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Executive Summary

- The original goal of this two-year project was to address priority 1 in the Federal Funding Opportunity, "Define localized depletion of herring on a spatial and temporal scale; further develop hydroacoustic surveys to provide and independent means to estimate stock sizes and/or define localized depletion (long-term research possibilities)".
- Due to logistical and budget constraints, efforts were re-focused to evaluate the use of available acoustic gear on commercial fishing boats (i.e., ES60 echosounders and SP90 omni-directional sonar) for assessing the possible impacts of paired midwater trawling on herring aggregations.
- Only 71% of the total available RSA quota (3,300 mt) was harvested. Consequently, only 71% of the projected budget was realized to support this project. Table 1 lists the herring catch and estimated bycatch for monitored trawl tows.
- We attempted to execute a before-after-control-impact (BACI) design in 2009 based on pilot work in 2008. However, sample sizes were low because of reduced budget.
- Because of small sample sizes, drawing conclusions from the results is not advised. However, this project has laid the groundwork for future studies to examine the potential impacts of midwater trawling on herring aggregations.
- A manuscript detailing the results of this work and outlining future collaborative studies is attached, and will be submitted ICES Journal of Marine Science or Fisheries Research.
- The Herring RSA program, if resurrected, can be improved by 1) harvesting the RSA quota a year in advance so that exact funding levels are known for executing projects, and 2) RSA quota is allocated from management areas where TACs are fully realized. Otherwise, awardees run the risk of falling short on funding.

Table 1. Estimated catch composition (kg) from pilot work in 2008 and from trawl tows in 2009 in Area 1A. Note approximately 300 mt of additional RSA quota was harvested in 2008 from Area 1A, but not during pilot work. "n/a" = not available.

Event	Vessel	Date	Atlantic herring	Alewife	Spiny dogfish	Blueback herring	Atlantic mackerel	Other[3]
Tow 1	CHR	10/30/08	181,313	127	84	0	0	0
Tow 2	CHR	10/31/08	126,970	0	117	0	0	38
Tow 2	VOY	10/31/08	81,648	0	0	0	0	0
Tow 1	EDR	11/17/08	198,481	1,420	46	0	0	100
Tow 2	EDR	11/17/08	159,681	144	30	0	0	187
Tow 2	VOY	11/17/08	58,892	53	0	0	0	0
Tow 1	CHR	11/24/08	121,801	n/a	n/a	n/a	n/a	n/a
Tow 2	CHR	11/24/08	127,679	516	203	116	674	13
A	CHR	7/7/09	249,455	0	907	0	0	25
B	EDR	7/7/09	126,995	0	4,536	0	0	3
C[2]	CHR	7/8/09	13,153	10	5,794	0	0	94
D	EDR	7/8/09	217,706	0	454	0	0	23
E & F[1]	CHR	7/9-7/10/09	294,840	n/a	n/a	n/a	n/a	n/a

[1]E&F estimates were based on Vessel Trip Report. Observation of catch was not available.
[2]Event C was terminated early due to lack of Atlantic herring and presence of dogfish.
[3]Other:
Tow 2 (10/31/08, CHR) = shortfin squid
Tow 1 (11/17/08, EDR) = silver hake, American shad
Tow 2 (11/17/08, EDR) = shortfin squid
A = silver hake
B = hake
C = silver hake, shortfin squid
D = hake

On the use of omni-directional sonars and downward-looking echosounders to assess pelagic fish distributions during and after midwater trawling

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Keywords: acoustics, omni-directional multibeam, Atlantic herring, aggregations, midwater trawling

Abstract

The sustainability of pelagic fisheries at a global scale is a contemporary topic in fisheries research and management. Small pelagic fishes 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 considerably less attention, with most of this effort devoted to impacts of vessel and gear avoidance on stock size estimates. We used concurrent deployment of a downward-looking echosounder (Simrad ES60 system) and an omni-directional sonar (Simrad SP90 system) during commercial pair trawling operations for Atlantic herring (*Clupea harengus*) in the Gulf of Maine to examine their potential for studying the impacts of fishing on their 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 pair trawling events to illustrate potential applications. Our results suggest that using both downward-looking and omni-directional systems provides complementary information on fishing aggregation metrics. Future application of these systems in a before-after-control-impact (BACI) design will help quantitatively inform management decisions that allow/restrict specific fishing operations.

Key words: acoustics, aggregation, Atlantic herring, midwater trawling, pelagic

Introduction

The impacts of fishing are typically examined in terms of direct effects, with attention focused on identifying, reversing, or mitigating negative impacts such as overfishing (Jackson, 2001; Lotze *et al*., 2006; Worm *et al*., 2009), seabed disturbance and destruction (Auster *et al*. 1996; Collie *et al*. 2005; Kaiser *et al*. 2006), bycatch of threatened or endangered species (Lewison *et al*. 2004; Brewer *et al*. 2006; Moore *et al*. 2009), and alteration of food webs (Daskalov 2002; Richardson *et al*. 2009; Shackell *et al*. 2010). In combination with other anthropogenic perturbations such as eutrophication and climate change, the negative impacts of fishing can contribute to the erosion of ecological function and socio-economic stability (Vasas *et al*. 2007; Jackson 2008; Kirby *et al*. 2009; Kahn and Neis 2010).

Fishing also may have indirect impacts or impacts that operate at smaller temporal or spatial scales, although these potential impacts have received less attention. Fishing has been shown to affect species interactions and behavior (see review in He 2010), as well as provide resource subsidies that otherwise would not exist. For example, Atlantic herring (*Clupea harengus*) bait in the American lobster (*Homarus americanus*) fishery in the Gulf of Maine may provide a resource subsidy to juvenile lobsters, enhancing lobster growth and economic value (Grabowski *et al*. 2010). Bluefin tuna (*Thunnus thynnus*) have been observed to aggregate around and follow commercial fishing boats to feed on escaping fish, discards, and entrails (Walter Golet, University of Maine, pers. comm.). Predation by scavenging fish after seabed disturbance by bottom trawls also has been implicated in the decline of benthic invertebrates (Kenchington *et al*. 2005).

