The efficiency of sieve-panels for bycatch separation in *Nephrops* trawls

Juan Santos[a]*[1], Bent Herrmann[b, c]*, Bernd Mieske[a], Ludvig A. Krag[d], Stefanie Haase[e], Daniel Stepputtis[a]

a: Thünen Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany
b: SINTEF Fisheries and Aquaculture, Fishing Gear Technology, Willemoesvej 2, 9850 Hirtshals, Denmark
c: Norwegian College of Fishery and Aquatic Science, University of Tromsø, 9037 Breivika, Tromsø, Norway
d: DTU Aqua, National Institute of Aquatic Resources, North Sea Science Park, DK-9850 Hirtshals, Denmark
e: Institute for Hydrobiology and Fisheries Sciences, Grosse Elbstrasse 143, 22767 Hamburg, Germany

*Equal authorship
[1]Corresponding author. Tel.: +49 (0) 381 - 8116 122

Email address: ***juan.santos@thuenen.de***

Abstract

This study investigates the efficiency of a sieve-panel concept, intended to separate bycatch species from *Nephrops* (Norway lobster) in a trawl gear via mechanical and behavioral means. Four different designs of varying panel mesh size or inclination were tested in experimental fishing. For each design, we estimated the length-dependent sieving efficiency, defined as the fraction of *Nephrops* or fish passing through the panel to the lower codend. The sieving efficiency for *Nephrops* increased from ~17% to ~71% as mesh size increased, and it decreased with increasing carapace length, but did so less as panel inclination and mesh size increased. The sieving efficiency for roundfish was low, as intended, while the efficiency for flatfish decreased with fish size. Although results are promising, the sieving efficiency for the largest, most valuable *Nephrops* remained too low. Therefore, further improvements are necessary before the concept is acceptable to the commercial fishing fleet.

Keywords: *Nephrops*, bycatch, trawl, sieve-panel, efficiency, Landing Obligation

1. Introduction

Nephrops (*Nephrops norvegicus*) directed fisheries are among the economically most important fisheries in European waters (Ungfors et al., 2013). Although some creel fisheries target *Nephrops* (Adey, 2007), 95% of total European landings are taken by demersal trawlers (Briggs, 2010; Ungfors et al., 2013). Catching *Nephrops* efficiently with trawls requires using relatively small mesh codends (Krag et al., 2008; Frandsen et al., 2010), which can lead to large bycatches of small fish co-habiting the fishing grounds (Alverson et al., 1994; Catchpole and Revill, 2008; Catchpole et al., 2007; Kelleher, 2005; Krag et al., 2008).

The problem of unwanted bycatch in *Nephrops* fisheries has been addressed mainly by attempting to provide additional escapement possibilities for fish species before they enter the codend (Catchpole and Revill, 2008). Although different in concept and purpose, all current devices are designed to reduce bycatch by selecting fish out of the catch. Probably the most used bycatch reduction devices (BRDs) are the Swedish grid (Valentinsson and Ulmestrand, 2008) for monospecific *Nephrops* fisheries, and square mesh panels (SMPs) for mixed fisheries (Armstrong et al., 1998; Briggs, 1992). Although it has been demonstrated that using these BRDs can significantly reduce bycatch rates, to date none of them have delivered an efficient size selectivity for the target and bycatch species simultaneously. Depending on the population structure fished, this can lead to a considerable number of bycaught small fish (Frandsen et al., 2009; Lövgren et al., 2016; Nikolic et al., 2015; Valentinsson and Ulmestrand, 2008), or losses of marketable *Nephrops* (Catchpole et al., 2006; Frandsen et al., 2009).

Achieving an efficient size selection for both the target and bycatch species is an increasingly important requirement in the wake of the Common Fisheries Policy (CFP) reform (EU 2013), implemented in *Nephrops* fisheries since 2016. The reform adopted the Landing Obligation (LO) for listed species, which forces fishers to land all catches of those species and count them against their quota. Under such a scenario, a large bycatch of fish species with limited quota can alter the fishing strategy or even force fishers to stop fishing completely, without exhausting the quota of *Nephrops*. Improving species and size selectivity is required now more than ever to secure both the biological and economical sustainability of *Nephrops*-directed fisheries.

This study presents an alternative concept for reducing fish bycatch in these fisheries. Our concept shares similarities with the sieve nets used in shrimp trawl fisheries, such as the brown shrimp fishery in the North Sea (Revill and Holst; 2004), and it is based on the assumptions that *Nephrops* has limited swimming activity and tends to roll over the floor of the trawl body (Briggs and Robertson, 1993; Main and Sangster, 1985), whereas fish tend to swim actively to stay clear of the surrounding net (Glass and Wardle, 1995). It consists of a 10-m-long square mesh sieve-panel, mounted in the extension piece of the trawl with a continuous upward inclination towards an upper and lower codend. The fore edge of the sieve-panel is attached to the floor of the gear, ensuring that all *Nephrops* and fish will enter on the upper side of the panel connected to the upper codend. Assuming that the behavioral differences between *Nephrops* and the fish species listed above can be utilized, the panel will sieve *Nephrops* towards the lower codend, and fish will be guided towards the upper codend. The mesh size used in the sieve- panel and its inclination should be sufficiently large to sieve all sizes of *Nephrops* towards the lower codend, without losing the ability to guide fish to the upper codend.

The aim of the study is to investigate and quantify the ability of different sieve-panel designs to separate *Nephrops* from different roundfish and flatfish species during the catching process.

2. Material and Methods

2.1 Sieve-panel designs and test gear

The 10-m-long sieve-panel was mounted in the four-panel extension piece of the trawl (Figure 1). The fore edge of the sieve-panel was attached at the front of the extension’s lower panel, and the sides were connected to the lateral panels with a cutting rate of 6N2B. This construction provides a monotonous upward–backward inclination of ~2.5°, and splits the aft of the trawl into two horizontal compartments, ending in the lower and upper codend (Figure 1).

Four different panel designs were tested during experimental fishing. All designs used square mesh netting (Figure 1). Design 1 was made of knotless PA netting with 45.2 mm measured bar length and 2.5 mm nominal twine thickness. Design 2 used knotless PE netting with 60.9 mm bar length and 5 mm twine thickness. Design 4 was constructed similarly to Designs 1 and 2, but used PE standard netting, with 94.3 mm mesh bar length and 3 mm twine thickness. Design 3 used the same sieve-panel as Design 2, but the monotonous inclination was altered by inserting six floating lines, arranged in two groups of three and attached at two different positions on the panel's lower side. The configuration was intended to create a hilly surface to increase the inclination of the panel (Figure 1). For a sieve-panel to perform well, sieving efficiency should be high for all sizes of *Nephrops* and low for all sizes of the bycatch species.

During experimental fishing, the sieve-panels were mounted one at a time for a group of hauls in the same extension piece, which was 11.5 m long, made of PE single netting with 1.8 mm twine thickness. The stretched mesh size obtained with the omega gauge (Fonteyne et al., 2007) was 47.9 mm (Figure 1). The codends were 6 m long and made of PA netting with ~1.2 mm twine thickness. The stretched mesh sizes of the codends were 48.4 mm and 49.6 mm for the upper and lower codends, respectively. The codend mesh sizes applied were considered sufficiently small to retain all *Nephrops* available in the targeted population. The extension piece and the double codend system were connected to a demersal trawl model Spaeghugger, spread by two Thyborön doors Type 2 (1.78 m^2).

2.3 Sea trials and data collection

The four sieve-panels were tested September 12–24, 2015, on Danish *Nephrops* fishing grounds in the Skagerrak (ICES Division IIIa), using the German research vessel "Solea" (42 m, 1780 kW). Catches obtained at haul level were sampled by species and for each codend separately.

Catch weight was collected using electronic scales. The *Nephrops* carapace length (CL) was measured to the nearest 0.5 mm using digital calipers. Total length (TL) was measured to nearest 0.5 cm for the fish bycatch species using electronic measuring boards. Subsampling was avoided in most of the experimental hauls. When subsampling occurred, the subsampling factor was calculated by dividing the subsampling weight by the total catch weight.

Underwater video recordings were collected during the experimental hauls to qualitatively assess the shape of the sieve panel and how different species interacted with it. The cameras used were GoPro model Hero 3+, mounted in deep-water housing, model GoBenthic2. The camera system was supplemented with flood-beam artificial light (1400 lumens).

2.4 Data analysis

The sieving efficiency was quantified separately for each of the sieve-panels and each species as described below.

With nlc_{il} as the number of individuals of length l (CL or TL) caught in the lower codend during Haul i, and nuc_{il} as the number of length l caught in the upper codend, the proportion of the total catch observed in the lower codend,

$$S_{il} = \frac{nlc_{il}}{nlc_{il} + nuc_{il}}, \qquad (1)$$

can be interpreted as the experimental sieving efficiency of the sieve-panel for individuals with length l. S_{il} can only take values in the range 0.0–1.0. Values of S_{il} close to 1.0 would mean that most individuals with length l were sieved and finally retained in the lower codend. On the other hand, S_{il} values close to 0.0 would mean low sieving efficiency, either because individuals of length class l were not physically able to pass through the meshes, or because the sieve-panel guided them towards the upper codend.

