Raising the bar

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Sistiaga, Grimaldo, Herrmann, and Larsen share the results of a small-scale experiment on how lifting trawl doors and sweeps from the seabed helps mitigate by-catch.

Who should read this paper?

Fishing gear scientists and fishermen around the world who work with towed gear.

Why is it important?

The Norwegian trawl fishery for deep water shrimp catches unsustainable numbers of juvenile fish. Regulations are in place to close fishing grounds when specified by-catch numbers of varying species have been exceeded – resulting in many northern inshore shrimp grounds being closed for several months.

This study compares two gear configurations: one with trawl doors and sweeps on the seabed and the other with doors and sweeps clear of the seabed. Results suggest that lifting shrimp trawl gear from the seabed can result in reduced by-catch; reduce the work load required on board by eliminating the need to sort the targeted species from by-catch species; and greatly reduce the environmental impact of the trawl fishery on the seabed.

About the authors

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THE EFFECT OF SEMI-PELAGIC TRAWLING ON AMERICAN PLAICE (*HIPPOGLOSSOIDES PLATESSOIDES*) BY-CATCH REDUCTION IN THE NORTHEAST ARCTIC SHRIMP FISHERY

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ABSTRACT

The present study reports results of a small-scale preliminary experiment to evaluate whether lifting trawl doors and sweeps from the seabed can lead to a reduction of by-catch in the Northeast Arctic shrimp trawl fishery. We carried out a catch comparison and catch ratio analysis between two gear configurations: one with trawl doors and sweeps on the seabed (traditional rigging) and the other with doors and sweeps clear of the seabed (semi-pelagic rigging). The study focused on the by-catch of American plaice (*Hippoglossoides platessoides*) and showed that the gear was significantly less efficient at catching this species when rigged in the semi-pelagic mode. When rigged this way, the gear captured 52%–66% fewer American plaice between 10 and 40 cm compared to traditional rigging. Moreover, this difference was significant for sizes between 12 and 31 cm, and it increased with fish size. The herding efficiency of doors and sweeps for American plaice was estimated to be 100% and significantly higher than 0 for these sizes. Finally, the analysis carried out did not detect a significant reduction in shrimp catch (in kg) with the experimental gear. This study demonstrates that in addition to having recognized environmental advantages, lifting the doors and sweeps from the seabed could help mitigate American plaice by-catch in the Northeast Arctic shrimp fishery. Although these preliminary results are promising, more extensive data collection is required before definitive conclusions can be reached.

KEYWORDS

Shrimp; Trawl; Semi-pelagic Rigging; American plaice; By-catch; Herding; Flatfish

INTRODUCTION

Norwegian trawl fisheries for deep water shrimp (*Pandalus borealis*) catch unsustainable numbers of retained juvenile fish (0- and I-group) such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes spp.*), Greenland halibut (*Reinhardtius hippoglossoides*), Norway pout (*Trisopterus esmarkii*), whiting (*Merlangius merlangus*), American plaice (*Hippoglossoides platessoides*), lemon sole (*Microstomus kitt*), capelin (*Mallotus villosus*), herring (*Clupea harengus*), polar cod (*Boreogadus saida*), and blue whiting (*Micromesistius poutassou*) [Norwegian Fisheries Directorate, 2017]. Even though fishermen are required to use a Nordmøre grid as a by-catch excluding device in their trawl [Isaksen et al., 1992], the numbers of juveniles still caught are often unsustainable, thus additional by-catch reduction measures are needed. According to current Norwegian Sea and Barents Sea deep water shrimp fishing regulations, a fishing ground is closed whenever shrimp catches contain more juveniles than eight cod or 20 haddock or three redfish or three Greenland halibut per 10 kg of shrimp. This means that many northern inshore shrimp grounds are closed for several months because these fish limits are exceeded.

Effective reduction of by-catch of juvenile fish, especially juveniles of commercially important species, has ecological benefits and multiple advantages for fishermen. These fish have no commercial value, and their retention reduces fishermen's access to fishing grounds due to fishing regulations. The by-catch also has an unnecessary negative environmental impact, in that loss of juveniles may impact future generations of these species. Furthermore, the by-catch requires additional sorting on board, which can lead to lower quality of the shrimp caught.

In the last decade, fishery authorities around the world have focused on reducing the environmental impact of trawl fisheries in general. Apart from the impact on the by-catch species and the impact on the seabed created by the trawl doors and ground gear, the high average fuel consumption values of shrimp trawlers have led to these types of vessels being particularly criticized [Jones, 1992; Schau et al., 2009]. In Norway, many whitefish trawlers have exchanged their traditional bottom trawl doors for semi-pelagic doors that are towed just above or in slight contact with the seabed [Sistiaga et al., 2015]. In some cases, this change alone has resulted in fuel savings of up to 17% [Eayrs et al., 2012; Grimaldo et al., 2015].

Lifting the doors from the seabed poses the risk of losing at least part of the herding efficiency of the doors and sweeps [Ryer, 2008]. Losing herding efficiency can be a disadvantage for whitefish fisheries as it can make the fisheries less effective [Sistiaga et al., 2015]. However, this loss could become an advantage for the shrimp fishery if it reduces fish by-catch. The swimming power of deep water shrimp is assumed to be limited [Broadhurst, 2000; He et al., 2015], and it is practically negligible compared to the towing speed of a trawl. Thus, lifting the doors from the seabed could potentially result in a reduction of fish by-catch with marginal or negligible shrimp loss.

