**Estimating purse seine volume during capture: implications for fish densities and survival of released unwanted catches**

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**Abstract**

High fish densities negatively impact catch welfare and the survival of unwanted catches released from purse seines. To avoid overcrowding fish before being released, regulations have been implemented in Northeast Atlantic mackerel and Atlantic herring fisheries that set a limit to the proportion of the full length of the seine that can be hauled in before catches are released. However, it is yet unknown how seine volume, and thus fish density, relates to proportion of seine hauled. In this study, we have estimated the in-water volume of purse seines during commercial fishing from multibeam sonar screen images and applied a log-linear mixed effects model to the data. The prediction intervals from the model in combination with a long-term dataset on mackerel and herring catch sizes were used to estimate fish densities inside the seine. The results indicate a 33-fold decrease in contained volume from 10 to 80% seine hauled in and significant differences between different sized seines. Average fish densities were predicted to be within safe crowding levels in median sized catches while mackerel densities may reach critical levels in larger catches at 80% seine hauled aboard. The results question the rationality of having the same catch release limit for all seine sizes.

Keywords: catch release, crowding density, multibeam sonar, 3-D reconstruction, purse seine volume

## Introduction

Purse seining is a highly efficient fishing method for catching aggregated and schooling pelagic species and accounts for about a quarter of the total world catch of all fish (Watson and Tidd, 2018). Research on purse seine performance has mainly focused on increasing catch success and efficiency by studying the sinking performance (Misund et al., 1992; Hosseini et al., 2011) and in-water behaviour of purse seines (Kim and Park, 2009) during the early catch stages. Purse seine geometry and behaviour during hauling has received relatively little attention but is of importance from a fish welfare point of view. Fish density in the seine is affected by the available volume and thein-water volume of the seine may thereby influence the survival of unwanted catches released from the net and catch quality. However, the seine can take a range of different shapes depending on environmental conditions and fishing techniques (Ben-Yami, 1994; Decew et al., 2013; Zhou et al., 2015) and the in-water volume may vary significantly under different fishing conditions. Understanding how the seine behaves in the water during hauling is also important for future developments in gear designs and by-catch release methods.

Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*) support large and valuable purse seine fisheries in NorwayWith annual landings ranging between 500 000 and 1 000 000 t since 2010 (data from the Norwegian Fisheries Directorate). Unwanted catches, e.g. large catches that exceed vessel handling capacity or the allocated fishing quota, by-catches of non-target species and low value target catches is a  are commonly released from the seine (slipped) before being brought aboard. The mortality rate of the released catches is density and time dependent and may be high if released at a late stage of the catch process. NEA Mackerel mortality has been estimated to be about 80% after 10 to 30 minutes crowding at a fish spatial density of about 200 kg $m^{-3}$ (Lockwood et al., 1983; Huse and Vold, 2010) while Atlantic herring mortality was estimated to be about 50% following 15 minutes crowding at fish densities between 400 and 480 kg $m^{-3}$ (Tenningen et al., 2012). The weight of large catches may also cause the net to burst with consequently high, up to 90%, fish mortalities (Misund and Beltestad, 1995).

In recent years, considerable effort has been made to reduce mortality of catches released from purse seines by developing better acoustic school biomass estimation before setting the net (Tang et al., 2009; Vatnehol et al., 2017), more gentle fish release methods (Vold et al., 2017), and introducing regulations that aim to ensure survival of the released catches (Anon, 2008; EU, 2013). The regulations for slipping in mackerel fisheries in Norwegian waters require that the seine is opened and ready for release before 88% of the seine length has been retrieved, to ensure survival of the released catch. In EU waters, mackerel and herring can be released as long as the proportion of the seine length retrieved is no more than 80% and 90% respectively.

The catch release limits are based on estimates of seine volume (Tenningen et al., 2015), observations at sea, and discussions between fishermen, managers and scientists. However, it is questionable whether it is sensible to have the same release limit for all seine and catch sizes. Ideally, fish density and behaviour should be monitored throughout the catch to ensure that any unwanted catches are released carefully and before harmful behaviour or densities occur, but monitoring fish schools inside the purse seine is challenging (Tenningen et al. 2015; 2017)

The objective of this study was to estimate the three-dimensional (3-D) shape and in-water volume of purse seines used in Norwegian mackerel and herring fishing as a function of proportion of seine retrieved and seine size. The data collected in this study was combined with previously collected data on purse seine geometry (Tenningen et al., 2015). Our hypothesis was that seine volume reduces as a function of proportion retrieved, at the same rate for different sized seines, but with initial volumes differing between different sized seines. The results were used to assess how variation and reduction in the contained volume may affect fish densities inside the seine and thereby the survival of released catches.

