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Reducing bycatch in beam trawls and electrotrawls with (electrified) benthos release panels

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Benthos release panels (BRPs) are known for their capacity to release large amounts of unwanted benthos and debris, which can decrease mortality on these animals and eases the on board sorting process aboard demersal beam trawlers. They can reduce the bycatch of undersized fish, which is desired once the European discard ban is implemented. However, unacceptable commercial losses of sole (*Solea solea* L.) and damage to the BRP as a consequence of suboptimal and unsuitable rigging in the traditional beam trawl with chain mat, is hampering a successful introduction in commercial beam-trawl fisheries. To eliminate these drawbacks, square-meshed BRPs with different mesh sizes (150, 200, and 240 mm) were rigged in a trawl with square net design as used in electrotrawls and tested for selectivity. In addition to this, the effect of electric stimulation at the height of the BRP to eliminate the loss of commercial sole was examined. According to our observations, no abrasion of the net attributable to suboptimal rigging occurred in any of the BRPs tested. The catch comparisons showed significant release of benthos and undersized fish in all panel mesh sizes, but there was always a significant loss of marketable sole in the 150, 200, and 240 mm BRPs. Adding a 80 Hz electric cramp stimulus to the BRP, resulted in equal catches of sole larger than 25 cm as the standard net, without negatively affecting the release of benthos and most undersized commercial fish. This clearly demonstrates the promising potential of electrified BRPs (eBRPs), but further optimization by using smaller BRP mesh sizes or optimized electric stimuli is warranted to retain all marketable sole.

Keywords: beam trawling, benthos release panel, bycatch, electric pulses, sole.

Introduction

Towed demersal fishing gears are used worldwide to catch seafood. Demersal fishing techniques have direct physical contact with the seabed to ensure adequate capture rates of target species (Depestele *et al.*, 2015), which can affect the marine environment and particularly the benthic communities, reducing their biomass, production and diversity (Lindeboom and de Groot, 1998; Kaiser *et al.*, 2006; Depestele *et al.*, 2014). Beam-trawl impact may result from the direct mortality caused by the trawl and the indirect effects of this mortality on species interactions (Ramsay *et al.*, 1997; Jennings *et al.*, 2002). Fishing with beam trawls causes direct unwanted mortality in invertebrates in two ways. First, injury and death result from physical contact with the shoes, tickler chains or chain mat (Bergman and van Santbrink, 2000). Second, animals caught in the trawl may die from injuries sustained in the net, during hauling, catch sorting or discarding (Lindeboom and de Groot, 1998).

Adverse effects of trawling on benthic communities can be reduced by developing alternative fishing methods and through technical modifications, which is one of the major knowledge needs to achieve best practices for bottom trawling in relation to seabed habitats (Kaiser *et al.*, 2015). Drop-out openings without netting and large diamond and square escape zones just behind the groundrope have proved to be ineffective in releasing bycatch causing unacceptable losses of commercial catch (Fonteyne and Polet, 2002; van Marlen *et al.*, 2005). Square-meshed windows inserted in the lower panel just in front of the cod-end, also known as benthos release panels (BRPs), have given much better results. Field trials with BRPs showed reductions in bycatch of invertebrates up to 80% and reductions in debris exceeding 50% (Fonteyne and Polet, 2002; Revill and Jennings, 2005). These mesh panels may help to release benthic invertebrates immediately after capture, eliminating prolonged retention and compression in the cod-end. Consequently exposure to the effects of hauling, deck sorting and discarding is avoided, contributing to a better survival of accidentally caught benthic invertebrates (Depestele *et al.*, 2014). Moreover, Fonteyne and Polet (2002) report substantial lower bycatches of undersized commercial fish. The latter will be important in the future, following the implementation of the discard ban in European fisheries in 2016 because it is expected that the discarding of undersized commercial fish will negatively affect total allowable catches (TAC) (NSAC, 2014). In the past, two main drawbacks have hampered the implementation of the BRP gear modification. First and foremost, catches of Dover sole (*Solea solea* L.), the most important economic species, fall by between 20 and 45% (Fonteyne and Polet, 2002; van Marlen *et al.*, 2005). Second, the implementation of a rectangular square-meshed panel in a traditional beam trawl with a round footrope proved to be suboptimal: BRP rigging resulting in slack and subsequent bag formation in the lower panel, just in front of the BRP, causing abrasion and unacceptable wear of the net fabric (H. Polet Pers. comm., ILVO, Belgium).

The aim of this study is to tackle these problems to promote a widespread commercial use. First by assessing the release capacity of a BRP inserted in a trawl design with a straight ground rope and a square chain mat, allowing a persistent, stretched geometry of the BRP in the lower panel of the trawl extension. This so called ‘square’ net design is typically used in the electric pulse fishery, facilitating the lengthwise rigging of the electrodes in the electrotrawl. Second, the use of electric stimulation to improve post-capture selectivity was evaluated. In recent years, electric pulse stimulation has been implemented in beam-trawl fisheries as an alternative for mechanical stimulation with tickler chains or bobbin ropes. Most of these so-called electrotrawls target sole by exposing them to an electric cramp stimulus that elicits a strong contraction in the muscles of the fish, which immobilizes the animal (Soetaert *et al.*, 2015a). This cramp of the fish’s muscles during this reaction is reported to harm gadoid roundfish such as Atlantic cod (*Gadus morhua* L.) and whiting (*Merlangius merlangus* L.) (van Marlen *et al.*, 2014; Soetaert *et al.*, 2016a,b). Four out of 45 cod exposed caught by electrotrawls were reported to have paravertebral haemorrhages (van Marlen *et al.*, 2014). This was confirmed in laboratory experiments showing 0-70% spinal injuries in cod exposed near the electrodes (Soetaert *et al.*, 2016a; de Haan *et al.*, 2016). However, no effects were demonstrated in an identical experiment with the non-gadoid roundfish European seabass (*Dicentrarchus Labrax* L.) (Soetaert, 2015b), dogfish (*Scyliorhinus Canicula* L.) (de Haan *et al.*, 2009) and dab (*Limanda limanda* L.) (de Haan *et al.*, 2015). Exposure of sole to a broad range of electric stimuli could also not provoque lesions or mortality (Soetaert *et al.*, 2016a). Finally, no increased impact of electric cramp stimuli compared to conventional mechanical stimulation has been evidenced for invertebrate species either (Smaal and Brummelhuis, 2005; van Marlen *et al.*, 2009; Soetaert et al., 2014; 2016c). The second part of the present study therefore investigated the effect of an electric cramp stimulus on the escape behaviour of marketable sole through the panel.

