Fishery Acoustic Indices for assessing Atlantic herring populations

by

R. R. Claytor[1], J. Allard[2], A. Clay[3], C. LeBlanc[4], G. Chouinard[4]

[1]Department of Fisheries and Oceans, Science Branch, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia, B2Y 4A2 Canada, e-mail ClaytorR@mar.dfo-mpo.gc.ca

[2] Université de Moncton and Maritime Statistical Analysis Inc.,Analyse Statistique des Maritimes Inc.,P.O. Box/C.P. 871, Moncton N.-B. CANADA E1C 8N6

[3] Femto Electronics Ltd., P.O. Box 690, Lower Sackville, Nova Scotia, Canada B4C 3J1

[4] Department of Fisheries and Oceans, Science Branch, P.O. Box 5050, Moncton, New Brunswick, Canada E1C 9B6

Abstract

A method for measuring the spatial and temporal distribution of fish school densities and exploitation rates using fishery collected acoustic data and voronoi polygons to estimate biomass is described. A herring purse seiner fishing on non-spawning feeding aggregations, and a herring gillnetter fishing on smaller, highly dense spawning aggregations, in the southern Gulf of St. Lawrence, Canada, collected acoustic data during regular fishing activity for this study. An individual boat with data collected in this manner was found to represent trends in the entire fleet. There was a threshold density beyond which exploitation rates remained low. This threshold provides managers with a method for identifying and eliminating spatial and temporal trends in high exploitation rates and preventing overfishing.

A simulation model calibrated with data from the Pictou 1997 inshore gillnet fishery compared the properties of abundance indices derived from fishery acoustic data to those derived from survey indices. The indices were examined over five fish distribution types ranging from a single spike to a uniform flat distribution, four conditions of fishing and fish movement, and sixteen stock sizes for each of these distribution and conditions. These data are suitable for deriving abundance indices provided the searching covers the entire temporal and spatial distribution of the population.

The fishery acoustic abundance indices provide a basis for adopting a decision rule management strategy, as an alternative to the current $F_{0.1}$ management strategy for herring populations. Decision rules would allow individual spawning components to become the basic management unit and would result more responsive management system for this fishery.

1. Introduction

Increasingly, conservation targets are defined not only by fishing mortality, but also by life history objectives (Anon 1997). This increased focus on life history characteristics reflects the realization that the spatial and temporal structure of a spawning component will be compromised if all the fishing mortality comes from one area and time, even if the fishing mortality summed over all components is within conservation limits. If, however, the overall fishing mortality is kept within conservation limits and is distributed in proportion to the relative abundance of the various spatial and temporal components it is expected that the conservation goals would be satisfied. A first step in achieving these goals is to provide managers with tools that would allow them to spatially and temporally distribute fishing mortality relative to the size of the schools being harvested. To meet these targets, information on the spatial and temporal distribution of fish biomass and exploitation rates is required (Claytor and Clay 2001). This paper describes a method for deriving indices of the spatial and temporal distribution of fish school densities and exploitation rates that depended on cooperative research with the fishing industry. The method was developed using acoustic data collected during regular fishing activity of a gillnet and purse seine fishing fleet in the fall herring fishery in the southern Gulf of St. Lawrence, Canada.

Fish movement and aggregation patterns can create high variance and changing and non-linear relationships between the abundance indices and stock size for pelagic species like herring, capelin, anchovetta, and sardines. For example, research surveys are often restricted to specific areas and times of year and even small changes in migration timing or aggregation patterns may bias results from otherwise robust statistical designs. Survey estimates with large variances and unknown relationships with stock size have resulted from fish movement and aggregation patterns for several pelagic stocks in Atlantic Canada and created difficulties in assessing their stock status (DFO 1996; DFO 1999ab; Wheeler et al. 1992). These difficulties have lead to criticism of the use of surveys by the fishing industry. The criticism most often voiced by the herring industry in the southern Gulf of St. Lawrence is that the surveys are not conducted during times when they observe large schools of fish. In addition, the size of most research vessels precludes surveys in shallow water and in areas where fishing gear such as lobster traps and gillnets are deployed. These areas are often where the fisheries occur and hence are of most interest to the fishing industry. These factors make it difficult to convince the fishing industry that survey indices are unbiased and accurate enough for fishery management decisions. Consequently, these issues are a major source of conflict in stock assessment and management.

Conflicts over surveys are difficult to resolve because there is often no alternative to government research vessels for surveys. Conflicts over catch rates are difficult to resolve because the fishing industry and stock assessment scientists often have divergent concerns about inconsistencies inherent in using catch rates as abundance indices. For example, scientists are often concerned that catch rates have remained high in spite of population density declines because of efficient search methods available to modern fishing fleets (Hilborn and Walters 1992). Alternatively, concerns among industry are that catch rates have been lowered because of management or market restrictions on daily catches, interference from other gear, and weather (Claytor et al. 1998).

The problem is made more difficult because providing advice on spatial and temporal trends in fishing mortality requires abundance indices collected on scales relevant to single spawning components rather than spawning component aggregations. For example, assessment advice for this stock has been provided only for the overall spring and fall spawning stocks and not for the local stock components within these seasonal stocks. The provision of overall advice is a concern for industry because sharing the TAC among components is not based on annual trends in estimated size of local spawning components, but on an historical sharing formula based on catch levels and historical data regarding the relative size of the stocks in the mid-1980s. As a result, groups that feel they have taken conservation measures, such as restricting boat limits and increasing mesh size, feel they are not reaping the relative benefits of those measures. Some industry groups feel penalized for these efforts when the overall TAC declines because stocks in other areas are going down, whereas, they feel their stock is increasing. This leads to conflicts in management of the resource and difficulties in ensuring that fishing mortality is spread equitably amongst the spawning components. As a result, in this fishery (Claytor et al. 1998) there is increasing demand for local area assessment and management and industry-collected data is the only viable method for collecting the data required for local assessments.

The approach developed with the fishing industry to overcome these problems consisted of using an acoustic recording system on board fishing vessels that was independent, but parallel to the system they used during fishing activity to locate schools. The system developed consisted of a sounder, a transducer, a global positioning system (GPS), and a computer for recording data. The vessel captain turned the system on when leaving port and off when returning to port, so that fish densities observed during the entire fishing trip were recorded (Claytor et al. 1999).

This paper describes how we developed abundance indices from these types of data and then tested their performance with simulations that were compatible with the spawning aggregations and fisheries associated with the southern Gulf of St. Lawrence gillnet fishery.

2. Fishery and Fleets

The data analyzed in this paper come from two of the herring fleets participating in the fall southern Gulf of St. Lawrence herring fishery. This fishery consists of several gillnet fleets with a total of about 1500 licenses of which about 600 - 1000 are active and a purse seine fleet with six active boats. The gillnet fleets fish inshore on spawning aggregations in five areas of the southern Gulf of St. Lawrence. Their allocation is about 80% of the total quota for the area and recent average landings range from 30,000 - 60,000t. Data from the gillnet fleet were collected from 7 September - 30 September 1997 from the Pictou, Nova Scotia area, by a commercial boat, the 'Broke Again' (Fig. 1A). In this area, the fleet consists of about 120 boats. The purse seine fleet fall fishery occurs on non-spawning feeding aggregations in the Chaleur Bay area and recent average landings have ranged from 6,000 - 16,000 t. Data from the purse seine fleet were collected from 23 August - 20 October 1995 by a commercial boat the 'Gemini' (Fig. 1B).

3. Acoustic data collection and calibration

3.1 Calibration

All data collection and processing for these calibrations were done using the Femto Hydroacoustic Data Processing System (HDPS). It is the software and hardware system used on all fishing vessels collecting acoustic data in the southern Gulf of St. Lawrence (Claytor et al. 1998, 1999a,b) and has also been used on fishing vessel surveys for herring stocks in Atlantic ocean coastal waters of Nova Scotia, Canada (Melvin 1998a,b), Newfoundland, Canada

(Wheeler et al., 1999), and the eastern United States (Yund 1998) Fishing vessels have also been used to collect acoustic data on groundfish such as cod in Newfoundland (Anderson et al., 1998) and rockfish in British Columbia, Canada (R. Kieser, PBS, Nanaimo, BC, Canada). The software and hardware has been used on research vessel acoustic surveys in several areas, including the southern Gulf of St. Lawrence (Clay and Castonguay 1996, Claytor and LeBlanc 1999).

A 120 kHz digital sounder was used on the gillnet boat because it would not interfere with the 200 kHz or 50 kHz systems used by the gillnet fleet. These systems were attached to separately installed transducers. For the purse seiners we utilized an extra sounder and transducer that was no longer required by the captain for fishing. Each system was coordinated with a global positioning system (GPS). As a result, the systems used for collecting data were completely independent but parallel to those used for fishing. This independence was essential to ensure that calibration settings remained unchanged throughout the data collection. Once in place, two standard calibrations were performed for each installation:

1.   Time varied gain (TVG) calibration - Each sounder has a TVG to adjust the gain of the received echo signal to account for losses due to attenuation and absorption. The TVG calibration accounts for the errors in the implementation of this curve.

2.   Ball calibration - This calibration is used to adjust the fixed gain of the TVG curve using one known data point, the echo return from a calibration sphere having a known TS.

Calibrations were conducted according to the methods described by MacLennan and Simmonds (1992) and detailed in Clay and Claytor (1998).

3.3 Acoustic data preparation for analysis

The fishing track was identified by recording latitude and longitude once per second using Garmin 45XL portable GPS units. Latitude and longitude coordinates for each remaining fix were converted to distances (metres) from a common reference (45° latitude, 67° longitude) taking into account the curvature of the earth.

