THE INCORPORATION OF ACOUSTIC TECHNOLOGY INTO THE CANADIAN PACIFIC SARDINE (*SARDINOPS SAGAX*) SURVEY

by

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Abstract

Hydroacoustics can provide cost-effective ways of improving the accuracy of non-acoustic surveys, such as Canada's annual nighttime Pacific sardine (*Sardinops sagax*) surface trawl survey. Seasonal sardine abundance in Canada is currently estimated by extrapolating average catch densities from this survey to 30 m depth over a distributional area. The primary goal of this thesis was to assess, using acoustic methods, the uncertainty associated with catch density extrapolation from the trawl survey. Nighttime bias in the acoustic data due to the near-field limits was also investigated. An alternative acoustic approach is then reviewed to direct future research.

Concurrent acoustic and trawl catch data from the 2011 Canadian sardine survey were analyzed to compare the two methodologies and approximate the species' vertical distribution within the near-surface layer at night. Acoustic observations made at 38 and 120 kHz were compared to determine if fish are present in the near-field safe range of the 38 kHz transducer. Acoustic observations indicated that sardine density was significantly greater ($P<0.05$) above the trawl's foot rope path than below it. Substantial backscatter in the surface scattering layer was observed within the near-field safe range of the 38 kHz transducer. No significant linear relationships between trawl-based density and acoustic backscatter or density estimates were found. These findings have important implications as sources of uncertainty in non-acoustic and acoustic methods were identified, including catch density extrapolation and the near-surface acoustic blind-zone and/or near-field safe range.

This thesis then reviews the potential of multi-beam acoustics as an alternative to single-beam. Multi-beam sonars (MBS) can sample the water column over a wide range of angles and

near-surface targets can be detected. Present methodologies and hardware, however, cannot yet quantify multi-beam backscatter as abundance. Calibration procedures for MBS's are undefined for most models. Hardware and software required for real-time interaction with acoustic gear have not been developed for many systems. Since MBS's insonify targets from multiple angles, the conversion of multi-beam backscatter to abundance is complex. Research on the natural orientation of fish and the accurate averaging of backscatter from multiple incidence angles is needed.

Preface

Chapter 2 has been submitted for publication in a scientific journal with the help of several co-authors, listed below. I am the primary author of the submitted manuscript as I wrote the research proposal, assisted with acoustic and catch data collection during Fisheries and Oceans Canada's (DFO) annual sardine survey, analyzed acoustic and catch data, wrote the final manuscript, and incorporated comments from all co-authors. Co-authors Drs. Gary Melvin and Stéphane Gauthier, DFO scientists at the St. Andrews Biological Station and the Institute of Ocean Sciences respectively, provided extensive guidance and commentary during the formation of the research proposal, analysis of acoustic data, and preparation of the final manuscript. Co-authors Linnea Flostrand, Jake Schweigert, and Gordon McFarlane, DFO scientists at the Pacific Biological Station, coordinated the sardine survey, led acoustic and catch data collection during the survey, provided me with access to the data, and gave commentary on the research proposal and final manuscript. Dr. R. Scott McKinley was my thesis supervisor at UBC. He provided vital technical and practical guidance throughout the process, and commentary on the thesis proposal and final manuscript.

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List of Abbreviations and Symbols

Abbreviations in text

ANOVA	Analysis of variance
BOT	Bottom of surface scattering layer
CCGS	Canadian Coast Guard specialty vessel
DFO	Department of Fisheries and Oceans Canada
MBCS	Mean backscattering cross section
MBS	Multi-beam sonar
Sa	Area backscattering strength
sa	Area backscattering coefficient
S.E.	Standard error
SSL	Surface scattering layer
Sv	Volume backscattering strength
sv	Volume backscattering coefficent
TS	Target strength
VBE	Vertically oriented single-beam echosounder

Symbols in equations

σ_{bs}	Backscattering cross section
ρ	Fish density
A	Area of ocean surface swept by trawl
c	Speed of sound
c_i	Total catch of species "i"
d	Transducer face diameter
f	Frequency
i	species "i"
L	Fish total length
T	Trawl duration
V	Velocity
W	Fish weight or width of trawl mouth (see text for context)

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First, I must thank my supervisor Dr. R. Scott McKinley. I am still surprised by the range of experiences and opportunities this thesis has brought me. With Scott's support I have witnessed a commercial fishing vessel capture an entire 100 t sardine school, been to remote parts of Alaska, and have formed a thesis I am proud of. He went beyond what any student can expect from their supervisor and I will always feel fortunate to have worked with him.

Collaborating with Fisheries and Oceans Canada gave me the opportunity to work with many fantastic people. I could have spent years trying to make sense of this field without the guidance and training I received from Drs. Gary Melvin and Stéphane Gauthier. I am very grateful for their contributions to my thesis, and for their patient responses to all of my questions. I am also thankful to Linnea Flostrand, Jake Schweigert, and Gordon (Sandy) McFarlane for their support, coordination, and help in shaping and executing my research. In addition, thank you to the crew and scientific staff aboard the CCGS "W.E. Ricker" during the 2011 Pacific sardine survey and to George Cronkite, Chelsea Stanley, and Jackie Detering. I greatly admire and respect all of these people's work ethic and extensive knowledge of their various fields of work.

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Special thanks must be given to my father, Allan Graas, who very patiently supported my education morally and financially. I am lucky to have such a dedicated and loving dad. Finally, thank you to Bianca Arney, for her love, support and exceptional aptitude to correct my grammar.

Dedication

To my mom, Beverley Graas

1 Introduction

Fish abundance estimates are of paramount importance to fisheries management. The accuracy of such estimates is vital as fisheries managers must balance the needs of the fishermen with the requirements of a sustainable fishery. These estimates can be derived from a variety of technologies and methodologies. This thesis will primarily focus on uncertainty in single-beam acoustic- and trawl-based abundance estimates of Pacific sardine (*Sardinops sagax*), with a secondary goal of reviewing an alternative acoustic technology: multi-beam sonar (MBS).

1.1 The Pacific sardine

Sardines are famous for forming densely packed schools in the upper water column, for their large annual migrations that occur around the world, and for dramatic population fluctuations (Baumgartner *et al.,* 1992; Yatsu *et al.,* 2005; van der Lingen *et al.,* 2010; Demer *et al.,* 2012; Zwolinski *et al.,* 2012). On the west coast of North America, sardine migrate northwards to feeding grounds in summer and return south to spawn in fall (Ware, 1999). Sardine populations around the world have a volatile history of large population changes, as illustrated by the history of the Canadian B.C. sardine fishery. A small Canadian fishery for the species began in 1917 and by 1925 the fishery had expanded to become the provinces largest fishery by catch weight, averaging 40 000 t each year (Ware, 1999). The fishery lasted only until 1947 when the sardine population collapsed. The sardine was not captured in significant quantities in Canadian waters until 1992, after an absence of 45 years (Hargreaves *et al.,* 1994). An experimental sardine fishery was later opened in Canada in 1995, and a commercial fishery in 2002. By 2010, the annual harvest in Canadian waters had reached 20 000 t (Flostrand *et al.,* 2011). Overfishing and climatic factors may have played a role in the population's mid-century rapid collapse (Radovich, 1982; Ware and Thomson, 1991; McFarlane and Beamish, 2001;

Chavez *et al.,* 2003). While overfishing may exacerbate these population fluctuations, it should be noted that this boom/bust cycle seems to be a natural and reoccurring process as it has repeated multiple times in the last 2000 years (Baumgartner *et al.,* 1992).

1.2 The annual sardine surface trawl survey

Currently, the primary indicator of sardine abundance and distribution in Canadian waters is the annual nighttime surface trawl survey performed along the west coast of Vancouver Island (Schweigert *et al*. 2009; Flostrand *et al.,* 2011). To estimate the abundance of sardine in Canadian waters, sardine catch density estimates determined from the annual surface trawl survey are applied to a 30 m depth across an estimated distribution area (Flostrand *et al.,* 2011). This abundance is converted into a Canadian migration rate and is reviewed by committees to provide catch level recommendations for the management of the fishery (Ware, 1999; Schweigert *et al.,* 2009; Flostrand *et al.,* 2011). The annual trawl survey has been regularly conducted since 1997. It usually occurs in July and, since 2006 trawling operations have been conducted primarily at night. The sardine abundance estimate from the trawl survey is usually viewed as conservative since current methods do not account for fish catchability or cover the sardine's entire distribution (Schweigert *et al.,* 2009).

1.3 Acoustic abundance estimation

The estimation of fish biomass in the water column has been a primary goal of fisheries acoustics since the field's inception. A variety of techniques have been applied to surmount this challenge, primarily echo-counting and echo-integration (Simmonds and MacLennan, 2005). The technique of echo-integration was developed in the 1960s and 70s, and estimates target (fish) density by first, compensating the reflected energy for range through increasing gain (sensitivity) with time, and second integrating the range-normalised echo energy. This value, known as the echo-integral, is averaged over a large number of transmissions and is used in the echo-integrator equation, along with the mean backscattering cross section of an individual target (target strength), to calculate target density (Simmonds and MacLennan, 2005). Echo-integration is the preferred method for abundance estimation of dense aggregations of fish, such as schools, where individual fish echoes are difficult to distinguish. Echo-integrator surveys have been successfully performed around the world and have permitted abundance estimates for stock assessment purposes in France, Japan, South Africa, Italy, Australia, New Zealand, USA, Canada, Chile, Ireland, Norway, and Russia (Hampton, 1996; Bonanno *et al.,* 2005; Masse *et al.,* 2006; Shida *et al.,* 2008; Cordova and Lang, 2008; Anon, 2009; Honkalehto *et al.,* 2009; Kloser *et al.,* 2009; Coetzee *et al.,* 2010; O'Donnell *et al.,* 2010; O'Driscoll *et al.,* 2011; Power *et al.,* 2010; Yasuma *et al.,* 2011; Demer *et al.,* 2012). This comparatively benign technology allows data collection from large sample volumes and permits the detection of fish and fish aggregations at range.

With the recent expansion of the fishery and installation of a scientific echosounder aboard the CCGS "W.E. Ricker", a government survey vessel, both government and industry have expressed interest in supplementing the annual sardine trawl survey with acoustic methods. Acoustic data are routinely collected as part of the trawl survey, but are not yet used in stock assessment. Acoustic methods have the potential to increase the water volume sampled compared to the surface trawl survey and provide an independent index of abundance at little additional cost. Limited resources at a government level, and a lack of research into the assumptions of acoustic survey design for sardine in Canadian waters, however, currently precludes an independent acoustic survey for sardine. For now, acoustics could be used to evaluate uncertainty of the trawl survey's assumptions, which would result in improved information for providing advice for management of the fishery. The assumption that a catch density determined in the upper 20 m of the water column can be safely extrapolated to a 30 m depth is of special interest to Fisheries and Oceans Canada, and was investigated in this thesis.

Like trawl-based fish biomass estimates, acoustic abundance estimation is not without sources of uncertainty. Since echoes recorded by acoustic instruments usually originate from several species in unknown proportions, backscatter must be partitioned to accurately estimate the abundance of the target species (Nakken and Dommasnes, 1975). Backscatter is often partitioned among species based on catch ratios from, for example, trawling or seining and each species' respective target strength (TS) (e.g. O'Driscoll *et al.,* 2002). Therefore, like trawl surveys, acoustic surveys are subject to bias due to non-100% and variable catchability among species, which distort catch ratios and subsequently the partitioned backscatter. Avoidance can be difficult to study and accurately quantify, as it can require the use of, for example, multiple research vessels, MBS, and buoy mounted transducers (Misund, 1990; Misund and Aglen, 1992; Soria *et al.,* 1996; Vabø *et al.,* 2002; Gerlotto *et al.,* 2004). Consequently, due to limited resources, this thesis could not include an investigation of this important bias.

A potential source of bias specifically relevant to acoustic survey design for sardine is the near-surface acoustic blind zone and near-field safe range. The blind zone is defined as the water column above the transducer, so targets in this region cannot be acoustically observed. The near-field is the region close to the transducer where non-parallel wave fronts form a complex pattern of constructive and destructive interference. The size of this region depends on the transmission frequency and transducer characteristics, with larger frequency transducers typically having smaller near-fields (Simmonds and MacLennan, 2005). The relationship between range and intensity in this region is difficult to calculate and measure, so it is usually excluded from acoustic analysis for practical reasons. As a result, acoustic abundance estimates may be biased if significant numbers of the target species are within the near-field (Demer and Hewitt, 1995; Massé e*t al.,* 2006; O'Driscoll *et al.,* 2009). To ensure near-field data is excluded, it is customary to begin analysis at twice the near-field range (Simmonds and MacLennan, 2005). In this thesis, this region is termed the near-field safe range. The near-surface blind zone and near-field safe range may be important sources of uncertainty when surveying pelagic species that occupy the uppermost portion of the water column, such as sardine (Yatsu *et al.,* 2005; Demer *et al.,* 2012; Zwolinski *et al.,* 2012). Partially due to the blind zone and near-field bias nighttime acoustic surveys can be problematic, since pelagic species tend to migrate towards the sea surface at night (Massé *et al.,* 2006; O'Driscoll *et al.,* 2009). This potential bias in acoustic abundance estimates was therefore investigated to provide confidence in the methodologies application to sardine.

