trout. Although the exposure time was more than 10 times higher than what is encountered in electrotrawls, this indicates that a long-term effect cannot be excluded and that the severity of injuries might even increase in time. Furthermore, the number and severity of injuries were positively related with the length of the fish (Dalbey and Mcmahon 1996). Large commercially important fish will normally be caught after exposure and slaughtered immediately. Only in discarded specimens such as larger non-commercial or undersized commercial species long-term effects are relevant. As such, the effect on electrosensitive species should be further investigated. Despite the reassuring results of De Haan *et al.* (2009a), who found no evidence of aberrant feeding behaviour, this does not prove that the electrosensitive organs of the fish are undamaged. Indeed, in their natural habitat, these fish fully depend on these organs to detect the very low electric fields produced by preys situated in the bottom. This is not the case in captivity, where they can easily find their daily meal in the clean survival tanks without having to resort to their electrosensitive organs.

The reported effects on early life stages are contradictory and could reflect the differences in species sensitivity. Nevertheless, according to Snyder (2003), a sufficient number of indications were found to consider that freshwater electrofishing over spawning grounds can harm embryos. For several reasons, it can be assumed that this effect will be more moderate in seawater. At first, the most critical parameters affecting embryos and larvae appeared to be the field intensity and duration of exposure (Dwyer and Fredenberg 1991; Dwyer *et al.* 1993). As mentioned before, these parameters have a much lower value in seawater. Second, the effect on mature fish is of minor importance for commercial species, because they are normally larger than the minimal landing size and will be landed after being caught. A last factor mitigating the risk on exposed embryos and larvae is their distribution in the water column. Whereas the electric field covers the whole water column in freshwater, the electric field is limited to the net opening in marine electric fishing. According to the results of Conway *et al.* (1997), less than 12% of the eggs and larvae of sprat (*Sprattus sprattus*, Clupeidae), dragonet (*Callionymus spp.*, Callionymidae) and dab (*Limanda limanda*, Pleuronectidae) were found in the 5-m-water column zone above the seafloor. Furthermore also the area of the North Sea being trawled is limited. This implicates that the chance for exposure of eggs and larvae is very small compared with the situation in freshwater. However, this obviously will need to be re-evaluated when electrotrawls are used in shallow spawning areas. Hence, further research on the effect of electric fields on the early life stages of marine species spawning in these shallow zones is strongly recommended.

Effect on the sediment

A last aspect that should be investigated in the future is the possible electrolysis effect of the sediment. The high peaks in current might possibly induce the formation of toxic metabolites or release of heavy metals, definitely in substrates rich in organic matter and bounded metals (Alvarez-Iglesias and Rubio 2009). No research whatsoever has been performed on this topic, but in view of the fact that a fan of chemical reactions is possible, this particular aspect also deserves further examination.

Reduction of discards and consequences

There are 5 major reasons explaining discard reductions: (i) larger animals will react more easily on a stimulus, induced by a certain electrical field strength than smaller ones (Bary 1956; Adams *et al.* 1972; Emery 1984; Dolan and Miranda 2003), which explains the decrease in the amount of undersized fish caught; (ii) the electric pulses stimulate especially the target species and most invertebrates will hardly be stimulated by the field (Smaal and Brummelhuis 2005; Van Marlen *et al.* 2009); (iii) the less intensive bottom contact prevents a part of the animals from being shovelled from the bottom (flatfish) or give the animals more chance to escape between the bobbins (shrimp); (iv) the reduced towing speed of electrotrawls results in a smaller fished surface, so fewer animals will be encountered and (v) this reduced towing speed also increases the chance of escape for the animal after it has entered the net.

The reduction in discards is an ecological improvement that all electrotrawls used in the North Sea have in common. The Hovercran shrimp pulse trawl showed a discard reduction of 35% with equal or increased shrimp catches (Verschueren *et al.* 2012). For the flatfish pulse trawls, Van Marlen *et al.* (2011) reported a 30–50% and 48–73% discards reduction measured in kg h^{-1}, for fish and benthos, respectively, but this goes together with a loss of commercially sized sole of 13–22%. However, the further development of this technique has led to better sole catches compared with the conventional beam trawls. Moreover, the so-called eurocutters, vessels allowed to fish within the 12 miles limit, equipped with pulse trawls are believed to catch much more sole than the conventional ones (Polet, H., personal communication and internal data of landings), which means a further decrease in discards per unit of fish landed.

