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Original Article

Efficiency changes in bottom trawling for flatfish species as a result of the replacement of mechanical stimulation by electric stimulation

Jan-Jaap Poos [1,2]*, Niels T. Hintzen [2], Jacco C. van Rijssel[2], and Adriaan D. Rijnsdorp [1,2]

[1]Department of Animal Sciences, Aquaculture and Fisheries, Wageningen University, Wageningen, Netherlands
[2]Wageningen Marine Research, Wageningen University and Resarch, IJmuiden, Netherlands

*Corresponding author: tel: +31 317 48 7189; e-mail: janjaap.poos@wur.nl.

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Although fishing with electricity is illegal in the European Union, a number of temporary licences allowed converting beam trawlers to pulse trawling. To analyse how the adaption of pulse trawling changed this fishery, we studied fishing speeds and landings per unit effort as proxies for catch efficiencies for the main target species. Compared to conventional tickler chain beam trawls, pulse trawls were towed at lower speeds (small vessels −10%, large vessels −23%). Large vessels that switched from conventional beam trawls to pulse trawls at the end of 2009 gradually increased catch efficiency for sole over the period of almost 1 year. While pulse trawling was found to have higher catch rates (kg/h) for sole (small vessels +74%, large vessels +17%), lower catch rates were observed for plaice (small vessels −31%, large vessels −32%). Vessels that switched later achieved immediate gains in catch efficiency for sole. The change in catch efficiency is likely due to the difference in cramp response between the species.

Keywords: beam trawling, ecosystem effects of trawling, environmental impact, fisheries management, North Sea, plaice, pulse trawling, sole, species selectivity

Introduction

Fisheries are characterized by a continuous development to improve their efficiency (Valdemarsen, 2001; Ward and Hindmarsh, 2007; Eigaard *et al.*, 2014). The average rate of efficiency increases due to the cumulative effect of improvements (technology creep) is estimated at 3% (Eigaard *et al.*, 2014). The increase in fishing efficiency is determined by improvement in fishing skills and developments in technology (Rijnsdorp *et al.*, 2008; Mahevas *et al.*, 2011). Technological improvements can lead to a gradual change in efficiency, for instance due to the cumulative effects of improvements in netting materials, trawl panel designs, hook and line designs or electronic equipment used for navigation, fish finding, or the increase in the size of the vessels and fishing gear (Rahikainen and Kuikka, 2002; Marchal *et al.*, 2007). Efficiency can also show a sudden jump that is related to major technological innovations. Examples of such radical changes are the introduction of steam propulsion that allowed bottom trawlers to switch from using a small mouthed beam trawl to a wide mouthed otter trawl, substantially increasing catch efficiency (Engelhard, 2008; Kerby *et al.*, 2012; Thurstan *et al.*, 2014). The catch efficiency of demersal otter trawls was increased by the application of sweeps between the otter board and the wing of the trawl (Wimpenny, 1953; Engelhard, 2008). The use of fish finders in combination with the introduction of synthetic fibres and pelagic otter boards resulted in the development of large freezer trawlers (Valdemarsen, 2001). Such technological improvements can have sudden effects on the exploitation of fish stocks. The introduction of the power block that facilitated the use of large purse seines in fisheries for pelagic schooling fish led to a quick increase in fishing pressure on pelagic stocks and the subsequent collapse (Whitmarsh *et al.*, 1995; Valdemarsen, 2001). The reintroduction of the beam trawl in flatfish fisheries allowed fishers to deploy an increasing number of tickler chains in front of the net. This greatly increased the catch efficiency for flatfish, in particular sole, and resulted in severe overfishing of flatfish stocks in the period 1970–2010 (Daan, 1997; Rijnsdorp *et al.*, 2008).

Technological developments and innovations pose a challenge to fisheries managers. Technology creep could bias the time series of catch per unit of effort, widely used to monitor changes in stock biomass (Marchal *et al.*, 2007), and may contribute to the growing overcapacity of fishing fleets if not counteracted by fisheries management actions (Eigaard *et al.*, 2014). Technological changes also affect the ecological side effects of a fishery. Changes in fishing technology may allow fishers to move into previously unfished grounds. Rock-hopper gear enabled fishers to safely tow their bottom trawls over hard grounds (Valdemarsen, 2001). This increased the spatial extent of the fishery but could also have increased the fishing pressure on stock components that previously found refuge in the hard grounds. The replacement of the otter trawl by the beam trawl in the flatfish fishery increased the impact on the sea floor because the tickler chains of a beam trawl gear penetrates to a greater depth into the sediment than the ground gear of an otter trawl (Eigaard *et al.*, 2016; Hiddink *et al.*, 2017; Depestele *et al.*, 2019). The use of heavy beam trawls towed at high towing speed not only increased the damage to the sea floor and benthic ecosystem but also increased fuel use and CO_2 emissions. The use of small cod-end mesh size required to retain slender soles results in substantial bycatches of undersized plaice and other fish species (van Beek, 1998; Catchpole *et al.*, 2008; Uhlmann *et al.*, 2014).

Insight in the consequences of technological developments in a fishery are important to provide a sound knowledge base on possible consequences for sustainable management. In the beam trawl fisheries for flatfish in the North Sea, a new fishing method replaced mechanical stimulation by electrical stimulation, the pulse trawl (Batsleer *et al.*, 2016; Haasnoot *et al.*, 2016). The pulse trawl was tested under commercial conditions in a year-round trial in 2004–2005 (van Stralen, 2005).

In pulse trawls, tickler chains were replaced by electrodes that fire pulses of alternating current at a frequency of 30–45 pulse cycles per second (de Haan *et al.*, 2016; Soetaert *et al.*, 2019). The pulses invoke a cramp response that causes sole to bend in a U-shape, facilitating their catch (van Stralen, 2005; Soetaert *et al.*, 2016a). The use of pulse trawls reduced fuel costs and mitigated ecological impacts of the fishery (van Balsfoort *et al.*, 2006; Soetaert *et al.*, 2015b).

The use of electricity in capture fisheries is illegal, but the European Union (EU) allowed a derogation of 5% of the fishing fleet to use the pulse trawl in 2006 [Annex III(4) EU Regulation 41/2006]. After a first successful application of pulse trawls, the interest of the Dutch fishing industry increased and the number of derogations was increased to a total of 42 in 2012 and 84 in 2014. These derogations were made possible under regulations for the protection of juvenile marine organisms and as a pilot project to study possible reductions in discarding (Haasnoot *et al.*, 2016).