## Methods

### *Field data collection*

In the current study, data were collected from five purse seine sets during the annual Northeast Atlantic (NEA) mackerel fishery in September and October in the northern North Sea and Norwegian Sea. These data were combined with previously collected at-sea measurements of purse seines (Tenningen et al., 2015) to increase the data set. Combining the two datasets resulted in data from 13 purse seine sets with four different seine sizes that represent seines use dby the larger off-shore fleet in Nordic mackerel and herring fisheries (Table 1).  A purse seine "set" refers to the full capture process from deploying the net in water until the whole net is retrieved aboard. The Norwegian purse seiners MS "Kings Bay" with a gross register tonnage (GRT) of 4027 and a length of 77.5m, and MS "Asbjørn Selsbane" with a GRT of 1191 and length of 55 m were used in this study and MS "Libas" with GRT of 4377 and length of 94 m was used in Tenningen et al., (2015).  The purse seines ranged from 677 – 796 m in length and 180 to 265 m in depth (Figure 1).

### *The proportion seine retrieved*

The proportion of the total length of the seine retrieved (proportion hauled) is the key explanatory variable of seine volume. We have assumed a constant hauling speed in our model approach. Thus, the proportion of the seine aboard the fishing vessel at any given time was estimated as the time since hauling started, divided by the time taken to retrieve the entire seine aboard. Average seine retrieval rates varied between 0.16 and 0.33 m $s^{-1}$ in the monitored purse seine sets (Table 1). Fishermen tend to maintain a constant hauling speed to avoid unnecessary strain on the gear and stressing the fish, but there may be short stops and changes in the hauling speed lasting from some seconds to some minutes due to gear related complications that may violate this assumption.

*Sonar data collection*

We used a multibeam fish finding sonar (Simrad SN90, Kongsberg Maritime AS) to monitor the seine. The SN90 sonar has a flat transducer with 265 transmission and receiver channels covering a 160-degree sector horizontally and a 90-degree sector vertically (Figure 1). The beam width varies with the frequency from 5 to 8 degrees. The transducer was mounted on the vessel hull in the starboard bow and the sonar was operated at 75 – 80 kHz frequency with a pulse duration varying between 4 and 7 ms and a pulse rate of about 2 $s^{-1}$. Tenningen et al. (2015) used a Simrad SH80 sonar mounted on the drop keel. The SH80 sonar is omnidirectional, has a slightly wider opening angle (9°), slower ping rate (about 1 $s^{-1}$) and higher frequency (116 kHz) compared with the settings used on the SN90 sonar.

The sonar data were collected by systematically moving the vertical sonar fan across the entire seine. One crossing lasted on average 73 s and consisted of 8-13 vertical cross-sections of the seine at 5 to 10-degree intervals (Figure 2, Table 1). The seine was crossed between 2 and 11 times during each purse seine set. The quality of the acoustic images varied depending on interference from propeller and wave created air bubbles. Only images where the seine contours were clearly visible were used for the analyses, resulting in a variable number of crossings per set.

*Sonar image analyses and volume reconstruction*

Tenningen et al (2015) extracted seine contours from single images by manually drawing the outline in the center of the visualized echoes from the cross-sections of the seine. In the current study we used image analyses to extract the contours. Grayscale images were captured from the SN90 software and processed using a custom Python script, using the OpenCV library for image processing (Bradski, 2000) (Figure 2a). First, a 21-by-21-pixel Gaussian blurring filter with a standard deviation of 3.5 pixels was applied to suppress small-scale features. A per-pixel median filter was then applied over several images from the same seine section, to suppress temporal noise, resulting in one grayscale image per seine section. The position of the sonar transducer was identified and used to define a coordinate system with the transducer location as the origin and the central beam projected at the horizontal plane as the x-axis. Next, the grayscale image was segmented into regions using an adaptive threshold with block size 251-by-251 pixels (Gonzalez and Woods, 2002) (Figure 2b). The local threshold was determined by the weighted average of the values in the respective block. Gaussian weights with a standard deviation of 38 pixels were used. From the thresholded image, the regions belonging to the seine were extracted using a watershed transform (Roerdink and Meijster, 2000), and its contours extracted (Figure 2c). The 3-D coordinates relative to the sonar position of the seine contour were generated using information about the sonar setting (inclination angle and heading) and the spatial resolution in the SN90 software display.

The extracted seine contours overestimate the real area of the seine cross section because the echoes are smeared over the entire sonar voxel (Misund, 1997) and the image analyses detects the outer edges of sonar voxels. To address this, a correction was applied across beams by moving each point in a seine cross section half a beam width towards the center beam. The along beam resolution is high, about 20 mm, and correction was not necessary.

Multiple cross-sections were merged into one file containing a 3-D point cloud representation of the seine (Figure 2d and e). 3-D point clouds extracted from previously collected data on purse seine geometry during commercial mackerel fisheries (Tenningen et al., 2015) were at this stage combined into one data set. 3-D Delaunay triangulation was used to construct a closed surface of the 3-D point cloud and calculate volume (Ahrens et al., 2005) (Figure 2d and e). The estimated seine volumes were related to corresponding proportions of seine retrieved.