Several researchers have reported the herding potential of sweeps to gather fish [Wardle, 1983; Ryer et al., 2010; Winger et al., 2010]. He et al. [2015] found that partially lifting the sweeps led to a reduction of by-catch in shrimp trawls without any noticeable loss of shrimp. Thus, the goal of the present investigation was to determine if lifting the doors and sweeps from the seabed can reduce the by-catch of American plaice in the Northeast Arctic shrimp trawl fishery.

MATERIALS AND METHODS

Sea Trials

Our trials were conducted on board the 30 m (LOA) research trawler *Johan Ruud*. We used a shrimp trawl with 1,400 meshes in the trawl mouth, a 53.2 m long fishing line, and a 44.9 m long head rope. The trawl body was built of 50 mm meshes and the codend of 35 mm meshes (i.e., a typical shrimp trawl size for the inshore/coastal fleets along the Norwegian coast). In the extension piece of the trawl, we inserted a standard Nordmöre grid with a bar spacing of 19 mm. The ground rope was built following a rock hopper design with 35.5 cm diameter discs that were spaced 30 cm in the centre and 60 cm in the side sections. The length of the toggles attaching the ground rope to the fishing line was ca. 30 cm. The experiments were performed at fishing depths of 183-186 m, and towing times were fixed to 40 minutes per tow (see Table 1). The bridles/sweeps were 40 m long, and the high aspect ratio trawl doors were of the type Injector XF9 (2.5 m^2 and 480 kg).

The experiments were carried out using a single trawl that was alternately operated with traditional rigging (doors and sweeps at the seabed) and with semi-pelagic rigging (Figure 1). To ensure that, independent of the sampling rigging used, the trawl had seabed contact at all times, we attached a clump of chains (38 mm diameter) weighing 100 kg to the lower tips of the trawl. These clumps were not removed throughout the experiments. To regulate the geometry of the trawl, we used a set of distance sensors at the trawl wings (Marport MFX, Marport Deep Sea Technologies Inc., Reykjavik, Iceland), a set of Marport door sounders, and a trawl height sensor (Scanmar HC4-HT60, Scanmar, Åsgårstrand, Norway). The sounders were used to regulate the height of the doors over the seabed at all times, which was crucial to ensure that the two different riggings were working as planned. The height of the doors was regulated by the skipper slightly adjusting the wire length and trawling

Haul nr.	Rigging	Start towing (hh:mm)	Depth at tow start (m)	# American plaice	Shrimp in codend (kg)
1	Traditional	08:25	184	218	83.2
3	Semi-pelagic	11:45	185	145	98
5	Semi-pelagic	15:00	186	26	*
6	Traditional	17:00	185	112	42
7	Traditional	19:20	183	215	41
8	Semi-pelagic	08:45	186	36	36
9	Semi-pelagic	10:15	186	34	38
10	Traditional	11:40	*	94	35

Table 1: Overview of the eight valid hauls carried out during the experimental period. The duration of all hauls was fixed to 40 minutes. Missing values are represented with *.

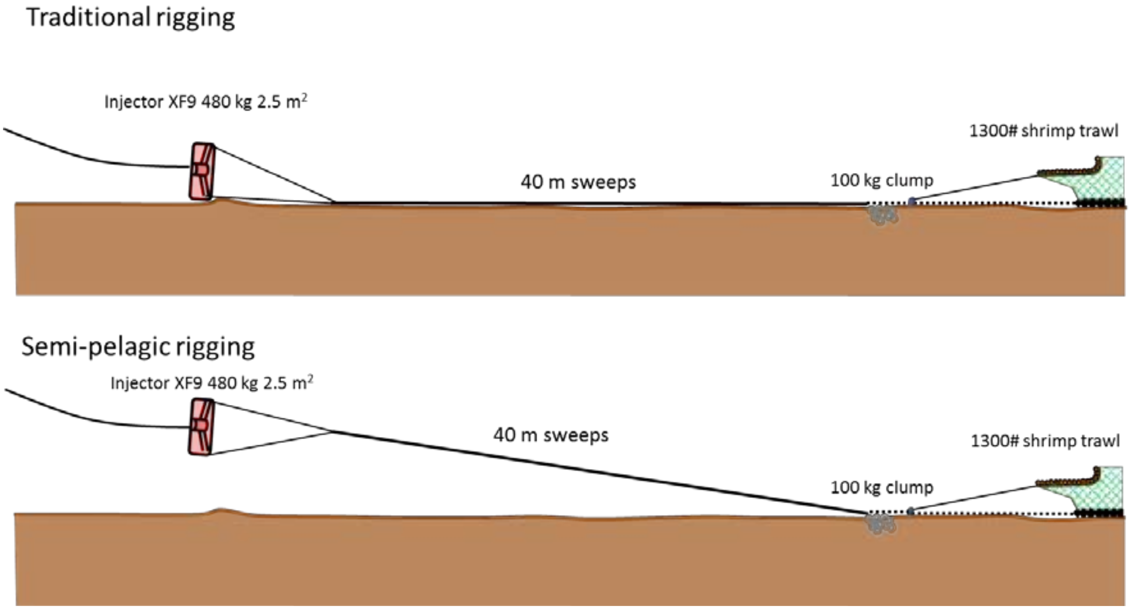


Figure 1: Traditional rigging (above) and semi-pelagic rigging (below) used during the sea trials.

speed. The trawl height sensor was placed in the middle of the headline and was used to keep the height of the trawl in the range between the expected values and to ensure that there was contact between the rockhopper gear and the seabed. Using the data from the different sensors, we manually registered the distance between the doors, the height of the doors over the seabed, trawl wing distance, trawl height, and towing speed every fifth minute during each haul. To avoid potential differences in light intensity in the hauls carried out with the two different riggings, the tows were alternated.