The stepwise increase in derogations resulted in "cohorts" of vessels adopting the use pulse trawls, while the pulse trawl was under development. This adoption likely had consequences for catchability and species selectivity of the fleet, which potentially increased over time (van Marlen *et al.*, 2014). Given that the three cohorts started at different times during the development of the gear, differences in the catchability trends can be expected. Here we study the transition of the three cohorts. Moreover, we study the changes in catch efficiency and species selectivity associated with the transition from the traditional beam trawl to the pulse trawl in the Dutch beam trawl fleet. We do so by applying a non-linear model in which the efficiency change over time is analysed. Finally, we test if the changes in efficiency over time differed for the cohorts.

Methods

The beam trawl fishery for flatfish is considered to be a mixed fishery targeting sole (*Solea solea*) and plaice (*Pleuronectes platessa*) with a by-catch of other flatfish, and roundfish such as cod (*Gadus morhua*) and whiting (*Merlangius merlangus*) (Gillis *et al.*, 2008). The fleet is managed by individual quota for the main target species sole and plaice and by a set of technical regulations. Beam trawling in coastal waters (12 nautical mile zone and Plaice Box) is restricted to vessels with a maximum engine power of 221 kW and a beam trawl width of 2 × 4.5 m (small vessels). In other areas, the engine power is maximized at 1471 kW and a beam trawl width at 2 × 12 m (large vessels). The minimum cod-end mesh is 80 mm in the area south of a demarcation line running from west to east at 55°N (west of 5°E) and 56°N (east of 5°E). North of this demarcation line the minimum mesh size in the cod-end is 100 mm.

Individual vessels may use different fishing gears during a year. Small vessels (Euro cutters) may alternate the beam trawl fishery for flatfish with, for example a bottom trawl fishery for brown shrimp (*Crangon crangon*) or an otter trawl for Norway lobster (*Nephrops norvegicus*). Large beam trawlers may alternate between fishing for sole with an 80-mm cod-end and fishing for plaice with a 100-mm cod-end or a twin otter trawl fishery for Norway lobster or mixed demersal fish.

Marketable catch and effort data

Fishing effort and landings from mandatory logbooks and Vessel Monitoring System (VMS) data of Dutch fishing vessels were used for the period 2009–2017. Fishing effort in logbooks was recorded as the time absent from port per trip as a proxy for the fishing effort per trip. The landings weight is reported for all commercially important species separately. These landings data were recorded per day by ICES rectangle (geographical areas of 30′ latitude and 1° longitude) and used as a proxy for the marketable catch. The landings data were aggregated to a single observation per fishing trip, assigned to the rectangle where the highest landings were reported. Gear use and mesh size were also recorded. However, the traditional beam trawl gear and the pulse gear were both recorded under the same "beam trawl" class.

Beam trawl fishing trips were classified as sole fishing trips when an 80-mm cod-end mesh was recorded or as plaice fishing trips when a cod-end mesh size of ≥100 mm was recorded. This large meshed plaice fishery occurs North of the demarcation line where pulse trawling is not allowed.

VMS data provided a set of vessel speed estimates for each trip (Lee *et al.*, 2010; Hintzen *et al.*, 2012). The VMS data are recorded continuously with a polling frequency of 0.5–2 h^{-1}. Erroneous VMS data were removed using the "vmstools" library in R (Hintzen *et al.*, 2012). Given that most beam trawlers are in port during weekends (Poos and Rijnsdorp, 2007), VMS records during weekends were removed.

Trip classification

Pulse and traditional beam trawls are recorded with the same gear code (TBB). Because pulse trawls are towed at a lower speed (van Marlen *et al.*, 2014), fishing trips with the pulse trawl were distinguished from fishing trips with the traditional beam trawl based on the mean towing speed. In the logbooks, skippers are expected to fill out the gear that has been used. These entries are not always filled out correctly, for example otter trawling activity could have listed as using the TBB gear. Distinguishing these erroneous entries are part of the following procedure.

For each combination of vessel and week, the VMS observations were categorized as being one of three activity modes: floating, towing, and steaming. These modes were categorized using an expectation-maximization (EM) algorithm for mixtures of normal distributions on the vessel speed for each ping (Dempster *et al.*, 1977; McLachlan and Peel, 2000; Benaglia *et al.*, 2009a, b; Poos *et al.*, 2013). Three normal distributions were assumed for the distribution of VMS speeds, given the three activity modes. The normal distribution in the centre is assumed to be associated with towing. The EM algorithm requires starting values for initial centres of the distributions, and these were chosen based on a visual inspection of a histogram of observed speeds of the entire data set. The estimated mean towing speeds for each vessel–week combination were extracted from the results and used in the next step.

In a second step, an EM algorithm for mixtures was used on the estimated mean towing speeds for all vessel–week combinations. Pulse trawling is done with a towing speeds of ∼5 knots, while traditional beam trawling is done with towing speeds of ∼6.5 knots (Poos *et al.*, 2013; van Marlen *et al.*, 2014). In the data, several different types of histograms were observed: unimodal histograms, bimodal histograms, and trimodal histograms (Figure 1), suggesting that different modes correspond to different gears used. The EM algorithm was applied on the weekly mean towing speeds, testing for the presence of two or three normal distributions. The estimated means and variances of these distributions were used to distinguish three different fishing activities: beam trawling, pulse trawling, or other. The speeds in the normal distribution with the highest mean was classified as beam trawling. Speeds in the normal distribution with a mean of ∼5 knots were classified as pulse trawling. If present, speeds in the normal distribution with a mean of ∼3 knots were classified as "other." This other category included the use of twinrigging gear.

The boundaries for the classifications were set by the standard deviation (*SD*) of the distributions: observations with towing speeds within 6 *SD* of each mean were assigned to the corresponding activities. Where these boundaries would overlap, they were set to be exactly in between the corresponding means. In a final step in this classification procedure, a filter was applied where single observations flanked by observations of a different category (e.g. a single pulse trawling week flanked by weeks of traditional beam trawling) are set to the category of the flanking observations.

