Fisheries Research 243 (2021) 106104

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

The effect of electrical stimulation on the footrope and cod-end selection of a flatfish bottom trawl

A.D. Rijnsdorp *, J. Batsleer, P. Molenaar

Wageningen Marine Research, Wageningen University and Research, P.O. Box 68, 1970 AB, IJmuiden, The Netherlands

ARTICLE INFO

Handling by Niels Madsen

Keywords:
Pulse trawl selectivity
Diurnal effect
Sole
Plaice
Covered cod-end
Electro-trawling

ABSTRACT

The beam trawl fishery targeting sole is known for their substantial bycatch of flatfish below the minimum landing size. Pulse trawls were developed to improve the selectivity by replacing mechanical stimulation with electrical stimulation which immobilises fish in front of the footrope. Results are presented of an experiment on board of a commercial pulse trawler studying the effect of electrical stimulation on footrope and cod-end selectivity for three flatfish species - sole (*Solea solea*), plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*) - in 29 paired hauls with electrical stimulation alternating between the starboard and portside gear. It was shown that electrical stimulation increased the footrope selection by a factor 2 in plaice and dab and a factor 7 in sole. The effect on sole is related to the specific response of sole which cramps into a U-shape. Footrope selection showed a small diurnal pattern with the highest selectivity of the pulse trawl during the day. Electrical stimulation and catch weight were shown to have a small effect on the cod-end selectivity retaining slightly more marketable sole. Cod-end mesh selection factors (SF) were estimated at 3.00 (se = 0.02), 2.11 (se = 0.02), and 2.3 (se = 0.1) for sole, plaice and dab, respectively. Selection ratio (SFA = selection range/mesh size) was estimated at 0.45 (se = 0.03), 0.23 (se = 0.02), and 0.41 (se = 0.04) for sole, plaice and dab, respectively. The SF and SFA of the pulse trawl is comparable to values reported for conventional beam or otter trawls.

1. Introduction

In many countries, fisheries land the marketable part of the catch and discard undersized or unwanted species. Discarding is particularly pronounced in bottom trawl fisheries. Discarding reduces the sustainable yield and may cause unwanted ecological consequences. FAO estimated global discards at 27 million tonnes in 1994 and 7.3 million tonnes in 2005 (Alverson et al., 1994; Kelleher, 2005). In order to reduce discarding the EU has imposed in the 2013 reform of the Common Fisheries Policy an obligation to land all fish caught (Borges, 2015; Uhlman et al., 2019). A ban on discarding is expected to create an incentive for fishers to develop discard avoiding technologies improving the selectivity of the gear or avoid fishing on fishing grounds with large quantities of discards (Condie et al., 2014; Gullestad et al., 2015; Guillen et al., 2018; O'Neill et al., 2019).

The North Sea flatfish fishery is one of the bottom trawl fisheries characterised by a large catch of undersized fish. The fishery uses a 80 mm cod-end mesh required to catch the slender and flexible sole (*Solea solea*) and also catch large numbers of undersized fish of commercial species (van Beek, 1998; Catchpole et al., 2008; Uhlmann et al., 2014). In addition, adverse impact on the benthic ecosystem is caused by the tickler chains used to chase sole out of the seabed (Kaiser and Spencer, 1996; Jennings and Kaiser, 1998; Bergman and van Santbrink, 2000).

In order to reduce the ecosystem impacts of the beam trawl fishery, electrified beam trawls also named pulse trawls, were introduced in 2011 on an experimental basis (Haasnoot et al., 2016; Poos et al., 2020). Because the response of fish to electrical stimulation is size dependent, gear selectivity may be improved (Stewart, 1975, 1977; Soetaert et al., 2015). Van Marlen et al. (2014) indeed showed that the pulse trawl caught fewer undersized plaice and sole than the conventional tickler chain beam trawl. A statistical comparison of the catch rate of undersized fish between pulse trawls and conventional beam trawls showed that pulse trawls have a reduced catch efficiency of dominant discarded species (ICES, 2020). Furthermore, the replacement of tickler chains by electrodes and the lower towing speed reduces the mechanical disturbance of the sea floor (Depestele et al., 2018; Rijnsdorp et al., 2020, 2021).

This paper studies the effect of electrical stimulation on the catch

* Corresponding author.
E-mail address: adriaan.rijnsdorp@wur.nl (A.D. Rijnsdorp).

https://doi.org/10.1016/j.fishres.2021.106104
Received 5 July 2021; Accepted 5 August 2021
Available online 16 August 2021

rate and mesh selectivity for three flatfish species, including sole (*Solea solea*), the main target species of the Dutch beam trawl flatfish fishery, and plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*) that dominate the bycatch and discard fraction. The realised catch rate is the combined result of proportion of the fish in the trawl path that enter the net (footrope selection; available-selection *sensu* (Millar and Fryer, 1999) and the proportion that is retained in the cod-end (cod-end mesh selection: contact-selection *sensu* (Millar and Fryer, 1999). The footrope selection was estimated by comparing the catch rate between the identical starboard and portside net where the electrical stimulation was alternatingly switched on and off. The cod-end selection was estimated by using a fine meshed cod-end cover to collect the fish that escaped through the meshes.

2. Material and methods

The 5-day experiment was conducted between 18–22 July 2016 on board of the 1467 kW commercial pulse trawler TX43 "Biem van der Vis" fishing two 12 m wide pulse-wing trawls with 26 electrodes from booms on either side of the vessel. Electrical stimulation was alternated between the starboard and portside gear. Electrical bipolar pulses were generated with a HFK pulse system with a peak voltage = 56 V, frequency = 30 Hz, pulse width = 350 μs and power 6 kW per trawl (Soetaert et al., 2019).

The pulse trawl was kept open by a wing-shaped foil with a "nose" in the centre (Fig. 1). The pulse trawl used represents the PUL-R type (*sensu* Rijnsdorp et al., 2021) with a 'rectangular' ground rope comprising of three segments of disc-protected chains, two of which were running at a small angle to the towing direction at either side of the net opening, and a central segment running perpendicular to the towing direction. The diameter of the rubber discs of the central segment was 170 mm. The shape of the ground rope is kept by tension relief cords. A second ground rope with 100 mm rubber discs was attached just in front of the ground rope to which the electrodes were attached.

The net plan is shown in Fig. 2. The aft part of the trawl was equipped with a 'Belgium panel[1] ', a round 140 mm mesh panel to enable undersized fish to escape from the trawl before entering the cod-end. This construction is used in the flatfish fishery to reduce the catch of flatfish below the minimum landing size as a contribution to the landing obligation. Net panels were made of nylon (PA), except for the large mesh top panels that were made of Dynema and the 'Belgium panel' that was made of 3 mm double braided polyethylene (Euroline). The diamond-shaped 90 mm cod-end was made of double braided 3 mm polyethylene (Powerblue). The 33 mm cover was made of 2.5 mm single braided nylon and attached at 17 meshes from the front of the cod-end.