1.4 Multi-beam sonar: an alternative

While single-beam acoustic surveys have been successfully employed around the world in abundance estimation, and provide valuable behavioural information, limitations of echosounder technology in sample volume and three-dimensional (3D) visualization have led to the investigation of MBSs for acoustic abundance estimation (Soria *et al.* 1996; Vabo *et al*. 2002; De Robertis *et al*, 2008). Furthermore, the near-surface blind zone and near-field characteristics and near-bottom "dead zone" do not permit data collection from the first several meters beneath the vessel and close to the seabed (Ona and Mitson, 1996; MacLennan *et al.,* 2004). These regions can negatively bias biomass estimates, especially for pelagic fish species that occupy the upper or lowermost portion of the water column (Ona and Mitson, 1996; Demer and Hewitt, 1995; O'Driscoll *et al.,* 2009). This concern is drastically reduced when utilizing certain models of MBS since the acoustic beams can be projected parallel to the boundary (bottom or surface) of interest, as well as the high resolution possible with such a system

(Mulligan, 2000). Concerns with vessel effects and low near-surface acoustic sample volume during echosounder surveys for shallow water pelagic species have further fuelled research and development of scientific MBS. Since MBS's can insonify schools at long ranges to the side of the vessel, depending on transmission power and frequency, target-vessel avoidance can be reduced. In addition, MBS's permit a larger sampling volume than echosounders, especially near the surface. Therefore, MBS's have the potential to decrease sampling error and bias in comparison to echosounder surveys (Simmonds *et al.,* 1992).

The use of multi-beam systems in abundance estimation is currently experimental and questions remain before it can be incorporated into stock assessment. Cochrane *et al.* (2003) outlined four major challenges in the quantification of MBS signals: 1) low precision and non-linear signal processing and 2) lack of digital data output in most MBSs, 3) complex and undefined calibration methodology, and 4) complications converting backscatter to biomass due to highly variable off-dorsal incidence angles. There have been many recent advances towards achieving precise and reliable biomass estimation with scientific MBSs. Since Cochrane *et al.*'s (2003) study, newly released MBS's have overcome the first two challenges. Therefore, the current state of research into the multi-beam calibration procedures and quantification of multi-beam backscatter from multiple incidence angles required for the use of multi-beam backscatter to estimate abundance are reviewed in chapter 3.

1.5 Thesis Objectives

With assistance from Fisheries and Oceans Canada scientists, four objectives were identified. The first objective was to evaluate the assumption that an average trawl catch density determined in the upper 20 m of the water column can be safely extrapolated to 30 m depth.

Sardine density was acoustically estimated above and below the foot rope of the trawl (~17 m depth) to estimate the species' vertical distribution and determine the validity of this assumption. The second objective was to identify if the transducers near-field can bias nighttime acoustic density estimates of sardine. This was determined by utilizing the size difference between 38 and 120 kHz transducers near-field. Sardine density was acoustically determined at each frequency and compared to ascertain if fish are missed within the 38 kHz near field. The third objective was to compare concurrent nighttime trawl catch densities and acoustic density estimates of sardine. Comparing the two methodologies provided a general indicator of uncertainty, and evaluated the potential of a nighttime acoustic survey for sardine. Since fisheries acoustics has been trending towards the use of multi-beam acoustic technology, the final objective of this thesis was to review research of the calibration of MBS and quantification of multi-beam backscatter as abundance.

2 Uncertainty in nighttime acoustic and trawl catch data from the 2011 Canadian Pacific sardine (*Sardinops sagax*) survey

2.1 Introduction

The near-surface habitat of certain pelagic species presents a challenge to abundance estimation with traditional trawl sampling and hydroacoustics. The proximity to the surface implies that the fish may react to the vessel and sampling gear thereby invalidating several survey assumptions. Conversely, standard acoustic technologies do not permit data collection within the first several metres from the ocean surface due to the near-surface blind zone and near-field, and the volume sampled by the narrow acoustic beam at shallow depths is small. Hydroacoustic data can, however, be used to investigate uncertainty of non-acoustic methods. This can be a cost-effective way of improving the accuracy of abundance estimates obtained from non-acoustic techniques, such as the Canadian Pacific sardine (*Sardinops sagax*) surface trawl survey, the primary indicator of sardine abundance and distribution in Canadian waters (Schweigert *et al*. 2009; Flostrand *et al.,* 2011).

The recent expansion of Canada's sardine fishery and the installation of a scientific echosounder system on the CCGS "W.E. Ricker", a government research vessel, have generated interest in complementing the annual surface trawl survey with acoustic methods (Flostrand *et al.,* 2011). Acoustic data were routinely collected during the 2011 sardine survey, but they have not been used for stock assessment. Limited resources and a lack of research into acoustic survey design for sardine in Canadian waters currently precludes an independent acoustic survey. Acoustics can, however, be used to evaluate the validity of some of the trawl survey's assumptions, which would result in improved information for providing advice for management of the fishery. In addition, this data could evaluate the potential of nighttime acoustic measurements to independently estimate sardine biomass.

Annual surface trawl surveys have been conducted each summer along the west coast of Vancouver Island since 1997 (Schweigert *et al*. 2009; Flostrand *et al.,* 2011). The survey, which usually occurs in July, has been conducted at night since 2006 to maximize sardine distribution in the surface waters. Seasonal abundance estimates in Canadian waters are based on the average catch density determined in the upper 20 m of the water column, which is applied to a 30 m vertical depth over the surveys geographical area (Ware, 1999; Schweigert *et al.,* 2009; Flostrand *et al.,* 2011). The validity of the consistent vertical density assumption within the upper 30 m surface layer is critical to the accuracy of the total seasonal sardine biomass estimate. If sardine density varies with depth within the 30 m surface layer or is constant to a larger depth, abundance estimates could be positively or negatively biased. To evaluate this assumption, acoustic data from the 2011 Canadian sardine survey were used to estimate sardine density above and below the trawl foot rope (~17 m depth).

Acoustic abundance estimates may be biased if significant numbers of the target species are within the near-surface blind zone and/or near-field safe range (Demer and Hewitt, 1995; O'Driscoll *et al.,* 2009). This region can be particularly problematic if backscatter measurements are recorded at night when pelagic species, including sardine, migrate towards the sea surface and tend to occupy the uppermost portion of the water column (Demer and Hewitt, 1995; O'Driscoll et al., 2009; Demer *et al.,* 2012; Zwolinski *et al.,* 2012). Since daytime acoustic data and simultaneous biological samples of backscatter are not currently available, the utility of nighttime acoustic data for sardine abundance estimation was evaluated by investigating the near-field bias and comparing concurrent catch and acoustic density estimates.

2.2 Materials and methods

Acoustic and trawl data were collected during the annual Canadian sardine survey aboard the CCGS "W.E. Ricker" in July, 2011. A Simrad EK60 scientific echosounder equipped with 38 and 120 kHz 7° split beam transducers was used to collect the acoustic data. The transducers were mounted on a ram so that they could be raised and lowered. With the ram in the "up" position, the transducers were at a depth of 4.5 m, while in the "down" position, they were at 5.2 m. Both positions were utilized during the survey. A 1.024 ms ping was transmitted simultaneously every two seconds at both frequencies. The echosounder was calibrated at the end of the survey following standard procedures (Foote *et al.,* 1987).

Quantitative fish density estimates and biological samples were collected with a model 250/350/14 mid-water rope trawl (Cantrawl Pacific Ltd.). The codend mesh was 1 cm. Each night 5 to 7 tows (20 – 30 minutes each) were conducted at predetermined locations at a speed of approximately 2.5 m/s. The predefined sampling region and its boundaries were based on sardine trawl density observations from previous surveys (Flostrand *et al.,* 2011). The trawl's head rope depth varied from 2 to 4 m depth, depending on ocean conditions, tow speed, and catch. The depth of the foot rope was calculated assuming a constant head rope depth of 3 m for all trawls. The trawl mouth height ranged from 11 to 18 m and the width 28 to 32 m. The estimated foot rope depth varied from 15 to 21 m. Seven sets were made with the vessels ram down and 16 with it up.

Each catch was sorted and weighed by species. For catches too large to be weighed, the chief fisherman and chief scientist provided a biomass estimate based on the volume of the catch in a calibrated hopper. Only sets that comprised of >40% by weight or at least 50 kg of sardine were considered in the analysis. Fork length (cm), weight (g), sex and maturity stage (1 – 4) were recorded for sardine. Fork length and weight were recorded for Pacific herring (*Clupea pallasi*) and only fork length for Northern anchovy (*Engraulis mordax*). Fork length, weight, sex, and stomach contents were recorded for all adult Chinook (*Oncorhynchus tshawytscha)* and Coho salmon (*O. kisutch*). Non-adult Chinook and Coho salmon were subsampled for length and weight. The total weight and number of each species of salmon was recorded. From these data, an average weight (W) of combined salmon species in each trawl was calculated. The general equation $W=aL^b$ was used to calculate mean total length (L) for use in the salmon TS equation. This equation was also used to estimate the mean weight of each 0.5 cm length bin for sardine and herring. The values of a and b were calculated via log-transformed linear regression from samples of sardine, herring, and salmon taken during the survey (Appendix A). Due to a lack of length and weight frequency data for anchovy, the equation determined for herring was also applied to anchovy. Chinook and Coho salmon data were combined to produce a single equation that was used for all salmon species length estimates.

The standard practice for sardine surveys is to measure fork length, however TS equations for common pelagic species are based on total length. A conversion between fork length and total length for sardine was therefore determined by linear regression based on analysis of fresh and thawed sardine samples after the survey (Appendix A). The same equation was applied to herring and anchovy, as no fresh samples of those species were available. Fork length measurements for salmon were converted to total length with published conversion equations (Pahlke, 1989). See Appendix A for a summary of length-weight and fork length-total length regression statistics.

All acoustic data were edited using Echoview 4.9. Echogram regions specific to the trawling section, adjusted for lag time between the vessel and trawl (i.e. distance), were identified. The upper boundary layers for analysis were established at twice the range of each transducer's near-field. This range was estimated by the equation "safe range" = $2d^2f/c$, where d is the diameter of the transducer's face, f is the transmitted frequency, and c is the sound speed (Simmonds and MacLennan, 2005). Estimated ranges were 3.77 m and 9.29 m respectively for the 120 and 38 kHz transducers, which corresponded to 8.27/8.97 m and 13.79/14.49 m beneath the ocean surface in turn, depending on whether the ram was in the "up" or "down" position. Editable lines were inserted into the echogram at ranges of the 120 kHz near-field safe range, the 38 kHz near-field safe range, the adjusted foot rope depth, and the approximate SSL bottom (table 2.1). The adjusted foot rope depth was calculated by subtracting the depth of the transducer from the recorded foot rope depth. The approximate SSL bottom was determined qualitatively for each trawl region echogram. The total area backscatter coefficient ($sa_{t,f}$) was estimated in echogram regions corresponding to the trawling times between each of the editable lines, down to the approximate lower limit of the SSL. A -65 dB volume backscattering strength (Sv) threshold filter was applied to the echogram to filter out backscatter from species lacking swim bladders, primarily jelly fish, salps, krill, and eulachon. The -65 dB Sv threshold was selected by examining plots of total backscatter against threshold level (Appendix B).

To apportion backscatter into species, sardine, herring and, anchovy were separated and subdivided into 0.5 cm total length classes. For each class, the mean TS at 38 kHz was estimated with previously published dorsal TS equations (table 2.2) (Lida *et al.,* 1991; Barange *et al.,* 1996; Thomas and Thorne, 2003). Salmon were not partitioned in length classes as no length frequency data were available. An average salmon length for each tow was determined with the general equation $W=aL^b$ to calculate TS. The 38 kHz TS equations were adjusted using the frequency term of Love's TS equation, 0.9logF, to obtain a 120 kHz TS (Love, 1971). Once TS was calculated, the backscattering cross section ($\sigma_{bs,i,f,l}$) of each length bin (l) for each species (i) and frequency (f) was determined with the equation $\sigma_{bs,i,f,l} = 10^{(TS/10)}$. A weighted mean $\sigma_{bs,i,f}$ per kg was determined for all species in each trawl and at each acoustic frequency. This was calculated by the sum of the product of $\sigma_{bs,i,f,l}$ and the proportion of each species (by weight) in all length bins. Total area backscatter ($sa_{t,f}$) was partitioned between species from the equation $sa_{i,f} = sa_{t,f}\ c_i\ \sigma_{bs,i,f} / \sum c_i\ \sigma_{bs,i,f}$, where c_i is the captured weight of species (i) in the trawl (Nakken and Dommasnes, 1975). The density (ρ) of sardine was then calculated from the equation $\rho_{i,f} = sa_{i,f} / \sigma_{bs,i,f}/kg$ (MacLennan *et al.,* 2002). Density estimates calculated based on acoustic observations are called "expected density" or "acoustic density" in the subsequent sections (O'Driscoll *et al.,* 2002).