The potential impacts of fishing at temporal and spatial scales that match distributional patterns of pelagic fishes may be substantial. Aggregations such as schools and shoals can

concentrate foraging activities of predators and fishing fleets alike. There is growing concern over the sustainability of fisheries operating on such fishes at a global scale (e.g., Peruvian anchovy *Engraulis ringens*, Atlantic herring, blue whiting *Micromesistius poutassou*; Naylor *et al*. 2009; Tacon and Metian 2009), but concern at local scales is also growing. For example, midwater trawling for Atlantic herring was banned in the Gulf of Maine each year from June 1 to September 30 starting in 2007 out of concern for depleting local aggregations to the detriment of various stakeholder groups and ecological processes (e.g., Lee 2010). Although much research has been devoted to the interaction of pelagic fishes with fishing gear, the focus has been almost entirely on survey assessments (Olsen, 1971; Olsen *et al*., 1983; Misund and Aglen, 1992; Mitson, 1995; Misund 1997; Misund and Coetzee, 2000; Vabø *et al*., 2002; Hjellvik *et al*., 2008) with little effort devoted to impacts on the structure and function of the aggregation themselves. Because of the important role small pelagic fishes 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 local scales is necessary from both ecological and management perspectives.

In this study, we use concurrent deployment of a downward-looking echosounder (Simrad ES60 system) and an omni-directional sonar (Simrad SP90 system) to examine their potential for studying the impacts of fishing on pelagic fish aggregations at the scale of the aggregation (Figure 1). Previous studies have integrated downward-looking echosounders and multibeam sonars to examine fish avoidance (Lamboeuf *et al*., 1983; Misund *et al*., 1996; Soria *et al*., 1996; Mackinson et al. 1999) or downward-looking echosounders and omni-directional sonars to

examine schooling behavior and swimming dynamics of pelagic fishes (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 downward-looking echosounders and omni-directional sonars to evaluate the potential impact of fishing on pelagic fish aggregations during commercial fishing operations.

We first characterize Atlantic herring aggregations detected by the ES60 system using metrics of volume backscattering (S_v) and shoal depth of aggregations. Because of i) potential vessel avoidance by the herring, ii) inherent differences in insonification volumes and parts of the water column relative to the fishing vessel between the ES60 and SP90 systems, and iii) lower dynamic range of SP90 data and a lower noise floor of the ES60 system, we expected aggregations only detected by the ES60 system to be deeper and exhibit weaker S_v compared to aggregations detected by both the ES60 and SP90 systems. Next, we estimated the number of SP90-detected aggregations that were on the fishing vessel track to assess the availability of herring aggregations to downward-looking echosounders for assessments of fishing impacts on aggregations. Further, we examined several metrics of the SP90-detected aggregations (area, effective length, perimeter, and tortuousity) as a function of distance from the vessel track to explore possible changes in fish behavior, which would suggest a response by fish to an approaching vessel. We conclude by comparing aggregation metrics during and immediately after commercial pair-trawl tows, and discuss how these acoustic systems could be used as a basis for assessing the immediate impacts of midwater trawling on pelagic fish aggregations.

Materials 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 omni-directional sonar. Acoustic sampling was conducted during standard pair trawl fishing operations on July 7-10, 2009 in the Gulf of Maine (Figure 2). Acoustic data collected while fishing are defined as "during" fishing. After termination of trawl tows, the "Voyager" re-traced the last 20 to 30 minutes of its fishing path while the sister vessel pumped the catch onboard. Acoustic data collected during this sampling period are defined as "after" fishing. 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 aggregations primarily consisted of Atlantic herring, several of the commercial trawl tows were sampled using standard protocols of 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 onboard. 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 weighed separately in aggregate. Composition of basket samples was used to infer acoustic targets.

Acoustic systems

The "Voyager" has two Simrad ES60 General Purpose Transceivers (GPT) (Andersen 2001). The first was a combination 50-, 120-, and 200-kHz GPT and the second a combination 38- and 200-kHz GPT. The 200-kHz capability of the first GPT was not used during data collection. The

transducers were hull mounted. The 50/200/120 GPT operated a C50/200, single-beam transducer with 13.5^{o} beam width (50 kHz) and an ES120-7C split-beam transducer with 7° beam width (total angular width as measured at the half-power points). The transmit power was set at 1000 W and 0.512 ms pulse duration for the 50- and 120-kHz systems. The 38/200 GPT operated a C38/200, single beam transducer with 15.2^{o} beam width at 38 kHz and 7.2^{o} beam width at 200 kHz. The transmit power was set at 1000 W for both frequencies. The pulse durations were 1.024 ms and 0.256 ms for the 38-kHz and 200-kHz system, respectively.

The ES60 echosounders were calibrated using the standard sphere method (Foote et al., 1987) on 2 June 2009. The 120-kHz split-beam was used to center a 38.1 mm tungsten carbide sphere in the 50/200/120 beam. The sphere was then maneuvered in the 38/200 beam. The gain settings were applied to the GPTs prior to data acquisition as follows: 38 kHz, No TVG = 49, School = 80, Fish = 66, Bottom = 69; 50 kHz, No TVG = 0; School = 81; Fish = 69; Bottom = 71; 120 kHz, No TVG = 1; School = 99; Fish = 87; Bottom = 71; 200 kHz, No TVG = 1; School = 85; Fish = 91; Bottom = 66.

The Simrad SP90 is an omni-directional multibeam sonar typically used for fishing operations (Simrad, 2007). It has an operational frequency of 26 kHz with a band width 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. Because the objective of using the SP90 was to detect presence/absence of fish aggregations, the SP90 was

not calibrated. As outlined below, thresholds of return signals were selected and criteria for defining aggregations used.