Material and Methods

Rigging of the (e)BRP

In the present study, the trawls had a straight bobbin- and footrope, which is a typical geometry for electrotrawls. However, they were equipped with a rectangular chain mat (Figure 1). Both the standard and the experimental net used in the comparative fishing experiments were constructed in 120 mm polyethylene (PE) netting. In order to reduce wear, the double braided lower panel was provided with bottom chafers made of PE ropes. In the double braided PE cod-ends with nominal mesh opening of 80 mm, an inner PE cod-end with a nominal mesh opening of 60 mm was inserted. The square-meshed (e)BRP measured 1.20 × 1.80 m and was inserted in the lower panel of the trawl extension, 10 meshes (1.20 m) in front of the cod-end of a 4 m flatfish beam trawl equipped with a chain mat (Figures 1 and 2), as described by Fonteyne and Polet (2002) and Revill and Jennings (2005). The BRP was made of single braided PE square meshes of three different sizes: 150, 200, and 240 mm. Small amounts of chafers were provided every 3d mesh of the BRP to protect it from possible wear without obstructing the BRP outlet. The different nets as well as the BRPs were checked for damage during and after the experimental hauls. The mesh size of the panels and cod-ends were determined with an omega mesh gauge, following the protocol described by Fonteyne (2005). The difference in mean mesh size of the standard and the experimental cod-end never exceeded 0.4 mm.

Electric power supply to generate the electric pulses on the eBRP was supplied by an on-board winch (EPLG, Belgium) equipped with 250 m reinforced coaxial conductor cable. This cable was attached to the bridle with a strain relief and then lead to a compact pulse generator device (EPLG, Belgium). The pulse generator was attached to the selvedges in the aft of the portside net close to the BRP, firing two electrode wires, each splitting up in three parallel conductors. Small wire shaped conductors (1.2 m length, 12 mm diameter) were used and consisted of 6 stainless-steel strands around a copper core. These conductors were attached transversally to the 240 mm BRP at a mutual distance of 0.48 m (four meshes in the BRP), starting from 0.6 m in front of the BRP to the very end of the panel (Figure 2). Electric stimuli similar to those used in commercial electrotrawls targeting sole were applied (80 Hz bipolar pulsed current, 0.25 ms pulse duration) (Soetaert *et al.* 2016a), aiming for an ‘immobilizing cramp reaction’ in the sole’s muscle to prevent it from escaping through the panel. The electric potential difference on the electrodes however, was limited to 40 V due to the capacity of the generator, whereas ±55 V is used in the commercial trawls (Soetaert *et al.*, 2015a).

Comparative fishing trials were carried out on board R.V. BELGICA (50.9 m L.O.A., 1154 kW) and R.V. Simon Stevin (36 m L.O.A., 2 × 520 kW). In contrast to commercial beam trawlers, these vessels are not equipped with derrick booms for towing two separate beam trawls simultaneously. To enable comparative fishing, two 4 m beam nets were attached next to each other on an 8 m twin beam trawl with an extra trawl head in the middle (Figure 1), with the (e)BRP always on port side, except during one trip. An overview of the sea trials and valid hauls is given in Table 1. Five control hauls before, 5 hauls during and three hauls at the end of the experiments were performed without a BRP to exclude possible side-specific effects of the beam and trawls.

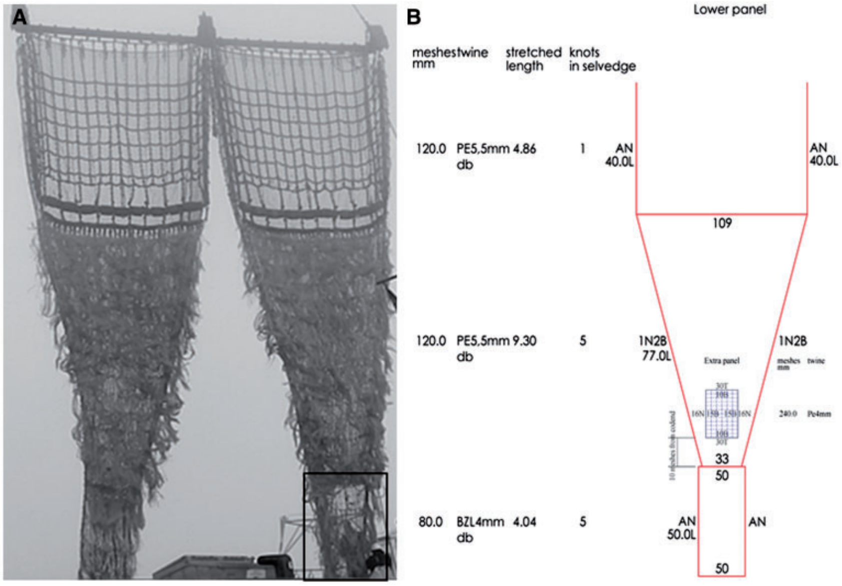

Figure 1. Rigging of the 8 m beam with two 4 m trawls with chain matrices, i.e. a reference net and experimental net rigged with an (e)BRP (1.20 × 1.80 m) **(A)**, and the net drawing of the lower panel of the square net with straight bobbin rope **(B).**