The sampled (swept) ocean surface area of the trawl equals: $A_t = W*V*T$, where W is the width of the trawls mouth (m), V is the velocity of the vessel during the trawl (m/s), and T is the duration of the trawl (s). The density of each species estimated with only trawl data was calculated with the equation $\rho_{trawl}\ (kg/m^2) = C_i / A_t$. Density estimates calculated based only on trawl observations are called the "trawl density" or "observed density" in the subsequent sections.

Linear regression analyses were used for the comparisons of acoustic and trawl density estimates. Single factor ANOVAs were performed to determine if sardine density above and below the foot rope were significantly different. Separate ANOVAs were performed for the 38 and 120 kHz data. The null hypothesis was rejected if $p<0.05$.

2.3 Results

Of the 68 stations occupied during the survey, 23 were used for the comparisons with the acoustic observations (figure 2.1). The primary swim bladder species captured by the trawl were sardine, herring, anchovy and salmon (>99% by weight and numbers) (tables 2.3-2.4). Qualitative observations of echograms indicated sardine were typically distributed in small to large schools or dispersed throughout the sampled volume. In three sets, acoustic observations indicated sardine schools were potentially captured while the trawl was being deployed and/or retrieved. This was determined if a school was acoustically observed close to the end deploy or start retrieve time. Those sets were excluded from the analysis. For analysis the overlap between the volume swept by the trawl and sampled by the echosounder at 38 and 120 kHz extended from the depth of the acoustic near-field to the trawls foot rope.

Sardine acoustic density appeared to decrease with depth at both frequencies (figure 2.2). This result was significant ($P<0.05$) at 120 kHz when the SSL was split into two layers: above and below the foot rope. At 38 kHz, there was no statistically significant difference in sardine density above and below the foot rope (table 2.5). Since biological samples of backscatter beneath the foot rope were not collected, the species composition of that backscatter must be interpreted with caution. Approximately 50% of 120 kHz total area backscatter was detected within the near-field safe range of the 38 kHz transducer, despite this region encompassing only a small portion of the SSL (figure 2.2; table 2.6).

No linear relationship was found between total catch and total area and volume backscatter within the overlap between each transducers near-field safe range and the trawls foot rope (figures 2.3-2.4; table 2.7). Herring had the highest mean backscattering cross section (MBCS) per kg for backscatter partitioning, ranging from $9.4\text{x}10^{-4}$ to $1.21\text{x}10^{-3}$ m^2 kg^{-1} among sets.

Sardine MBCS per kg ranged from 3.3 – 3.4x10^{-4} m^2 kg^{-1} among sets. Salmon ranged from 3.2x10^{-4} to 1.01x10^{-3} m^2 kg^{-1}. The large ranges for herring and salmon were due to more variable total length distributions among sets compared to sardine.

There was no linear relation between estimated acoustic and trawl sardine densities at either frequency (figure 2.5; table 2.7). The mean trawl density for the survey was 0.0082 kg sardine m^{-2} (S.E.=0.002, n=23), while the mean acoustic densities (from end of 38/120 kHz near-field to foot rope) were 0.026 kg sardine m^{-2} at 38 kHz and 0.049 kg sardine m^{-2} at 120 kHz. Out of 23 sets, 11 had a higher and 11 a lower acoustic density (>10% difference) at 38 kHz than observed with the trawl. At 120 kHz, 19 sets had a higher and 3 a lower acoustic density than observed. At both frequencies, observed and acoustic density were similar for one set (<10% difference). For several sets, especially at 38 kHz, despite acoustic analysis predicting very little or no catch, a large catch was observed.

Raw acoustic area backscatter and density estimates at 38 and 120 kHz were correlated between the end of the 38 kHz near field to the trawls foot rope, and beneath the foot rope to the bottom of the SSL (figures 2.6-2.7; table 2.7). Raw backscatter at 38 kHz was greater than at 120 kHz. Density estimates within the same volume of water at each frequency were not significantly different (9.29-SSL bottom (BOT)). Total density estimates at 120 kHz (3.77-BOT) were not significantly greater than at 38 kHz (9.29-BOT) (table 2.5).

2.4 Discussion

Annual estimates of the seasonal sardine biomass in B.C. waters are determined from the product of the mean trawl survey catch density and a regional surface volume estimate. These estimates are used to determine migration rates from the ratio of Canadian seasonal biomass and a corresponding estimate of the population's biomass (Ware, 1999). The depth assigned to calculate surface volume estimates for extrapolations of mean sardine catch densities is 30 m (Schweigert *et al.,* 2009; Flostrand *et al.,* 2011). Acoustic data at 120 kHz demonstrated that sardine density decreases with depth within the SSL at night. Yatsu's *et al.* (2005) observations of Japanese sardine (*Sardinops melanostictus*) found a distribution similar to our study; *S. melanostictus* were concentrated in the upper 20 m of the water column, but still present to 40 m depth. Demer *et al.* (2012) also found *S. sagax* to be concentrated in the upper 40 m in U.S.A. waters. During the 2011 Canadian sardine survey, we observed the majority of sardine to be above the trawl's foot rope (average depth = 17 m). This observation was, however, only significant for acoustic density estimates at 120 kHz. The absence of a significant difference at 38 kHz is likely due to the larger size of the near-field safe range. At 120 kHz, an average of 18% of total sardine density within the acoustically observable SSL was present below the trawl's foot rope. Therefore, based on the observed vertical distribution of sardine, the extrapolation of a catch density determined at less than 20 m depth to a 30 m depth potentially results in a positive bias in current trawl-based abundance calculations. A larger sample size is needed to improve the resolution of vertical sardine distribution and to investigate variability in vertical distribution before definitive conclusions regarding the importance of this bias can be made.

The results of this study indicate that nighttime acoustic abundance estimates of sardine may be negatively biased since fish within the near-surface blind zone and/or near-field safe range are not accounted for. Approximately 50% of the total sardine density within the SSL estimated at 120 kHz was observed in the 5.52 m interval between the end of the 120 and 38 kHz near-field's safe range. In addition, there were several sets where expected fish density was less than captured in the trawl. This was primarily observed when the expected density was calculated with 38 kHz data and was infrequently observed at 120 kHz. This was likely due to the 120 kHz transducer's shorter near-field safe-range and implies a large proportion of sardines were within the 38 kHz near-field safe range. The blind zone and/or near-field bias has also been found to impact abundance estimates for mesopelagic fish on Chatham Rise near New Zealand and Antarctic krill (Demer and Hewitt, 1995; O'Driscoll *et al.,* 2009). This bias may be offset by fish diving vertically downward in reaction to an approaching vessel, decreasing the number of fish in the near-field and potentially altering TS (Gerlotto and Fréon, 1990; Gerlotto *et al.,* 2004; Ona *et al.,* 2007). Demer *et al.* (2012) indicated that near-field bias for sardine abundance estimation on the U.S.A's west coast may be negligible, based on strong diving reactions observed with a horizontally oriented multi-beam sonar (Cutter and Demer, 2008). Our observations indicate that this behaviour was not strong enough to compensate for the blind zone and/or near-field bias for sardine during nighttime surveys off Canada's west coast. These seemingly conflicting observations are most likely the result of the U.S.A. survey being carried out during the day, whereas the Canadian survey occurs at night. Also, the Canadian surveys take place in the summer, while the species is principally foraging, whereas the U.S.A. surveys are during spring months, while spawning is occurring (Ware, 1999; Zwolinski *et al.,* 2006; Demer *et al.,* 2012; Zwolinski *et al.,* 2012). The sardines vertical distribution and response to an approaching vessel may therefore differ between the surveys due to behavioural variation.

Based on the poor correlation between acoustic- and trawl-based sardine density estimates, additional uncharacterised sources of uncertainty may affect density estimates from the Canadian sardine survey. In addition to the near-surface blind zone and near-field, the lack of observed correlation between survey types could be due to fish-vessel avoidance reactions, small near-surface acoustic sampling volume, and/or patchy sardine distribution. It is also possible that the trawl was not directly behind the vessel for some sets, meaning the narrow acoustic beam did not capture the swath of the trawl. Similar research conducted by O'Driscoll *et al.* (2002) found strong relationships between mid-water trawl and acoustic predictions of capelin catch; however, in that study the trawl sampled the water column between 20 and 60 m, well away from the vessel's draft and near-field of the transducers. Avoidance, the blind zone and near-field biases were therefore likely less important, and the sample volume of the beam was greater than for the near-surface measurements made during our research.

Avoidance is a complicated behaviour that has been extensively researched in fisheries acoustics, but is still poorly understood (Mitson and Knudsen, 2003; Soria *et al.*, 2003; Gerlotto *et al.*, 2004; Ona *et al.*, 2007; De Robertis *et al.*, 2006 and 2008). In some cases fish avoidance to a vessel was minimal or absent, while others report measureable lateral and vertical avoidance (Misund and Aglen, 1992; Soria *et al.,* 1996; Fernandes *et al.,* 2000; Gerlotto *et al.,* 2004). Avoidance reactions can also differ among species (Misund and Aglen, 1992). Misund and Aglen (1992) found stronger avoidance reactions for herring when the research vessel was trawling, compared to cruising, as herring were observed behind the vessel and in front of the trawl. Sardine attempting to avoid capture could explain why most acoustic density estimates at 120 kHz were greater than the corresponding trawl catch densities. The equipment and methodology in our study could not, however, directly investigate bias due to avoidance of the vessel and/or trawl. In this study, catchability of all species in the path of the trawl was assumed to be 100% (q=1), however, it is likely less and variable among species. Future research on sardine avoidance reactions is strongly encouraged.

While fish behavioural response to an approaching trawl and the near-field may partially explain why acoustic density estimates differed from trawl catch densities, it is also possible that some of the variation can be attributed to the small near-surface sampling volume of the narrow acoustic beam. If sardine were patchily distributed within the trawl regions, the thin slice acoustically observed (~2.4 m diameter at a depth of 10 m; ~4.2 m diameter at 17 m) may not be representative of the actual sardine density. In contrast, the trawl sweeps a width of 30 m, so a patchy, near-surface sardine density may be more representatively sampled by trawl. This advantage would be offset to an unknown degree by fish avoiding capture and intermittent sampling by trawls. The use of multi-beam sonar and horizontally oriented echosounders could potentially provide additional information on the behavioural reaction of sardines to approaching vessels and towed gear.

This study identified that the under estimation of the trawl's effective fishing time is a potential positive bias in abundance estimates from the trawl survey. Sardine abundance is estimated from the trawl's swept volume by multiplying fishing time, average speed, and the cross sectional area of the trawl mouth. Fishing time is measured from the time the trawl is fully deployed, to the start of trawl retrieval. For a few sets, schools were encountered prior to the complete deployment and/or retrieval of the trawl. These sets yielded high catch densities, but low acoustic densities and fish did not appear to be present in the near-field "safe range". It is possible that fish were captured during trawl deployment and/or retrieval, thus fishing time and volume fished may have been under estimated. If true, these sets would have overestimated sardine density, assuming all fish in the trawl's swept volume were captured. Since these sets represented a large portion of the survey's total sardine catch (22.7%), their inclusion in abundance estimates may bias the total sardine biomass. However, since the vessel moves forward slowly (~0.26 m/s) for most of trawl deployment and the net mouth does not begin to open until late in the process (30-45 s prior to end deploy), and it is not fully open until the winches are locked and the net doors are spread, there is only a short period of time in which fish could be captured during trawl deployment. Consequently, the validity of fishing time as an important source of bias is uncertain and it may be minimal compared to biases due to vessel avoidance and net catchability, with the exception when dense aggregations are encountered during the critical deployment/retrieval period. This bias could not be confirmed with our methods, but could be further investigated with net mounted acoustic technology. Alternatively, a "multisampler" trawl, which allows for the remote opening and closing of multiple cod-ends at the desired depth(s) and time intervals, would allow fishing time to be precisely recorded (Skeide *et al.,* 1997).