*Modeled seine volume as a function of haul proportion and seine size*

To estimate how seine volume relates to proportion hauled and seine size, we log transformed the data, and fitted a mixed effects model with gaussian error distribution to the data: log(Volume) ~ log(1-proportion hauled)+log(seine size) +(log(1-proportion hauled)|Set). The linear mixed effects model was implemented in the R-environment, package lme4 (Bates et al., 2015; R-Core-Team, 2018). The amount of seine still in the water (1-proportion hauled) and seine size were used as fixed explanatory variables. Seine size was expressed as the theoretical maximum volume of the net (net length^2 * net height / 4π) corresponding to the point where the whole net is in water, but not pursed, i.e the seine takes the shape of a cylinder. When the fishermen start hauling, the seine is usually pursed and the volume is smaller than the maximum theoretical volume. We included purse seine set as a random factor and allowed both the slope and intersect to vary between sets. We tested whether including random slopes or an interaction effect between the theoretical maximum volume and the proportion hauled improved model fit with AICc in package AICcmodavg (Mazerolle, 2017). AICc is an adaptation of AIC for small sample sizes, a decrease in AICc of more than two indicates a significant increase in model fit (Mazerolle, 2017). We simulated the posterior predictive distribution with sim (10000 simulations) (Gelman and Yu-Sung, 2018) and provided the mean and the 95% credible interval controlling for net size. The credible interval is an estimate of the interval in which future observations will fall with a 95% probability. We used likelihood ratio test to obtain statistical significance of net size on contained volume by comparing the full model with a model where net size was left out. The model was based on the assumption that the reduction in the contained seine volume follows a power law, i.e.. $V = \sim V_0 * p^b$. Where $p$ is the proportion of the net that is still in the water, i.e. $p$ = (1- proportion hauled), V is the seine volume at p, $V_0$ is the initial volume at start of hauling, and $b$ is how the change in volume relates to p. The value of b will then tell whether a seine behaves more like a cylinder (b ~ 2) or more like a sphere (b ~ 3) when it is hauled in.

*Fish density predictions*

To get an idea of how seine volume may affect fish densities, hypothetical fish density estimates were made by dividing common catch sizes with the predicted purse seine volumes from our model (mean and 95% credible intervals). The same purse seine is used for catching NEA mackerel and Atlantic herring and densities were also predicted for herring catches. For catch sizes we chose to use median, upper 95$^{th}$ quantile and maximum size of individual catches reported in the years 2015 – 2017. In the data were included purse seine catches of Atlantic herring (Norwegian spring spawning herring stock) and

NEA mackerel landed in Norway by vessels with GRT larger than 1000 to represent the fleet that uses the seine sizes measured. The median, 95$^{th}$ quantile and maximum catch sizes were 190, 620 and 1100 t for herring and 270, 650 and 985 t for mackerel, respectively(data from electronic catch log books, the Norwegian Fisheries Directorate). Translating volume predictions directly into fish densities in this way assumes that fish are evenly distributed in the whole seine volume and thereby provides an estimate of average fish density inside the seine. Patchy distribution could result in higher densities in parts of the seine and lower densities in other parts of the seine.

## Results

### *Estimated at-sea seine volume*

The in-water volume of the purse seines was estimated to reduce by on average 17 times from < 20% to > 70% hauled seine. The estimated volume reduced from 500 000 $m^3$ at 12% seine retrieved to 53 000 $m^3$ at 80% retrieved in the 7 $hm^3$ seine and from 2 350 000 $m^3$ at 7% retrieved to 99 000 $m^3$ at 72% retrieved in the 13 $hm^3$ seine (Figure 3). The volume in the 13 $hm^3$ seine was on average 3.8 times greater than in the 7 $hm^3$ seine before 20% was hauled and on average 1.7 times larger when more than 70% of the seine was hauled.

### *Predicted seine volume and fish density*

Seine size had a significant effect on contained volume ($\chi^2(1)=9.31$, $p=0.00228$). The model predicted that the contained volume reduced from 800 000 $m^3$ at 10% to 23 000 $m^3$ at 80% hauled seine for the 7 $hm^3$ net and from 2 399 000 $m^3$ to 73 000 $m^3$ for the 13 $hm^3$ net (Figure 3). This reflects a 33-fold decrease in contained volume from 10 to 80% hauled seine and about three times larger volume in the largest (13 $hm^3$) compared with the smallest (7 $hm^3$) measured seine.

Average fish densities were predicted to below 5 kg $m^{-3}$, credible intervals ranging from 0.2 to 6.9 kg $m^{-3}$, until 50% of the seine was hauled in (Figure 5). At 80% seine hauled in, fish density was predicted to below 10 kg $m^{-3}$ (credible intervals: 1.2 - 17.9 kg $m^{-3}$) in median sized mackerel and herring catches. In maximum and 95$^{th}$ quantiles of catch sizes, densities were predicted to range from 8 to 39 kg $m^{-3}$ (credible intervals: 4 - 73 kg $m^{-3}$) for herring and from 8 to 35 kg $m^{-3}$ (credible intervals: 4 - 65 kg $m^{-3}$) for mackerel at 80% seine hauled in. Beyond 80% seine hauled in the predicted fish densities increase dramatically, but few estimates of net volume are available, and the model fit is weak.