In the pulse trawl for shrimp, the by-catch can be further reduced by raising the footrope (Verschueren and Polet 2009). Consequently, also more shrimp tend to escape beneath the ground rope. This means that the height of the footrope will always be a trade-off between acceptable shrimp catches and sufficient by-catch reduction, offering fishery management two possible directions for ecological improvement with constant shrimp landings. The first is the Hovercran like it is used on 4 commercial vessels today, without raised footrope and with (a reduced number of) bobbins. The benefit in bottom contact and by-catch will be limited, but more shrimp will be caught. If total allowable catches for shrimp would be restricted with the wider introduction of the pulse trawl, the hours trawled would decrease due to the increased catching efficiency. Fewer hours trawled also means less surface dragged, less by-catch produced and less fuel consumed. The second scenario is the one with a bobbin-free and raised footrope. In this case, the shrimp catches will not increase, but the seafloor disturbance and by-catch will be reduced drastically. The economic advantage for the fisherman would be an easier access to vulnerable fishing grounds and an easier access to the market of sustainably caught fish.

Last but not least, the reduction in discards of commercial species may also have large economic implications. Cappell (2001) calculated that 70% of the total landing value of the Dutch beam trawl fleet was lost due to this discarding. Based on the landings of this fleet in 2011 (€ 210 million), one can calculate that a saving of 30% in fish discards would lead to an annual increase in landing value of the Dutch fleet of several ten millions.

Altered fishing effort

The shift to pulse fishery on flatfish will definitely affect the accessibility of new fishing grounds. Muddy fishing grounds, however, that could previously not be fished with tickler chains can more easily be fished with pulse trawls. As such an extension of fishing grounds may occur for some fishing fleets of which the consequences should be carefully monitored, as pulse fishers, for example could shift their fishing activity to the territory of passive fishers.

The pulse trawl for shrimp may have increased catch efficiencies. As there are no quota or total allowable catches for shrimp, this can lead to a higher fishing effort, which has to be approached with care. Yu *et al.* (2007) describe how the use of electrotrawls on several shrimp species in inshore waters of the East China Sea has led to a large decrease in the biomass due to increased catch rates and total landings. To compensate for the reduction in catch rates due to the overfishing, electrical output was increased to catch also the undersized shrimp, resulting in complete biomass depletion until electrofishing was banned in 2001. The pulse technology used in the brown shrimp fishery in the North Sea increases the catching efficiency of the trawl significantly. Overfishing of the stock in the North Sea is, however, unlikely for multiple reasons. First, the demand on brown shrimp is limited and characterized by a price flexibility of about 1 (Revill *et al.* 1999). An increased landing of 1% will thus make the price drop with 1%, so strongly increased landings are not beneficial to the fisherman. This is reflected in the limitation of the number of shrimp pulse licences in the Netherlands in 2012. Second, there is no incentive of the fishermen to catch undersized shrimp, as there is a minimum size for shrimps to be sold. Finally, the electrical output of the Hovercran equipment is limited and researchers of ILVO even proved that catching efficiencies were highest at 80% of the output (Verschueren *et al.* 2012), so manipulating the output will not result in higher catches. However, this cannot be explained by the author and additional catch comparisons should be performed to further confirm this result (Personal Communication with Verschueren, B.).

Nevertheless, good management measures will be necessary to guarantee a positive application of this innovative technology, both in flatfish as in shrimp fishery. As suggested by Yu *et al.* (2007), this management should include (i) certification procedures for device manufacturers and maintenance agents to avoid illegal production, trade and use; (ii) introduction of tamper-proof key settings for the output power parameters; (iii) introduction of specialized equipment to monitor the electrical parameters in the field and (iv) strict control of total fishing effort and total allowable catch.