Our research has demonstrated how hydroacoustic data may be used in a complementary role to characterise sardine distribution and sources of uncertainty for non-acoustic methods. The use of acoustics in this way is a cost-effective approach to improve the accuracy of non-acoustic fish abundance estimates for fisheries that do not have the resources to implement independent acoustic surveys. For example, as shown in this study, nighttime acoustic data can be used in conjunction with the sardine surface trawl survey to estimate the species' vertical distribution in the surface scattering layer. This information could be considered in catch density extrapolations for stock assessment purposes. The acoustic data identified the under estimation of fishing time as a potential positive bias of sardine catch density from trawls. The extent in which these positive biases are countered by fish capture avoidance and gear corralling is unknown. Further research into these areas would be facilitated with multi-beam sonar, net-mounted acoustic equipment and/or buoyed or anchored transducers, and could characterise the relative contribution of each bias to trawl catch density estimates. Such research would also be relevant to the development of an acoustic survey of sardine in Canada, since trawl catch information is still required to partition backscatter.

2.5 Tables

Table 2.1. Boundary layer depths used in analysis (near-field safe range=NF).

Line	Echogram depth (m)	Depth (m) (ram up/ down)	Min. real depth (m)	Max. real depth (m)	S.E.	n
120 kHz NF	3.77	8.27/8.97	-	-	-	-
38 kHz NF	9.29	13.79/14.49	-	-	-	-
Foot rope	12.20	16.96	15	21	0.22	27
Bottom SSL	21.03	25.80	20	40	0.74	27

Table 2.2. TS equations used to partition backscatter and convert to acoustic abundance.

Species	Type	Freq.	TS Equation
Pacific sardine (*Sardinops sagax*)	dB ind.$^{-1}$	38	17.07logL – 66.73 (Barange et al., 1996)
Pacific herring (*Clupea pallasi*)	dB ind.$^{-1}$	38	26.5logL – 76.4 (Thomas and Thorne, 2003)
South African anchovy (*Engraulis capensis*)	dB ind.$^{-1}$	38	19.5logL – 75.57 (Barange et al., 1996)
Salmonids (*Oncorhynchus* spp.)	dB ind.$^{-1}$	50	20logL – 66 (Lida et al., 1991)

Table 2.3. Summary of analyzed trawl catches in % weight of sardine (sar.), salmon (sal.), herring (her.), anchovy (anc.) and other (oth.).

Set #	Date (Jul 2011)	Net width (m)	Net height (m)	Total catch (kg)	% Kg Sar.	% Kg Sal.	% Kg Her.	% Kg Anc.	% Kg Oth.
13	23	32	12	2100.0	97.1	0.7	2.0	0.0	0.2
15	23	30	14	1750.0	88.5	2.9	8.6	0.0	0.0
16	23	28	14	370.9	84.5	13.2	2.3	0.0	0.0
17	23	28	14	1138.4	91.6	8.4	0.0	0.0	0.0
18	24	28	14	2000.0	95.1	4.8	0.0	0.0	0.0
20	24	28	14	196.1	77.7	3.1	9.2	6.6	3.4
22	24	29	14	369.4	40.0	8.7	49.9	0.0	1.3
25	25	32	13	174.7	52.6	17.3	15.8	4.6	9.7
26	25	28	14	2200.0	95.6	4.2	0.0	0.0	0.2
28	25	29	14	1000.1	33.8	1.4	64.7	0.0	0.1
29	25	29	14	157.6	79.5	20.5	0.0	0.0	0.0
37	27	33	17	2000.0	97.4	2.6	0.0	0.0	0.0
38	27	31	15	329.9	73.1	26.9	0.0	0.0	0.0
39	27	28	14	1430.0	40.1	13.5	45.7	0.0	0.6
40	27	30	15	38.3	89.3	4.8	0.0	0.0	5.9
41	27	30	15	2200.0	21.0	3.5	73.5	0.0	1.9
44	28	32	12	1035.2	7.1	2.3	90.3	0.0	0.4
45	28	30	15	1400.0	84.9	8.9	1.7	0.0	4.5
47	28	30	15	933.4	96.5	2.3	0.0	0.0	1.2
50	29	32	12	12.5	77.9	0.0	0.0	0.0	22.1
53	29	28	15	302.1	85.6	7.2	0.9	0.0	6.3
57	30	30	13	2555.9	62.6	2.2	35.1	0.0	0.1
60	30	30	15	2700.0	42.2	1.7	56.0	0.0	0.1

Table 2.4. Summary of analysed trawl catches in % number of sardine (sar.), salmon (sal.), herring (her.), and anchovy (anc.).

Set #	Total catch (# of fish)	% # sar.	% # sal.	% # her.	% # anc.
13	11924	96.4	0.0	3.6	0.0
15	10350	85.0	0.2	14.8	0.0
16	1913	93.7	1.7	4.5	0.1
17	5882	99.3	0.7	0.0	0.0
18	11245	99.7	0.3	0.0	0.0
20	2106	51.3	0.7	9.6	38.4
22	2682	31.9	0.4	67.6	0.0
25	1366	39.6	1.7	21.5	37.1
26	12098	99.6	0.4	0.0	0.0
28	9264	20.9	0.5	78.6	0.0
29	774	95.9	4.1	0.0	0.0
37	11472	99.8	0.2	0.0	0.0
38	1446	98.3	1.7	0.0	0.0
39	11287	29.5	0.6	70.0	0.0
40	199	99.5	0.5	0.0	0.0
41	22235	12.4	0.1	87.5	0.0
44	11723	3.7	0.1	96.3	0.0
45	7826	88.0	1.1	10.9	0.0
46	2250	99.3	0.7	0.0	0.0
47	5377	99.8	0.2	0.0	0.0
50	57	100.0	0.0	0.0	0.0
51	27156	63.0	0.1	36.9	0.0
53	1646	93.5	0.7	5.8	0.0
55	32372	99.9	0.1	0.0	0.0
56	9044	33.0	0.4	66.6	0.0
57	22019	43.1	0.1	56.8	0.0
60	24899	26.9	0.1	73.0	0.0

Table 2.5. Summary of single factor ANOVA results for the vertical distribution of sardine at 38 and 120 kHz.

Frequency/Region	DF	Mean Squared	P-value
120 kHz:			
3.77-FR vs. FR-BOT			
Between	1	0.019	0.022
Within	44	0.0033	
38 kHz:			
9.29-FR vs. FR-BOT			
Between	1	0.0012	0.39
Within	44	0.0016	
120 kHz and 38 kHz			
9.29-BOT			
Between	1	0.0018	0.45
Within	44	0.0031	
120 kHz vs. 38 kHz			
3.77-BOT vs. 9.29-BOT			
Between	1	0.0036	0.42
Within	44	0.0055	

Table 2.6. Average depth difference between echogram lines and proportion of total sardine density at 120 and 38 kHz between each line region.

Range	Mean difference (m)	S.E. (m)	n	% sardine density (120 kHz) (3.77 – BOT)	% sardine density (38 kHz) (9.29 – BOT)
120 kHz near field – bottom SSL	17.27	0.73	27	100%	-
38 kHz near field – bottom SSL	11.75	0.73	27	-	100%
120 kHz near field – 38 kHz near field	5.52	-	-	50.4%	-
120 kHz near field – foot rope	8.43	0.26	27	82.2%	-
38 kHz near field – foot rope	2.91	0.26	27	31.8%	62.7%
Foot rope – bottom SSL	9.39	1.13	27	17.8%	37.3%

Table 2.7. Summary of linear regression analysis results for acoustic data.

Comparison	R^2	DF	Mean Squared	P-value
sa vs. Total Catch				
38 kHz	0.018			
Regression		1	1.9	0.54
Residual		21	4.7	
120 kHz	0.049			
Regression		1	8.5×10^{-10}	0.31
Residual		21	7.8×10^{-10}	
sv vs. Total Catch				
38 kHz	0.041			
Regression		1	2.9×10^{-11}	0.35
Residual		21	3.2×10^{-11}	
120 kHz	0.047			
Regression		1	8.8×10^{-12}	0.32
Residual		21	8.3×10^{-12}	
Trawl Density vs. Acoustic Density				
38 kHz	0.025			0.48
Regression		1	0.0015	
Residual		21	0.0029	
120 kHz	0.074			
Regression		1	0.010	0.21
Residual		21	0.0067	
38 kHz sa vs. 120 kHz sa	0.95			
NF – FR				
Regression		1	9.6×10^{-9}	<0.01
Residual		21	2.5×10^{-11}	
FR – BOT	0.99			
Regression		1	1.1×10^{-8}	<0.01
Residual		21	7.7×10^{-12}	

2.6 Figures

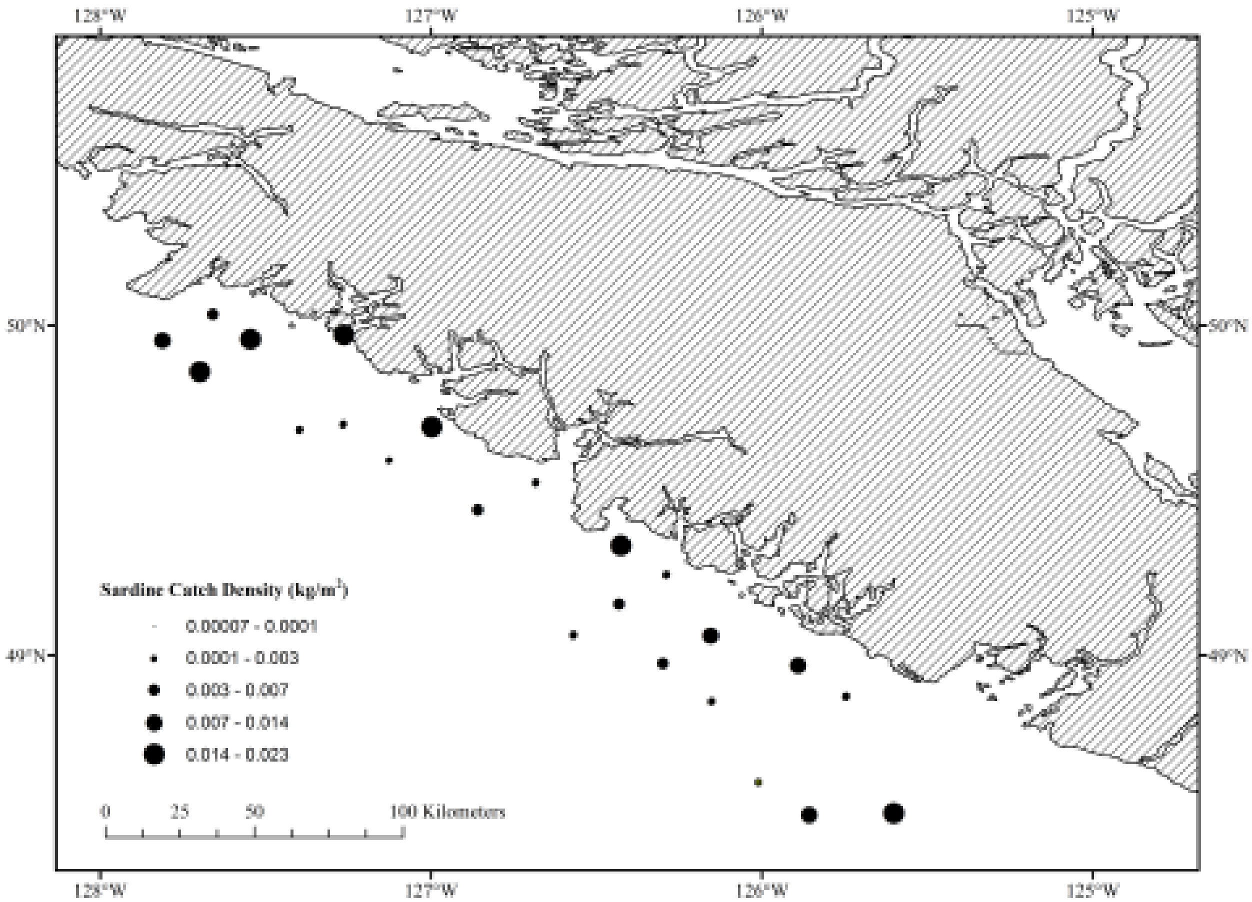

Figure 2.1 Locations of trawl stations for the 2011 sardine survey along the west coast of Vancouver Island.