Data Analysis

We calculated the average distance between the doors, average height of the doors over the seabed, average trawl wing distance, average trawl height, and average towing speed for each of the riggings by first calculating the average values for each haul and thereafter using the average of each haul to calculate a cruise average.

The entire shrimp catch was weighed for each haul, and all fish captured during the cruise were measured to the nearest cm. Although species such as cod, haddock, and Norway pout were also present in the by-catch, we concentrated the study on American plaice because it was the only species that was captured in sufficient numbers to carry out a meaningful analysis. Furthermore, as flatfish are well known to be herded by approaching trawl gear [Winger et al., 2010], the American plaice was an appropriate choice for these tests. American plaice is a typical by-catch species in shrimp fisheries, including the Norwegian shrimp fisheries [He et al., 2015].

Unpaired Catch Comparison

To assess the effect of changing from traditional rigging to semi-pelagic rigging on the relative length-dependent catch efficiency, we used an unpaired catch comparison analysis [Sistiaga et al., 2015; Herrmann et al., 2017]. We were interested in the length-dependent catch comparison rate values summed over the hauls carried out with traditional rigging and semi-pelagic rigging, which is expressed by:

$$cc_l = \frac{\sum_{j=1}^{bq} nb_{lj}}{\sum_{i=1}^{aq} na_{li} + \sum_{j=1}^{bq} nb_{lj}} \tag{1}$$

where l denotes the fish length and na_{li} and nb_{lj} are the numbers of American plaice measured in each length class l for the traditional rigging and semi-pelagic rigging, respectively. aq and bq are the number of hauls carried out with traditional rigging and semi-pelagic rigging, and the summations in the equation represent the summations of the data from the hauls.

The experimental cc_l is often modelled by the function $cc(l,\boldsymbol{v})$, which has the following form [Krag et al., 2014]:

$$cc(l,\boldsymbol{v}) = \frac{exp(f(l,v_0,\ldots,v_k))}{1+exp(f(l,v_0,\ldots,v_k))} \tag{2}$$

where f is a polynomial of order k with coefficients v_0 to v_k. Thus, $cc(l,\boldsymbol{v})$ expresses the probability of finding a fish of length l in the catch of one of the hauls with semi-pelagic rigging given that it is found in the catch of one of the riggings. The values of the parameters v describing $cc(l,\boldsymbol{v})$ are estimated by minimizing Equation (3):

$$-\sum_l \left\{ \sum_{i=1}^{aq} na_{li} \times ln\left(1.0 - cc(l,\boldsymbol{v})\right) + \sum_{j=1}^{bq} nb_{lj} \times ln\left(cc(l,\boldsymbol{v})\right) \right\} \tag{3}$$

The outer summation in Equation (3) is the summation over the length classes l and the inner summation is that over the hauls conducted. Minimizing Equation (3) is equivalent to maximizing the likelihood for the observed data based on a maximum likelihood formulation for binominal data (see Herrmann et al. [2013] for further information on this subject). In Equation (2) we considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $cc(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multi-model inference [Burnham and Anderson, 2002; Herrmann et al., 2017]. We use the name combined model for the result of this multi-model averaging.

When the catch efficiency between the riggings, trawling time (t), average area swept by the wings (ω) in each rigging, and the number of hauls (q) are equal ($at = bt$, $a\omega = b\omega$, and $aq = bq$) (Figure 2), the expected value for the summed catch comparison rate would be 0.5. If differences between the riggings for any of these three parameters occur, $bt \times b\omega \times bq \,/\, (at \times a\omega \times aq + bt \times b\omega \times bq)$ would be the baseline to judge whether or not there is a difference in catch efficiency between riggings.

The ability of the combined model to describe the experimental data was evaluated based on the p-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy as that found between the experimental data and the model, assuming that the model is correct. This p-value, which was calculated based on the model deviance and the degrees of freedom, should in principle not be < 0.05

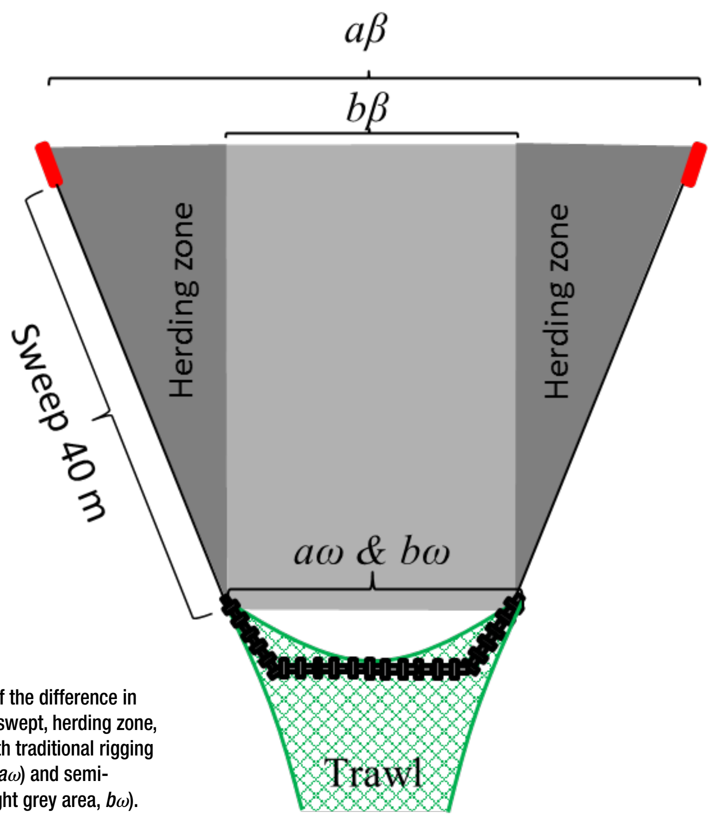


Figure 2: Illustration of the difference in the width of the area swept, herding zone, and wing distance with traditional rigging (*aβ*, whole grey area, *aω*) and semi-pelagic rigging (*bβ*, light grey area, *bω*).

for the combined model to describe the experimental data sufficiently well unless the experimental data are overdispersed [Wileman et al., 1996].