The sieving efficiency might be influenced by the size selection of the square meshes and by species behavior when interacting with the sieve-panel, which at the same time might be length dependent. Therefore, length-dependent sieving efficiency is modelled by applying a highly flexible function $S(l,\mathbf{q})$:

$$S(l,q) = \frac{\exp\left(f\left(l,q_0,\ldots,q_j\right)\right)}{1+\exp\left(f\left(l,q_0,\ldots,q_j\right)\right)}, \qquad (2)$$

where f is a polynomial of order j, with coefficients q_0 to q_j, which provide great flexibility to the functional form of the resulting sieve efficiency curve. The estimation of the values of the parameters $\mathbf{q} = (q_0,\ldots,q_j)$, which make the observed experimental data averaged over hauls most likely, was carried out by minimizing the negative log likelihood function for the binomial data:

$$\log L_{model} = -\sum_{l}\sum_{i}\left\{nlc_{il} \times \ln\left(S(l,q)\right) + nuc_{il} \times \ln\left(1.0 - S(l,q)\right)\right\}, \qquad (3)$$

where the summations are for group of hauls i with the specific sieve-panel design and length classes l. In Equation 2, we considered f as a polynomial up to the order 4 with parameters q_0, q_1, q_2, q_3, and q_4. Leaving out one or more of the parameters q_0–q_4 led to 31 additional simpler models that were also considered potential candidates for the sieve efficiency curves $S(l,\mathbf{q})$, and therefore they were also estimated using Equation 3. Selection of the best model for $S(l,\boldsymbol{q})$ among the 32 competing models was based on a comparison of their respective Akaike information criterion (AIC) values (Akaike, 1974). The model with the lowest AIC value was selected to describe the experimental sieving efficiency.

The model's ability to describe the data was evaluated based on an inspection of the fit statistics, i.e. the *p*-value and the model deviance vs. the degrees of freedom (df), following the procedures described by Wileman et al. (1996). The *p*-value expresses the likelihood of obtaining a discrepancy at least as large as between the fitted model and the observed experimental data by coincidence. In case of poor fit statistics (*p*-value <0.05; deviance >>df), we examined if the poor result was caused by structural problems when describing the experimental data using the model, or if it was the result of overdispersion in the data (Wileman et al., 1996).

The 95% confidence intervals (CI) for the averaged sieve efficiency curve $S(l,\boldsymbol{q})$ were estimated using a double bootstrap method with 1000 replications. This approach, which avoided underestimating confidence limits when averaging over hauls, is identical with the one described in Sistiaga et al. (2010). Traditionally, the CIs are estimated without accounting for potentially increased uncertainty resulting from uncertainty in the selection of the model used to describe the curve (Katsanevakis, 2006). Following the same method used by Krag et al. (2015), we accounted for this additional uncertainty, by incorporating an automatic model selection based on which of the 32 models produced the lowest AIC for each of the bootstrap iterations.

In addition to the assessment of the uncertainty of the individual averaged sieve curves, the bootstrap CIs were used to compare *Nephrops* sieving efficiencies obtained for the different sieve-panel designs. Such assessments were carried out as pairwise comparisons, and the differences within pairs were considered statistically significant only in the range of individual lengths, where the compared CIs did not overlap. The analysis of sieve-panel efficiency was carried out using the software tool SELNET (Herrmann et al., 2012).

3. Results

3.1. Description of experimental hauls and catches

The experimental hauls were conducted in Danish fishing grounds within 57°–58°N and 009–010°E (Figure S1 in supporting material) at fishing depths between 54 and 136 m (Table 1). Haul duration ranged from 28 to 118 minutes. In all, 13, 10, 7, and 11 valid hauls were conducted using Designs 1, 2, 3, and 4, respectively, a total of 41 experimental hauls. A total of 108 *Nephrops* were caught and measured with Design 1, a very small number compared with the 2155, 3669, and 1627 individuals measured in Designs 2–4 (Table 1). Two roundfish and two flatfish species were caught in sufficient numbers to warrant investigating the sieving efficiencies on the fish species: American plaice (*Hippoglossoides platessoides,* 45363 fish measured), blue whiting (*Micromesistius poutassou,* 13677 fish measured), cod (*Gadus morhua,* 7804 fish measured), and witch flounder (*Glyptocephalus cynoglossus,* 5471 fish measured; Table 1).

Of the *Nephrops* caught in the hauls with Design 1, 17% were collected in the lower codend, increasing to 71% with Design 4 (Table 1). On the contrary, less than 10% of the cod, blue whiting, and witch flounder caught were observed in the lower codend. Larger numbers of American plaice were observed in the lower codend than the other fish species, increasing from

12% with Design 1 to 50% with Design 4.

A short haul in shallow and clear waters was conducted to collect video recordings showing the shape and mechanical behavior of the extension piece with the sieve-panel mounted. video recordings were collected during seven of the experimental hauls (Table 1), for a total of 561 minutes. Exploratory analysis of catch data indicated no clear influence of the camera system on sieve panel performance; therefore, these hauls were used in the quantitative analysis.

3.2. Assessment of the length-dependent sieving efficiency

The sieving efficiency of each of the sieve-panel designs was successfully obtained using the model described in Equation 2. *P*-values >0.05 were obtained in all cases, except for *Nephrops* in Design 4, confirming the model's ability to describe the length-dependent sieving efficiency in the experimental data (Table 2). The low *p*-value obtained for *Nephrops* Design 4 could indicate the model's inability to describe the experimental data. However, inspection of the deviations between the observed and modelled sieving efficiency did not reveal any clear pattern (Figure 2). Therefore, we concluded that, in this case, the low *p*-value was caused by overdispersion in the experimental data; therefore, we were confident in applying the model to describe the sieving efficiency curve for *Nephrops* in Design 4 as well.

The model for *Nephrops* predicted a sieving curve with values of less than 40% for Design 1, decreasing in efficiency as carapace length increased (Figure 2). Larger percentages of *Nephrops* catches were sieved using Designs 2–4, but many of the large individuals were still found in the upper codend. The larger mesh size applied in Design 2 improved the sieving efficiency of Design 1 significantly, estimated as being greater than 86% for CL ≤30 mm, but decreasing drastically as CL increased. Increasing the inclination with the float lines applied in Design 3 reduced the monotonic decreasing trend in the sieving efficiency curve from Design 2, thereby reducing the loss in sieving efficiency for the largest sizes. Finally, Design 4 clearly reduced the negative trend observed in the previous designs, and the average sieving efficiency was not lower than 45% throughout the experimental CL classes (Figure 2).

The increased mesh sizes from Design 1 to Design 2 resulted in an overall and significant improvement in sieving efficiency, except for CL, which was larger than ~60 mm. Design 3's sieving values were higher on average than Design 2's, but the improvement was not statistically significant over the available CL range. Design 4 improved the sieving efficiency of Designs 2 and 3 on CL ~50 mm significantly and the efficiency of Design 2 on CL greater than 60 mm (Figure 2).

For the bycatch species, less than 1% of cod (18 fish) were caught in the lower codend using Design 1. A larger number of individuals (4.3%) were sieved in Design 2, mostly in the range of 20–40 cm TL. Designs 3 and 4 increased the probability of small cod being sieved towards the lower codend. Nevertheless, the averaged sieve curve from Design 4 remains below 20% for most of the TL classes available (Figure 3).

Negligible catches (3%) of blue whiting were observed in the lower codend over the different designs. Only the steeper inclination of the panel in Design 3 resulted in an increased sieving efficiency for TL less than 30 cm, however still less than 20% (Figure 3).

A considerable number of American plaice were observed in the lower codend and, as with *Nephrops*, the sieving efficiency was strongly and negatively related to fish length. Similar curves were obtained for Designs 1–3. Sieving efficiency was increased over the whole length range by Design 4 (Figure 4).

Sieve efficiency was lower and less dependent on fish length for witch flounder than for American plaice. Consistent with results from the previous flatfish species, Design 4 raised the sieving efficiency obtained by the other three designs considerably (Figure 4).

3.3. Underwater video recordings

The images collected confirmed that the shape of the sieve-panels were as intended. The sieve-panel had a slight U-shape resulting from the drag of the water flow during towing (Figure S2 in supporting material).

The sediments suspended in the water column made it difficult to collect quality video sequences, and only a few of them revealed *Nephrops* interacting with the sieve-panels. Contrary to expectations, most observations of *Nephrops* passing through the sieve-panel meshes occurred through individuals' active behavior. One observation involved a first swimming phase, where the individual contacted an open mesh tail-first (Figure S3, A.1 in supporting material). After penetrating the mesh tail-first, the individual pushed the body downwards attempting to burrow below the sieve-panel (Figure S3, A.2 in supporting material). At this stage, the individual stayed with the claws upwards above the panel surface, and most of the body below it (Figure S3, A.3 in supporting material), before pushing downwards again to pass the mesh completely and fall into the lower compartment (Figure S3, A.4 in supporting material). On the contrary, other individuals actively avoided being sieved by lying on the bar meshes (Figure S3, B in supporting material), holding the mesh twines with the chelipeds, both in the natural or reverse body orientation (Figure S3, C-E in supporting material), or simply by walking over the panel. In the last case, some specimens were observed walking over the panel until they lost their balance and finally drifted with the water flow towards the upper codend.