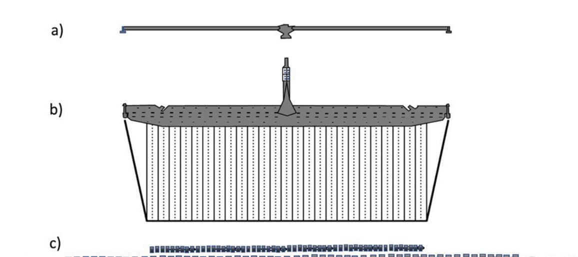

Fig. 1. Schematic drawing of the 12 m wide pulse trawl used in the experiment: a) frontal view of the hydrodynamic foil and central placed nose that fixes the horizontal and vertical net opening; b) top view of the hydrodynamic foil and nose and the matrix of electrode arrays (vertical lines) and tension relief cords (hatched vertical lines); c) double ground rope of disc-protected chain links. The main ground rope is attached to the tip of the wings and comprise of a central part perpendicular to the towing direction and two parts that are attached to the tips of the foil. A second ground rope with smaller discs is attached at a few centimeters in front of the main ground rope. Tension relief cords are attached to the main ground rope to support the rectangular shape, while the electrodes are attached to the second ground rope to prevent damage.

Twenty-nine of the 35 hauls taken on various fishing grounds in the southern North Sea were analysed (Fig. 3). Towing speed was about 5 knots. Haul duration varied between 90 and 120 min (mean = 113 min, sdev = 8 min) which is similar to the haul duration in the commercial fisheries. The weight of the total catch was measured with a load cell for the cover and cod-end of the starboard and portside trawl separately (4 catch samples per haul). All individual sole and plaice (29 hauls) and dab (3 hauls) were collected from the sorting belt and their length distribution (total length, cm-below) was determined. If the total number per species exceeded 150 fish, a subsample was taken. This occurred in 2 out of 116 catch samples of sole, 64 out of 116 catch samples of plaice, rand 9 out of 12 catch samples of dab. Subsample factors ranged between 2–4 with a maximum of 8. In total 9239 sole, 14615 plaice and 1794 dab were measured before subsampling. The weather conditions during the experiment were good with median wind force 2.5 $m.s^{-1}$ (range = 1–9 $m.s^{-1}$).

Mesh sizes of 20 meshes of wet nets was measured twice on the 2nd and 4th day of the experiment in the longitudinal direction of both cod-end and cover with an Omega gauge at 125 N (cod-end) and 50 N (cover). The average mesh size was 88.1 mm (sd = 1.64) and 86.5 mm (sd = 1.97) and 36.7 mm (sd = 2.39) and 37.1 mm (sd = 1.10) for the cod-end and cover of the starboard and portside net, respectively.

The effect of electrical stimulation on the footrope selection was estimated by calculating the ratio of the number of fish caught in the net with electrical stimulation (pulse net, n_p) over the sum of the catch of the pulse and reference net (n_r). The ratio $Y_r = \frac{n_p}{n_p + n_r}$ follows a binomial distribution $Y_r \sim B(n_r, \mu_r)$. The diurnal pattern and the effect of water depth was studied using a general additive model with a logit link function.

$$logit(\mu_{ij}) = \alpha + s(T) + s(D) \tag{1}$$

where $s(T)$ is a cyclic smoother of the time of day and $s(D)$ is a smoother of water depth.

Cod-end mesh selection is commonly studied by fitting a logistic function (Millar and Fryer, 1999; Madsen, 2007). Selection curves were estimated using a mixed effect model of the cod-end retention probabilities (p_{ij}) as a function of length class i (1 cm) and haul number j. The retention probability (p_{ij}) follows a binomial distribution $B(n_{ij}, \mu_{ij})$ where n_{ij} is the number of fish caught in length class i and haul j, and μ_{ij} is the mean retention probability for length class i and haul j. To take account of the variation in the selection curves between hauls, a random intercept $a_j \sim N(0,\sigma_a^2)$ and random slope $b_j \sim N(0,\sigma_b^2)$ were included to allow the selection curves of individual hauls to vary randomly around the mean selection curve,

$$logit(\mu_{ij}) = \alpha + \beta_1 L_{ij} + a_j + b_j L_{ij} \tag{2}$$

The effect of electrical stimulation or relative catch weight on the mesh selection was estimated by including the covariate (X_{ij}) and its interaction with length ($L_{ij}X_{ij}$) in Eq. (2):

$$logit(\mu_{ij}) = \alpha + \beta_1 L_{ij} + \beta_2 X_{ij} + \beta_3 L_{ij} X_{ij} + a_j + b_j L_j \tag{3}$$

Because electrical stimulation and relative catch weight are positively correlated (r = 0.820), the covariates were analysed separately. The effect of the relative catch weight, calculated as the $\log_e$ cod-end weight divided by the mean $\log_e$ cod-end weight over all hauls (mean = 0.273, range = -0.40 to 1.77), was estimated using data of hauls with electrical stimulation only.

Model selection was based on the AIC criterion choosing the simplest

[1] https://pure.ilvo.be/ws/portalfiles/portal/4238903/2016_Depestele_Vlaams_paneel_als_antwoord_op_aanlandplicht.pdf

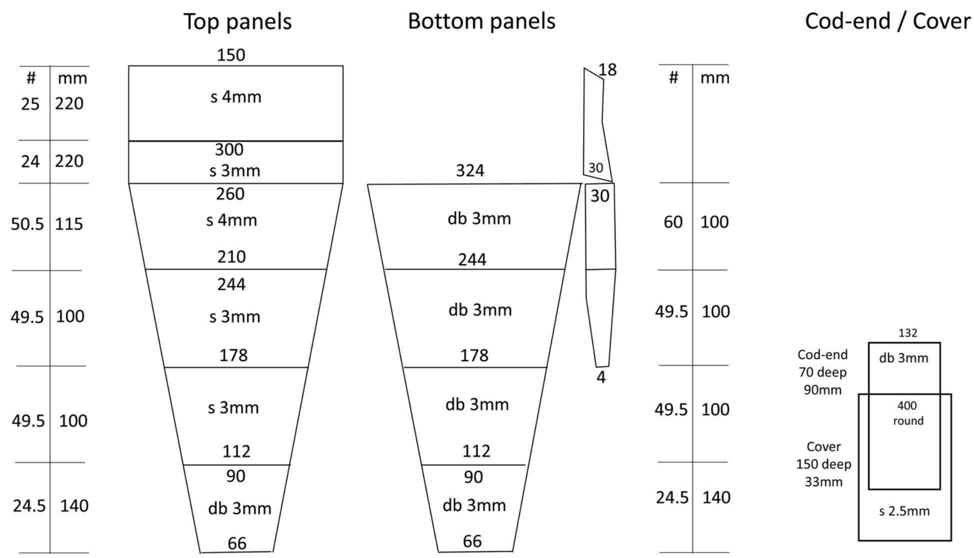

Fig. 2. Net plan of top and bottom panels and cover used in the mesh selection experiment: # number of meshes deep, mm mesh size between knots, s = single braid, db = double braid. The cover was attached at 17 meshes from top of cod-end.