The activities along each fishing track were then identified as traversing (traveling to or from port to the fishing grounds), searching which included looking for fish and setting the net on the fishing grounds, hauling the net, and other activities that were not part of the directed fishing, such as waiting in port and unloading the catch. Once these activities were identified the fishing track was divided into equal 100m increments by activity. The area backscatter coefficients at each of these positions were linearized and a distance weighted average of these linearized coefficients along each 100m increment was calculated.

The next step in the analysis was to estimate target strength of the acoustic signals during each night of data collection so that biomass abundance indices could be estimated. Samples for estimating length and weight of the acoustically recorded herring for gillnet fishing trips were collected from experimental gillnets fished in the Nova Scotia area of the southern Gulf of St. Lawrence. Samples for estimating length and weight of the acoustically recorded herring for purse seine fishing trips came from daily sampling from the Gemini by shipboard observers (Claytor et al. 1996). The length - weight relationship from these samples estimated the target strength using Foote's (1987) formula.

Only the portion of the fishing track associated with searching and setting the net (see above) was selected for spatial analysis. Searching was generally triggered at densities >= 0.0625 kg/m^2 or about 1/4 herring/ m^2 and setting the net occurred only in areas that had been searched. Hauling the net was always associated with setting the net, but this activity created a lot of debris in the water, primarily from fish scales, and these data were not suitable for biomass estimation and were eliminated. A polygon drawn around the boundary of the searching and setting data points defined the area for spatial analysis and biomass estimation (Fig. 1C). The density estimate used in all analyses was the biomass estimate within the polygon divided by the area of the polygon.

Details for the data preparation are provided in (Claytor et al. 1998 and Claytor and Clay 2001).

4. Stock assessment parameters

4.1 Methods and models

The stock assessment parameters presented for this analysis are: density of the schools on the fishing grounds as defined above and an exploitation rate index (ER) defined as the reported catch / biomass estimate from the school as defined above. Regions for the gillnet fishery are defined as: 1; eastern most zone, 2; mid-zone, and 3 as the western most zone of the Pictou, Nova Scotia fishing area (Fig.1A). Regions for the purse seine fishery are defined as: 1; Rivière-au-Renard, 2: Gaspé side of Chaleur Bay, 3; Pointe de la Maisonnette, and 4; Miscou Bank (Fig. 1B).

We have examined other stock assessment parameters, such as the relationship between catch / net in gillnets and catch / set in purse seines, with these data and details of those analyses are in Claytor and Clay (2001). Density was estimated using voronoi polygons. A previous comparison of this method to inverse distance weighting and kriging indicated no difference in trends among these three methods (Claytor and Clay 2001).

4.2 Stock assessment parameter results

A reciprocal model significantly explained the relationship between exploitation rate (ER) and density for the each of the purse seine and gillnet fleets (p<0.001) (Fig. 2). These results indicate that ER increases as density decreases.

All above average exploitation rates for the Purse Seine Fleet occurred after 13 September, 1995 (Fig. 3A,B). All high exploitation rates in the gillnet fishery occurred at the beginning and end of the season when densities were lowest (Fig. 3C,D).

5. Simulation to test the analytical method

5.1 Introduction

A simulation model was developed to determine whether or not biomass estimates from acoustic data collected during regular fishing are abundance indices. The simulation focused on three questions for this test. These were: How does the movement of fish during the searching activity affect the estimate? How does the distribution of the fish affect the estimate? How does fishing and depleting the resource during the searching activity affect the estimate? The model was restricted to conditions that were compatible with the inshore gillnet herring fishery in the southern Gulf of St. Lawrence. The reason for this restriction was that the scale was smaller and the model was more easily developed than one that would have been compatible with the purse seine fishery. A simulation compatible with the purse seine fishery would provide a test for the effect of scale in interpreting the results and is planned for the future.

The simulation objective was to create a variety of models compatible with what is known from the literature and experience, rather than an exact replicate of fish movement and fishing captain's behavior, and to study the properties of various stock indices under these assumptions. The rationale for this approach was that a good index should display consistent properties throughout the range of fish and fishing captain's behavior that is plausible according to current knowledge and experience.

5.2 Simulation Methods

5.2.1 General Model Description

The model simulates a local spawning herring aggregation and a gillnet fishery. The 1997 Pictou gillnet fishery was used as the template for the simulation model. One boat is simulated to collect the type of acoustic data obtained during the gillnet fishery and is designated the acoustic boat. It searches for fish schools and fishes following a simple set of searching and fishing rules. Fishing locations for the remainder of the fleet were selected in a manner that was consistent with captains being able to locate higher than average densities for fishing. A simple probability model using the cumulative distribution of densities was used to determine these locations.

All boats in the fleet were subject to a nightly boat limit. This regulation had the effect of restricting catches even when densities were high and its effect was examined in the simulation. The average number of nets used per gillnetter per night in this fishery was five. Catch rates

(CPUE) were calculated as the catch divided by nets (kg/net) for the acoustic boat and all fleet boats.

Four conditions of fish movement and fishing fleet activity were examined. These were fishing and movement of the fish school, fishing with no school movement, no fishing but with school movement, and no fishing and no school movement. Five fish distribution types were examined. These were: a single spike (spiky), average, flat, and intermediate between spiky and average (IAS), and intermediate between average and flat (IAF) (Fig. 4). The fish schools forming these distribution types consisted of one to ten clusters. Each cluster was defined by a bi-normal density function with the cluster centre defined by x-y coordinates and with a cluster covariance matrix equal to a multiple of the identity matrix.   Thus, the clusters were radially symmetric about their centres.   The number of clusters and their standard deviations varied depending on the type of distribution to be created. These were subsequently quantified using the percentage of the area that contains the mid 75% of the biomass, in a manner similar to Swain and Morin (1996). The simulated search area was scaled to the average area searched each night in the Pictou, Nova Scotia gillnet fishery (490,000 m^2). Each of the distributions, except flat, were observed in the gillnet data collected in the 1997 Pictou fishery. Fish movement was simulated by moving the cluster centres up to 200 meters every five minutes of simulated time.

Each night of the simulated fishery consisted of four hours of data collection, searching, and fishing. Small equally spaced time intervals were used to control simulation events. These time intervals were equal to the length of time required for the acoustic boat to travel 100m at the average speed observed in the Pictou fishery. All biomass index data, from fishing and surveys, were collected simultaneously during each simulation.

The simulation tested three biomass indices derived using data collected by a fishing boat while it searched for schools of fish, and three indices derived from survey techniques. The searching indices were Searching - Total, where the index was based on data collected throughout the simulated fishing trip, Searching - Fishing, where the index was based on data collected only up until the time that the boat limit was caught. These two indices used voronoi polygons to derive area weighted biomass indices. The third index from the searching data was simply the arithmetic average of the Searching - Total data points and was designated as Arithmetic.   The three survey indices were derived from a simulated random tow survey, a simulated random transect survey, and a simulated systematic transect survey. In total six indices were compared against the known simulated biomass (Fig. 5).

5.2.2 Survey Indices.

Random tow locations were selected within the search area using a uniform random distribution. Tows were evenly distributed at 30 minute intervals and the length of each tow was 200 meters. Tows were made in a random direction from each starting point. Starting points for random transects were selected along the y axis for each simulation using a uniform random distribution and were ordered by distance from the origin. Systematic transects were selected so that there was equal spacing between the transects. The time allowed for each transect was 30 minutes. Data along the transect and tow tracks were estimated in 100 m increments by numerical integration. Biomass indices from the surveys were determined by taking the arithmetic average of the data points collected during each of the surveys and expanding these densities to the area surveyed.

5.2.3 Searching Indices

The acoustic boat started collecting data at the edge of the search area. The acoustic boat moved 100 meters at each sampling or clock interval. The searching method consisted of random and directed searches. The turning direction of the simulated acoustic boat was determined by the change in density of fish observed over each 100 meter increment. The decision on turning angle was made every 200 meters for random searches and every 100 meters during the directed search. Regardless of when the turning angle decision occurred, data were stored every 100 meters as in the real data set. The average density over this increment was determined by numerical integration.

Searching for each simulation began by collecting data during a random search for 20 time intervals. The direction of turning at each of these decision points was randomly selected

from 0 to 360 degrees. After this initial random search period, the directed search algorithm was initiated. The direction of turning was based on the slope of the data points collected at 20 meter increments along the 100 meter search track increment. For example, if the slope and hence, biomass was increasing along the track then, the boat tended to keep going in the current direction. If the slope and biomass were decreasing then the boat tended to turn back towards the direction it had just been searching. If the slope was near zero (-0.5 to 0.5) then the boat would make a right or left turn between 60° and 120°. The angle of the turn was determined by the magnitude of the slope and the direction (left or right) of the turn was randomly determined.

Using these rules, the boat would tend to circle in one spot if it found a peak in the distribution. If it circled 7 times in a small area, then it was directed to fish, or if the boat limit had already been caught, it was directed to search randomly for another 20 time intervals. In both these cases, the direction of the first turn was towards the highest density observed up to that point.

Voronoi polygons as described above were used to estimate biomass using the searching data. The only change in the methodology for the simulation was in defining the exterior boundaries of the data points. In the analysis of the data, polygons drawn around each outside data point defined this boundary. This was not practical for the simulation and the convex hull, expanded by 20 metres, was used to define the exterior boundary of the data points in order to include the convex hull points in the voronoi polygons (Cressie 1991). The convex hull was determined using the MATLAB (1998, ver 5.3) convhull function. Voronoi polygons were determined using the MATLAB (1998, ver 5.3) voronoi function altered to output voronoi edge coordinates, Delaunay triangle indices, and circle centre indices. This function produced some voronoi polygons whose vertices were outside the convex hull. The intersection points between the polygon edges and the convex hull were found and these points were substituted for the vertices that were outside the convex hull.