Most fish observed in the recordings followed the bottom–up inclination of the sieve-panel without attempting to pass through the meshes. Few active passages of cod were observed during the haul-back process, when cod attempted to swim downwards to balance the decrease in hydrostatic pressure caused by the loss of depth.

4. Discussion

The progressive improvement in *Nephrops* sieving efficiency from Design 1 to Design 4 was related to increments in the mesh size applied to the different panels. Although Design 2 clearly improved on the performance of Design 1, the strong and negative length dependence in the efficiency of this design makes it unfeasible for commercial adoption. Further increasing the mesh size in Design 4 reduced the length dependence of the average sieve curve, but even with such improvement, only 45% of the *Nephrops* larger than 55 mm CL were found in the lower codend. Although Design 3 did not improve significantly on the efficiency of Design 2, the form of the predicted curve indicates that increasing the inclination of the panel might benefit the sieving efficiency..

Contrary to the original design assumptions, many sieving events observed in the underwater video recordings occurred when individuals actively positioned the body in an optimal orientation towards the open meshes (Figure S3, A1–A4 in supporting material), whereas other active interactions counteracted the sieving process (Figure S3, B–E in supporting material). Based on the quantitative results and observation of the video recordings, we speculate that, in addition to the passive process assumed in the design of the device, the sieving of *Nephrops* might also be influenced by avoidance behavior, which could be stronger in large individuals. Investigations conducted in tank aquariums demonstrated length-dependent avoidance behavior only for male *Nephrops* (Newland et al., 1998). In particular, it was observed that larger males reacted to tactile stimulus by producing fewer swimming bouts with more tail-flips per bout than smaller individuals. Assuming that these findings can be extrapolated to the fishing grounds, we speculate that avoidance behavior expected for large individuals could reduce the number of times they contact the surface of the sieve panel compared to smaller individuals, reducing therefore the sieving occurrences. Since the relationship between swimming performance and individual length was found sex-dependent, *Nephrops* sex ratios in both the lower and upper codend could be used as indicators to clarify if the behavioral observations in Newland *et al.* (1998) could explain the length-dependent efficiency of the gear.

The sieving efficiency of cod was estimated at less than 20% for all reference lengths considered (Table 3). In particular, the efficiency of TL = 34 cm was 13%, meaning that 87% were directed towards the upper codend. It was assumed that using *Nephrops*-selective netting in the lower codend would provide some escapement possibilities for small fish, thus lowering even further the catch probability of undersized cod. The combination of a sieve-panel and selective codends would therefore significantly improve the cod bycatch rates in trawls mounting the Swedish grid, estimated at ~30% for lengths ~34 cm (Lövgren et al., 2016).

The sieve-panel performed differently on roundfish and flatfish. The greater and strongly length-dependent sieving efficiency observed for flatfish species is a consequence of their natural behavior, tending to swim in close contact with the floor of the net (Ryer, 2008), and therefore increasing the probability of being mechanically sieved to the lower codend.

Although the sieve-panel concept tested here is a promising tool for improving the exploitation patterns in *Nephrops* fisheries, further improvements are necessary before the concept will be acceptable to commercial fishing fleets. The results of the present study provide further development opportunities of the concept in three different dimensions. First, a steeper inclination of the sieve-panel could improve the sieving efficiency for *Nephrops*. We speculate that this alteration in the original design might reduce the longitudinal transportation of Nephrops over the panel, enhancing the possibility of being sieved through the meshes. On the downside, a steeper angle might reduce the guiding effect, leading to larger fractions of fish passing through the panel into the lower codend. Alternative mounting angles to be considered for future designs should be between 30° and 45°, a range used for other devices applied in *Nephrops* fisheries such as the Swedish grid (Valentinsson and Ulmestrand, 2008), or separator panels (Rihan and McDonnell, 2003). Increasing the mesh size used in Design 4 could facilitate the sieving efficiency for *Nephrops,* whereas changing the mesh geometry to a rectangular shape with the longitudinal opening oriented in the towing direction might reduce the sieving efficiency for flatfish, because of the species' flat body shape. Finally, using thicker twine in the panel construction might limit the *Nephrops'* ability to hold the twines and avoid being sieved.

Efficient separation of *Nephrops* and fish species might substantially reduce the unwanted bycatch in European *Nephrops*-directed fisheries. By securing the *Nephrops* catch in a lower codend, fishers could mount an upper codend with a larger mesh size to catch larger fish. Under fish quota exhaustion, catches of fish might be avoided by opening the upper codend during towing. In addition to a better utilization of available quotas, other benefits can be expected by dividing the species efficiently into separate codends: A proper separation would improve the quality of marketable fish catches, as they are not subjected to damages in the skin and internal tissues caused by the contact with the spiny appendixes of *Nephrops* (Karlsen et al., 2015; Galbraith and Main, 1989). Exemptions to the Landing Obligation are contemplated in the European legislation for species with scientific evidences of high survival rates after catch and release. Most recent studies on *Nephrops* reported survival rates in the range of ~20-60% (Méhault et al., 2016; Castro et al., 2003), therefore *Nephrops* could be one of these exemptions under evidences of improved survival rates. Achieving “clean” *Nephrops* catches would drastically reduce the overall catch volume in the lower codend, sorting time on deck and air exposure, improving survival probability (Méhault et al., 2016; Harris and Andrews, 2005; Castro et al., 2003).

Further investigations combining quantitative analysis of *Nephrops* behavioral patterns with sieve-panels having different inclinations, mesh geometries, and twine thickness are planned. Such future investigations could provide a better understanding of how mechanical and behavioral size selection contributes to the observed sieving efficiency for *Nephrops*. This information is required to create design guides for more efficient *Nephrops* sieve-panels to achieve clean *Nephrops* catches in the lower codend, while ensuring minimal or no losses of marketable individuals, so providing the industry with new technological alternatives to dealing with the landing obligation enforced by the new European Fishing Policy.

References

Adey, J.M. (2007). Aspects of the sustainability of creel fishing for Norway lobster, *Nephrops norvegicus* (L.), on the west coast of Scotland. Doctoral dissertation, University of Glasgow.

Alverson, D.L., Freeberg, M.H., Murawaski, S.A., & Pope, J.C. (1994). A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper No. 339, Rome, FAO.

Akaike, H. (1974). A new look at the statistical model identification. IEEE Trans. Auto. Control, **19**, 716–723. 10.1109/tac.1974.110

Armstrong, M. J., Briggs, R. P., & Rihan, D. (1998). A study of optimum positioning of square-mesh escape panels in Irish Sea *Nephrops* trawls. *Fisheries Research*, **34**, 179–189. http://doi.org/10.1016/S0165-7836(97)00078-7

Briggs, R. P. (2010). A novel escape panel for trawl nets used in the Irish Sea *Nephrops* fishery. *Fisheries Research*, **105**, 118–124. http://doi.org/10.1016/j.fishres.2010.03.012

Briggs, R. P., & Robertson, J. H. B. (1993). Square mesh panel studies in the Irish Sea *Nephrops* fishery. ICES C.M. 1993/B20. (pp. 1–10).

Briggs, R. (1992). An assessment of nets with a square mesh panel as a whiting conservation tool in the Irish Sea *Nephrops* fishery. *Fisheries Research*, **13**, 133–152. https://doi.org/10.1016/0165-7836(92)90023-M

Castro, M., Araújo, A., Monteiro, P., Madeira, A. M., & Silvert, W. (2003). The efficacy of releasing caught *Nephrops* as a management measure. *Fisheries Research*, *65*(1-3), 475-484.

Catchpole, T. L., & Revill, A. S. (2008). Gear technology in Nephrops trawl fisheries. *Reviews in Fish Biology and Fisheries*, **18**, 17-31. doi:10.1007/s11160-007-9061-y.

Catchpole, T. L., Tidd, A. N., Kell, L. T., Revill, A. S., & Dunlin, G. (2007). The potential for new *Nephrops* trawl designs to positively effect North Sea stocks of cod, haddock and whiting. *Fisheries Research*, **86**, 262–267.

Catchpole, T. L., Revill, A. S., & Dunlin, G. (2006). An assessment of the Swedish grid and square-mesh codend in the English (Farn Deeps) *Nephrops* fishery. *Fisheries Research*, **81**, 118–125.

EU 2013. Regulation No. 1380/2013 of The European Parliament And Of The Council of 11 December 2013, On The Common Fisheries Policy, Official Journal of the European Union L 354/22.

Fonteyne, R., Buglioni, G., Leonori, I., & O'Neill, F. G. (2007). Review of mesh measurement methodologies. *Fisheries Research*, **85**, 279–284. http://doi.org/10.1016/j.fishres.2007.02.012

Frandsen, R., Herrmann, B., & Madsen, N. (2010). A simulation-based attempt to quantify the morphological component of size selectivity of *Nephrops norvegicus* in trawl codends. *Fisheries Research*, **101,** 156–167. http://doi.org/10.1016/j.fishres.2009.09.017

Frandsen, R. P., Holst, R., & Madsen, N. (2009). Evaluation of three levels of selective devices relevant to management of the Danish Kattegat–Skagerrak *Nephrops* fishery. *Fisheries Research*, **97**, 243–252. http://doi.org/10.1016/j.fishres.2009.02.010

Galbraith, R.D., & Main, J. (1989). Separator panels for dual purpose fish/prawn trawls. Scottish Fisheries Information Pamphlet Number 16.