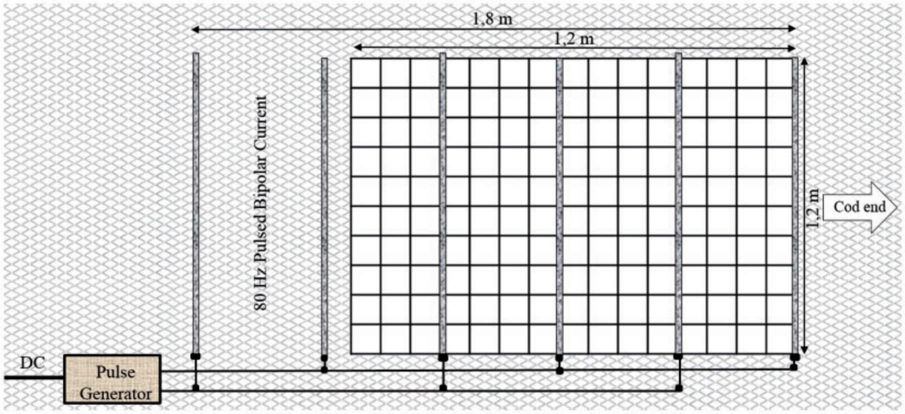

Figure 2. Scheme of the 240 mm eBRP configuration with six transversal electrodes.

Table 1. Overview of the sea trials

Panel design	Date	ICES area	Location	Vessel	Depth (m)	No. valid hauls	Exp. Net	Electrodes	Pulse
150 mm BRP	April 2014	IVc	Shipwash, England	R.V. Belgica	24–32	10	portside	no	no
200 mm BRP	November 2014	IVc	Belgian coast	R.V. Simon Stevin	10–35	5	portside	yes	no
	December 2014	IVc	E coast England	R.V. Belgica	24–48	5	starboard	no	no
240 mm BRP	December 2014	VIId	NE coast England	R.V. Belgica	30–63	10	portside	yes	no
	December 2014	IVc	Shipwash, England	R.V. Belgica	24–30	12	portside	yes	no
240 mm eBRP	February 2015	IVc	SE coast England	R.V. Belgica	26–55	16	portside	yes	yes

The average haul duration was ~1.5 h, covering ~45 000 m^2 with each trawl.

Catch analysis

The entire catches of both the standard and the experimental trawl were collected in baskets immediately after hauling and the total catch weight was recorded. All commercial fish species were sorted, counted and measured to the centimetre below. All cod were filleted and examined for potential spinal injuries, induced by the electric pulses. The remainder of the catch was separated into a benthos fraction (non-commercial fish and invertebrate species) and a coarse debris fraction (stones, litter, and other inert

Table 2. The number of hauls, the average catch weights of benthos and debris fractions (± s.d.) for both the standard trawl and the trawl fitted with an (e)BRP, the percentage difference and the P-values of the linear mixed-effects models are given for each panel design with significant values in bold italics

	No. hauls	Average benthos weight				Average debris weight			
		standard (kg)	BRP (kg)	difference	*P*-value	standard (kg)	BRP (kg)	difference	*P*-value
150 mm BRP	10	133 ± 49	43 ± 18	−68%	***0.000***	39 ± 38	41 ± 46	5%	0.757
200 mm BRP	10	51 ± 27	24 ± 12	−53%	***0.000***	15 ± 12	10 ± 11	−33%	***0.017***
240 mm BRP	22	124 ± 90	36 ± 51	−71%	***0.000***	41 ± 49	17 ± 15	−59%	***0.003***
240 mm eBRP	16	119 ± 71	22 ± 29	−82%	***0.000***	18 ± 17	5 ± 4	−72%	***0.001***

material). These fractions were weighed separately to determine the overall amount of benthos and debris released through the BRP. Subsequently, a subsample (5–8 kg) of the benthos fraction was sorted by species. All animals were counted and the total weight per species was determined. Residual debris in the benthos sample was weighed separately, scaled up and added to the total debris weight.

Paired haul catch data, i.e. overall benthos and debris weights on the one hand and numbers of fish and benthos per species on the other hand, were analysed using linear mixed models (LMMs) with haul as random effect. Concerning commercial fish species, the bycatch reduction was split up into the reduction of undersized and marketable fish. Those numbers, as well as these of the benthos species were statistically compared, only if the numbers were sufficiently large (i.e. at least five individuals per haul). In this manuscript, all shown numbers include only those animals caught in hauls that accord to these restrictions. The (bycatch) reductions given in Table 2–5 were calculated as the percentage difference on pooled weights based as follows: [(catch experimental trawl – catch standard trawl)/catch standard trawl] * 100. The sampling occurred within ongoing sampling campaigns.

The analysis of the catch comparison to appraise the catch efficiency (at length) of one gear relative to that of another gear was done based on the method of Holst and Revill, (2009). This method uses Generalized LMMs and a polynomial approximation for the logit function with haul and day as random effect. It describes the probability of retaining a fish at length in an experimental gear related to the total catch in the ‘experimental and ‘standard’ gear. As a consequence, a probability of 0.5 indicates equal catches in both gears. The method produces a curve with 95% confidence bands expressing this probability. Different distributions were modelled and the best fitting model, based on the Akaike information criterion, was retained. This was only conducted for sole, the target species of major importance.

