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Electrofishing for Razor Clams (*Ensis siliqua* and *E. arquatus*): Effects on Survival and Recovery of Target and Non-Target Species

Fiona Murray[1], Philip Copland[2], Philip Boulcott[2], Mike Robertson[2] and Nick Bailey[2]

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Fiona Murray[1], Philip Copland[2], Philip Boulcott[2], Mike Robertson[2] and
Nick Bailey[2]

[1] Razorclam Fishermen's Forum; [2] Marine Scotland Science

Razor clams (*Ensis siliqua*) caught near Skye, Scotland

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This report presents the results of marine and freshwater scientific work carried out by Marine Scotland Science.

Marine Scotland Science
Marine Laboratory
375 Victoria Road
Aberdeen
AB11 9DB

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Executive Summary

Trawling and tank based trials were conducted to assess whether electrofishing (which is currently prohibited under EU regulations) for razor clams (*Ensis siliqua* and *E. arquatus*) affects survival and behaviour patterns in *Ensis* spp. and non-target species.

Boat trials in a number of areas identified that the main non-target species most likely to be affected by this fishery are starfish species, crab species (predominantly hermit crabs), flatfish and sandeels. No mortalities were recorded as a direct result of the fishing equipment or electric field generated and any induced behavioural responses in non-target species were exhibited for a maximum of 10 minutes following exposure. However, during this time stunned animals may be vulnerable to predation.

Tank trials indicated that exposure to an electric field typical of that generated through electrofishing by the vessels involved in this project did not affect short term (5 days) survival in razor clams, surf clams, starfish or hermit crabs.

These results suggest that electrofishing for razor clams does not have immediate or short term lethal effects, or prolonged behavioural effects, on vertebrate or invertebrate species exposed to the electric field generated. Further research is required to determine medium and long term effects. However, as electrofishing has a very low short term impact on non-target species and the seabed it warrants consideration as a viable fishing method for the commercial razor clam fishery in Scotland within sustainable limits.

This project set out to examine the electrofishing process and the potential localised effects on associated fauna. The study did not address the broader question of long term sustainability of razor clam populations under various levels of commercial fishing activity. This report does not offer any advice on the amount of fishing effort which could be applied in the different areas supporting razor clam populations. The authors recognise the need for such assessments to take place and recommend that the next stage should be quantitative assessments of stock size towards the development of a sustainable fishery scaled to the size of the resource.

Introduction

Razor clams (*Ensis* spp. also known as razorfish or, more colloquially, “spoots” in Scotland) are common burrowing bivalve molluscs found in sandy intertidal and subtidal areas throughout Europe (Muir 2003). They burrow in sandy sediments and position themselves perpendicular or diagonal to the seabed with their valves and siphons extended into the water column to suspension feed. When threatened they are able to rapidly withdraw deep into the sediment using a strong muscular foot (Muir 2003). In Scottish waters there are two commercially important species: *Ensis arcuatus*, colloquially known as bendies; and the larger and more valuable pod razor *Ensis siliqua* (Breen et al. 2011) which have different habitat preferences but can occur in the same areas. *E. arcuatus* inhabits coarse sandy areas which are partially sheltered (Breen et al. 2011). It can reach 180 mm in length and reaches sexual maturity between 73 and 130 mm (Muir and Moore 2003). *E. siliqua* generally prefers more sheltered areas with finer sand or muddy sand (Breen et al. 2011). In Scottish waters they are slow growing, taking 4-5 years to reach 100 mm, in comparison to 3-4 years in Wales and 1 year in Portugal. They also mature at larger sizes: between 118 - 140 mm in Scotland compared to between 60 – 100 mm in Portugal (Muir and Moore 2003). Both species require oxygenated sands and have a low tolerance of reduction, where low oxygen levels cause anoxic conditions within the sand, indicated by a characteristic black colouration below the surface (Holme 1954). As such, populations may be vulnerable to organic enrichment and increased freshwater runoff (Muir 2003) which can lead to a reduction in sediment oxygen levels. Razor clams are highly mobile and the ability of individuals that live on the edge of a fished ground to rapidly move into a depleted bed following fishing activity can lead to an overestimate of the abundance of the species and its ability to recover. This can lead to intense and sustained fishing effort of known fishing grounds as has been observed in Spain (1980s), Portugal (1990s) and Ireland (2000s) where profitable razor clam fisheries have been depleted (Fahy 2011). Once depleted, studies on Irish populations have shown that razor clam stocks are very slow to recover (Fahy 2011).

Ensis Fishery in Scotland

At present the market preference is for the larger and more valuable *E. siliqua* (Muir and Moore 2003) which are priced by size (small, medium and large) for live animals (N. Grieve pers. comm.). *E arcuatus* are all sold at the same price and generally at a lower value per kilo than *E. siliqua*. *Ensis* spp. caught in Scottish waters supply a limited market in the UK (mostly restaurants), shrinking Spanish and Portuguese markets, and, for *E. siliqua*, a rapidly growing market in South East Asia, predominantly in China (J. Grieve and A. Forbes pers. comm.). There has been a small fishery in Scotland since at least 1990 (Hauton et al. 2011), which has steadily grown (Figure 1). Razor clams were first mentioned in the Scottish Sea Fisheries Statistics in 1994, when around 43 tonnes were landed in Scottish ports valued at £60,000 (Muir 2003). By 1997 landings were up to 200 tonnes worth £500,000 (Scottish Government 2013a), and in recent years reported landings of *Ensis* spp. have increased to 526 tonnes in 2008 and to 900 tonnes in 2012 (Scottish Government 2013b). The value of the 2012 landings in Scotland was £2,559,000. *Ensis* spp. are the main species (defined as where more than 20 tonnes of a given species were landed in 2010) at Anstruther, Mallaig, Oban, Ayr and Campbelltown (Scottish Government 2013b).

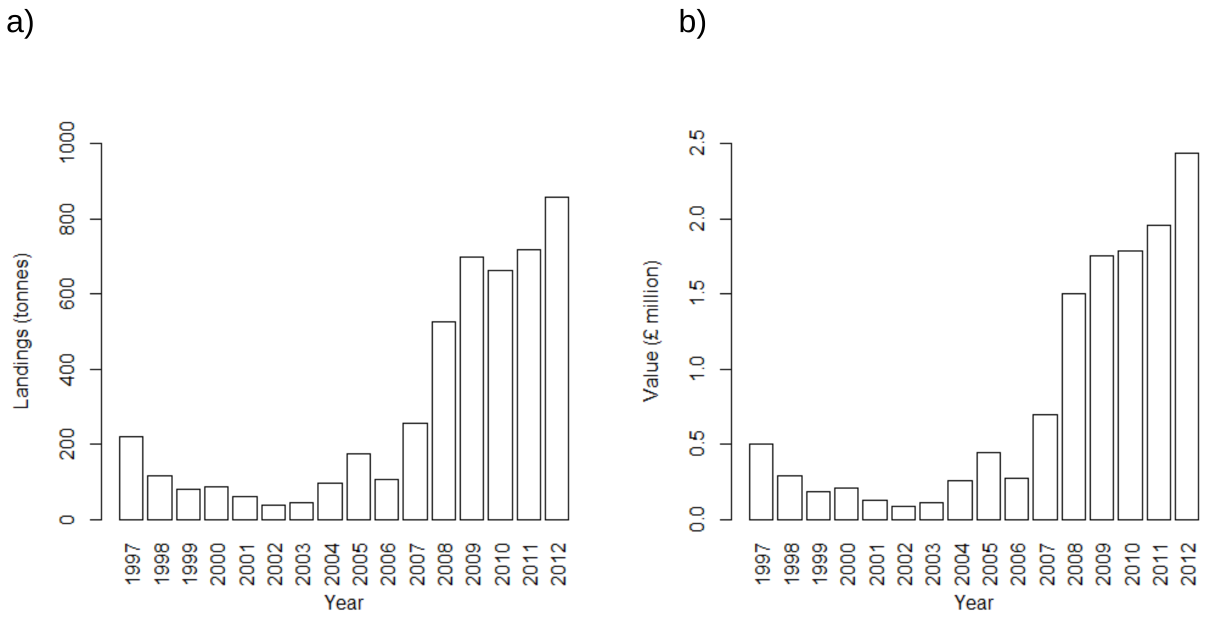

Figure 1: Scottish landings of *Ensis* spp. 1997-2012 by tonnage (a) and value (b). Source: Scottish Sea Fisheries Statistics 2012 (Scottish Government 2013b).

Available information on the size and extent of Scottish razor clam stocks is limited. There are no stock estimates and population dynamics are poorly understood. At present there are few measures limiting this fishery as there are no quota systems and no total allowable catch (TAC) figures (Hauton 2011) however, from Autumn 2014 vessels will require a licence to land razor clams. Currently the only restriction on landings is a minimum landing size (MLS) of 100 mm (EU Regulation 850/98, Annex XII), which is set for the genus and applied to all European stocks. This is considered to be too low to ensure that all individuals in Scottish waters have reached sexual maturity prior to capture (Muir 2003). Under management proposals for Inshore Fisheries Groups (Scottish Government 2013c) there is a suggestion that the MLS should be increased for Scottish landings.

Fishing Methods

Salting and Hand-Pulling

Historically, razor clams were collected from Scottish beaches during low spring tides, often as an additional source of income for crofters. This was usually done by “salting” whereby salt is poured onto indentations in the sand which indicate the presence of razor clams. Salting irritates the clams into emerging from their burrows and they can then be collected. This method has been adapted for divers working in sub-tidal waters. Salt is dissolved into hot seawater to create a hyper-saline solution that divers take down in small watering cans. The solution is poured onto the indentations in the seabed and the clams will usually emerge within 15 minutes. Salting in the intertidal zone causes a localised increase in salinity which dissipates following a flood tide and has not been shown to have any effect on benthic communities (Constantino et al. 2009). When used by divers, however, localised increased salinity at the seabed can be persistent (Muir 2003). Skilled divers are also able to pick razor clams directly out of the sediment by gripping the valves and pulling the clam up with a twisting motion. This hand-pulling technique requires a great deal of skill and practice to perfect but can be very effective. It is much more difficult in intertidal areas as the clams can detect footsteps approaching and withdraw into the sand (Muir 2003). Both intertidal salting and hand-pulling by divers are considered environmentally friendly (Constantino et al. 2009). Neither has associated bycatch nor impacts on the benthic habitat, however, both methods are low yield and are unlikely to be widely adopted by the commercial fishery (J. Grieve pers. comm.).

Hydraulic and Suction Dredging

Two dredge types have been developed for fishing Ensis species: the suction dredge and the hydraulic dredge. Suction dredges operate by using a suction pump to remove razor clams and any other animals living in the seabed, which are then pumped through a pipe onto the boat. Their use in the Scottish razor clam fishery has been reported in Loch Gairloch and Orkney (Hall et al. 1990). Hydraulic dredging is thought to be the favoured dredge method in Scotland and its impacts are the best studied (Hall et al. 1990, Tuck et al. 2000, Hauton et al. 2003, Hauton et al. 2007). It involves pumping water into the seabed to fluidise the sand (Tuck et al.

2000) in the first instance, and then dragging a metal frame box dredge through the fluidised sand to harvest any animals living in the seabed. The seabed itself can remain fluidised for some time after dredging (over 11 weeks, Tuck et al. 2000, Figure 2), and traces of the dredged trench can remain visible for three years (Gilkinson et al. 2003). Repetitive fluidising of sediment has the potential to make the substratum inhospitable to species which prefer finer particulates, including *E. siliqua*, as the smallest particles may be lost, changing the properties of the seabed (Fahy 2011). Hydraulic dredging can remove up to 90 % of the target species from the seabed (Hauton et al. 2003), however, there are high levels of bycatch associated with this method. Whilst in some parts of Scotland over 70 % of the catch are Ensis species (Tuck et al 2000), in the Clyde it can be far lower (25 %, Hauton et al. 2003) due to the high abundance of the burrowing urchin *Echinocardium cordatum*. Dredging is restricted in sheltered areas to protect sensitive habitats under the Inshore Fishing (Scotland) Act 1984 (Tuck et al. 2000).