The area of each polygon was found using the MATLAB (1998, ver 5.3) polyarea function and the biomass in each polygon was determined by multiplying the density of the data point by the area. The sum of these biomass estimates formed the biomass index. If the boat limit was caught before the end of the four hours, the Search - Total estimate usually covered a smaller portion of the search area than the Searching - Fishing estimate (Fig. 6).

5.2.4 Fishing

To determine the effect that depleting the resource had on the development of biomass indices, a simulated fishery was included in the model. Depletion occurred from fishing by the acoustic boat and the gillnet fleet. Natural mortality was assumed to be zero during the fishing period. The searching simulation for the rest of the fleet applied rules to the entire fleet rather than to individual boats as was done for the acoustic data collection boat. However, catches for the fleet and the acoustic boat were calculated in the same manner and were a function of net length, net influence width, local catchability, and stock density at the fishing location in both cases. These parameters were equal for each type of boat.   For the acoustic boat, the stock at the fishing location was estimated using numerical integration over the net length. For the fishing fleet, the point of the fishing location (described below) was used and this value was assumed to be the average over the net length. This simplifying assumption was made to save computation time. Fishing depleted the overall stock on a cluster by cluster basis. Each cluster was depleted in proportion to its contribution to the density at the fishing location. Thus, if fishing occurred at the centre of one cluster but at the edge of another, most of the fish would be removed from the cluster which had the fishing near its centre.

Catch rates from the Pictou fishery and simulated acoustic boat and fleets were described as functions of density using von Bertalanffy curves (Quinn and Deriso 1999). SAS Proc NLIN (1999) was used to estimate the model parameters and r^2 values.

5.2.5 Fishing - Acoustic boat

Fishing by the acoustic boat only occurred during a directed search and only when certain conditions associated with the density of the stock and the slope were met. Fishing occurred if the boat was at a density very similar to the highest so far observed by the boat during the night. Fishing could occur at a lower density if the slope was below a critical negative value,

or if the boat had gone over the area 7 times as described above. In addition, if no fishing had occurred during the first half of the night, then the critical density threshold for fishing was lowered. Fishing by the acoustic boat continued until the boat limit was caught or the allotted four hour time limit was reached. After the boat limit was caught, the acoustic boat continued to collect data under the searching rules but would not fish. Each fishing event took 30 minutes. During this time, data collection by the boat stopped, to simulate the time required for the net to be set and hauled. After each fishing event the boat would search randomly for 20 time intervals before beginning the directed search again.

5.2.6 Fleet Fishing

The simulation time interval between fishing events for the fleet was 30 minutes, the average time to set and haul nets. There were eight fishing events spread evenly through the four hour searching period. The fleet size was determined using a function derived from real data. A random effect was added to the fleet size so that it closely resembled the variation in number of boats in the Pictou fishery. Minimum and maximum fleet size were fixed to be consistent with the fishery, the minimum number of boats fishing in a night was 10, and the maximum was 120, including the acoustic boat.

There were 8 fleet fishing events throughout the night but not each vessel fished at each event. The proportion of the fleet that fished at each event was determined using the data from the acoustic boat. Three nights of fishing data were collected from the acoustic boat during each simulation at a given stock size and condition. The average number of sets made by the acoustic boat during these three trips was used to determine the initial proportion of the fleet fishing on each trip. This average was updated throughout the simulation for each stock size, distribution, and fishing - movement condition. The data from the first three trips were not used in any analysis.

5.2.7 Evaluating indices

Two methods were examined for evaluating indices. The first determined the slope between the estimated biomass and true stock and the slope between the standard deviation of the estimated biomass at each stock size and stock size. The best indices would not necessarily have a one-one relationship with true stock, but would have a relatively precise and linear relationship regardless of the distribution, fishing, or movement condition. That is, when the slopes of biomass are plotted against distribution type for each condition, the best indices would have a positive slope and little variation around the regression line.

The second method, closed loop (Anon 1998), for evaluating the indices, compared exploitation rates that would result from managing the simulated fishery assuming that the indices represented a one-one relationship with the true biomass. For example, what would the true exploitation rate be if the target fishing mortality was 20% and a quota was set at 20% of the estimated biomass, given that the true simulated biomass is known. This comparison was made using the average exploitation rate that would result at each stock size and by determining the percentage of exploitation rates that would be > greater than twice the 20% target. This method was only examined for the Movement – Fishing condition.

The closed loop evaluations indicate the magnitude of the mistakes that would be made using each index. Such evaluations are one way of taking into account the variability in the estimates, of evaluating one index against another, or of evaluating the cost effectiveness of collecting data for the different indices.

5.3 Simulation results

5.3.1 Model Validation

A comparison was made between the catches and catch rates (kg/nets), from the acoustic boat collecting data during the Pictou 1997 gillnet fishery with those obtained from the simulated acoustic boat. This comparison indicates that the simulated values are consistent with those from the 1997 fishery. Trip catches from the acoustic boat collecting data during the Pictou and the simulated fishery were low and rose quickly to an asymptote consistent with the boat limit at densities > 2 kg/m^2 (Fig. 7). The exception were catches for the simulated spiky distribution, because sometimes the spike was missed entirely resulting in low catches at all densities.

Similar trends were observed for catch rates (CPUE). The catch rates from the acoustic boat reached an asymptote slightly below the maximum that would occur if the boat limit were caught each time (1500 kg/net). The number of sets made each night in the fishery by the acoustic boat and the simulated acoustic boat declined with increasing density. This finding is consistent with the expectation that fewer sets should be necessary as density increases. The exception were trends associated with the spiky distribution.

A similar consistency was observed between the Pictou fishery fleet catches and the simulated fleet catches. Catches in the Pictou fishery tended to increase steadily with fish density for density < 6 kg/m^2. Catches by the simulated fleet increased similarly and reached an asymptote for densities exceeding 6 kg/m^2. This similarity was true for all the distributions. Catch rates showed an asymptote near the boat limit at 4 kg/m^2 or less for all distributions and in the Pictou fishery. The number of sets tended to decrease as density increased in the simulated fishery. These data were not available from the Pictou fishery.

Parameters from von Bertalanffy models were similar for the Pictou 1997 acoustic boat, the simulated acoustic boat, the Pictou fleet, and the simulated Pictou fleet. The model with the greatest difference was for the spiky distribution which had a lower asymptotic CPUE$_{inf}$ value than the others and a lower r^2 value. These lower values were probably a function of the difficulty, that the simulated acoustic boat occasionally had in finding the spike (Fig. 8).

5.3.2 Index Comparison - Estimated vs. True Biomass

Plots of estimated biomass against true biomass indicate that variance in estimated biomass increases as true stock size increases for all distributions in the Movement - Fishing condition. Except for the flat distribution, the arithmetic index always over-estimates true biomass (slope > 1). The fishing index usually underestimates biomass except for the spiky distributions. The highest variances generally occur with the random tow surveys. The searching, random tow, random transect, and systematic transect methods consistently give biomass estimates that appear close to the true values (Fig. 9).

Regression analysis on a case by case basis by survey type, distribution, fishing, and movement condition indicate that the standard error of the regression slope (sse) is < 0.10 for all regressions except those with the spiky distribution. All regressions were significant (p < 0.0001). The low sse's indicate that there will likely not be any differences in interpretation between these unweighted regressions and weighted regressions between the true and estimated biomass in the simulation models.

For all conditions, the arithmetic index had the widest range in slopes between estimated and true biomass, followed by Searching - Fishing. Random tow indices had the highest standard deviations for spiky distributions. Spiky distributions generally had the highest standard deviations, followed by IAS. The Searching - Total, random tow, random transect, and systematic transect indices generally had slopes between the estimated and true biomass of between 0.5 - 1.5 (Fig. 10).

Overall, the survey methods random tow, random transect, and systematic transect had slopes between the true and estimated biomass that were closest to zero. Searching - Total slopes were higher for spiky compared to flat distributions. Slopes for spiky, IAS, and average distributions were close to zero. There was least variation in slopes with the random transects index.

Of the four methods most practical to use in forming an abundance index in this situation, slopes between random transects and systematic transects were most consistent across conditions. The Searching - Fishing index was the most inconsistent. The Searching - Total was in between the survey methods and the Searching - Fishing index in meeting the goal of displaying proportional response to the density, across distribution and condition patterns (Fig. 11).

5.3.3 Index Comparison - TAC closed loop

Evaluation by the TAC closed loop method indicates that average exploitation rates are usually within 10% of the target using the Searching – Total biomass estimate for the spiky distribution. For the other distributions the Searching – Total biomass estimates were similar to

the target but well under the target for flat distributions. In contrast, the arithmetic biomass estimates produced exploitation rates that were usually above the target, while the Searching – Fishing index gave results that were usually below the target (Fig. 12). Survey indices usually produced average exploitation rates that were similar to the target, except for the spiky distribution where they performed worse than the searching indices.

The percentage of cases with exploitation rates > 40% were greatest for the spiky distribution for Searching and Survey biomass estimates. The arithmetic and Searching - Fishing biomass estimates generally had percentages > 40% that were higher than those for Searching – Total. Arithmetic biomass estimates were always produced the highest exploitation rates regardless of distribution (Fig. 13). Percentages of exploitation rates > 40% were similar to Searching – Total for all survey indices at the spiky distribution. For IAS and Average distributions, the Searching indices had lower percentages > 40% than the survey indices.   Flat and IAF distributions had no cases > 40% for any index method.

