ICES Journal of
Marine Science

ICES Journal of Marine Science (2019), 76(7), 2481–2488. doi:10.1093/icesjms/fsz119

Original Article

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

Maria Tenningen [1]*, Armin Pobitzer [2], Nils Olav Handegard[1], and Karen de Jong[1]

[1]Institute of Marine Research, PO Box 1870 Nordnes, 5817 Bergen, Norway
[2]Sintef Ålesund, Sintef PO Box 5760 Torgarden, 7465 Trondheim, Norway

*Corresponding author: tel: + 47 93653972; e-mail: maria.tenningen@hi.no

Tenningen, M., Pobitzer, A., Handegard, N. O., and de Jong, K. Estimating purse seine volume during capture: implications for fish densities and survival of released unwanted catches. – ICES Journal of Marine Science, 76: 2481–2488.

Received 21 November 2018; revised 27 May 2019; accepted 30 May 2019; advance access publication 4 July 2019.

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 the Northeast Atlantic mackerel and herring fisheries that limit the proportion of the seine that can be retrieved before catches are released. However, it is yet unknown how seine volume, and thus fish density, relates to proportion of seine retrieved. In this study, we have estimated the in-water volume of purse seines used in the Norwegian mackerel and herring fisheries as a function of proportion seine hauled and seine size. Purse seine geometry was monitored with multibeam sonar at sea and a log-linear mixed effects model was applied to the estimated seine volumes. The results indicate a 33-fold decrease in contained volume from 10 to 80% seine hauled and a threefold difference in volume between the largest and smallest measured seines. Fish densities in the seine were predicted to vary greatly depending on seine and catch size and under some conditions exceed safe crowding levels before the catch release limit is reached. This study questions the rationale of having the same catch release limit for all seine and catch sizes.

Keywords: 3D reconstruction, catch release, crowding density, multibeam sonar, 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 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. The in-water volume of the seine may 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 Norway with annual landings ranging between 500 000 and 1 000 000 t (data from 2010 to 2018 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, 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 ∼80% after 10–30 min crowding at a fish spatial density of ∼200 kg m^{-3} (Lockwood *et al.*, 1983; Huse and Vold, 2010) while Atlantic herring mortality was estimated to be ∼50% following 15 min 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; European Union, 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 >80 and 90%, respectively.

The catch release limits are based on estimates of seine volume (Tenningen *et al.*, 2015), observations at sea, and discussions among 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 (3D) 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 this study, data were collected from five purse seine sets during the annual 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 data sets resulted in data from 13 purse seine sets with four different seine sizes (Table 1). The monitored purse seines represent seines used by the larger off-shore mackerel and herring fleet. 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 77.5 m, 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 to 796 m in length and 180 to 265 m in depth (Figure 1, Table 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 speed varied between 0.16 and 0.33 m s^{-1} (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 2). 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 $\sim$2 s^{-1}. Tenningen *et al.* (2015) used a Simrad SH80 sonar mounted on the drop keel. The SH80 sonar is omnidirectional, has a slightly wider opening angle (9°), slower ping rate ($\sim$1 s^{-1}), and higher frequency (116 kHz) compared to the settings used for the SN90 sonar.

The sonar data were collected by systematically moving the vertical sonar fan across the entire seine while keeping the horizontal sonar fan tilt angle stable. 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 sonar images by manually drawing the outline in the centre of the visualized echoes from the cross-sections of the seine. In this study, we used image analyses to extract seine contours from sonar images. Greyscale images were captured from the SN90 software and processed using a custom Python script, using the OpenCV library for image processing (Bradski, 2000) (Figure 3a). 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 greyscale 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 greyscale image was segmented into regions using an adaptive threshold with block size 251-by-251 pixels (Gonzalez and Woods, 2002) (Figure 3b). 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 3c). The 3D coordinates