Figure 2: Photograph of cross section of water jet dredge track with depth marker in place. Banding on vertical rod = 5 cm. (Figure 4 in Tuck et al. 2000).

Dredging has advantages over diver caught clams (by salting or hand-pulling) as it results in a larger catch. This catch, however, is generally of a poorer quality as valves can be chipped or broken in the dredge and the clams tend to accumulate grit in their valves during dredging, making them more difficult to sell on the more profitable live market. Dredging for razor clams is not currently believed to be widespread in Scottish waters. There have been several studies conducted on the immediate and short term impacts of dredging in Scotland (Hall et al. 1990, Tuck et al. 2000, Hauton et al. 2003), but the widespread long term effects have been more comprehensively studied in Ireland. As commercial SCUBA diving for shellfish is illegal in Ireland, Irish razor clam stocks have been exploited almost exclusively using dredges. Gormanstown bed in Co. Meath was heavily exploited using hydraulic dredges between 1997 and 2005 which impacted on biodiversity. In the seven years following, the number of species present in the seabed did not recover to pre-1997 levels. Furthermore, the species composition changed. Scavengers and opportunistic deposit feeders are now more abundant and *E. siliqua* stocks have never recovered. *E. siliqua* has been replaced with another suspension feeding bivalve *Lutraria lutraria* (Fahy 2011).

Electro-Fishing

Since 2004 divers have been using electricity to stimulate razor clams to emerge from the seabed (Breen et al. 2011). Up to three pairs of electrodes are slowly dragged across the seabed, followed by divers who collect emerging razor clams (Video A1). Electrofishing is currently illegal in European waters (EU Regulation 850/98, Article 31) and at present any vessel caught using electrical fishing gear in Scotland will have their equipment confiscated and face a fine of up to £2,000. It is proposed that this penalty will rise to a maximum fixed penalty of £10,000 in late 2014 (Scottish Government 2014) to address potential financial gain. Despite these measures, electrofishing is likely to be a widespread method of collecting razor clams in Scotland as alternative methods available are either far less efficient (hand pulling and salting) or yield a poorer quality, less valuable product (broken shells and excessive grit in dredged razor clams). Marine Scotland estimated that there were 14 – 27 vessels actively fishing for *Ensis* spp. in Scotland throughout the year in 2011 (Breen et al. 2011). Under new 2014 legislation vessels will require a licence to land razor clams and licences will be issued this year (Marine Scotland Licencing pers. comm.). Within the fishing community it is believed that all boats currently harvesting razor clams in Scotland are electrofishing to some degree (R. Grieve pers. comm.), and that this is the only method currently available that is economically viable (J. Grieve and A. Forbes pers. comm.).

Although electrofishing is not a new concept (Stewart 1967) there has been a recent resurgence in research into electrical fishing techniques in Europe. Where there is evidence to support the assertion that electrofishing can be less damaging to the marine habitat or reduce bycatch in comparison to conventional fishing methods, derogations have been issued to allow electrofishing for specified target species in European waters. Recent research has focused on the effects of electric trawling for flatfish by the Dutch fishery (van Marlen et al. 2014) and the brown shrimp *Crangon crangon* by the Belgian fishery (Polet et al. 2005a). Studies on the effects of electric trawling on benthic invertebrates have concluded that effects are low, but that subsequent survival and food intake rates are affected in some species (van Marlen et al. 2009). Research on the effects of electrofishing for *Ensis* spp. is limited. Organisms are likely to be exposed to an electric field for far longer in the razor clam fishery than the 4 s exposure used in the van Marlen et al. (2009) study. Whilst a fishing derogation was issued in Ireland in 2010 to develop an electric dredge for razor clams (Breen et al. 2011), to date no research has been published on this technology. The only experimental study on electrofishing effects in UK waters so far was conducted in Wales (Woolmer et al. 2011) and focused on short term effects on behaviour and medium term effects on biodiversity. They found organisms to be stupefied and disorientated in the minutes following electrofishing activity but found no change in species composition or abundances in the short (24 hour) and medium (28 day) terms.

Objectives of this Study

This study aimed to investigate the immediate behavioural and short term survival effects of electrofishing on *Ensis* spp.; identify the main non-target species likely to be affected by electrofishing; determine whether exposure to electrofishing affects invertebrate survival in the short term; and to define the field properties of the electrodes used through a combination of *in situ* boat observations and tank based experiments.

The specific objectives for the boat trials were:

- To monitor and record recovery rates of *Ensis* spp. following emergence from the sediment stimulated by the electrodes
- To identify non-target species which may be affected by *Ensis* electrofishing
- To record the recovery of non-target species following exposure to electrofishing
- To determine if electrofishing may cause mortalities in sandeels
- To make video observations of the impact of the electric rig on the seabed.

The objectives for the tank experiments were:

- To determine the properties of the electric field generated by electrofishing
- To record the behavioural response to, and recovery from exposure to, an electric field in *E. siliqua*
- To monitor the short term survival of *E. siliqua* (for five days) following exposure to an electric field
- To record the behavioural response to, and recovery from exposure to, an electric field in three non-target invertebrate species
- To monitor the short term survival of three non-target invertebrate species (for five days) following exposure to an electric field.

This study did not make any attempt to assess the state of the numerous razor-clam populations around Scotland or to offer advice on the likely scale of fisheries in any of the areas. Regardless of the method of fishing, it is clear that the level of fishing activity and removal rate of razor clams needs to be carefully aligned with the available resource in order to maintain a sustainable fishery. The authors recognise that appropriate stock assessments will necessarily form the main objective of any follow up work conducted in future studies.

Materials and Methods

Boat Trials

Vessels and Electrofishing Equipment

The study was carried out on three commercial inshore fishing vessels (Table 1). Each vessel was equipped with an AC generator and a rig of either two (FV Lucky Lucy) or three pairs of brass electrodes (FV Ensis and FV Nicola Jane). The electric rig on these vessels was connected by copper cables to the generator via a transformer to reduce the output voltage to ~ 25 v and the current to ~ 80 A (Table 2). These voltages were the maximum output possible for the equipment used on these vessels. Previous reports on electrofishing have looked at DC systems (Woolmer et al. 2011) where the electrodes have been shown to corrode and release chlorine gas when the generator is switched on. This has not been observed using an AC system either in tanks (see below) or whilst fishing (Video A1). Furthermore, razor clam divers have reported metal components of the divers' equipment, such as the inflator hose connecting the drysuit and the exposed metal components of regulators and cylinders also corrode when a DC system is used (R. Grieve pers. com.). As the use of electric currents is prohibited under Article 31 of EU regulations 850/98 "unconventional fishing methods" a derogation was required to legally use the equipment in this study. Derogations for each vessel were issued by Marine Scotland Licencing on the basis that a research scientist was on board at all times the equipment was in use.

Table 1: Vessel data (from Marine Management Organisation (MMO) lists of registered vessels, UK Government 2014)

Vessel	FV Ensis	FV Nicola Jane	FV Lucky Lucy
Length	10.65	11.32	11.25
Port letters and number	OB1004	OB1043	SR48
Administrative port	Oban	Oban	Ayr
Home port	Fort William	Oban	Ayr
Launch port	Pittenweem	Mallaig	Largs
Registry of Shipping	C18291	A16424	B10363
Licence number	41516	50107	41644
Skipper	David Simister	Robbie Grieve	Michael Crowe

Study Areas

The study was carried out in three sites around Scotland: East Fife, Loch Nevis and the Clyde sea area around the Isle of Cumbrae (Figure 3). The sites are in shallow inshore waters (< 10 m) with a sandy seabed; and are currently viable fishing grounds used by the vessels. Measurements of seawater salinity (using a hand held optical refractometer) and temperature at the seabed were taken at each location (Table 2). Sediment cores (5 cm diameter, 10 cm high, 196 cm^3) were collected (6 in Fife and Loch Nevis, 4 in the Clyde) and particle size analysis was conducted (Table A1, Figure A1).

Table 2: Location, water temperature, salinity, target species and electrical output for each vessel.

Vessel	FV Ensis	FV Nicola Jane	FV Lucky Lucy
Date	24 Sept 2013	30 Sept 2013	9 Dec 2013
Location	East Fife	Loch Nevis	Isle of Cumbrae
Target species	*Ensis siliqua*	*Ensis arcuatus*	*Ensis siliqua*
Water temperature (°C)	12	12	9
Salinity	34	31	33
Voltage	24	24	Missing value*
Current (A, mean ± 1 SD)	83 ± 2.07	82 ± 1.73	80

* The transformer on this vessel did not have a voltage meter, however, current was standardised across vessels so the voltage is believed to be comparable.

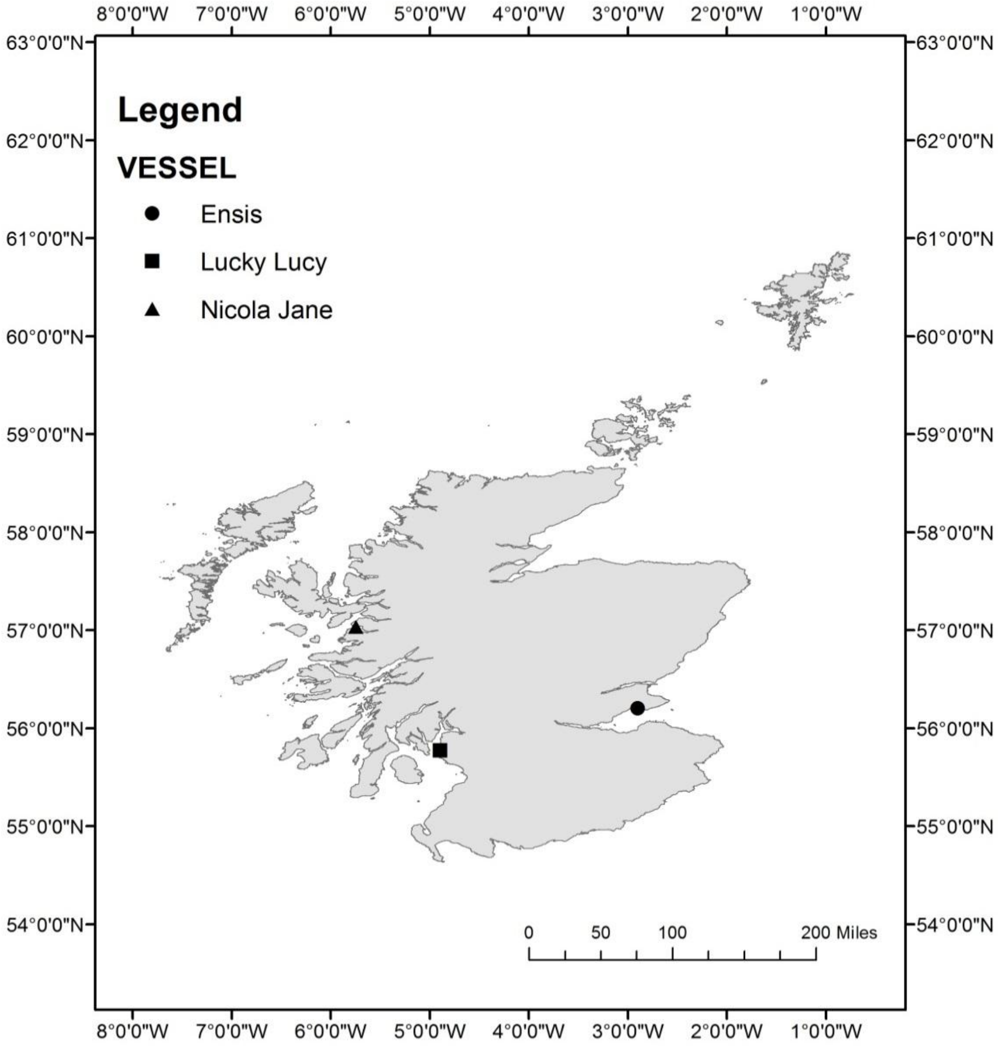

Figure 3: Map of trial locations by vessel. Projection: WGS1984.