Results

Control hauls

Statistical comparison of the 13 control hauls demonstrated no difference between starboard and portside catches in either total catch weight ($P = 0.518$), benthos weight ($P = 0.068$) or debris weight ($P = 0.592$). Nor was any significant difference in catch rate observed in the number of sole, plaice (*Pleuronectes platessa* L.), brill (*Scophthalmus rhombus* L.), turbot (*Scophthalmus maximus* L.), dab (*L. limanda* L.), lemon sole (*Microstomus kitt* W.), red mullet (*Mullus surmuletus* L.), pouting (*Trisopterus luscus* L.), whiting (*M. merlangus* L.), cod (*G. morhua* L.), dogfish, and ray spp. (*Raya* spp.) between sides.

Experimental hauls

The actual inner mesh size of the 150, 200, and 240 mm BRP was 158 ± 3; 178 ± 3; and 223 ± 10 mm respectively. The 200 and 240 mm BRP were always well stretched in the belly of the net. The 150 mm BRP in contrast, was hand-knitted on board, which resulted in a mesh size slightly larger than intended, and subsequently a panel length larger than the opening cut out in the lower panel. As a consequence limited, but non progressive, ‘bag formation’ occurred as a result of the slack. None of the panels showed wear at the end of the experiment and although the chafers were tattered at the last 5–10 cm, no abrasion was seen. No damage was observed to the belly surrounding the BRP or the electrodes.

The total benthos weight was significantly lower for all (e)BRP designs tested (Table 2) and all, except the 150 mm BRP showed a significant loss of debris. When analysed at species level, starfish (*Asterias rubens* L.), whelk (*Buccinum undatum* L.), sea urchins (Echinoidea), harbour crab (*Liocarcinus depurator* L.), serpent star (*Ophiura texturata* L.), and hermit crab (Paguridae) were significantly less abundant in the catches of the trawl fitted with BRPs (Table 3). Similarly, the loss of swimming crab (*Liocarcinus holsatus* L.), long legged spider crab (*Macropodia rostrate* L.) and velvet crab (*Necora puber* L.) was (nearly) significant for all (e)BRPs tested. Almost all benthic invertebrates species were significantly less caught in the 240 mm eBRP compared to the standard net. Finally, in line with previous, also the number of non-commercial fish species (Table 3) were almost invariably lower in the experimental net fitted with a (e)BRP, although this was only significant for the number of Mediterranean scaldfish (*Arnoglossus laterna* W.) in the 200 mm BRP and the number of hooknose bullhead (*Agonus cataphractus* L.) in the 240 mm eBRP.

Catch data for commercial fish (Table 4) show that sole is lost in all BRP configurations, and significantly in the 150 and 240 mm BRPs. The 42% sole loss in the 240 mm BRP is reduced to 17% when the electric stimulus was added to the BRP. Plaice is caught significantly less in the 240 mm BRP, while this reduction is not observed in the 200 mm BRP or the 240 mm eBRP. The number of red mullet and gurnards (*Chelidonichtys* spp.) is consistently lower if a BRP is used, although this reduction was only significant for the 240 mm BRP. Finally, dogfish (*S. canicula*) was also lost in all BRP configurations, although only significantly in the 150 and 240 mm BRP.

The bycatch reduction of undersized sole was highly significant for all BRPs tested and was not affected by the electric stimulus (Table 5). It was also much higher than the relative loss of marketable sole. Pouting (*T. luscus* L.) escaped significantly through 150 and 200 mm BRP configurations tested, but the escape rate doubled in the eBRP. Using a 240 mm BRP resulted in a

Table 3. Total numbers of non-commercial fish species and benthos caught in the standard net (A) and experimental net with BRP (B), the percentage difference in catch of the experimental net compared to the standard net (C) and the *P*-value (D) of the linear mixed-effects models with significant values in bold italics

	150 mm BRP				**200 mm BRP**				**240 mm BRP**				**240 mm eBRP**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Non commercial fish species																
A. laterna					357	143	−60%	***0.000***	80	108	35%	0.122	115	85	−26%	0.337
A. cataphractus					24	48	100%	0.257	218	202	−7%	0.836	35	19	−46%	***0.002***
Callyonimus lyra	33	10	−70%	0.495	324	193	−40%	0.285	905	370	−59%	0.288	326	269	−17%	0.694
Echiichthys vipera	59	27	−54%	0.141	315	146	−54%	0.219	29	44	52%	0.582	63	47	−25%	0.368
Benthic invertebrates species																
Aequipecten opercularis									11033	2433	−78%	***0.007***	100	0	−100%	***0.007***
Anemone (indet.)									290	126	−57%	***0.011***	175	21	−88%	***0.044***
Aphrodita aculeata	1745	425	−76%	0.118	51	8	−84%	***0.000***	629	129	−79%	0.113	5565	1624	−71%	***0.012***
A. rubens	20251	7984	−61%	***0.001***	4997	1696	−66%	***0.008***	44739	11013	−75%	***0.036***	26435	5568	−79%	***0.000***
Atelecyclus rotundatus	133	18	−86%	***0.014***									60	2	−97%	***0.007***
B. undatum	3967	359	−91%	***0.000***	378	164	−57%	***0.017***	1765	160	−91%	***0.001***	6875	265	−96%	***0.000***
Eggs *Buccinum undatum*	1062	483	−55%	***0.000***									831	257	−69%	***0.006***
Cancer pagarus	1476	39	−97%	0.296					109	65	−40%	0.436	68	16	−76%	0.160
Echinoidea	77216	18159	−76%	***0.000***	5068	1487	−71%	***0.001***	60297	6704	−89%	***0.001***	88031	6128	−93%	***0.000***
Hyas araneus									4016	497	−88%	0.318	114	1	−99%	***0.005***
L. depurator	1123	431	−62%	***0.020***	755	230	−70%	***0.028***	1098	451	−59%	***0.008***	419	118	−72%	***0.012***
L. holsatus	572	193	−66%	***0.030***	1075	386	−64%	***0.005***	1957	925	−53%	0.057	2031	863	−58%	***0.003***
Liocarcinus marmoreus	43	15	−65%	0.306	185	54	−71%	0.053	18	11	−39%	0.39	144	53	−63%	***0.000***
Macropodia rostrata	283	72	−75%	***0.022***	560	66	−88%	***0.026***	5044	749	−85%	0.158	198	67	−66%	***0.007***
N. puber	1109	436	−61%	0.058	838	397	−53%	0.094	903	265	−71%	***0.049***	716	156	−78%	0.084
O. texturata	397	21	−95%	***0.019***	696	119	−83%	***0.000***	1115	35	−97%	***0.000***	362	52	−86%	***0.017***
Paguridae (indet.)	1298	131	−90%	***0.000***	749	105	−86%	***0.000***	4167	309	−93%	***0.000***	2038	50	−98%	***0.000***
P. serratus	61	107	75%	***0.003***	38	15	−61%	0.544	1135	703	−38%	0.129	211	40	−81%	0.073
Porifera spp.					260	236	−9%	0.858	17405	2535	−85%	0.256	222	38	−83%	0.053
Sepia officinalis					62	5	−92%	***0.019***	2409	565	−77%	0.436				
Pooled totals																
Non−commercial fish		122	44	−64%		1058	575	−46%		1243	749	−40%		2134	442	−79%
Crustacea		5050	1051	−79%		3551	1044	−71%		13489	3101	−77%		5514	1259	−77%
Echinodermata		97864	26164	−73%		10761	3301	−69%		106410	18003	−83%		116273	13426	−88%
Mollusca		4038	382	−91%		470	173	−63%		16249	3649	−78%		7090	284	−96%
All species		111205	29016	−74%		16991	5597	−67%		164311	29653	−82%		138645	17516	−87%