Conclusion

The future of the flatfish fishery, in particular by beam trawls, is endangered as fuel costs and obligations to reduce by-catch will further increase. Pulse fishery with electrotrawls may pose a promising alternative, offering multiple improvements. Unfortunately, not all possible negative side effects can be excluded yet. Although various studies elucidating the effects of electrical fields on fish have been performed, various major gaps of knowledge still remain and need to be investigated:

1. Is there a safe range of pulse parameters that allow application without (significant) side effects for any marine organisms?
2. What are the differences in sensitivity between different (in)vertebrate marine species and what is the effect on designing electrotrawls and setting the protocols?
3. What are the effects on early life stages of marine species spawning in shallow zones where electrified trawls might be used?
4. What is the long-term effect on small non-commercial species or undersized commercial species that can be exposed repeatedly?
5. What is the effect on the electrosensitive organs of electrosensitive fishes?
6. Is there an electrolysis effect of the substrate and water column resulting in the formation of toxic metabolites?

Although fishing with electrical pulses might still have some unknown side effects, the negative impact of beam trawls with tickler chains or bobbins on the environment probably is more significant. The evidence presented here suggests that the electrified trawls are superior to conventional trawls regarding different aspects, including ecological impact on the North Sea (less bottom impact), management of commercial fishing stocks (less discards) and carbon footprint (reduction of fuel consumption). At the same time, this alternative technique seems more beneficial for the fishermen, because their earnings can be increased drastically and because they can catch more and independent of the time of the day and weather. Therefore, electric pulse fishery seems to be the most promising alternative meeting both the fisherman's aspirations and the need for ecological progress.

Acknowledgements

Maarten Soetaert received a PhD grant from the Agency for the Promotion of Innovation by Science and Technology in Flanders (IWT-Vlaanderen). Additional support is given by the Flemish Scientific Institute for Agricultural and Fisheries Research (ILVO) and the Ghent University. The author gratefully thanks Fernand Delanghe for the assembled collection of all publications over electrotrawls from 1949 to the end of the 80s and Ellen Renders for her preparatory work. Prof. Dr. Paul Simoens and Leendert Vergeynst are also acknowledged for critically reviewing this manuscript.

References

Adams, W.J., Behmer, D.J. and Weingarten, W.O. (1972) Recovery of shocked common shiner, Notropis cornutus, related to electric energy. *Transactions of the American Fisheries Society* **101**, 553–555.

Agricola, J.B. (1985) Experiments on electrical stimulation of flatfish in beamtrawling during 1984. ICES CM 1985/B:36, pp, 21.

Alvarez-Iglesias, P. and Rubio, B. (2009) Redox status and heavy metal risk in intertidal sediments in NW Spain as inferred from the degrees of pyritization of iron and trace elements. *Marine Pollution Bulletin* **58**, 542–551.

Anonymous. (1969) The electric deep-sea trawl. *World Fishing* **18**, 37.

Anonymous. (1970) Electric trawling in the GDR: Some of the problems encountered by the GDR and how they were overcome. *World Fishing*, 2.

Anonymous. (1988a) Dutch government backed trials. *Fishing News*, 7.

Anonymous. (1988b) Electric beam gear goes on sale. *Fishing News International* **27**, 17.

Anonymous. (1988c) Electric beaming gear switches on. *Fishing News*, 6–7.

Bary, B.M. (1956) *The effect of electric fields on marine fishes*. Scotland Home Department 1, 32.

Bergman, M.J.N. and Van Santbrink, J.W. (2000) Fishing mortality of populations of megafauna in sandy sediments. *Ices Journal of Marine Science* **57**, 1321–1331.

Bird, D.J. and Cowx, I.G. (1993) The selection of suitable pulsed currents for electric fishing in fresh-waters. *Fisheries Research* **18**, 363–376.

Blancheteau, M. (1967) Contribution to the study of taxis in interrupted and alternating currents. Fishing with electricity, its application to biology and management. R. Vibert. London, Fishing News 93–99.

Boonstra, G.P. (1978) A few notes on the 1977 and 1978 experiments with comparative electrical fishing for flatfish. ICES progress report for the Fish Reaction Working Group.

Boonstra, G.P. (1979) Onderzoek naar de mogelijkheden van toepassing van elektrische visserij op garnalen en platvis 1968–1978. *Visserijblad* **32**, 107–121.

Boonstra, G.P. and de Groot, S.J. (1970) Report on the development of an electrified shrimp-trawl in the Netherlands. ICES report for the Gear and Behaviour Committee.

