On the use of omnidirectional sonars and downwards-looking echosounders to assess pelagic fish distributions during and after midwater trawling

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Small pelagic fish can play an important role in the structure and function of ecosystems, and there is increasing interest in their non-market value. At the scale of fish aggregations, however, the impact of fishing has received relatively little attention, with most effort devoted to impacts of vessel and gear avoidance on stock size estimates. We used concurrent deployment of a downwards-looking echosounder (Simrad ES60 system) and an omnidirectional sonar (Simrad SP90 system) during commercial pairtrawling operations for Atlantic herring (Clupea harengus) in the Gulf of Maine to examine their potential for studying the impacts of fishing on herring aggregations. We compared a number of aggregation metrics to illustrate similarities and differences between the two systems, and then qualitatively examined their properties during and after pairtrawling events to illustrate potential applications. Our results suggest that using both downwards-looking and omnidirectional systems provides complementary information on fish aggregation metrics. Future applications of these systems in before–after–control-impact (BACI) designs may help inform management agencies when evaluating potential impacts of fishing at the time and space scales of pelagic fish aggregations.

Keywords: acoustics, aggregation, Atlantic herring, midwater trawling, pelagic.

Introduction

Although much research has been devoted to the interaction of pelagic fish with fishing gear, the focus has been almost entirely on survey assessments (e.g. Olsen, 1971; Misund and Aglen, 1992; Vabø et al., 2002). Little effort has been devoted to impacts of fishing on the short-term structure and function of fish aggregations. Because of the important role small pelagic fish can play in the structure and function of ecosystems (Rice, 1995; Cury et al., 2000; Bakun, 2006) and increasing concern or recognition for the non-market value (i.e. ecosystem value) of pelagic forage fishes (e.g. Read and Brownstein, 2003; Hannesson et al., 2009; Lee, 2010), research that examines the potential impacts of fishing on pelagic fish aggregations at the time and space scales of the aggregation itself is necessary from both ecological and management perspectives.

Pelagic fisheries often operate at temporal and spatial scales that match distributional and behavioural patterns of pelagic fish; aggregations such as schools and shoals can concentrate activities of fishing fleets and predators alike. Management decisions, although generally operating at a population level at time-scales of a year or more, affect fishing practices at the scale of aggregations. For example, in the Gulf of Maine, management decisions to ban
midwater trawling for Atlantic herring (*Clupea harengus*) each year from June to September (New England Fishery Management Council, 2006) were based, in part, on the argument by a number of stakeholder groups that midwater trawling disrupted herring aggregations to the detriment of ecological processes (e.g., predator–prey interactions) and other user groups (e.g., bluefin tuna *Thunnus thynnus* fishers, ecotourists). Such management decisions, while embedded within a framework for managing at the level of a population or stock, were implemented at the individual fisher level, with fishers required to modify their fishing behaviour (i.e., selection of time and place) and equipment (e.g., midwater trawl vs. purse-seine) to comply with the management decisions. The supposition was that modifying fishing behaviour by limiting the ability to fish aggregations efficiently would have desirable effects at the population and food web levels as well as reducing resource-user conflicts. However, the management decision to ban midwater trawling was based on scant scientific data, and no plans were put in place to evaluate the effectiveness of the decision.

In this study, we use concurrent deployment of a downwards-looking echosounder (Simrad ES60 system) and an omnidirectional sonar (Simrad SP90 system) to study the short-term impacts of fishing on pelagic fish aggregations at the scale of the aggregation (Figure 1). Previous studies have integrated downwards-looking echosounders and multibeam sonars to examine fish vessel avoidance (Lamboeuf *et al*., 1983; Misund *et al*., 1996; Soria *et al*., 1996; Mackinson *et al*., 1999) or downwards-looking echosounders and omnidirectional sonars to examine schooling behaviour and swimming dynamics of pelagic fish (Misund *et al*., 2005). Additionally, SP90 systems have been used to monitor and examine pelagic fish schools (Brehmer *et al*., 2006, 2007; Trygonis *et al*., 2009). However, we are not aware of any study that has attempted to use both downwards-looking echosounders and omnidirectional sonars to evaluate the potential impact of fishing on pelagic fish aggregations during commercial fishing operations.