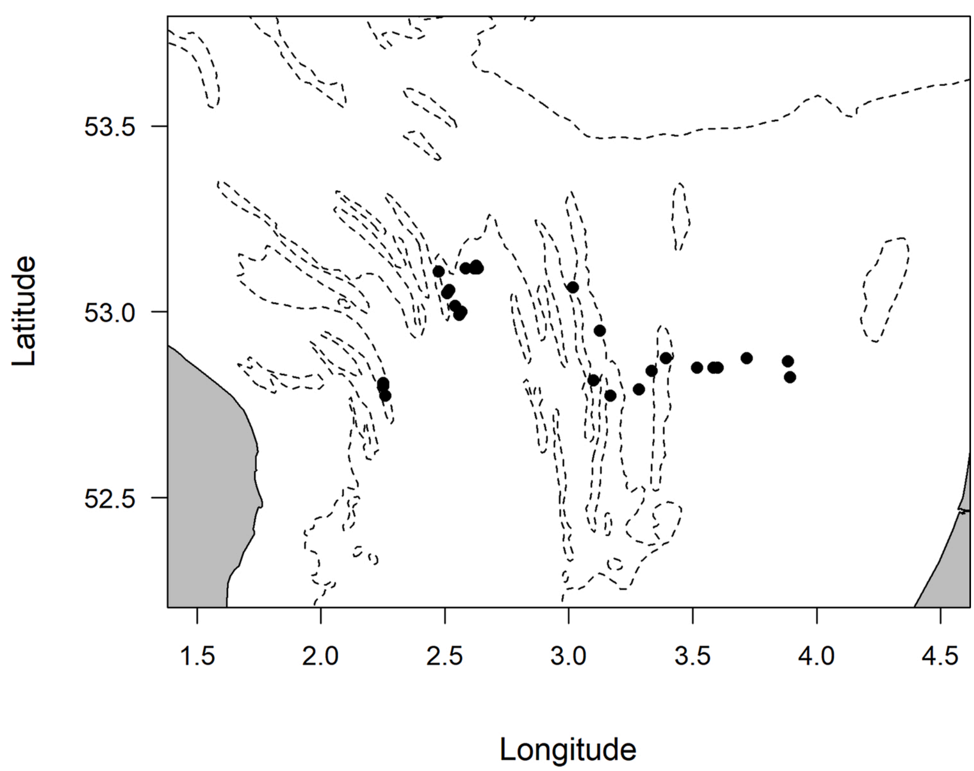

Fig. 3. Trawling stations in the southern North Sea and 30 m depth contour.

model where the addition of a covariate did not reduce the AIC by more than 2 units. Confidence intervals around the mean selection curve were calculated by bootstrapping taking account for the uncertainty in the fixed effects (α,β) using the function *predictInterval* in R (Knowles and Frederick, 2019).

The selection factor (*SF*) was estimated as the ratio of the length at 50 % retention (L_{50}) and mesh size (*M*) where the $L_{50} = -\alpha/\beta_1$. The selection range (*SR*), being the length interval between the length at 25 % and 75 % retention is given by $SR = 2\, log_e 3/\beta_1$ and presented as selection ratio $SFA = SR/M$ (Wileman et al., 1996; Herrmann et al., 2013). Confidence intervals of SF, SR and SFA were derived by bootstrapping given the estimated fixed effect coefficients [Eq. (2)] and estimated correlation coefficient (ρ) between α and β_1 and mean and standard deviation of the cod-end mesh size. The confidence intervals relate to the mean selection curve estimated for all sampled hauls.

The Minimum Conservation Reference Size (MCRS) for sole and plaice is 24 cm and 27 cm, respectively. For dab there is no MCRS.

3. Results

3.1. Footrope selection

Electrical stimulation increased the total catch weight by 42 % (95 % cl = 39%–46%). The proportion of the total catch retained in the cod-end was about 65 % and did not differ between the pulse and reference net (Table 1).

The number of flatfish caught in the pulse net was substantially higher than in the reference net where the electrical stimulation was switched off (Fig. 4). The effect of electrical stimulation was particularly pronounced for sole. The proportion of sole caught in the pulse net was on average 0.87 (confidence limits: 0.66 – 0.96) of the total number caught, as compared to 0.69 (confidence limits: 0.51 – 0.83) and 0.72 (confidence limits: 0.31 – 0.94) in plaice and dab, respectively. Expressed relative to the catch of the reference net, the pulse net caught on average 6.9 times more sole than the reference net where the pulse stimulus was switched off. For plaice and dab the catch in the pulse net was 2.2 and 2.5 times higher than in the reference net, respectively.

The effect of electricity on the catch proportion of the pulse trawl was significantly ($P < 0.001$) affected by both the time of day and the water depth (Fig. 5). The gam model explained 63 % and 54 % of the deviance in sole and plaice, respectively. The pulse trawl caught relatively more during the afternoon and in shallower water and relatively less during the night and in deeper water, although the diurnal effect was rather small.

3.2. Cod-end mesh selection

Cod-end selection curves were estimated for hauls with the pulse net (electrical stimulation switched-on) with [Eq. (2)] including a random intercept and random slope for sole and plaice, and a random intercept only for dab (Fig. 6). The parameter estimates of the random and fixed effects and the derived L_{50} and SR are presented in Table 2. The corresponding SF of the mean selection curve of all sampled tows were estimated at 3.00 (se = 0.02), 2.11 (se = 0.02), and 2.3 (se = 0.1) for sole, plaice and dab, respectively.

Electrical stimulation significantly affected the cod-end selection (Table 3). The pulse net retained slightly more of the larger soles than the reference net as shown by the steeper selection curve (Fig. 7a). In plaice, the effect was marginally significant and the selection curve of the pulse net was shifted to smaller sizes although the effect was very small with a decrease in L_{50} of 0.2 cm (Fig. 7b).

Cod-end selection was significantly affected by the catch weight of the cod-end (Table 3). The effect is illustrated by the difference in the fitted selection curves for three levels of relative catch weight (−0.20, 0.23 and 0.72 representing the 10th, 50th and 90th percentiles). For sole, an increase in the relative catch weight hardly affects the L_{50}, but results in a shallower slope of the selection curve due to a larger proportion of the small soles being retained in the cod-end (Fig. 7c). For plaice, the selection curve shifts to smaller sizes with the L_{50} decreasing by 0.65 cm when the relative catch weight increases from the 10th to the 90th percentile (Fig. 7d).

Table 1
Mean and standard deviation of the total catch weight (kg) and the catch weight (kg) of the cod-end and cover of the net with electrical stimulation (pulse net) and the net where the electrical stimulation was switched off (reference net).