Acoustic data processing

Data from the ES60 systems were processed using Echoview software (Myriax, Ltd., version 4.90.58.16982). We limited our analyses to 38-kHz data. The echogram minimum threshold was set at -66 dB and a 3 x 3 median filter was applied to the data to reduce noise and interference. The seafloor was defined using a best bottom candidate line pick algorithm. The data were then edited to isolate targets believed to be herring aggregations based on prior 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 to 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 school detection. For each aggregation, mean S_v 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 270 to 90˚ of the vessel (with 0˚ as the vessel's heading) and within 200 to 400 m range from the vessel were processed to minimize reverberation from the seafloor 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. Any values 26 dB lower than the maximum, at a given range, were assumed to be a sidelobe. 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. Subsets of pings were combined in 120 second blocks. At a sustained swimming speed of 0.33 m/s (Misund 1990), 120 seconds is the time it would take a fish to swim half of the maximum resolution (~ 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. Each cluster was then gridded on a 25 x 25 m grid, and the area and circumference were calculated. Sequential 120 second ping subsets had 50% overlap (e.g., 0-120 seconds, 60-180 seconds, 120-240 seconds, etc.).

ES60 aggregations

Aggregation detection was not concurrent between the two acoustic systems because they ensonify different parts of the water column at different times. Therefore, it is difficult to unequivocally confirm 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, a 300 m range (half-way between 200 and 400 m), a vessel speed of 2 m/s, and a maximum herring swimming speed of 1.26 m/s (Misund 1990) were used to estimate a range of 190 m over which a herring could swim during the 150 s between SP90 detection at 300 m range and ES60 detection at 0 m range. A190-m (horizontal) radius around the detected ES60 aggregations was used to account for possible fish movement between detection with the SP90 (at a range of 200 to 400 m) and detection with the ES60 (range 0 m). This process definitively identified an "ES60-only" aggregation if no SP90-detected aggregations occurred within the 190-m radius. Because SP90-detected aggregations that were within 190 m of ES60 aggregations ("ES60-SP90 match") likely were 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.

The ES60-detected aggregations defined as ES60-only were expected to be deeper and weaker (lower S_v) than those defined as ES60-SP90 match, because the SP90 field of view was limited to an 11˚ pointing nearly horizontal, and because the dynamic range of the SP90 was far less than that of the ES60. The time-difference between the observations of aggregations thought to be detected by both the ES60 and SP90 create some uncertainty about what the data subset consisting of ES60-SP90 matches actually represent and so, conservatively, comparisons of shoal depth and S_v were limited to ES60-only versus all ES60 aggregations rather than ES60-only versus 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 versus all aggregations. The Wilcoxon rank sum test was used to test for differences in the medians of mean shoal depth and mean S_v between ES60-only and all ES60-detected aggregations. This nonparametric 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 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 behavior of Atlantic herring aggregations in the vicinity of fishing vessels using the omni-directional sonar. First, the number of SP90-detected aggregations on the vessel paths ("on-path") was compared to the number of ES60-detected aggregations. If aggregations evaded vessels at ranges of 200 to 400 m, the number of aggregations detected by the downward-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*sqrt(area/π), of each SP90 aggregation was divided by two. The aggregation was considered on the vessel's path if a circle with a radius of the effective length centered 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 to the number of aggregations detected by the downward-looking ES60 system. A one-tailed test was used and α was set at 0.05.

To evaluate if vessel operations affected the behavior of Atlantic herring aggregations, the area, perimeter, effective length, and tortuousity 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 treatments were pooled for this analysis. Significant trends in these metrics with distance from the vessel's path would suggest Atlantic herring respond to vessels at ranges of 200 to 400 m. Trends were tested using linear regression analysis. Tortuousity, R, is a metric akin to the fractal dimension (Weber et al. 2009) and is calculated by perimeter/sqrt(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 pair trawling 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, median area, median perimeter, and median tortuousity from both acoustic systems and median S_v from the ES60 system. The control treatment also was used in the comparison to illustrate the need to separate the impacts of fishing from the influence of the vessels and/or "normal" fish behavior. 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 pair trawl fishing tows were analyzed. Tow durations lasted from 2.3 to 3.3 hrs and estimated harvest ranged from 146 250 to 247 475 kg/tow (Table 1). Catch composition, based on biomass, was 99.6 and 99.8% Atlantic herring for 2 of the 4 tows examined (Table 1). These data suggest almost all of the biomass observed with the acoustic systems was likely Atlantic herring.

ES60 aggregations

A total of 74 ES60-detected aggregations were identified. Median shoal depth of ES60-only aggregations was deeper than median shoal depth of all aggregations at a window radius 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 3). Median S_v was no 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 dB vs -55.0 dB, P = 0.033) (Figure 4).

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 31aggregations 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 1 875 to 139 375 m^2 with a median (1st and 3rd quartiles) of 10 625 (6 875, 18 600) m^2. Perimeter estimates ranged from 200 to 4 200 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 tortuousity 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 (Figure 5).

Fishing Impacts

The number of aggregations/km is 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 during fishing were relatively distant from the 1:1 line, suggesting a drop in the number of aggregations after fishing in these instances (Figure 6a). Median area of ES60-detected aggregations was lower after fishing compared to during fishing in three of the four pair trawl tows, but the area for the control transect was also lower in the after treatment compared to during (Figure 6c). Similar results were observed for area of SP90-detected aggregations, although differences between during and after were less pronounced than the ES60 data (Figure 6d). Aggregation perimeter estimates during and after fishing were similar for the SP90 aggregations, but the ES60 data tended to show decreases after fishing (Figure 6e). However, once again, the control for the ES60 data also showed a decrease in the after treatment.

Tortousity did not deviate substantially from the 1:1 line for both systems (Figure 6f). Estimates of S_v from the ES60 system were lower in three of the four pair trawl tows after fishing, but the control treatment also showed a similar decrease (Figure 6b).

Discussion

We evaluated the use of two very different acoustic systems to characterize the potential impacts of pair trawl fishing on Atlantic herring at the time and space scale of actual fishing. Downward-looking echosounders are standard use 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. Omni-directional sonars provide a different and complementary view of fish aggregations in that fish may be observed prior to any possible reaction to vessels, search volume is much greater, and areas near the surface that are difficult to assess with downward-looking echosounders are readily sampled with SP90s. However, omni-directional sonars provide other challenges including reverberation from the seabed and shipwakes, variation of target strength as 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.