*Model fit*

Including net size as a factor in the model significantly improved the model (AICc 86.2 vs 93.2). While including an interaction effect between net size and the proportion hauled did not further improve model fit (AICc 86.2 vs 86.2). A model where random slopes were used was significantly better than a model with only random intercepts (AICc 90.1 vs 170.1). The estimate for slope of the effect of log(1-proportion hauled) of the model was 2.28, with a credible interval between 1.8 and 2.6 (Table 2). Resulting in a volume reduction of the seine that goes as $V \sim x^{2.28}$. Thus, the reduction is more similar to a cylinder (b ~2) than a sphere (b ~ 3). The model fitted well up to around 80% seine hauled onboard, but poorly beyond this due to few data-points and increased variation in the measured volume (Figure 5).

## Discussion

The purpose of regulating at which time during purse seining unwanted catches can still be released is to avoid detrimental fish densities inside the seine before release. Fish density in the seine is affected by catch size and seine contained volume. Our results indicate that the in-water volume of purse seines used by the larger vessels in the Norwegian mackerel and herring fisheries reduces by 33 from start of hauling until 80% of seine was hauled in. Furthermore, the volume of the largest seine used was 3 times greater compared with the smallest measured seine. Large variation in fish densities at the point where the decision of keeping or releasing a catch needs to be made is problematic. In some situations, fish densities may already be above safe levels. While in other situations, fish density may be so low that no fish can be observed at the surface and the skipper has no visual cues about the catch quantity or quality and nothing to base his decision on. To ensure high survival among released unwanted catches while maintaining high catch values, catch release limits should consider variations in seine size. Alternatively, efficient catch monitoring systems should be developed. Acoustic and optic methods for estimating fish school biomass (Nishimori et al., 2009), spatial density (Peterson et al., 1976), size (Rosen et al., 2013) and species (Korneliussen et al., 2009) are available but applying these methods into a purse seine capture situation can be challenging. This is due to the large size and flexible, continuously changing, shape of purse seines under operation. Monitoring systems where stereo-cameras and echosounders are deployed inside the seine and with real time data transfer are currently being tested and developed.

Acceptable short-term stressor limits for mackerel have previously been set to a crowding density of 30 kg $m^{-3}$ (Handegard et al., 2017). These stressor limits are supported by the results from crowding experiments on mackerel carried out by Lockwood et al. (1983). Herring has been shown to tolerate considerably higher crowding densities than mackerel.

A crowding density of 150 kg herring $m^{-3}$ held for 10 minutes was estimated to result in a mortality rate below 2% (Tenningen et al., 2012). In the Norwegian mackerel and herring purse seine fisheries catches range from less than 50 t to over 1000 t (data from the Norwegian Fisheries Directorate). To get an idea of what levels of fish densities may be expected in the predicted seine volumes, common mackerel and herring catch sizes were divided with seine volume. Fish densities in common mackerel and herring catch sizes were predicted an average fish density in median sized mackerel  and herring catches (270 t) to be well below critical densities at 80% hauled seine. In larger catches average fish densities were predicted to be below 20 kg $m^{-3}$ in all seine sizes, but the upper credible interval exceeded 30 kg $m^{-3}$ in all but the largest seine size.   . These results suggest that fish densities in Nordic mackerel and herring fisheries are generally within safe limits when 80% of the seine is hauled in. However, mackerel densities may reach detrimental levels in large schools caught in smaller seines. It is also important to consider that catch quantities including slipped catches may be greater than the reported catches as slipped catches are not reported. Furthermore, our study only represents the larger vessels in the purse seine fleet. Smaller vessels tend to have somewhat smaller seines than the ones used in this study and even though average catch sizes are smaller due to smaller loading capacity it is not sure whether  smaller schools are always targeted and caught. The current limits for catch release are at 80% (EU) and 87% (Norway) for mackerel and 90% (EU) for herring. Beyond 80% seine hauled our seine volume predictions are highly uncertain. During later stages of hauling the net may take complex shapes with large folds of netting, as observed by cameras inside the net (M. Breen, pers. comm.), making it difficult to predict seine volume. Thus, fish densities may unexpectedly reach high crowding levels when most of the net is hauled in.

Fish densities predicted in this study are based on the assumption that fish in the seine use the whole available volume. Acoustic (Tenningen et al., 2017) and camera-based (M. Breen, pers. comm.) observations of fish schools inside purse seines indicate that this is not the case in the early stages of capture. Therefore, our density predictions are likely to underestimate real fish densities in the beginning of hauling. However, experiments where small mackerel schools were crowded in net pens show that the fish initially maintained a density independent of available volume, but eventually utilized all available volume as the volume was reduced (Handegard et al., 2017). In the later stages of purse seine capture estimates of seine volume combined with catch size may then give a realistic indication of fish density.