Experimental Design

Electrical Stimulus

An electrical stimulus was applied to the seabed, designed to mimic commercial electrofishing activity as closely as possible. The vessel anchored in shallow water and let out a 100 m line. Pairs of brass electrodes connected to an onboard generator were lowered to the seabed to tow behind the vessel (a more detailed description of the electrical equipment is provided below in the Tank Trials section). Once the line was let out, the diver entered the water and took up position behind the electrodes. The diver instructed the skipper when to start the generator powering the electrodes and to start the winch, either through pulling a rope attached to a clanger on the vessel or via a divers voice communication unit installed in the mask. The on-board winch was then used to drag the vessel towards the anchor, towing the brass electrodes across the seabed, a technique known as fly-dragging (Figure 4). The speed at which the vessel is fly-dragged was determined by the diver based on visibility and the population density of razor clams (mean speed of 3 m min^{-1}). When the electrodes exited a patch of razor clams, the diver signalled the skipper to turn off the electrodes. Replicate short tows were conducted: seven on the FV Ensis, six on the FV Nicola Jane and four on the FV Lucky Lucy.

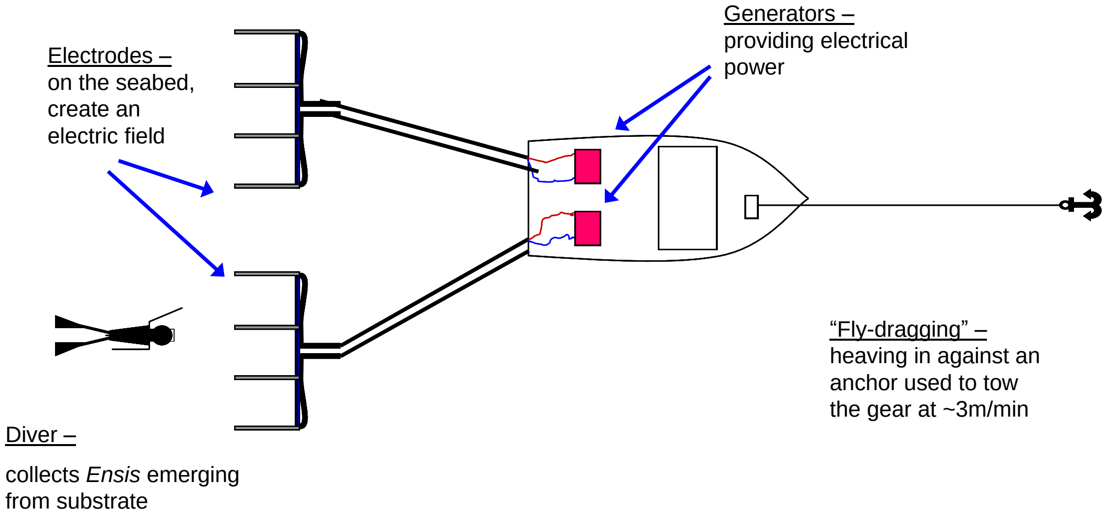

Figure 4: Schematic diagram of electrofishing for *Ensis* spp. (Figure 1.7, Breen et al. 2011)

In situ Recovery

Once the electrodes were switched off, the diver placed quadrat frames (1 m^2 base, n = 2) where the electrodes had been active within minutes of switching off the electricity (time between electrodes turned off and quadrats placed: mean ± sd = 2 min 13 s ± 54 s). A high definition camera (GoPro Hero3 Black Edition, Woodman Labs, USA) was mounted to the top of each frame and used to record high-definition, wide-angle video footage (resolution: 1920 x 1440 pixels, 48 frames s^{-1}) to a 32 GB memory card accessed after recovery of the cameras. Video footage was downloaded to a laptop computer between replicate runs. The footage recovered was used to observe the recovery of *Ensis* spp. and other species, and to identify the non-target species encountered during electrofishing activity. The quadrats were left *in situ* until all the animals within the quadrat had recovered or for a maximum of 30 minutes. The quadrat frames were rotated between electrode pairs between runs.

Four replicate videos were taken for each pair of electrodes (12 videos for the FV Ensis and FV Nicola Jane, 8 videos for the FV Lucky Lucy).

The recovery start times were recorded as the first sign of movement from each individual animal in the videos after the electrodes were turned off. The quadrat placement time was recorded as the recovery time for non-target species that were displaying normal movement patterns when the quadrat was placed. This gave a conservative estimate of recovery times. For *Ensis* spp. missing values for the recovery start times due to recovery starting before the quadrat was placed were omitted from recovery analyses, but these individuals were accounted for in calculating the population densities. A recovery end point was also noted for *Ensis* spp. when the clams had less than 1 cm of shell left showing above the sediment. The shell lengths of the razor clams were estimated from freeze frame stills taken from the videos. In order to minimise error due to visual distortion in the videos, shells were measured relative to the side of the quadrat they were closest and most parallel to. Lengths were recorded to the nearest cm. Videos from the FV Lucky Lucy were excluded from the analysis owing to logistical problems including: time constraints forcing FV Lucky Lucy trials to be conducted in December; use of a sheltered bay as the weather was poor, which restricted the space available for fly-dragging; and low light levels resulting in a lower quality of video footage in which it was more difficult to distinguish organisms from the seabed.

Table 3: Location, depth and speed data for tows conducted and analysed.

Date	Vessel	Trawl	Electrodes on			Electrodes off			Length of trawl				
			Time (min)	Location	Depth (m)	Time	Location	Depth (m)	Time (min)	Distance (m)	Direction	Speed (m min^{-1})	Organism exposure time to electric field (decimal min)
24 Sept 2013	Ensis	1	0948	056°12.133 N 002°53.915W	4.1	0952	056°12.133 N 002°53.923 W	4.1	4	4	270°	1	3
24 Sept 2013	Ensis	2	1040	056°12.132 N 002°53.925 W	4.2	1044	056°12.132 N 002°53.934 W	4.2	4	9	270°	2.25	1.33
24 Sept 2013	Ensis	3	1105	056°12.138 N 002°53.947 W	4.1	1107	056°12.140 N 002°53.948 W	4.1	2	3	344°	1.5	2
24 Sept 2013	Ensis	4	1251	056°12.231 N 002°54.464 W	5.8	1253	056°12.232 N 002°54.462 W	5.8	2	2	048°	1	3
24 Sept 2013	Ensis	5	1438	056°12.112 N 002°54.097 W	6.8	1446	056°12.108 N 002°54.085 W	6.8	8	14	120°	1.8	1.67
24 Sept 2013	Ensis	6	1517	056°12.100 N 002°54.068 W	7.2	1519	056°12.101 N 002°54.064 W	7.2	2	4	065°	2	1.5
24 Sept 2013	Ensis	7	1623	056°12.104 N 002°54.042 W	7.8	1626	056°12.104 N 002°54.039 W	7.8	3	3	089°	1	3
30 Sept 2013	Nicola Jane	1	1215	057°01.699 N 005°44.782 W	8.0	1217	057°01.695 N 005°44.766 W	7.9	2	17	114°	8.5	0.35
30 Sept 2013	Nicola Jane	2	1256	057°01.688 N 005°44.763 W	8.4	1258	057°01.690 N 005°44.753 W	8.2	2	10	069°	5	0.6
30 Sept 2013	Nicola Jane	3	1332	057°01.704 N 005°44.743 W	7.2	1334	057°01.703 N 005°44.732 W	7.9	2	11	099°	5.5	0.55
30 Sept 2013	Nicola Jane	4	1418	057°01.702 N 005°44.730 W	8.1	1419	057°01.698 N 005°44.723 W	8.2	1	10	136°	10	0.3
30 Sept 2013	Nicola Jane	5	1503	057°01.689 N 005°44.736 W	8.8	1505	057°01.690 N 005°44.728 W	8.7	2	8	077°	4	0.75
30 Sept 2013	Nicola Jane	6	1618	057°01.686 N 005°44.729 W	8.6	1620	057°01.687 N 005°44.717 W	8.6	2	12	081°	6	0.5

Sandeel Recovery

A diver survey was conducted in Ayrshire to focus on potential impacts on sandeels (*Ammodytes marinus*) caused by electrofishing. Sandeels are fish which bury into the seabed, and as such are potentially at risk from electrofishing activity. Sandeel species, notably *A. marinus*, are ecologically important as prey for breeding seabirds such as puffins, guillemots and kittiwakes (Wanless et al. 2005). Two short transects (055° 18.780 N, 004° 50.488 W - 055° 18.743 N, 004° 50.594 W, and 055° 18.743 N, 004° 50.594 W - 055° 18.709 N, 004° 50.698 W) were surveyed by divers from the FV Ensis launching out of Girvan (14 May 2014). Electric rods were fly-dragged across the seabed as described above. Divers followed the rods and collected any stunned sandeels in a hand held net. The survey was recorded by Go-Pro cameras mounted to the diver and the number of sandeels collected was counted from the video footage. Stunned fish were placed in a bucket of seawater on deck within 10 minutes of collection from the seabed and their recovery, taken as restoration of normal swimming behaviour, was monitored. The number of transects was limited by mechanical failure of the winch the vessel was using to fly-drag.

Physical Impact of Fishing Gear on the Seabed

An additional diver survey was conducted in Loch Nevis to make observations on the impact of the electric fishing equipment on the seabed. A second diver entered the water to video normal fishing activity conducted by a diver fisherman with a mounted GoPro camera.

Statistical Analysis

Linear models were constructed to test for the effects of species identity and location in non-target species recovery and for the effects of species identity, location, population density and shell length on the recovery start and end times of *Ensis* spp. Criteria for normality and homogeneity of variance were met (following Quinn and Keough 2002) for the recovery times of non-target species and the recovery end times for *Ensis* spp.. However, during the initial model building phase of the *Ensis* recovery start time analysis, diagnostic residual plots indicated the presence of heterogeneity of variance due to differences in density variances, not accounted for by the fixed effects. A linear model with a generalised least squares(GLS) estimation was used, which allows variance functions to be explicitly included to model the variance structure, avoiding the need for data transformation. Therefore, a density-specific variance-covariate was included to model the variance (Pinheiro &

Bates 2000). Following the inclusion of density-specific variance covariates, diagnostic residual plots indicated homogeneity of variance. Parameters in the final models were estimated using restricted maximum likelihood (REML, following West et al. 2007). REML was used in preference to maximum likelihood (ML) as it accounts for the loss of degrees of freedom in estimating the fixed effects, thus producing unbiased estimates of the covariance parameters (West et al. 2007). All statistical analyses were carried out in the R statistical and programming environment (version 2.15.0, R Development Core Team). GLS analysis was conducted using the nlme package (v3.1-101; Pinheiro et al. 2011) in R.

Tank Trials

Two large fibreglass stimulus tanks (Tanks A and B, 3.76 m x 1.86 m x 1 m deep) and five smaller fibreglass holding tanks (Tanks C and D: 1 m diameter x 0.80 m deep; Tanks E and F: 1.07 m x 0.83 m x 0.6 m deep; Tank G: 0.7 m x 2.1 m x 0.82 m deep) were assembled at Loch Leven Shellfish Ltd, Onich, Scotland. Sand (30 cm deep in tanks A and B, 5 cm deep in tanks C-G, Table A1, Figure A1) was overlain with seawater (20 cm depth in tanks A and B, mean depth of 36 cm in tanks C-G) which was pumped continuously to all tanks from Loch Leven by a submersible pump at a depth of 15 m on a flow through system, and returned to the loch. Seawater temperature, salinity and dissolved oxygen were measured daily on all tanks for the duration of all experiments (Table A2). The sand in tank A was replaced between the initial survival trials and the later stimulus trials. No other tanks were used in the initial survival trials.

Electrical Tests

The electrical stimulus applied and the rig geometry used during vessel and tank trials represent one of a number of systems thought to be in use commercially. The illegal and unregulated nature of the fishery means that little information is available as to type of electrical stimulus and the construction and design of the electrode system as there is no defined industry or regulatory standard. The parameters used were those presented to the research team as being a “commonly used” commercial system. (J and R. Grieve pers. comm.). Observations, measurements and conclusions reported relate only to these specific gear parameters.