Our results show that when no aggregations were detected with the omni-directional sonar, the aggregations detected by the downward-looking echosounder were deeper. This demonstrates 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 aggregations closer to the sea floor. 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 to 400 m to limit reverberation from the sea floor. Thus, we were less likely to detect deeper aggregations as a result our sampling and analytical methodology. Further work that compares data collected on the same aggregation with the SP90 in a downward-looking mode and the ES60 would help resolve these questions.

Our observations suggest the herring were not actively avoiding the fishing vessel – at least within a 400-m range to the vessel. For example, there was no difference between the number of SP90 aggregations/km and the number of ES60 aggregations/km and we found no consistent trends in the area, perimeter, effective length, or tortuousity of SP90-detected aggregations with distance from the vessel path. These results suggest fish behavior, as measured by these metrics, did not change in response to the vessels. Because vessel avoidance is not a consistent behavior (e.g., De Robertis and Wilson 2006; De Robertis et al. 2008) and can be influenced by a multitude of environmental (physical and biological) factors, it is important to garner as much information as possible under as many conditions as possible before generalizations can be proffered or management actions taken in response to trawling activity.

Investigations on the impacts of vessels and fishing operations on pelagic fishes have largely focused on the consequences of fish avoidance during fishery independent acoustic and trawl surveys (e.g., De Robertis et al. 2008). Understanding how pelagic fishes interact with and react to survey vessels is of great consequence for estimating stock size (Misund, 1997; Fréon and Misund, 1999). However, the ecological impacts of fishing on abundant pelagic forage fishes, at the time and space scales of actual fishing operations, has received very little attention. The time and space scales of actual fishing are the same scales that other predators (e.g., marine mammals, seabirds, piscivorous fishes) or indirect consumers (e.g., ecotourism, tuna industry) make use of concentrated but ephemeral aggregations of forage fishes. Fishing, by definition, removes fish

and thus may represent interference competition with these other predators and user groups. Our results suggest that using both downward-looking and omni-directional systems, both during and immediately after fishing, can provide the level of information needed to inform management decisions that may allow/restrict specific fishing operations. The omni-directional system increases the number of observed aggregations, which potentially improves our ability to characterize the spatial distribution and behavior of these herring, while the downward-looking echosounders provide scientifically proven quantitative metrics for those aggregations that overlapped both systems.

Although the comparison of aggregation metrics during and after pair trawl fishing was limited to a few observations, our results suggest future work would greatly benefit from implementing a before-after-control-impact (BACI) design (Smith 2002). Our results suggested some metrics decreased after fishing (e.g., S_v, area, and perimeter estimates from ES60 data and aggregations/km estimates for SP90 data for the larger estimates), but in many of these cases the single control observation also suggested a decrease. The inclusion of the control-impact treatment in future studies will be critical for proper evaluation, but will likely be the most logistically difficult to implement because the control treatment would result in lost fishing and searching time and increased fuel costs.

There is growing interest in using fishing vessels to conduct scientific investigations (ICES 2007). Commercially-available echosounders have been used by commercial operators for decades to find and target fish aggregations. The ability to record acoustic data from these systems has greatly increased the potential for fisheries assessments and research through i) collection of data during actual fishing operations, and ii) contracting fishing vessels as research platforms. A number of studies demonstrate the usefulness of working cooperatively and

collaboratively with fishing industry members that use commercial echosounders with data recording capability (Melvin *et al*., 2002; Neilson *et al*., 2002; Shen *et al*. 2009). Recent application of commercial omni-directional sonars for research purposes, alone or with downward-looking echosounders, demonstrates the potential for these systems to increase scientific understanding (Melvin *et al*., 2002; Misund *et al*., 2005; Brehmer *et al*., 2006, 2007). Moreover, these omni-directional sonars provide an opportunity to examine fish distributions up to 100s or 1000s of m away from the moving vessel and thus overcome concerns of fish reaction. Our demonstration highlights the potential for using both downward-looking echosounders and omni-directional sonars, which are common to commercial fishing vessels targeting pelagic fishes, to evaluate the impacts of fishing at time and space scales that are relevant to individual aggregations and that may serve as proxies to predator-prey interactions.

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Table 1. Estimated catch composition (kg) for observed trawl catches (Events A and D). Estimates of total tow duration and Atlantic herring catch for Events E and F were based on vessel trip reports and are reported as the average of the two events. “n/a” denotes observation of catch was not available.

Event	Vessel	Date	Tow duration (hrs)	Atlantic herring	Spiny dogfish	Silver hake
A	CHR	7/7/09	3.3	247 475	900	25
D	EDR	7/8/09	3.0	215 978	450	22
E	CHR	7/9/09	2.3	146 250	n/a	n/a
F	CHR	7/10/09	2.3	146 250	n/a	n/a

Figure Captions

Figure 1. Example visualization of data from concurrently deployed SP90 and ES60 systems on 7 July 2009 at approximately 23:20 GMT. The vertical scale is exaggerated by four times for presentation purposes. The ES60 data are S_v (in dB) and the SP90 data are in relative units (dB, uncalibrated).

Figure 2. Area of pair trawl fishing operations (stippled box) where acoustic sampling was conducted from July 7 to 10, 2009, in the Gulf of Maine.

Figure 3. Median shoal depth of ES60-only versus all ES60-detected aggregations as function of horizontal windows of (a) 30 m, (b) 110 m, and (c) 190 m radii used to define ES60-only aggregations. Only those ES60-detected aggregations without SP90-detected aggregations within the window radii were classified as ES60-only. Error bars represent 1st and 3rd quartiles.

Figure 4. Median volume backscattering (S_v) of ES60-only versus all ES60-detected aggregations as function of horizontal windows of (a) 30 m, (b) 110 m, and (c) 190 m radii used to define ES60-only aggregations. Only those ES60-detected aggregations without SP90-detected aggregations within the window radii were classified as ES60-only. Error bars represents 1st and 3rd quartiles.

Figure 5. Area (a, b), perimeter (c, d), effective length (e, f), and tortuousity (g, h) of aggregations detected by the SP90 omni-directional sonar, as a function of distance from the vessel path, during (left column) and after (right column) pair trawl fishing.