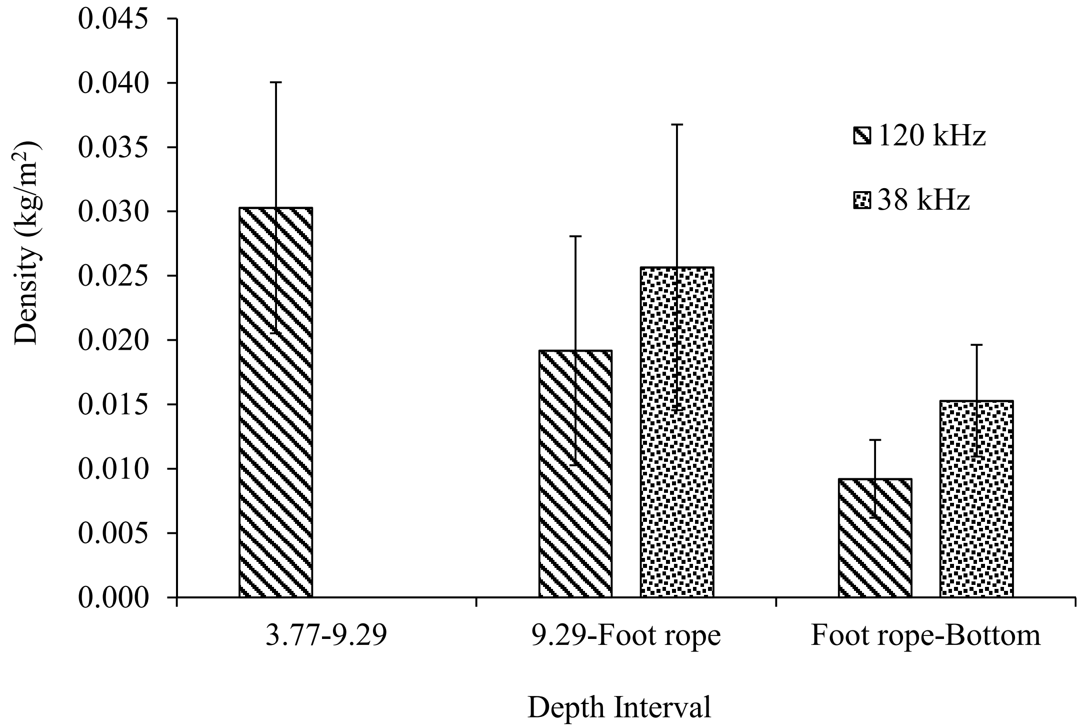

Figure 2.2. Mean sardine density and standard error at 120 and 38 kHz between 3.77 – 9.29 m, 9.29 m to the trawls foot rope, and foot rope to the bottom of the SSL. The foot rope and bottom of the SSL were on average 12.2 m and 21.03 m from the transducer respectively. There is no estimate of fish density at 38 kHz between 3.77-9.29 m since that depth range is within the 38 kHz near-field safe range.

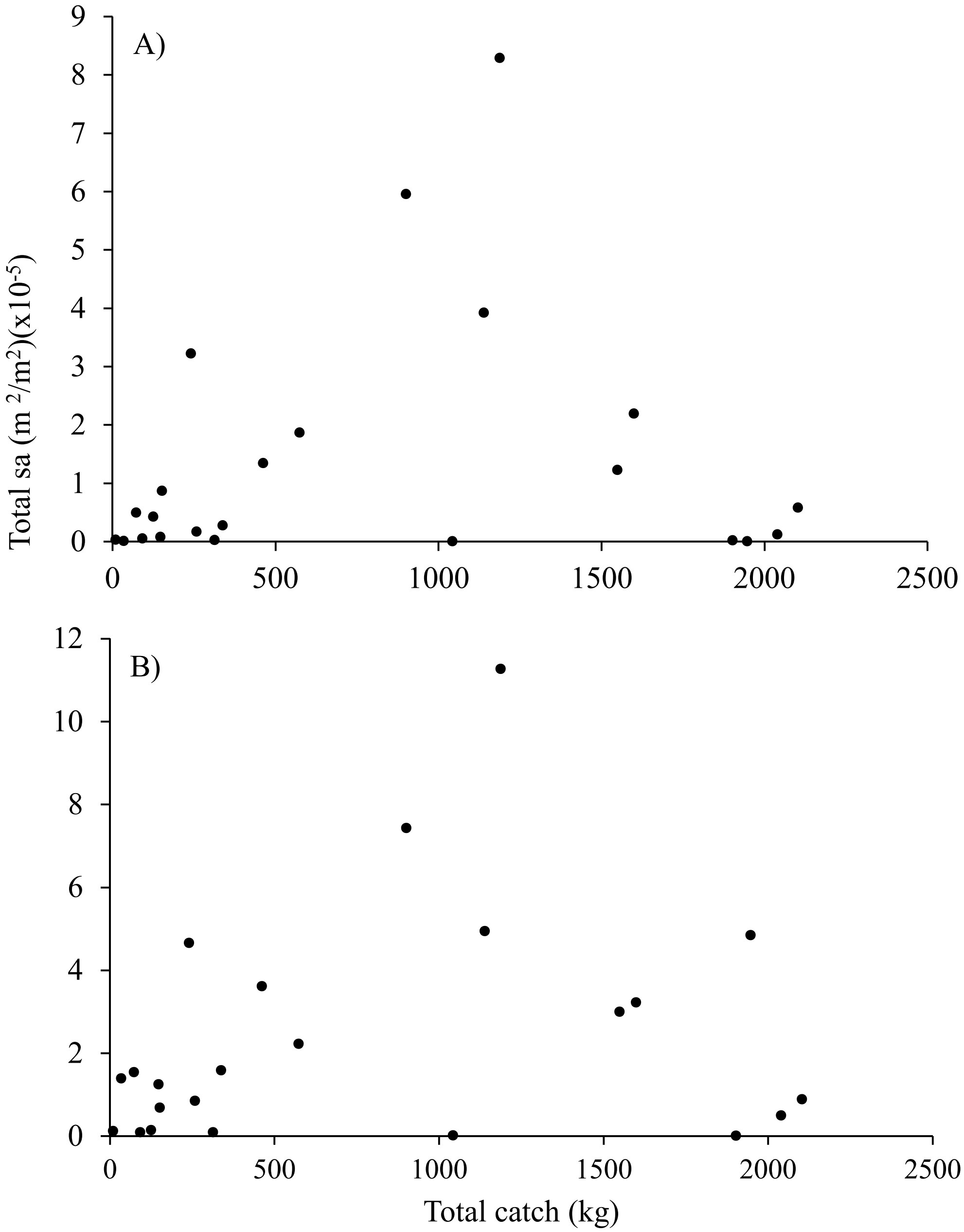

Figure 2.3. Comparison of total catch and un-partitioned area backscatter at (A) 38 kHz (end of 38 kHz near-field safe range to foot rope) and (B) 120 kHz (end of 120 kHz near-field safe range to foot rope). There were no significant (P>0.05) relationships.

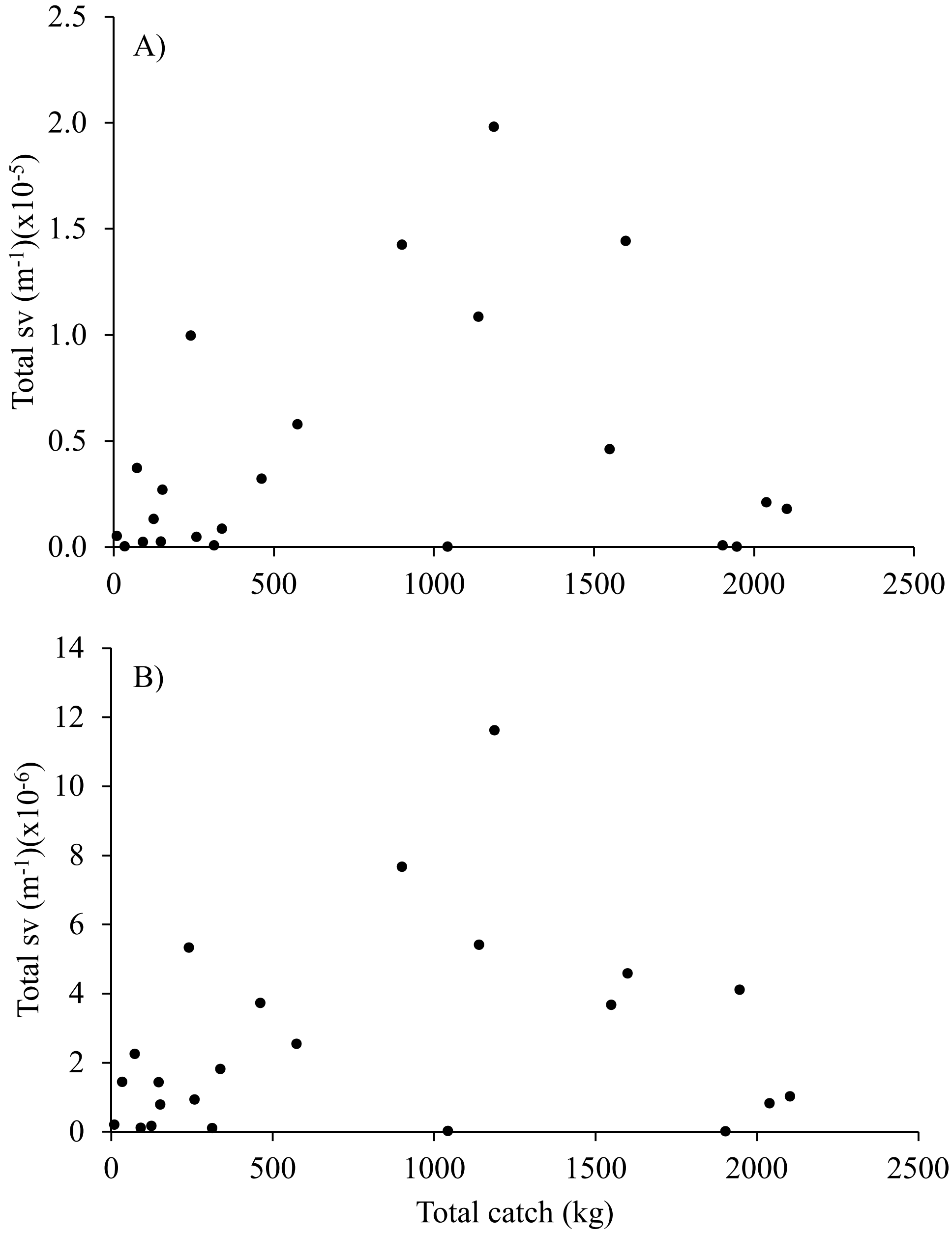

Figure 2.4. Comparison of total catch and un-partitioned volume backscatter at (A) 38 kHz (end of 38 kHz near field to foot rope) and (B) 120 kHz (end of 120 kHz near field to foot rope). There were no significant (P>0.05) relationships.

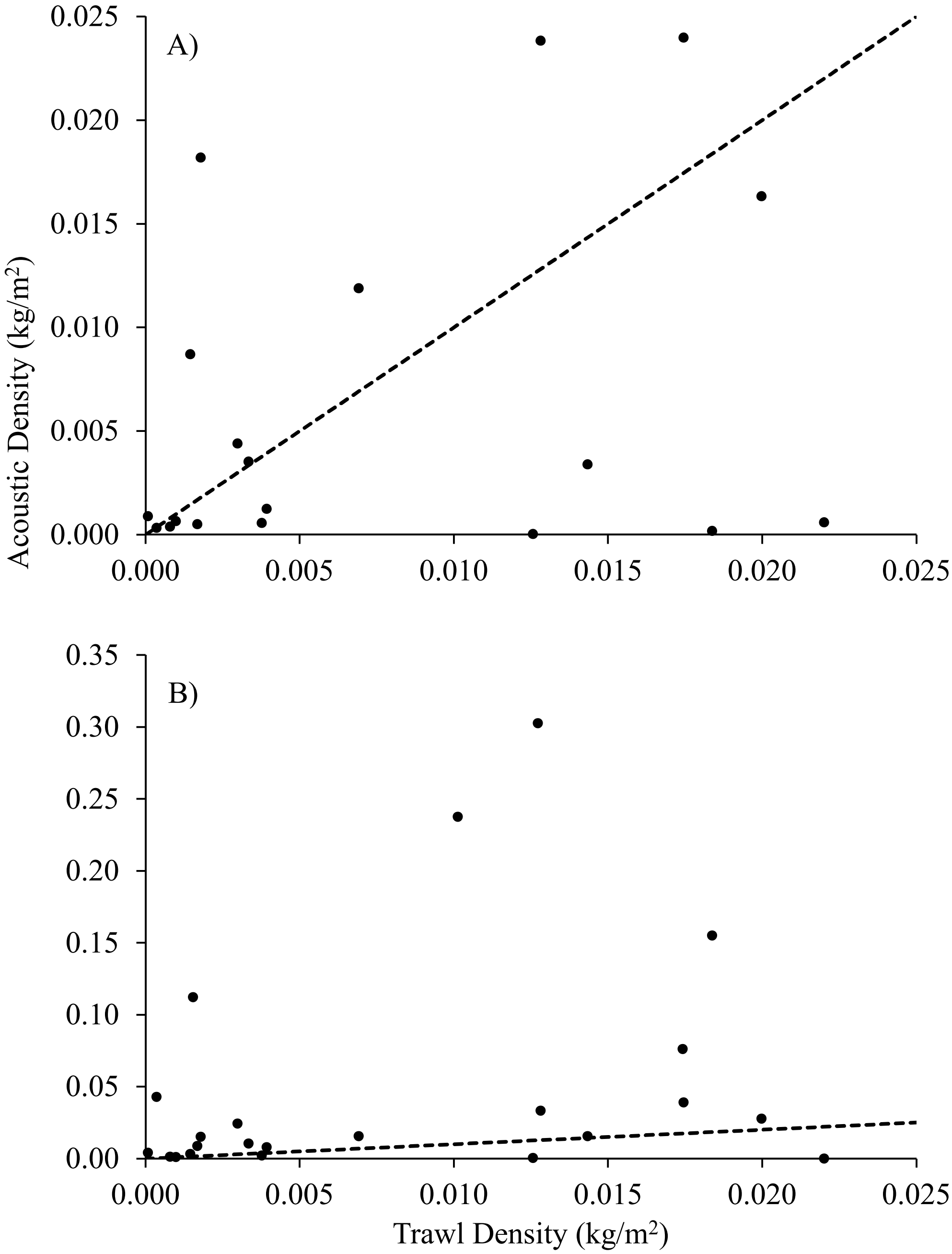

Figure 2.5. Comparison of trawl density and acoustic density for all species at (A) 38 kHz (end of 38 kHz near-field safe range to foot rope) and (B) 120 kHz (end of 120 kHz near-field safe range to foot rope). There were no significant relationships ($p>0.05$). The dashed line represents a 1:1 ratio. Several data points overlap.