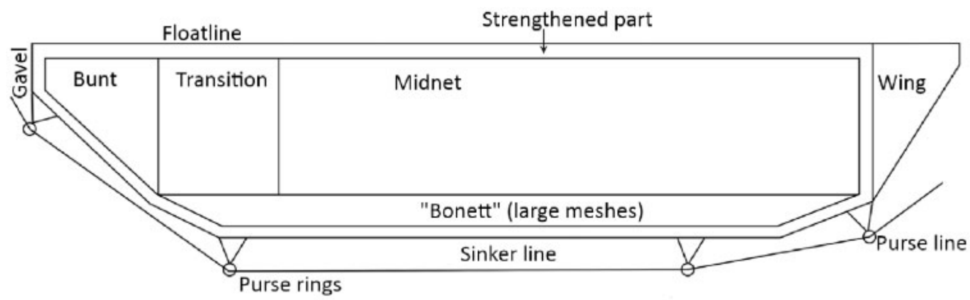

Figure 1. A draft of a common Norwegian mackerel and herring purse seine with the main parts illustrated. The seine in this example is 720 m long and 200 m deep. Different mesh sizes and twine diameters are used in the different parts of the seine, e.g. 34-mm meshes are common in the bunt, 39 mm in the 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.

Table 1. Summary of the acoustic data used to reconstruct the 3D shape and in-water volume during seine hauling.

			Seine		Wind		Current		Catch	Haul r		
Year	Set	Vessel	*L*	*D*	(kn)	(°)	(kn)	(°)	(t)	m s^{-1}	Rec.	Sections
2011	1[a]	Libas	720	220	–	–	–	–	0	0.16	8	3.8 (0.9)
2011	2[a]	Libas	720	220	–	–	–	–	0	0.26	5	4.6 (0.9)
2011	3[a]	Libas	720	220	–	–	–	–	320	0.33	12	9.1 (3.3)
2011	4[a]	Libas	720	220	–	–	–	–	115	0.21	3	5.3 (0.6)
2012	5[a]	Libas	720	200	–	–	–	–	635	0.24	10	5.5 (1.4)
2012	6[a]	Libas	720	200	–	–	–	–	150	0.18	21	5.3 (0.9)
2012	7[a]	Libas	720	200	–	–	–	–	0	0.26	9	5.6 (0.7)
2012	8[a]	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)

Purse seine volume was estimated in 13 sets targeting mackerel (*S. scombrus*) using three vessels and four different seine sizes. Seine size is presented as length (*L*) and depth (*D*) in metres, 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.

[a]Data re-used from Tenningen *et al.* (2015).

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 centre beam. The along beam resolution is high, ~20 mm, and correction was not necessary.

Multiple cross-sections were merged into one file containing a 3D point cloud representation of the seine (Figure 3d and e). 3D Delaunay triangulation was used to construct a closed surface of the 3D point cloud and calculate volume (Ahrens *et al.*, 2005) (Figure 3d and e). The surface of the 3D point clouds in Tenningen *et al.* (2015) were calculated using the ball-pivoting algorithm (Bernardini *et al.*, 1999). These were recalculated using 3D Delaunay triangulation for consistency. The seine was reconstructed several times during a set and the estimated seine volumes were related to corresponding proportions of seine retrieved.

Modelled seine volume as a function of haul proportion and seine size

To estimate how seine volume relates to proportion seine 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 (Table 1) was expressed as the theoretical maximum volume of the seine (net length^2 * net height/4π) corresponding to the point where the whole seine 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 as defined here. 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 seine size and the proportion hauled improved model fit

