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Changes in catch efficiency and selectivity in the beam trawl fishery for sole when mechanical stimulation is replaced by electrical stimulation

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ABSTRACT

Beam trawl fisheries for sole are characterised by large amounts of unwanted bycatch (i.e. discards) consisting of fish below the Minimum Conservation Reference Size, unwanted fish due to low commercial value or lack of quota, and benthic invertebrates. In order to reduce the quantity of discards, a substantial part of the Dutch beam trawl fleet was allowed to replace the conventional tickler chain beam trawl (BT) with the pulse trawl (PT) on an experimental basis. The PT used electrical stimulation to immobilise and capture fish. Here we study whether pulse trawling reduced the amount of discards by comparing catch rates of landings and discards of BT and PT in the period 2009–2018 for a wide range of species. The PT caught ($kg.km^{-2}$) significantly more marketable sized sole (*Solea solea,* 48 %), turbot (*Psetta maxima,* 8 %), brill (*Scophthalmus rhombus,* 28 %) and whiting (*Merlangius merlangus,* 95 %), and significantly less marketable sized plaice (Pleuronectes platessa, −16 %), cod (*Gadus morhua,* −32 %) and gurnards (−12 %). No significant difference was found for dab (*Limanda limanda*), gadoids, or rays and sharks. Among discards, the PT caught more undersized sole (27 %) and whiting (42 %) but less undersized plaice (−21 %), dab (−19 %) and grey gurnard (*Eutrigla gurnardus,* −31 %). The observed differences in species selectivity are discussed in relation to the response of fish to bottom trawl gear and the effects of pulse stimulation. For the benthic invertebrates Ophiuroidae, bivalves and crabs the PT caught fewer individuals (between −38 % and −57 %). No significant difference was observed in sea urchins and sea stars. Overall, this study shows that the transition from the BT to PT resulted in a 36 % decrease (95 % prediction interval: 31–42 %) in discards ($kg.hour^{-1}$).

1. Introduction

The beam trawl was re-introduced in the early 1960 s in the Netherlands and became the most dominant bottom trawl technique in Dutch mixed fishery, targeting deep burying flatfish, such as sole (*Solea solea*) and plaice (*Pleuronectes platessa*) (Gillis et al., 2008; Rijnsdorp et al., 2008). The conventional beam trawling technique (BT), which deploys tickler chains to chase fish out of the sea floor, is characterised by a substantial amount of unwanted bycatch (i.e. discards), consisting of fish below the Minimum Conservation Reference Size (MCRS), unwanted fish due to low commercial value or lack of quota, and benthic invertebrates that is then discarded during the fishing operation (van Beek, 1998; Catchpole et al., 2008; Uhlmann et al., 2014). The survival rate of the flatfish discards is considered to be low, generally less than 30 % (van Beek et al., 1990; Depestele et al., 2014; van der Reijden et al., 2017).

In order to reduce discards in European fisheries, an obligation to land all catches of quota-regulated species was included in the 2013 reform of the Common Fisheries Policy (EU, 2013). The foreseen impact of this landing obligation prompted the Dutch beam trawl fishery to consider novel technological improvements. Pulse trawling (PT) was one of the promising alternative methods, where mechanical stimulation by tickler chains was replaced with electrical stimulation. The electrical stimulus generated by a PT causes involuntary muscular contractions (“cramp”) in fish, thereby causing immobilisation and enabling capture (Soetaert et al., 2015). As the PT can be towed at a lower speed, it consumes less fuel. Its use can therefore be expected to improve economic viability, and to reduce ecosystem impacts caused by discarding and seafloor disturbance (van Marlen et al., 2014; Depestele et al., 2016; Haasnoot et al., 2016; Rijnsdorp et al., 2020). The use of electricity for catching fish is illegal under EU law. A number of beam trawl vessels were granted temporary licences to use the PT. Licences

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were granted, in part, to study the potential for reducing discards within in the context of the landing obligation (Haasnoot et al., 2016). A total of 76 Dutch beam trawl vessels made the transition from the conventional BT to PT from 2009 to 2018 (Poos et al., 2020). In 2019 the EU decided to maintain the ban on pulse trawling and withdrew the temporary licences despite the evidence from ICES that pulse trawling reduced ecosystem impacts (Kraan et al., 2020; ICES, 2020; Delaney et al., 2022).

The PT is particularly effective in catching sole because this species bends into a U-shape when it is exposed to the electrical stimulus (van Stralen, 2005; Soetaert et al., 2016a). Poos et al. (2020) found that, pulse trawling had a higher catch efficiency (by unit area swept) for marketable sole (small vessels +94 %, large vessels +52%) but a lower catch efficiency for marketable plaice (small vessels −23 %, large vessels −12 %). The first group of vessels that switched to PT gradually increased their catch efficiency for sole over a period of almost one year, while vessels that switched later achieved an increase in catch efficiency immediately (Poos et al., 2020). Electrical stimulation may also improve the size selectivity of the gear as the susceptibility to electrical pulse increases with fish size (Stewart, 1977; Soetaert et al., 2015). A comparative fishing experiment with a conventional BT vessel and two PT vessels did indeed show that PT generated fewer fish discards, including undersized plaice (van Marlen et al., 2014).

Building on Poos et al. (2020), the aim of this paper is to investigate whether, and if so by how much, the transition from conventional BT to PT reduced discarding in the beam trawl fishery for sole. Using census landings data and sample discards data collected during the pulse experimental period (i.e. 2009–2018), differences in catch efficiency between BT and PT are estimated for the target species and the main bycatch species, separated into landings and discard size fractions. We estimated the change in discarding by comparing the observed discard and landing fractions per species of the sampled BT fishing trips with the simulated discard and landing fractions for vessels that would have used PT. Finally, the differences in species selectivity are discussed in relation to the knowledge of the response potential of fish to bottom trawl gear and to the effect of pulse stimulation.

2. Material and methods

2.1. Beam trawl fleet

The Dutch beam trawl fleet consists of two groups of vessels: large and small. Each group operates under different management rules (Rijnsdorp et al., 2008). Large vessels with engine powers > 221 kW fish with two 12 m wide beam trawls in waters outside the 12 nm zone and the Plaice Box (Beare et al., 2013). Small vessels with engine power < = 221 kW are allowed to fish with two beam trawls of up to 4.5 m wide within a North Sea's special protection zone (i.e. within 12 nm off the coast and in the Plaice Box). When targeting sole, both groups use 80 mm stretched meshes while fishing in the sole fishing area (SFA) of the North Sea. This area lies south of a demarcation line running at 55°N, west of 5°E and 56°N, east of 5°E. North of this demarcation line, beam trawlers use mesh sizes > =100 mm, when targeting plaice and other demersal fish. Fishing trips for all vessels generally start on Monday, and end on Friday of the same week.

The EU landing obligation was phased in over a number of years, starting in 2016 and full implementation in 2019, within the beam trawl fleet. Under the landing obligation all catches of quota regulated species need to be landed. However, in practice discarding can continue under various forms of exemptions (for species that show 'high' survivability, or a specific *de minimis* discard allowance under certain conditions has been assigned).