The procedure is illustrated in Figures 1 and 2. Figure 1 shows the unimodal, bimodal, and trimodal frequency distributions of the towing speeds of four vessels. The vessels with bimodal and trimodal frequency distributions switched to pulse trawling. Figure 2 shows the time series of towing speed of these vessels clearly showing the discontinuity in towing speed reflecting the transition to the pulse gear. Two vessels can be seen switching back to traditional beam trawling for a brief periods of time.

In order to validate the accuracy of the classification based on vessel speeds, the results were contrasted against two data sets of on-board observer records. The observers recorded the gears used while on board and provided an independent classification of gear use. The first data set comprises observer trips that estimated discarding fish at sea (see, e.g. Uhlmann *et al.* 2013). This data set is maintained by Wageningen Marine Research and consists of 61 trips on board of large fishing vessels in the period 2009–2017. The second data set consists of eight fishing trips on-board beam trawl vessels published in van der Reijden et al. (2017). The total of 69 trips were matched to the fishing trips from the classification strategy described above using a vessel identifier and landing dates.

Transition from mechanical to electrical stimulation

The start date of pulse fishing was estimated as the week of the first fishing trip with the pulse towing speed. The estimated start date was validated against the start date of the pulse licence in the vessel register (from data held at the Dutch Ministry Agriculture, Nature, and Food Quality). The estimated start data showed small deviations (<3 weeks) from the date recorded in the vessel register. For the small vessels, the difference in towing speed between using traditional trawls and pulse trawls was small, and all start dates were based on the vessel register alone.

After the fishing trips are classified as trawling with the traditional gear or with the pulse gear, means and *SD*s of trawling speeds were calculated for the small and large vessels. This was done for three gear categories: pulse trawling, trawling for sole with 80 mm, and trawling for plaice with 100 mm.

Catch efficiency

The difference in catch efficiency (kg/h) for the marketable catch between pulse trawls and traditional beam trawl was calculated from landings and effort data by trip. First, only those vessels were selected that switched during the study period. Then, a homogenous set of fishing trips was selected from the database with trips lasting between 72 and 120 h. The analyses of relative catch efficiency were further restricted to those observations where both gears were present within a week and ICES rectangle combination. These fishing trips were used to calculate catch rates by landings in kilograms by trip duration in hours.

The comparison of catch rates of traditional gear and pulse gear was done using a set of non-linear models of increasing complexity. In all models, catch weight was estimated as a function of ICES rectangle and week, with multipliers to account for trip duration, differences among vessels/skippers, and a difference in catch efficiency between the traditional gear and the pulse gear. The effect of ICES rectangle and week was modelled using a design matrix $\mathbb{X}_1$. Each row in $\mathbb{X}_1$ represented a trip *i*, and columns

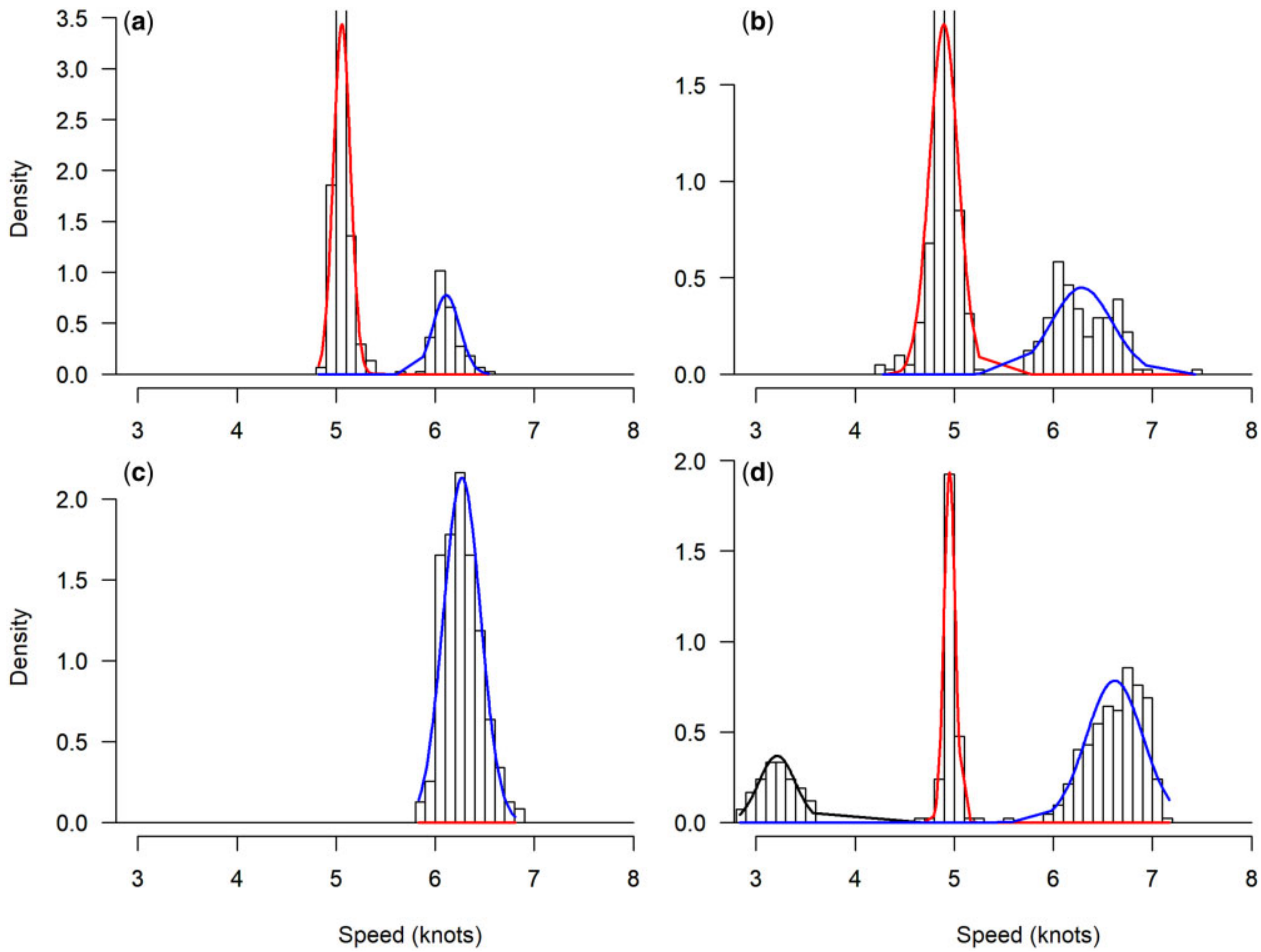

Figure 1. Examples of the histograms and density curves of the vessel speed (knots) determined by the EM for four vessels. (a, b) Vessels that made a switch from traditional beam trawling to pulse trawling, with a clear bimodal distribution in towing speeds. (c) A vessel that did not switch from traditional trawling to pulse trawling. (d) A vessel that switched, but that also has a third mode of fishing a twin otter trawl. The black, red, and blue curves indicate the normal density curves for the different fishing activities.