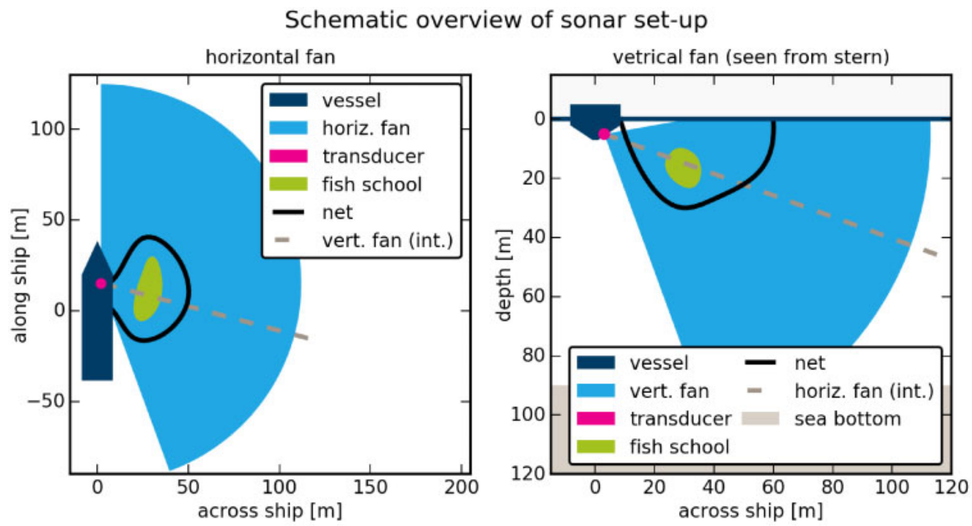

Figure 2. A schematic overview of the monitoring setup, indicating the position of the SN90 sonar transducer and the area covered by the acoustic beams in relation to the vessel.

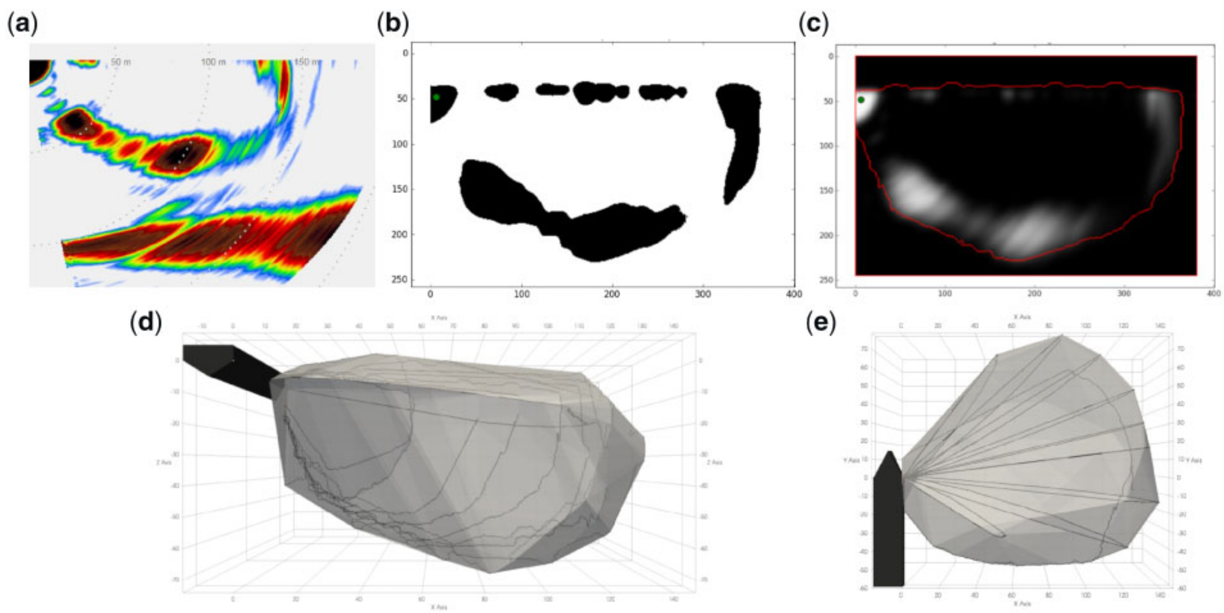

Figure 3. The method used to reconstruct the 3D shape of a purse seine during hauling from sonar screen images. An original screen dump is shown in panel a. The colours indicate the strength of the received echo. The sea bottom can be seen below the seine. The vertical sonar fan was used to obtain cross sections of the seine (a). An adaptive threshold was used to segment the image into regions (b). The regions belonging to the seine were extracted using watershed segmentation and the contours of the regions were computed (c). Multiple slices were merged to construct a 3D point cloud and 3D Delaunay triangulation was used to create a closed surface (d: side-view from stern and e: plan-view from above). The scales in panels (a), (d), and (e) are in metres and the scales in panels (b) and (c) is in pixels. The example is from set 10 at 50% seine retrieved.

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 (10 000 simulations) (Gelman and Yu-Sung, 2018) and provided the mean and the 95% credible interval controlling for seine 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 seine size on contained volume by comparing the full model with a model where seine 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 seine that is still in the water, i.e. $p = (1-$ proportion hauled), V is the seine volume, 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 indicate whether the seine contracts like a cylinder ($b \sim 2$) or sphere ($b \sim 3$) when hauled.