Boonstra, G.P. and de Groot, S.J. (1974) The development of an electrified shrimp-trawl in the Netherlands. *Journal du Conseil/Conseil International pour l'Exploration de la Mer* **35**(2), 165–170.

Breen, M., Howell, T. and Copland, P. (2011) A report on electrical fishing for razor clams (ensis sp.) and its likely effects on the marine environment. *Marine Scotland Science Report*, 118.

Cappell, R. (2001) *Economic aspects of discarding. UK case study: discarding by North Sea Whitefish Trawlers*. Nautilus Consultants, Edinburgh, 104 pp.

Conway, D.V.P., Coombs, S.H. and Smith, C. (1997) Vertical distribution of fish eggs and larvae in the Irish Sea and southern North Sea. *Ices Journal of Marine Science* **54**, 136–147.

Dalbey, S.R. and Mcmahon, T.E. (1996) Effect of electrofishing pulse shape and electrofishing-induced spinal injury on long-term growth and survival of wild rainbow trout. *North American Journal of Fisheries Management* **16**, 560–569.

Danyulite, G.P. and Malkevicius, S.K. (1967) Investigation of the physiological mechanism of action of a Direct-Current electrical field on fish Behaviour and reception in Fish [translation from Russian by Howland, R.]. *Moscow State University* 56–62.

De Groot, S.J. and Boonstra, G.P. (1970) Preliminary notes on the development of an electrical tickler chain for sole (Solea solea L.). ICES report for the Gear and Behaviour Committee.

De Groot, S.J. and Boonstra, G.P. (1974) Kunnen we elektrisch garnaal en tong vangen? *Visserijnieuws*.

De Haan, D., Van Marlen, B., Velzenboer, I., Van der Heul, J. and Van der Vis, H. (2009a) The effect of pulse stimulation on biota – Research in relation to ICES advice – Effects on dogfish. Wageningen, the Netherlands, IMARES C105/09: 32 pp.

De Haan, D., Van Marlen, B., Kristiansen, T.S. and Fosseidengen, J.E. (2009b). The effect of pulse stimulation on biota - Research in relation to ICES advice – Progress report on the effects on cod, IMARES C098/08: 25 pp.

De Haan, D., Fosseidengen, J.E., Fjelldal, P.G. and Burggraaf, D. (2011) The effect of electric pulse stimulation to juvenile cod and cod of commercial landing size, IMARES C/141/11: 44 pp.

Delanghe, F. (1983) Toepassing van een geëlectrificeerd net in de bordenvisserij. Mededelingen van het Rijksstation voor Zeevisserij, Rijksstation voor Zeevisserij nr. 195, 24 pp.

Delanghe, F. and Vanden Broucke, G. (1983) Electrische visserij op garnaal uitgevoerd met bordennet. Mededelingen van het Rijksstation voor Zeevisserij, 199-TZ/106, 22 pp.

Delgado-Escuata, A.V. (1986) *Basic Mechanisms of the Epilepsies: Molecular and Cellular Approaches*, 1st edn. Raven Press, New York.

Den Heijer, W.M. and Keus, B. (2001) Bestaande vistuigen als mogelijk alternatief voor de boomkor. *Report of Rijksinstituut voor Kust en Zee*. RIKZ-2001.037, 76 pp.

Dolan, C.R., Miranda, L.E. and Henry, T.B (2002) Electrofishing for crappies: Electrical settings influence immobilization efficiency, injury, and mortality. *North American Journal of Fisheries Management* **22**, 1442–1451.

Dolan, C.R. and Miranda, L.E. (2003) Immobilization thresholds of electrofishing relative to fish size. *Transactions of the American Fisheries Society* **132**, 969–976.

Dolan, C.R. and Miranda, L.E. (2004) Injury and mortality of warmwater fishes immobilized by electrofishing. *North American Journal of Fisheries Management* **24**, 118–127.

Dwyer, W.P. and Fredenberg, W.A. (1991) The effect of electric current on rainbow and cutthroat trout embryos. *American Fisheries Society Fisheries Management* **12**, 6.