In this study the focus was on describing the in-water volume of purse seines, how it varies with seine size and hauling proportion and what the implications may be on fish crowding densities. Monitoring the fishing gear during operation and understanding how it behaves under different fishing conditions is also essential for any future development of the purse seine gear and for controlling fishing operations. It may also be important for estimating by-catch quantities when only parts of the catches are sampled and fishing effort is used to estimate the total quantity (Hall et al., 2017). Our study has demonstrated that multibeam sonar can be used to obtain rough estimates of seine geometry until about 80% of the seine is hauled aboard. After this the resolution of the sonar may not be high enough to capture the shape of the net. Previously, purse seine geometry during hauling has been studied in small scale experiments in tanks (Kim, 2000) and using positioning transponders under commercial fishing (Tenningen et al., 2015). Computer simulation models have been developed to describe the geometry and performance during deploying and pursing the seine (Kim and Park, 2009; Hosseini et al., 2011; Zhou et al., 2015) but are still lacking for the hauling phase. Future work should aim at further developing real time monitoring systems of purse seine geometry and improve our understanding of purse seine performance during hauling under different environmental and operational conditions.

The results in this study provide estimates of in-water volume of different sized seines used in the Nordic mackerel and herring fisheries. Based on the volume estimates we have predicted fish densities and considered the effects on mortality following slipping. The results suggest that regulations on release of unwanted catch from purse seines should take into consideration the potential effect of seine size on fish densities. Ideally, release limits should reflect real fish densities, but that will require further development of real-time catch and gear monitoring methods and instruments. There are currently no efficient methods available for estimating catch size or content inside the seine. Target school size is usually estimated before capture with sonar, but it may be difficult to get accurate estimates, especially when schools form large and dense aggregations and only parts of the school is targeted.

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# Tables and figures

**Table 1.** Summary of the acoustic data used to reconstruct the 3-D shape and in-water volume during seine hauling. Purse seine volume was estimated in 13 sets using three vessels and four different seine sizes. Seine size is presented as length (L) and depth (D) in meters, wind and current speed at 30 m depth in knots (kn) and direction relative to vessel heading (°), catch size in tonnes, haul rate (Haul r), the number of times the seine was reconstructed during the set (Rec.) and the average number (± standard deviation) of cross sections used in each reconstruction.

| Year | Set | Vessel | Seine | | Wind | | Current | | Catch | Haul r | Rec. | Sections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | L | D | (kn) | (°) | (kn) | (°) | (t) | m $s^{-1}$ | | |
| 2011 | 1* | Libas | 720 | 220 | - | - | - | - | 0 | 0.16 | 8 | 3.8 (0.9) |
| 2011 | 2* | Libas | 720 | 220 | - | - | - | - | 0 | 0.26 | 5 | 4.6 (0.9) |
| 2011 | 3* | Libas | 720 | 220 | - | - | - | - | 320 | 0.33 | 12 | 9.1 (3.3) |
| 2011 | 4* | Libas | 720 | 220 | - | - | - | - | 115 | 0.21 | 3 | 5.3 (0.6) |
| 2012 | 5* | Libas | 720 | 200 | - | - | - | - | 635 | 0.24 | 10 | 5.5 (1.4) |
| 2012 | 6* | Libas | 720 | 200 | - | - | - | - | 150 | 0.18 | 21 | 5.3 (0.9) |
| 2012 | 7* | Libas | 720 | 200 | - | - | - | - | 0 | 0.26 | 9 | 5.6 (0.7) |
| 2012 | 8* | Libas | 720 | 200 | - | - | - | - | 440 | 0.19 | 7 | 6.3 (0.8) |
| 2014 | 9 | Kings Bay | 796 | 265 | 11 | 9 | 0.2 | 238 | 68 | 0.23 | 8 | 8.0 (2.1) |
| 2014 | 10 | Kings Bay | 796 | 265 | 8 | 148 | 0.3 | 326 | 0 | 0.26 | 2 | 10.0 (3.5) |
| 2014 | 11 | Kings Bay | 796 | 265 | 7 | 93 | 0.8 | 345 | 25 | 0.28 | 8 | 7.0 (1.0) |
| 2016 | 12 | A. Selsbane | 677 | 182 | 4 | 74 | 0.6 | 280 | 0 | 0.22 | 8 | 13.0 (3.5) |
| 2016 | 13 | A. Selsbane | 677 | 182 | 5 | 160 | 0.5 | 27 | 170 | 0.25 | 3 | 13.0 (2.5) |

**Table 2.** Results from the linear mixed effects model: log(Volume) ~ log(1-proportion hauled) + log(Seine Size) + (log(p) | Set), where proportion hauled is the amount of seine still in water. Credible intervals (95% CI) were estimated by simulating (10000 runs) the posterior predictive distribution.