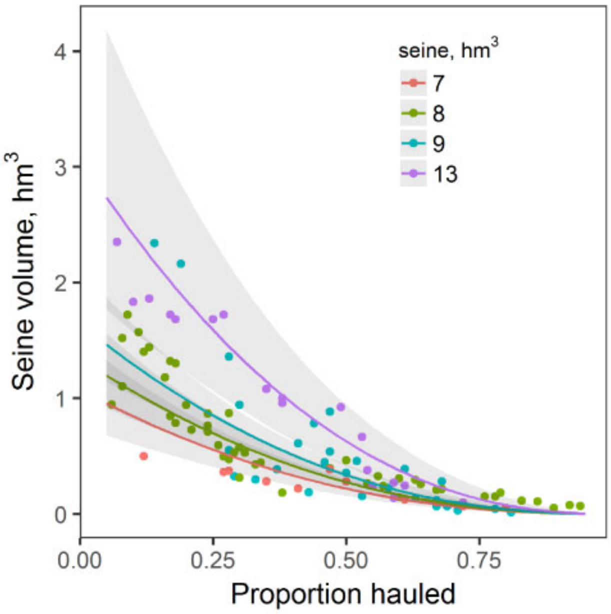

Figure 4. Estimated seine volume as a function of proportion of the seine hauled. Points represent at-sea estimated seine volumes and the lines are values predicted from the linear mixed effects model matrix, including 95% credible intervals in the linear domain (grey-shadowed regions), 0.5–0.95 proportion seine hauled.

Fish density predictions

Hypothetical fish densities in the seine were estimated 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 therefore also estimated for herring. For catch sizes we chose to use median, 95th quantile and maximum size of individual catches reported between 2015 and 2017. Atlantic herring (Norwegian spring spawning herring stock) and NEA mackerel landed in Norway by purse seiners (GRT > 1000) were included in the data. The median, 95th 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 in-water 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 4). 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 >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 4). 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 to the smallest (7 hm^3) measured seine.

Average fish densities were estimated 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 estimated 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 95th 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 increased dramatically, but few estimates of seine volume are available, and the model fit is weak.

Model fit

Including seine size as a factor in the model significantly improved the model (AICc 86.2 vs. 93.2). While including an interaction effect between seine 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 6).

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. Our results indicate that the in-water volume of purse seines used in the Norwegian mackerel and herring fisheries may reduce to 1/33 of the initial volume at start of hauling when 80% of the seine has been retrieved. The results further indicate that the in-water volume of the largest seines may be three times greater than the volume of the smaller seines. The seines monitored in this study represent seines used by the large off-shore vessels. Smaller coastal purse seiners use smaller seines that are commonly 100–150 m deep and 600–650 m long (J. Saltskår, pers. comm.). However, it is likely that this part of the fleet target smaller schools. The current limits for catch release from purse seines are fixed at 80% (EU) and 88% (Norway) for NEA mackerel and 90% (EU) for Atlantic herring regardless of seine size (Anon., 2008; European Union, 2013). 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