### Material and methods

#### Study site and data collection

Acoustic data were collected on the FV 'Voyager', a 45 m midwater trawler based out of Gloucester, MA, USA. The 'Voyager' is equipped with Simrad ES60 echosounders and a Simrad SP90 omnidirectional sonar. Acoustic sampling was conducted during standard pairtrawl fishing operations on 7–10 July 2009 in the Gulf of Maine (Figure 2). The sister vessel always fished on the starboard side of the 'Voyager' at a range of ~125 m. Acoustic
data collected while fishing are defined as 'during' fishing. After termination of trawl tows, the 'Voyager' re-traced the last 20–30 min of its fishing path while the sister vessel pumped the catch on board. Acoustic data collected during this sampling period are defined as 'after' fishing and commenced 20–30 min after termination of trawl tows. A single additional transect was sampled acoustically by the 'Voyager', and then re-sampled similar to the 'after' fishing treatment, but no fishing occurred. Acoustic data from this transect are defined as 'control'.

To confirm that aggregations primarily consisted of Atlantic herring, several of the commercial trawl tows were sampled using standard protocols of the National Marine Fisheries Service Observer Program (National Marine Fisheries Service, 2010). Ten baskets of fish were collected prior to any sorting process while the catch was pumped on board. The ten subsamples were spaced evenly throughout the pumping process to account for any stratification that may occur while the net is alongside the vessel. Species were sorted and the composition of basket samples was used to infer acoustic targets.

**Acoustic systems**

A combination 38 and 200 kHz Simrad ES60 General Purpose Transceiver (GPT) (Andersen, 2001) was used to collect vertically oriented echosounder data. Analyses were limited to 38 kHz data. The 38/200 GPT operated a hull-mounted C38/200, single-beam transducer with 15.2° beam width at 38 kHz and a 7.2° beam width at 200 kHz (total angular width as measured at the half-power points). The transmit power was set at 1000 W and the pulse duration was 1.024 ms for the 38 kHz system. The ES60 echosounder was calibrated using the standard sphere method (Foote et al., 1987) on 2 June 2009 using a 38.1 mm diameter tungsten carbide sphere.

The Simrad SP90 is an omnidirectional multibeam sonar typically used for fishing operations (Simrad, 2007). It has an operational frequency of 26 kHz with a bandwidth of ± 4 kHz. The cylindrical transducer contains 256 elements, providing 360° coverage of the water column. The beam widths are 11° horizontal and 9° vertical, and can be tilted from +10° to –60°. Each acoustic transmission is saved as a binary file which contains sonar settings, auxiliary information (e.g. latitude, longitude, pitch, roll, etc.), and acoustic raw data. Brehmer et al. (2007) and Trygonis et al. (2009) provide complete descriptions of the SP90 system. Due to logistic constraints, the SP90 was not calibrated, but because the data used in all analyses were collected over a 2 d period and from a restricted range (200–400 m from the vessel), relative comparisons among metrics should be valid. As outlined below, thresholds of return signals were selected, and criteria for defining aggregations were used.

**Acoustic data processing**

ES60 38 kHz data were processed using Echoview software (Myriax, Ltd, version 4.90.58.16982). The echogram minimum threshold was set at –66 dB, and a 3 × 3 median filter was applied to the data to reduce noise and interference. The seabed was defined using the 'best bottom candidate' algorithm. The data were then edited to isolate targets believed to be herring aggregations based on previous experience (Jech and Michaels, 2006). Echoview’s school detection algorithm was used to outline specific aggregations, and the outlines were then applied to unfiltered data. The settings in the school detection algorithm (minimum school length = 1 m, minimum school height = 0.5 m, minimum candidate length = 1 m, minimum candidate height = 0.5 m, maximum vertical linking distance = 40 m, and maximum horizontal distance = 40 m) were comparable with the resolution of the SP90 sonar output. The SP90 has a 9° vertical beam width, which gives 40 m resolution at 200 m, so we used a 40 m vertical linking distance in the Echoview sonar detection. For each aggregation, mean $S_v$ (calculated in the linear domain) and mean shoal depth (mean depth – mean height/2) were calculated.