Figure 6. Comparison of aggregation metrics of ES60 and SP90 data during and after commercial pair trawl fishing: number of aggregations/km (a); median S_v for aggregations detected by the ES60 system (b); median area, plotted on two separate graphs because of

discrepancies in scales (c, d); median perimeter (e); and median tortuousity (f). The legend for each panel is located in panel f. Control data represent during-after comparisons with no fishing taking place.

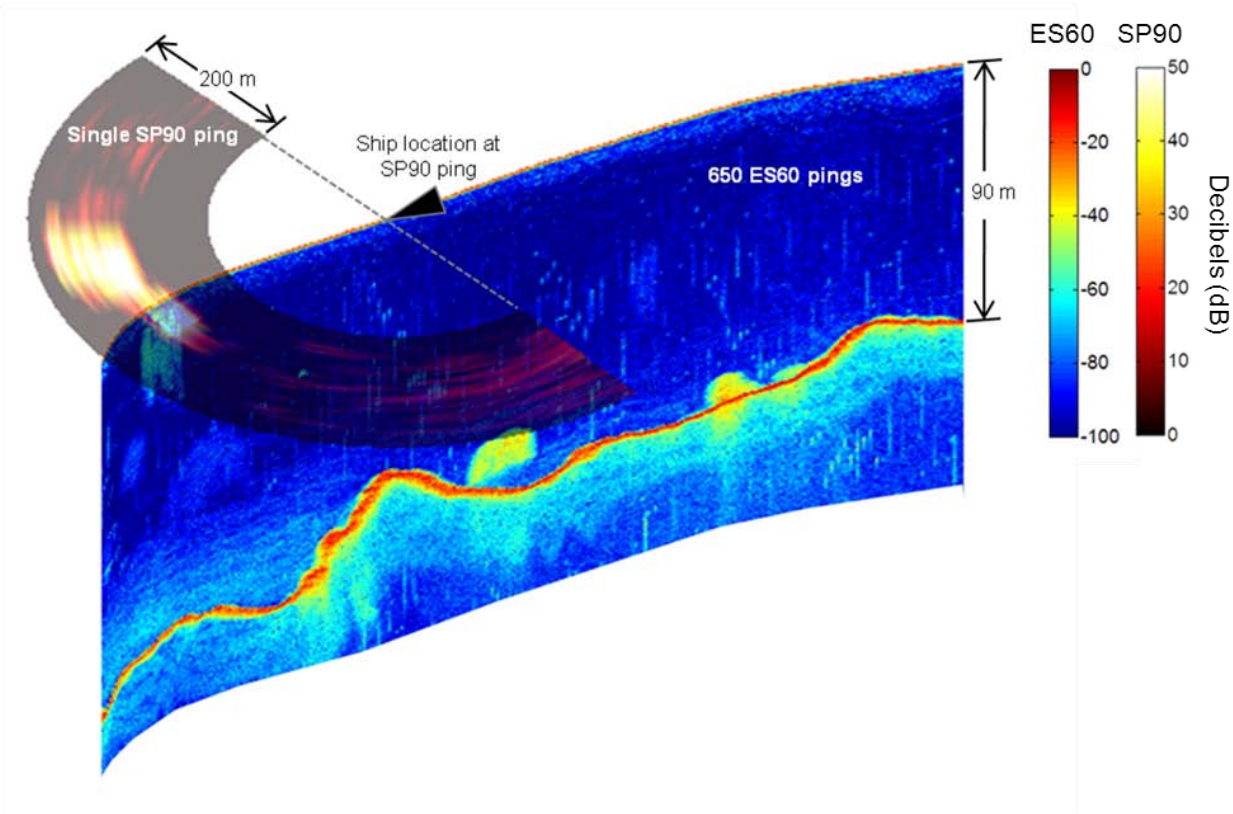
200 m
Single SP90 ping
Ship location at
SP90 ping
650 ES60 pings
90 m
ES60
SP90
0
-20
-40
-60
-80
-100
50
40
30
20
10
0
Decibels (dB)