The main gears used by the fleet during the pulse experimental period (i.e. 2009–2018) were conventional tickler chain beam trawls (BT) and pulse trawls (PT) (Fig. 1). The BT gear consisted of a number of tickler chains extending from the shoes and the ground rope. The ground rope was V-shaped and consisted of a chain covered with rubber discs in the centre. The PT gear used a matrix of 24 – 28 electrodes in an array covering about 80–93 % of its total width, depending on the rigging (Soetaert et al., 2019; Rijnsdorp et al., 2021b). The matrix of electrodes was attached between the beam and the ground rope. The ground rope was rectangular in shape and consisted of a chain covered with rubber discs. Some vessels attached the matrix of electrodes to a second ground rope (sole rope) with smaller rubber discs running in front. A detailed description of the BT and PT gears as used in Dutch beam trawl fishery, including the dimensions of the gear components, is provided by Rijnsdorp et al. (2021b). Photographs of the gear are provided by Depestele et al. (2018).

2.2. Data

The analysis was restricted to Dutch large vessels fishing for sole with two 12 m wide beam trawls with a cod-end mesh-size of 80 mm in the SFA during the pulse experimental period. These vessels were the dominant component of the Dutch beam trawl fleet, being responsible for approximately 95 % of the total Dutch beam trawl sole landings.

Landings and discards data collected in separate monitoring

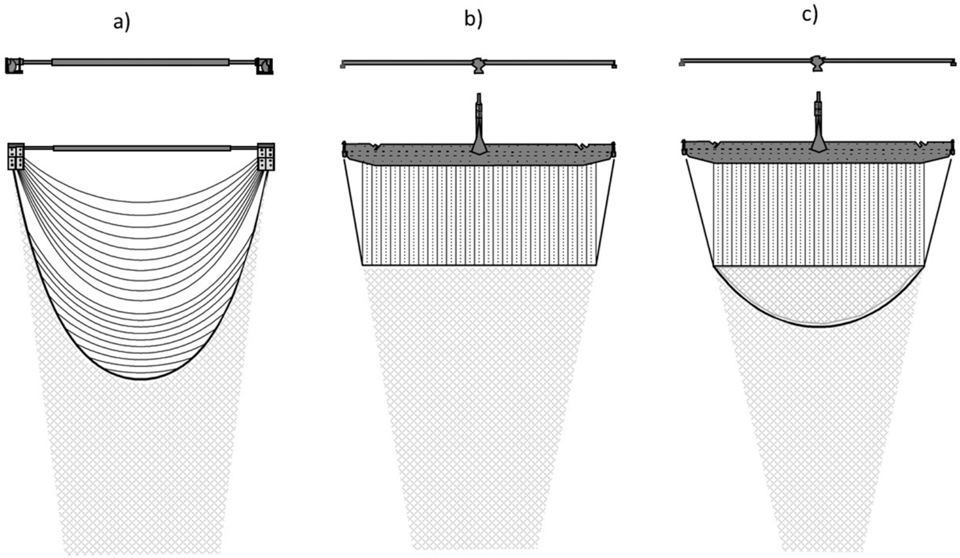

Fig. 1. Schematic drawing of the main beam trawl types used in the fishery for sole in the North Sea: a) conventional beam trawl (BT) with beam, shoes and tickler chains attached to either the shoes (shoe ticklers) or ground rope (net ticklers); b) pulse beam trawl (PT) with rectangular ground rope with electrodes (thin lines) and tension relief cords (dashed lines) attached between the Sumwing and the ground rope; c) PT with U-shaped ground rope and lighter sole rope and sole panel with electrodes (thin lines) and tension relief cords (dashed lines) attached between the Sumwing and the ground rope. Top panels show the frontal view of the beam and wing. Bottom panels show the bottom view including the part of the net panel. The tickler chains and electrodes can be attached to either a beam or a Sumwing. (modified from Rijnsdorp et al. (2021a)).

programmes were used for this study. Census data of landings were available by trip for all Dutch vessels, while discards were available for a number of hauls sampled on board of a subset of vessels. Landings and discards were analysed separately because of the different nature of the data.

2.2.1. Landings

Census landings data for the Dutch beam trawl fleet was available from the official Dutch logbook database held by Wageningen Marine Research (WMR). The database contains mandatory logbook data on the landed catch (kg) by fishing trip, species, trip duration, fishing area (ICES rectangle of 0.5° latitude x 1° longitude), gear type and gear width. Swept area was calculated for each fishing trip by multiplying the gear width with the mean towing speed (extracted from the Vessel Monitoring System data) and trip duration.

Landings per swept area (LPUA, kg.km^{-2}) were calculated for each fishing trip for the commercially important flatfish species: sole, plaice, turbot (*Psetta maxima*), brill (*Scophthalmus rhombus*), dab (*Limanda limanda*); and gadoid species: cod (*Gadus morhua*) and whiting (*Merlangius merlangus*). In addition, the following species groups were created for the analysis: flatfish, gadoids, gurnards, rays, sharks and "all fish" (i.e. all fish specimens).

2.2.2. Discards

Discards data (i.e. fish below the MCRS, unwanted fish due to low commercial value or lack of quota, and benthic invertebrates) was available per haul from two discard-monitoring programmes: the Discard Observer Programme (DOP) and the Discard Self-sampling Programme (DSP). The DOP has annually sampled approximately 200 hauls from around 10 trips since 2000. The DSP has annually sampled approximately 320 hauls from around 160 trips since 2009 (Uhlmann et al., 2011; Kraan et al., 2013). For each sampled haul, the gear type, mesh-size, haul position and duration, the total weight of the catch, total weight of the landings, and weight of the discard sample were recorded. For each sampled trip, the sum of all (sampled and unsampled) haul durations was recorded, as well as the total landings for all species in the trip.

Discard samples were taken in compliance with set protocols. In the DOP, scientific observers sampled about 60 % of the hauls during a trip evenly distributed over day and night. Hauls were sampled by taking 5–7 buckets of the discards from the end of the processing conveyor belt after all landings had been removed. This was done at regular intervals during the processing of the haul. The resulting sample of multiple buckets were combined, weighing approximately 40 kg, and considered as a representative discards sample for the haul. In the DSP, crew members sampled two separate hauls set at two different days during a trip. A haul was sampled by scooping 20 kg of discards from the end of the processing conveyer belt into large plastic bags four times at regular intervals during the processing of the haul (Uhlmann et al., 2011). The bags were sealed off using cable tires, labelled and cool-stored until the vessel returned to the port. Back at port, the discard samples were collected by WMR staff and taken to the laboratory for analysis. Each sample consisted of two fish boxes (approximately 80 kg) of discards.

Discard samples were processed by scientific observers either on board (DOP) or in the laboratory (DSP). For both programmes, processing consisted of recording numbers at length for all fish species, and numbers of specimens for all benthic invertebrate species, in each sample. Whenever a species was very abundant within a sample (i.e. > 50 individuals), a sub-sample was taken, so that the sub-sampled fraction contained approximately 50 individuals. The numbers (at length) were then multiplied by the sub-sample fraction to estimate the total numbers (at length) within the discard sample.