Glass, C. W., & Wardle, C. S. (1995). Studies on the use of visual stimuli to control fish escape from codends. II. The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends. *Fisheries Research*, **23,** 165–174. https://doi.org/10.1016/0165-7836(94)00331-P

Harris, R. R., & Andrews, M. B. (2005). Physiological changes in the Norway lobster Nephrops norvegicus (L.) escaping and discarded from commercial trawls on the West Coast of Scotland: II. Disturbances in haemolymph respiratory gases, tissue metabolites and swimming performance after capture and during recovery. *Journal of Experimental Marine Biology and Ecology*, **320** (2), 195-210.

Herrmann, B., Sistiaga, M. B., Nielsen, K. N., Larsen, R. B. (2012). Understanding the size selectivity of redfish (*Sebastes spp.*) in North Atlantic trawl codends. *Journal of Northwest Atlantic Fishery Science*, **44**, 1–13. doi:10.2960/J.v44.m680

Karlsen J.D., Krag L.A., Albertsen C.M. & Frandsen R.P. (2015). From Fishing to Fish Processing: Separation of Fish from Crustaceans in the Norway Lobster-Directed Multispecies Trawl Fishery Improves Seafood Quality. *PLoS ONE,* **10** (11), e0140864. http://doi:10.1371/journal.pone.0140864

Katsanevakis, S. (2006). Modelling fish growth: model selection, multi-model inference and model selection uncertainty. *Fisheries Research*, **81**, 229–235.

http://doi.org/10.1016/j.fishres.2006.07.002

Kelleher, K. (2005). Discards in the world's marine fisheries: an update. FAO Fisheries Technical Paper No. 470, Rome, FAO.

Krag, L. A., Herrmann, B., Karlsen, J. D., & Mieske, B. (2015). Species selectivity in different sized topless trawl designs: Does size matter?. *Fisheries Research*, **172**, 243–249. http://doi.org/10.1016/j.fishres.2015.07.010

Krag, L. A., Frandsen, R. P., & Madsen, N. (2008). Evaluation of a simple means to reduce discard in the Kattegat–Skagerrak Nephrops (*Nephrops norvegicus*) fishery: Commercial testing of different codends and square-mesh panels. *Fisheries Research*, **91**, 175–186. http://doi.org/10.1016/j.fishres.2007.11.022

Lövgren, J., Herrmann, B., & Feekings, J. (2016). Bell-shaped size selection in a bottom trawl: A case study for *Nephrops* directed fishery with reduced catches of cod. *Fisheries Research*, **184**, 26–35. http://doi.org/10.1016/j.fishres.2016.03.019

Main, J. & Sangster, G. I. (1985). Trawling experiments with a two-level net to minimise the undersized gadoid by-catch in a *Nephrops* fishery. *Fisheries Research*, **3**, 131–145.

https://doi.org/10.1016/0165-7836(85)90014-1

Méhault, S., Morandeau, F., & Kopp, D. (2016). Survival of discarded *Nephrops norvegicus* after trawling in the Bay of Biscay. *Fisheries Research*, **183**, 396-400.

Nikolic, N., Diméet, J., Fifas, S., Salaün, M., Ravard, D., Fauconnet, L., & Rochet, M-J. (2015). Efficacy of selective devices in reducing discards in the *Nephrops* trawl fishery in the Bay of Biscay. *ICES Journal of Marine Science*, **72**, 1869–1881. https://doi.org/10.1093/icesjms/fsv036

Revill, A. & Holst, R. (2004). The selective properties of some sieve nets. *Fisheries Research*, **66**, 171–183. http://doi.org/10.1016/S0165-7836(03)00198-X

Rihan, D.J. & McDonnell, J. (2003). Protecting spawning cod in the Irish Sea through the use of inclined separator panels in *Nephrops* trawls, ICES CM2003/Z:02

Ryer, C. H. (2008). A review of flatfish behavior relative to trawls. *Fisheries Research*, **90**, 138–146. http://doi.org/10.1016/j.fishres.2007.10.005

Sistiaga, M., Herrmann, B., Grimaldo, E., & Larsen, R. B. (2010). Assessment of dual selection in grid based selectivity systems. *Fisheries Research*, **105**, 187–199. http://doi.org/10.1016/j.fishres.2010.05.006

Ungfors, A., Bell, E., Johnson, M. L., Cowing, D., Dobson, N. C., Bublitz, R., & Sandell, J. (2013). *Nephrops* fisheries in European waters. Advances in Marine Biology, the ecology and biology of *Nephrops norvegicus (pp. 247–306)*. UK: Elsevier.

Valentinsson, D. & Ulmestrand, M. (2008). Species-selective *Nephrops* trawling: Swedish grid experiments. *Fisheries Research*, **90**, 109–117. http://doi.org/10.1016/j.fishres.2007.10.011

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., & Millar, R. B. (1996). Manual of methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. No. 215.

Table 1. Summary of hauls conducted with the different *Nephrops* sieve-panel designs, including the average towing duration (standard deviation in round brackets), and the number of individual length-measurements obtained from each of the analyzed species and sampling compartments. Subsampling rates are presented in square brackets for those cases where not all fish were measured.

			Nephrops		Cod		Blue whiting		American plaice		Witch flounder	
Design	Number hauls	Duration (minutes)	Lower codend	Upper codend	Lower codend	Upper codend	Lower codend	Upper codend	Lower codend	Upper codend	Lower codend	Upper codend
1	13	54.5 (31.0)	19	89	18	2082	33	2530	1609	6246 [0.973]	0	1085
2	10	100 (29.0)	1349	806	76	1693	24	3863 [0.700]	2561	6799 [0.885]	12	1034
3	7	100.9 (16.0)	2537	1132	31	563 [0.998]	376	3606	2570	7110	14	898
4	11	96.4 (13.9)	1156	471	106	1135	18	664 [0.730]	5393	5220 [0.856]	134	1209 [0.799]

Table 2. Sieving efficiency model statistics for the different species analyzed (df = model degrees of freedom, n hauls = number of hauls included in the analysis).

Species	Parameter	Design 1	Design 2	Design 3	Design 4
Nephrops	P-value	0.90	0.86	0.15	0.04
	deviance	36.79	72.07	98.68	101.29
	df	49	86	85	78
	n hauls	2	10	7	7
Cod	P-value	>0.99	>0.99	>0.99	0.99
	deviance	56.90	50.54	34.57	64.78
	df	111	108	86	93
	n hauls	13	10	7	11
Blue whiting	P-value	0.87	0.99	0.98	0.98
	deviance	41.62	30.8	29.96	23.35
	df	53	51	48	39
	n hauls	7	9	7	11
American plaice	P-value	0.13	>0.99	0.97	0.65
	deviance	54.76	25.14	30.48	42.81
	df	44	50	47	47
	n hauls	7	10	7	11
Witch flounder	P-Value	>0.99	>0.99	0.95	0.64
	deviance	0.00	23.52	35.41	46.89
	d.o.f	47	51	51	51
	n hauls	11	10	7	11

Figure captions:

Figure 1. Top: Side view of the experimental gear with the general design of the sieve-panel (blue stippled line) mounted ahead of the double codend setup. For the sorting system to work efficiently, the following selection events have to take place consistently: (1) Assuming that *Nephrops* travels towards the codends by rolling and hitting the lower panel of the net, it is expected that they will be sorted by the sieve-panel to the lower codend (orange path); (2) the bottom–up inclination of the panel should guide fish upwards towards the upper codend (green path). Middle: Number of meshes of the different sieve-panel designs; additional floats (blue) were mounted in Design 3. Bottom: Netting used in the different designs and the measured mesh bar length of each (s.d. in parentheses). Nets were scanned using the same scale, allowing a direct comparison between meshes.

Figure 2. First and second rows show the sieving efficiency curves (solid lines), 95% bootstrap CIs (dashed lines), and experimental sieving data (points) obtained for *Nephrops* by each sieve-panel design (D1= Design 1 ,…, D4= Design 4). Total catches (light grey shading) and catches in lower codend (dark grey shading) are plotted in the background. Third and fourth rows show pairwise comparisons of the *Nephrops* sieving efficiency achieved by each of the designs. The grey bands represent the CI associated to each of the estimated sieving efficiency curves. The top-right to bottom-left diagonal can be used to assess the effect of increasing mesh size, and the opposite diagonal to compare the effect of uneven sieve-panel inclination.

Figure 3. Sieving efficiency curves (solid lines), bootstrap CIs (dashed lines), and experimental sieving data (points) obtained by each design (D1= Design 1 ,…, D4= Design 4) on cod (top rows) and blue whiting (bottom rows). Total catches (light grey shading) and catches in the lower codend (dark grey shading) are plotted in the background.