Net	Total catch (kg)		Cod-end catch (kg)		Cover catch (kg)		Number of hauls
	mean	sd	mean	sd	mean	sd	n
Pulse	537	324	352	230	185	145	29
Reference	378	302	237	191	141	151	29

4. Discussion

4.1. Footrope selection

Electrical stimulation substantially increased the number of flatfish caught as well as the total weight of the catch. The footrope selection was particularly increased for sole, where the pulse net caught on average 6.9 times more fish (numbers) than the net where the pulse stimulus was switched off. For plaice and dab the catch numbers in the pulse net increased by a factor of 2.2 and 2.5, respectively. These results are consistent with the cramp response of fish to the electrical stimulation (van Stralen, 2005; de Haan et al., 2016; Soetaert et al., 2016) which immobilises the fish that will no longer be able to escape from the approaching gear by flight or burrowing behaviour. The effect is particularly strong in sole which curls up into a U-shape where the nose and tail may even touch each other (van Stralen, 2005). By forming a U-shape, sole will come lose from the sea floor and may easily pass over the ground rope. Because the electric field penetrates into the sediment (de Haan and Burggraaf, 2018), sole that are buried into the sediment will become available to the trawl that otherwise would have been overran by the ground rope. The effect of electrical stimulation on the footrope selection is less in other flatfish, such as plaice, as these only marginally bend their body when cramped in response to a pulse stimulus (van Stralen, 2005), but still led to about twice as much plaice and dab being caught compared with the reference tows.

The diurnal pattern in footrope selection observed in sole and plaice is likely related to their activity pattern that increase the escape probability for the reference net during the day. Sole has a nocturnal activity pattern and may be buried in the sediment during the day (Kruuk, 1963; de Groot, 1971). Hence, more sole are expected to pass under the ground rope of the reference net during the day. Plaice does not have a clear diurnal activity pattern, except during the winter spawning period (de Groot, 1971), and may visually respond to the approaching gear during day time increasing the flight or burrowing escape probability for the reference trawl. This interpretation is corroborated by the known diurnal pattern in the catch rate of conventional beam trawlers (de Groot, 1971; Rijnsdorp et al., 2000). The implication of the diurnal pattern is that the footrope selection in pulse trawls is expected to be less sensitive for the differences in activity of the target species between day and night as compared to the conventional tickler chain beam trawl.

The effect of water depth on the relative catch rate of the pulse net may be related to the difference in sediment grain size. On the deeper trawling stations, the sediment comprised of muddy sands, as compared to fine sands and coarse sands on the more shallow trawling stations. In the finer sediments, the ground rope is expected to penetrate deeper into the sediment which will reduce the probability of flatfish to escape underneath the ground rope.

In the conventional beam trawl fishery, the footrope selection is increased by deploying multiple tickler chains in front of the footrope that will chase flatfish up from the seafloor. The tickler chains run at fixed distances in front of the footrope and prevent flatfish to dig into the sediment and escape underneath the footrope (Creutzberg et al., 1987). A comparison of the catch rate of large pulse trawlers and conventional tickler chain beam trawlers revealed that the pulse trawl caught 52 % more marketable sized sole and 12 % less marketable sized plaice per area of seafloor swept (Poos et al., 2020). Hence, the effect of electrical stimulation on the footrope selection will be larger than the effect of tickler chains for sole, but smaller for plaice.

4.2. Cod-end mesh selection

Electrical stimulation resulted in a slightly steeper selection curve reflecting a higher retention of soles above the MCRS. The difference between the selection curves of the pulse and reference nets may be explained by the possibility that larger soles may escape through the net opening of the reference net as suggested by underwater video

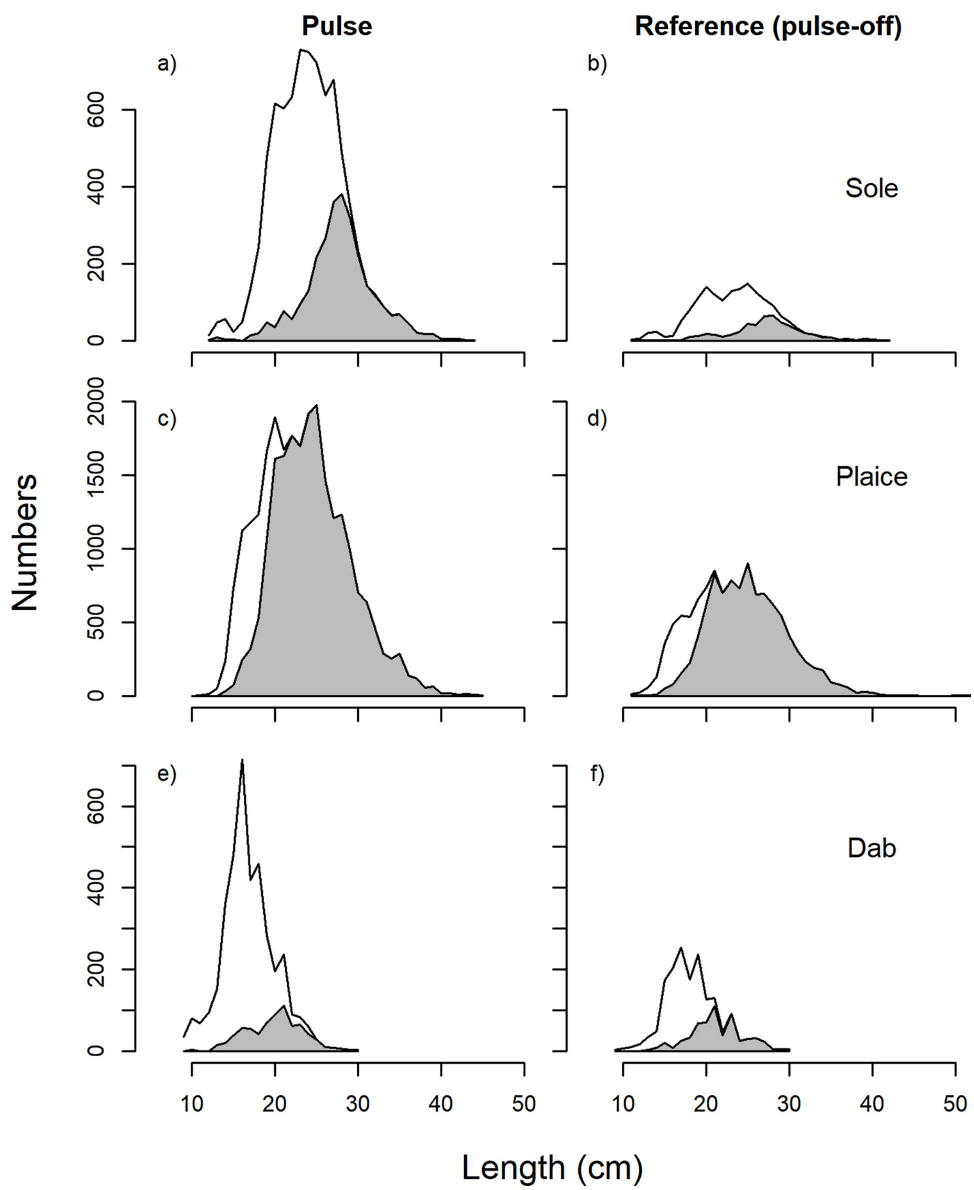

Fig. 4. Size distribution of sole (a, b), plaice (c, d) and dab (e, f) caught in the pulse (a, c, e) and reference (no-pulse: b, d, f) net and the part of the catch retained in the cod-end (grey).