Table 4. Total numbers of commercial fish in the catch of every panel design for the standard net (A) and experimental net with BRP (B), the percentage difference in catch of the experimental net compared to the standard net (C) and the *P*-value (D) of the linear mixed-effects models with significant values in bold italics

	150 mm BRP				**200 mm BRP**				**240 mm BRP**				**240 mm eBRP**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
S. solea	660	547	−17%	***0.000***	247	229	−7%	0.436	1377	800	−42%	***0.000***	909	753	−17%	***0.000***
P. platessa					767	828	8%	0.091	944	869	−8%	***0.010***	103	105	2%	0.972
L. limanda					45	46	2%	0.858					208	202	−3%	0.914
M. kitt					27	29	7%	0.825	137	123	−10%	0.584	13	18	38%	0.365
M. merlangus					28	26	−7%	0.886	70	68	−3%	0.869	42	80	90%	0.393
T. luscus	16	9	−44%	0.127	70	60	−14%	0.192	364	383	5%	0.777	14	19	36%	0.490
G. morhua	104	84	−19%	0.207	55	52	−5%	0.807	41	46	12%	0.567	32	38	19%	0.517
M. surmuletus					181	126	−30%	0.092	618	430	−30%	***0.000***	36	21	−42%	0.187
S. canicula	166	119	−28%	***0.006***	146	128	−12%	0.226	769	639	−17%	***0.010***	355	302	−15%	0.115
S. rhombus					8	11	38%	0.317	41	48	17%	0.487				
P. flesus													18	10	−44%	***0.046***
P. maxima					10	5	−50%	0.407	24	13	−46%	0.071				
Chelidonichthys spp.					184	133	−28%	0.257	250	161	−36%	***0.044***				
Raya spp.	217	203	−6%	0.676	29	38	31%	0.272	299	290	−3%	0.668	741	725	−2%	0.610
Total	1177	984	−16%		1797	1711	−5%		4934	3870	−22%		2471	2273	−8%	

Table 5. Total numbers of undersized fish in the catch of each panel design for the standard net (A) and experimental net with BRP (B), the percentage difference in catch of the experimental net compared to the standard net (C) and the *P*-value (D) of the linear mixed-effects models with significant values in bold italics

	150 mm BRP				200 mm BRP				240 mm BRP				240 mm eBRP			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
S. solea	899	622	−31%	***0.000***	706	458	−35%	***0.000***	2156	1134	−47%	***0.000***	1748	880	−50%	***0.000***
P. platessa					2005	2097	5%	0.539	435	365	−16%	0.117	1360	1202	−12%	***0.028***
L. limanda					126	108	−14%	0.517	41	30	−27%	0.326	2009	1723	−14%	0.064
M. kitt					100	101	1%	0.956	131	100	−24%	***0.016***	47	34	−28%	0.189
M. merlangus	74	76	3%	0.886	784	548	−30%	***0.031***	913	600	−34%	***0.000***	1803	1167	−35%	***0.000***
T. luscus	90	64	−29%	***0.009***	820	634	−23%	***0.000***	2904	2587	−11%	0.064	724	289	−60%	***0.000***
G. morhua					20	13	−35%	0.305								
S. canicula									20	11	−45%	0.058	80	33	−59%	0.079
Chelidonichthys spp.					26	6	−77%	***0.040***	65	26	−60%	***0.000***	112	35	−69%	0.060
Raya spp.	25	24	−4%	0.872					153	104	−32%	***0.010***	149	95	−36%	***0.002***
Total	1094	789	−28%		4592	3974	−13%		6818	4957	−27%		8032	5458	−32%	

decreased catch of undersized lemon sole and gurnard, although these reductions were not significant for the 240 mm eBRP. Finally, significantly high bycatch reductions of undersized whiting and small ray were seen in the 240 BRP, both in the presence and absence of the electric stimulus.