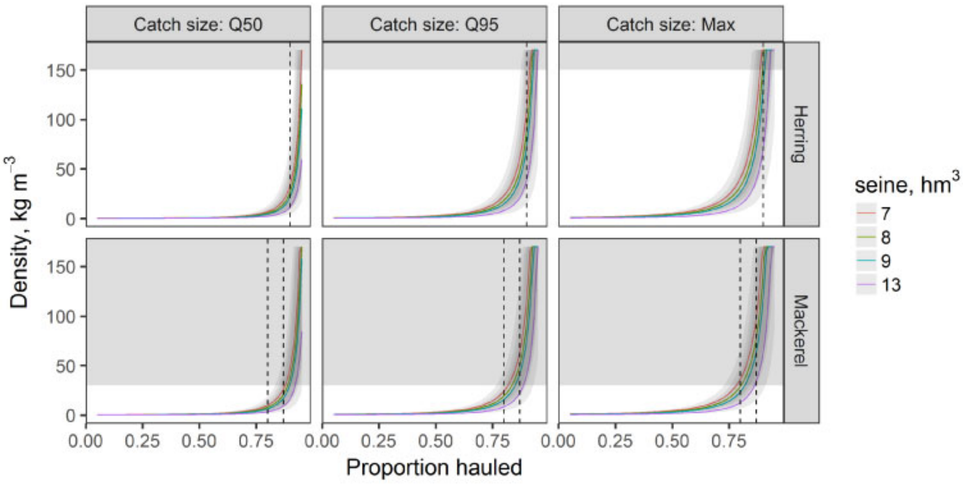

Figure 5. Expected average fish densities in the seine volumes predicted by the model in median (mackerel = 270 t; herring = 190 t), 95th quantile (mackerel = 650 t; herring = 620 t), and maximum (mackerel = 985 t; herring = 1 100 t) catch sizes in 2015–2017. The densities are presented as mean (coloured lines represent different seine sizes) and 95% credible intervals (grey areas). The vertical stippled lines represent the slipping limits (mackerel = 0.88 in Norway and 0.8 in EU; herring = 0.9 in EU). 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}.

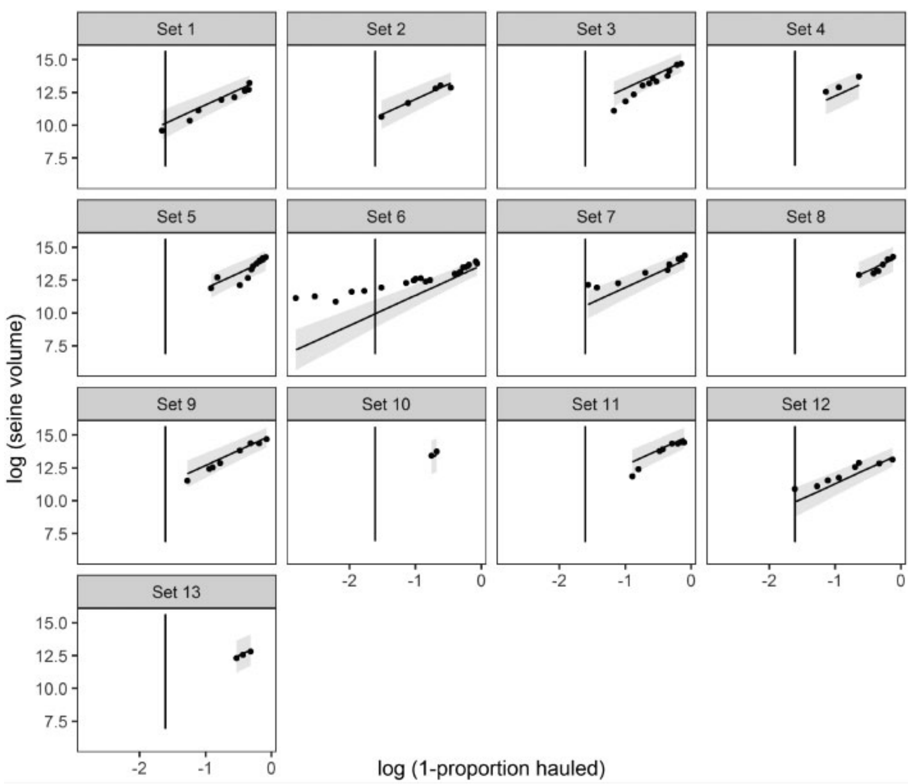

Figure 6. Posterior distribution of the in-water seine volume predicted from the model matrix, including 95% credible intervals by purse seine set (1–13). The vertical line is at log (1–0.8), i.e. 80% haul proportion and haul proportions beyond this are to the left of the vertical line. The discrepancy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

decision on. Regulations regarding slipping from purse seines should consider variation in seine sizes and the consequent variation in fish densities in the seine. By doing this, it is likely that that the survival of released catches can be increased while providing fishermen with better information to base their decision on keeping or releasing catches.

Acceptable short-term stressor limits for mackerel have previously been set to a crowding density of 30 kg m^{-3} (Handegard

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.

Fixed effects					Random effects		
	Estimate	s.e.	*t*-Value	95% cri		Variance	*SD*
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

Credible intervals (95% cri) were estimated by simulating (10 000 runs) the posterior predictive distribution.