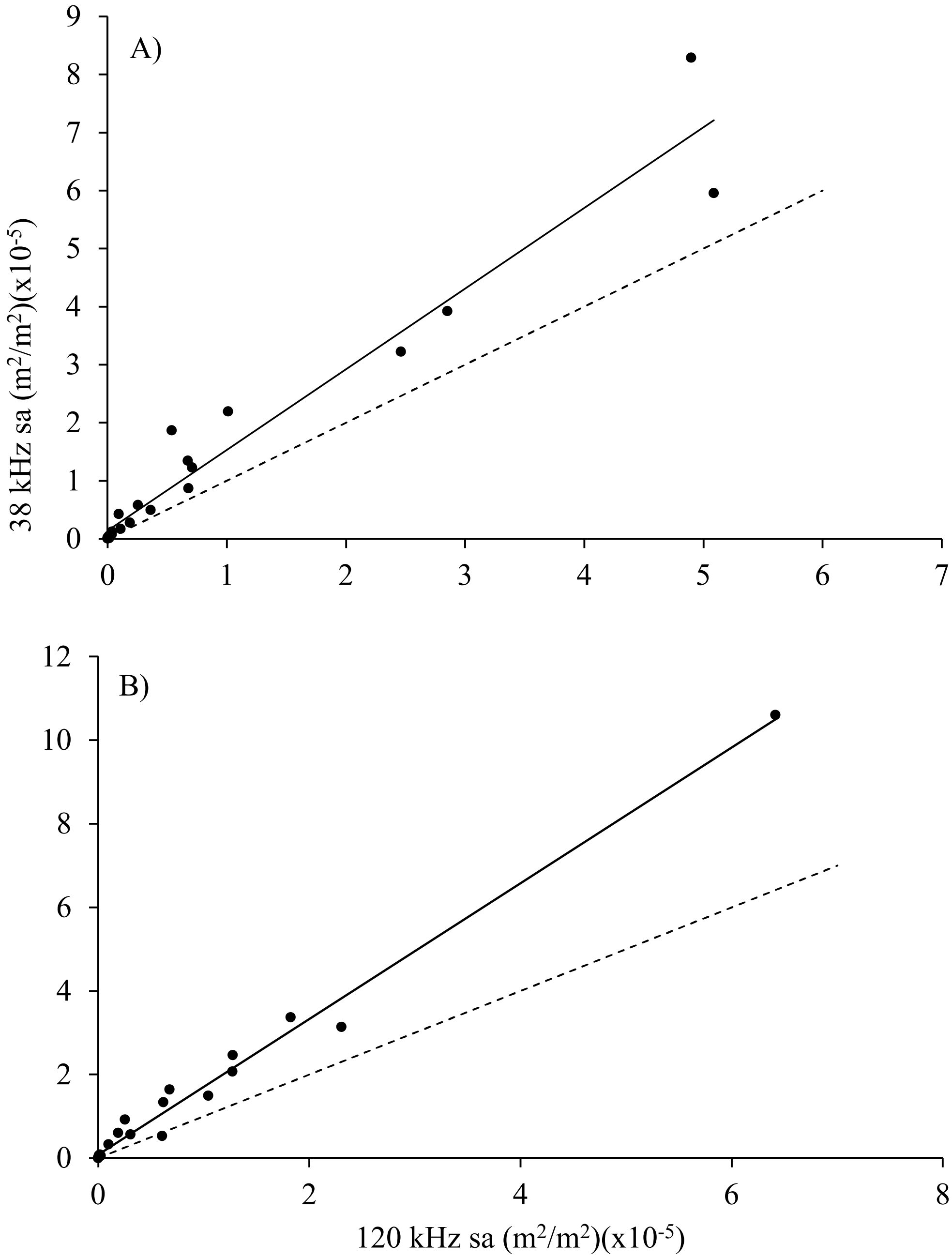

Figure 2.6. Comparison of raw acoustic backscattering area at 38 and 120 kHz from (A) end of 38 kHz near field to foot rope and (B) the foot rope to SSL bottom. Backscatter at each frequency was significantly related in both regions (R^2=0.95, n=23, p<0.01). The solid line is the linear trendline. The dashed line represents a 1:1 ratio.

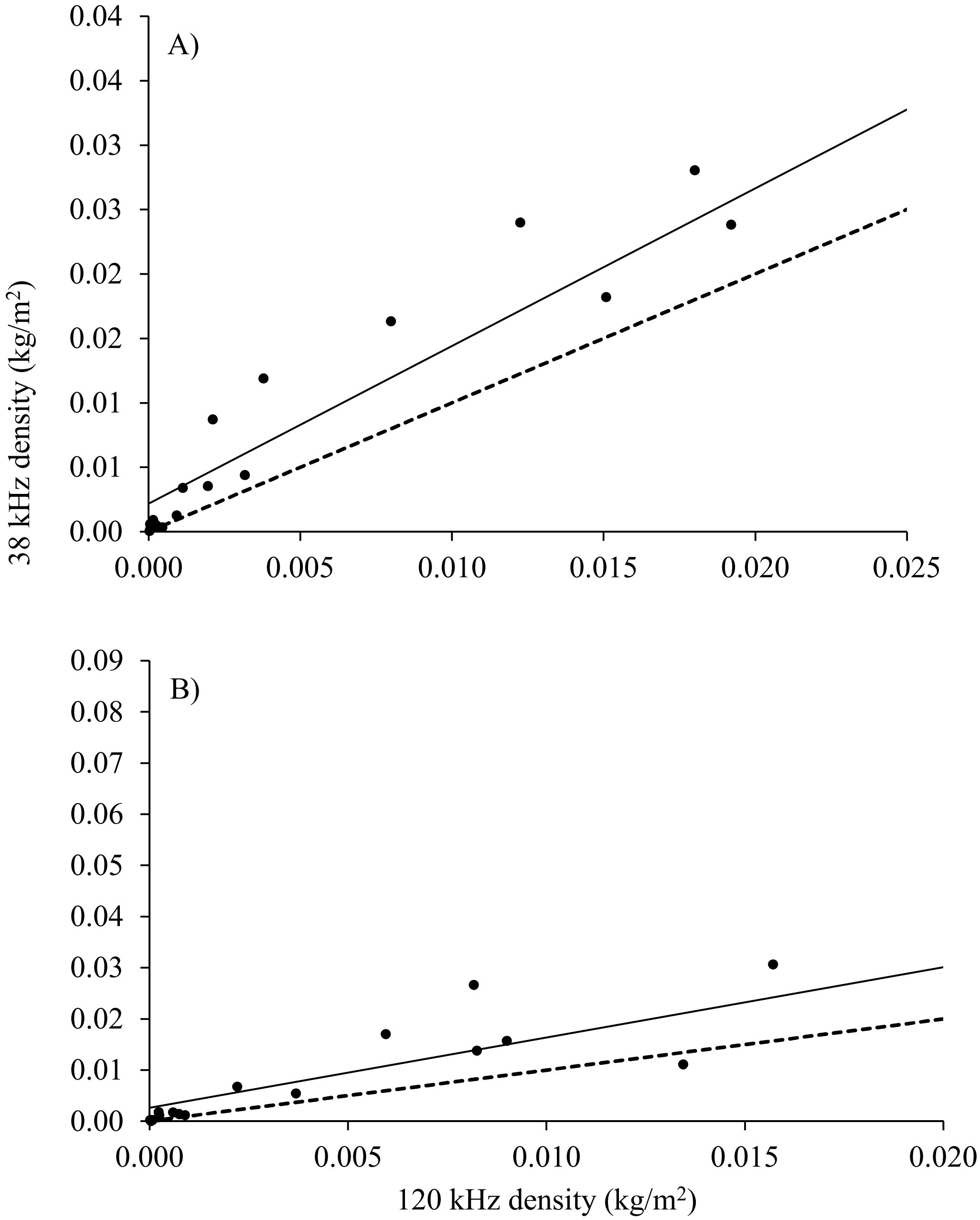

Figure 2.7. Comparison of acoustic estimates at 38 and 120 kHz from (A) end of 38 kHz near field to foot rope and (B) foot rope to bottom of surface layer. The two frequencies produced related estimates (A: R^2=0.97, n=23; B: R^2=0.88, n=23; p<0.01). The solid line is the linear trendline. The dashed line represents a 1:1 ratio.

3 Potential for echo-integration with multi-beam sonar

3.1 Introduction

Chapter 2 of this thesis questioned the use of nighttime acoustic data recorded with a vertically oriented echosounder for abundance estimation of near-surface pelagic species. While single-beam daytime acoustic measurements have been used for successful sardine biomass estimates in the U.S.A. and could prove useful to the Canadian fishery, the use of multi-beam sonar (MBS) presents several advantages over single-beam echosounder technology (Demer *et al.,* 2012; Zwolinski *et al.,* 2012). MBS can incorporate multiple beams to sample the water column from a variety of angles, from parallel to the sea surface to vertically downward. Targets can therefore be detected at both horizontal and vertical ranges from the vessel, meaning the avoidance and the blind zone and near-field bias will impact multi-beam acoustic measurements less than those taken with vertically oriented single-beam echosounders (VBE's). In addition, MBS's are capable of insonifying large volumes of water and could sample more of a species distribution than a VBE. The use of MBS's, however, present challenges to data analysis that must be surmounted before the technologies various advantages can be realized. This chapter therefore reviewed these two areas and identified specific topics where future research should be directed.

3.2 Background

Early attempts to quantify multi-beam acoustic data utilized old model, analog sonars and focussed on relationships between school geometry, acoustic backscatter from an echosounder and biomass (Misund and Aglen, 1992; Misund, 1993a; Misund *et al.,* 1992, 1995, 1996). Since this technique of multi-beam biomass estimation is based on school dimensions, rather than on digital echo energy data from a MBS, it is likely dependent on temporal and spatial variables, as well as on the location of the vessel relative to the school (Misund *et al.,* 1992; Misund, 1993b and 1997). In addition, the methodology would be difficult to apply to non-schooling fish species.

In the late 1990s, with the release of scientific MBS's capable of digital data output over their entire range, along with improved data storage and processing technology, the potential data output from MBS were expanded from simple analog measurements to digital acoustic backscatter (Gerlotto *et al.,* 1999; Mayer *et al.,* 2002). This allowed well established methodologies for converting single-beam acoustic backscatter to biomass to be extended to multi-beam acoustic surveys. Digital output of acoustic backscatter data was, however, only an initial step. The usefulness of MBS for direct density estimation is currently limited due to challenges involved in accurately converting backscatter to biomass, largely owing to a lack of knowledge relating to the calibration of modern MBS's and the quantification of backscatter originating from multiple angles of incidence as abundance.

3.3 Calibration

Prior to the development of calibration methodologies the echo energy returns obtained by VBE's were not useful for abundance estimation (Foote *et al.,* 1987). Calibration ensures acoustic instruments display the correct value of backscatter and is therefore a critical component of accurately quantifying the acoustic signal (Simmonds and MacLennan, 2005). The procedure involves the use of a standard target of known acoustic scattering properties, which is guided across the acoustic beam at a given range to determine transducer directionality (Foote *et al.,* 1987). This technique can be difficult to apply to MBS's, due to the large number of overlapping beams. In general, the goal of MBS calibration is to achieve backscatter measurement accuracies comparable to modern VBE's.