Figure 1

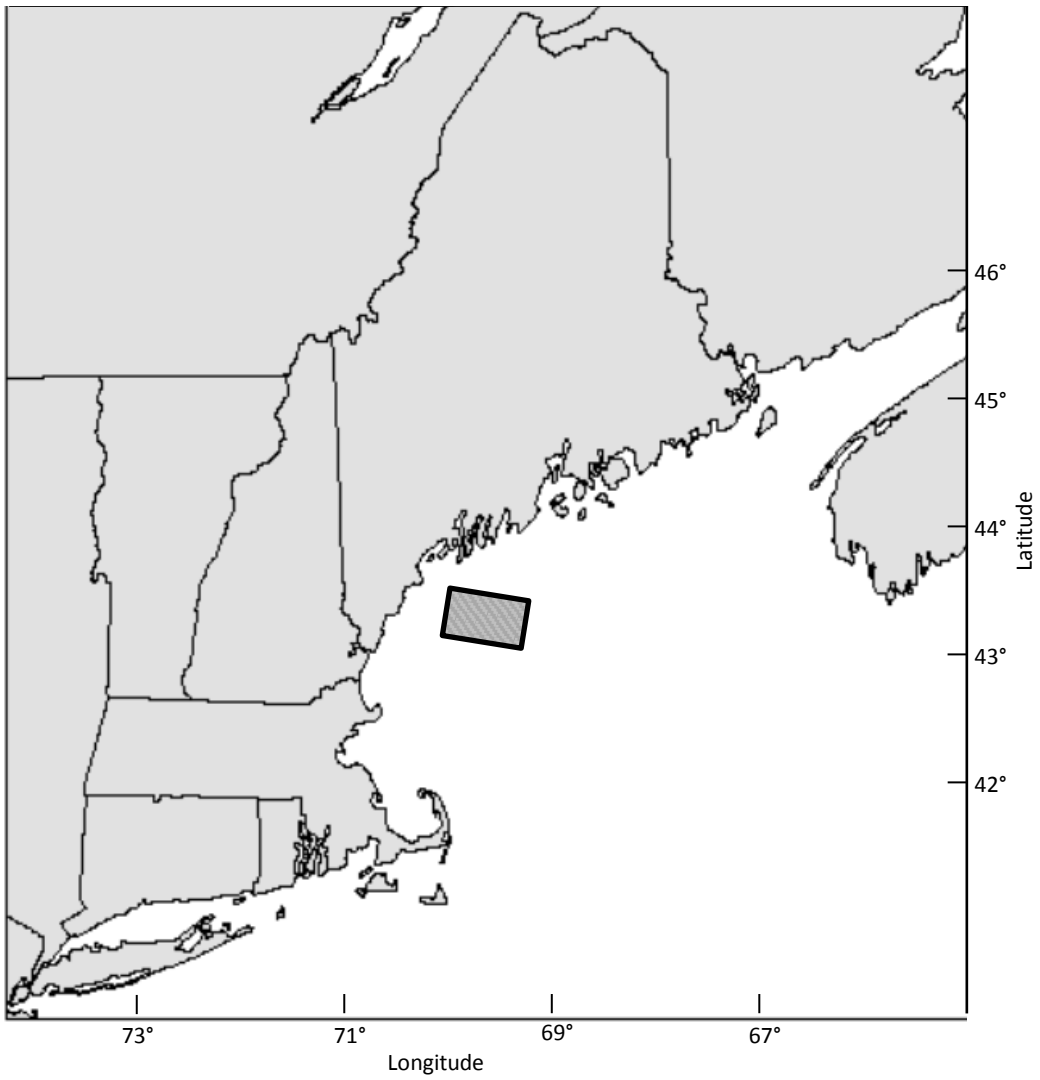

Figure 2

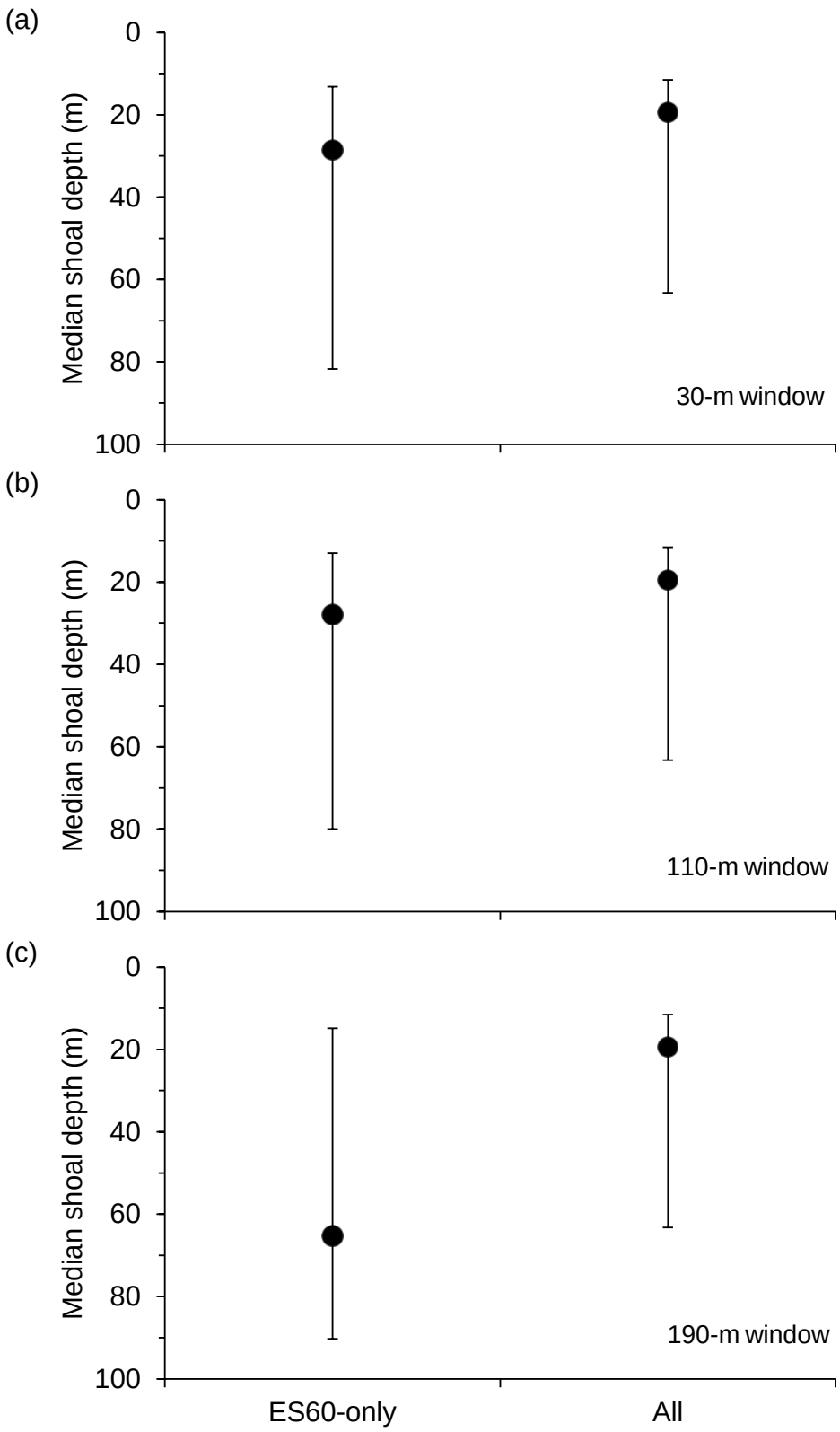
(a)
Median shoal depth (m)
0
20
40
60
80
100
30-m window
(b)
Median shoal depth (m)
0
20
40
60
80
100
110-m window
(c)
Median shoal depth (m)
0
20
40
60
80
100
190-m window
ES60-only
All