Figure 4. Sieving efficiency curves (solid lines), bootstrap CIs (dashed lines), and experimental sieving data (points) obtained by each design (D1= Design 1 ,…, D4= Design 4) on American plaice (top rows) and witch flounder (bottom rows). Total catches (light grey shading) and

catches in the lower codend (dark grey shading) are plotted in the background.

Supporting material:

Figure S1. Map of the fishing area (Skagerrak; ICES Division IIIa), where the experimental sea trials took place. The top-right panel shows the towing tracks.

Figure S2. Pictures taken in shallow waters from Design 1 before beginning experimental fishing. Above: View of the panel in the middle section with the camera oriented backwards towards the codends. Below: Insertion of the sieve-panel to the floor of the extension.

Figure S3. Left: Screenshots from underwater video recordings taken in haul 25 (Design 3), showing *Nephrops* individuals actively passing through the sieve-panel. Right: Different behavioral patterns observed for *Nephrops* on the panel. Arrows point to chelipeds hanging on to the mesh twines.

Figure 1

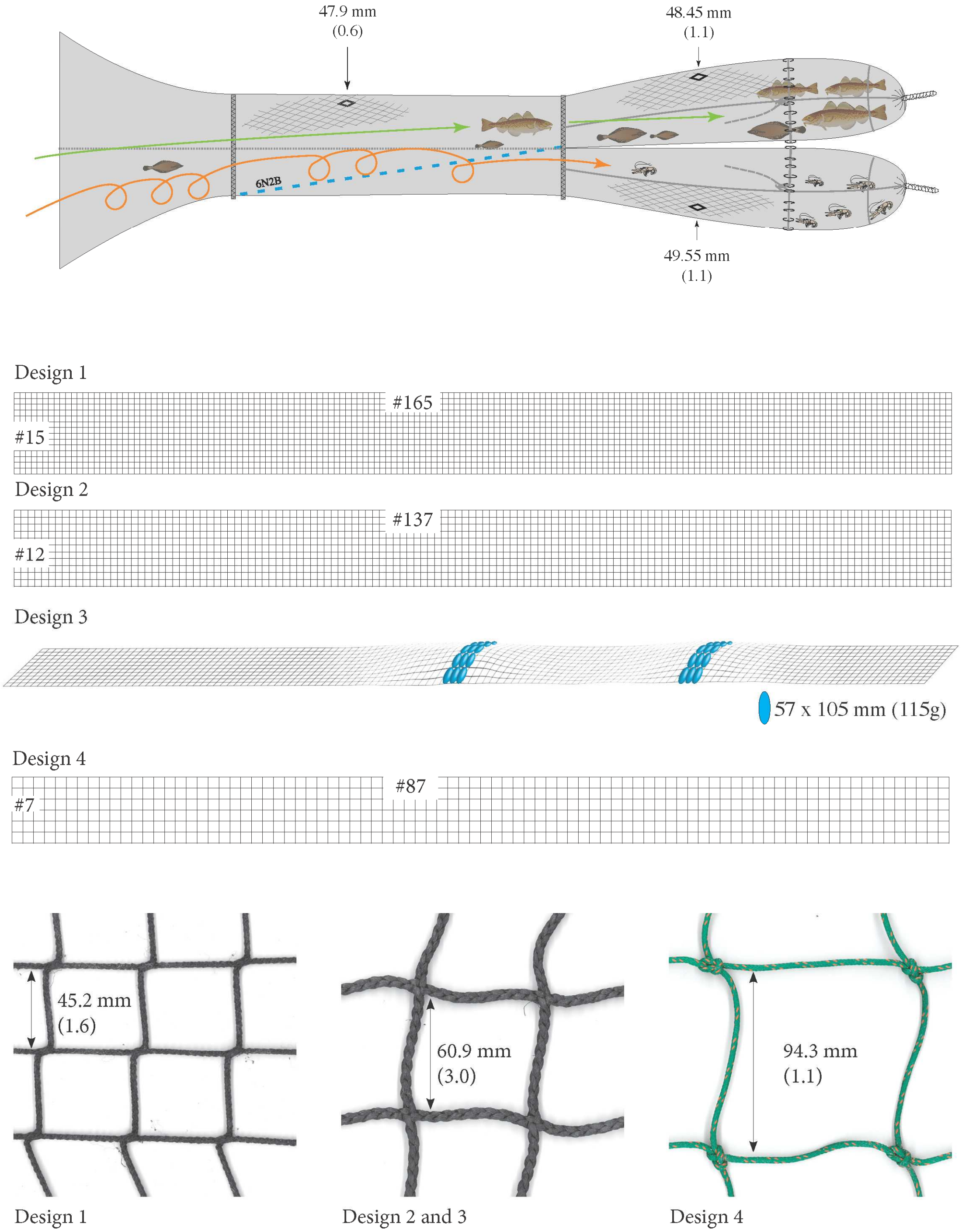
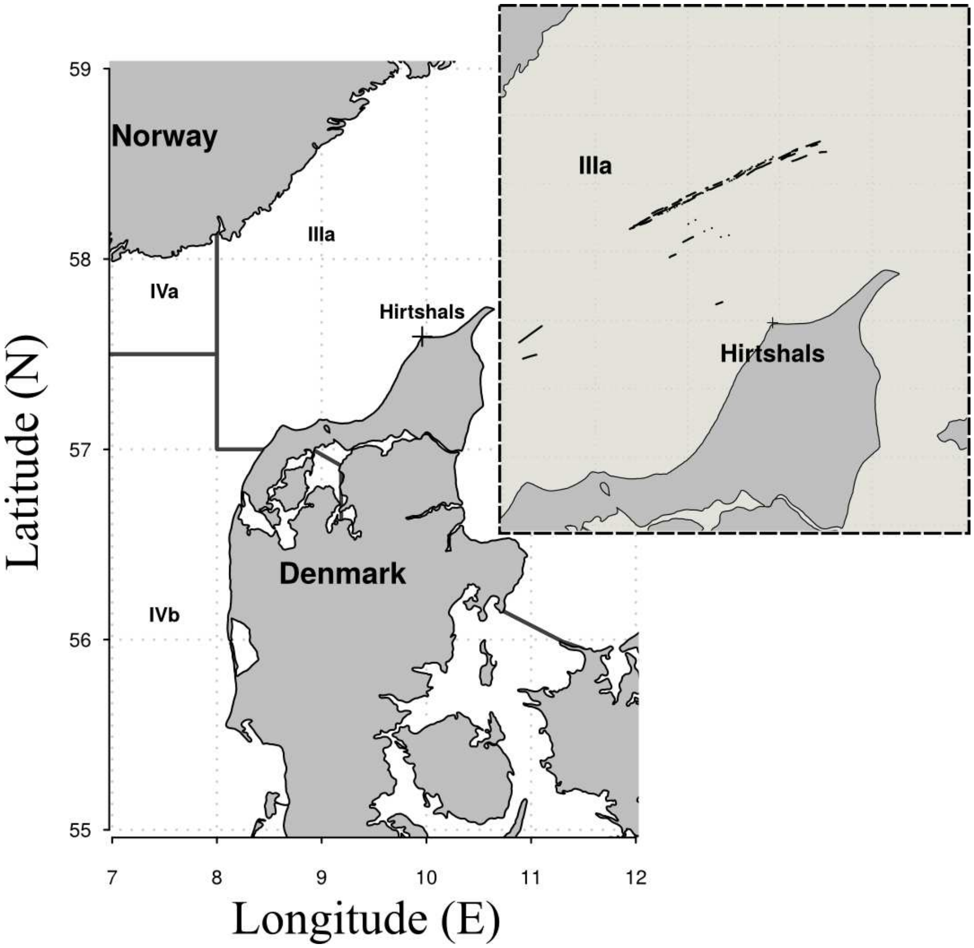

47.9 mm
(0.6)
48.45 mm
(1.1)
6N2B
49.55 mm
(1.1)
Design 1
#165
#15
Design 2
#137
#12
Design 3
57 x 105 mm (115g)
Design 4
#87
#7
45.2 mm
(1.6)
60.9 mm
(3.0)
94.3 mm
(1.1)
Design 1
Design 2 and 3
Design 4

Figure 2



Norway
IIIa
IVa
IVb
Hirtshals
Denmark
59
58
57
56
55
7
8
9
10
11
12
Latitude (N)
Longitude (E)
IIIa
Hirtshals