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 min 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 <50 to over 1000 t (data from the Norwegian Fisheries Directorate) and catches that include slipped fish are even greater. However, little information is available on slipped quantities and there is no requirement for reporting slipping in Norway. To get an idea of what densities may be expected in the seine as it is retrieved, we translated predicted seine volumes to fish densities by dividing common catch sizes by the seine volume predicted by the model. Average fish densities in median sized mackerel (270 t) and herring (190 t) catches may be expected to be below critical densities until 80% of the seine is retrieved. Herring densities were estimated to be within safe crowding levels also in the largest reported catches (620–1100 t) at 80% hauled seine, while mackerel that are more sensitive to crowding were predicted to reach critical crowding levels in the larger catches (650–985 t) by 80% seine hauled. Beyond 80% seine hauled our seine volume predictions are highly uncertain. During later stages of hauling the seine may take complex shapes with large folds of netting, as observed by cameras inside the seine (M. Breen, pers. comm.), making it difficult to predict seine volume. Thus, fish densities may unexpectedly reach high crowding levels when most of the seine 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.

There is a need to develop efficient catch monitoring systems for purse seines that can monitor the seine and provide catch information in real time. 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 is challenging. This is due to the large size and flexible, continuously changing, shape of purse seines under operation. 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 are targeted. Monitoring systems where stereo-cameras and echosounders are deployed inside the seine and with real-time data transfer are currently being tested and developed.

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 ~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.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

We would like to thank the skippers and crew on MS "Kings Bay," MS "Asbjørn Selsbane" and MS "Libas."

Funding

We also thank The Research Council of Norway for funding this study through project no. 243885 and Neil Anders for spelling and grammar check.

References

Ahrens, J., Geveci, B., and Law, C. 2005. ParaView: an end-user tool for large data visualization. *In* Visualization Handbook, pp. 717–731. Ed. by C.D. Hansen and C.R. Johnson. Elsevier, Inc, Oxford, UK.

Anon. 2008. Act of 6 June 2008 no. 37 relating to the management of wild living marine resources ("The marine resources act"). Norwegian Ministry of Trade, Industry and Fisheries.

Bates, D., Mächler, M., Bolker, B. M., and Walker, S. C. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67: 1–48.

Ben-Yami, M. 1994. Purse Seining Manual. Fishing News Books, Oxford. 416 pp.

Bernardini, F., Mittleman, J., Rushmeier, H., Silva, C., and Taubin, G. 1999. The ball-pivoting algorithm for surface reconstruction. IEEE Transactions on Visualization and Computer Graphics, 5: 349–359.

Bradski, G. 2000. The OpenCV library. Dr. Dobb's Journal: Software Tools for the Professional Programmer, 25.11: 120–123.

Decew, J., Fredriksson, D. W., Lader, P. F., Chambers, M., Howell, W. H., Osienki, M., Celikkol, B. *et al.* 2013. Field measurements of cage deformation using acoustic sensors. Aquacultural Engineering, 57: 114–125.

European Union. 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No1954/20 03 and (EC) No1224/20 09 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/58 5/EC. Official Journal of the European Union, L354: 22–61.

Gelman, A., and Yu-Sung, S. 2018. arm: Data Analysis Using Regression and Multilevel/Hierarchical Models, version 1.10-1. https://cran.r-project.org/package=arm.

Gonzalez, R. C., and Woods, R. E. 2002. Digital Image Processing, 2nd edn. Prentice Hall, Upper Saddle River, NJ.

Hall, A. J., Gilman, E., Minami, H., Mituhasi, T., and Carruthers, E. 2017. Mitigating bycatch in tuna fisheries. Reviews in Fish Biology and Fisheries, 27: 881–908.

Handegard, N. O., Tenningen, M., Howarth, K., Anders, N., Rieucau, G., and Breen, M. 2017. Effects on schooling function in mackerel of sub-lethal capture related stressors: crowding and hypoxia. PLoS One, 12: 16.

Hosseini, S. A., Lee, C. W., Kim, H. S., Lee, J., and Lee, G. H. 2011. The sinking performance of the tuna purse seine gear with large-meshed panels using numerical method. Fisheries Science, 77: 503–520.

Huse, I., and Vold, A. 2010. Mortality of mackerel (*Scomber scombrus* L.) after pursing and slipping from a purse seine. Fisheries Research, 106: 54–59.