6.1 Discussion

Three important points regarding collaborative projects arise from these results and our experience in developing collaborative assessment projects with industry. First, new methods of data collection and analysis are likely to be required and a flexible approach is needed, second, testing the new methods in order to determine appropriate protocols is essential, and third, new assessment and management strategys can result from successful implementation of these projects.

Taking a flexible approach to data collection was an important reason for the success of this project. Several concerns and management requirements required us to seek and evaluate new methods for gathering stock assessment data. First, we needed to develop a method that would identify the spatial and temporal trends in abundance and exploitation for individual spawning components. Second, we needed to overcome the concerns that industry had with traditional surveys and catch rate analyses. The fish movement and aggregation patterns of southern Gulf of St. Lawrence herring preclude the use of one time surveys for this task. We solved these problems by developing a data collection method that used the everyday fishing tools employed by industry in the fishery.

Our solution was to let the fishing fleet find the schools in the area and then use a boat equipped with automated acoustic recording gear to collect quantitative data on the schools being fished. This method allowed us to collect data that was compatible with the way that industry gathers information on stock size. Flexibility was required to find and develop an analytical method that could quantify industry's experience on the water and produce estimators that could be evaluated for their use as abundance indices. We chose voronoi polygons as the most convenient method for us, but results were similar using inverse distance weighting and kriging methods (Claytor and Clay 2001). We then tested these methods using a simulation that was compatible with the characteristics of the gillnet fishery and spawning fish aggregations from which the method and data collection originated.

The results of these simulations indicate that data collected during regular fishing activity (Searching - Total) can be used to derive useful abundance indices. The Searching - Total index had lower variance, lower bias, and lower risk of high exploitation rates than survey indices. Survey indices were, however, slightly more consistent overall conditions than the Searching - Total index. As a result, management actions are likely to be similar whether assessments are based on Searching - Total or survey indices.

The results of the Searching – Total index are important because they indicate that clear protocols must be developed for collecting data. For example, if data collection ceases immediately after nightly limits are caught then the resulting estimates are not suitable indices. Protocols must ensure that the entire school is covered during the data collection. One proposal from the Pictou group is that a boat be designated to collect data for the night rather than fish. This proposal has not been implemented because of cost and emphasizes the importance of developing clear protocols for data collection. These protocols will likely require some flexibility on the part of industry.

The fishery acoustic abundance indices developed in this project provide a basis for adopting spawning component life history targets as well as exploitation rate targets as a management strategy for this fishery.   The addition of spawning component life history targets would represent a change from the current $F_{0.1}$ management strategy for this herring population. The total allowable catch (TAC) has generally been set at the best estimate of $F_{0.1}$ for the entire spring or fall spawning stock. Inshore fleets associated with geographically defined spawning components are annually assigned proportions of the TAC. These proportions were established in the late 1980s. A six vessel purse seine fleet is allocated a fixed percentage of the overall TAC. This management strategy combines all the herring populations within the southern Gulf of St. Lawrence as the basic management unit and has not been greatly modified since its implementation.

This change in management could be implemented by adopting a decision rule strategy that puts the emphasis on localized data collection in determining whether or not specific goals have been met, and serves as a basis for setting and changing the rules that govern a fishery. The elements of this strategy have been described by Pearse and Walters (1992) and de la Mare (1998) and a form of these has been implemented in the 4Vn overwintering southern Gulf of St. Lawrence herring fishery (Claytor 2000).

The abundance and exploitation rate indices derived from the acoustic data allow managers to directly measure the effects of decisions regarding when to fish and where to fish. For example, even without formal definition of these rules, it is clear that the gillnet exploitation rates which are 2 to 4 times the average should be avoided and could be prevented by shortening the season.

One advantage of the decision rule approach is that the process becomes transparent to the fishing industry. In contrast to the current model which requires the use of population and statistical models to provide assessment advice, the decision rule strategy utilizes the abundance and exploitation indices directly to make decisions regarding the elimination of high exploitation rates and identification of under-utilized fishing opportunities.

Another advantage of this approach is that it provides the fishing industry with the flexibility to collect data outside the fishing season, in order to determine the effects of the decision rules on the population. The Pictou, Nova Scotia group has conducted systematic surveys before and after the fishing season for this purpose. In 1997, pre-season surveys led to a fleet decision to delay the opening of the season by one week.

While indices derived from these data could be processed and made available for real time in-season management, such opportunities are limited within the southern Gulf of St. Lawrence because many of the fisheries occur simultaneously.   A more realistic approach for this fishery would be to adopt rules for the fishing season, collect the data, and evaluate the performance of the decision rules as part of an annual stock assessment (Claytor 2000). In-season management by this method may be possible in areas where a single fleet sequentially harvests populations from various geographic areas.

Throughout this paper we have restricted our interpretations of acoustic biomass estimates to those of relative rather absolute estimates. Some of the factors that preclude an absolute biomass interpretation are: the variability of backscattering in high target concentrations, the relationship between target strength and fish size, vessel avoidance, and acoustic extinction from near surface reverberation (MacLennan and Simmonds 1992; Clay and Claytor 1998; Fréon and Misund 1999).   The fisheries we examined occur over a short period of time and on a single species in particular phases of its life history, either as spawning or feeding aggregations. As a result, our estimates are likely to be relatively consistent and while we cannot claim that we have estimates of absolute biomass of the schools, spatial and temporal changes in exploitation rate in these fisheries may be identified from changes in relative indices.

The indices of spatial and temporal exploitation rates provided by the fishery collected acoustic data provide a foundation for establishing a management strategy based on decision rules in the southern Gulf of St. Lawrence herring fishery. By providing a nightly measure of 'proven stock' (Pearce and Walters 1992) they furnish a method for investigating biological and management factors that lead to the feedback effects of the decision rules.

References

Anderson, J.T., J. Brattey, E. Colbourne, D.S. Miller, D.R. Porter, C.R. Stevens, and J.P. Wheeler. 1998. Distribution and abundance of Atlantic Cod from the 1997 Division 3KL Inshore Acoustic Survey. DFO Canadian Stock Assessment Secretariat Research Document 98/49.

Anon. 1997. Report of the Maritimes Region herring workshop, 18-19, February, 1997. Canadian Stock Assessment Proceedings Series 97/12.

Anon. 1998. Improving fish stock assessments. Committee on fish stock assessment methods, Ocean Studies Boat, Commission on Geoscience, Environment, and Resources, National Research Council. National Academy Press, Washington, D.C.

Clay, A. and M. Castonguay. 1996. In-situ target strengths of Atlantic cod (*Gadus Morhua*) and Atlantic mackerel (*Scomber scomberous*) in the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 53:87-98.

Clay, A. and R. Claytor. 1998. Hydroacoustic calibration techniques used for southern Gulf of St. Lawrence herring fishing vessels – 1997. Canadian Stock Assessment Secretariat Research Document 98/96. Canadian Stock Assessment Secretariat, 200 Kent St. Ottawa, Ontario, Canada, K1A 0E6. 12 pp.

Claytor, R. 2000 (in press). Conflict resolution in fisheries management using decision rules: an example using a mixed-stock Atlantic Canadian herring fishery. ICES J. Mar. Sci. xx:xxx-xxx.

Claytor, R., and A. Clay. 2000 (in preparation). Distributing fishing mortality in time and space to prevent overfishing. p. xx-xx. In. D. Pelletier, G. Kruse, T. Booth, S. Smith, R. Lipcius, S. Hills, C. Roy, N. Bez, and D. Witherell [ed.] Symposium proceedings: Spatial Analysis of fisheries data, 17th Lowell Wakefield Conference

Claytor, R. and C. LeBlanc. 1999. Assessment of the NAFO Division 4T southern Gulf of St. Lawrence herring stock, 1998. Canadian Stock Assessment Secretariat Research Document 99/54. Canadian Stock Assessment Secretariat, 200 Kent St. Ottawa, Ontario, Canada, K1A 0E6. 169 pp.

Claytor, R., A. Clay, E. Walter, J. Jorgenson, M. Clément, and A. St-Hilaire. 1999. National Hydroacoustic Program Client Participation Projects: Fleet Acoustics, Partnership Review, Potential Users, Equipment Inventory. Can. Tech. Rep. Fish. Aq. Sci. No. 2272. 76 pp.

Claytor, R., A. Clay, and C. LeBlanc. 1998. Area assessment methods for 4T fall spawning herring. Canadian Stock Assessment Secretariat Research Document 98/97. Canadian Stock Assessment Secretariat, 200 Kent St. Ottawa, Ontario, Canada, K1A 0E6. 63 pp.

Claytor, R., C. LeBlanc, J. Dale, G. Nielsen, L. Paulin, C. MacDougall, and C. Bourque. 1996. Assessment of the NAFO Division 4T southern Gulf of St. Lawrence herring stock, 1995. DFO Atlantic Fisheries Research Document 96/79. 136 pp.

Cressie, N.A.C. 1991. Statistics for spatial data. Wiley and Sons, New York. 900 pp.

de la Mare, W.K. 1998. Tidier fisheries management requires a new MOP (management-oriented paradigm). Rev. Fish. Biol. Fish. 8:349-356.

DFO. 1996. CAPELIN IN SUBAREA 2 + DIV. 3KL. Stock Status Report, Newfoundland Region, P.O. Box 5667, St. John's, Newfoundland.