observations which showed that sole may hold tight to the bottom net panel and move forward towards the net opening (Pieke Molenaar, pers observation). In contrast to the reference net, electrical stimulation will immobilise sole again at the net entrance and reduce their chance to escape through the net entrance. The small effect of electrical stimulation on the selection curve in plaice is likely due to the higher catch weight in the cod-end in the pulse trawl compared to the reference net.

The effect of catch weight on the cod-end selection found in the current study and in other studies (Van Beek et al., 1983; O'Neill et al., 2016) is likely related to the decrease in lateral mesh opening with increasing catch weight. In addition, the catch of a beam trawl also includes benthic invertebrates and debris (van Marlen et al., 2014) which may hamper the fish from reaching the cod-end meshes to escape. Also, small fish may hide between the bulk catch and therefore not actively searching for an escape. Since the total catch weight of pulse trawl is around 50 % of the total catch weight of tickler chain beam trawls (van Marlen et al., 2014), the negative effect on cod-end selection in pulse trawls is expected to be less than in conventional tickler chain beam trawls.

There is only one other study of the cod-end selection in pulse trawls, which reported a lower selection factor for both sole and plaice (Table 4). The difference may be related to the different rigging of the gear. The pulse trawler studied by Molenaar and Chen (2018) was equipped with a trouser trawl dividing the catch in two cod-ends, which may have resulted in a reduced lateral mesh opening and therefore a reduced cod-end selection.

Given the lower catch weight of the pulse trawls (van Marlen et al., 2014; ICES, 2020) and its effect on cod-end selection discussed above, we expect that pulse trawls may show a better cod-end selection (higher SF, lower SFA). Comparison of the SF and SFA estimated in two pulse trawl experiments with the results of mesh selection studies in conventional tickler chain beam trawls and otter trawls does not support this inference. The large variability in reported SF and SFA exceed the effects of catch weight observed in our study (Table 4). The variability in SF and SFA between studies will be related to differences in netting material and number of meshes in the circumference (Herrmann et al., 2013, 2015; O'Neill et al., 2016), sea conditions during the experiment and weight of the catch (O'Neill and Kynoch, 1996; O'Neill et al., 2020).

The pulse trawl selection factors (SF_p) fall within the range reported in the literature (SF_L) for sole (SF_p = 2.58–3.00, SF_L = 2.55–3.34) and

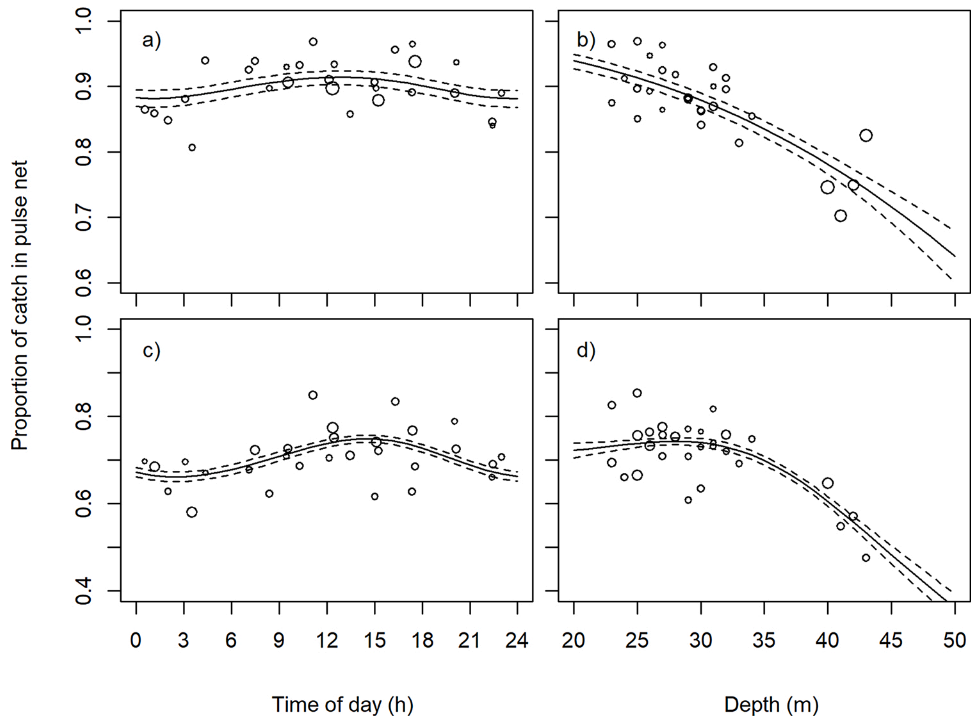

Fig. 5. Footrope selection. Proportion of the pulse net catch of the total catch of the pulse and reference net in relation to the time of day and depth for sole (a, b) and plaice (c, d). The size of the bubbles is proportional to the square root of the number of fish caught. Observations (bubbles), predictions (full line) and confidence intervals (dashed lines) were standardised to a depth of 25 m (a, c) and time of day of 12 h (b, d).

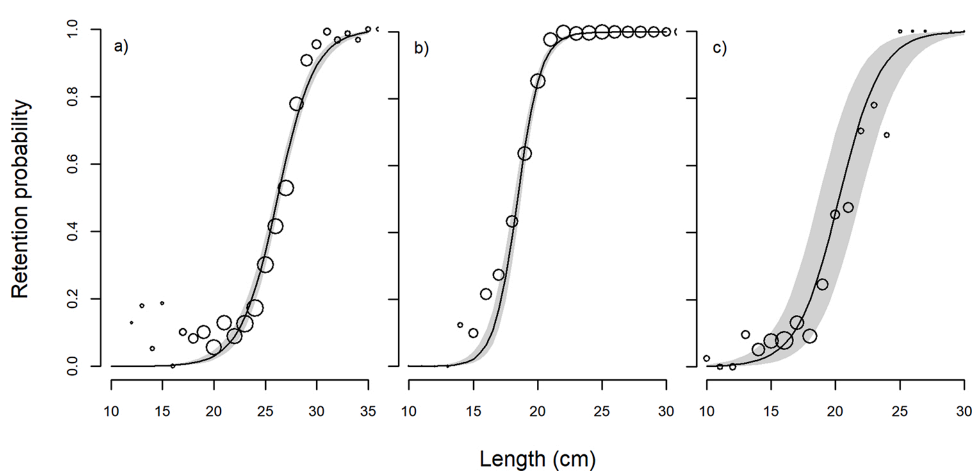

Fig. 6. Cod-end mesh selection curves for sole (a), plaice (b) and dab (c) of the pulse trawl net with electrical stimulation estimated with the mixed effect model with random intercept and slope (sole and plaice) and random intercept (dab). The size of the symbols is proportional to the square root of the number of fish caught by 1 cm length class. Shaded envelopes show 95 % confidence intervals.