Kim, Y.-H. 2000. Geometry of the model purse seine in relation to enclosed volume during hauling operation. Journal of Fisheries Science and Technology, 3: 156–162.

Kim, Y. H., and Park, M. C. 2009. The simulation of the geometry of a tuna purse seine under current and drift of purse seiner. Ocean Engineering, 36: 1080–1088.

Korneliussen, R. J., Heggelund, Y., Eliassen, I. K., and Johansen, G. O. 2009. Acoustic species identification of schooling fish. ICES Journal of Marine Science, 66: 1111–1118.

Lockwood, S. J., Pawson, M. G., and Eaton, D. R. 1983. The effects of crowding on mackerel (*Scomber scombrus* L.)—physical condition and mortality. Fisheries Research, 2: 129–147.

Mazerolle, M. J. 2017. Model Selection and Multimodel Inference Based on (Q)AIC(c), version 2.1-1. https://cran.r-project.org/package=AICcmodavg.

Misund, O. A. 1997. Underwater acoustics in marine fisheries and fisheries research. Reviews in Fish Biology and Fisheries, 7: 1–34.

Misund, O. A., and Beltestad, A. K. 1995. Survival of herring after simulated net bursts and conventional storage in net pens. Fisheries Research, 22: 293–297.

Misund, O. A., Dickson, W., and Beltestad, A. K. 1992. Optimization of purse seines by large-meshed sections and low lead weight—theoretical considerations, sinking speed measurements and fishing trials. Fisheries Research, 14: 305–317.

Nishimori, Y., Iida, K., Furusawa, M., Tang, Y., Tokuyama, K., Nagai, S., and Nishiyama, Y. 2009. The development and evaluation of a three-dimensional, echo-integration method for estimating fish-school abundance. ICES Journal of Marine Science, 66: 1037–1042.

Peterson, M. L., Clay, C. S., and Brandt, S. B. 1976. Acoustic estimates of fish density and scattering function. The Journal of the Acoustical Society of America, 60: 618–622.

R-Core-Team. 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Roerdink, J. B. T. M., and Meijster, A. 2000. The watershed transform: definitions, algorithms, and parallelization strategies. Fundamenta Informaticae, 41: 187–228.

Rosen, S., Jorgensen, T., Hammersland-White, D., and Holst, J. C. 2013. DeepVision: a stereo camera system provides highly accurate counts and lengths of fish passing inside a trawl. Canadian Journal of Fisheries and Aquatic Sciences, 70: 1456–1467.

Tang, Y., Nishimori, Y., and Furusawa, M. 2009. The average three-dimensional target strength of fish by spheroid model for sonar surveys. ICES Journal of Marine Science, 66: 1176–1183.

Tenningen, M., Macaulay, G. J., Rieucau, G., Pena, H., and Korneliussen, R. J. 2017. Behaviours of Atlantic herring and mackerel in a purse-seine net, observed using multibeam sonar. ICES Journal of Marine Science, 74: 359–368.

Tenningen, M., Pena, H., and Macaulay, G. J. 2015. Estimates of net volume available for fish shoals during commercial mackerel (*Scomber scombrus*) purse seining. Fisheries Research, 161: 244–251.

Tenningen, M., Vold, A., and Olsen, R. E. 2012. The response of herring to high crowding densities in purse-seines: survival and stress reaction. ICES Journal of Marine Science, 69: 1523–1531.

Vatnehol, S., Pena, H., and Ona, E. 2017. Estimating the volumes of fish schools from observations with multi-beam sonars. ICES Journal of Marine Science, 74: 813–821.

Vold, A., Anders, N., Breen, M., Saltskår, J., Totland, B., and Øvredal, J. T. 2017. Beste praksis for slipping fra not (Best practice of slipping from purse seines). Rapport fra Havforskningen, Nr. 6-2017. Bergen, Norway. 64 pp.

Watson, R. A., and Tidd, A. 2018. Mapping nearly a century and a half of global marine fishing: 1869–2015. Marine Policy, 93: 171–177.

Zhou, C., Xu, L. X., Tang, H., and Wang, X. F. 2015. *In-situ* dynamics of tuna purse seine deployment in various operations and currents. Fisheries Science, 81: 1003–1011.

Handling editor: Finbarr O'Neill