| Fixed effects | | | | | Random effects | | |
|---|---|---|---|---|---|---|---|
| | Estimate | Std. error | t-value | 95% CI | | Variance | Std.Dev. |
| Intercept | 10.58 | 1.02 | 10.41 | 8.52 – 12.09 | Intercept | 0.15 | 0.39 |
| Log (1 - proportion hauled) | 2.29 | 0.22 | 10.39 | 1.85 – 2.62 | Set | 0.47 | 0.68 |
| Log (Seine size) | 1.70 | 0.46 | 3.69 | 0.78 – 2.39 | Residual | 0.07 | 0.26 |

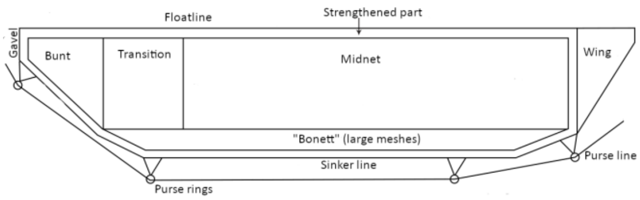


**Figure 1.** A draft of a common Norwegian mackerel and herring purse seine with the main parts illustrated. Mesh size and twine diameter vary in the different parts of the seine, e.g. 34 mm meshes are common in the bunt, 39 mm in the main body of the seine and 157 mm in the “bonett”. Catches are crowded in the bunt before being pumped aboard. If catches are released it is done by creating an opening in the bunt gavel or by allowing fish to swim over the floatline.

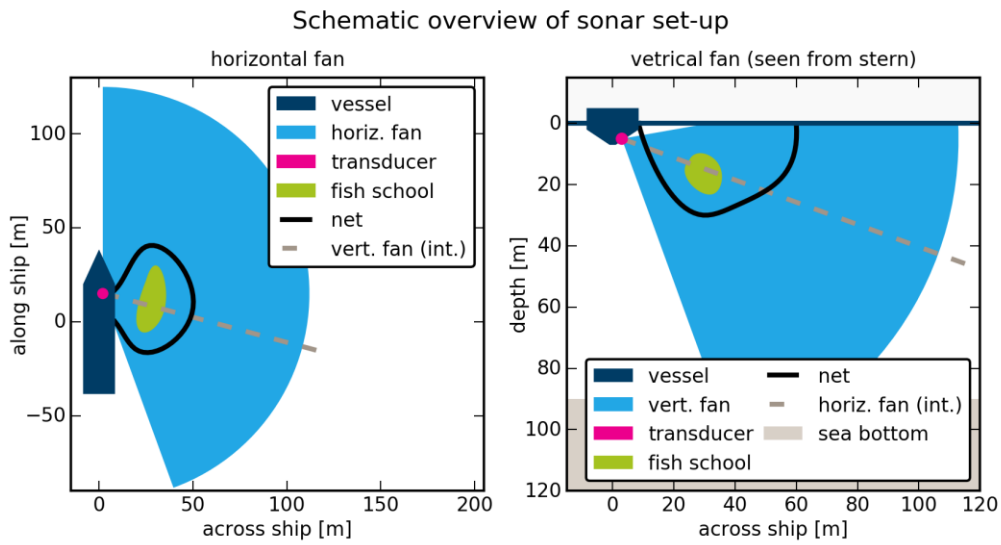


**Figure 2.** A schematic overview of the monitoring setup, indicating the position of the SN90 sonar transducer and the area covered by the acoustic beams in relation to the vessel vertically and horizontally.