corresponded to variables that indicate membership of rectangle–week combinations. The model estimated parameter vector β_1 in length equal to the number of columns of $\mathbb{X}_1$.

The effect of vessels was included by adding a random effect for the difference in catch rates per vessel. The model estimated a random effect V_j for vessel *j*. This random effect is a multiplication factor so that the vessel effect was distributed as $N(1, \sigma_v{}^2)$. The effect of trip duration *E* on catches was assumed to be linear, with a parameter estimate of 1, so that a doubling of trip duration implied a doubling of catch weight (i.e. modelled as an offset). The effect of using a pulse gear rather than the traditional gear was added to the model as a multiplier Γ, so that the expected catches were modelled as follows:

$$E(C_{ij}) = \mu = (\beta_1 \mathbb{X}_1) V_j E\ \ (1 + \Gamma\ \ \mathbb{X}_2).$$

In the most complex model, the catch efficiency multiplier Γ is a function that depends on the number of weeks *e* since the adoption of the pulse gear by an individual vessel: $\Gamma = r + (a - r) \times\ \ 1 - \mathrm{e}^{(-z\ \ e)}$. The functional form of Γ is known as the exponential learning equation (Heathcote *et al.*, 2000). It is one of the standard equations to describe the improvement in the performance of tasks with practice (Leibowitz *et al.*, 2010). In the equation, *r* represented an initial increase or decrease in catch efficiency in the first week of the adoption of the pulse. Parameter *a* defines the asymptote that represents the difference in efficiency between the gears when experience with the pulse gear becomes very large. Finally, *z* is a constant rate coefficient. To map these parameters to observations, a second design matrix $\mathbb{X}_2$ is added. Each row in $\mathbb{X}_2$ represents a trip, and columns correspond to variables that indicate cohort membership, where 0 indicates no membership, and 1 indicates membership. All columns or rows connected to fishing trips that used traditional gear were set to 0, so that the efficiency of traditional trawling was equal to 1.

To test if the three different groups of vessels, each with a different pulse licence entry date (i.e. three cohorts), differ in terms of their initial difference *r* and change rate *z*, each is estimated as a vector of length 3. Hence, for each cohort *i*, there are parameters r_i and z_i.

Simplified adaptations of the most complex model were also tested, where, for example all cohorts were assumed to have identical initial differences and/or change rates (Table 1). In addition, a model was tested that only contained an asymptote, and a model where no difference between pulse fishing and traditional