Figure 3

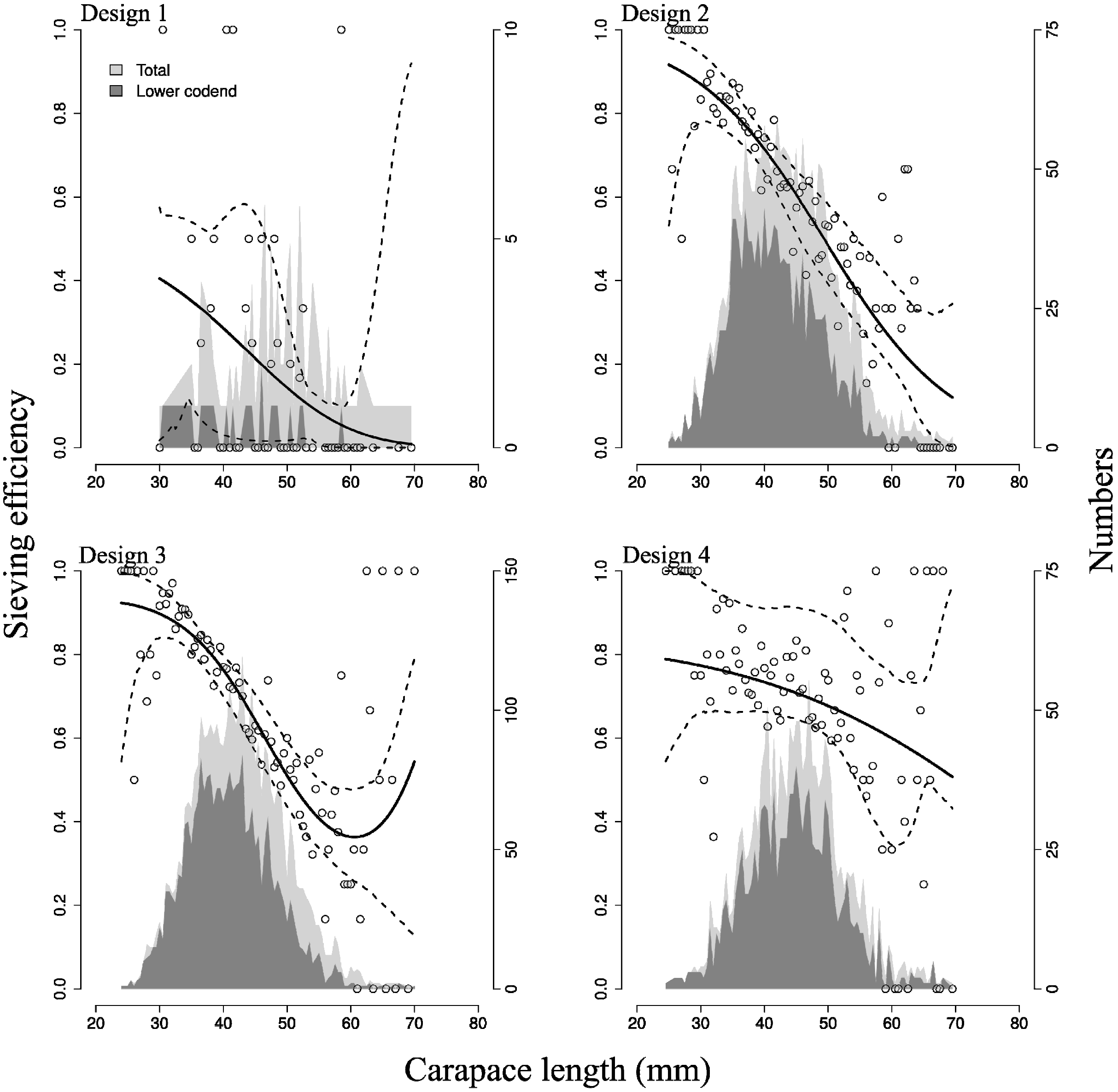
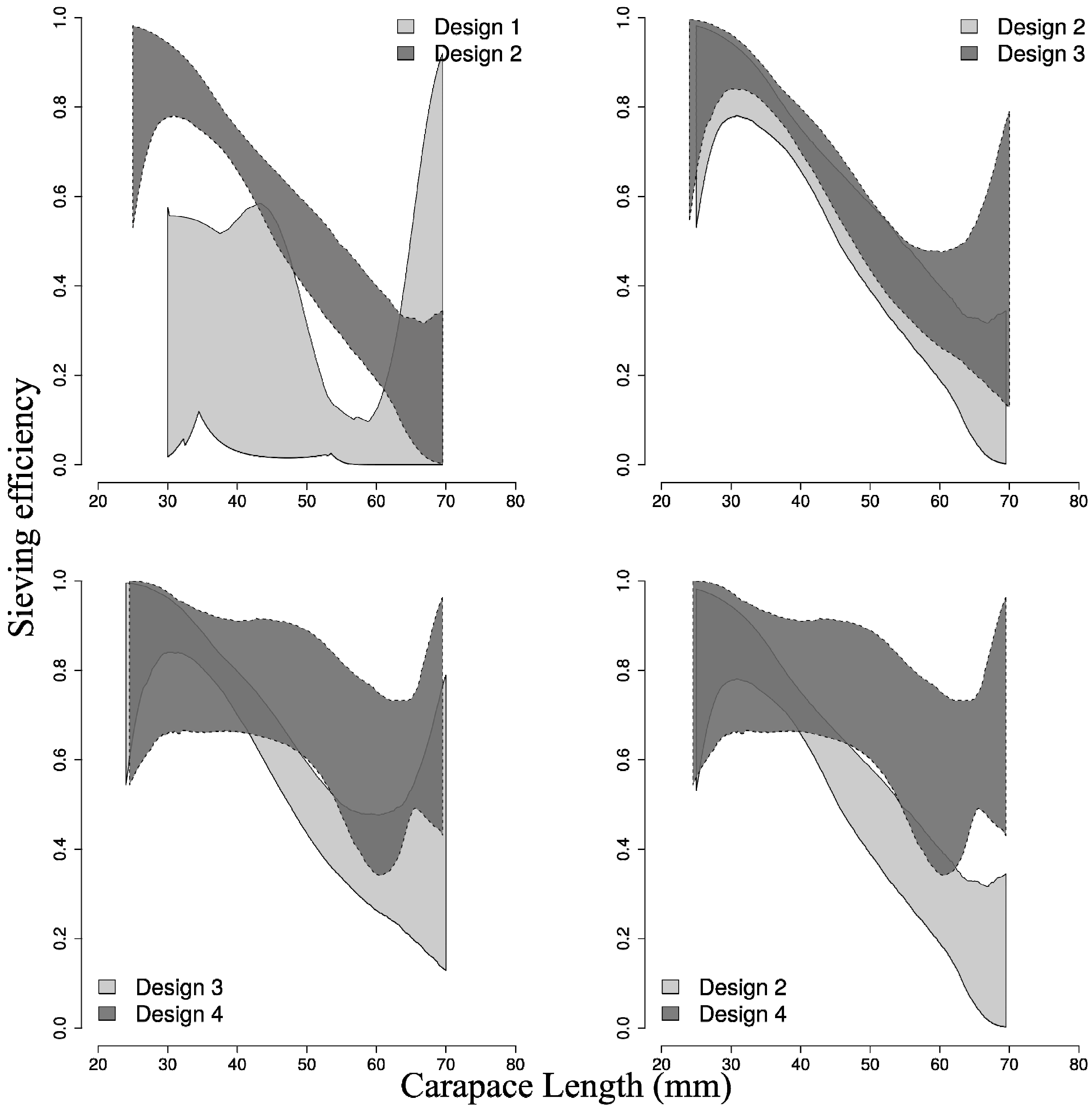

Design 1
Design 2
Design 3
Design 4
▨ Total
■ Lower codend
Sieving efficiency
Numbers
Carapace length (mm)
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
25
50
75
100
150
20
30
40
50
60
70
80

Figure 4



Sieving efficiency
Carapace Length (mm)
Design 1
Design 2
Design 2
Design 3
Design 3
Design 4
Design 2
Design 4
0.0
0.2
0.4
0.6
0.8
1.0
20
30
40
50
60
70
80