DFO. 1999a. Southern Gulf of St. Lawrence Herring. DFO Science Stock Status Report B3-01 (1999) (Revised).

DFO. 1999b. 4VWX and 5Z Herring. DFO Science Stock Status Report B3-05 (1999).

Fréon, P., O.A. Misund. 1999. Dynamics of pelagic fish distribution and behaviour: effects on fisheries and stock assessment. Fishing News Books, Oxford.

Foote, K.G. 1987. Fish target strengths for use in echo integrator surveys. J. Acoust. Soc. Am. 82:981-987.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment. Chapman and Hall, New York. 570 pp.

MacLennan, D.N., and E.J. Simmonds. 1992. Fisheries Acoustics. Chapman and Hall, London.

Melvin, G.D., K.J. Clark, F.J. Fife, M.J. Power, S.D. Paul and R.L. Stephenson. 1998a. Quantitative acoustic surveys of 4WX herring in 1997. DFO Atlantic Research Document 98/81.

Melvin, G.D., Y. Li, L.A. Mayer and A. Clay. 1998b. The development of an automated sounder/sonar acoustic logging system for deployment on commercial fishing vessels. ICES, CM 1998/S:14.

Pearse, P.H. and C.J. Walters. 1992. Harvesting regulation under quota management systems for ocean fishes: decision making in the face of natural variability, risks and conflicting incentives. Marine Policy 16:167-182.

Quinn, T.J.,II, and R.B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York. 542 pp.

SAS. 1999. SAS/STAT User's Guide. SAS Institute, Cary, N.C. 1848 pp.

Swain, D.P. and R.Morin. 1996. Relationships between geographic distribution and abundance of American plaice (*Hippoglossoides platessoides*) in the southern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 53: 106-119.

Wheeler, J.P., G.H. Winters, and R. Chaulk. 1992. Newfoundland East and Southeast coast herring - 1991 Assessment. Canadian Atlantic Fisheries Scientific Advisory Committee 92/49.

Wheeler, J.P., B. Squires, and P. Williams. 1999. Newfoundland East and Southeast Coast Herring - An Assessment of Stocks to the Spring of 1998. Canadian Stock Assessment Secretariat Research Document 99/13.

Yund, P.O. 1998. Fishing vessel acoustic survey of Gulf of Maine herring stocks: 1998 project report. Gulf of Maine Aquarium, Portland, Maine.
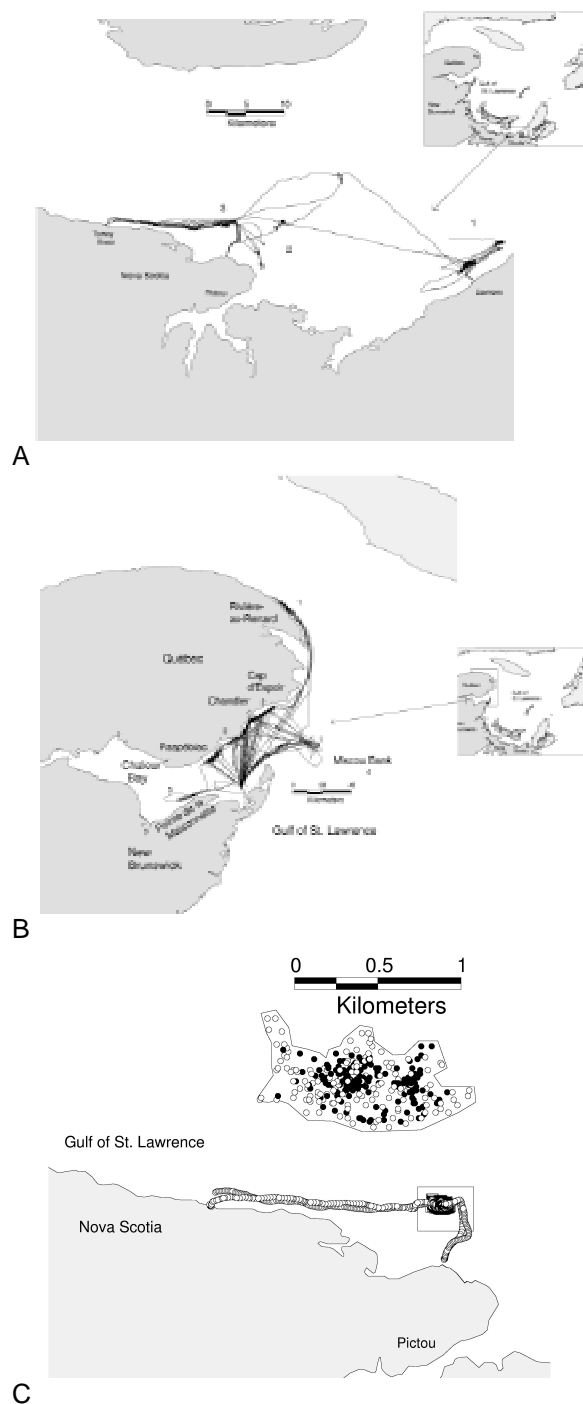
Fig. 1. (A) Fishing and searching tracks for Pictou area gillnetter from 7 September - 30
September, 1997. Key to map regions: 1; Eastern area, 2; Mid-zone, 3; Western area.
(B) Fishing and searching tracks for Chaleur Bay area purse seiner from 23 August - 20
October, 1995. Key to map regions: 1; Rivière-au-Renard, 2: Gaspé side of Chaleur Bay,
3; Ponte de la Maisonette, and 4; Miscou Bank. (C). An example of an identified herring
school from Pictou area gillnetter data collection, 26 September, 1997. Solid squares are
fish densities $\geq$ 0.0625 kg/m^2, open squares are fish densities < 0.0625 kg/m^2. School
is outlined by polygon used to delineate school area(Claytor and Clay 2001).
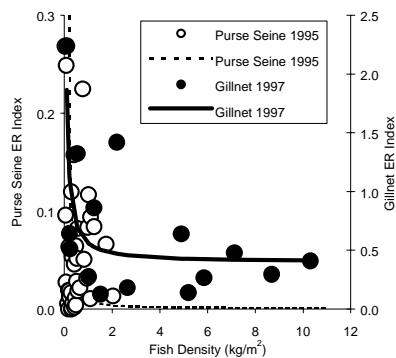
Fig. 2. Scatterplots and regression lines for relationship between exploitation rate index (ER) and fish density for purse seine and gillnet boat collecting acoustic data (Claytor and Clay 2001).
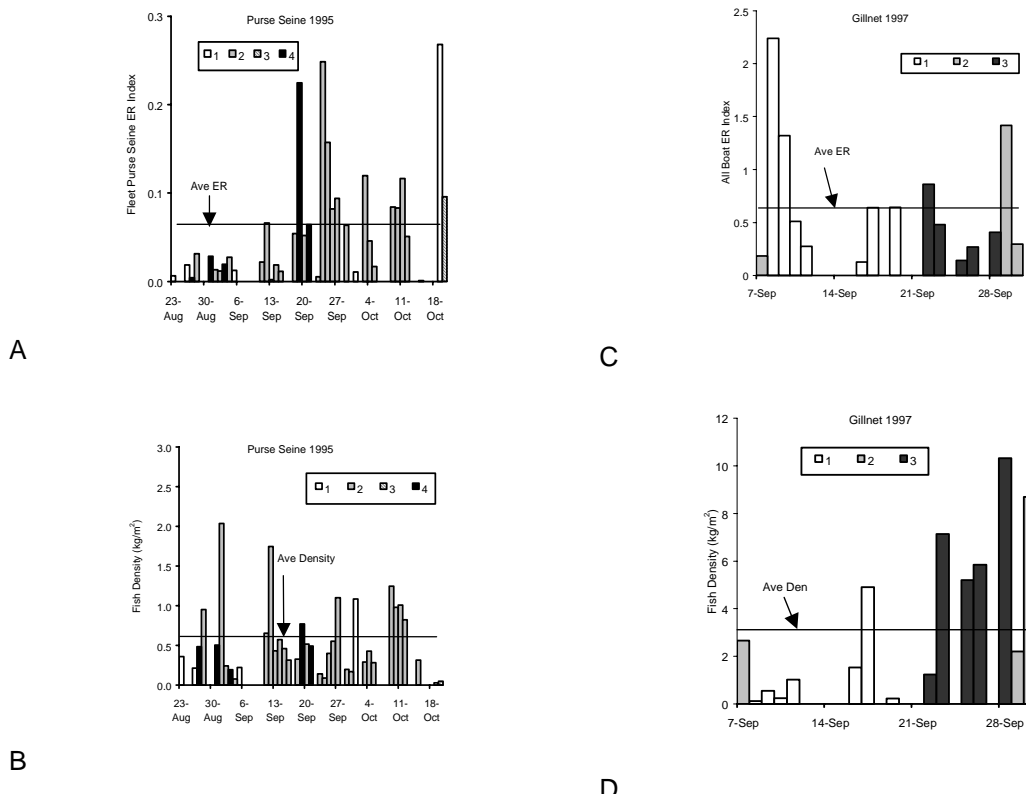
Fig. 3. Distribution over time by region of ER and fish density for (A, B) purse seiner and (C, D) gillnet collected data. Regions are those defined in Fig. 1A, B (Claytor and Clay 2001).