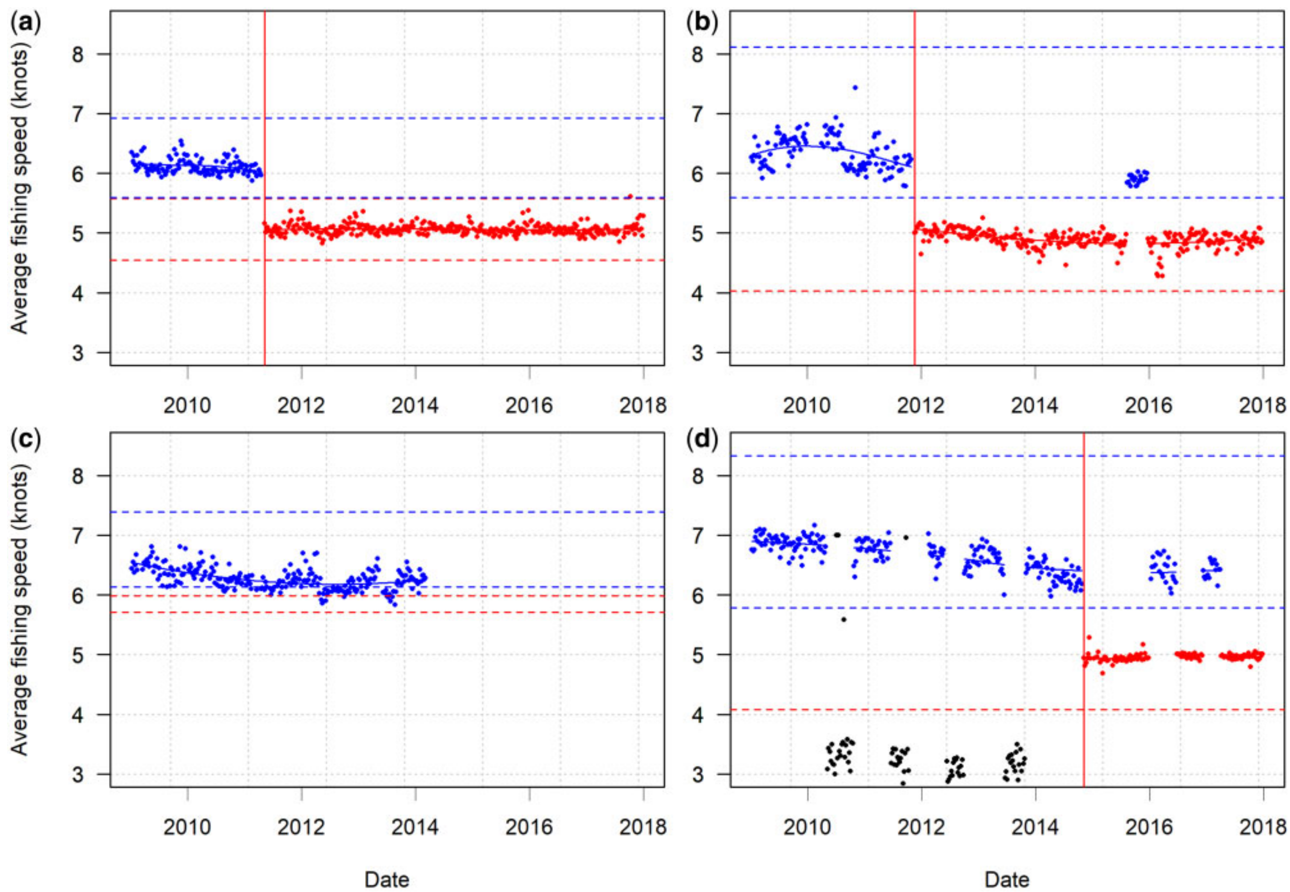

Figure 2. Examples of the evolution of speeds for the same data as used for Figure 1. (a, b) Vessels that made a switch from traditional beam trawling to pulse trawling, with a clear bimodal distribution in towing speeds. (c) A vessel that did not switch from traditional trawling to pulse trawling. (d) A vessel that switched, but that also has a third mode of fishing a twin otter trawl. Blue dots indicate observations associated with the high mean towing speed, associated with beam trawling. Red dots indicate observations associated with the intermediate mean towing speed, associated with pulse trawling. Black dots indicate observations associated with the low mean towing speed, associated with the "other" fishing activity that included twinrigging. Dashed horizontal lines indicate boundaries used for the classifications. Vertical red line indicates first observation classified as pulse trawling.

Table 1. Descriptions of the catch efficiency models.

Model	Model description
1	Cohorts have different starts, different slopes to common asymptote
2	Cohorts have different starts, common slope to common asymptote
3	Cohorts have same starts, different slopes to common asymptote
4	Cohorts start at efficiency multiplier of 1, different slopes to common asymptote
5	Cohorts start at efficiency multiplier of 1, common slope to common asymptote
6	All cohorts jump immediately to common asymptote
7	No difference between pulse and traditional

Model 1 is the most complex model, where each cohort has a different start in comparison to traditional trawling and different slopes towards a common asymptote. Model 7 is the simplest model where there is no difference in catch efficiency between pulse trawling and traditional trawling.

trawling was assumed. All models were fit to the data using a maximum likelihood approach, assuming that the data are log-normally distributed. Model fitting was done using Template Model Builder (TMB)(Kristensen *et al.*, 2016) in R (R Core Team, 2018). The variance component in the log-likelihood calculation (σ_l^2) was the final parameter to be estimated in the model. 95% *CI*s for the observed trajectories of catchability over time were calculated from parameter estimates using the Delta method implemented in TMB.

Model selection based on Bayesian Information Criteria (BIC) was used to find the best model for each (Wit *et al.*, 2012). Model diagnostics for the model favoured by the BIC estimate were evaluated for response and normalized residuals vs. fitted values and showed no apparent trend.

Once catch efficiency changes in terms of catch per unit time were estimated, efficiency changes in terms of catch per unit area swept were estimated. Percentual efficiency changes in terms of catch per unit area swept were calculated using $(((1 + \Gamma) \times \tau_e/\tau_t) - 1) \times 100$, where τ_e is the mean pulse trawling speed and τ_t is the trawling speed for sole with 80 mm.

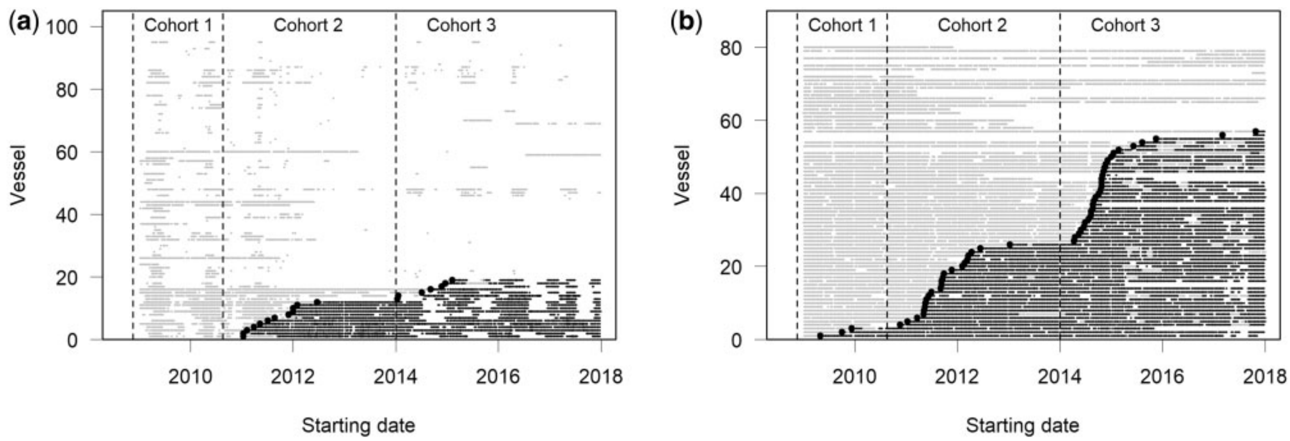

Figure 3. Fishing activity and transition dates of the vessels switching to pulse trawling for small (≤221 kW) (a) and large (>221 kW) (b) vessels. The black dots indicate the vessel-specific transition dates. The horizontal lines indicate observations of fishing activity with the traditional tickler chain beam trawl (grey) and with the pulse trawl (black). The vertical dashed lines in (a, b) show the distinction among the three cohorts used in the analysis of the change in catch efficiency.

Results

Classification strategy

The classification of trips resulted in 26 913 trips that were classified for the large beam trawlers, and 9653 trips that were classified for the small trawlers. Of the large trawlers, 15 889 trips were classified as traditional trawling, while 10 944 trips were classified as pulse trawling. The remaining 80 trips were classified as other. Of the small trawlers, 5141 trips were classified as traditional trawling, while 4490 trips were classified as pulse trawling. The remaining 22 trips were classified as other.

Matching the observer trips to the classified trips resulted in a match for 63 fishing trips. Of the matching observer trips, 28 were recorded as pulse fishing, while 35 trips were recorded as traditional fishing. All trips were classified correctly, resulting in a classification accuracy of 100%.