Table 2
Parameter estimates of the random and fixed effects of the mixed effect model (Eq. (2)) of the retention probability as a function of body length (cm) and the length at 50 % retention (L_{50}) and selection range (SR) for the pulse trawl with electrical stimulation turned on.

	Random effects			Fixed effects					Derived metrics			
Species	$\sigma\ a_j$	$\sigma\ b_j$	ρ	α	SE	β_1	SE	ρ	*L50*	SE	*SR*	SE
Sole	3.956	0.145	−1.00	−14.570	0.862	0.557	0.032	−0.995	26.2	0.17	4.0	0.24
Plaice	5.092	0.242	−1.00	−20.358	1.400	1.105	0.071	−0.996	18.4	0.15	2.0	0.13
Dab	0.831			−12.521	1.168	0.618	0.054	−0.904	20.3	0.83	3.6	0.32

plaice ($SF_p = 1.88$–2.11, $SF_L = 1.79$–2.15), but is larger than the value reported for the tickler chain beam trawl fishery for dab ($SF_p = 2.32$, $SF_L = 1.78$). Also the steepness of the selection curve of the pulse trawl (SFA_p), reflected by the selection ratio, corresponds to the values reported in the literature (SFA_L) for conventional beam trawls (tickler chain beam trawl, chain mat beam trawl) and otter trawls for sole (SFA_p

Table 3
Parameter estimates of the effect of electrical stimulation and relative catch weight on the cod-end selection with mixed effect model including random intercept and slope using equation Eq. (3).

Fixed terms	Sole			Plaice[1]		
	estimate	SE	P-value	estimate	SE	P-value
Electrical stimulation (T)						
β_0	−14.37	0.832	<0.001	−17.75	0.505	<0.001
$\beta_1 L$	0.55	0.031	<0.001	0.98	0.026	<0.001
$\beta_2 T$ (pulse-off)	1.51	0.602	<0.05	−0.17	0.086	0.05
$\beta_3 L * T$ (pulse-off)	−0.07	0.024	<0.01			
Relative catch weight (W)						
β_0	−16.15	0.836	<0.001	−20.72	1.453	<0.001
$\beta_1 L$	0.61	0.031	<0.001	1.11	0.074	<0.001
$\beta_2 W$	5.81	1.404	<0.001	0.78	0.263	<0.01
$\beta_6 L * W$	−0.21	0.053	<0.001			

1) Effect electrical treatment estimated with random intercept only.

= 0.45 – 0.59 vs SFA_L = 0.45 – 0.85) and plaice (SFA_p = 0.23 – 0.26 vs SFA_L = 0.20 – 0.46). For dab the pulse trawl selection ratio (SFA_p = 0.41) is smaller than the value reported for the chain mat trawl (SFA_L = 0.76).

We used the covered cod-end method to estimate the contact selection parameters, but did not use rigid hoops recommended to avoid the possible masking of the cod-end meshes by the cover (Wileman et al., 1996). Pulse wings only hover 40 cm above the seabed with the trawl in between the wing and the seabed, using hoops makes the cover prone to damage as those would drag over the seabed. Although the possibility that a part of the cod-end meshes was masked by the cover cannot be excluded, we believe that this effect will be relatively small. The cover used is rather wide and has a large twine surface area that will have pushed the cover by the waterflow passing through the cod-end meshes. As the catch weight in the cover increases during the tow, the hydrodynamic drag force on the cover will be counteracted by the increasing drag force of the cover filling and the probability of masking will increase. Further, sole is known to force itself through rather narrow meshes and will be less sensitive for the potential masking effect. If the masking effect of the cod-end meshes by the cover would have affected the selection parameters, the selection factor estimated will be underestimated and the selection range will be overestimated. Also Molenaar and Chen (2018) used the cover cod-end with kites but found lower SF than in this study.

5. Conclusion

Our study showed that electrical stimulation, which immobilises the fish in front of the ground rope, primarily affected the footrope selection which increased by a factor between 2 and 7. The effect differed between the three flatfish species studied showing the largest effect for sole. The effect of electrical stimulation on cod-end selection was small and the selection factor and selection ratio of the pulse trawl were comparable to values reported for conventional beam or otter trawls targeting flatfish.

Author contributions

A.D. Rijnsdorp: Conceived and designed the analysis, Collected the data, Contributed data or analysis tools, Performed the analysis, Wrote the paper, Other contribution, Obtained research funding.
J. Batsleer: Conceived and designed the analysis, Collected the data, Wrote the paper.
P. Molenaar: Conceived and designed the analysis, Contributed data or analysis tools, Wrote the paper.

Funding

FP7 Food, Agriculture and Fisheries, Biotechnology ('BENTHIS/312088'). Dr J. Batsleer was funded by VisNED.