To estimate the total numbers (at length) within each haul (N_{ijk}), the total numbers (at length) within the discard sample (n_{ijk}) of species i in trip j and haul k were multiplied by the ratio between the weight of the discard sample (d_k) and total discard weight. The latter was estimated using the total weight of the catch (C_k) minus the total weight of the landings (L_k):

$$N_{ijk} = \frac{C_k - L_k}{d_k} n_{ijk}.$$

For each fish species, the total number at length N_{ijk} was converted to total discards weight per haul (D_{ijk}) using species-specific length-weight relationships (based on Robinson et al., 2010; Coull et al., 1989) and aggregating over length. Total discards per haul and per species were converted into discards per swept area (DPUA, $\text{kg}\cdot\text{km}^{-2}$ for fish species and $\text{nr}\cdot\text{km}^{-2}$ for benthic invertebrates) by dividing them by the surface area swept. The surface area swept was calculated by multiplying the gear width by the mean towing speed (extracted from the Vessel Monitoring System data) and trip duration.

DPUA data were analysed for those species that were common in the discards data, namely undersized sole and plaice, dab, scaldfish (*Arnoglossus laterna*), solenette (*Buglossidium luteum*), whiting, grey gurnard (*Eutrigla gurnardus*), and flatfish, gadoid and "all fish" (i.e. all fish specimens) groups. Undersized cod was included in the analysis as this species is of particular interest due to pulse-induced injuries (van Marlen et al., 2014; de Haan et al., 2016; Soetaert et al., 2016b). For benthic invertebrates, DPUA data were analysed for two epibenthic species groups (crabs, sea stars) and three species groups that bury entirely or partly into the seafloor (bivalves, sea urchins, Ophiuroidae).

2.3. Analysis

2.3.1. Species composition of the catch

The species composition of the two gear types was estimated from the landings and discards data of the sampled discard trips. This was done in several steps. First, we calculated the discard weight of species i in trip j (D_{ij}) by raising the weight (D_{ijk}) of species i in trip j in haul k to trip level with the ratio between sampled fished duration (T_k) and total fished duration (T_j):

$$D_{ij} = \frac{T_j}{\sum_k T_k} \sum_k D_{ijk.}$$

Then we calculated the total catch weight C_{ij} of species i in trip j as the sum of the recorded landings in each trip L_{ij} and the calculated discard weight D_{ij}:

$$C_{ij} = L_{ij} + D_{ij}.$$

Subsequently, the species-specific sample mean catches ($\overline{C}_i^{\text{BT}}$, $\overline{C}_i^{\text{PT}}$), landings ($\overline{L}_i^{\text{BT}}$, $\overline{L}_i^{\text{PT}}$), and discards ($\overline{D}_i^{\text{BT}}$, $\overline{D}_i^{\text{PT}}$) per trip were calculated for the BT and PT gear types from C_{ij}, L_{ij}, and D_{ij}. Finally, within each gear type, we calculated the catch composition as the fraction of catch (C_i^{BT}, C_i^{PT}), landings ($L_i^{\text{BT}}, L_i^{\text{PT}}$), and discards ($D_i^{\text{BT}}, D_i^{\text{PT}}$) per species compared to the total catch of the gears ($\sum_i \overline{C}_i^{\text{BT}}$, $\sum_i \overline{C}_i^{\text{PT}}$). For the discards of the BT the catch composition is thus calculated as:

$$D_i^{\text{BT}} = \overline{D}_i^{\text{BT}} \Big/ \sum_i \overline{C}_i^{\text{BT}},$$

likewise for the catches ($C_i^{\text{BT}}, C_i^{\text{PT}}$), landings ($L_i^{\text{BT}}, L_i^{\text{PT}}$), and discards ($D_i^{\text{BT}}$, D_i^{PT}) for both gear types.

2.3.2. Catch efficiency of landings

Species-specific LPUAs of BT and PT were compared by selecting subsets of trips by ICES rectangle (of 0.5° latitude and 1° longitude) * week combinations for which both BT and PT trips were available. Overall, a total of 6133 trips occurring in 1361 rectangle-week combinations were selected for analysis (Table 1; Fig. 2). To account for a

Table 1
Overview of the number of observations included in the analysis by dataset and gear type.

Dataset	Tickler chain beam trawl (BT)	Pulse Trawl (PT)
Landings logbooks (trips)	3270	2863
Discards DOP (hauls)	514	422
Discards DSP (hauls)	533	552

possible vessel effect and the effect of rectangle-week combinations in the comparison, log-transformed LPUA data were analysed using a linear mixed-effects model with vessel ID and rectangle-week combination entering as random effects, and gear type entering as fixed effect. The model assumed a normal error distribution:

$$\mathrm{Log}(LPUA) = intercept + gear + \alpha + \beta + \varepsilon$$

$$\alpha \sim N\left(0, \sigma^2_{\mathrm{vessel}}\right)$$

$$\beta \sim N\left(0, \sigma^2_{\mathrm{rectangle-week}}\right)$$

$$\varepsilon \sim N\left(0, \sigma^2\right)$$

In this model, *gear* reflected the effect of gear type, entering the model with two levels: BT and PT, with the effect of gear being the additive term of PT to the intercept. The term α was a random intercept