Data from the SP90 were processed using purpose-built routines in MatLab. Only those data ranging from –90° to 90° of the vessel (with 0° as the vessel’s heading) and between 200 and 400 m range from the vessel were processed (Figure 3) to minimize reverberation from the seabed and the potential confounding influence of the reverberation from the wake of the other fishing vessel. Data were thresholded at 18 dB, and sidelobes were removed with the following procedure. At each sample in time (i.e. each range), any values that were found to be 26 dB lower than the maximum were assumed to be backscatter appearing on a sidelobe of the beam containing the maximum value. Targets within 40 m of each other were assumed to be from the same aggregation. If an aggregation of detections touched either...
the minimum (200 m) or maximum (400 m) ranges, the aggregation was deemed ‘partial’ and was removed from subsequent analyses (Figure 3). Subsets of pings were combined in 120 s blocks. At a sustained swimming speed of 0.33 m s\(^{-1}\) (Misund, 1990), 120 s is the time it would take a fish to swim half of the maximum resolution (\(\sim 40\) m). Each subset of pings was considered a ‘snapshot’ in time and the data were clustered using the same 40 m linking distance used for each individual ping (Figure 3). Each cluster was then gridded on a 25 \(\times\) 25 m grid, and the area and perimeter were calculated. Sequential 120 s ping subsets had 50% overlap (e.g. 0–120 s, 60–180 s, 120–240 s, etc.).

**ES60 aggregations**

Aggregation detection was not concurrent between the two acoustic systems because they insonify different parts of the water column at different times. Therefore, it is difficult to confirm unequivocally that aggregations detected by each system, which appeared to overlap on or near the vessel path, were the same aggregation (‘true matches’). To work within this constraint, we estimated the distance a herring could swim between the time it takes the vessel to travel the 300 m between a SP90 detection (300 m is in the middle of the 200–400 m window range used for SP90 detections) and an ES60 detection (0 m range). At a vessel speed of 2 m s\(^{-1}\) and a maximum herring swimming speed of 1.26 m s\(^{-1}\) (Misund, 1990), a herring could swim 190 m in the time it took (150 s) for the vessel to travel 300 m. Based on these calculations, an ES60 aggregation was definitively identified as an ‘ES60-only’ aggregation if no SP90-detected aggregations occurred within a 190 m radius of the ES60 aggregation; in this case, herring could not swim fast enough to be detected by both systems. Because SP90-detected aggregations that were within 190 m of ES60 aggregations (‘ES60–SP90 match’) were probably not the same aggregation detected by the ES60 in all cases (i.e. the ES60- and SP90-detected aggregations within 190 m may or may not have been the same aggregation), two smaller ranges (30 and 110 m) similarly were used to define ES60-only aggregations and examine how results may change with different radii.

Because of (i) potential vessel avoidance by the herring; (ii) inherent differences in sonification volumes and parts of the water column relative to the fishing vessel between the ES60 and SP90 systems; and (iii) the lower dynamic range of SP90 data and a lower noise floor of the ES60 system, we expected ES60-detected aggregations defined as ES60-only to be deeper and exhibit weaker mean \(S\) compared with aggregations detected by both the ES60 and SP90 systems. The time difference between the observations of aggregations thought to be detected by both the ES60 and SP90 creates some uncertainty about what the data subset consisting of ES60–SP90 matches actually represents, and so, conservatively, comparisons of mean shoal depth and mean \(S\) were limited to ES60-only vs. all ES60 aggregations rather than ES60-only vs. ES60–SP90 match.

Data from all treatments (during fishing, after fishing, and control) were examined to test the expected patterns in the ES60-only aggregations vs. all aggregations. The Wilcoxon rank sum test was used to test for differences in the medians of mean shoal depth and mean \(S\) between ES60-only and all ES60-detected aggregations. This non-parametric test was used because data distributions were non-normal. Tests were run at different window sizes (radii of 30, 110, and 190 m) to evaluate the effect of the observational window on results. A one-tailed test with \(\alpha = 0.05\) was used to ascertain statistical significance.

**SP90 aggregations**

A number of metrics for SP90-detected aggregations were examined to better understand the distribution and behaviour of Atlantic herring aggregations in the vicinity of fishing vessels using the omnidirectional sonar. First, the number of SP90-detected aggregations on the vessel paths (‘on-path’) was compared with the number of ES60-detected aggregations. If aggregations evaded vessels at ranges of 200–400 m, the number of aggregations detected by the downwards-looking ES60 system should be lower than SP90 on-path aggregations. To define an SP90 aggregation as on or off the vessel path, the effective length, \(L = 2 \times \sqrt{\text{area}/\pi}\), of each SP90 aggregation was divided by two. The aggregation was considered to be on the vessel’s path if a circle with a radius of the effective length centred on the midpoint of the aggregation intersected the vessel’s path. Acoustic data from all during and after fishing treatments and the control were included. The Wilcoxon rank sum test was used to test for differences in the median number of aggregations detected by the SP90 system that were on the vessel path compared with the number of aggregations detected by the downwards-looking ES60 system. A one-tailed test was used and \(\alpha\) was set at 0.05.