Dwyer, W.P., Fredenberg, W.A. and Erdahl, D.A. (1993) Influence of electroshock and mechanical shock on survival of trout eggs. *North American Journal of Fisheries Management* **13**, 839–843.

Emery, L. (1984) The physiological effects of electrofishing. *California-Nevada Wildlife Transactions*, 59–62.

European Commission (E.C.) (2011) Impact assessment of discard reducing policies. Common Fisheries Policy Impact Assessment report.

European Council (2012) Proposal for a Regulation of the European Parliament and of the Council on the European Maritime and Fisheries Fund [repealing Council Regulation (EC) No 1198/2006 and Council Regulation(EC) No 861/2006 and Council Regulation No XXX/2011 on integrated maritime policy.], COUNCIL OF THE EUROPEAN UNION, Brussels, 89 pp.

Fink, M. (1979) *Convulsive Therapy: Theory and Practice*. Raven Press, New York.

Fonteyne, R., Ball, B., Kujawski, T., Munday, B.W., Rumohr, H. and Tuck, I. (1998) Physical impact. In: *Impact-II. The Effects of Different Types of Fisheries on the North Sea and Irish Sea Benthic Ecosystems* (eds H.J. Lindeboom and S.J. de Groot). RIVO, Wageningen, pp. 120–156.

Godfrey, H. (1957) Mortalities among developing trout and salmon ova following shock by direct-current electrical fishing gear. *Journal of the Fisheries Research Board of Canada* **14**, 153–164.

Graham, A.L. and Cooke, S.J. (2008) The effects of noise disturbance from various recreational boating activities common to inland waters on the cardiac physiology of a freshwater fish, the largemouth bass (*Micropterus salmoides*). *Aquatic Conservation-Marine and Freshwater Ecosystems* **18**, 1315–1324.

Groody, T. (1952) A preliminary report on the behavior of the pacific sardine (sardinops caerulea) in an electrical field. *Proceedings of the California Academy of Sciences* **27**, 311–323.

Growns, I., Pollard, D.A. and Harris, J.H. (1996) A comparison of electric fishing and gillnetting to examine the effects of anthropogenic disturbance on riverine fish communities. *Fisheries Management and Ecology* **3**, 13–24.

Halsband, E. (1967) Basic principles of electric fishing. In: *Fishing with Electricity, its Application to Biology and Management* (ed. R. Vibert). Fishing News, London, pp. 57–64.

Halsband, E. and Halsband, I. (1984) Electrofishing [English translation of Halsband and Halsband, 1975 by R.W. McCauley]. Canadian Translations in Fisheries and Aquatic Sciences 5048.

Hartley, W.G. (1967) Electronarcosis of fish for handling. In: *Fishing with Electricity, its Application to Biology and Management* (ed. R. Vibert). Fishing News, London, pp. 276.

Highman, J.B. (1956) The behaviour of Pink Grooved Shrimp, Penaeus Duorarum Burkenroad, in a Direct Current Electric Field. Technical Series Marine Laboratory of State of Florida: Board of Conservation.

Horn, W. (1976) Rationalisierung der Seezungenfischerei durch Einsatz elektrifizierter Baumkurren. *Informationen for die Fischwirtschaft* **23**, 20–22.

Horn, W. (1977) Weitere Ergebnisse von Untersuchungen an elektrifizierten Baumkurren für den Seezungenfang. *Informationen for die Fischwirtschaft* **24**, 226–228.

Horn, W. (1982) Fortschritte bei der Elektrifizierung von Baumkurren für den Plattfischfang. *Informationen for die Fischwirtschaft* **29**, 76–77.

Horn, W. (1985) Fortsetzung der Versuche mit elektrifizierten Baumkurren. *Fischerblatt* **33**, 40.

Horton, R.S. and Tumilty, J.E. (1983). SFIA electrotrawling trials onboard MT boltby queen. SEAFISH Technical Report No. 206: 102.

Houston, R.B. (1949) German commercial electrical fishing device Special Scientific Report: Fish. *US Fish and Wildlife Service* **34**, 1–4.

Hovart, P. (1985) Zeevisserijbeheer in vroegere eeuwen: een analyse van normatieve bronnen. Mededelingen van het Rijksstation voor Zeevisserij. Ostend, Ministerie van Landbouw: 188.