Figure 5

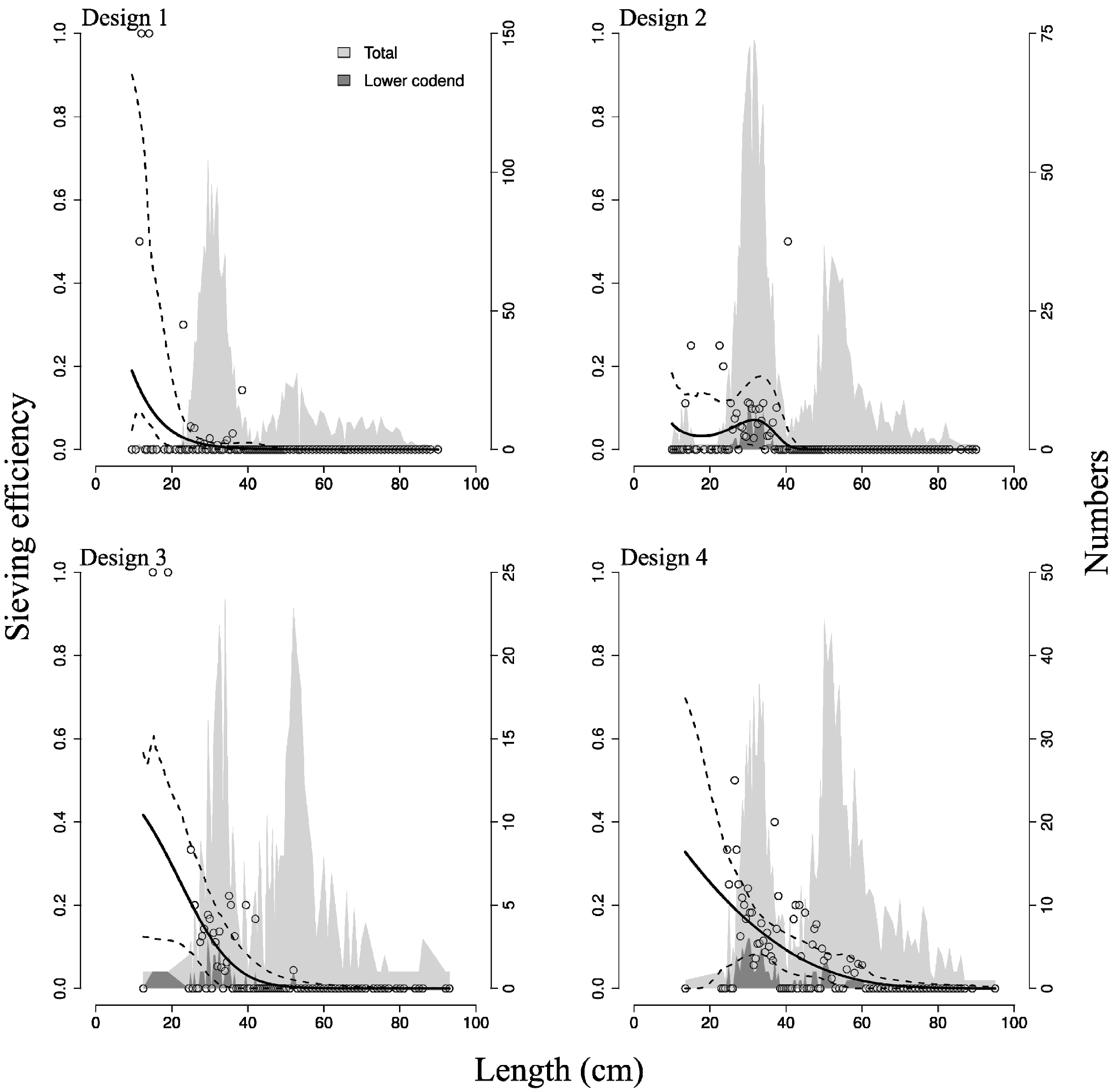

Design 1
Design 2
Design 3
Design 4
Total
Lower codend
Sieving efficiency
Numbers
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
0
50
100
150
0
25
50
75
0
5
10
15
20
25
0
10
20
30
40
50

Figure 6

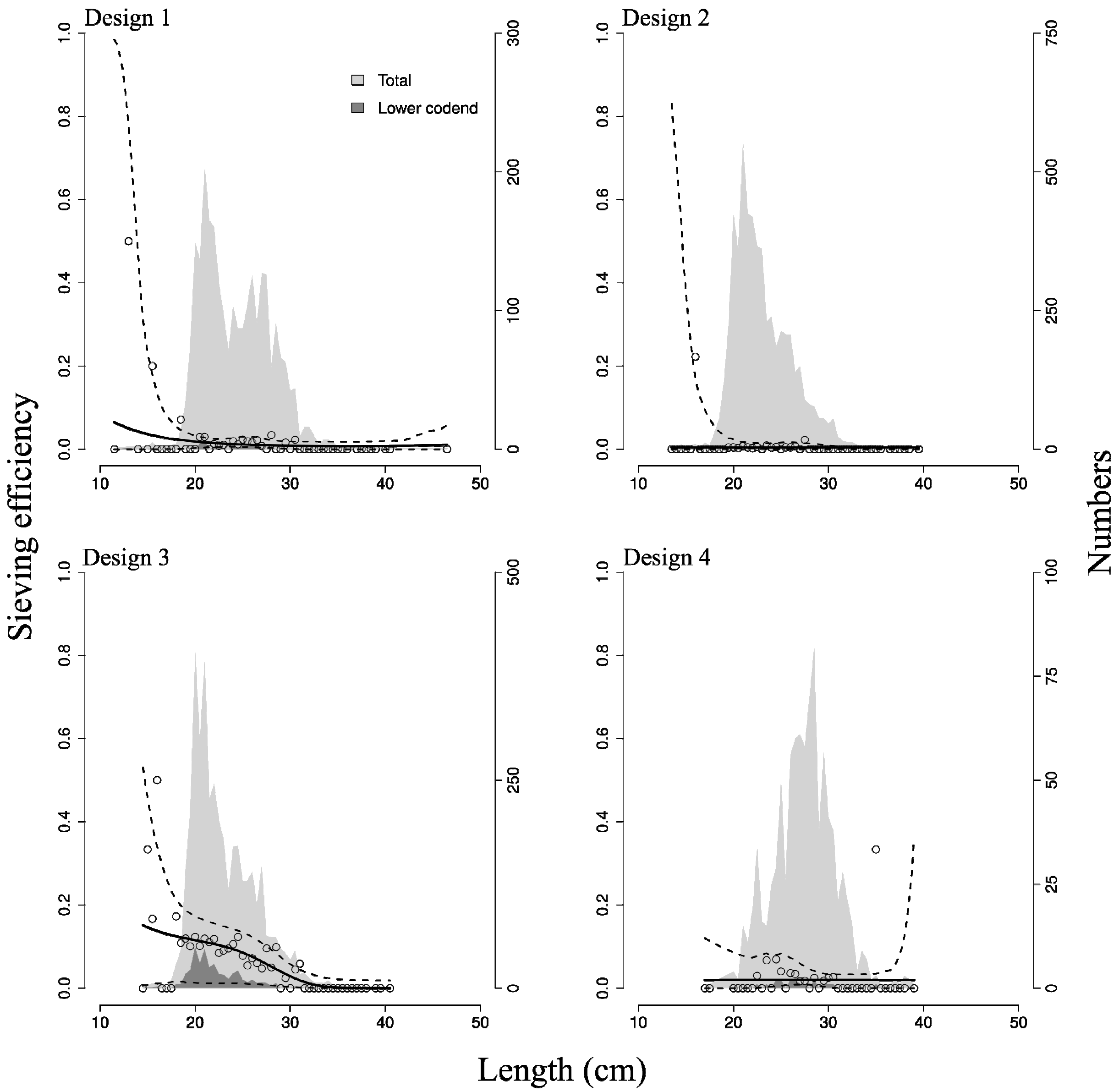

Design 1
Design 2
Design 3
Design 4
▨ Total
▨ Lower codend
Sieving efficiency
Numbers
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
0
100
200
300
0
250
500
750
0
250
500
0
25
50
75
100