The confidence limits for the catch comparison curve were estimated using a double bootstrapping method as described in Herrmann et al. [2017]. We performed 1,000 bootstrap repetitions and calculated the Efron 95% confidence limits [Efron, 1982] for the catch comparison curve. To identify sizes of fish with significant difference in catch efficiency between the two riggings, we checked for length classes for which the confidence limits for the combined catch comparison curve and the baseline rate for no effect $(=bt \times b\omega \times bq / [at \times a\omega \times aq + bt \times b\omega \times bq])$ did not overlap.

Catch Ratio

The catch comparison rate $cc(l,\mathbf{v})$ cannot be used to quantify directly the ratio between the catch efficiency of traditional rigging versus semi-pelagic rigging for a fish of length l. Instead, we used the catch ratio $cr(l,\mathbf{v})$. For the experimental data, the average catch ratio for a length class l is expressed as follows:

$$cr_l = \frac{\frac{1}{bq}\sum_{j=1}^{bq} nb_{lj}}{\frac{1}{aq}\sum_{i=1}^{aq} na_{li}} \qquad (4)$$

Simple mathematical manipulation based on Equations (2) and (4) yields the following general relationship between the catch ratio and the summed catch comparison:

$$cr_l = \frac{aq \times cc_l}{bq \times (1 - cc_l)} \qquad (5)$$

which also means that the same relationship exists for the functional forms:

$$cr(l,\boldsymbol{v}) = \frac{aq \times cc(l,\boldsymbol{v})}{bq \times \left(1 - cc(l,\boldsymbol{v})\right)} \qquad (6)$$

One advantage of using the catch ratio the way it is defined by Equations (4) and (6) is that it gives a direct relative value of the catch efficiency of the semi-pelagic rigging relative to the traditional rigging, whereas the catch comparison rate does not. Furthermore, the way catch ratio is defined by Equations (4) and (6) provides a value independent of the number of hauls carried out with each type of rigging. Thus, if the catch efficiency of both riggings and also the trawling time (*t*) and average area swept by the wings (ω) are equal ($at = bt$, $a\omega = b\omega$), $cr(l,\boldsymbol{v})$ should always be 1.0. It follows that $cr(l,\boldsymbol{v}) = 1.25$ would mean that if trawling time and average swept area are the same, the semi-pelagic rigging catches on average 25% more fish with length l than the traditional rigging. In contrast, $cr(l,\boldsymbol{v}) = 0.75$ would mean that the semi-pelagic rigging catches 75% of the fish with length *l* that the traditional rigging catches. For cases in which there are differences between the riggings in any of these three parameters, $(at \times bt) / (at \times a\omega)$ would be the baseline to judge whether or not there is a difference in catch efficiency between traditional rigging and semi-pelagic rigging.

Using Equation (6) and incorporating the calculation of $cr(l,\boldsymbol{v})$ for each relevant length class into the double bootstrap procedure described for the catch comparison rate, we estimated the confidence limits for the catch ratio. We used the catch ratio analysis to estimate the length dependent effect on catch efficiency of changing from traditional rigging to semi-pelagic rigging.

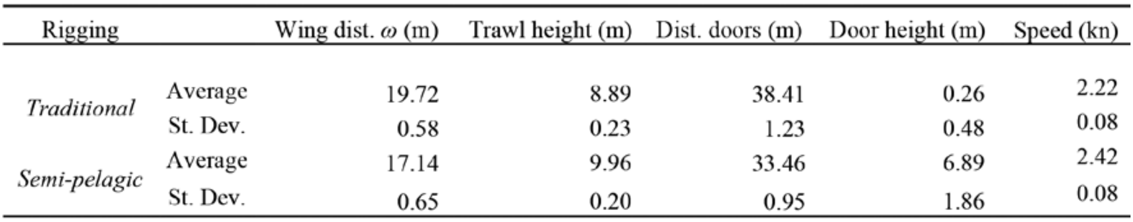
The analyses for the current study were carried out using SELNET, which was previously applied to analyze size selectivity data [e.g., Sistiaga et al., 2010; Eigaard et al., 2011; Frandsen et al., 2011; Herrmann et al., 2012] and catch comparison data [Krag et al., 2014; Sistiaga et al., 2015] collected with trawls.

Herding Efficiency

Sistiaga et al. [2015] defined herding efficiency as the ratio between the fish available in the herding zone and the fish that actually become available to the trawl net. Assuming that doors and sweeps have a herding effect on American plaice, more or fewer fish would move from the herding zone into the catch zone depending on the herding efficiency of the gear (Figure 2). We assumed that the herding efficiency of the doors and the sweeps was negligible. Following the definition given by Sistiaga et al. [2015] for herding efficiency, we estimated the herding efficiency of the gear used in these experiments on American plaice by:

$$hf(l,\boldsymbol{v}) = \frac{cr(l,\boldsymbol{v}) \times a\omega - b\omega}{b\beta - b\omega - cr(l,\boldsymbol{v}) \times a\beta + cr(l,\boldsymbol{v}) \times a\omega} \qquad (7)$$

where $a\beta$ and $b\beta$ are the distances between the foremost part of the gear with bottom contact in each of the cases ($a\beta$ would be the door distance and $b\beta$ would be equal to $b\omega$). The confidence limits for the herding efficiency were estimated using the same bootstrap procedure as that used for the catch comparison and catch ratio procedures.