Simulation
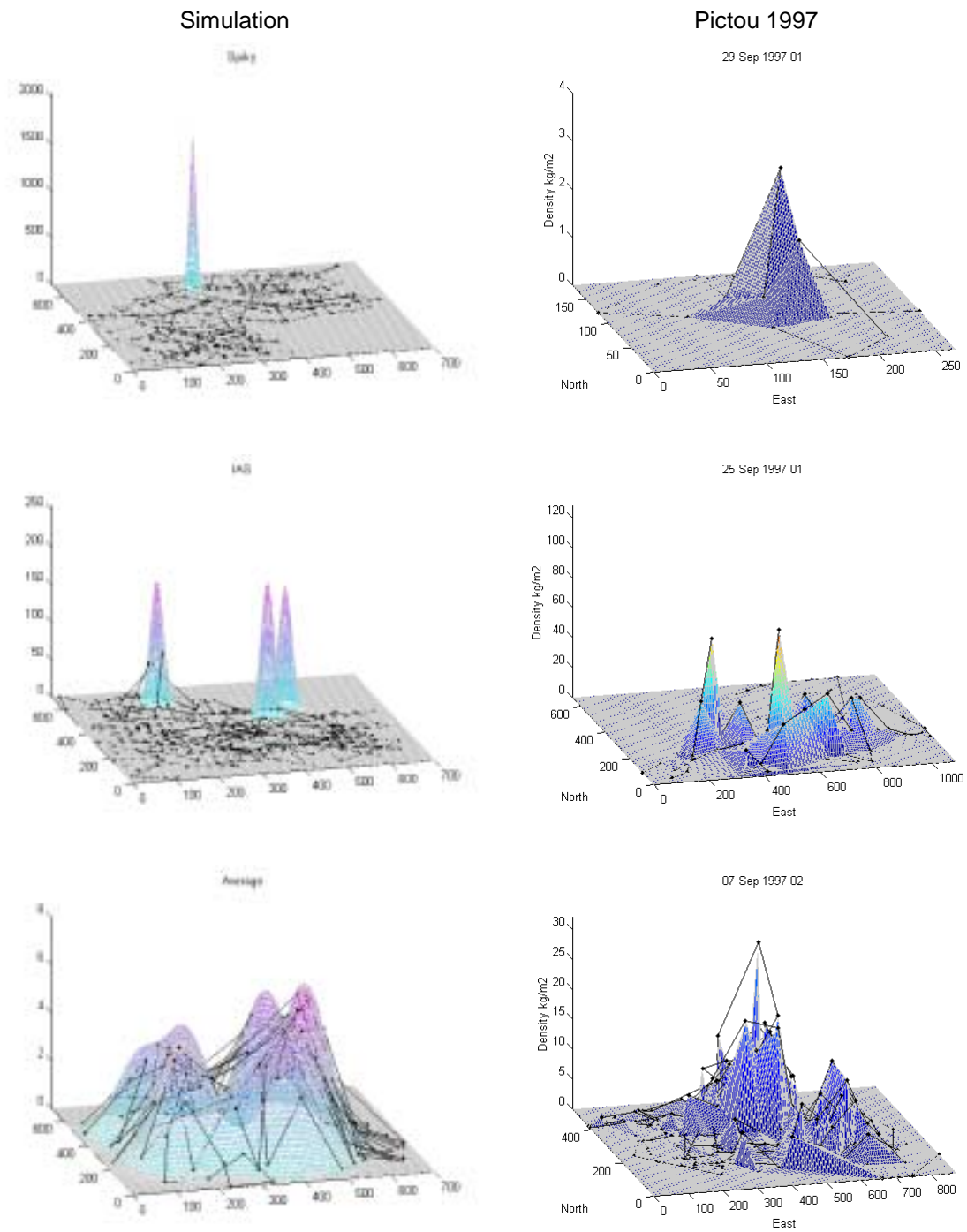
Pictou 1997

Fig. 4. Sample of distributions tested in simulation compared to samples from Pictou 1997 gillnet fishery. Black lines show the fishing track of the simulated gillnet test fishing boat as it collected acoustic data.
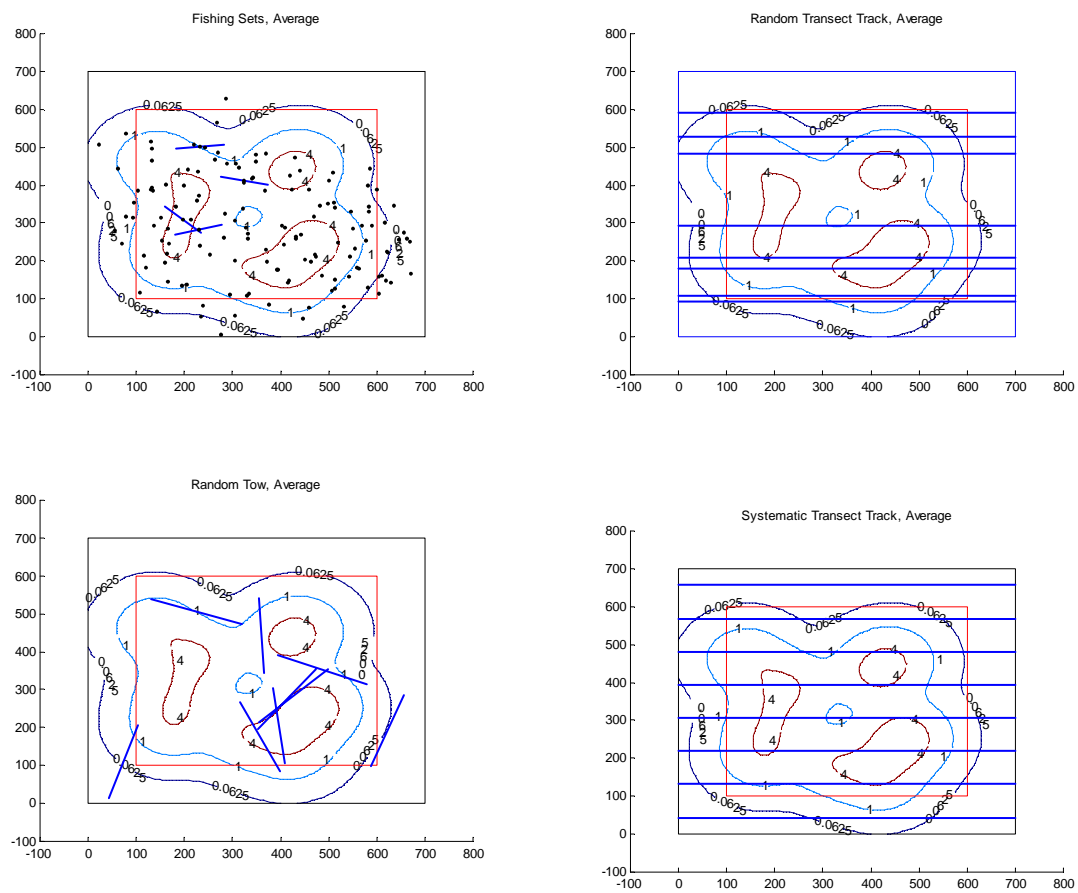
Fig. 5. Illustration of searching, random tows, random transects, and systematic transects average distribution.
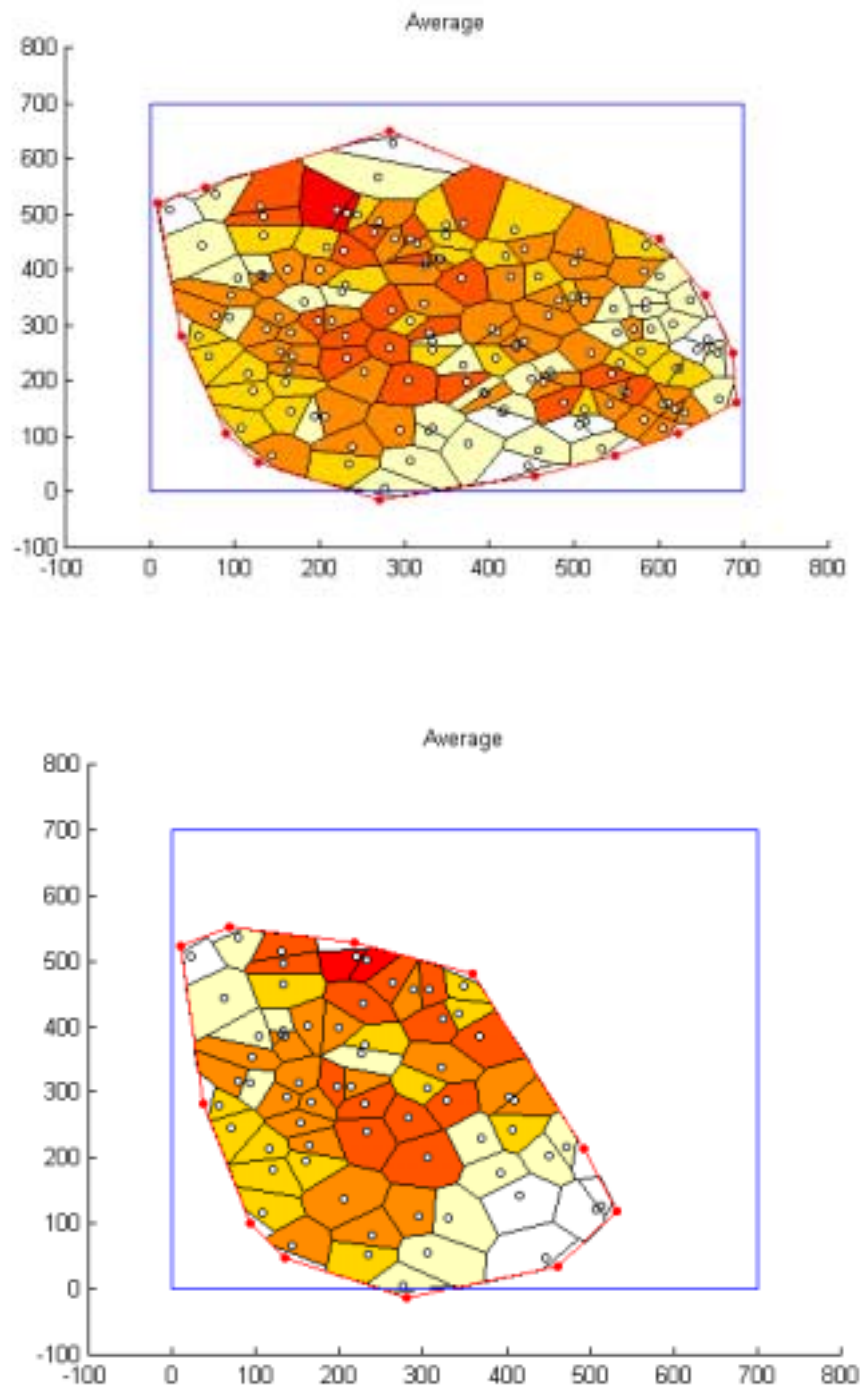
Fig. 6. Illustration of final voronoi diagram for estimation of biomass using Searching – Total (upper) and Searching – Fishing (lower) for an average distribution.
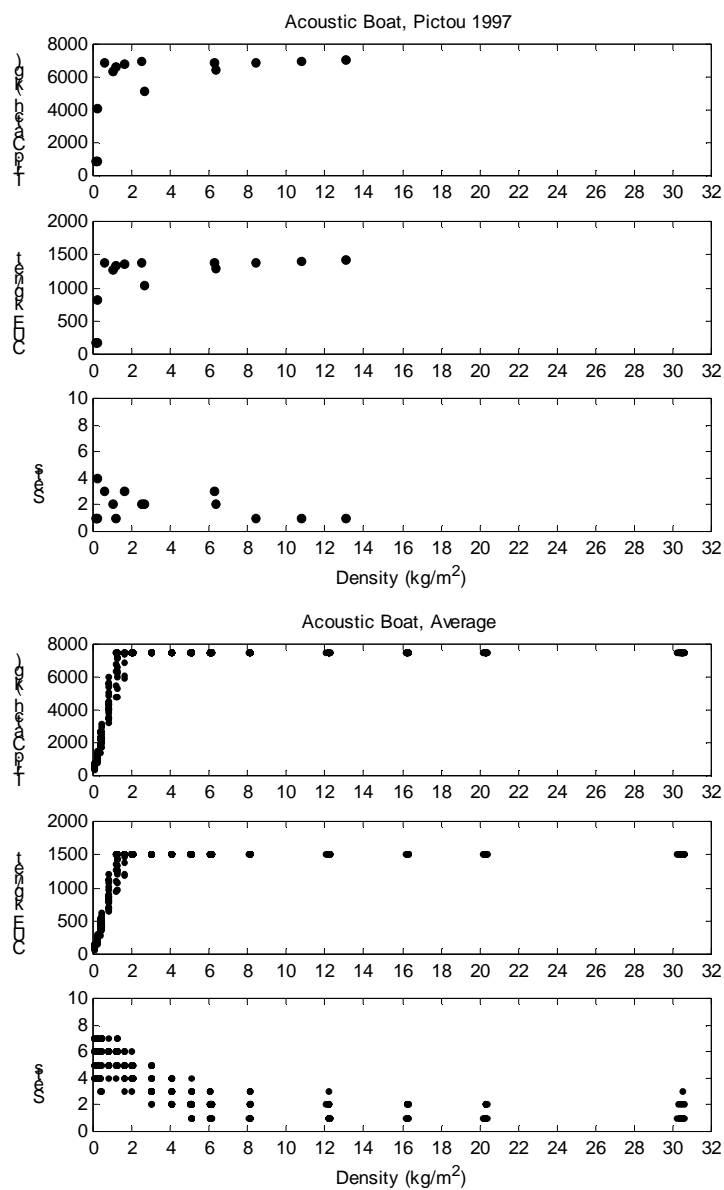
Fig. 7. Illustration of gillnet data from boat collecting data at Pictou, Nova Scotia, 1997 compared to simulation Acoustic Boat at various distributions.