The length frequency distributions of sole (Figure 3) clearly illustrate the considerable bycatch reduction of undersized sole. Additionally, the modelled probability distribution shows that the minimum length for which no difference in catch can be demonstrated increases with BRP mesh size from 28 cm (150 mm BRP) to 30 cm (200 mm BRP), whereas the 240 mm BRP lost sole of all size. However, after adding an electric stimulus to the 240 mm BRP, no differences in catch rates were recorded for sole of 28 cm and larger. Additionally, the loss of marketable sole smaller than 28 cm is reduced from 43% in the 240 mm BRP ($P = 0.000$) to 18% in the 240 mm eBRP ($P = 0.001$) is found.

During the eBRP trials, four cod (47, 48, 54, and 55 cm) from the experimental net had paravertebral hemorrhages. Over the entire trial period, 52 cod individuals (0.438 ± 0.014 m) were caught in the experimental trawl, and 7.7% were injured by the electric cramp stimulus. A dark discoloration of the skin, as well as the spinal injuries were the same as previously reported for this species (de Haan *et al.*, 2016; Soetaert *et al.*, 2016a,b).

Discussion

BRP in traditional round vs. square nets

BRPs tested in the past were rigged into typical chain mat beam trawls in which the U-shaped bobbin- and groundrope determine the geometry of the trawl (Fonteyne and Polet, 2002; Revill and Jennings, 2005). One of the characteristics peculiar to this trawl design is the presence of considerable slack in the lower panel. Consequently the rigging of a rectangular square-meshed panel, that has to be applied fully stretched for optimal performance, is not straightforward in such trawls. Indeed, practice illustrated that slack in front of the BRP caused 'bag formation' and damage to the BRP and the surrounding netting. These issues were not observed during the present experiments, which indicate that no bag formation occurred in the BRPs tested. This result proves that inserting a BRP in a beam trawl with straight bobbin- and groundrope (the so called 'square' trawl) instead of a traditional net successfully eliminates these drawbacks. Moreover, only limited abrasion was seen on the chafers, which indicates that the BRPs were positioned well above the seafloor, which facilitates an optimal release mechanism. However, in the 150 mm BRP, limited slack was caused by the fact that the mesh size of the hand knitted 150 mm BRP was larger than intended. Consequently, the panel was slightly longer than the opening in the belly of the net, creating a less stretched geometry of the BRP itself.

The extent to which the BRP is stretched inside the trawl undoubtedly affects the release capacity of the panel. Slack in the panel prevents benthos and stones from easily rolling over it and make them accumulate in front of the BRP or on the BRP promoting a better release. This may be one of the reasons why Fonteyne and Polet (2002) reported a 83% benthos reduction with a 200 mm BRP in a round net, whereas this was only 53% in the present study (Table 2). On the other hand, a good match is seen with the benthos release in a 150 mm BRP (70%) and the 68% reduction of the 150 mm BRP with limited slack in the present study. Finally, results of the present study also confirm the finding of Fonteyne and Polet (2002) that body weight was a determining factor, illustrated by significant bycatch reductions of 90% and more of species like whelk and hermit crab.

The observed loss of marketable sole in the BRPs tested, was similar to the unacceptably high rates reported by Fonteyne and Polet (2002), but they contrast with the minor sole losses <5% achieved by Revill and Jennings (2005). This discrepancy may be explained by the fact that small marketable sole (24–25 cm), which are the predominant escapees in this study, were scarce on the fishing grounds where Revill and Jennings did their experiments (H. Polet Pers. comm..). Fonteyne and Polet (2002) report a commercial loss of sole of 18% with the 150 mm BRP, which is similar to the 17% obtained with the 150 mm BRP, rigged with undesirable slack, in this study. However, the latter authors observed a 45% loss of sole with the 200 mm BRP, which was much higher than the 7% observed in this study with a 200 mm fully stretched BRP without slack and similar to the 42% loss found for the fully stretched 240 mm BRP.

These results accord to the benthos data, which also showed decreased losses in BRP less slack/bag formation. The same trend, but weaker, was observed for undersized sole, showing a 35 and 45% reduction for the 150 and 200 mm BRP in a round net respectively (Fonteyne and Polet, 2002), while in the present study