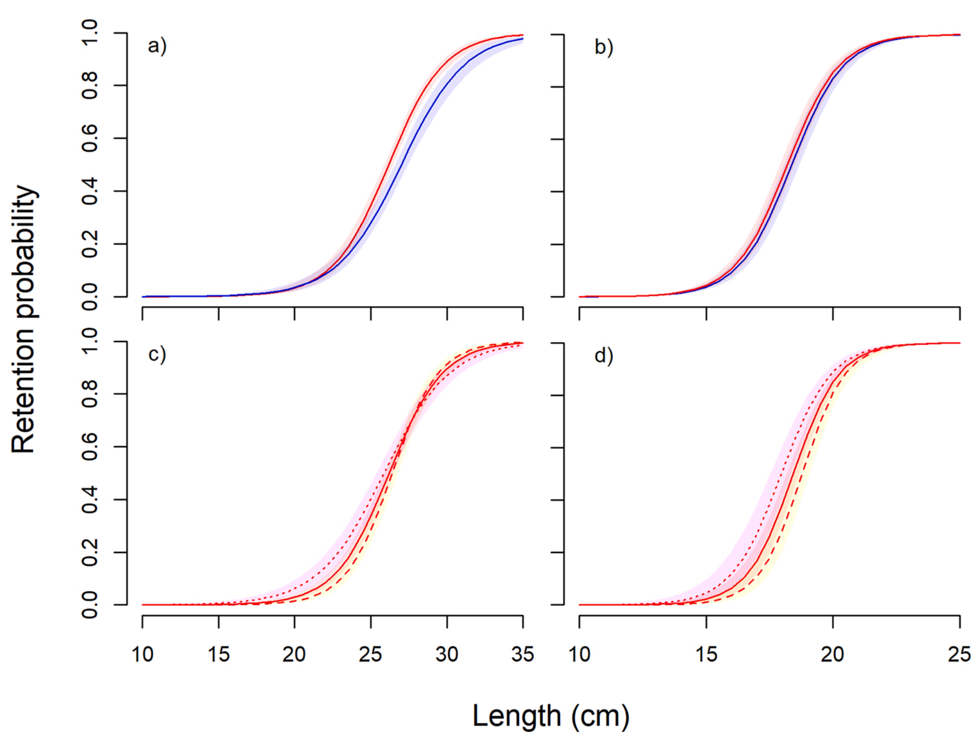

Fig. 7. Effect of electrical stimulation (a, b) and catch weight (c, d) on the cod-end mesh selection curves for sole (a, c) and plaice (b, d). Panels (a, b) show selection curves for tows with electrical stimulation (red) and reference tows without pulse stimulation (blue). Panels (c, d) show selection curves for three levels of cod-end catch weight (10 % percentile – hatched line, 50 % percentile – full line, 90 % percentile - dotted line). Shaded envelopes show 95 % confidence intervals.

Table 4
Comparison of the selection factor (SF) and selection ratio (SFA = selection range / mesh size) estimated in this study with results from previous bottom trawl studies. PT = pulse trawl, TBC = chain mat beam trawl, TBT = tickler chain beam trawl, OTB = otter trawl.

Species	Gear (width, m)	SF		SFA		Source
		mean	SD	mean	SD	
Sole	PT (12)	3.00	0.020	0.45	0.028	This study
	PT (12)	2.58	0.268	0.59	0.033	Molenaar and Chen (2018)
	TBC (4)	2.55	0.051	0.85	0.105	Bayse et al. (2016)
	TBT (4)	2.90	0.142	0.72	0.025	Fonteyne and M'Rabet (1992)
	TBT (12)	3.34	0.159	0.45	0.160	van Beek et al. (1983)
Plaice	PT (12)	2.11	0.018	0.23	0.015	This study
	PT (12)	1.88	0.166	0.26	0.031	Molenaar and Chen (2018)
	TBC (4)	1.79	0.070	0.46	0.077	Bayse et al. (2016)
	OTB	1.78	0.11	0.20	0.049	Herrmann et al. (2013)
	OTB	2.12	0.036	0.23	0.045	Herrmann et al. (2015)
	OTB-nephrops	2.15	0.117	0.32	0.068	Frandsen et al. (2009, 2010, 2015)
	TBT (12)	2.24	0.108	0.31	0.077	van Beek et al. (1983)
Dab	PT	2.32	0.10	0.41	0.037	This study
	TBC (4)	1.78	0.54	0.76	0.179	Bayse et al. (2016)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The study was carried out within the EU-funded FP7-project BENTHIS (312088). The conclusions does not necessarily reflect the views of the European Commission and does not anticipate the Commission's future policy in this area. The authors want to thank the skipper and crew of the TX43 for their support. The field work was carried out with permission to use a fine meshed cod-end cover and keep undersized fish on board of the Dutch ministry of Economic Affairs (RVO-VIR/16085962).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2021.106104.