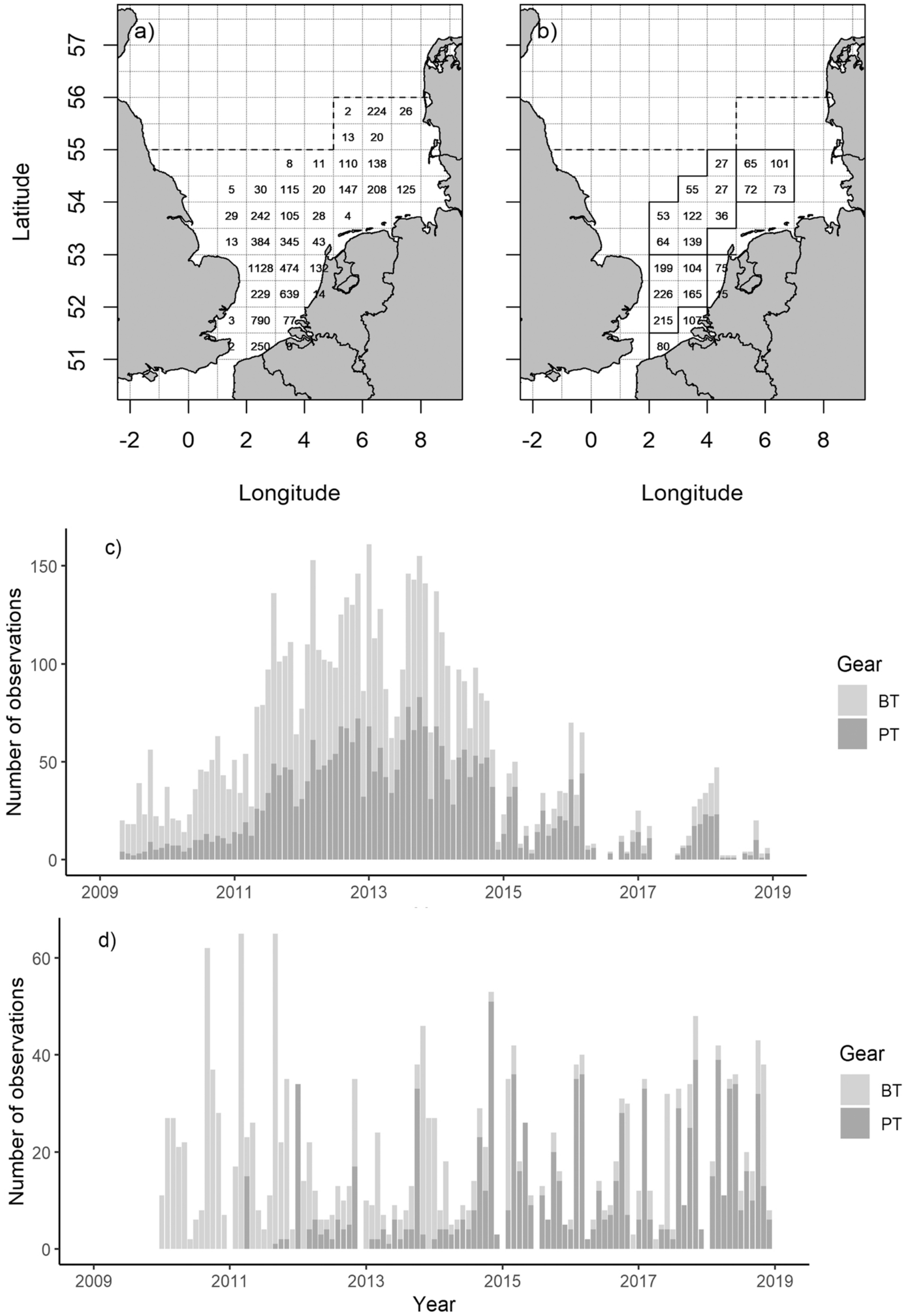

Fig. 2. Map of the number of observations of landings (a, c) and discards (b, d) by rectangle (a, b) and month (c, d). Observations of landings refer to fishing trips where BT and PT were used in the same rectangle and week. Observations of discards refer to the individual hauls sampled. The bold lines in (b) indicate the boundaries between the four fishing areas used in the analysis of the discards. The dashed line shows the demarcation line of the sole fishing area (SFA) below which vessels may fish with an 80 mm cod-end mesh size.

representing the vessel effect. This effect was assumed to be normally distributed with mean 0 and variance σ^2_{vessel}. Likewise, the term β was a random intercept representing the rectangle-week effect. This effect was assumed to be normally distributed with mean 0 and variance $\sigma^2_{\text{rectangle-week}}$. The term ε represented the residual noise in the observations, assuming that it was normal, homogenous, and independently distributed.

Because differences between the two gear types were estimated for log-transformed LPUA, exponentiation of the estimated parameter for the difference between the two gears was interpreted as species-specific landings multiplier (λ_i) of the PT gear compared to the BT gear. An alpha level of 0.05 was used when testing the difference between the two gear types.

Because log-transformation can only be performed for non-zero LPUAs, rectangle-week combinations for species and species groups for which LPUA of both gears were zero, were removed from the analysis. For rectangle-week combinations for which the LPUA for only a single gear type was zero, the lowest observed catch weight of the species and species groups in the dataset per gear was added to calculate LPUA. The analysis was carried out using an lmer model (R-library lme4).

2.3.3. *Catch efficiency of discards*

The number of discard observations was much lower than the number of landings observations. In addition, because discards were recorded per haul, rather than per trip for the landings, discard observations contained many more zeroes. Hence, there were too few positive observations for each gear type in identical rectangle-week combinations to apply the same method as used for the LPUA analysis. DPUA data were therefore assigned to larger fishing areas containing multiple ICES rectangles (Fig. 2) based on the spatial distributions of sole and plaice used in earlier papers (Rijnsdorp et al., 2012; Batsleer et al., 2016). The analysis was limited to fishing areas with at least 90 sampled hauls in order to reliably estimate the temporal evolution of DPUA. This resulted in 2021 sampled hauls from 636 trips to be included in the analysis of DPUA (Table 1).

The selected DPUA data were analysed using models of increasing complexity, using model selection to determine the optimal model. This was done for each species and species group separately. All models used to estimate the effect of gear type on DPUA assumed negative binomial likelihoods with log links, so that

$$DPUA = NB(\mu, \omega)$$

$$E(DPUA) = \mu \text{ and } \mathrm{var}(DPUA) = \mu + \frac{\mu^2}{\omega}$$

The parameter ω determined the overdispersion in the data and was estimated by the model. The simplest model (m1) for the DPUA data included fixed effects for gear type, discard-monitoring programme, and fishing area.

$$\log(\mu) = intercept + gear + programme + area. \qquad [\text{m1}]$$

In m1, *gear* reflected the effect of gear type, entering the model with two levels: BT and PT. The effect of *programme* allowed estimating a possible effect of the discard-monitoring programme on discard observations, entering the model with two levels: DOP and DSP. Finally, *area* reflected the effect of fishing area, resulting from e.g. habitat heterogeneity, entering the model with 4 levels (Fig. 2).

To test for long-term trends and seasonality in DPUA, we introduced two random walks to describe smooth relationships between the week since 1 January 2010 and DPUA, and between the week within year and DPUA. A random walk of order 2 was included for the number of weeks since 1 January 2010, and a cyclic version of a random walk of order 2 for week within year. This model was named m2:

$$\log(\mu) = intercept + gear + programme + area + f_1(week) + f_2(weekYear). \qquad [\text{m2}]$$

In m2, $f_1(week)$ represented a random walk of order 2 (Zuur et al., 2017) and $f_2(weekYear)$ represented a cyclic version of a random walk of order 2.

To capture the dependence of observations from the same trip M2 was further extended to include a random intercept for trip, so that model M3 was:

$$\log(\mu) = intercept + gear + programme + area + f_1(week) + f_2(weekInYear) + \gamma. \qquad [\text{m3}]$$

$$\gamma \sim N\left(0, \sigma^2_{\text{trip}}\right)$$

In m3 γ was the random intercept for trip, which was assumed to be normally distributed with mean 0 and variance σ^2_{trip}.

Models m1 to m3 assumed that the temporal pattern in DPUA was equal across the fishing areas. In order to account for possible differences in seasonal pattern among the fishing areas, two additional models were studied. Model m4 extended m2 by allowing a different seasonal pattern among the fishing areas:

$$\begin{aligned}\log(\mu) = {} & intercept + gear + programme + area + f_1(week) \\ & + f_3(weekInYear|area).\end{aligned} \qquad [\text{m4}]$$

In M4, the term $f_3(weekYear|area)$ allows the cyclic version of a random walk of order 2 for week within year to differ among the fishing areas. Finally, m5 allowed for possible differences in seasonal pattern among the fishing areas and included a random intercept for trip:

$$\begin{aligned}\log(\mu) = {} & intercept + gear + programme + area + f_1(week) \\ & + f_3(weekInYear|area) + \gamma.\end{aligned} \qquad [\text{m5}]$$

$$\gamma \sim N\left(0, \sigma^2_{\text{trip}}\right)$$

All models for DPUA were analysed using the Integrated Nested Laplace Approximation implemented in R (R-INLA) (Rue et al., 2009; Martins et al., 2013). R-INLA allows approximate Bayesian inference for complex models, including those with random intercepts and random walks in R. Model selection was carried out on the basis of the Deviance Information Criterion (DIC) (Spiegelhalter et al., 2002; Zuur et al., 2017). The model with the lowest DIC was chosen for each species and species group.