Transition from mechanical to electrical stimulation

The transition from traditional beam trawling to pulse trawling in the 80-mm fishery for sole took place between May 2009 and the beginning of 2016 (Figure 3). The first cohort of three large vessels switched to pulse trawling in 2009. It took almost 1 year before the next cohort of vessels switched in 2011 and 2012. This cohort consisted of both large and small vessels. A third cohort of vessels followed in 2014 and 2015 after the total number of licences was increased to 84. A total of 76 vessels switched to pulse trawling for sole: 57 large vessels and 19 small vessels (Figure 3). The remaining eight licences were issued to shrimp fishers or never used. Several vessels that did not switch ceased fishing altogether. During the study period, 13 pulse licences were transferred to another vessel. Not all vessels used the pulse trawl throughout the year after the transition but seasonally switched back to the traditional beam trawl or shrimp beam trawl as shown by alteration of black and grey or white lines in Figure 3.

Pulse trawls were towed at a lower speed than traditional beam trawls. For small vessels, the difference in trawling speed between the traditional gear and the pulse trawl is limited (−10%): the mean for the pulse trawlers was 4.64 knots, while the mean for the traditional trawlers was 5.17 knots (Table 2). For the large trawlers, the difference was substantially larger (−23%): trawling with the pulse gear occurred at 4.92 knots, whereas the traditional gear was towed at 6.38 knots.

Table 2. Mean towing speed by fishing trip as recorded with VMS for pulse trawls (PUL_SOL) and traditional beam trawls deployed in the fishery for sole (TBB_SOL) and plaice (TBB_PLE) with small and large vessels.

	Small vessels			Large vessels		
Gear	**Mean**	***SD***	***N***	**Mean**	***SD***	***N***
PUL_SOL	4.64	0.30	4 490	4.92	0.26	10 944
TBB_PLE	4.97	1.04	168	6.34	0.44	2 197
TBB_SOL	5.17	0.71	4 973	6.38	0.39	13 692

N denotes the number of fishing trips in the sample and *SD* denotes the standard deviation.

Catch efficiency

For the small vessels, the selection criteria for comparison of catch efficiency resulted in a set of 489 trips in 159 unique week–rectangle combinations to be used in the efficiency analyses for marketable catch. For the large vessels, the selection criteria resulted in 4994 trips in 1157 unique week–rectangle combinations to be used in the catch efficiency.

For the small vessels, model selection based on BIC suggested that the best model was model 6. This was the simplest model that included a difference in catch efficiency between pulse trawling and traditional trawling (Table 3). For large vessels, the best model for sole was model 3. This model has the same initial changes in catch efficiency for the three cohorts but with different slopes for the three cohorts. For plaice, model 6 was selected based on BIC, similar to best models for the small vessels.

The switch to pulse trawling coincided with an overall increase in the catch efficiency of sole for both small and large vessels (Figure 4). For small vessels, that were only represented in cohorts 2 and 3, the switch to pulse trawling was associated with an instantaneous increase in catch efficiency. The parameter a was estimated to be 0.743 and the increase was thus estimated to be ∼74.3% (SD = 8.0%). The SD in the random effect for the sole catches of small vessels σ_v was estimated to be 0.181. The *SD* of the log-transformed observations σ_l was estimated to be 0.224.

For the large trawlers, the switch from traditional to pulse trawling of the first cohort was associated with a decrease in catch efficiency for sole of roughly −47.7% (*SD* = 6.8%). This was followed by a gradual increase ($z = 0.07\ \text{week}^{-1}$) to an asymptote of 0.171 (*SD* = 0.02). Hence, the pulse gear is ultimately 17.1% more efficient for sole (in terms of kg sole landed per hour) than the traditional gear when fishing in the same ICES rectangle and week. Cohort 1 vessels gradually improved their efficiency to catch sole and achieved the long-term gain only after almost 1 year. Although the initial decrease (at 0 week) in the other two cohorts was equal to the decrease in the first cohort, the estimated *z* values were much higher, $z = 1.28\ \text{week}^{-1}$ for cohort 2 and $z = 10.7\ \text{week}^{-1}$ for cohort 3. In practice, this means that cohorts 2 and 3 almost immediately increased their efficiency to the asymptote (Figure 4). For small vessels, parameter *a* was estimated to be 0.743 and the increase was thus estimated to be ∼74.3% (*SD* = 8.0%). The *SD* in the random effect for the sole catches σ_v was estimated to be 0.244. The *SD* of the log-transformed observations σ_l was estimated to be 0.220.

For plaice, model 6 for small vessels estimated a stepwise decrease in catch rate of 31.1% (*SD* = 6.53%). The *SD* in the random effect for the plaice catches of small vessels σ_v was estimated to be 0.225. The *SD* of the log-transformed observations σ_l was estimated to be 0.5406. For large vessels, model 6 estimated a stepwise decrease in catch rate of 32.3% (*SD* = 1.41%). The *SD* in the random effect for the plaice catches of large vessels σ_v was estimated to be 0.172. The *SD* of the log-transformed observations σ_l was estimated to be 0.351.

Table 3. Model selection results for sole and plaice, for small and large vessels.

	Plaice			Sole		
Model number	**Nll**	**df**	**BIC**	**Nll**	**df**	**BIC**
Small vessels						
1	404.81	166	1 838	−21.12	166	986
2	404.81	165	1 831	−21.45	165	979
3	406.60	165	1 835	−21.12	165	980
4	410.19	164	1 836	−3.45	164	1 009
5	410.19	163	1 830	−3.44	163	1 003
6	**407.10**	**162**	**1 817**	**−14.99**	**162**	**973**
7	414.37	161	1 826	46.33	161	1 090
Large vessels						
1	1 933.56	1 166	13 794	−350.33	1 166	9 229
2	1 936.59	1 164	13 786	−347.73	1 164	9 217
3	1 933.57	1 164	13 780	**−349.07**	**1 164**	**9 215**
4	1 936.30	1 163	13 777	−325.25	1 163	9 254
5	1 936.60	1 161	13 760	−310.55	1 161	9 265
6	**1 936.60**	**1 160**	**13 752**	−306.22	1 160	9 266
7	2 095.93	1 159	14 062	−259.70	1 159	9 351

Model selection was done using the BIC. Selected models are in bold; nll denotes negative log-likelihood of the model. df denotes model degrees of freedom.