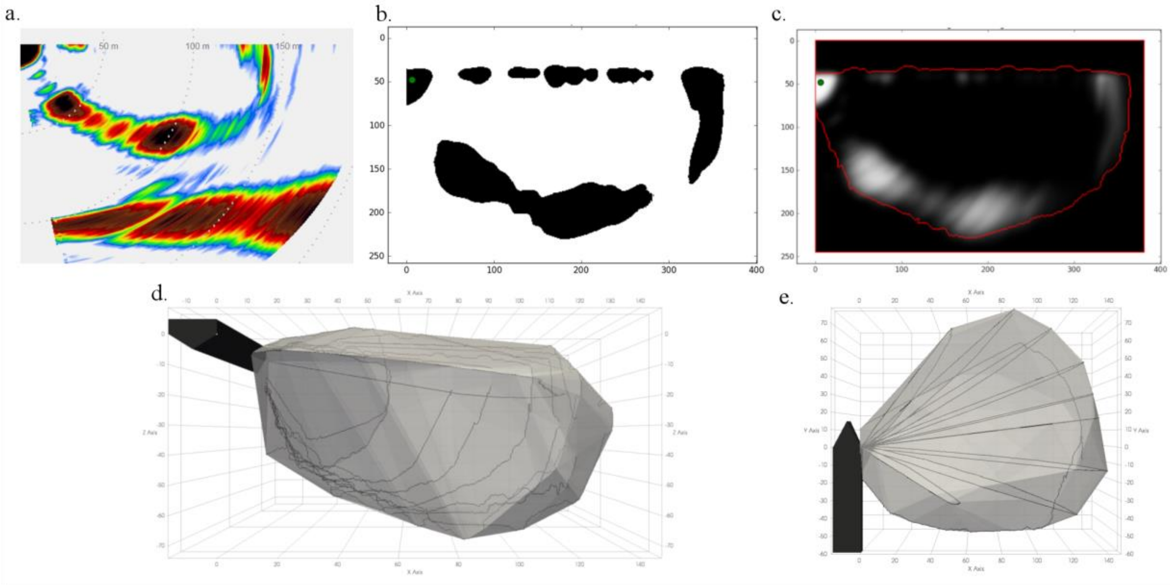


**Figure 3.** The method used to reconstruct the 3-D shape of a purse seine during hauling from sonar screen images. The vertical fan was used to obtain cross sections of the seine (a). An adaptive threshold was used to segment the image into regions (b). The regions belonging to the seine were then extracted using watershed segmentation and the contours of the regions was computed (c). Multiple slices were merged to construct a 3-D point cloud and 3-D Delaunay triangulation was used to create a closed surface (sideview from stern:d and planview fomr above: e). The scale in panels  and c is in pixels while the other scales are in meters.

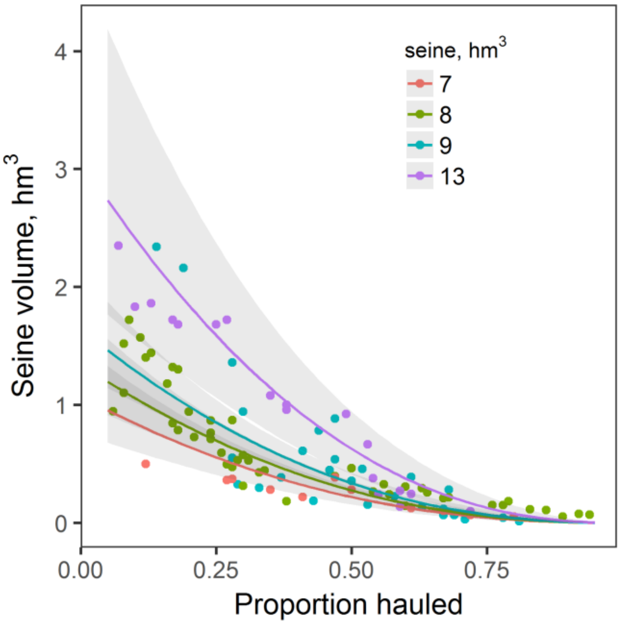


**Figure 4.** Estimated seine volume as a function of proportion of the seine hauled based on 3-D reconstructed seine shape from acoustic data. Colours represent different seine sizes and the lines are values predicted from the linear mixed effects model matrix, including 95% credible intervals in the linear domain, 0.5 to 0.95 proportion seine hauled.

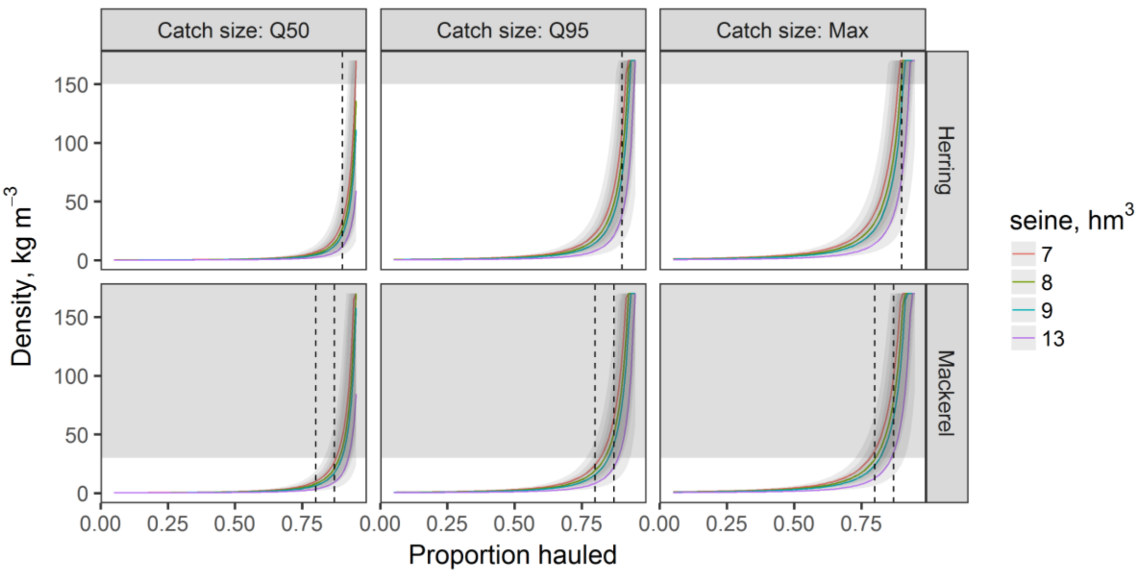


**Figure 5**. Predicted average fish density in the estimated seine volumes in median (mackerel: 270t; herring: 190t), upper 95th percentile (mackerel: 650t; herring: 620t) and maximum (mackerel: 985t; herring: 1100t) catch sizes in 2015 to 2017. The vertical

stippled lines represent the slipping limits (Norway mackerel = 0.87, EU mackerel = 0.8 and EU herring = 0.9). The white regions represent safe crowding limits for herring (150 kg $m^3$) and mackerel (30 kg $m^3$). The y-scale has been truncated to 170 kg $m^{-3}$ .