Tank tests were designed to look at the electrical properties of a fishing rig being used for harvesting razor clams in the Scottish fishery. All electrical tests were conducted in stimulus tank A and survival tests were conducted in both stimulus tanks A and B. The system used, supplied by Lochleven Shellfish Ltd., was an alternating current (AC) single phase version of the three phase system normally used on commercial vessels and the same type used on the FV Nicola Jane. One pair of brass electrodes (12.75 mm diameter, 2.3 m length) spaced 1 m apart was placed in each stimulus tank (A and B, Figure 5). They were supported by pieces of slate to prevent them sinking into the sand and connected to an auto-transformer connected to a generator. The input power was estimated as 10 kW. The transformed output voltages could be varied using rotary selector switches and varied from 16.6 – 25.89 v on no load. The auto-transformer was fitted with an RCD (Residual Current Device) and a remote kill switch to control the output. A Dinse type cable connector (positive locking) was used to connect the transformer to the deck cables. These were connected to the underwater electrode pair using a male to female Dinse plug set. For the survival experiments the 220 – 240 v, 50 Hz input was reduced to 25 v. The current passing between the electrodes (mean = 42 A) was lower than those recorded on the boats (mean = 82 A) as a lower current was required to deliver 25 v to one pair of electrodes rather than two or three pairs.

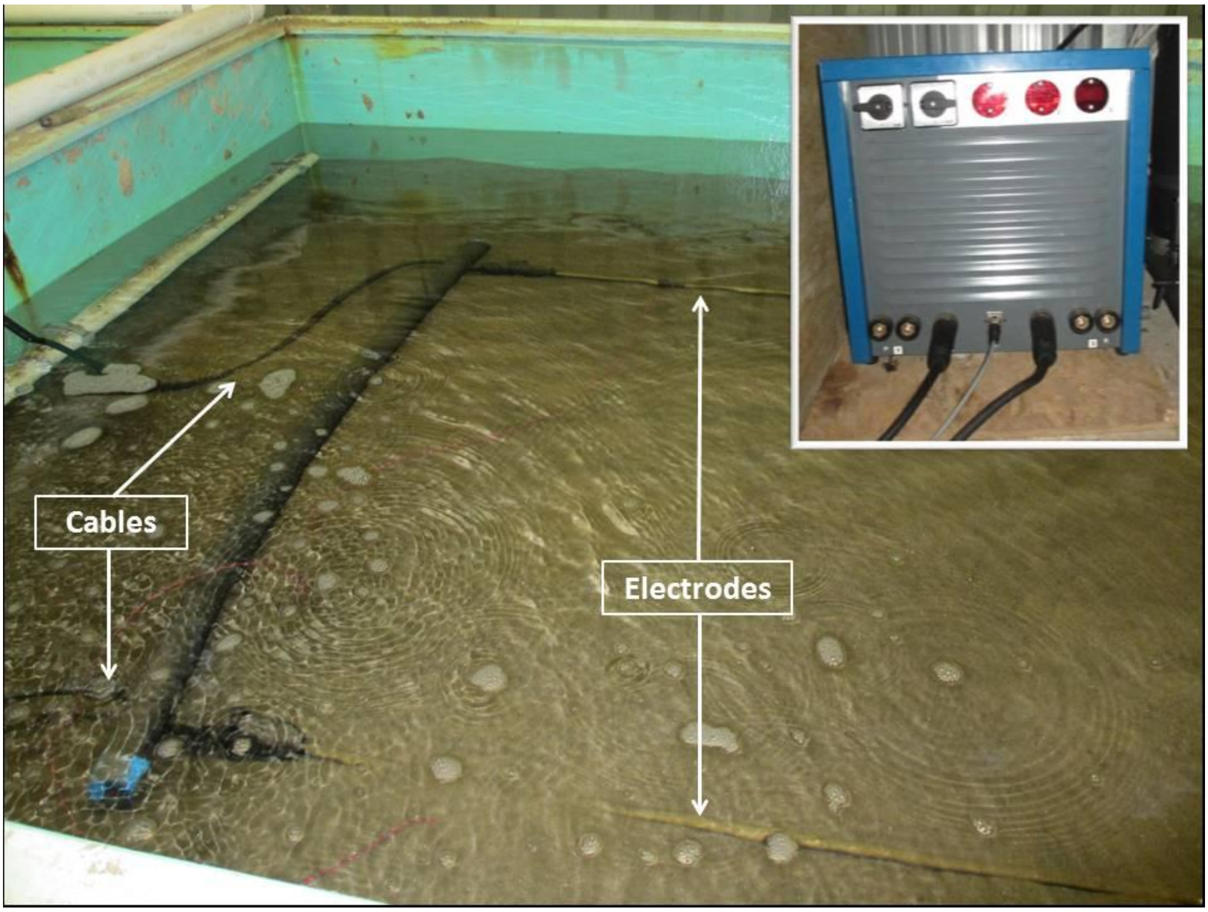

Figure 5: Set up of stimulus tanks (A and B). Electric rig is submerged and lying on the sand. It is connected to a transformer (inset) and controlled by a switch. An electric field is generated between the electrodes that stimulate razor clams buried in the sand.

A rig was constructed with test points at fixed distances to establish the effective field strength or voltage gradient around the electrodes (Figure 6). One electrode was used as the reference and voltages were measured at the measuring points using an AC voltmeter. The output waveform was recorded on a number of occasions (for example see Figure A2). Three different configurations were tested in order to establish voltages around the electrodes. The selector switches on the generation system matched the settings as reportedly used in the fishery, with the settings selected giving the largest power output.

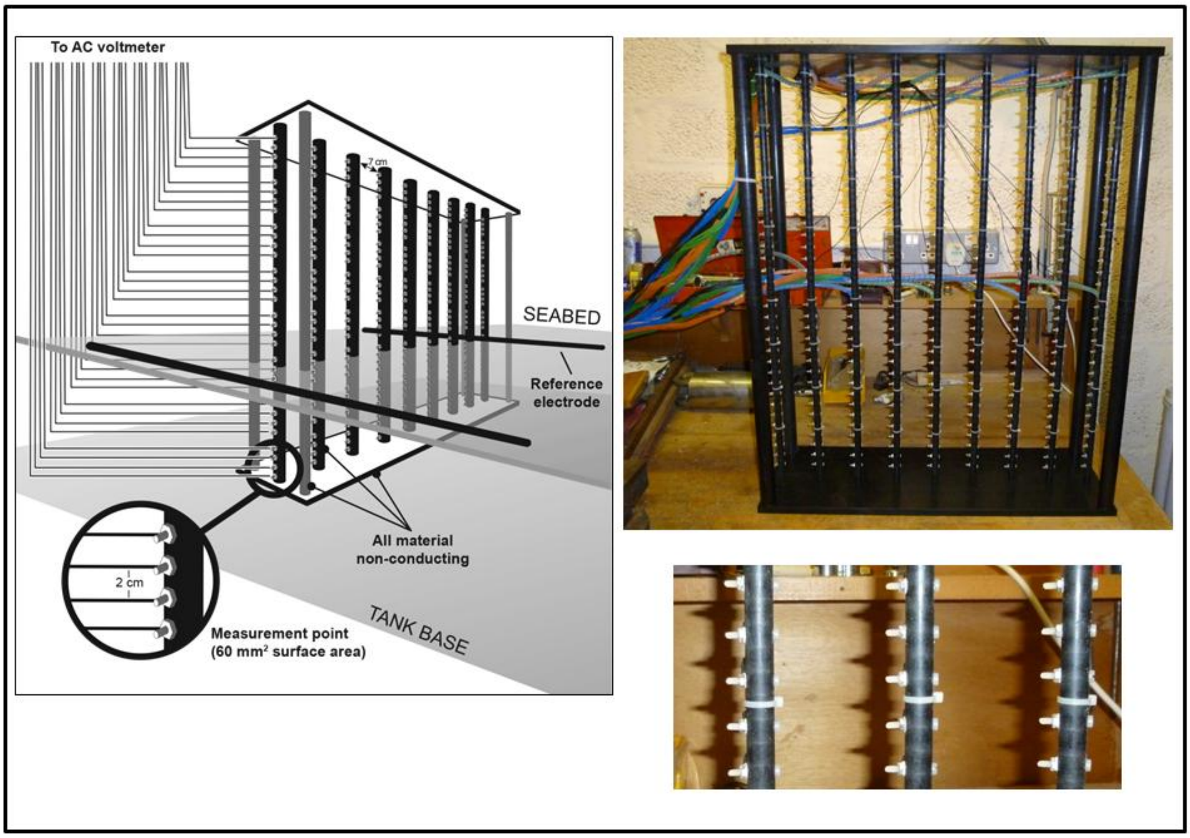

Figure 6: Schematic diagram and photographs of the test rig used to measure the properties of the electric field produced by the electrodes.

Configuration 1

The layout of electrodes in Configuration 1 was identical to that used by the commercial vessels involved in the project. The electrodes were placed on top of the sediment in the tank at 1 m separation. The reference electrode passed between vertical columns 7 and 8 of the measurement rig. In order to prevent the electrodes sinking into the sediment, small pieces of roofing slate were used below them to support the load. Additional wires were attached directly to the electrodes along their length in order to measure possible voltage drops that might occur due to the resistance of the electrode material. To ensure that no harmful contaminants might be released into adjoining tanks, and to evaluate if chlorine gas was being evolved at the electrodes, the water circulation system was disabled during the trials. Weighted upturned plastic boxes (200 cm^3 volume) were placed over a section of the electrodes to collect any gas released. Water in the collectors was tested at the end of the trial for chlorides using a Palin test (detects 0.1 – 3 mg/L Cl^-, DPD01 tablets used).

Configuration 2

The distance between the electrodes was reduced to 70 cm with the reference electrode remaining in the same position between columns 7 and 8. This allowed a fuller voltage plot to be made to investigate symmetry. This was necessary due to the limited dimensions of the measurement rig used that could not span to the voltage mid-point in the commercial electrode configuration.

Configuration 3

It had been reported by divers in the fishery that razor clams also emerge from the sediment on the outside of the electrodes in some instances, i.e. not between electrodes. In order to investigate this phenomenon the reference electrode was moved to between columns 4 & 5 of the measurement rig. Electrode spacing was retained at approximately 70 cm. This configuration allowed the field shape to be more closely investigated outside the electrodes.

Ensis Survival and Behaviour

All razor clams used in both survival and stimulus trials were collected by divers who hand pulled the clams in Loch Nevis and the Clyde Sea area near the Isle of Cumbrae. A preliminary survival trial was conducted in Tank A in September 2013. 44 individuals of *Ensis siliqua* were labelled with plastic identifying tags adhered to the shell surface with superglue, weighed, measured and allowed to burrow into the sand. Initial burrowing times were recorded and survival was monitored over a three week period.

Stimulus trials were conducted using *E. siliqua* in February 2014. Six individuals were introduced to both tanks A and B. Initial burrowing behaviour was recorded using high definition GoPro cameras mounted above each tank. Any individuals that did not burrow within 12 hours were replaced. Following successful burial, the razor clams were left for 24 hours to acclimate to the tanks. In order to account for possible tank effects the experiment was repeated four times over four consecutive weeks. Stimulus and control tanks were alternated weekly. Razor clams in the stimulus tank (Tank A on weeks 1 and 3, Tank B on weeks 2 and 4) were exposed to an electric field for 2 minutes, based on the observed exposure of subjects in the commercial fishery (v = 25, A = mean 42). An average exposure time of 1 min was calculated from fishing activity conducted on the FV Nicola Jane, 2 min exceeded the maximum recorded exposure time, and was therefore considered appropriate to give a cautious estimate of exposure effects. Current (LEM current clamp, Model LH1040) and voltage (Tektronix multimeter, Model TDS 3034) outputs to the electrodes were recorded (Table A3). Emergent and “kicking” behaviours during exposure were recorded. The razor clams were videoed for the duration of the stimulus and for one hour following the stimulus to record reburying behaviour.