Cochrane *et al.* (2003) were among the first to calibrate a MBS with digital data output: the Simrad SM2000 (200 kHz). Cochrane (2002) first characterised the near field of the SM2000 in order to ensure calibration with a standard target is performed outside ranges where significant near field effects occur, or, in situations where it is only possible to take measurements close to the transducer, ensure near field calibration can be extrapolated to the far field. It is still recommended that calibration measurements be performed in the far field if possible. Since MBS's consist of multiple overlapping beams, the calculation of sample volume is more complicated than for single-beam systems. Cochrane *et al.* (2003) developed a new volume backscattering strength (Sv) equation for MBS. The Sv equation formulated is now used in multi-beam post-processing software.

One limitation in the application of the standard target technique to MBS's is the physical challenge of moving the standard target through all beams over a potentially wide array to measure the beam pattern. Melvin *et al*. (2003) overcame this difficulty by rotating the transducer relative to a stationary standard target, rather than attempting to maneuver the tungsten carbide sphere through each of the SM2000's 128 beams. The slow rotation of the transducer allowed the researchers to measure the equatorial sensitivity pattern of the SM2000; however no measurements of the polar beam pattern were made. To test the accuracy of their preliminary multi-beam calibration technique, Melvin *et al.* (2003) compared area backscatter of a confined herring school from the SM2000 to a calibrated echosounder and achieved correlated outputs, although with differing magnitudes. The different area backscattering strengths (Sa) observed with each system were primarily due to a non-even distribution of herring within the weir. Variable insonification angles of the SM2000, which can alter TS, and the different operating frequencies of the sonar and echosounder also likely contributed to differences in area backscatter. Cochrane *et al*.'s and Melvin *et al*.'s (2003) research demonstrated that multi-beam measurements of backscatter can reflect true values; however it also highlighted the difficulty in quantifying backscatter as biomass when targets are insonified from multiple off-dorsal incidences.

Foote *et al*. (2005) expanded upon initial calibration studies of the SM2000 by developing standard protocols for multi-beam calibration (Simmonds *et al*., 1999; Chu *et al.,* 2003). In addition to rotating the transducer, the standard target was raised and lowered in the water column, permitting the measurement of both equatorial and polar beam patterns. Procedures for selecting the proper gain function, and measuring environmental conditions of calibration site, system stability, and directionality of individual beams were also described. The gain function must be determined to prevent saturation and/or under-stimulation of the elements. Foote *et al.* (2005) suggested the selection of gain function by recording the echo amplitude of the standard target over a series of gain function settings at a given range, frequency, hydrographic condition, and sonar settings. System stability was determined by plotting echo strength of the standard target over large number of consecutive pings to determine variation in target measurements. It should be noted that recently released sonars are compensated for transducer motion and are more stable than early versions of the SM2000. The measurement of the directionality of individual beams was suggested in order to accurately calculate sampled volume, which is of importance to produce fish density estimates through echo integration or counting.

The protocols outlined by Cochrane *et al.* (2003), Melvin *et al.* (2003), and Foote *et al.* (2005) are difficult to apply to a hull mounted sonar on a fisheries research vessel in the field due to practical challenges with moving the standard target through a hull mounted sonars many beams. The application of these protocols in the field has been demonstrated by Ona *et al.* (2009) for the recently released Simrad MS and ME70 MBS's. Since these modern sonars produce actual beam patterns closely matching theoretical predictions, simple procedures for determining transducer gain in target direction, on-axis transducer gain, and Sa correction factor can be used. Beam pattern was therefore determined entirely theoretically. As a result, the standard target only needed to be moved through each of the beams to measure TS and volume backscattering strength of the sphere to compensate differences between actual and theoretical measurements of sphere TS. To calibrate the horizontally oriented MS70 sonar, Ona *et al.* (2009) utilized a two point suspension system mounted on the side of the survey vessel, while a three point system was used for the vertically oriented ME70, similar to systems used for the calibration of a single-beam vertical echo sounder. Like Melvin *et al*. (2003), Ona *et al*. (2009) emphasized the importance further characterising the relationship between incident angle and TS to facilitate the use of quantitative MBS in fish biomass estimation.

The above research has established the theory of MBS calibration and the remaining challenges are practical. There is a lack of quantitative software to carry out the calibration of a wide range of multi-beam systems. The hardware and software required for real time interaction with MBS for calibration purposes are not well developed for many systems. For example, a quantitative acoustic survey of fish biomass with an omnidirectional sonar would dramatically increase the sample volume of acoustic surveys, as well as reduce target-vessel avoidance, however the calibration of such a system has never been demonstrated, nor has essential hardware and software been developed to assist in real time signal quantification (Tang *et al.,* 2006). Future research should adapt well defined calibration theory and methodologies to other sonars, such as omni-directional systems.

3.4 The quantification of backscatter from multiple incidence angles

Calibration studies of MBS emphasized the challenge of converting scaled multi-beam backscatter to target abundance. Since MBS's can insonify targets at many different angles simultaneously, the TS of an individual fish depends on the tilt angle of the beam it is sampled by, in addition to the targets size and orientation in the water column. The quantification of multi-beam backscatter originating from multiple angles of incidence and target orientations is therefore very problematic. Data from a large number of beams must be appropriately weighted and averaged based on target length, target orientation, and beam tilt angle. The quantification of data from a large number of beams at a range of incident angles has become a central challenge in fisheries acoustics; yet, research on this topic is limited. TS must be estimated at any incidence angle. In addition, since TS depends on target orientation, the natural orientation of targets must be determined. The combination of *in situ* measurements and mathematical modelling may help in the quantification of multi-beam data as fish abundance (Jech and Horne, 2002). With the development of scientific MBS's that insonify fish from a range of angles this research has become increasingly important.

Research on the natural *in situ* fish orientation is scarce and has been strongly encouraged (Foote, 1980; McClatchie *et al.,* 1996). Fish orientation relative to the transducer can be quantified with pitch, yaw, and roll angles, all of which impact TS to varying extents, depending on the tilt angle of the acoustic beam (Love, 1977; McClatchie *et al.,* 1996). In the past, TS has been primarily measured from the dorsal perspective (*in situ* and in captivity) with echosounders and/or mathematically modelled (Simmonds and MacLennan, 2005). From this aspect, pitch is the primary orientation angle contributing to TS, while yaw and roll are generally not considered (Cutter and Demer, 2007). From a lateral perspective, however, pitch is far less important.

Field measurements of lateral aspect TS have been primarily carried out in freshwater environments, such as rivers, lakes, and ponds where a horizontally oriented echosounder is the only practical acoustic survey methodology (Kubecka, 1994; Burwen and Fleischman, 1998; Lilja *et al.,* 2000; Pederson *et al.,* 2009). Utilizing *in situ* measurements, mathematical modelling and immobilized or captive fish, it has demonstrated that TS from this aspect is highly dependent on the yaw angle of the fish relative to the transducer (Kubecka, 1994; McClatchie *et al*., 1996; Burwen and Fleischman, 1998; Frouzova *et al.,* 2005; Cutter and Demer, 2007; Tang *et al.,* 2009). The maximum lateral aspect TS occurs at yaw angles of 90° and 270° where the length of the fish is oriented perpendicular to the acoustic beam, or "side on". The minimum lateral aspect occurs at yaw angles of 0° and 180° where the length of the fish is oriented parallel to the acoustic beam, or "head/tail on" (Kubecka, 1994; Burwen and Fleischman, 1998). At present, few studies have measured off dorsal TS and natural fish orientation of marine species *in situ* (Pedersen *et al.,* 2009).

Mathematical models of TS at any aspect have been well developed and are outside the scope of this review (Love, 1977; Foote, 1985; Clay and Horne, 1994; Jech *et al*., 1995; Jech and Horne, 2002; Towler *et al.,* 2003; Tang *et al.,* 2009). Instead, models of multi-beam backscatter will be briefly reviewed, although it should be noted that KRM models are not accurate at head and tail on orientations, which is a topic that could be addressed in future modelling research (Jech and Horne, 2002). Cutter and Demer (2007) developed a model to predict 3D scattering directivity patterns of fish at various orientations in a simulated multi-beam echosounder. They found backscatter in the outer beams, which insonify fish from the side were highly dependent on yaw, but not on pitch. In contrast, TS of more vertical beams was more dependent on pitch than yaw (Cutter and Demer, 2007). Utilizing the Cutter and Demer's (2007) model for predicting 3D scattering directivity, Cutter et al. (2009) modelled the 3D scattering directivity of Antarctic krill (*Euphausia superba*) based on the beam directions from a multi-beam echosounder and compared predictions with *in situ* multi-beam echosounder measurements of krill. The model assumed a natural pitch and yaw angle determined in a previous study and that all krill were concentrated on the beam axis (Conti and Demer, 2006). Field measurements did not match model predictions, potentially due to these assumptions, vessel avoidance reactions, and/or non-uniform krill orientation across all beams. The study emphasized the need for studying the orientation of target species *in situ* under many different conditions, including natural state and avoidance reactions, and the lack of acoustic data analysis programs able to appropriately average data from a large number of beams at a variety of tilt angles (Cutter *et al.,* 2009). *In situ* investigations of natural marine fish orientation are scarce and are needed if MBS is to be used for abundance estimation.

In comparison to research in shallow freshwater ecosystems, the conversion of off-dorsal backscatter to abundance with MBS in marine environments is more complicated. The two branches of fisheries acoustics share several challenges, such as the need for lateral aspect TS, interference from the sea surface or bottom, and lower signal to noise ratios in comparison to mid-water returns, however, many differences also exist (Mulligan, 2000). Converting TS at any aspect to abundance in a marine environment requires different considerations than in most shallow freshwater systems and requires specialized research. For example, in rivers the fish pitch orientation is not important since fish are insonified only laterally, whereas multi-beam acoustic surveys in marine environments incorporate beams at a range of angles from near-parallel to perpendicular to the sea surface, so the tilt angle of the beams and 3D orientation (pitch, yaw and roll) must be considered (Cutter and Demer, 2007). In addition, large survey vessels are used during marine acoustic surveys, which can impact fish behaviour (orientation) (Olsen *et al.,* 1983). Marine acoustic surveys also usually utilize lower frequencies than freshwater studies and at larger transducer to target distances. As a result, the effect of orientation on TS may be less and gradients in salinity and temperature could affect acoustic data (Jech *et al.,*1995; Mulligan, 2000). In order to accurately estimate TS to convert multi-beam backscatter to abundance, these topics must be investigated.

4 Conclusion

4.1 The incorporation of acoustic methods into the Canadian Pacific sardine survey

This thesis has provided an example of how acoustics can be used in a supplementary role to trawl-based abundance estimates in the Canadian Pacific sardine survey. Extrapolations to determine Canadian seasonal sardine biomass can be performed according to average vertical distribution determined with acoustic techniques. Acoustics could also be used in real-time during the survey to focus sampling effort to the appropriate depth region. If a complementary acoustic survey is developed to independently estimate seasonal sardine biomass, nighttime acoustic measurements should be interpreted with caution due to the significant near-surface acoustic blind zone and near-field bias. The use of daytime acoustic data to estimate sardine density should be evaluated in the future as an alternative to nighttime observations, since the blind zone and near-field bias may be less important. In addition, the desirable avoidance reaction where fish dive out of the near-surface acoustic blind zone and near-field into far-field, where targets can be observed and backscatter quantified, may be more pronounced during the day.

To facilitate the incorporation of acoustic data into future sardine surveys, I suggest the following minor changes be made to survey biological sampling protocols in order to more accurately partition acoustic backscatter. Most TS equations are based on total length; however only fork length was recorded during the 2011 survey. As a result, total length had to be estimated with a fork length-total length conversion equation. Due to a lack of resources herring and anchovy samples were not collected. Therefore, the equation determined for sardine was also applied to herring and anchovy. In addition, lengths and weights were recorded for coho and chinook salmon, but not for pink, chum or sockeye salmon. Total weight and a count of each salmon species were also recorded, which was used to determine the average weight of salmon in each set. The length/weight data recorded for coho and chinook was used to create a weight-length conversation equation that was subsequently applied to all salmon. Furthermore, several sets were missing pieces or sections of data, most often salmon counts and/or herring and anchovy length data. For those sets, average weight and/or length was approximated with data from geographically nearby sets. Partitioning backscatter accurately requires data not only on the target species, but also on all other species present (Hampton, 1996). To more accurately partition backscatter from the next surveys, total length and weight for all species should be recorded so that these approximations do not need to be made in future acoustic analysis. It is acknowledged that due to limited staff and time constraints during the survey, as well as the disruption of data collection protocols used in the trawl survey time series, that this suggestion may not be practical. These suggestions would, however, only need to be applied when significant quantities of sardine are captured.