References

Alverson, D.L., Feeberg, M.H., Murawsky, S.A., Pope, J.A., 1994. A Global Assessment of Fisheries By-Catch and Discards. FAO, Rome.
Bayse, S.M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fish. Res. 174, 201–209.
Bergman, M.J.N., van Santbrink, J.W., 2000. Mortality in megafaunal benthic populations caused by trawl fisheries on the Dutch continental shelf in the North Sea in 1994. ICES J. Mar. Sci. 57, 1321–1331.
Borges, L., 2015. The evolution of a discard policy in Europe. Fish Fish. 16, 534–540.
Catchpole, T., van Keeken, O., Gray, T., Piet, G., 2008. The discard problem – a comparative analysis of two fisheries: the English Nephrops fishery and the Dutch beam trawl fishery. Ocean Coast. Manag. 51, 772–778.
Condie, H., Grant, A., Catchpole, T., 2014. Incentivising selective fishing under a policy to ban discards; lessons from European and global fisheries. Mar. Policy 45, 287–292.
Creutzberg, F., Duineveld, G.C.A., Van Noort, G.J., 1987. The effect of different number of tickler chains on beam trawl catches. Journal Conseil international Exploration de la Mer 43, 159–168.
de Groot, S.J., 1971. On the interrelationships between morphology of the alimentary tract, food and feeding behaviour in flatfishes (pisces: pleuronectiformes). Netherlands J. Sea Res. 5, 121–196.
de Haan, D., Burggraaf, D., 2018. Field Strength Profile in and Above the Seabed as Reference to Pulse Trawl Fishing on Dover Sole (*Solea solea*). Wageningen Marine Research report C022/18, p. 32.
de Haan, D., Fosseidengen, J.E., Fjelldal, P.G., Burggraaf, D., Rijnsdorp, A.D., 2016. Pulse trawl fishing: characteristics of the electrical stimulation and the effect on behaviour and injuries of Atlantic cod (*Gadus morhua*). ICES J. Mar. Sci. 73, 1557–1569.
Depestele, J., Degrendele, K., Esmaeili, M., Ivanović, A., Kröger, S., O'Neill, F.G., Parker, R., et al., 2018. Comparison of mechanical disturbance in soft sediments due to tickler-chain SumWing trawl vs. electro-fitted PulseWing trawl. ICES J. Mar. Sci. 76, 312–329.
Fonteyne, R., M'Rabet, R., 1992. Selectivity experiments on sole with diamond and square mesh codends in the Belgian coastal beam trawl fishery. Fish. Res. 13, 221–233.
Frandsen, R.P., Holst, R., Madsen, N., 2009. Evaluation of three levels of selective devices relevant to management of the Danish Kattegat–Skagerrak Nephrops fishery. Fish. Res. 97, 243–252.
Frandsen, R.P., Madsen, N., Krag, L.A., 2010. Selectivity and escapement behaviour of five commercial fishery species in standard square- and diamond-mesh codends. ICES J. Mar. Sci. 67, 1721–1731.
Frandsen, R.P., Eigaard, O.R., Poulsen, L.K., Tørring, D., Stage, B., Lisbjerg, D., Dolmer, P., 2015. Reducing the impact of blue mussel (*Mytilus edulis*) dredging on the ecosystem in shallow water soft bottom areas. Aquat. Conserv. Mar. Freshw. Ecosyst. 25, 162–173.
Guillen, J., Holmes, S.J., Carvalho, N., Casey, J., Dörner, H., Gibin, M., Mannini, A., et al., 2018. A review of the European Union landing obligation focusing on its implications for fisheries and the environment. Sustainability 10 (4), 900.
Gullestad, P., Blom, G., Bakke, G., Bogstad, B., 2015. The "Discard Ban Package": experiences in efforts to improve the exploitation patterns in Norwegian fisheries. Mar. Policy 54, 1–9.
Haasnoot, T., Kraan, M., Bush, S.R., 2016. Fishing gear transitions: lessons from the Dutch flatfish pulse trawl. ICES J. Mar. Sci. 73, 1235–1243.
Herrmann, B., Wienbeck, H., Moderhak, W., Stepputtis, D., Krag, L.A., 2013. The influence of twine thickness, twine number and netting orientation on codend selectivity. Fish. Res. 145, 22–36.
Herrmann, B., Wienbeck, H., Stepputtis, D., Krag, L.A., Feekings, J., Moderhak, W., 2015. Size selection in codends made of thin-twined Dyneema netting compared to standard codends: a case study with cod, plaice and flounder. Fish. Res. 167, 82–91.
ICES, 2020. ICES working group on electrical trawling (WGELECTRA). ICES Sci. Rep. 2 (37), 108. https://doi.org/10.17895/ices.pub.6006.
Jennings, S., Kaiser, M.J., 1998. The effects of fishing on marine ecosystems. Adv. Mar. Biol. 34, 201–352.
Kaiser, M.J., Spencer, B.E., 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. J. Anim. Ecol. 65, 348–358.
Kelleher, K., 2005. Discards in the World's Marine Fisheries: an Update. Food and Agriculture Organisation, Rome, p. 131.
Knowles, J., Frederick, C., 2019. merTools: Tools for Analyzing Mixed Effect Regression Models. R package version 0.5.0. https://CRAN.R-project.org/package=merTools.
Kruuk, H., 1963. Diurnal periodicity in the activity of the common sole, *Solea vulgaris* Quensel. Netherlands J. Sea Res. 2, 1–28.
Madsen, N., 2007. Selectivity of fishing gears used in the Baltic Sea cod fishery. Rev. Fish Biol. Fish. 17, 517–544.
Millar, R.B., Fryer, R.J., 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. Rev. Fish Biol. Fish. 9, 89–116.
Molenaar, P., Chen, C., 2018. Cod End Selectivity for Sole (*Solea solea*) and Plaice (*Pleuronectes platessa*) in North Sea Pulse Trawl Fisheries. Wageningen University & Research rapport C049/18, p. 31.
O'Neill, F.G., Kynoch, R.J., 1996. The effect of cover mesh size and cod-end catch size on cod-end selectivity. Fish. Res. 28, 291–303.
O'Neill, F.G., Kynoch, R.J., Blackadder, L., Fryer, R.J., Eryasar, A.R., Notti, E., Sala, A., 2016. The influence of twine tenacity, thickness and bending stiffness on codend selectivity. Fish. Res. 176, 94–99.
O'Neill, F.G., Feekings, J., Fryer, R.J., Fauconnet, L., Afonso, P., 2019. Discard avoidance by improving fishing gear selectivity: helping the fishing industry help itself. In: Uhlmann, S.S., Ulrich, C., S.J, K. (Eds.), The European Landing Obligation – Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries. Springer, pp. 279–296.
O'Neill, F.G., Fryer, R.J., Frandsen, R.P., Herrmann, B., Madsen, N., Mieske, B., 2020. A meta-analysis of plaice size-selection data in otter trawl codends. Fish. Res. 227, 105558.
Poos, J.J., Hintzen, N.T., van Rijssel, J., Rijnsdorp, A.D., 2020. Efficiency changes in bottom trawling for flatfish species as a result of the replacement of mechanical stimulation by electric stimulation. ICES J. Mar. Sci. 77, 2635–2645.
Rijnsdorp, A.D., Broekman, P.L.V., Visser, E.G., 2000. Competitive interactions among beam trawlers exploiting local patches of flatfish in the North Sea. ICES J. Mar. Sci. 57, 894–902.
Rijnsdorp, A.D., Depestele, J., Eigaard, O.R., Hintzen, N.T., Ivanovic, A., Molenaar, P., O'Neill, F.G., et al., 2020. Mitigating seafloor disturbance of bottom trawl fisheries for North Sea sole *Solea solea* by replacing mechanical with electrical stimulation. PLoS One 8 (4), e61357.

Rijnsdorp, A.D., Depestele, J., Molenaar, P., Eigaard, O.R., Ivanovic, A., O'Neill, F.G., 2021. Sediment mobilization by bottom trawls: a model approach applied to the Dutch North Sea beam trawl fishery. ICES J. Mar. Sci. https://doi.org/10.1093/icesjms/fsab029.

Soetaert, M., Decostere, A., Polet, H., Verschueren, B., Chiers, K., 2015. Electrotrawling: a promising alternative fishing technique warranting further exploration. Fish Fish. 16, 104–124.

Soetaert, M., Decostere, A., Verschueren, B., Saunders, J., Van Caelenberge, A., Puvanendran, V., Mortensen, A., et al., 2016. Side-effects of electrotrawling: exploring the safe operating space for Dover sole (*Solea solea* L.) and Atlantic cod (*Gadus morhua* L.). Fish. Res. 177, 95–103.

Soetaert, M., Boute, P.G., Beaumont, W.R.C., 2019. Guidelines for defining the use of electricity in marine electrotrawling. ICES J. Mar. Sci. 76, 1994–2007.

Stewart, P.A.M., 1975. Catch selectivity by electrical fishing systems. ICES J. Mar. Sci. 36, 106–109.

Stewart, P.A.M., 1977. A study of the response of flatfish (Pleuronectidae) to electrical stimulation. ICES J. Mar. Sci. 37, 123–129.

Uhlman, S.S., Ulrich, C., Kennelly, S.J., 2019. The European Landing Obligation. Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries. Springer, Cham, p. 431.

Uhlmann, S.S., van Helmond, A.T.M., Kemp Stefánsdóttir, E., Sigurðardóttir, S., Haralabous, J., Bellido, J.M., Carbonell, A., et al., 2014. Discarded fish in European waters: general patterns and contrasts. ICES J. Mar. Sci. 71, 1235–1245.

van Beek, F.A., 1998. Discarding in the Dutch Beam Trawl Fishery. ICES CM 1998/BB:5.

van Beek, F.A., Rijnsdorp, A.D., Van Leeuwen, P.I., 1983. Results of the Mesh Selection Experiments on Sole and Plaice with a Commercial Beam Trawl Vessels in the North Sea in 1981. ICES C.M. 1983/B:16.

van Marlen, B., Wiegerinck, J.A.M., van Os-Koomen, E., van Barneveld, E., 2014. Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fish. Res. 151, 57–69.

van Stralen, M.R., 2005. De Pulskor. Samenvatting van het onderzoek naar de ontwikkeling van een alternatief vistuig voor de vangst platvis gebaseerd op het gebruik van elektrische stimuli. MarinX-rapport 2005.26 27 pp..

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gears. ICES Cooperative Research Report No. 215, p. 126.