Rigging		Wing dist. ω (m)	Trawl height (m)	Dist. doors (m)	Door height (m)	Speed (kn)
Traditional	Average	19.72	8.89	38.41	0.26	2.22
	St. Dev.	0.58	0.23	1.23	0.48	0.08
Semi-pelagic	Average	17.14	9.96	33.46	6.89	2.42
	St. Dev.	0.65	0.20	0.95	1.86	0.08

Table 2: Trawl geometry data and towing speed for the hauls carried out during the cruise.

Shrimp Catches

To investigate whether we could detect any significant difference in the shrimp catches (in kg) between traditional rigging and semi-pelagic rigging, we carried out a Welch's t-test (or unequal variances t-test) for unpaired data. An equal shrimp catching efficiency was used as the zero hypothesis for this test. We used a Welch's t-test because it is more reliable than a Student's t-test when the two samples compared have unequal variances and unequal sample sizes [Welch, 1947].

RESULTS

We carried out eight hauls in the North Norwegian fjord of Balsfjord (69°21'310"N–69°22'524"N / 19°03'415"E–19°06'650"E), four with traditional rigging and four with semi-pelagic rigging, between the 3rd and the 4th of February 2015. We measured 880 American plaice and caught 373.2 kg of shrimp (see Table 1).

The trawl geometry data collected during the cruise (Table 2) illustrated the difference between the average trawl door height when using traditional rigging versus semi-pelagic rigging. Lifting the doors from the seabed decreased the distance between the doors by a few metres on average, which in turn decreased the distance between the wings by about 2.5 m on average. The reduction in wing distance increased the trawl height by about 1 m. The trawling speed generally was slightly higher (0.2 kn) for the semi-pelagic rigging than for the traditional rigging.

Figure 3a shows the results of the catch comparison analysis for American plaice. Because the trawling time and number of hauls collected with traditional rigging and semi-pelagic rigging were equal, the expected value for the summed catch comparison rate was 17.14 / (17.14 + 19.72) = 0.465 (assuming both riggings were fishing with equal efficiency).

The p-value for the model fit was 0.0209 and therefore below the reference value of 0.05. Moreover, the deviance, with a value of 40.1, was far above the degrees of freedom at 24. However, the lack of pattern in the deviations between the catch comparison curve modelled and the experimental rates suggests that the low p-value was due to overdispersion in the data resulting from the experimental method applied (Figure 3a). Therefore, we assume that the model represents the experimental catch comparison results well.

When the average wing distance between the riggings (in addition to the trawling time) is the same, the reference line (equal fishing efficiency for both riggings) in a catch ratio

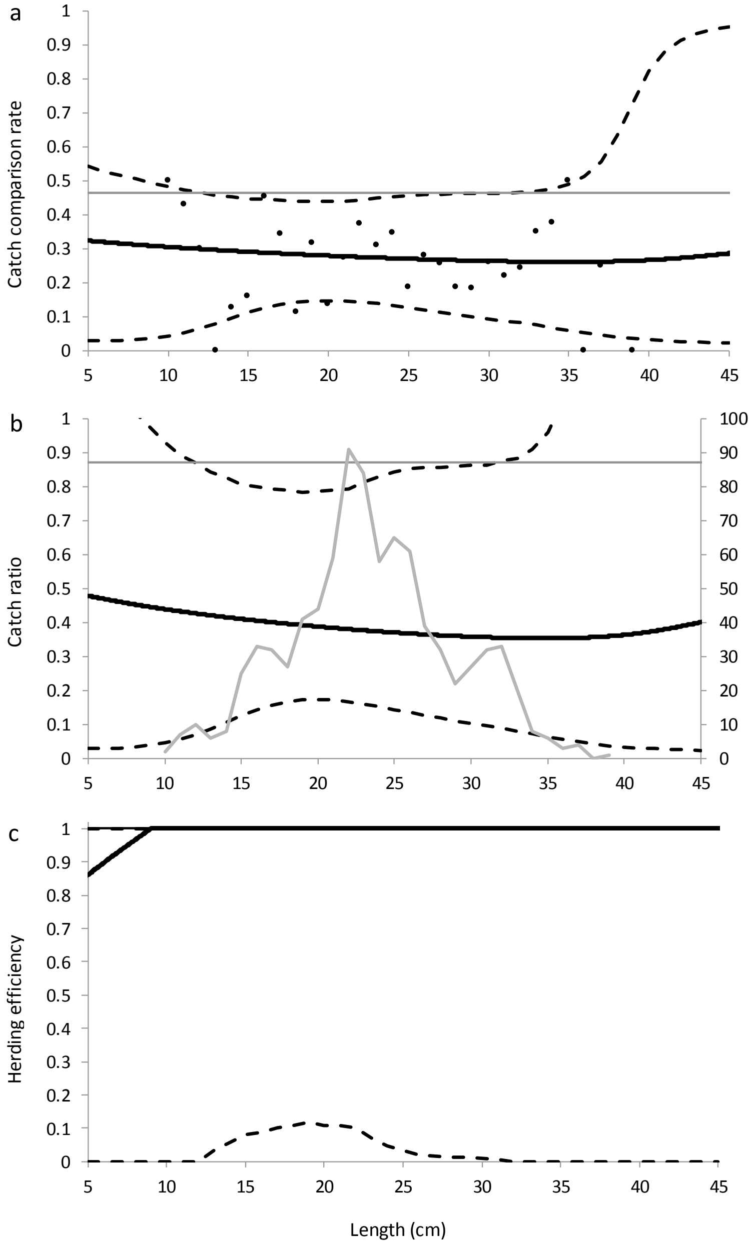


Figure 3: a) Catch comparison curve (black line) and CIs (stippled lines) estimated for American plaice. The horizontal grey line represents the line where traditional rigging and semi-pelagic rigging would be fishing equally. b) Catch ratio curve (black line) and CIs (stippled lines) estimated for American plaice. The horizontal grey line represents the line where traditional rigging and semi-pelagic rigging would be fishing equally. c) Average herding efficiency (black line) and confidence intervals (stippled lines) estimated for American plaice.