4.2 The future of multi-beam sonar in acoustic abundance estimation

The applications of MBS currently remain limited to studies of fish behaviour and school geometry (volume and shape), as the quantification of multi-beam data as abundance is not yet possible. Calibration theory is well established, but methodologies are undefined for most multi-beam systems and many models lack real time data processing software and hardware required for practical calibration. In addition, practical procedures for moving standard targets through all of MBS's beams have not been developed for most sonar systems. The TS of fish from any aspect has been well studied with mathematical models, but *in situ* measurements of lateral aspect TS are rare. Variables influencing TS, primarily natural fish orientation, avoidance reactions and beam tilt angle, are poorly understood and could vary among species. Challenges still exist in the accurate interpretation of backscatter originating from targets in several beams at multiple tilt and incidence angles. Future research in these areas is strongly encouraged.

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Appendices

Appendix A: Total length length-weight and total length-fork length relationships for Pacific sardine, herring, and salmon

Table A.8. Length-weight relationships for Pacific sardine, herring, and salmon estimated from survey samples. $W=aL^b$.

Species	a	b	n
Pacific sardine	0.094	2.29	181
Pacific herring	0.0020	3.45	180
Salmon	0.00061	3.68	326

Table A.9. Total length (TL)-fork length (FL) relationships for Pacific sardine (estimated from survey samples) and chinook and coho salmon (Pahlk, 1989) used to convert FL to TL to estimate TS. TL=mFL+c.

Species	m	c	n	R^2	P	Reference
Pacific sardine	1.061	0.82	175	0.99	<0.01	-
Chinook salmon	1.015	39.02	449	0.98	<0.01	Pahlke (1989)
Coho salmon	1.055	4.92	100	0.99	<0.01	Pahlke (1989)

Table A.10. Summary of linear regression analysis results for biological data.

Comparison	R^2	DF	Mean Squared	P-value
Length vs. Weight				
Sardine	0.61			
Regression		1	0.20	<0.01
Residual		180	0.00070	
Herring	0.87			
Regression		1	0.93	<0.01
Residual		179	0.00077	
Salmon	0.94			
Regression		1	18.64	<0.01
Residual		325	0.0035	
Fork Length vs. Total Length				
Sardine	0.99			
Regression		1	2008.63	<0.01
Residual		173	0.14	

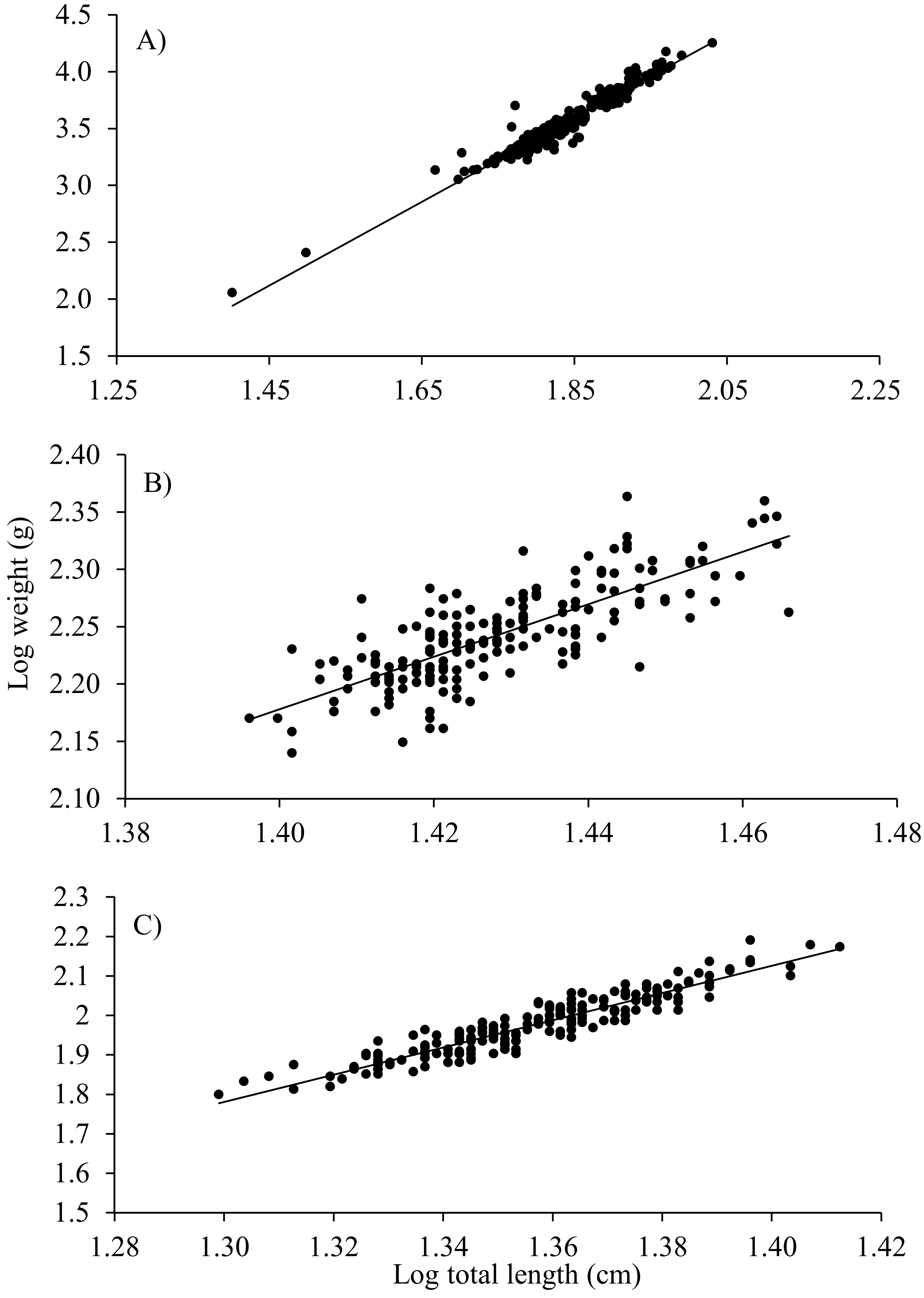

Figure A.8. Length-weight relationship for (A) chinook and coho salmon (combined), (B) Pacific sardine and (C) Pacific Herring. Linear trendline shown (A: R^2=0.94, p<0.01, n=326; B: R^2=0.61, p<0.01, n=181, C: R^2=0.87, p<0.01, n=180).

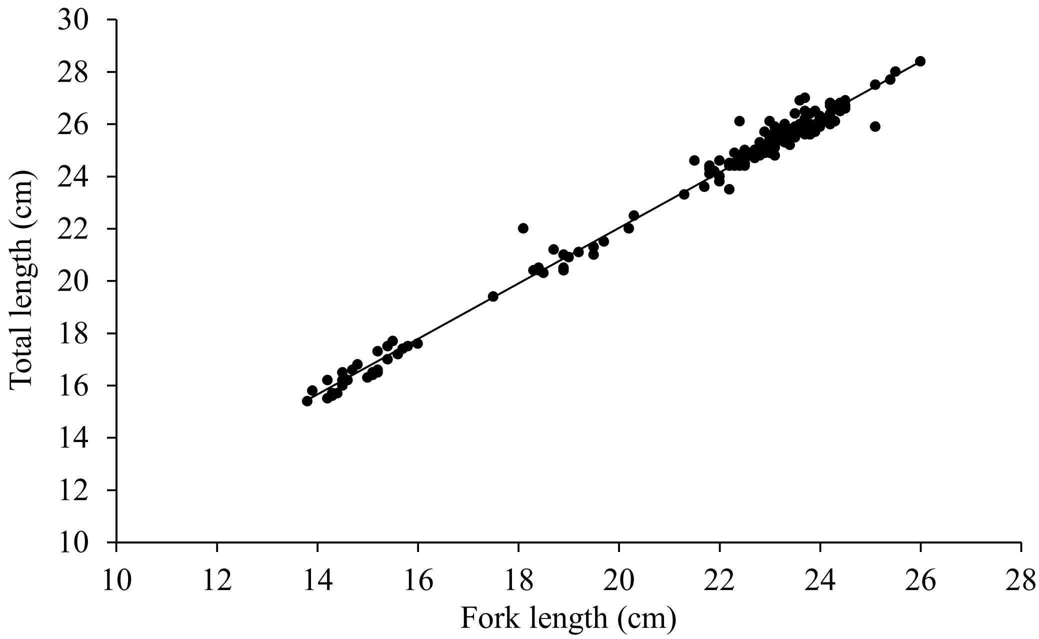

Figure A.9. Fork length-total length relationship for Pacific sardine. This relationship was also applied to herring and anchovy. Linear trend line shown (R^2=0.99, p<0.01, n=175).

Appendix B: Sv threshold filter selection

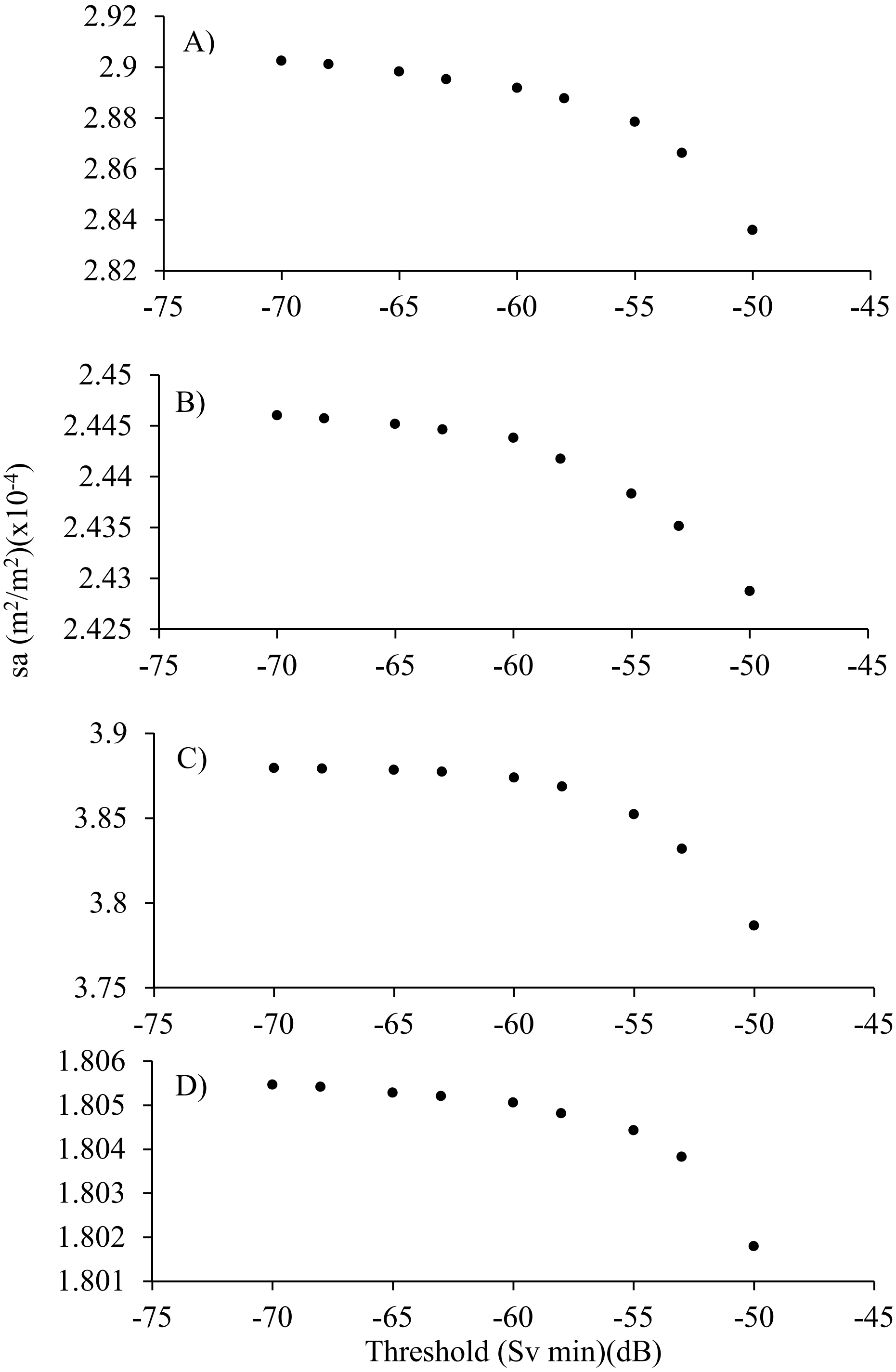

Figure B.10. Area backscatter coefficient plotted against minimum Sv threshold in Echoview for sets 13 (A), 39 (B), 46 (C) and 55 (D). A - minimum Sv threshold of -65 dB was selected partially based on these plots.