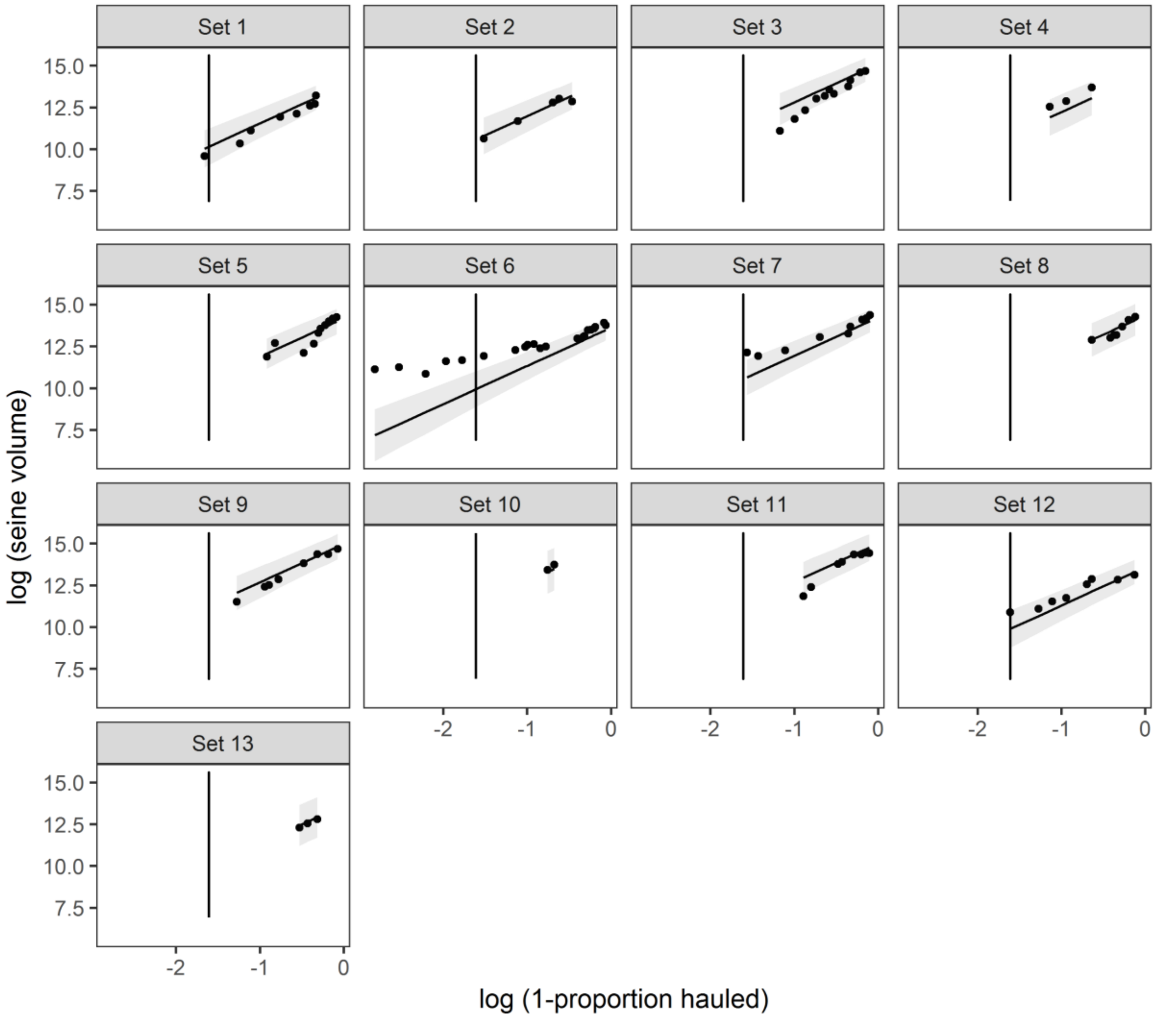


**Figure 6.** Posterior distribution of the in-water seine volume predicted from the model matrix, including 95% credible intervals by purse seine set (1-13). The vertical line is at log (1-0.8), i.e. 80% haul proportion and haul proportions beyond this are to the left of the vertical line. The discrepancy between the predicted (blue) and observed (green) data to the left of this line indicates a decrease in model fit at around 80 % haul proportion.