Figure 3

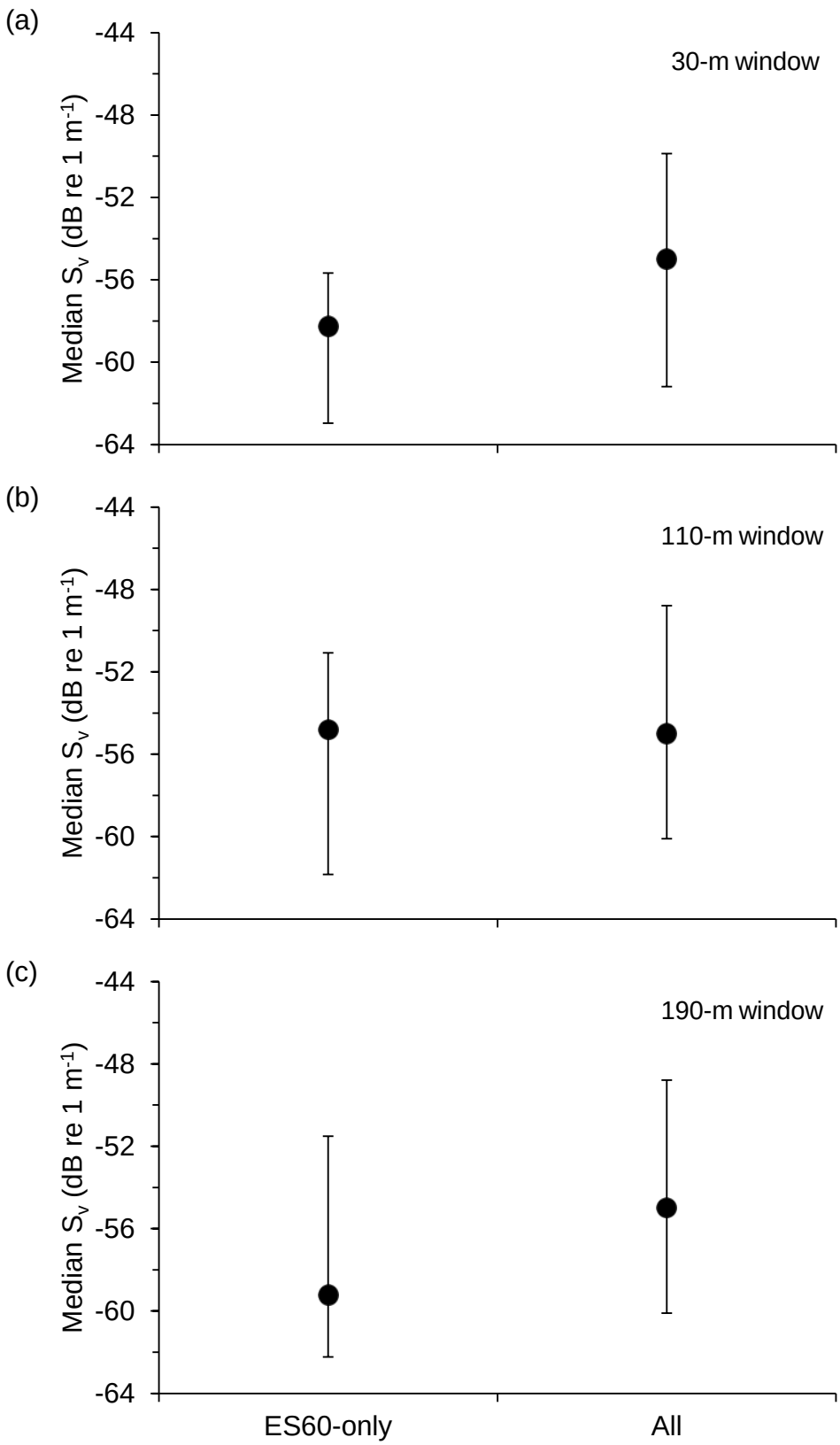
(a)
30-m window
Median S_v (dB re 1 m^{-1})
-44
-48
-52
-56
-60
-64
(b)
110-m window
Median S_v (dB re 1 m^{-1})
-44
-48
-52
-56
-60
-64
(c)
190-m window
Median S_v (dB re 1 m^{-1})
-44
-48
-52
-56
-60
-64
ES60-only
All

Figure 4

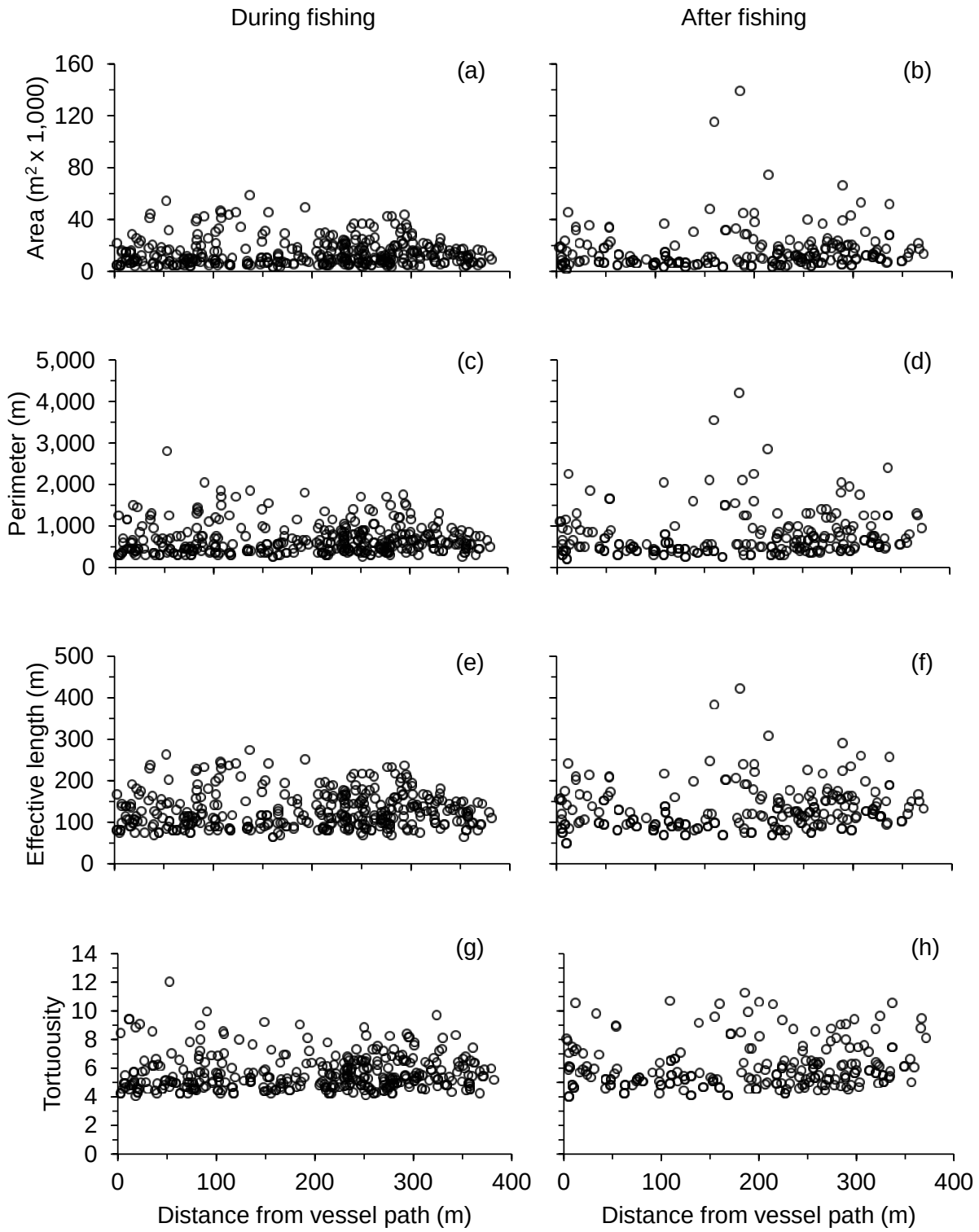
During fishing
After fishing
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Area (m2 x 1,000)
Perimeter (m)
Effective length (m)
Tortuousity
0
40
80
120
160
1,000
2,000
3,000
4,000
5,000
100
200
300
400
2
4
6
8
10
12
14
Distance from vessel path (m)
Distance from vessel path (m)