analysis is 1. However, the average wing distance differed between the riggings, resulting in a reference line for the catch ratio analysis of 17.14 / 19.72 = 0.869.

The catch comparison and catch ratio results demonstrate that semi-pelagic rigging was less efficient at catching American plaice than traditional rigging. The results indicate that the difference was length dependent, as the difference between riggings increased with increasing fish size. Furthermore, these differences were significant for length classes between 12 and 31 cm (Figure 3a-b). The catch ratio figure (Figure 3b) shows that on average, the semi-pelagic rigging captured 52%–66% fewer American plaice than the traditional rigging, demonstrating a clear effect of using a semi-pelagic rigging on the catch efficiency of this species.

The herding efficiency results show that when using the traditional rigging the sweeps were able to herd 100% of the American plaice between 9 and 40 cm into the catch zone of the gear and that the difference in herding between the two tested riggings was significantly different from 0 for length classes between 12 and 31 cm (i.e., lower confidence intervals [CIs]) (Figure 3c).

The amount of shrimp captured in haul number 5 could not be determined because the sample was lost, so we used shrimp catch data from four hauls with the traditional rigging and three hauls with the semi-pelagic rigging to carry out Welch's t-test for unpaired data. No significant differences in the shrimp catching performance was detected between the traditional rigging and the semi-pelagic rigging ($p = 0.7802$).

DISCUSSION

Although gear selectivity measures such as sorting grids have partially reduced the problem of juvenile by-catch in shrimp trawl fisheries [e.g., Isaksen et al., 1992; He and Balzano, 2012], the excessive by-catch of different juvenile species is still a challenge in the Northeast Atlantic [e.g., Parsons and Foster, 2015]. One of the main problems with separating fish juveniles and shrimp is that they can be very similar in size. One approach is to use behavioural differences (e.g., greater swimming ability of most fish species compared to shrimp) to separate them [Broadhurst, 2000]. However, because most selection processes in trawl fisheries are concentrated in the aft of the gear, where fish juveniles have very little swimming power left, moving the separating process to an earlier part of the gear could make the process more effective.

Lifting the doors and sweeps of trawls from the seabed initially had an environmental purpose, as it reduces fuel consumption and seabed damage [Grimaldo et al., 2015]. However, the results of the present study show that using a semi-pelagic rigging can move the separating process between shrimp and juvenile fish forward in the gear, which effectively reduces juvenile fish by-catch in shrimp trawls. The results of this study agree well with those of He et al. [2015], who reported a significant catch reduction (20% reduction) of American plaice by partially lifting the lower bridle of the gear. However, the differences between the tested riggings were bigger in the present investigation. Lifting the doors and lower bridles from the seabed resulted in an average reduction of 52%-66% of American plaice caught, and this difference was significant for sizes between 12 and 31 cm. Furthermore, the herding efficiency of the gear for practically the whole length span of American plaice measured was 100% with the traditional rigging. The greater difference observed in the present study compared to that of He et al. [2015] is probably related to the complete lifting of the lower bridles from the seabed and the pelagic towing of the trawl doors in the present study.

Several researchers have described the herding potential of approaching ropes/wires on flatfish [Ryer et al., 2010; Winger et al., 2010], which is consistent with the results obtained in this study and the results presented by He et al. [2015] for American plaice and Witch flounder (*Glyptocephalus cynoglossus*). The extent to which herding is as efficient for roundfish as for flatfish is debated in literature [e.g., Winger et al., 2010]. However, studies have shown that herding efficiency for roundfish also is substantially reduced when the sweeps are lifted from the seabed [He et al., 2015; Sistiaga et al., 2015]. He et al. [2015] showed that in addition to the reduction in catches of American plaice, the catches of roundfish species such as the Acadian redfish (*Sebastes fasciatus*) are also significantly reduced (28.0% reduction) when the sweeps are lifted from the seabed. If these results could be achieved for a semi-pelagic rigging such as the one used in the present study, where both the trawl doors and sweeps are completely off the bottom, it would mean that shrimp fisheries would be more environmentally friendly and that fish by-catch would be reduced. In the Northeast Atlantic, where good shrimp grounds can be closed if the proportion of juvenile by-catch reaches certain levels, a level of reduction like that for American plaice reported herein or that obtained by He et al. [2015] for Acadian redfish in the Northwest Atlantic could have important implications for the fishery. Redfish together with cod, haddock, and Greenland halibut are the most problematic by-catch species in the Northeast Atlantic shrimp fisheries [Aldrin et al., 2012], and measures to reduce the catches of these species are crucial for this fishery that is expected to grow in coming years.