Non-Target Species Survival and Behaviour

Individuals (n = 5) of the Atlantic surf clam *Spisula solida*, the sea star *Asterias rubens*, and the hermit crab *Pagurus bernhardus* were collected using non-electrical methods to examine the effects of electrofishing on non-target species. *A. rubens* and *P. bernhardus* were selected as these were the most frequently observed non-target species from the boat trial videos. *S. solida* were selected because they are known to emerge from the sediment on exposure to electricity, and there is the potential for fishing vessels to exploit electrofishing to harvest them (J. Grieve pers. comm.) *A. rubens* and *P. bernhardus* used in the trials were collected using *Nephrops* creels in Loch Leven. *S. solida* were dredged by the FV Ensis. Five stimulus and five control groups of five randomly assigned individuals of each species were used in six consecutive experimental runs to account for potential tank and run effects. Each group was individually transferred to the stimulus tank A. Stimulus groups were exposed to an electric field for two minutes and then transferred to holding tanks C-G to monitor survival over a five day period. Control groups were also transferred to the stimulus tank for two minutes and then transferred to holding tanks to eliminate handling effects. Current and voltage outputs to the electrodes were recorded for each run (Table A3).

Statistical Analysis

ANOVAs (Analysis of Variance) were used to test the relationships between the length of the shells and emergence time, the time of the first movement following the end of the electrical stimulus and the reburial times of the razor clams. A linear model was used to test the effects of species identity and electrical treatment on survival in the non-target species. All statistical analysis was conducted in R.

Results

Boat Trials

Observations

Razor clams were the dominant species at all sites, making up 73 % of individual organisms observed (145 of 200). Razor clam species were the only organisms evidenced in the quadrat videos to emerge from the sediment and, as such, all non-target species observed were epifaunal (species which live on, rather than in, the seabed, Figures 7 and 9). Species assemblages varied with site: in Fife *E. siliqua* was the only razor clam species observed, and epifaunal species observed were the sea mouse *Aphrodita aculeata*, the sea star *Asterias rubens*, crab species (predominantly hermit crabs), ophiuroids (brittle stars) and shrimp similar to *Crangon* spp. (Video A2 shows a sequence of video clips of *E. siliqua* from one quadrat placement). None of the ophiuroids or crustaceans could be identified to species level from the videos. In Loch Nevis there were two razor clam species, *E. siliqua* and *E. arcuatus*, and hermit crabs and gobies which could not be identified to species level (Video A3 shows a series of clips taken from sampling in Loch Nevis). In the Clyde *E. siliqua*, *A. rubens* and hermit crabs were observed. Several mobile epifaunal organisms were observed entering quadrats in Fife and Loch Nevis following placement: *Crangon* like shrimp, gobies, flatfish, *A. rubens* and crab species.

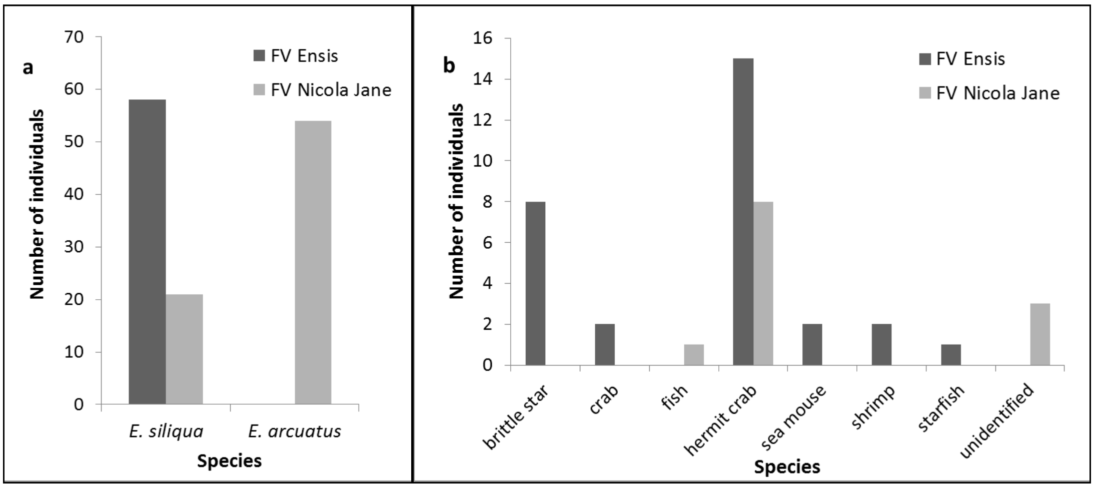

Figure 7: Number of each species observed in East Fife (FV Ensis) and Loch Nevis (FV Nicola Jane).

Tracks made by the electric rods were visible in the sediment but the physical impact on the seabed was minimal. The brass rods leave shallow indentations, less than 1 cm deep on the seabed which can be seen in the video footage (Video A1, Figure 8a). Occasionally debris on the seabed such as strands of kelp may get caught on the electric rig and dragged with it, increasing the physical impressions left on the seabed (Figure 8b). The divers also leave tracks in the sediment by dragging the bag that the razor clams are collected in (Figures 8c and d). Such disturbances are comparable to those left by the natural movement of debris in strong currents and would be expected to have a lower impact than the effects of bad weather.

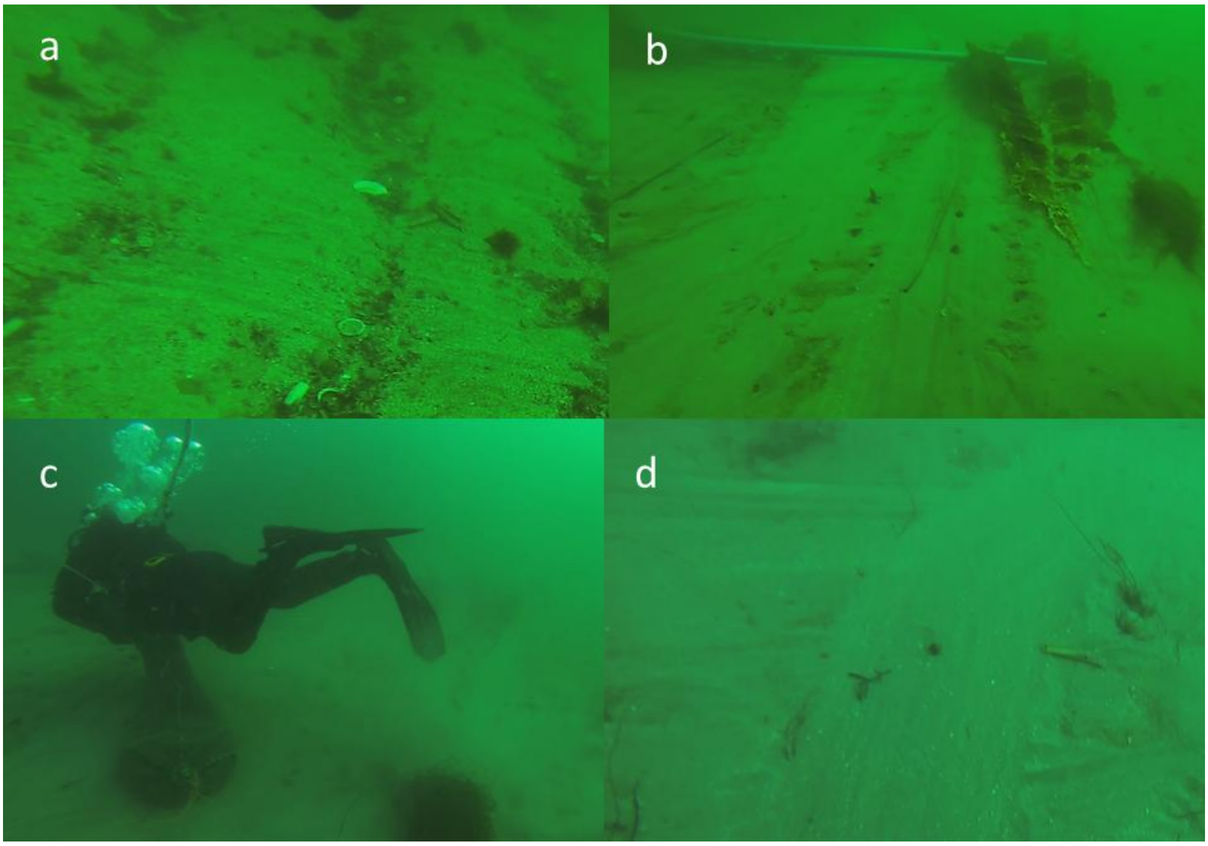

Figure 8: Freeze frame stills of impact on seabed. a) lines from the electrodes; (b) kelp fronds caught on electric rig; (c) diver dragging bag of razor clams; (d) track from the dragged bag of razor clams.

Ensis Species

Divers reported that some razor clams had re-buried prior to placing the quadrats. Characteristic indentations in the sediment were evident in the video footage. However, it could not be ascertained if these represented buried clams or recently vacated burrows, so these were not included in the analysis. Eight clams were observed to have re-buried to the extent that 1 cm or less was showing (these clams were all still visible). These eight individuals were included in calculating the density of razor clams in the quadrat but excluded from analysis of recovery times to provide conservative estimates. All razor clams observed in Loch Nevis and 93 % of those observed in East Fife (54/58) recovered within 30 minutes following exposure to the electric field (Figure 9). The mean length of time between the electricity turning off and re-burial was 7 m 28 s (SD = ± 5 m 10 s).

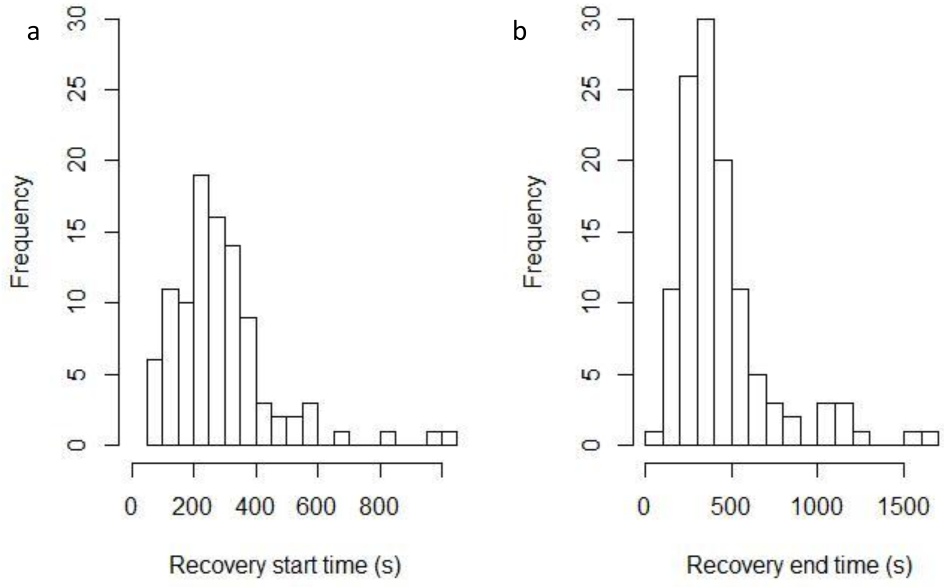

Figure 9: Frequency at which razor clams recovered over time. Each bar represents the number of individual razor clams that had recovered by the time shown after the electrodes had been switched off. Recovery start times are the first sign of movement from the razor clams. Recovery end time is the time of reburial to less than 1 cm showing above the sediment.

Razor clams in Mallaig began to recover, i.e. show first signs of movement following exposure to the electric field, significantly more quickly than those in East Fife ($F_{99,96}$, p = <0.001, Figure 10), and razor clams were more likely to start to move earlier in more densely populated ground ($F_{99,96}$, p = 0.004, Figure 10). Sea water temperature recorded was 12 °C at both sites and was therefore not a factor in the differences in recovery times. There was no effect detected for the size of the razor clams, nor were differences detected between species. None of the variables examined (species, density of razor clams, shell length or location) were found to have a significant effect on the end recovery time, i.e. re-burial to 1 cm shell left showing.