ICES. (2009) 1.5.6.3 Answer to The Netherlands' request on Electric Pulse Trawl, ICES advice 2009, Book 1, 9 pp.

Jennings, S., Dinmore, T.A., Duplisea, D.E., Warr, K.J. and Lancaster, J.E. (2001) Trawling disturbance can modify benthic production processes. *Journal of Animal Ecology* **70**, 459–475.

Jones, J.B. (1992) Environmental-impact of trawling on the seabed - a review. *New Zealand Journal of Marine and Freshwater Research* **26**, 59–67.

Kalmijn, A.J. (1966) Electro-perception in sharks and rays. *Nature* **212**, 1232.

Kalmijn, A.J. (1982) Electric and magnetic-field detection in elasmobranch fishes. *Science* **218**, 916–918.

Kolz, A.L. and Reynolds, J.B. (1990) Principles and techniques of electrofishing [outline manual for course]. Leetown, US, Fish and Wildlife Service Fisheries Academy.

Lamarque, P. (1963) Les réactions du poisson dans la pêche électrique et leur explication neurophysiologique. *Science Progres La Nature* **3336**, 137–148.

Lamarque, P. (1967) Electrophysiology of fish subject to the action of an electric field. In: *Fishing with Electricity, its Application to Biology and Management* (ed. R. Vibert). Fishing News, London, pp. 65–92.

Lamarque, P. (1990) Electrophysiology of fish in electric fields. In: *Fishing with Electricity, Applications in Freshwater Fisheries* (eds I.G.L. Cowx and P. Lamarque). Fishing News Books, Blackwell Scientific Publications, Oxford, pp. 4–33.

Lindeboom, H.J. and de Groot, S.J. (1998) Impact II, the effects of different types of fisheries on the North Sea and Irish Sea benthic Ecosystem. RIVO, 404 pp.

Linnane, A., Ball, B., Munday, B., Van Marlen, B., Bergman, M. and Fonteyne, R. (2000) A review of potential techniques to reduce the environmental impact of demersal trawls. *Irish Fisheries Investigation* **7**, 39.

Marriott, R.A. (1973) Effects of electric shocking on fertility of mature pink salmon. *Progressive Fish-Culturist* **35**, 191–194.

Maxfield, G.H., Lander, R.H. and Liscom, K.L. (1971) Survival, growth, and fecundity of hatchery-reared rainbow trout after exposure to pulsating direct current. *Transactions of the American Fisheries Society* **100**, 546–552.

Mc Rae, E.D. and French, L.E. (1965) An experiment in electrical fishing with an electric field used as an adjunct to an otter trawl net. *Commercial Fisheries Review* **27**, 1–11.

Miranda, L.E. and Kidwell, R.H. (2010) Unintended effects of electrofishing on nongame fishes. *Transactions of the American Fisheries Society* **139**, 1315–1321.

Morgan, M.E. (1951) *The Response of a Tropical Fish to Interrupted Direct Current and Its Application to the Problem of Electrofishing in Sea Water*. The University of Hawaii, Honolulu.

Muth, R.T. and Ruppert, J.B. (1996) Effects of two electrofishing currents on captive ripe razorback suckers and subsequent egg-hatching success. *North American Journal of Fisheries Management* **16**, 473–476.

Muth, R.T. and Ruppert, J.B. (1997) Effects of electrofishing fields on captive embryos and larvae of razorback sucker. *North American Journal of Fisheries Management* **17**, 160–166.

Paschen, M., Richter, U. and Köpnick, W. (2000) *Trawl Penetration in the Seabed* (TRAPESE). Project no 96/006, Rostock, 104 pp

Pease, N.L. and Seider, W.R. (1967) Development of the Electro-shrimp trawl system. *Commercial Fisheries Review* **29**, 8–9.

Penfield, W. and Jasper, H. (1954) *Epilepsy and the Functional Anatomy of the Human Brain*. Brown Little, New York.

Polet, H., Delanghe, F. and Verschoore, R. (2005a) On electrical fishing for brown shrimp (*Crangon crangon*) – I Laboratory experiments. *Fisheries Research* **72**, 1–12.