Similar to the approach for landings, exponentiation of the estimated parameter for the difference between the two gears was interpreted as species-specific discards multiplier (δ_i) of the PT gear compared to the BT gear. These discards multipliers were provided together with their 95 % credible intervals. Only those discard multipliers for which the 95 % credible intervals did not include the value 1 were classified as important.

2.4. *Effect gear type on discarding*

The effect of the gear transition on the discards and landings weights per unit area of the PT was estimated by calculating a set of metrics that combined the catch composition and catch efficiency multipliers. First, we estimated the proportions of discards ($\widehat{D}_i^{\text{PT,A}}$) and landings ($\widehat{L}_i^{\text{PT,A}}$) expected in PT by multiplying the observed proportions of discards ($D_i^{\text{BT,A}}$) and landings (L_i^{BT}) of BT with the catch efficiency multipliers of discards (δ_i) and landings (λ_i):

$$\widehat{D}_i^{\text{PT,A}} = \delta_i * D_i^{\text{BT}},$$

$$\widehat{L}_i^{\text{PT,A}} = \lambda_i * L_i^{\text{BT}}.$$

$\widehat{D}_i^{\mathrm{PT,A}}$ and $\widehat{L}_i^{\mathrm{PT,A}}$ provide estimates of species-specific changes in landings and discards per unit area swept when an average BT vessel would use the PT gear. For those species groups where δ_i and/or λ_i were missing, values were used from similar species groups, e.g. the δ_i values for turbot and brill were assumed to be equal to the δ_i of flatfish. After $\widehat{D}_i^{\mathrm{PT,A}}$ and $\widehat{L}_i^{\mathrm{PT,A}}$ were calculated, the corresponding catch $\widehat{C}_i^{\mathrm{PT,A}}$ was calculated as $\widehat{L}_i^{\mathrm{PT,A}} + \widehat{D}_i^{\mathrm{PT,A}}$.

To also calculate the changes in discarding per unit time, the 23 % lower towing speed of PT (Poos et al., 2020) was accounted for when calculating the changes in discard ($\widehat{D}_i^{\mathrm{PT,T}}$) and landings ($\widehat{L}_i^{\mathrm{PT,T}}$) per unit of time:

$$\widehat{D}_i^{\mathrm{PT,T}} = 0.77 * \widehat{D}_i^{\mathrm{PT,A}},$$

$$\widehat{L}_i^{\mathrm{PT,T}} = 0.77 * \widehat{L}_i^{\mathrm{PT,A}},$$

and the corresponding catch $\widehat{C}_i^{\mathrm{PT,T}}$ was calculated as $\widehat{L}_i^{\mathrm{PT,T}} + \widehat{D}_i^{\mathrm{PT,T}}$.

The effect of gear transition on the overall ratio of discards to landings was subsequently estimated using the simulated discards to landings ratio over the observed discards to landings ratio of the BT gear:

$$\left(\frac{\sum_i \widehat{D}_i^{\mathrm{PT,T}} \Big/ \sum_i \widehat{L}_i^{\mathrm{PT,T}}}{\sum_i D_i^{\mathrm{BT}} \Big/ \sum_i L_i^{\mathrm{BT}}}\right).$$

The 95 % prediction intervals of the above metrics were estimated by bootstrapping ($n = 1000$) the catch efficiency multipliers (d_i, l_i) from the estimated means and standard deviations of the *gear* coefficients in the selected models.

3. Results

3.1. Species composition of the catch

In both gears, the total catch weight was dominated by flatfish; approximately 90 % of the catch of the fishing trips in the discard-monitoring programmes consisted of flatfish (Table 2). Plaice and dab were the most abundant flatfish species in the catch, followed by sole, while the commercially valuable species turbot and brill contributed less than 3 % to the catch weight. Cod, whiting, and the gurnards (grey gurnard, tub gurnard) contributed up to 3–5 % to the total fish catch in BT and PT. Other fish species contributed 6 %− 9 % to the total fish catch. The landings of sole in PT were more than twice as high as in BT, whereas the landings of plaice in PT was less than half as in BT landings. Discards were dominated by undersized plaice and dab. Although the discards of undersized plaice appeared to be higher in PT than in BT (31 % in PT versus 26 % in BT), the overall contribution of plaice (marketable and undersized) to the total fish catch was lower in PT (46 %) than in BT (60 %).

Table 2

Catch composition for different fish species (presented as proportion of the total fish catch weight) in the tickler chain beam trawl (BT) and pulse trawl (PT) of the Dutch beam trawl fishery using an 80 mm cod-end mesh size. Species are ordered based on the decreasing catch proportions of the BT gear. The presented information is based on the data collected within the two Dutch discard-monitoring programmes.

	BT			PT		
Fish species (group)	Landings (L_i^{BT})	Discards (D_i^{BT})	Catch (C_i^{BT})	Landings (L_i^{PT})	Discards (D_i^{PT})	Catch (C_i^{PT})
Plaice	0.342	0.259	0.601	0.148	0.309	0.457
Dab	0.019	0.203	0.222	0.016	0.208	0.224
Sole	0.057	0.008	0.066	0.135	0.023	0.158
Other	0.020	0.037	0.056	0.036	0.050	0.086
Turbot	0.017	0.001	0.018	0.017	0.002	0.019
Gurnards	0.000	0.018	0.018	0.002	0.015	0.017
Whiting	0.002	0.007	0.009	0.002	0.024	0.026
Brill	0.006	0.001	0.007	0.009	0.001	0.010
Cod	0.003	0.001	0.004	0.002	0.001	0.003
Total	0.466	0.535	1.000	0.367	0.633	1.000

3.2. Catch efficiency of landings

The estimated landings multiplier λ_i for sole was 1.48 (Table 3), meaning that per unit of swept area, PT landed 48 % more sole (95 % CI: 44 %–52 %, p-value <0.001). For the other species, the landings multiplier indicated 8 % more turbot (95 % CI: 4 %–13 %, p-value <0.001), 28 % more brill (95 % CI: 22 %–35 %, p-value <0.001) and 95 % more whiting (95 % CI: 58 %–140 %, p-value <0.001) than BT. At the same time, the landings multiplier indicated 16 % less plaice (95 % CI: 13 %–19 %, p-value <0.001), 32 % less cod (95 % CI: 23 %–40 %, p-value <0.001) and 12 % less gurnards (95 % CI: 1 %–21 %, p-value = 0.038) than BT. No significant differences were found for the other species. For "all fish", the PT landed 3 % more fish (95 % CI: 0 %–5 %, p-value 0.039) per unit swept area than BT.

3.3. Catch efficiency of fish discards

For all species that were abundant in the discards (sole, plaice, dab), model M5 had the lowest DIC values. This model included a temporal pattern in discarding that differed among fishing areas (Table 4). For whiting, model M3 was chosen on the basis of its DIC value. For the less abundant species (solenette, scaldfish, cod, grey gurnard) the simplest model was chosen, being model M1.