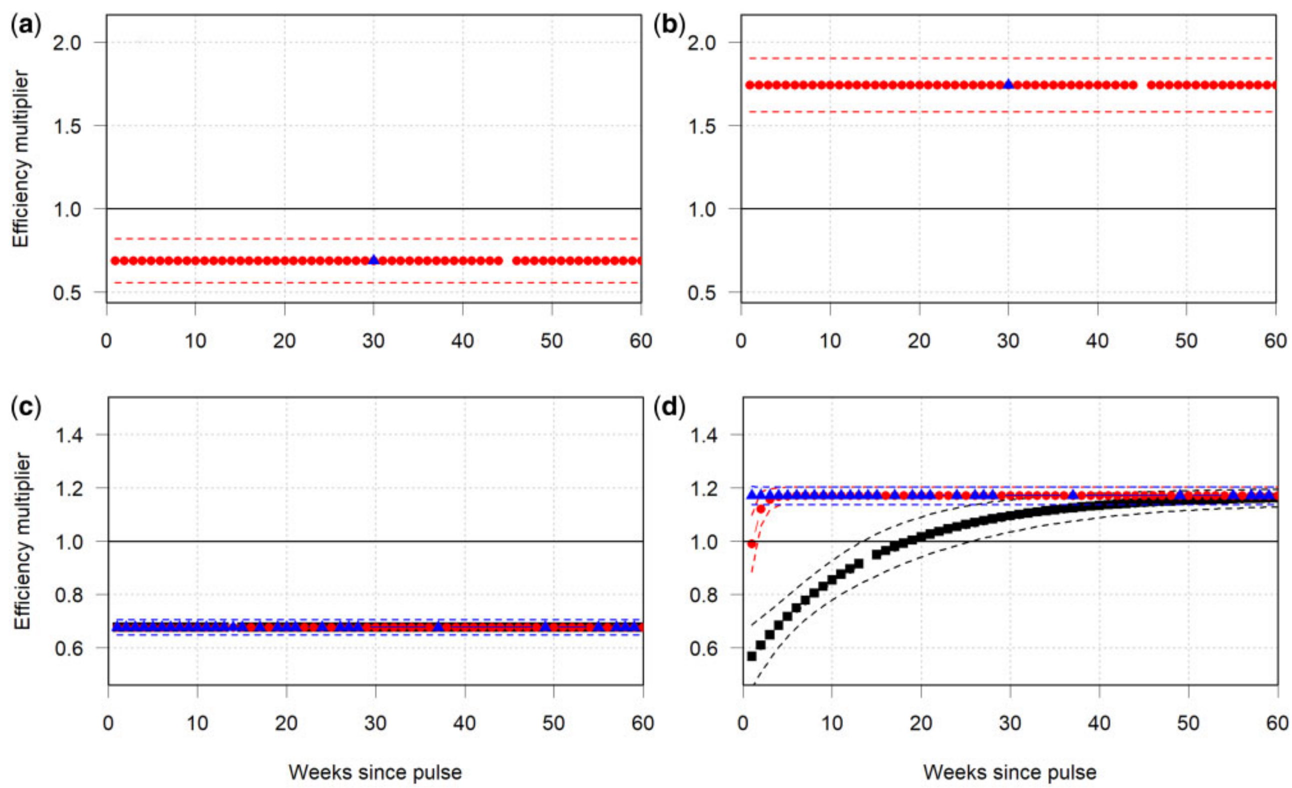

Figure 4. Estimates of the catch efficiency multiplier (when catch rates are compared as kg/h) for plaice (a) and sole (b) for the small trawlers over time, for the two cohorts: cohort 2 (red circles) and cohort 3 (blue triangles). Estimates of the catch efficiency multiplier for plaice (c) and sole (d) for the large trawlers over time, for the three cohorts: Cohort 1 (black squares), cohort 2 (red circles), and cohort 3 (blue triangles). Drawn lines indicate maximum likelihood estimates, dashed lines indicate 95% *CI*s. Note that in (a–c) no difference among cohorts was found so that there is a single line for all cohorts.

Because of the difference in towing speed between pulse trawls and traditional beam trawl, the change in marketable catch efficiency in terms of catch per unit area swept can be estimated from the change in catch per unit of time and the difference in towing speed. The transition to pulse trawling increased the catch efficiency for sole by $(((1.743 \times 5.17/4.64) - 1) \times 100=)$ 94% and $(((1.171 \times 6.38/4.92) - 1) \times 100=)$ 52% for small and large vessels, respectively, while the catch efficiency for plaice decreased by 23 and 12%.

Discussion

Catch efficiency and species selectivity

The transition from the traditional beam trawl to the pulse trawl resulted in an increase in catch efficiency for marketable sole and a reduced catch efficiency for marketable plaice. This difference is likely caused by the difference in response of sole and plaice to the electrical stimulation. Both species show a cramp response that immobilizes the fish and prevent them to actively escape from the approaching gear by digging in the seabed or swimming away in front of the gear (van Stralen, 2005; de Haan *et al.*, 2016). However, only sole bends in a U-shape when cramped, where the tail is reaching the nose, and come loose from the sea floor and can be easily scooped up in the net increasing the catch efficiency (van Stralen, 2005; Soetaert *et al.*, 2015b). A cramped plaice maintains its flat shape and may more easily pass underneath the ground gear than a cramped sole. The pulse trawl may also catch a larger proportion of sole because the electric field penetrates deeper into the sediment than tickler chains. Tickler chains penetrate a few centimetres into the sediment up to a maximum of ~8 cm (Paschen *et al.*, 2000; Depestele *et al.*, 2016, 2019). Electric field strength decreases exponentially with distance to conductors (de Haan *et al.*, 2016). de Haan and Burggraaf (2018) measured field strengths high enough to invoke muscular contractions in cod at a depth of 20 cm around a commercial pair of electrodes in soft sediments (de Haan *et al.*, 2016). Finally, pulse stimulation may prevent fish, which have been caught, to escape through the mouth of the net, because the pulse field creates a barrier at the front of the net (Pieke Molenaar, pers. comm.). The higher catch efficiency per unit swept area of sole and lower catch efficiency of plaice are generally in line with the results of comparative trawling experiments in which both pulse and traditional beam trawls were towed side by side (Van Marlen *et al.*, 2001; van Marlen *et al.*, 2014). Experiments carried out with pulse trawl prototypes on board of research vessels before commercial application suggested improved catch efficiency for sole and reduced catch efficiency for plaice and other species (Van Marlen *et al.*, 2001). In the first comparison of two experienced pulse trawlers and one traditional beam trawler in May 2011, van Marlen *et al.* (2014) found a 2.5% higher catch efficiency for sole, based on 66 hauls. For plaice, a 6.1% lower catch efficiency was found, based on 60 hauls. The difference to our findings may be due to the small number of hauls in these comparative trawling experiments.