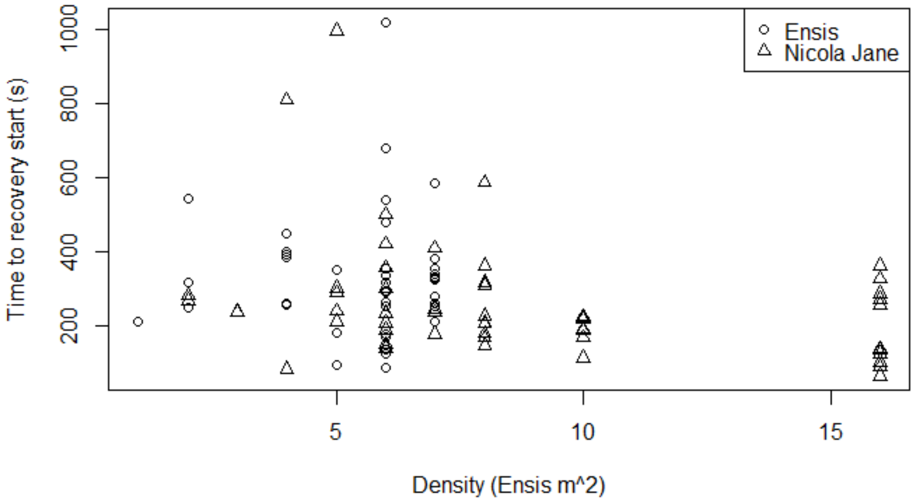

Figure 10: The effects of population density on the recovery start times of *Ensis* spp. The sampling vessel is indicated, which also corresponds to the location of the sampling: Ensis: East Fife, Nicola Jane: Loch Nevis.

Non-Target Species

Over half of the non-target individuals observed (24 of 42) had either recovered before the quadrat was positioned or did not react to the electric field. Most of the individuals observed were crustaceans (27, 23 of which were hermit crabs) or echinoderms (9). Three organisms observed in the quadrats could not be identified from the videos. All of the non-target epifaunal organisms observed recovered within 8 minutes of the electricity being switched off (mean = 3 m 20 s, sd = 1 m 22 s). There were significant differences between recovery times in different species observed ($F_{34} = 2.375$, $p = 0.043$, Figure 11). The fish and the starfish *Asterias rubens* were either unaffected by the electrofishing or had recovered before the quadrats were positioned. The crustacean, ophiuroid and polychaete species observed took several minutes to recover. There were no differences in the recovery times observed for non-target species between the locations studied.

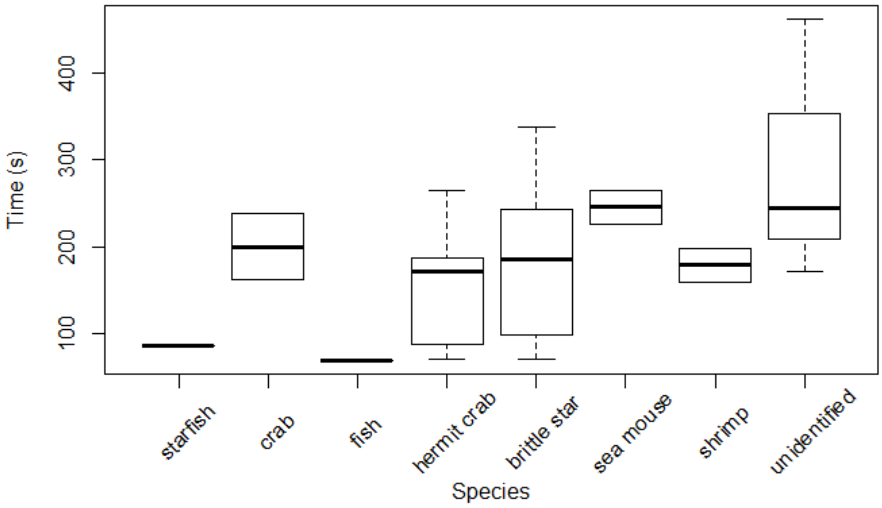

Figure 11: The times of the first sign of movement following exposure to the electric field for non-target species.

Sandeels

Divers reported that some of the sandeels emerging following exposure to the electric field were not stunned and could not therefore be caught. However, reduced visibility and a limited field of view prevented the number of sandeels present being estimated from video footage. Of the 31 sandeels that were stunned and collected by divers, 20 had recovered within minutes of collection and escaped the net the diver used to collect them. 11 sandeels were landed and all recovered within five minutes of being placed in a bucket of seawater (Video A4).

Tank Trials

Electrical Tests

During the 20 hour period in which the electric trials were run, the tank water was not recycled or replaced. Salinity remained constant at 35 ppm, and water temperature rose by 1 °C from 10.6 °C to 11.6 °C. Dissolved oxygen varied from 84 – 92.5 % saturation. Observations of the system in use and testing of water samples suggest that there was no appreciable liberation of any gaseous products. Further, none of the gas collection receptacles used for the duration of the tank trials showed any evidence of gas being evolved.

Configuration 1

Potential differences were measured at three points along the electrode and values of 22.6 – 22.9 v were recorded. These values were lower than the no-load measurement of 25 v due to the resistance of the cables, connectors and electrodes. This suggests that there was no significant voltage loss along the electrodes. The input current was 48.5 A. The power output from the system was calculated at 1.1 KW for the 1 m electrode separation (Power = Volts * Amps). An attempt was made to estimate field strength or voltage gradient. Further investigation of this may be required as the test point spacing was relatively coarse between the electrodes. Preliminary results suggest that field strengths in the order of 50 v m^{-1} were present at distances within 10 cm of the reference electrode. These reduced to less than 10 v m^{-1} at distances greater than 20 cm from the electrode. The vertical voltage profile showed no significant differences in measured voltages between the water column and the sediment. Within the limits of the measurement system this suggests that the field is symmetrical around the reference electrode (Figure 12).

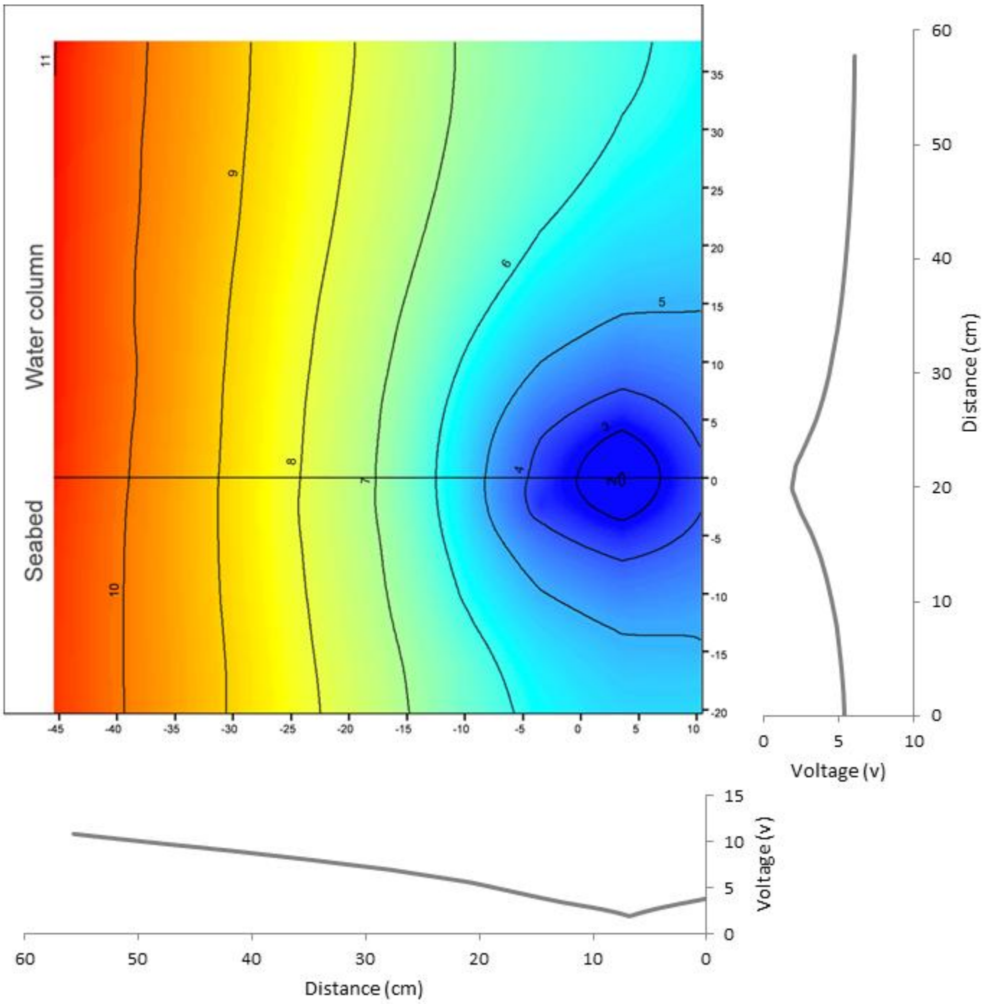

Figure 12: Voltage contour plot around the reference electrode (voltage = 0) for Configuration 1. Voltage profiles are displayed for the vertical section from water surface to tank base on the right hand side; and for horizontal section between electrodes below each contour plot (distances in the voltage profiles are referenced to the bottom corner of the measurement rig).

Configuration 2

After reducing the separation distance between electrodes, a comparison of the voltage contour plots from Configurations 1 and 2 showed no significant differences. This suggests that, despite the limited space in the tank, the electric field properties could be determined in electrodes spaced 1 m apart as used in the fishing industry (Figure 13).

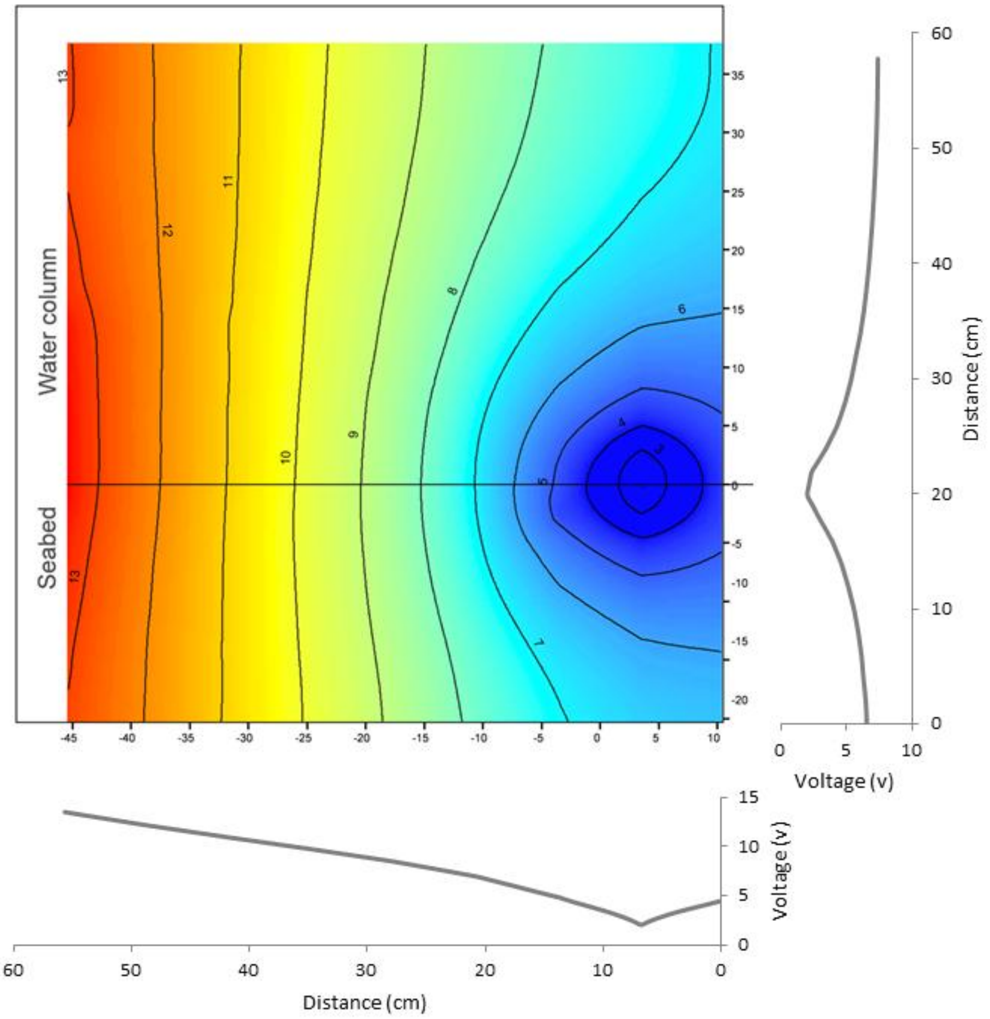

Figure 13: Voltage contour plot around the reference electrode (voltage = 0) for Configuration 2. Voltage profiles are displayed for the vertical section from water surface to tank base on the right hand side; and for horizontal section between electrodes below each contour plot (distances in the voltage profiles are referenced to the bottom corner of the measurement rig).