PT discarded 27 % more undersized sole (95 % CI: 2 %–57 %), 42 % more whiting (95 % CI: 11 %–82 %) and 55 % more gadoids (95 % CI: 21 %–97 %), but 21 % less undersized plaice (95 % CI: 9 %–32 %), 19 % less dab (95 % CI: 6 %–30 %) and 31 % less grey gurnard (95 % CI: 10 %–47 %) than BT. For the other species, the credible intervals included 1 (Table 4). The sampling programmes had an effect for some of the species, but not for all species combined. The estimated coefficients for sampling programme are presented for completeness in Supplementary SM1.

3.4. Catch efficiency of benthic invertebrates

For three of the benthic invertebrate species groups in the discards data, PT caught fewer individuals (Table 5). The lower catch number was particularly prominent for the Ophiuroidae with a reduction of 57 % (95 % CI: 45 %–67 %), and bivalves with a reduction of 51 % (95 % CI: 36 %–62 %). For crabs, a reduction of 38 % (95 % CI: 25 %–48 %) was observed. For the other benthic invertebrate species, the credible intervals included 1. The estimated coefficients for sampling programme are presented for completeness in Supplementary SM1.

3.5. Effect gear type on discarding

A comparison of the landings and discards multipliers indicates that PT caught relatively fewer discards than landings in comparison with BT once spatial, temporal, and vessel effects on landings and discards are corrected for (Fig. 3).

The discarding metrics indicated how catch weights may have changed if the sampled beam trawlers (BT in Table 2) would have used a PT instead of a BT, all else being equal. Table 6 presents the results per unit area swept and per unit time. The results per unit area swept reflect the effect of the change in selectivity, while the results per unit time estimate the change in discarding between the gears that also takes account of the difference in towing speed. The simulation showed that

Table 3

Estimated landings multiplier by species (exponent of the gear effect; λ_i) of PT relative to BT (kg.km^{-2}) and corresponding 95 % confidence interval (CI). The t-value and p-value of the difference between gear estimated in the mixed effects models by fish species and species groups are listed, as well as information about sampling depth.

Species (group)	λ_i	95 % CI	t-value	p-value	Number of rectangle-week combinations	number of vessels	number of trips	% non-zero observations
Sole	1.48	1.44 – 1.52	28.49	< 0.001	1361	76	6133	100 %
Plaice	0.84	0.81 – 0.87	-9.10	< 0.001	1361	76	6133	100 %
Turbot	1.08	1.04 – 1.13	3.51	< 0.001	1267	75	5807	99 %
Brill	1.28	1.22 – 1.35	9.32	< 0.001	1264	75	5799	99 %
Dab	1.02	0.94 – 1.10	0.47	0.639	1355	76	6115	94 %
Cod	0.68	0.60 – 0.76	-6.33	< 0.001	999	76	4825	65 %
Whiting	1.95	1.58 – 2.40	6.19	< 0.001	597	74	3078	48 %
Flatfish	1.04	1.02 – 1.07	3.37	0.001	1361	76	6133	100 %
Gadoids	0.88	0.75 – 1.03	-1.56	0.120	1035	76	4960	69 %
Gurnards	0.88	0.79 – 0.99	-2.07	0.038	1173	76	5420	80 %
Rays	0.99	0.85 – 1.15	-0.15	0.884	939	74	4381	68 %
Sharks	1.06	0.79 – 1.41	0.38	0.702	227	49	1249	21 %
All fish	1.03	1.00 – 1.05	2.06	0.039	1361	76	6133	100 %

Table 4

Estimated discards multiplier by fish species(group) (exponent of the gear effect; δ_i) of PT relative to BT (kg.km^{-2}) and corresponding 95 % credible interval (CI) for the selected model.

Fish species (group)	δ_i	95 % CI	Selected model
Sole	1.27	1.02 – 1.57	M5
Plaice	0.79	0.68 – 0.91	M5
Dab	0.81	0.70 – 0.94	M5
Solenette	0.77	0.45 – 1.30	M1
Scaldfish	0.90	0.62 – 1.29	M1
Whiting	1.42	1.11 – 1.82	M3
Cod	0.64	0.23 – 1.68	M1
Grey gurnard	0.69	0.53 – 0.90	M1
Flatfish	0.88	0.77 – 1.01	M5
Gadoids	1.55	1.21 – 1.97	M3
All fish	0.92	0.81 – 1.04	M5

Table 5

Estimated discards multiplier by benthic species group (exponent of the gear effect; δ_i) of PT relative to BT (kg.km^{-2}) and corresponding 95 % credible interval for the selected model.

Benthic species group	δ_i	95 % CI	Selected model
Crabs	0.62	0.52 – 0.75	M5
Bivalves	0.49	0.38 – 0.64	M5
Sea stars	0.85	0.69 – 1.04	M5
Sea urchins	1.30	0.99 – 1.72	M5
Ophiuroidea	0.43	0.33 – 0.55	M5

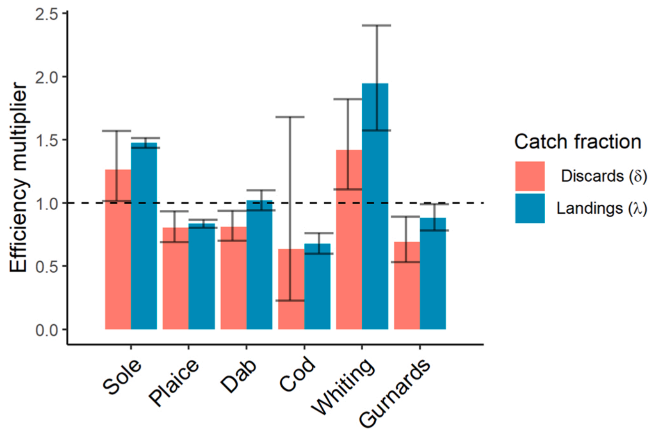

Fig. 3. Estimated catch multiplier (back transformed from $\log_e$ scale) of the PT relative to the BT for the landings and discards by fish species.

Table 6

Simulated catch of a beam trawl vessel when using the PT gear instead of the conventional BT gear. For this analysis, the catch compositions in Table 2 were combined with the landings and discards multipliers in Tables 3 and 4. Changes are given per unit swept area and per unit time. Species are ordered following Table 2, allowing for easy comparison.