The marketable catch used in the analyses is under the influence of discarding decisions. While incidental discarding of marketable catches occurred in this fishery (Poos *et al.*, 2010), this practice has been prohibited since 2009 (Batsleer *et al.*, 2015). The compliance to this rule is unknown but is expected to be equal for the two gear types. The difference in marketable catch may also be due to differences in fishing grounds within an ICES rectangle between pulse trawling and traditional beam trawling. Beam trawl effort in the southern North Sea occurred in persistent hot spots characterized by depressions between sand ridges with low wave action (van der Reijden *et al.*, 2018; Hintzen *et al.*, 2019). Anecdotal information from the fishing industry suggests that pulse trawlers were able to locally fish in previously untrawlable areas where they found high sole densities. The ridges and troughs occurring in the southern North Sea, which occur at a spatial scale of ~100 m (van Dijk *et al.*, 2012; van der Reijden *et al.*, 2019) could be used differentially by both gears. The analysis of the fine grained spatial distribution (150 m × 150 m), however, did not show a significant difference in the bathymetric distribution of pulse trawls and tickler chain beam trawls within the ICES rectangles of the southern North Sea (Hintzen *et al.*, under review). Although it cannot be excluded that subtle differences in fishing grounds have contributed to the estimated change in catch efficiency, the surface area of these seabed habitats is too small to fully explain the increase in catch efficiency. We therefore conclude that the transition to pulse trawling improve the species selectivity of the flatfish fishery by increasing the catch efficiency for marketable sole and reducing the catch efficiency for marketable plaice.

Transition process

After three vessels made the transition in 2009 and one fishing company ordered pulse trawl equipment for four of their vessels, the number of applications for a licence grew quickly and exceeded the number of available licences (Haasnoot *et al.*, 2016). The number of vessels using the pulse trawl increased stepwise in 2011 and in 2015 to a number of 76 Dutch-flagged vessels in 2016 targeting sole.

The first three vessels that switched to pulse trawling in 2009 experienced an initial reduction in catch efficiency. The application of electrical stimulation required adapting the design of the net and ground rope. In order to generate a stable electrical field, electrodes had to be of equal length and the V-shaped ground gear of a traditional beam trawl was replaced by a horizontal ground gear. Given these constraints, fishers explored different possibilities to find the optimal rigging of their gears (Arie Lokker, Cooperatie Westvoorn, pers. comm.).

Problems with electrodes and a lack of experience with handling the new fishing gear reduced effective fishing time. The pulse gear was difficult to repair at sea and in case of failure vessels had to return to port. After various modifications, the operational reliability of the gear improved (Taal and Klok, 2014) and changes in pulse parameters were explored to improve catch efficiency (Harmen Klein-Woolthuis, HFK-engineering, pers. comm.). When the vessels of the second cohort switched to pulse trawling improved pulse technology was available, allowing vessels to almost immediately obtain the increased catch efficiency.

Management implications

In the Netherlands, the flatfish fishery is managed by Individual Transferrable Quotas for the main target species sole and plaice. The higher catch efficiency for sole implies that sole quotas can be caught with less fishing effort. Nevertheless, pulse licence holders were able to maintain their fishing effort by leasing or buying sole quota from other vessels. The lease price of sole increased from ~0.60 Euro/kg in 2012 to 3.38 Euro/kg in 2015 (Turenhout *et al.*, 2016). To harvest their plaice quota, several pulse licence holders temporarily switch back to the traditional beam trawl gear with a large mesh size.

The application of the pulse trawl may reduce the discard problem in the flatfish fishery with beam trawls that is characterized by a substantial discarding of undersized fish (mainly plaice and dab) (van Beek, 1998; Catchpole *et al*., 2008). In a fishery that is constrained by sole quotas, the increased catch efficiency for sole and reduced catch efficiency for plaice may reduce discarding. Pulse licence holders using 80 mm trawls targeting sole will land fewer plaice per unit time and spend less time at sea to fill their quotas. The remaining fishing effort of the pulse licence holders targeting plaice with traditional beam trawl will have a modest contribution to the discarding of plaice because the fishing effort is exerted with a larger mesh size and concentrated in areas where larger plaice are more abundant (Wimpenny, 1953; Poos and Rijnsdorp, 2007). Discarding could be further reduced due to improved size selectivity of the pulse trawls (van Marlen *et al*., 2014).

The pulse trawls also reduce other adverse ecosystem effects in the flatfish fishery. Replacing tickler chains by electrodes reduced the mechanical disturbance of the sea floor and the impact on the benthic ecosystem (Depestele *et al*., 2016; ICES, 2018; Depestele *et al*., 2019). The reduced towing speed results in a reduction of the surface area trawled when catching the sole quota and in a reduction of the fuel consumption and corresponding CO_2 emissions (Turenhout *et al*., 2016). For large trawlers, the reduction in fuel consumption per day fishing is estimated to be up to 46%, while for small trawlers, it is estimated to be 12%. Possible adverse effects of electrical stimulation on marine biota and the benthic ecosystem are currently being investigated. Except for the spinal injuries in cod and whiting (de Haan *et al*., 2016; Soetaert *et al*., 2016b), the available studies have not shown adverse effects on other fish species and benthic invertebrates (Soetaert *et al*., 2015a; Soetaert *et al*., 2016a; Desender *et al*., 2017a, b).

Data availability statement

Primary VMS-data and catch and effort data of the mandatory logbook are subject to confidential agreements. One should contact Sieto Verver, Head of the Centre for Fisheries Research (sieto.verver@wur.nl) for permission using these data.

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