Using semi-pelagic rigging created some differences in the geometry and operation of the trawl compared to the traditional rigging (Table 2). The distance between the doors, and consequently the distance between the wings, was lower for the semi-pelagic rigging, which resulted in a higher opening of the trawl. These differences affected the trawl operation, as it had to be towed slightly faster (on average 0.2 kn) when using the semi-pelagic rigging. The differences in door distance resulted in differences in the angle of attack of the sweeps, which is known to affect the herding efficiency of sweeps [Strange, 1984]. However, the American plaice catch differences between the riggings were so profound that they must have been caused by the differences between the traditional and semi-pelagic riggings.

In the present investigation, the comparison of shrimp catch between the two riggings was based on seven hauls, and no significant difference between the riggings was detected. This result closely mirrors that reported by He et al. [2015] and the general view of shrimp having limited swimming capacity, which would imply that the herding efficiency of trawl doors and sweeps would be low compared to their effect on fish. Nevertheless, considering the implications the results of this study could have on the fishery, the potential risk of shrimp loss or differences in the shrimp size distribution captured by lifting the doors and sweeps should be further tested.

Due to time constraints, we could not conduct enough hauls to identify any possible day/night differences in herding between the two riggings, but visual stimuli are important to consider when studying fish herding [Jones et al., 2004; Ryer and Barnett, 2006]. He et al.

[2015] were not able to measure the potential effect of this factor either because the fishery functions only during the day, but Ryer et al. [2010] reported differences in the reduction in the catch of several flatfish species between day and night when using a trawl rigging with elevated sweeps versus a trawl rigging with conventional sweeps. Therefore, the implications of light level for the reduction of by-catch in shrimp fisheries need to be evaluated further. This is especially true for fisheries such as the Northeast Atlantic shrimp fishery, where fishing is conducted in total darkness for long periods of the year.

The results of this study show that, in addition to the known effect of reducing towing drag and seabed impact [Grimaldo et al., 2015], using a semi-pelagic rigging can reduce juvenile fish by-catch in shrimp fisheries. Considering these results for American plaice and recent results obtained in similar shrimp fisheries in other seas, further research in this area is recommended. The results presented herein must be interpreted with caution because they are based on only eight hauls, and only 880 American plaice and 373.2 kg shrimp were caught (Table 1). The low number of American plaice caught leads to uncertainty in the estimated catch ratio curve, which must be considered when drawing conclusions based on the results obtained. The limited number of hauls also makes it difficult to detect potential differences between shrimp catches based on the Welch's t-test. However, for American plaice the uncertainties are reflected in the wide confidence bands around the catch ratio curve, and as long as these are respected the limited number of hauls is to some extent considered. Other studies in the literature that were based on limited numbers of hauls have applied bootstrapping to estimate selectivity [e.g., Brčić et al., 2015; Larsen et al., 2016; Stepputtis et al., 2016; Grimaldo et al., 2017]. However, because of our limited experimental sampling, this study should be treated as preliminary research with promising results. This study should be continued with more extensive data collection with more hauls in order to produce definitive conclusions. A more comprehensive dataset will provide a catch ratio curve with narrower confidence bands and will make the Welch's t-test result more robust.

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REFERENCES

Aldrin, M.; Mortensen, B.; Storvik, G.; Nedreaas, K.; Aglen, A.; and Aanes, S. [2012]. *Improving management decisions by predicting fish by-catch in the Barents Sea shrimp fishery*. ICES Journal of Marine Science, Vol. 69, pp. 64-74.

Brčić, J.; Herrmann, B.; and Sala, A. [2015]. *Selective characteristics of a shark-*

excluding grid device in a Mediterranean trawl. Fishery Research, Vol. 172, pp. 352-360.

Broadhurst, M.K. [2000]. *Modifications to reduce by-catch in prawn trawls: a review and framework for development*. Reviews in Fish Biology and Fisheries, Vol. 10, pp. 27-60.

Burnham, K.P. and Anderson, D.R. [2002]. *Model selection and multimodel inference: a practical information-theoretic approach*. 2nd edition, Springer, New York.

Eayrs, S.; Thorbjornson, T.; Ford, J.; Deese, H.; and Smith, G. [2012]. *Saving fuel to increase profitability and reduce environmental impact in a U.S. ground fish fishery*. 2nd International Symposium on Fishing Vessel Energy Efficiency. Vigo. Spain. May 22-24.

Efron, B. [1982]. *The jackknife, the bootstrap and other resampling plans*. SIAM Monograph No. 38, CBSM-NSF.

Eigaard, O.; Herrmann, B.; and Nielsen, J.R. [2011]. *Influence of grid orientation and time of day on grid sorting in a small-meshed trawl fishery for Norway pout (Trisopterus esmarkii)*. Aquatic Living Resources, Vol. 25, pp. 15-26.

Frandsen, R.P.; Herrmann, B.; Madsen, N.; and Krag, L.A. [2011]. *Development of a codend concept to improve size selectivity of Nephrops (Nephrops norvegicus) in a multi-species fishery*. Fishery Research, Vol. 111, pp. 116-126.

Grimaldo, E.; Pedersen, R.; and Sistiaga, M. [2015]. *Energy consumption of three different trawl configurations used in the Barents Sea demersal trawl fishery*. Fishery Research, Vol. 165, pp. 71-73.

Grimaldo, E.; Sistiaga, M.; Herrmann, B.; Larsen, R.B.; Brinkhof, J.; and Tatone, I. [2017]. *Improving release efficiency of cod (Gadus morhua) and haddock (Melanogrammus aeglefinus) in the Barents Sea demersal trawl fishery by stimulating escape behavior*. Accepted at Canadian Journal of Fisheries and Aquatic Sciences.

He, P. and Balzano, V. [2012]. *The effect of grid spacing on size selectivity of shrimps in a pink shrimp trawl with a dual-grid size-sorting system*. Fishery Research, Vol. 121-122, pp. 81-87.