Polet, H., Delanghe, F. and Verschoore, R. (2005b) On electrical fishing for brown shrimp (*Crangon crangon*) – II Sea trials. *Fisheries Research* **72**, 13–27.

Polet, H., Depestele, J., Van Craenest, K. *et al.* (2010) LOT 3, Scientific advice concerning the impact of the gears used to catch plaice and sole, Summary Studies and pilot projects for carrying out the common fisheries policy Ostend. *Instituut voor Landbouw- en Visserijonderzoek* **28**, 23.

Rabaut, M., Guilini, K., Van Hoey, G., Magda, V. and Degraer, S. (2007) A bio-engineered soft-bottom environment: The impact of Lanice conchilega on the benthic species-specific densities and community structure. *Estuarine Coastal and Shelf Science* **75**, 525–536.

Revill, A., Pascoe, S., Radcliffe, C. *et al.* (1999) Economic consequences of discarding in the crangon fisheries. *Final Report to the European Commission*, 118.

Rijksoverheid Nederland (2012) Nieuwe toestemmingen pulsvisserij. Retrieved 1 December, 2012, from http://www.rijksoverheid.nl/nieuws/2011/05/16/nieuwe-toestemmingen-pulsvisserij.html.

Roach, S.M. (1996) Influence of electrofishing on the survival of Arctic grayling, chinook salmon, least cisco, and humpback whitefish eggs. Alaska Department of Fish and Game Division of Sport Fish Fishery, no 96-1, 26.

Schreer, J.F., Cooke, S.J., Connors, K.B. and McKinley, R.S. (2001) Cardiac response to variable forced exercise at different temperatures: An angling simulation for smallmouth bass. *Transactions of the American Fisheries Society* **130**, 783–795.

Schreer, J.F., Cooke, S.J. and Connors, K.B. (2004) Electrofishing-induced cardiac disturbance and injury in rainbow trout. *Journal of Fish Biology* **64**, 996–1014.

Sharber, N.G. and Black, J.S. (1999) Epilepsy as a unifying principle in electrofishing theory: A proposal. *Transactions of the American Fisheries Society* **128**, 666–671.

Sharber, N.G. and Carothers, S.W. (1988) Influence of electrofishing pulse shape on spinal injuries in adult rainbow trout. *North American Journal of Fisheries Management* **8**, 117–122.

Sharber, N.G., Carothers, S.W., Sharber, J.P., de Vos, J.C. and House, D.A. (1994) Reducing electrofishing-induced injury of rainbow trout. *North American Journal of Fisheries Management* **14**, 340–346.

Smaal, A.C. and Brummelhuis, E. (2005) Onderzoek naar mogelijke effecten van de pulskor op bodemdieren, RIVO C089/05, 15.

Snyder, D.E. (2003) Invited overview: conclusions from a review of electrofishing and its harmful effects on fish. *Reviews in Fish Biology and Fisheries* **13**, 445–453.

Sternin, V.G., Nikonorov, I.V. and Bumeister, Y.K. (1976) Electrical fishing - Theory and Practice [published in 1972, English translation by E. Vilim]. Israel Program for Scientific Translations, Jerusalem, Keter Publishing House Jerusalem Ltd.: 316.

Stewart, P.A.M. (1967) Observations on flat fish reactions to a model electrified beam trawl. *ICES report for the Gear and Behaviour Committee*, 8.

Stewart, P.A.M. (1971) *A review of Marine Electrical Fishing*. IF Meeting, Bergen, 9 pp.

Stewart, P.A.M. (1972) *An Exploratory Investigation into the Effects of Electric Fields on Burrowed Nephrops*. SOAFD Marine Lab, Aberdeen, 15 pp.

Stewart, P.A.M. (1974) An investigation into the effect of electric field on Nephrops norvegicus. *Journal du Conseil/Conseil International pour l'Exploration de la Mer* **35**, 249–257.

Stewart, P.A.M. (1975a) Catch selectivity by electrical fishing systems. *Journal du Conseil/Conseil International pour l'Exploration de la Mer* **36**, 106–109.

Stewart, P.A.M. (1975b) Experiments in burghead bay on the reaction of flat fish to electrical stimulation Internal Report. *Marine Laboratory of Aberdeen*, 27.