Configuration 3

Study of the voltage contour plot suggests that the voltage gradient outside the electrode will be significantly less than those between the electrodes (Figure 14).

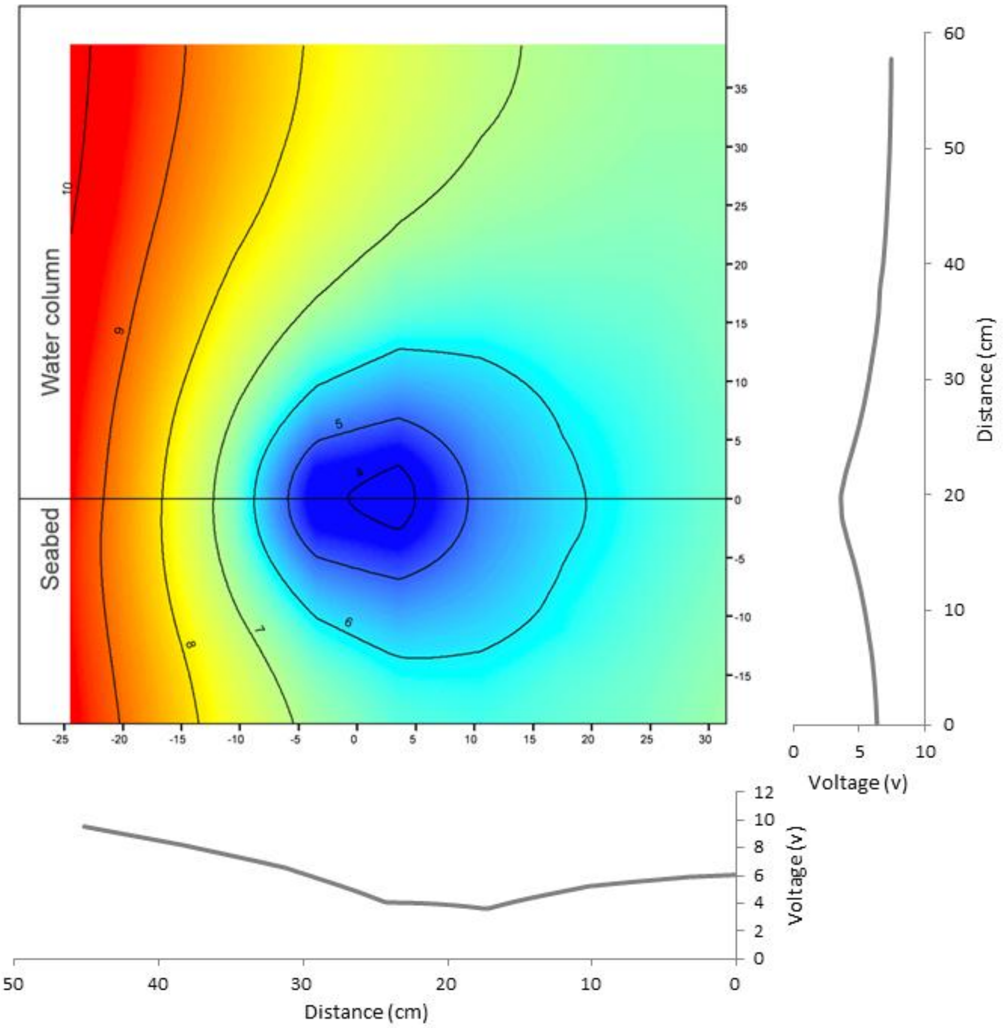

Figure 14: Voltage contour plot around the reference electrode (voltage = 0) for Configuration 3. Voltage profiles are displayed for the vertical section from water surface to tank base on the right hand side; and for horizontal section between electrodes below each contour plot (distances in the voltage profiles are referenced to the bottom corner of the measurement rig).

Ensis Siliqua

Initial experiments without electrical stimuli showed 91 % survival over three weeks. One individual died after three days, a further three died in week three and 40 survived for the full length of the trial. From this it was determined that the conditions in the tanks were suitable for addressing the aims of this study, but that survival should not be monitored for more than one week to avoid mortalities due to husbandry difficulties, in particular those associated with reduced oxygen tensions within the sand. There was 100 % survival in both the control and stimulus tanks in all four experimental runs. All razor clams responded to the electrical stimulus and emerged from the sand within 37 seconds of exposure to the electric field (mean ± 1SD = 13 ± 8.5 s, Video A5). Once emerged from the sediment the razor clams were observed to repeatedly "kick" their muscular foot whilst the electricity was switched on. 65 % of the razor clams reburied within 1 h and the remainder within 12 h following the stimulus. All remained in the sand until they were removed at the end of the experiment. The recovery times observed in the tank trials were slower than those observed in the boat trials (mean of 14 min not including those that took over 1 h c.f. 7 min 28 s in the boat trials). Shell length was not a significant explanatory variable for emergence or recovery times.

Non Target Species

There was no significant difference in survival between species or treatment groups ($F_{5,24} = 1$, $p = 0.439$). Of the 60 individuals used two individuals died. Both were *P. bernhardus* and were in the same stimulus trial (dying after 2 and 3 days). There were observed behavioural responses to the electrical stimulus that were highly consistent within a species and varied between species.

Asterias rubens (common starfish)

A. rubens did not appear to respond to the electrical field (Video A6). Individuals that were traversing the sediment at the time the electricity was switched on continued to do so, and did not change direction. Those that were not moving did not start to move in response to the electricity. (Picture: Keith Summerbell, Marine Scotland Science).

Pagurus bernhardus (common hermit crab)

All individuals of *P. bernhardus* exposed to the electric field retreated into their shells and did not re-emerge until after the electrodes were turned off (Video A7). (Picture: Keith Summerbell, Marine Scotland Science).

Spisula solida (surf clam)

In response to the electric field some individuals of S. solida were observed to kick their muscular foot, a behaviour that was not observed in the control individuals. Kicking stopped after the electric field was switched off. Most individuals showed no visible reaction to the electric field and remained stationary with their valves closed for the duration of the trial (Video A8). (Picture: Bob Williams, www.marlin.ac.uk).

Discussion

The tank tests of the properties of the generated electric field show that between the electrodes animals are exposed to field strengths to a maximum of approximately 50 v m^{-1} close to the electrodes. The field extends outside of the pairs of electrodes and downwards into the seabed. Videos from the boat trials suggest many razor clams respond to the electric field by emerging from the seabed, although it cannot be ascertained from this study if all razor clams will emerge. This is supported by data from the tank trials where all individual razor clams in the stimulus tanks emerged from the sediment within seconds of exposure to the electric field. The size of the razor clams was not an important variable for emergence or recovery times in either the boat or the tank trials, which is consistent with other studies (Henderson and Richardson 1994, Muir 2003), and there were no differences in recovery times between *Ensis* species. Whilst the overall recovery time was not found to be influenced by any of the variables studied, razor clams in Loch Nevis were quicker to start recovering than those in East Fife. The density of razor clams also affected recovery start times, as razor clams in more densely populated areas started to recover more quickly. It may be that competition for space within the population drives razor clams to rebury faster. Razor clams are known to be highly mobile (Fahy 2011) and fished ground is quickly recolonized (Fahy 2011), so it may be that competition for a good space is high.

Of the 133 razor clams observed to emerge from the seabed during the boat trials, four were unable to rebury within 30 minutes. Of these, one was trying to bury into the metal frame of the quadrat, one had kicked its foot out of its shell and seemed unable to recover (Figure 15b), one was predated by a crab and fish before it could recover and the fourth was moving its foot but had not yet reburied after 30 minutes. This indicates that whilst most of the razor clams to emerge in response to the electric field recover and rebury quite quickly, those that are slower are left vulnerable to predation (Figure 15b and c). Whilst most of the razor clams caught during commercial fishing will be removed by divers, smaller undersized clams are left behind and their recovery is important to the sustainability of the fishery. Recovery times recorded during the boat trials were much shorter than those observed in the tanks trials. This is most likely a result of the colder water temperatures in the tanks (12 °C during the sea trials compared to 8 °C in the tanks,) and because razor clams in the tanks did not have the opportunity to establish semi-permanent burrows as they would in their natural habitat (Muir 2003). Recovery into a pre-established burrow is more rapid than creating a new one (Muir 2003). In addition, the electric stimulus used was longer and other cues for recovery that may be important such as water movement and the presence of predators were absent. Longer exposure to an electric field may also increase the likelihood that a razor clam has “kicked” itself out of reach of its own burrow, increasing recovery time. The repeated kicking observed in both boat and tank trials appears to be an involuntary response to the electric field, emphasised where the foot kicks out of the shell and the clam seems incapable of pulling it back in.

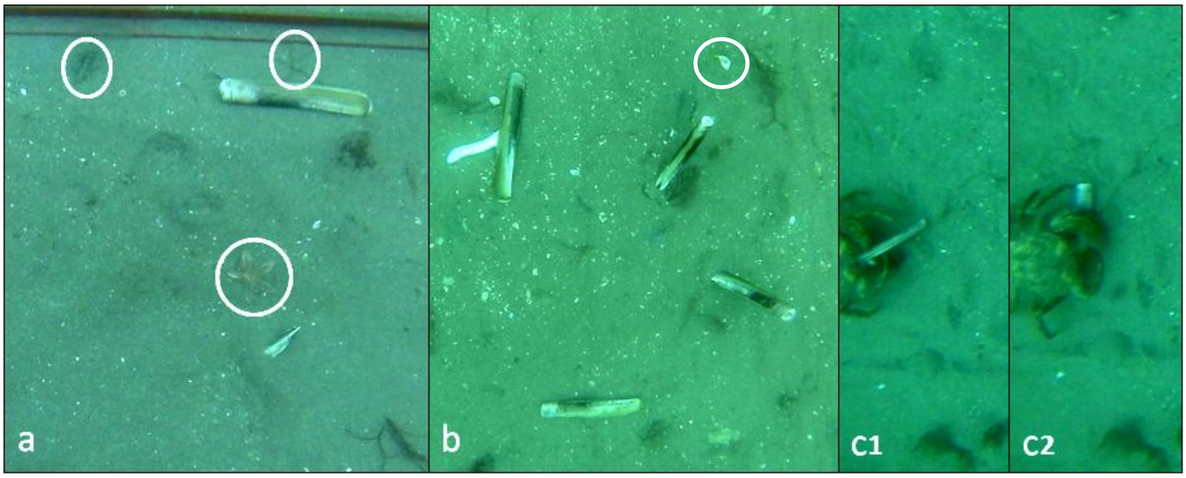

Figure 15: Observations from the boat trials. (a) Three non-target species with an emerged razor clam. The top left circled animal is a shrimp, the top right an ophiuroid and the centre is a starfish *A. rubens*. (b) Razor clams in different stages of recovery within a single quadrat from almost completely buried in the top right (circled) to one which has kicked its foot out of its shell and is unlikely to recover. (c) A crab eating an emerged razor clam.