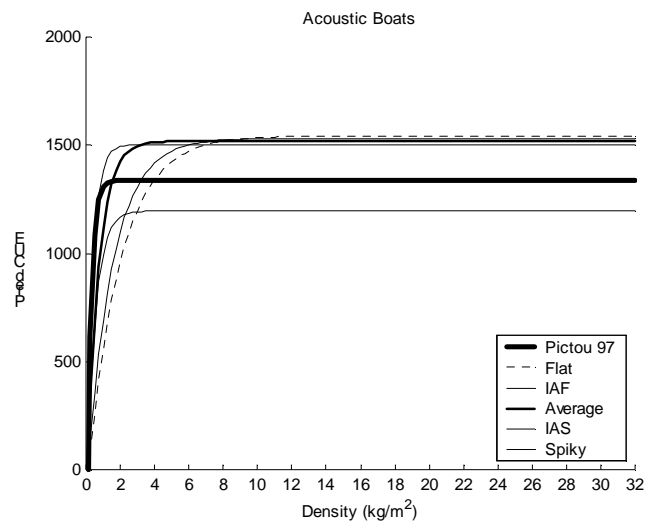
Fig. 8. von Bertalanffy models for acoustic boat collecting data from Pictou, Nova Scotia 1997 inshore fishery and simulated acoustic boat at various distributions.
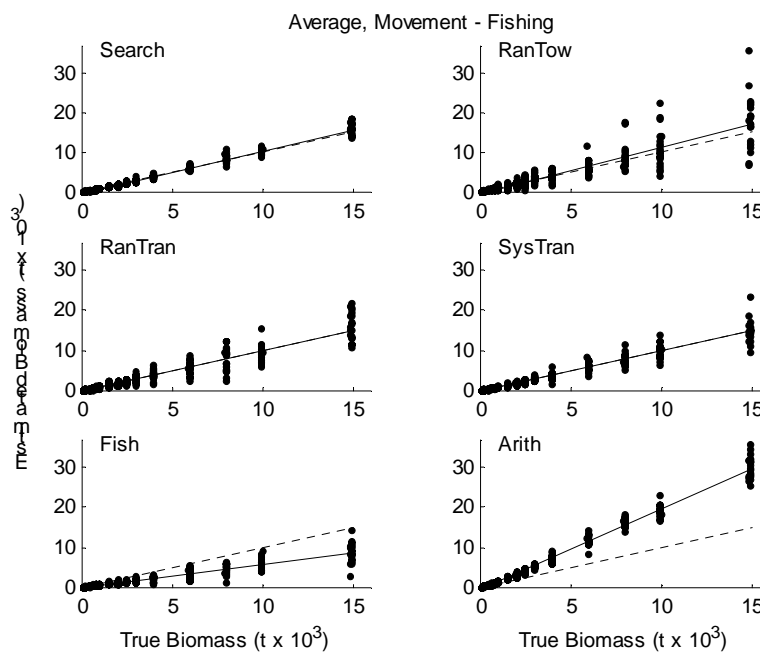
Fig. 9. Scatterplots of true and estimated biomass for Movement - Fishing condition for simulation for all distributions and survey types.
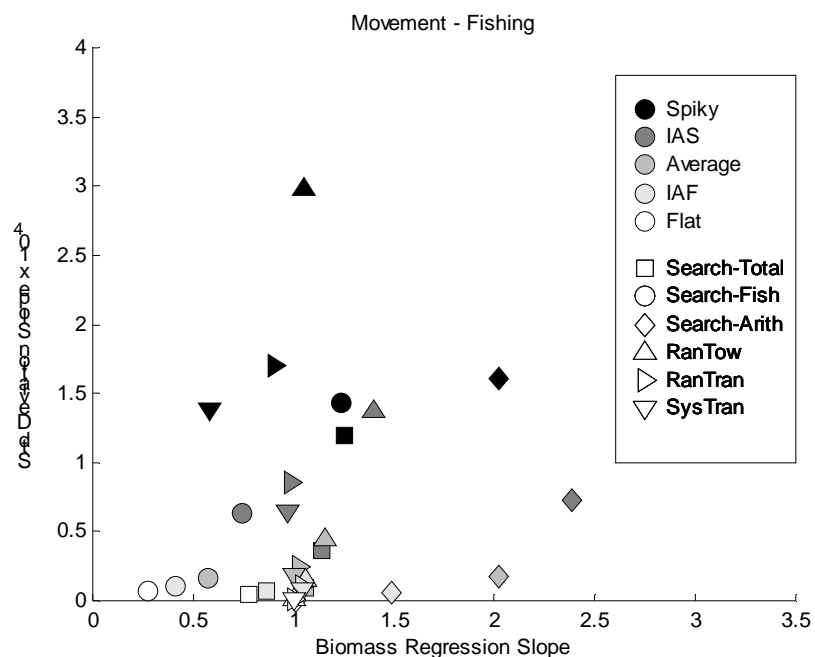
Fig. 10.   Summary of analysis of regression between true and estimated biomass for six indices and five distribution types, for the Movement - Fishing condition.   The standard deviation of the biomass estimates are plotted against the slope of the regression for each distribution.
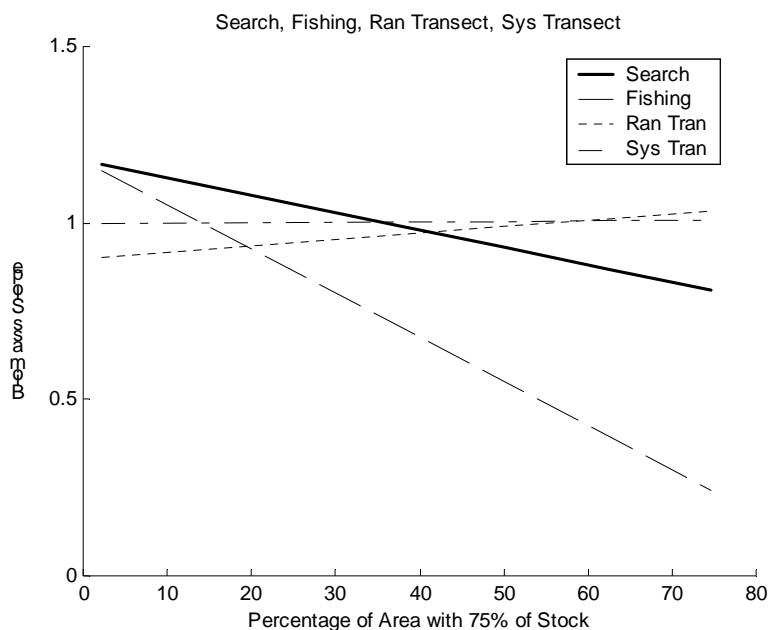