Figure 5

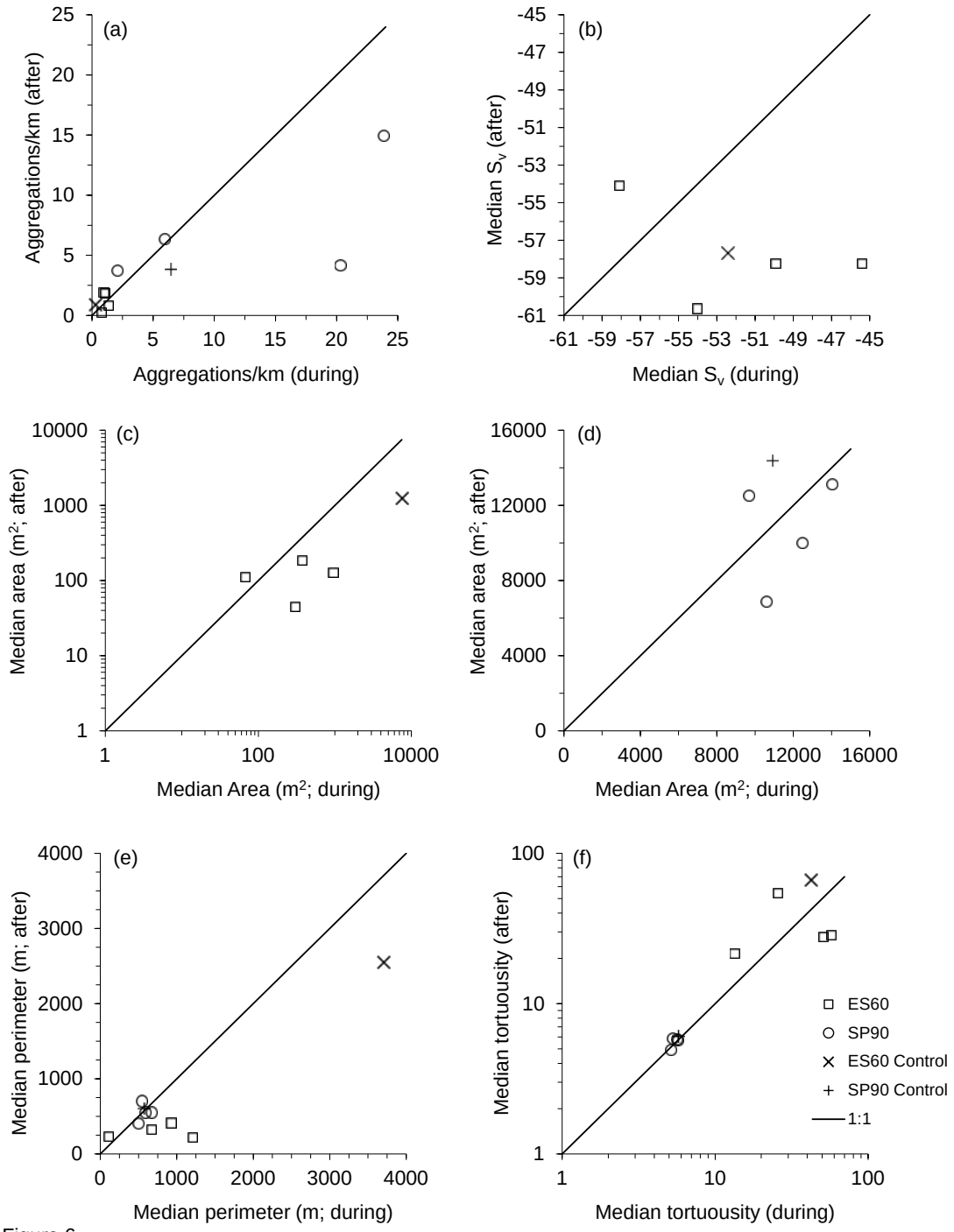
(a)
Aggregations/km (after)
Aggregations/km (during)
(b)
Median S_v (after)
Median S_v (during)
(c)
Median area (m^2; after)
Median Area (m^2; during)
(d)
Median area (m^2; after)
Median Area (m^2; during)
(e)
Median perimeter (m; after)
Median perimeter (m; during)
(f)
Median tortuousity (after)
Median tortuousity (during)
ES60
SP90
ES60 Control
SP90 Control
1:1

Figure 6