Ensis spp. were the only invertebrates observed emerging from the seabed. Burrowing urchins such as *Echinocardium cordatum,* which are known to inhabit *Ensis* grounds in the Clyde (Hauton et al. 2003), are related to *A. rubens* and so may be similarly unaffected. Other species may be stunned, but not stimulated to emerge from the sediment. This may increase their vulnerability to burrowing predators, but will not expose them to fish or crustaceans. Further research is required to establish the effects of electrofishing on burrowing species. The non-target species observed on the seabed (Figure 15a), and the sandeels recorded separately, recovered much more quickly than *Ensis* spp., as did the non-target species studied in the tank trials. The physical impact of the fishing gear on the seabed was minimal and comparable to that caused by bad weather. As razor clam beds occur in moderately exposed areas, the habitat and benthic communities are adapted to recover quickly from physical effects of the extent caused by electrical fishing equipment. There was no evidence of chemicals being released into the seawater, as chloride compounds were not found to evolve from the electrodes during the tank trials, nor was there any indication of erosion of the electrodes as has been reported in DC systems (Woolmer et al. 2011). This fishing method appears, therefore, to have a low effect on non-target species and the marine environment.

These results are consistent with other studies on electrofishing. Survival and behaviour of adult and juvenile freshwater mussels have been found to be unaffected by exposure to electrofishing in freshwater (Holliman et al. 2007), and high survival rates with no impacts on feeding and behaviour has been reported for *Crangon* spp. and non-target invertebrate species likely to be affected by the *Crangon* fishery (Polet et al. 2005a). In both the Dutch flatfish fishery (ICES 2006) and the Belgian *Crangon* fishery (Polet et al 2005b) the use of electric trawling instead of tickler chains has reduced bycatch and the physical impact of trawling on the seabed. Similarly, where electrofishing for razor clams is used as an alternative to dredging both bycatch and habitat destruction are greatly reduced. Whilst electrofishing is not a zero impact fishing method (a feature shared by all methods), the low effects on non-target species and the benthic habitat make it a far more environmentally friendly method than dredging, as has been acknowledged by Scottish Natural Heritage (SNH 2014).

The razor clam fishery in Scotland has grown rapidly. In an effort to provide some restraint on further uncontrolled growth, new national legislation has recently been introduced and vessels now require a specific licence to land razor clams (Scottish Government 2014), as electrofishing remains illegal. In order to achieve better compliance with the EU regulation banning electrofishing, the new legislation also increases the penalty for using electrofishing to catch razor clams to a maximum of £10,000. If this legislation pushes more vessels towards hydraulic or suction dredging for *Ensis* spp. there is a risk that razor clam populations would be more rapidly impacted. Widespread habitat destruction could occur, similar to that reported in Ireland in the 2000s (Fahy 2011), where the *Ensis* populations and the seabed habitats are yet to fully recover.

Such a development would be unfortunate given the observations in this study pointing to the potential environmental benefits of electrofishing for razor clams. Other advantages conferred by the method include the highly selective nature of the fishery, where clams are selected at the seabed avoiding the need to bring young recruits or undersized individuals onto the deck of a boat. Waste of the type associated with mechanical dredging, where shell damage and breakage reduces the potential value of a catch, is also highly reduced.

It is also true however, that electrofishing is very efficient with little opportunity for marketable razor clams to escape capture once the track of a pair of electrodes passes them. This, in combination with a relatively slow growth rate and late maturity, makes them potentially vulnerable to overexploitation. As with all exploited fish and shellfish species, the rate of harvesting should be regulated to safeguard sustainability. Given the patchy distribution of this species, occurring as it does in discrete populations, it is important that regulatory measures tailored to the different areas are developed. Ahead of this, there is an urgent need to determine the size of the different populations and follow up work should include stock assessments using appropriate survey techniques.

This study has made important observations on the immediate and short term effects of electrofishing on individual species. Further research may be required to establish the medium to long term implications and if there are any effects of electrofishing on fertility and fecundity of both razor clams and non-target species.

Conclusions

- The results of this study indicate that electrofishing using the system described is a low impact method of harvesting razor clams. The impact on the seabed is minimal in comparison to conventional dredge and trawl fisheries.
- The immediate effects on non-target species are non-lethal and effects on invertebrate behaviour are short term.
- Electrofishing for razor clams is potentially very efficient, and regulation of outtake and fishing effort may be required to ensure that the Scottish razor clam fishery is sustainable.

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Appendix

Video Clips

Video A1: Diver collecting razor clams following electric rig
Video A2: Sample video clips from FV Ensis
Video A3: Sample video clips from FV Nicola Jane
Video A4: Sandeels recovered on deck
Video A5: *E. siliqua* emerging from the sediment during the tank trials
Video A6: *A. rubens* exposed to the electric field
Video A7: *P. bernhardus* exposed to the electric field
Video A8: *S. solida* exposed to the electric field

Supplementary Data

Sediment Properties

Table A1: Particle size analysis summary for sediment samples taken during the boat trials and the sand used in the tanks.

Particle size range	Mean Percentage			
	Fife	Loch Nevis	Clyde Sea Area	Tanks
% >2 <63 µm	2	0	3	2
% >63 <125 µm	34	0.2	3	14
% >125 <150 µm	35	7	12	7
% >150 <250 µm	22	25	28	39
% >250 <500 µm	7	59	51	28
% >500 <1000 µm	0	7	3	7
% >1000 <2000 µm	0	0	0	2

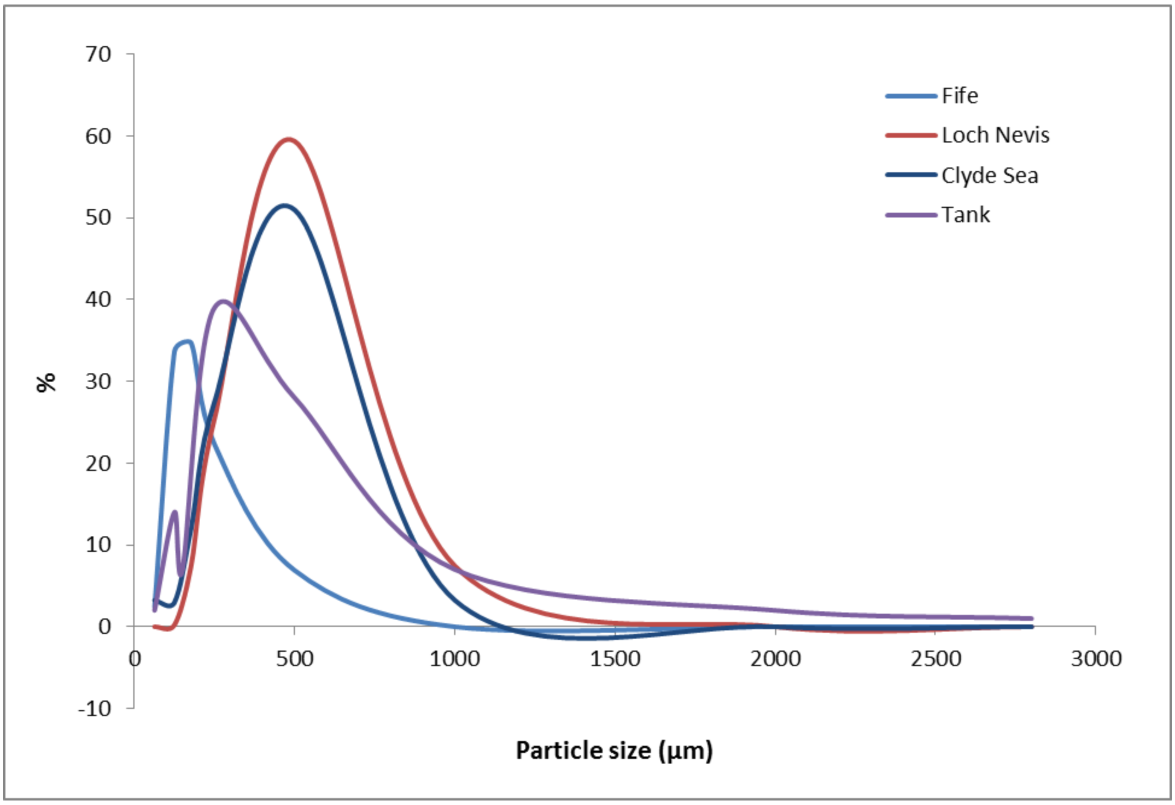

Figure A1: Particle size distributions for sediment samples taken during the boat trials and the sand used in the tanks.

Tank Experiments Supplementary Data

Table A2: Salinity, temperature and dissolved oxygen data for experimental tanks.

Tank	Salinity (ppm) Mean ± 1 SD	Temperature (°C) Mean ± 1 SD	Dissolved oxygen (% saturation) Mean ± 1 SD
A	32 ± 2.165	7.9 ± 0.375	80 ± 7.044
B	32 ± 2.059	7.8 ± 0.435	84 ± 4.434
C	32 ± 2.201	7.7 ± 0.441	87 ± 6.468
D	32 ± 2.100	7.8 ± 0.413	87 ± 6.387
E	32 ± 2.160	7.8 ± 0.444	88 ± 6.258
F	32 ± 2.137	7.7 ± 0.393	81 ± 8.357
G	32 ± 2.110	7.7 ± 0.364	76 ± 6.770

Table A3: Electrical data from stimulus trials.

Species	Voltage (v) Mean ± 1 SD	Current (A) Mean ± 1 SD
E. siliqua	25.45 ± 0.115	43.2 ± 2.051
A. rubens	25.29 ± 0.499	41.6 ± 2.142
P. bernhardus	25.61 ± 0.087	43.0 ± 0.694
S. solida	25.56 ± 0.055	41.5 ± 2.039

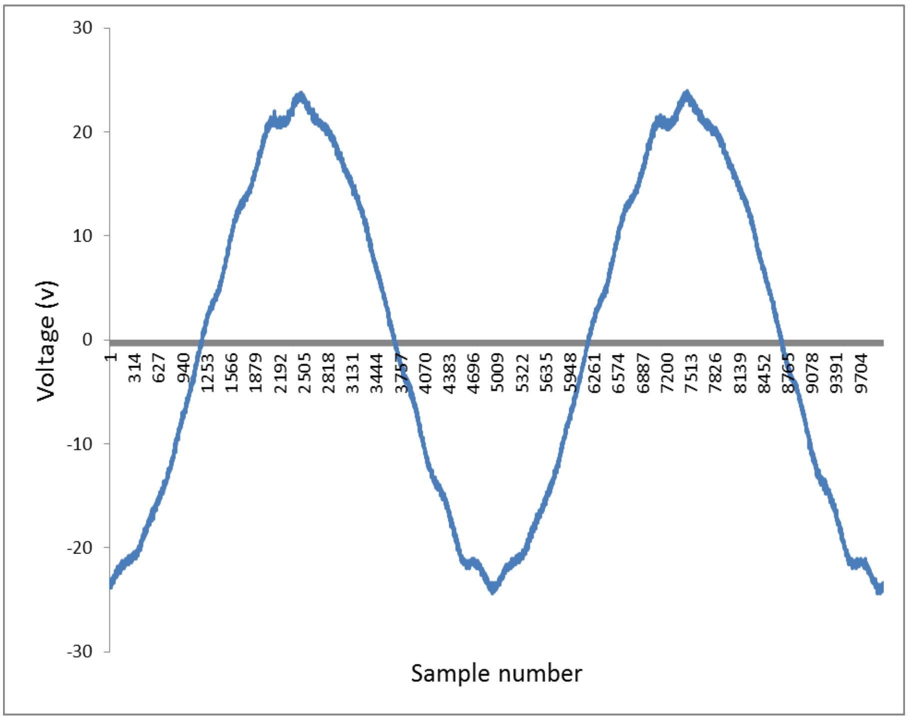

Figure A2: Example voltage output of electric waveform.

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