Stewart, P.A.M. (1975c) Results of a comparative fishing experiment for flat fish using an electrified beam trawl. *ICES Report for the Gear and Behaviour Committee*, 7.

Stewart, P.A.M. (1977) A study on the response of flatfish (pleuronectidea) to electrical stimulation. *Journal du Conseil/Conseil International pour l'Exploration de la Mer* **37**, 123–129.

Stewart, P.A.M. (1978) Comparative fishing for flatfish using a beam trawl fitted with electric ticklers. *Scottish Fisheries Research Report No 11*, 10.

Tester, A.L. (1952) Reaction of tunas and other fishes to stimuli Part V: Notes on the response of a tropical fish (Kuhlia sandvicensis) to interrupted direct current Special Scientific Report: Fish. *US Fish and Wildlife Service*, 69–83.

Thrane, M. (2004) *Environmental impacts from Danish fish product*. PhD-thesis, Department of Development and Planning, Denmark, 535 pp.

Tricas, T.C. (2001) The neuroecology of the elasmobranch electrosensory world: Why peripheral morphology shapes behavior. *Environmental Biology of Fishes* **60**, 77–92.

Van Beek, F.A. (1998) Discarding in the Dutch beam trawl fishery. ICES CM 1998/BB:S, 28 pp.

Van Beek, F.A., Van Leeuwen, P.I. and Rijnsdorp, A.D. (1990) On the survival of plaice and sole discards in the otter-trawl and beam-trawl fisheries in the North-Sea. *Netherlands Journal of Sea Research* **26**, 151–160.

Van Marlen, B. (1997) Alternative Stimulation in fisheries. Final report for European commission, 190 pp.

Van Marlen, B., de Haan, D., Van Gool, A. and Burggraaf, D. (2009) The effect of pulse stimulation on marine biota – Research in relation to ICES advice – Progress report on the effects on benthic invertebrates, IMARES C103/09, 53 pp.

Van Marlen, B., Wiegerinck, J.A.M., Van Os-Koomen, E.. *et al.* (2011) Vangstvergelijking tussen pulskorschepen en een conventioneel boomkor-vaartuig, IMARES C122b/11, 65 pp.

Van Stralen, M.R. (2005) De Pulskor. marinX-rapport 2005.26, 26 pp.

Vanden Broucke, G. (1973) *Further investigations on electrical fishing*. ICES C.M. 1973/B:14. 5pp.

Vanden Broucke, G. and Van Hee, J. (1976) Ontwerp van rapport: electro-visserij op tong. Internal report Fisheries Research Station, Ostend, 11 pp.

Vanden Broucke, G. and Van Hee, J. (1977) *Vorderingsverslag Over de Electrovisserij op Tong en Garnalen*. Internal report Fisheries Research Station, Ostend, 15 pp.

Verschueren, B. and Polet, H. (2009) Research summary on hovercran: hovering pulse trawl for a selective Crangon fishery. *Institute for Agricultural and Fisheries Research*, 23.

Verschueren, B., Vanelslander, B. and Polet, H. (2012) Verduurzaming van de garnalenvisserij met de garnalenpuls: eindrapport. ILVO mededelingen, ILVO, Institute for Agricultural and Fisheries Research, 102 pp.

Vibert, R. (1963) Neurophysiology of electric fishing. *Transactions of the American Fisheries Society* **92**.

Vibert, R. (1967) *General Report of the Working Party on the Applications of Electricity to Inland Fishery Biology and Management*. Fishing News, London.

Walker, M.K., Yanke, E.A. and Gingerich, W.H. (1994) Use of electronarcosis to immobilize juvenile and adult northern pike. *Progressive Fish-Culturist* **56**, 237–243.

Woolmer, A., Maxwell, E. and Lart, W. (2011) SIPF C0083 - Effects of electrofishing for Ensis spp. on benthic macrofauna, epifauna and fish species. Seafish Report SR652, 60 pp.

Yu, C.D., Chen, Z.H., Chen, L.Y. and He, P.G. (2007) The rise and fall of electrical beam trawling for shrimp in the East China Sea: technology, fishery, and conservation implications. *Ices Journal of Marine Science* **64**, 1592–1597.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Electrical fields in water.