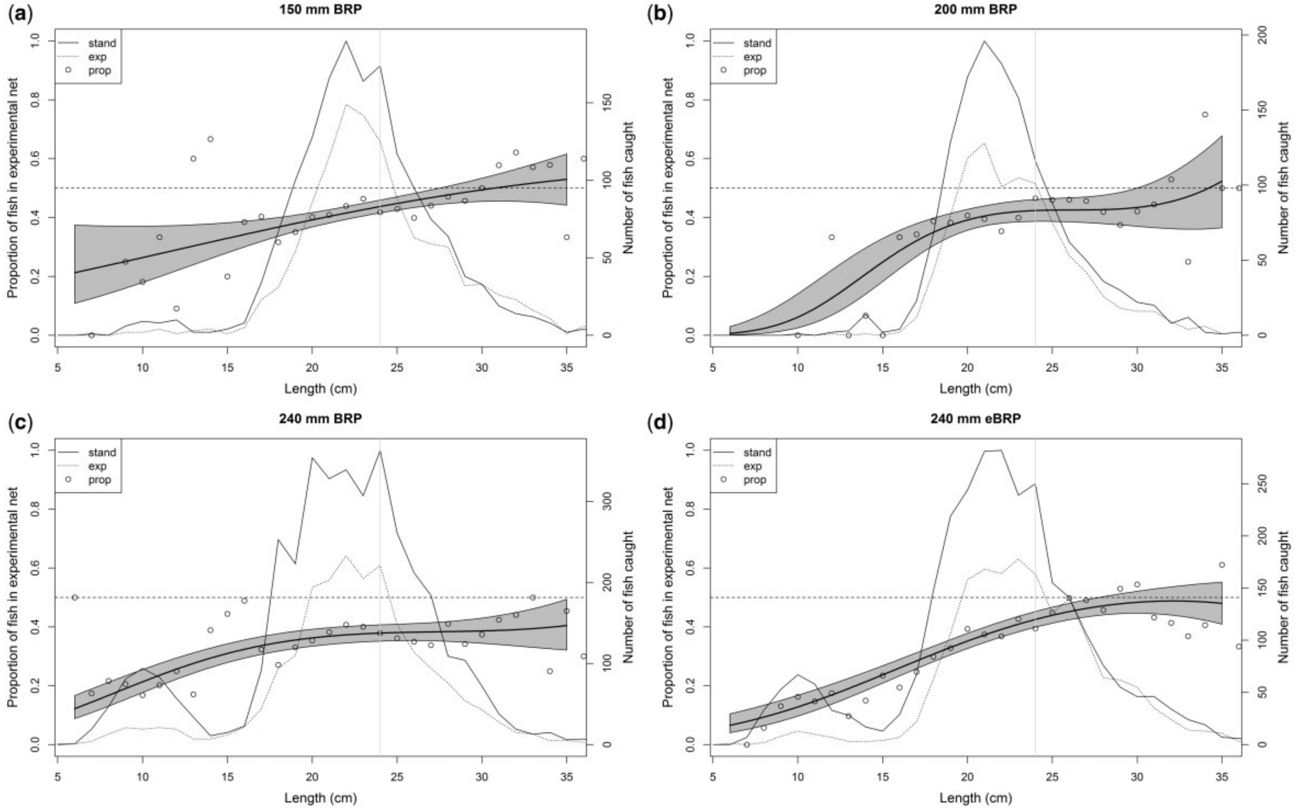

Figure 3. Proportion and length frequency distributions for sole for four different BRP-set ups. The left Y-axis gives the proportion of fish retained in the experimental net (=experimental/(experimental + standard)) per length. The horizontal dashed line indicates the 0.5 proportion, i.e. both nets catch equal numbers of sole. The solid curve in the grey band gives the mean proportion per length, with the grey band indicating the 95% confidence limit. The right Y-axis gives the length distribution, i.e. the total number caught per length. Reference net data are given in solid lines, (e)BRP data in dotted lines. The minimum landing size for marketable sole is 24 cm (light grey line).

this was only 31, 35, and 47% for the 150, 200, and 240 mm BRP, respectively. The loss of sole may be explained by the fact that sole tend to dive as soon as they are caught and stay close to the belly of the net (Fonteyne and Polet, 2002). A stretched BRP demands a more difficult and fast vertical diving movement to escape, whereas bag formation creates escape openings in front of the animal, enabling it to escape horizontally through it. These findings are important, as they indicate that it might be possible to further reduce the 17% loss of sole to an acceptable rate by using a fully stretched 150 or 120 mm BRP, which would allow conventional beam trawls to release large amounts of benthos, debris and undersized sole, with either no, or minor, commercial loss.

The results for plaice, the most important commercial species for beam trawlers by weight (Catchpole *et al.*, 2005) were less consistent. The significantly lower catch rates of commercial plaice (Table 4) in the 240 mm BRP contrasts with the (non-significantly) higher catch rates in the 200 mm BRP. A similar trend was observed for undersized plaice (Table 5) and was also previously reported by Fonteyne and Polet (2002). Commercial red mullet and large dogfish were caught less in all BRPs, which may indicate that these species tend to swim low and follow the belly of the net, as sole does. The large and significant reductions of undersized fish such as sole, lemon sole, whiting, pouting, gurnards and small rays are important side-effects and probably result from the smaller overall catch volumes, enabling a better escapement through the cod-end.

BRP vs. eBRP

The highest losses of benthos and debris were observed in the 240 mm eBRP (Table 2). This may have resulted from different benthos composition or the smaller quantities caught in the eBRP trials, allowing a better release. When the effect of electric stimulation on the release of benthic invertebrates is examined, no direct effect can be discerned, with exception for prawn (*Palaemon serratus* L.). This does not surprise as lab experiments reported that the behavioural reaction to a cramp stimulus of most benthic invertebrates was limited: Echinodermata showed no reaction, molluscs retreated in their shells and crabs demonstrated no or hampered movement (Smaal and Brummelhuis, 2005; van Marlen *et al.*, 2009). Shrimp however, show jump and escape behaviour when exposed to electric stimuli (Polet *et al.*, 2005; Soetaert et al., 2014, 2016c), which may promote escape through the panel, the side or the back of the net resulting in the observed higher loss.

The electric 80 Hz cramp stimulus had the intended effect on sole: no difference in catch rate between the eBRP and reference trawl could discerned for sole smaller than 28 cm (Figure 3). The loss of small commercial sole of 24, 25, 26, and 27 cm was reduced to approximately 18%, resulting in a total reduction of lost marketable sole from 42 to 17%. Interestingly, losses of undersized sole were unaffected. These observations may have three possible explanations. First, small cod escape through the cod-end, which is promoted by the low catch volumes when a BRP is used. This may be valid for undersized sole, but it does not explain the loss of sole of 24 and 25 cm as they should be retained by the 60 mm inner cod-end used. Second, the electric stimulus may not have been strong enough to effectively force all sole smaller than 26 cm to a cramp. However, this is unlikely because the orientation of the animal greatly affects the electric field experienced (Snyder, 2003) and a relatively sharp cut-off retention size was observed. Nevertheless this might have had an influence, since the strength of the electric stimulus was indeed limited. Although the frequency, pulse type and pulse duration used was the same as used by commercial electrotrawls (Soetaert *et al.*, 2015a), the amplitude was only 47 V instead of 55–60 V, the electrodes were also much thinner (12 mm instead of 33) and their intermutual distance was 48 instead of 42 cm. All these parameters contribute to a weaker electric field strength, and thus reaction of the animal. Further experiments are therefore recommended to determine the minimal pulse settings and electrode set-up to affect all marketable sole. The third and last explanation is that the smaller sole are indeed also forced into a cramp and bend in a U-form, but are still able to passively fall through the large 12 × 12 cm meshes when passing the eBRP. Further research is needed to prove if this hypothesis is correct, by reducing the mesh size of the eBRP from 240 to 200 mm and examining if the cut-off retention size shifts to 24 cm, the minimum landings size of sole. Additionally, video recording the panel during trawling should be included in further field trials in order to get a better insight into the release mechanisms and fish behaviour in relation to (e)BRPs.