To evaluate if vessel operations affected the behaviour of Atlantic herring aggregations, the area, perimeter, effective length, and tortuosity of SP90 aggregations were plotted as a function of distance from the vessel’s path. The mean school location, with the mean weighted by the amplitude of the detection, was used to measure the distance from the vessel path. Acoustic data from each during and after fishing treatment were pooled for this analysis. Significant trends in these metrics with distance from the vessel’s path would suggest that Atlantic herring respond to vessels at ranges of 200–400 m. Trends were tested using linear regression analysis. Tortuosity, \(R\), is a metric akin to the fractal dimension (Weber et al., 2009) and is calculated by perimeter/\(\sqrt{\text{area}}\). For a circle, \(R = 3.5\), and higher values indicate a more tortuous or fragmented aggregation shape.

**Fishing impacts**

To demonstrate how the acoustic systems could be used to evaluate the possible impacts of pairtrawling on aggregations, a number of metrics from the two acoustic systems were compared between the during and after fishing treatments. These metrics included number of aggregations km\(^{-1}\), median area, median perimeter, and median tortuosity from both acoustic systems, and median \(S\), from the ES60 system. The control treatment was also used in the comparison to illustrate the need to separate the impacts of fishing from the influence of the vessels and/or ‘normal’ fish behaviour. Because of small sample sizes (\(n = 4\) during and after comparisons and \(n = 1\) control), a quantitative analysis was not feasible. However, data were qualitatively evaluated against a 1:1 line, which is indicative of no change during and after fishing, to provide a preliminary examination of patterns to be considered for future work.

**Results**

**Catch composition**

Acoustic data from four pairtrawl fishing tows were analysed. Tow durations lasted from 2.3 to 3.3 h, and estimated harvest ranged from 146 250 to 247 475 kg per tow (Table 1). Catch composition, based on biomass, was 99.6% and 99.8% Atlantic herring for two
of the four tows examined (Table 1). These data suggest that almost all of the biomass observed with the acoustic systems was probably Atlantic herring.

ES60 aggregations
A total of 74 ES60-detected aggregations were identified. The median shoal depth of ES60-only aggregations was deeper than the median shoal depth of all aggregations at a window radius of 190 m (65 m vs. 19 m; \( p = 0.045 \)), but not at window radii of 110 m (\( p = 0.195 \)) and 30 m (\( p = 0.107 \)) (Figure 4a). Median \( S_v \) was not different between ES60-only and all aggregations at window radii of 190 (\( p = 0.080 \)) and 110 m (\( p = 0.199 \)), but was significantly less at a window radius of 30 m (\(-58.3 \text{ dB} \) vs. \(-55.0 \text{ dB}, \ p = 0.033 \)) (Figure 4b).

SP90 aggregations
Of the 615 aggregations detected by the SP90 system, 99 intersected the vessel path. The number of on-path detections per transect ranged from 0 to 31 aggregations, with a median of 9.5, while the number of aggregations per transect for the ES60 system ranged from 0 to 15, with a median of 7. There was no statistically significant difference between medians (\( p = 0.352 \)).

Area estimates of SP90 aggregations ranged from 1875 to 139375 m\(^2\), with a median (1st and 3rd quartiles) of 10 625 (6875, 18 600) m\(^2\). Perimeter estimates ranged from 200 to 4200 m, with a median of 550 (400, 837.5) m; effective length from 48.9 to 421.3 m, with a median of 116.3 (93.6, 153.9) m; and tortuosity from 4.0 to 12.0, with a median of 5.3 (4.8, 6.4). No significant trends were found with distance from the vessel path for any of the aggregation metrics and treatments.