	Unit swept area			Unit time		
Species	$\widehat{L}_i^{PT,A}$	$\widehat{D}_i^{PT,A}$	$\widehat{C}_i^{PT,A}$	$\widehat{L}_i^{PT,T}$	$\widehat{D}_i^{PT,T}$	$\widehat{C}_i^{PT,T}$
Plaice	0.287	0.205	0.492	0.221	0.158	0.379
Dab	0.019	0.164	0.184	0.015	0.127	0.142
Sole	0.085	0.010	0.095	0.065	0.008	0.073
Other	0.026	0.034	0.060	0.020	0.026	0.046
Turbot	0.018	0.001	0.019	0.015	0.001	0.015
Gurnards	0.000	0.013	0.012	0.000	0.010	0.010
Whiting	0.004	0.010	0.014	0.003	0.008	0.011
Brill	0.008	0.001	0.009	0.006	0.001	0.007
Cod	0.002	0.001	0.003	0.002	0.000	0.002
Total	0.449	0.438	0.887	0.341	0.345	0.683

the gear transition to PT would have decreased discarding from $\sum_i D_i^{BT} = 0.535$ (Table 2) to $\sum_i \widehat{D}_i^{PT,T} = 0.345$ (Table 6). This is a reduction of 36 % (95 % prediction interval: 31–42 %). Meanwhile, the total landings would have decreased from $\sum_i L_i^{BT} = 0.466$ (Table 2) to $\sum_i \widehat{L}_i^{PT,T} = 0.341$ (Table 6); a reduction of 27 % (95 % prediction interval: 25–28 %). The landings of marketable sole, the main target species of the fleet, could have increased from $L_{\text{sole}}^{BT} = 0.057$ (Table 2) to $\widehat{L}_{\text{sole}}^{PT,T} = 0.065$ (Table 6), while the discards of undersized sole (D_{sole}^{BT}; $\widehat{D}_{\text{sole}}^{PT,T}$) remained the same (0.008). The ratio of discards over the total landings weight decreased by 12 % (95 % prediction interval: 5–21 %).

4. Discussion

4.1. Effect of gear transition on the discarding and selectivity

Replacing mechanical stimulation with electrical stimulation increased the catch efficiency of the main target species (sole) and two commercially important bycatch species (turbot, brill), and reduced the catch efficiency of fish species dominating the discards (i.e. undersized plaice, dab) and benthic invertebrates. The reduction in undersized plaice and dab discards is in line with the improved size selectivity reported in a comparative trawling experiment (van Marlen et al., 2014). The observed change in catch efficiency of marketable sole (+48 %) and plaice (−16 %) is in agreement with the results of the study of Poos et al. (2020), who demonstrated how the efficiency changed for marketable sole (+52 %) and plaice (−12 %) since the transition to PT of different cohorts of vessels.

The differences in discarding between the two gear types results from a combination of gear use, the temporal and spatial distribution of the fleet. The estimated landings and discards multipliers aim to isolate the effect of the gear change from the other effects. The subsequent use of these multipliers for estimating discarding metrics are also conditional on the relative weights of the species in the landings and discards of the sampled discard trips of the reference gear.

The beam trawl vessels that made the transition from BT to PT during the gear transition period 2009–2018 reduced the surface area swept from 57.10^3 to 41.10^3 km^2 while the number of fishing hours remained the same irrespective of the gear when targeting sole (Rijnsdorp et al., 2020). A good proxy for the change in discarding as a result of the gear changes is therefore based on discard ratio estimated per unit of time. The change was estimated at − 37 % (95 % prediction interval: 31 %–42 %). Expressing the changes as discards relative to the total landings, the discard ratio of the PT gear was 12 % lower than the BT gear, all else being equal (95 % prediction interval: 5 %–21 %). Because the abundance of the discard and landing fractions of the target and bycatch species show inter-annual variations and the spatial distribution of the beam trawl fleet changed during the 5-year transition period from BT to PT (Rijnsdorp et al., 2020; Hintzen et al., 2021), these changes will have affected the catch composition and discard fraction of the BT and PT vessels.

The lower towing speed and absence of tickler chains of the PT gear reduced the total catch volume, including the catch of benthic invertebrates and debris that may damage fish during their stay in the cod-end (this study; van Marlen et al., 2014; Rijnsdorp et al., 2021a). Schram et al. (2020) indeed showed that undersized plaice, turbot, and brill discards were in better condition when caught with PT gear compared to BT gear. The condition of undersized sole, thornback ray, and spotted ray, on the other hand, was not affected by gear type (Schram et al., 2020). Better fish condition will consequently lead to a higher survival of fish discards in the PT gear (van der Reijden et al., 2017; Schram and Molenaar, 2018; Uhlmann et al., 2016). Furthermore, Schram et al. (2022b) showed that direct mortality among fish and benthic invertebrates sampled in the wake of PT gear was low (0–10 %) and did not differ between PT and the untrawled controls.

Meanwhile, the exposure to an electrical stimulus in the PT gear may inflict injuries to fish, like the spinal fractures observed in cod (van Marlen et al., 2014; de Haan et al., 2016; Soetaert et al., 2016a, 2016b). A study of pulse-induced injuries in 13 fish species sampled from commercial PT vessels showed that the proportion of pulse-induced injuries is low (<= 1 %), except for cod and sandeel (Boute, 2022; ICES, 2020). The injuries observed in sandeel, however, are likely due to mechanical impact during the catch process: none of the sandeels exposed to a field strength of up to 600 $V.m^{-1}$ developed injuries in a tank experiment (Schram et al., 2022a).

These injuries reduce survival and the pulse-induced injuries observed in cod could have a population level effect. Currently, the consequences of pulse-induced injuries on the cod population level are expected to be low because (i) the pulse-induced injury probability in the sizes that escape the 80 mm cod-end meshes used in the sole fishery is low, and (ii) there is little overlap in the spatial distribution between the cod population and the pulse fishery (ICES, 2020).

4.2. Understanding the difference in selectivity in fish

The differences in species selectivity observed for the two gear types can be explained by the response potential of fish to the fishing gear during different phases of the catch process (Fig. 4). First, fish may detect approaching trawls because of the noise they generate. In response, fish may escape by swimming away perpendicular to the path of the approaching vessels (Albert et al., 2003; De Robertis et al., 2010) or seek refuge by burying into the sediment (Kruuk, 1963; Gibson et al., 2014). Because the PT fish with a lower towing speed and without tickler chains (Poos et al., 2020), they likely produce less noise than conventional beam trawls. Hence, it is likely that fewer fish swim away or seek refuge from the path of a PT compared to a beam trawl.

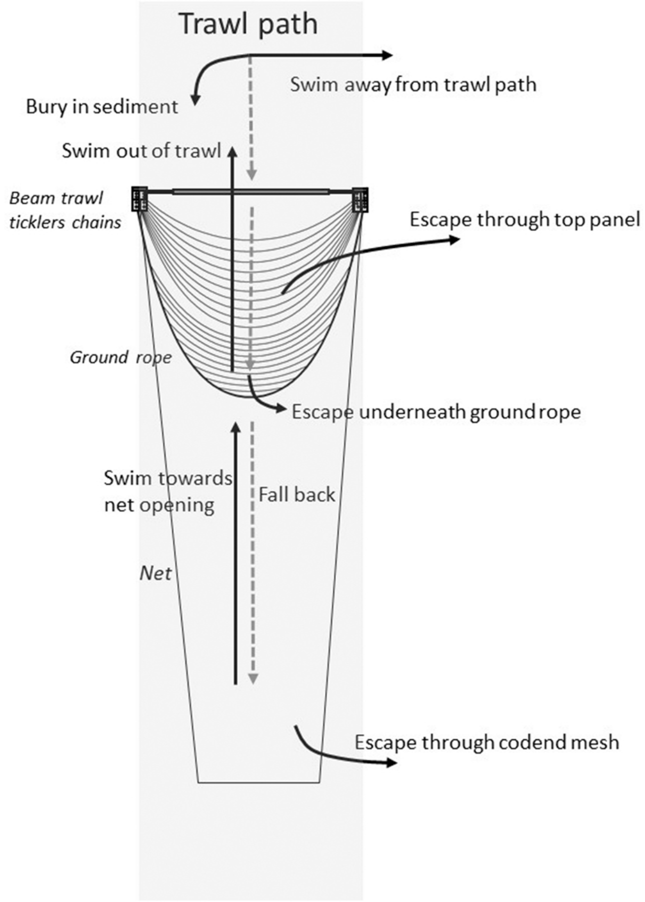

Fig. 4. Schematic representation of the response potential of fish during the catch process towards a beam trawl. Fish may detect the trawl at some distance and swim away or bury into the sediment. When overtaken by the trawl, fish may enter the net or escape beneath the ground rope. Once in the net, the fish may be retained or escape through a mesh or by swimming backwards and escaping through the mouth of the trawl.
(modified from Ryer, 2008).