The electric pulse stimulation seems to have no effect on the catch of most undersized fish species. Species like plaice, whiting, and raya spp., of which sufficiently large numbers were caught, show similar reductions in the 240 mm BRP and the 240 mm eBRP. This may indicate that their loss was attributed to increased escapement through the cod-end, promoted by the smaller catch volumes, which were similar for both net designs. The results for these species contrast however with those of pouting, demonstrating an increase in reduction from 11 to 60%. This points to a stronger escape response as a consequence of the electric stimulus for some species. Since it is unlikely that small pouting are not immobilized by the pulse and pass through the panel, the observed loss probably results from escapement through the side and back of the net after being startled by the electric pulse. Similarly, physical and visual stimuli have also been reported to promote fish escape behaviour and increase the selectivity of panels in trawls (Glass and Wardlle, 1995; Kim and Whang, 2010; Herrmann *et al.*, 2015). This increased escape behaviour was not observed in the whiting. This might be caused by whiting's typical upward flight behaviour (Ferro *et al.*, 2007; Krag *et al.*, 2009) as a result of which it does not encounter the electric field at all. These findings emphasize the importance of video recordings in future research in order to fully unravel and understand underlying mechanisms.

Finally, the implementation of the electric pulse had unwanted side-effects on cod, with 7.7% (4 out of 52) having paravertebral hemorrhages. This incidence was slightly lower than the previously reported 9–11% (van Marlen *et al.*, 2014) and may result from the reduced electric field strength (de Haan *et al.*, 2016) or the reported strongly variable sensitivity of this species (Soetaert *et al.*, 2016b).

Reduced environmental impact

Survival of several benthos species will be positively affected as they drop out directly from the trawl, at the site of capture without additional stress and harm suffered in the cod-end or on board processing. According to Revill and Jennings (2005) survival rates for many BRP escapee crustaceans, molluscs and echinoderms are close to 100% and they therefore conclude that the implementation of a BRP can reduce the overall environmental impact expressed as invertebrate mortality of beam-trawl fisheries by 5–10%.

In contrast to a relatively high discard survival of invertebrates in beam-trawl fisheries, the survival rates of discarded undersized fish of commercial species are generally low: 0–50% for Pleuronectiformes, over 70% for Rajiformes and 0% for whiting and pouting (Van Beek *et al.*, 1990; Benoit *et al.*, 2012; Depestele *et al.*, 2014), stressing the importance of minimizing the bycatch of undersized fish. The numbers given in Table 5 are therefore promising, and probably an underestimate because the in-liners used in the present study hamper the escape of undersized fish. Moreover, the survival chances of the bycaught undersized fish will also increase as a consequence of smaller catch volumes (Depestele *et al.*, 2014) and subsequent shorter on-board processing time, resulting in less stress and harm (Davis, 2002).

Promising perspectives

Looking from a fisher's perspective at the distinctive advantages of BRPs, the bycatch reduction of undersized fish may become far more important than the drop-out of unwanted benthos. From 2016 on, discarding will be prohibited in Europe and fishermen will be obligated to land undersized fish of commercial species, directly influencing TAC and quota allocation (NSAC, 2014). The implementation of (e)BRPs may therefore become increasingly beneficial, as it can possibly help to reduce unwanted bycatches. In addition, smaller catch volumes as a result of lower benthos and debris proportions may result on one hand in a better bycatch survival and on the other hand in better fish quality, due to diminished damage in the cod-end and consequently a better market price. These economic and environmental benefits offer promising opportunities and an incentive for further optimization and investigation of BRPs.

Further research should try to include underwater video recording of the fish behaviour in relation the (e)BRP, despite that the required clear water conditions may affect the result. As previously discussed, the key questions are (i) how do we lose marketable sole? Are they actively diving through the panel, passively 'falling' through or escaping elsewhere? (ii) is a size or species effect of the electric stimulus, and (iii) does an electric stimulus indeed promote escape behaviour in undersized pouting? For the implementation in conventional trawls, BRP are the most obvious to implement as it does not require any investment in electric devices. Further development should focus on determining the ideal mesh size allowing sufficient bycatch drop-out and the retention of adequate commercial catches of sole. For electrotrawls however, it is a much smaller step to implement an electrified BRP since the electric equipment is already installed in the fishing gear. This would enable the use of larger eBRP meshes, resulting in higher loss of benthos debris and undersized fish, without extra loss of marketable sole. In practice the relative bycatch reduction of benthos and debris will be smaller than observed in this study, as the amounts of benthos and debris entering the net of an electrotrawl is much smaller due to the elimination of tickler chains or chain mats. However, a better retention of commercial sole is required first to enable a successful commercial introduction.

This may be achieved by optimizing the cramp stimulus and electrode configuration, as well as a reduction of the eBRP mesh size to 200 mm. If a similar increase in retention is achieved as observed for the 240 mm (e)BRP, the implementation of a cramp stimulus in a 200 mm eBRP may be sufficient to completely eliminate the loss of marketable sole.

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