He, P.; Rillahan, C.; and Balzano, V. [2015]. *Reduced herding of flounders by floating bridles: application in Gulf of Maine Northern shrimp trawls to reduce by-catch*. ICES Journal of Marine Science, Vol. 72, pp. 1514-1524.

Herrmann, B.; Sistiaga, M.; Nielsen, K.N.; and Larsen, R.B. [2012]. *Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic trawl codends*. Journal of Northwest Atlantic Fishery Science, Vol. 44, pp. 1-13.

Herrmann, B.; Sistiaga, M.; Larsen, R.B.; Nielsen, K.N.; and Grimaldo, E. [2013]. *Understanding sorting grid and codend size selectivity of Greenland halibut (Reinhardtius hippoglossoides)*. Fishery Research, Vol. 146, pp. 59-73.

Herrmann, B.; Sistiaga, M.; Rindahl, L.; and Tatone, I. [2017]. *Estimation of the effect of gear design changes on catch efficiency: Methodology and a case study for a Spanish longline fishery targeting hake (Merluccius merluccius)*. Fishery Research, Vol. 185, pp. 153-160.

Isaksen, B.; Valdemarsen, J.W.; Larsen, R.B.; and Karlsen, L. [1992]. *Reduction of fish by-catch in shrimp trawl using a rigid separator grid in the aft belly*. Fishery Research, Vol. 13, pp. 335-352.

Jones, E.; Glass, C.; and Milliken, H. [2004]. *The reaction and behaviour of fish to visual components of fishing gears and the effect on catchability in survey and commercial situations*. ICES WGFTFB Working Group meeting, Gydnia, Poland. April 20-23, pp. 58.

Jones, J.B. [1992]. *Environmental impact of trawling on the seabed: a review*. New Zealand Journal of Marine and Freshwater Research, Vol. 26, pp. 59-67.

Krag, L.A.; Herrmann, B.; and Karlsen, J. [2014]. *Inferring fish escape behaviour in trawls based on catch comparison data: Model development and evaluation based on data from Skagerrak, Denmark*. PLoS ONE 9(2): e88819.

Larsen, R.B.; Herrmann, B.; Sistiaga, M.; Grimaldo, E.; Tatone, I.; and Onandia, I. [2016]. *Size selection of redfish (Sebastes spp.) in a double grid system: quantifying escapement through individual grids and comparison to former grid trials*. Fishery Research, Vol. 183, pp. 385-395.

Norwegian Fisheries Directorate [2017]. J-82-2017. Retrieved from: www.fiskeridir.no/Yrkesfiske/Regelverk-og-reguleringer/J-meldinger/Gjeldende-J-meldinger/-82-2017 (In Norwegian).

Parsons, G.R. and Foster, D.G. [2015]. *Reducing by-catch in the United States Gulf of Mexico shrimp trawl fishery with an emphasis on red snapper by-catch reduction*. Fishery Research, Vol. 167, pp. 210-215.

Ryer, C.H. and Barnett, L.A.K. [2006]. *Influence of illumination and temperature upon flatfish reactivity and herding behavior: potential implications for trawl capture efficiency*. Fishery Research, Vol. 81, pp. 242-250.

Ryer, C.H. [2008]. *A review of flatfish behavior relative to trawls*. Fishery Research, Vol. 90, pp. 138-146.

Ryer, C.H.; Rose, C.S.; and Iseri, P.J. [2010]. *Flatfish herding behavior in response to trawl sweeps: a comparison of diel responses to conventional sweeps and elevated sweeps*. NOAA Fishery Bulletin 108, pp. 145-154.

Schau, E.M.; Ellingsen, H.; Endal, A.; and Aanondsen, S.A. [2009]. *Energy consumption in the Norwegian fisheries*. Journal of Cleaner Production, Vol. 17, pp. 325-334.

Sistiaga, M.; Herrmann, B.; Grimaldo, E.; and Larsen, R.B. [2010]. *Assessment of dual selection in grid based selectivity systems.* Fishery Research, Vol. 105, pp. 187-199.

Sistiaga, M.; Herrmann, B.; Grimaldo, E.; Larsen, R.B.; and Tatone I. [2015]. *Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (Gadus morhua) trawl fishery*. Fishery Research, Vol. 167, pp. 164-173.

Stepputtis, D.; Santos, J.; Herrmann, B.; and Mieske, B. [2016]. *Broadening the horizon of size selectivity in trawl gears*. Fishery Research, Vol. 184, pp. 18-25.

Strange, E.S. [1984]. *Review of the fishing trials with Granton and Saro deep sea trawl gear 1963-1967*. Scottish Fisheries Working Paper 8/84.

Wardle, C.S. [1983]. *Fish reactions to towed fishing gears*. In: Mac-Donald, A. and Priede, I.G. (Eds.), Experimental Biology at Sea. Academic Press, New York, pp. 167-195.

Welch, B.L. [1947]. *The generalization of "Student's" problem when several different population variances are involved.*

Biometrika, Vol. 34, pp. 28-35.

Wileman, D.; Ferro, R.S.T.; Fonteyne, R.; and Millar, R.B. (Eds.). [1996]. *Manual of methods of measuring the selectivity of towed fishing gears*. ICES Cooperative Research report No. 215.

Winger, P.D.; Eayrs, S.; and Glass, C.W. [2010]. *Fish behaviour near bottom trawls*. In: Behaviour of Marine Fishes: Capture Processes and Conservation Challenges (He, P., ed.), Wiley–Blackwell, Ames, IA, pp. 67-103.