Fig. 11. Summary of slopes between estimated and true biomass and distributions for key survey type, all distributions and conditions.
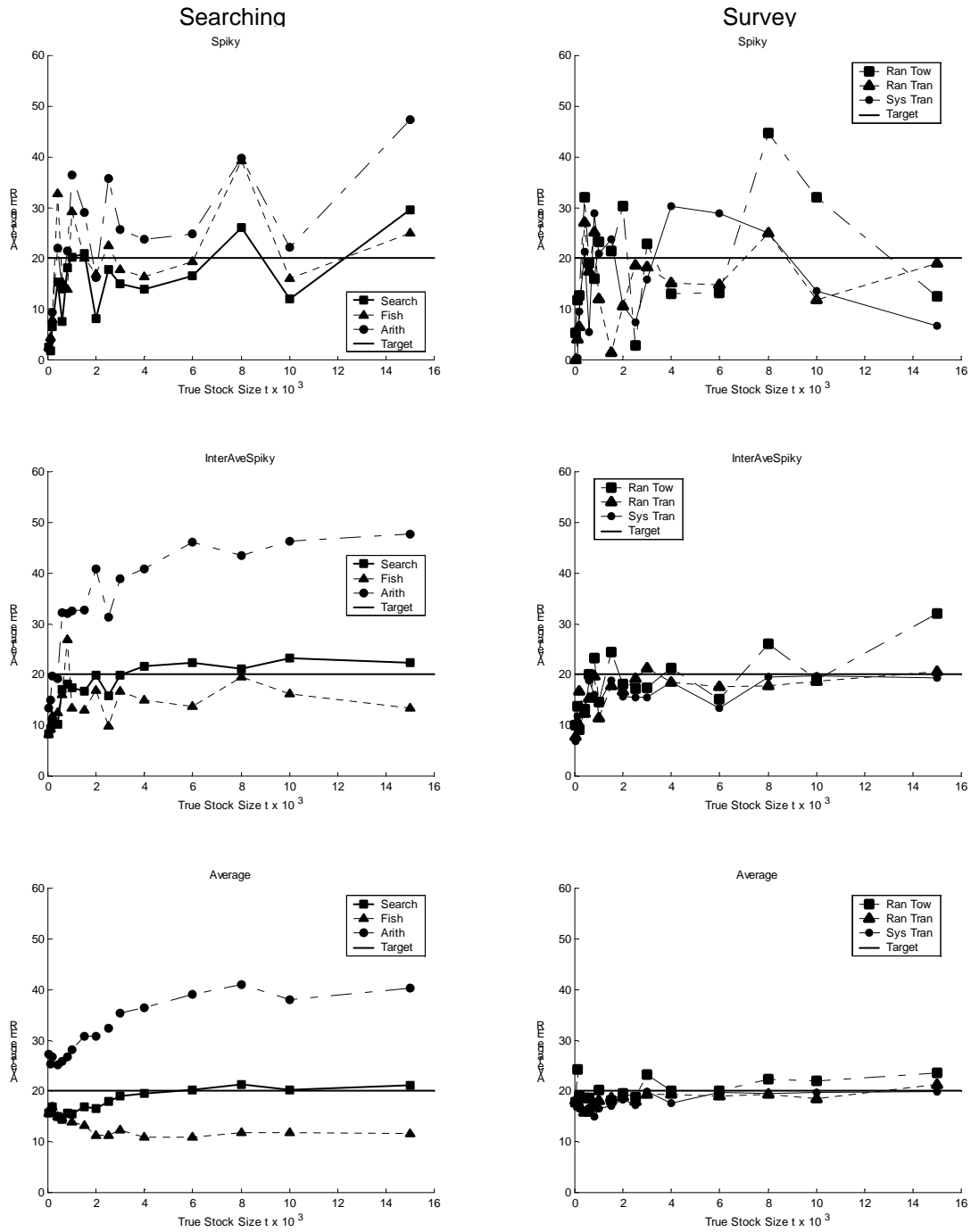
Fig. 12. Average exploitation rates obtained using a target of 20% to set the TAC based on the estimated biomass, for each data collection method, all distributions, and the Fishing - Movement condition.
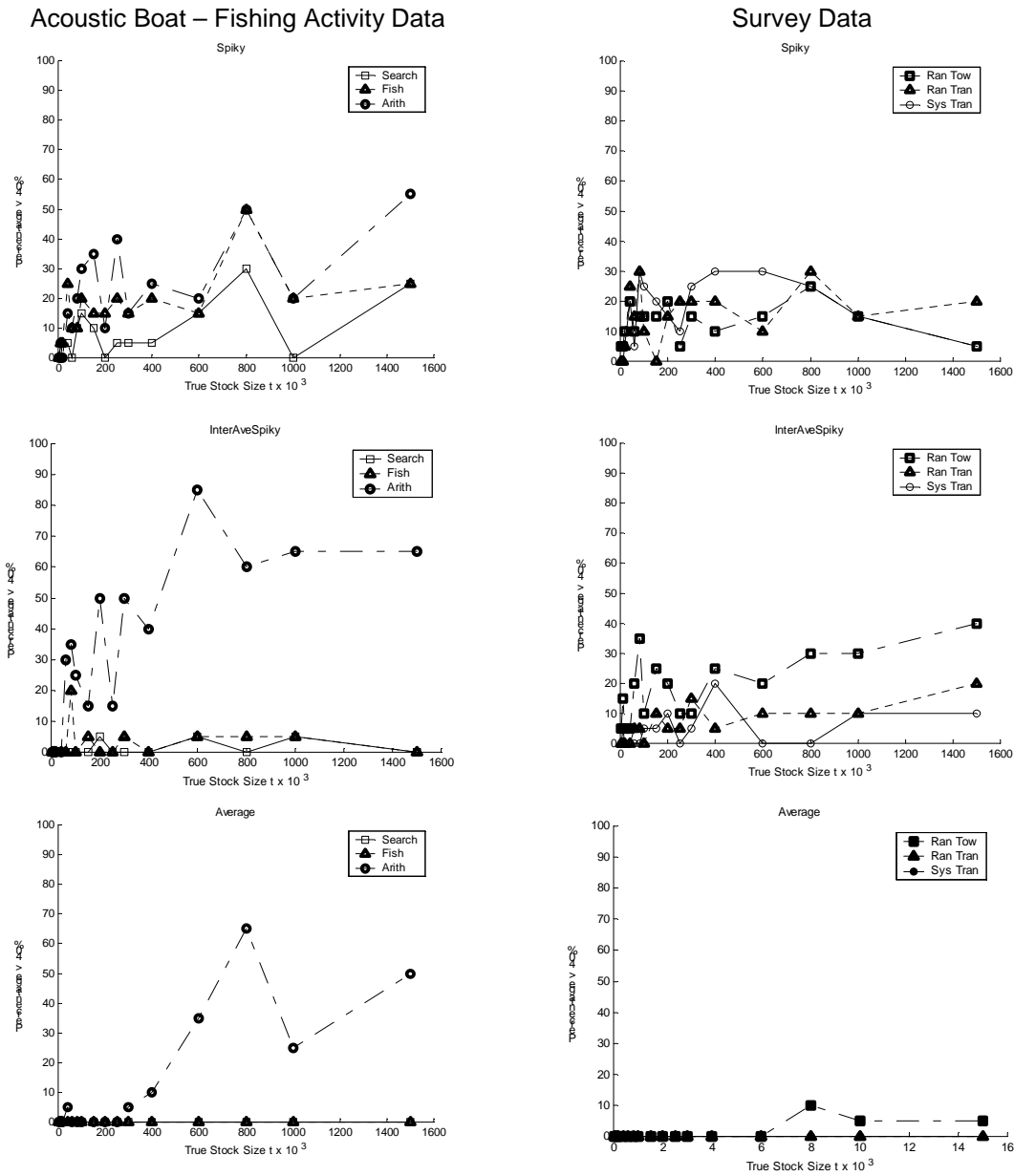
Fig. 13. Trends in the percentage of exploitation rates that were over 40% or double the target
for each data collection method on each distribution, as a function of biomass.
Percentages for InterAveFlat (IAF) and Flat were all zero and are not shown.