Figure 7

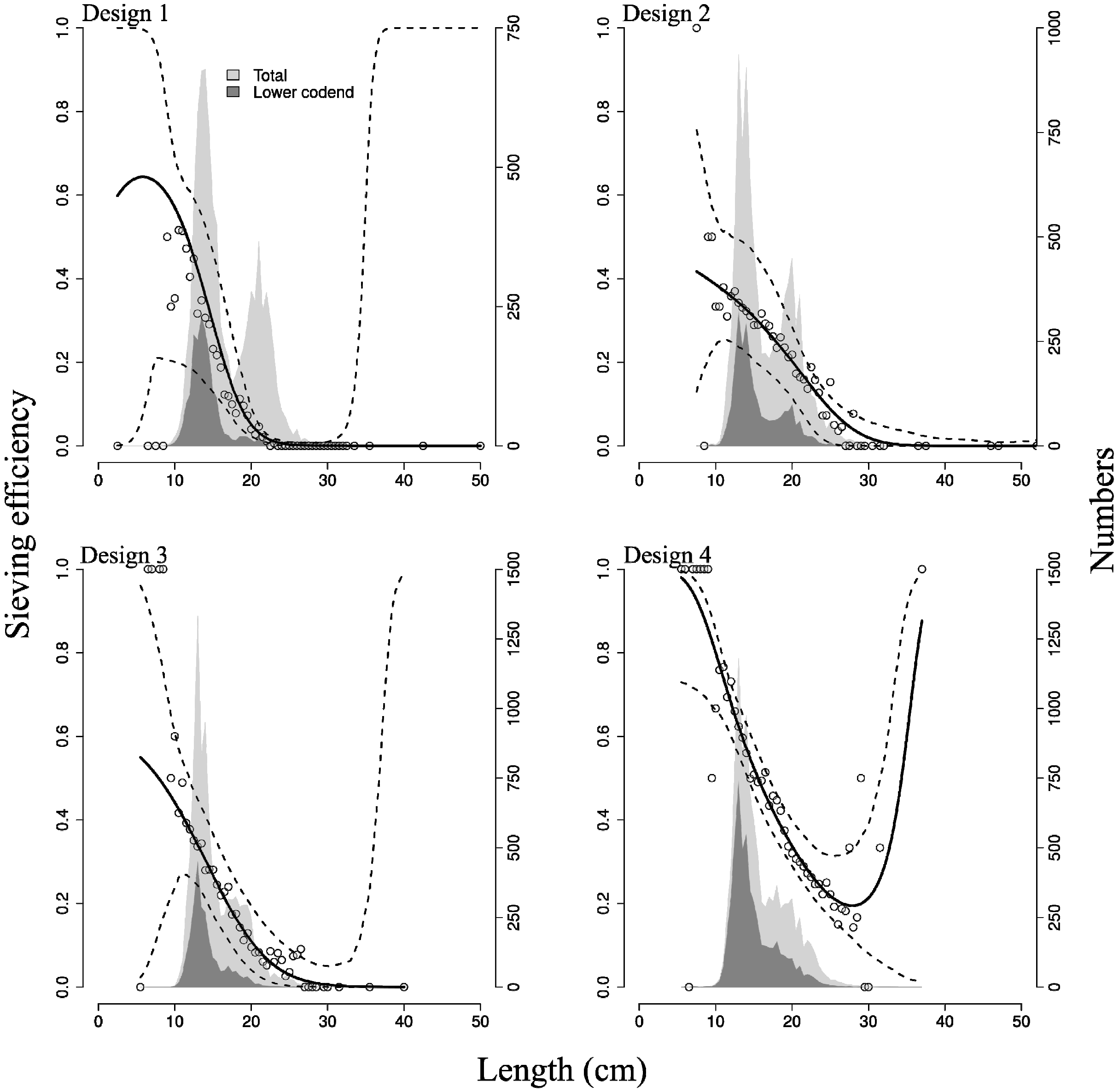
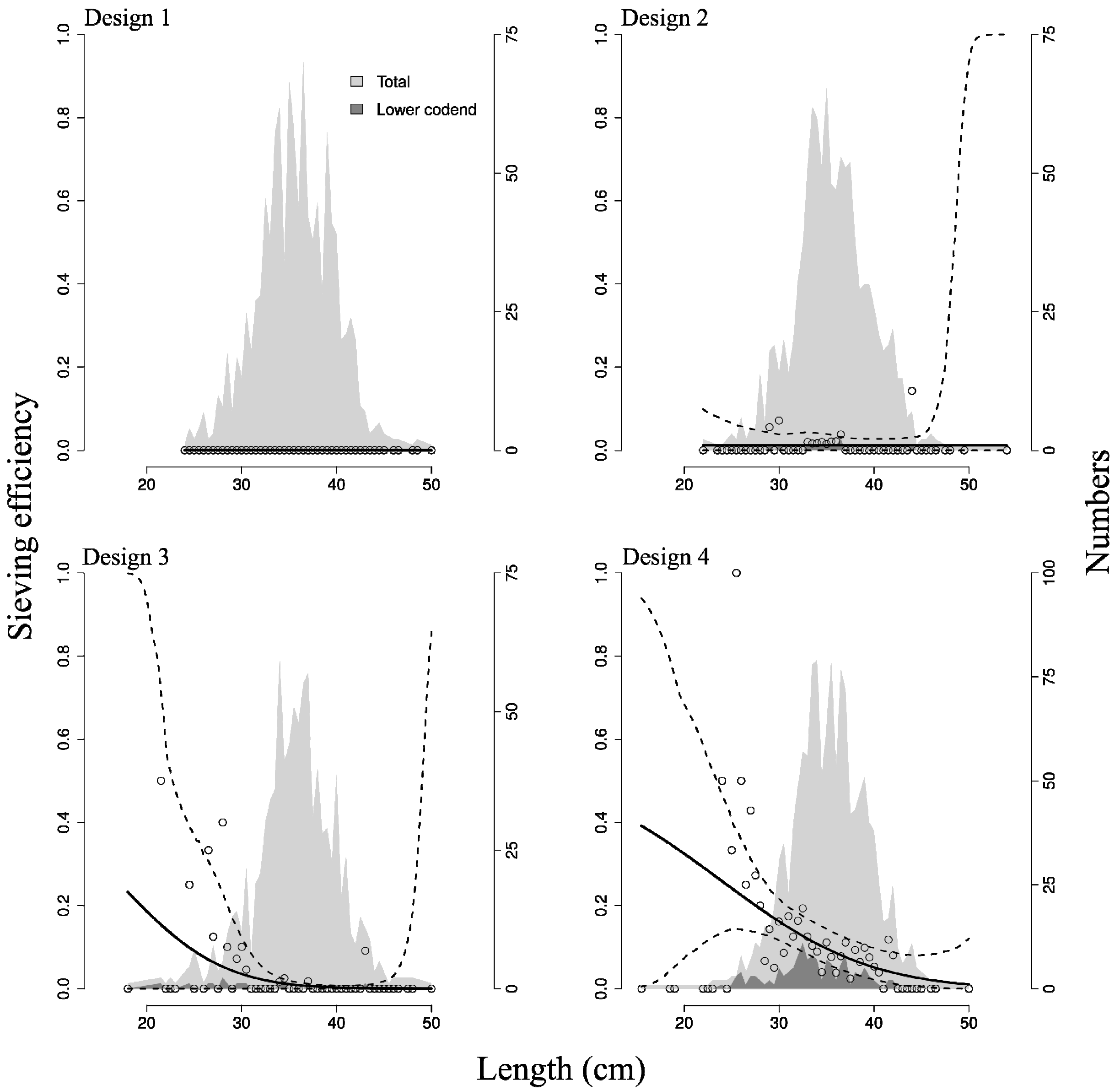

Design 1
Design 2
Design 3
Design 4
Total
Lower codend
Sieving efficiency
Numbers
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
250
500
750
1000
1250
1500

Figure 8



Design 1
Design 2
Design 3
Design 4
Total
Lower codend
Sieving efficiency
Numbers
Length (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
25
50
75
100
20
30
40
50

Figure 9

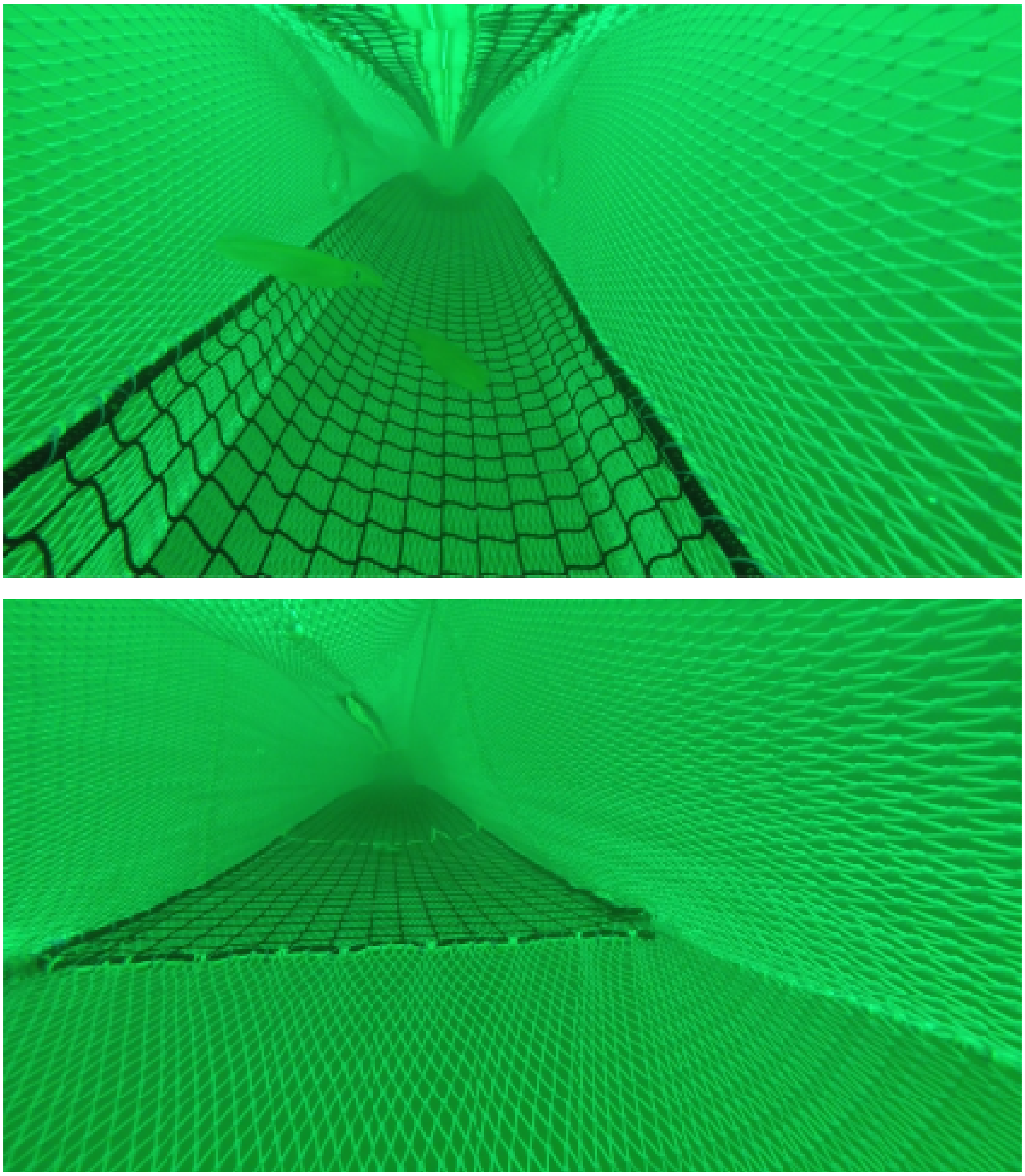


Figure 10