Fishing impacts
The number of aggregations km\(^{-1}\) was similar for the ES60 data, the controls for each acoustic system, and two of the four SP90 observations. The two transects with the largest number of SP90-detected aggregations km\(^{-1}\) during fishing were relatively distant from the 1:1 line, suggesting a drop in the number of aggregations after fishing in these instances (Figure 5a). The median area of ES60-detected aggregations was lower after fishing compared with during fishing in three of the four pairtrawl tows, but the area for the control transect was also lower in the after treatment compared with during (Figure 5c). Similar results were observed for area of SP90-detected aggregations, although differences between during and after were less pronounced than for the ES60 data (Figure 5d). Aggregation perimeter estimates during and after fishing were similar for the SP90 aggregations, but the ES60 data tended to show decreases after fishing (Figure 5e). However, once again, the control for the ES60 data also showed a decrease in the after treatment. Tortuosity did not deviate substantially from the 1:1 line for both systems (Figure 5f). Estimates of \( S_v \) from the ES60 system were lower in three of the four pairtrawl tows after fishing, but the control treatment also showed a similar decrease (Figure 5b).

Discussion
We evaluated the use of two very different acoustic systems to characterize the potential impacts of pairtrawl fishing on Atlantic herring at the time and space scale of actual fishing. Downwards-looking echosounders are standard in both scientific surveys and commercial fishing operations, but may be limited in their ability to assess potential impacts of fishing on aggregations because sampling is limited to directly beneath vessels. Omnidirectional sonars such as the SP90 provide a different and complementary view of fish aggregations in that fish may be observed hundreds to thousands of metres away from the vessel.
in all directions, search volume is much greater, and areas near the surface that are difficult to assess with downwards-looking echo-sounders are readily sampled with SP90s. However, omnidirectional sonars provide other challenges, including reverberation from the seabed and ship wakes, variation of target strength as a function of fish orientation (e.g. Cutter and Demer, 2007), potential issues related to sound wave refraction (not considered here), and difficulties in obtaining valid calibrations.

The results show that when no aggregations were detected with the omnidirectional sonar, the aggregations detected by the downwards-looking echosounder were deeper. This suggests a potential weakness in the SP90 for detecting ‘deeper’ aggregations and is consistent with our initial expectation that the ES60 may be better at detecting deeper aggregations. The tilt angle of the SP90 was close to horizontal during fishing operations. Changing the angle presumably would have impacted fishing operations. Additionally, we limited our analyses to SP90 data at a range of 200–400 m to limit reverberation from the seabed. Thus, we were less likely to detect deeper aggregations as a result of our sampling and analytical methodology. Further work that compares data collected on submerged buoys, or data collected on the same aggregation with the SP90 in a downwards-looking mode and the ES60, would help resolve these questions.

Our limited observations suggest a range of possibilities with regard to vessel avoidance by Atlantic herring. On the one hand, there appeared to be no difference in the number of aggregations km\(^{-1}\) during and after fishing in all three ES60 comparisons, two of the four SP90 comparisons, and the two controls. Additionally, we found no consistent trends in the area, perimeter, effective length, or tortuosity of SP90-detected aggregations with distance from the vessel path. Overall, these results suggest that fish behaviour, as measured by these metrics for our limited number of
observations, did not change in response to the vessels. On the other hand, the relatively large deviations for two of the SP90 comparisons (see Figure 5a) suggest that fishing operations and/or avoidance may have occurred in these two instances. Additionally, the fewer on-path detections with the ES60 compared with the SP90 suggest fishing avoidance. The difference in on-path detection between ES60 and SP90 was not statistically significant, but this may be an artefact of low power to detect a difference given our small sample size. Collectively, our results are consistent with other studies suggesting that vessel avoidance is not a consistent behaviour (e.g. De Robertis and Wilson, 2006; De Robertis et al., 2008). Future application of concurrent downwards-looking and omnidirectional sonars could provide real-time, in situ observations of fish during fishing activities to help resolve these questions and provide a means to correct for bias due to fish avoidance.

The chosen criteria for selecting aggregations within the 200–400 m range of the SP90 sonar inherently filter the observations and thus influence interpretations. For example, large and small aggregations may not have the same chance of being selected given that ‘partial’ aggregations (those that overlapped with the 200 or 400 m range boundaries) were removed from analyses. Additionally, distance from the vessel track depended on the distribution of aggregations relative to the vessel’s orientation, which was influenced by fishing decisions; an aggregation detected at 0° to the vessel’s heading would have a shorter distance to the vessel track than an aggregation detected at 45° to the vessel’s heading. Pairtrawling attempts to place fish aggregations in the path of the midwater trawl, between the two vessels, so active fishing operations may ‘select for’ aggregations that have larger distances to the vessel track. In the future, simulation modelling of various sampling designs could help resolve potential biases associated with these types of studies.


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