Once the gear is in proximity, fish are herded towards the centre of the trawl path (Main and Sangster, 1981; Bublitz, 1996) where they must swim at a speed equal to or greater than the speed of the trawl in order to avoid being caught. This herding phase provides an opportunity for individuals to escape the catch process. The towing speed of conventional beam trawls is about 3.3 $m.s^{-1}$ (Rijnsdorp et al., 2021b), being faster than the burst swimming speed of most fish (Videler, 1993; Kim and Wardle, 1997). Hence, such an escape from the gear is unlikely and fish will move directly into the net. It is possible that in the mouth of the trawl irregularities in the surface of the seafloor provide an opportunity for the fish to escape underneath the ground rope of the trawl (Walsh, 1992; Ingólfsson and Jørgensen, 2006). For beam trawls, the average distance between tickler chains is 0.55 m, which, combined with 3.3 $m.s^{-1}$ towing speeds, provide fish with a time window of less than 0.2 s to bury into the seafloor. For the PT, the distance between the last conductor and the ground rope is less than 0.25 m, which, combined with 2.5 $m.s^{-1}$ towing speeds, provide fish with a time window of less than 0.1 s to escape underneath the ground rope. However, because the electric field extends beyond the area adjacent to the conductor and because fish will need time to recover from the involuntary muscular contractions induced by the electrical stimulus, the time interval to escape will be shorter than the 0.1 s time window. Hence, it is unlikely that fish will be able to actively escape underneath the approaching ground rope when electrical stimulation is used in the catching process.

Electrical stimulation changes the shape of fish, particularly in the case of sole, which bends into a U-shape when exposed to a pulse stimulus. This U-shape increases their susceptibility to the gear (van Stralen, 2005; Soetaert et al., 2016a). The U-shape resembles the omega body shape observed when sole buries itself in the sediment (Kruuk, 1963). The U-shape of sole and the deeper penetration of the electric field into the sediment compared to tickler chains (de Haan and Burggraaf, 2018; Depestele et al., 2018) increase the proportion of sole that is available to the PT compared to beam trawls. Other flatfish, such as plaice, dab, turbot and brill, have a more rigid skeleton that does not allow the body to bend in a U-shape. Indeed, plaice will not curl up like sole when exposed to pulse stimuli (van Stralen, 2005) and as a result, it may be more easily overrun by the ground rope. Further corroboration of the proposed mechanisms for the observed differences can be found in an experiment that showed that switching off the pulse generator in the pulse gear resulted in 7 times less sole being caught, but only half the plaice and dab the being caught, compared to a reference net (Rijnsdorp et al., 2021a). Clearly, the pulse field works differently for sole compared to most other flatfish when catching the fish.

Once fish are caught in the net, they may escape through a mesh, fall back to the cod-end where they may be retained or escape through the cod-end mesh, or swim against the current towards the net opening and escape out of the trawl mouth or through the large meshed top panel. Although the latter mechanism will apply mainly to fast swimming pelagic fish, there are indications that it may play a role in demersal species such as sole (underwater observation by Pieke Molenaar, pers. comm). In a PT, fish are immobilised by electrical stimulation in the net opening, so they are less likely to escape once they have entered the net.

Although the above reasoning may explain the increased species selectivity of the different flatfish species in the PT, the suggested increase in catch efficiency of PT for both landings and discards of whiting is puzzling. While a reduced catch efficiency of whiting in a BT could be explained by the large mesh sized top panels used directly behind the beam/wing to reduce drag, a higher catch efficiency for whiting in PT is not supported by a comparative trawling experiment (van Marlen et al., 2014). Because whiting catches are highly variable in space and time and landings may be affected by market conditions and quota constraints, the interpretation of the estimated higher catch efficiency of whiting in the PT should therefore be treated with caution.

The reduced catch efficiency of PT for cod landings could be related to the proportion of marketable cod that develop a spinal fracture (van Marlen et al., 2014; Soetaert et al., 2016b). The dark colour markings on injured cod (de Haan et al., 2016) may prompt fishers to land only non-injured specimens. The proportion of injured cod in the catch is estimated at between 10 % and 36 % (van Marlen et al., 2014; ICES, 2020), which is in broad agreement with the presented estimated reduction in catch efficiency of 32 % in the PT.

The improved size selectivity (i.e. fewer fish discards) of the PT, as suggested by our analysis, may be caused by a combination of mechanisms. Smaller-sized fish will experience a lower field strength over their bodies than larger-sized fish (Stewart, 1977; Soetaert et al., 2015 and references therein), and may be more likely to pass underneath the ground rope than larger-sized fish (Walsh, 1992).

4.3. Understanding the difference in catch efficiency of benthic invertebrates

The reduced catch of benthic invertebrates in the PT, which is supported by a comparative trawling experiment (van Marlen et al., 2014), is likely related to the difference in penetration of the gear into the sediment between the BT and PT. The tickler chains of the BT, that run perpendicular to the towing direction, penetrate on average 4 cm into the sediment, whereas the electrodes of the PTs, that run parallel to the towing direction, penetrate less than 2 cm into the sediment (Depestele et al., 2016, 2018). Tickler chains will also erode the top layer of soft sediment of the seafloor and bring hard-bodied objects such as stones and hard shells to the surface of the seafloor (Bridger, 1970; Margetts and Bridger, 1971; Depestele et al., 2018). The suggested reduction in catch rate by the PT of bivalves and Ophiuroidae that are entirely or partly buried in the seabed is consistent with the lower penetration depth of the PT. The higher catch rate of sea urchins in the PT, although not significant, may be due to the lower towing speed and lighter weight of the PT that will reduce the damage to the fragile sea urchins. It is well known that many of the sea urchins that are caught in BT gear are severely damaged, making it difficult to identify them and therefore likely resulting in an underestimate of the numbers caught (personal observation). For the epifaunal group of sea stars, the catch efficiency of the PT does not differ from that of the beam trawl.

CRediT authorship contribution statement

Harriet van Overzee: Conceptualization, Methodology, Data curation, Investigation, Analysis, Writing. **Adriaan Rijnsdorp**: Conceptualization, Methodology, Analysis, Writing, Visualization. **Jan Jaap Poos**: Conceptualization, Methodology, Analysis, Writing.

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.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106603.

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