Executive Summary

Acadian redfish (*Sebastes fasciatus*) is among a few groundfish stocks in the northeast US that have a relatively large Annual Catch Limit (ACL) that have not been fully utilized during the last several years. With reduced ACLs for many important groundfish species, full and sustainable utilization of the redfish resource is thus critical to the economic
survival of fishermen and to the success of groundfish sectors. The allocations of redfish could not be fully utilized under current regulations because the minimum codend mesh size is too large to effectively retain redfish. Beginning in 2010, the REDNET project seeks to achieve three fishery conservation and management goals:

1) Redirecting fishing effort in the multispecies fishery away from stocks that are overfished to stocks that are considered rebuilt (e.g. redfish).
2) Achieving optimum yield, by increasing commercial landings of redfish through development of a directed fishery under the adaptive management ability of groundfish sectors.
3) Increasing the economic viability of groundfish sectors by providing access to the ACL of a recovered species and thus generating much-needed revenue for the industry.

REDNET includes six components:

- Component 1: Network Meetings
- Component 2: Baseline Catch and Bycatch Evaluation
- Component 3: Codend Selectivity
- Component 4: Conservation Engineering and Bycatch Reduction
- Component 5: Processing/Marketing
- Component 6: Outreach/Implementation

This report describes work carried out in Component 3 – Codend Selectivity. The final report for Component 2 has been submitted.

A trouser trawl was used to determine the size selectivity of three sizes of mesh opening (4.5, 5.5 and 6.5 in double 5 mm twine diamond) on a commercial fishing vessel. Fishing off Provincetown, Massachusetts, 56 tows were completed in March and April 2013, catching over 42,000 kg of redfish and about 6,000 kg of other species. Adequate length frequencies of redfish and pollock were collected to produce selectivity models; only redfish results are reported here. Neither species has been the subject of a trawl selectivity study in the Northeast US before.
Robust models for the mean $L_{50s}$ and selection ranges, and confidence intervals, were developed for all three tested codends, incorporating both within and between haul variability. All measures of model validity were positive. These models are fully adequate to provide guidance to managers and fishermen on size retention of redfish and appropriate codend mesh size.

$L_{50}$ and selection ranges were determined for 4.5 in ($L_{50}$: 22.3 cm (8.8 in); SR: 4.5 cm), 5.5 in ($L_{50}$: 29.2 cm (11.5 in); SR: 4.4 cm), and 6.5 in ($L_{50}$: 33.6 cm (13.2 in); SR: 5.1 cm) codends. Simulation of fishing of the three tested codends on the observed population indicated that substantial escape of redfish through codend meshes occurs (48-94%), suggesting that investigation of escape of redfish is warranted to support a sustainable fishery. The observed population also indicates that inadequate numbers of larger redfish may be available to support a higher-priced market.

**Introduction**

Acadian redfish (*Sebastes fasciatus* – “redfish”) is the only groundfish species in the northeast US with a relatively large Annual Catch Limit (ACL) but has not been fully utilized by the current multispecies fishery participants during the last several years. The requirement for codends with large mesh sizes (6.5”) and a lack of market may be the primary reason for the underutilization. The implementation of a sector management system with catch retention rules and accountability measures makes it possible to target redfish with codend mesh sizes smaller than the current regulated mesh size. The Maine Department of Marine Resources, the Massachusetts Division of Marine Fisheries and the University of Massachusetts School for Marine Science and Technology joined with other members of the scientific community and the industry have developed a research plan that draws on wide-ranging expertise in order to conduct comprehensive research on the development of a sustainable redfish trawl fishery in the Gulf of Maine. The project, called “REDNET”, includes components of catch and bycatch assessment through exploratory fishing, evaluation of codend mesh size, testing of size and species selective design and devices, processing and marketing, outreach, and implementation. The project is funded by NOAA Fisheries Northeast Cooperative Research Partners Program’s 2010 funding cycle.
The redfish cooperative research project or “REDNET” seeks to achieve three fishery conservation and management goals:

- Redirecting fishing effort in the multispecies fishery away from stocks that are overfished to stocks that are considered rebuilt (e.g. redfish).
- Achieving optimum yield, by increasing commercial landings of redfish through development of a directed fishery under the adaptive management ability of groundfish sectors.
- Increasing the economic viability of groundfish sectors by providing access to the ACL of a recovered species and thus generating much-needed revenue for the industry.

Groundfish management in the Northeast made a dramatic shift in May of 2010 from primary input controls to primary output controls. Amendment 16 to the Northeast Multispecies Fishery Management Plan (FMP) established the rules for sector management, as well as catch limits and accountability measures mandated by the 2006 reauthorization of the Magnuson-Stevens Act. If multispecies sector management is to be successful, the fleet must be able to catch and land stocks of fish with high abundance such as redfish while exercising their ability to avoid quota-limiting species (e.g. most recently, Gulf of Maine cod).

Historically, redfish represented a significant fishery and income in the region. The directed redfish fishery in the northeast began in the 1930s and total landings rose from 100 mt to a peak of over 117,000 mt in 1951 and then steadily declined. By 1983, the total US landings of redfish were 5,328 mt, and in 2008 landings were only 1,189 mt. The current best available estimates assert that the resource can support a larger fishery.

The redfish fishery in the Gulf of Maine was traditionally prosecuted by vessels using otter trawls with relatively small mesh codends in the range of 70 - 80 mm (2.5 - 3”). Since 1950s and through 60s and 70s, the population of redfish declined, likely as a result of overexploitation. In 1977, the minimum codend mesh size increased from 114
to 130 mm (4.5 to 5”) and increased again in 1994 to 152 mm (6”). Today the minimum codend mesh size mandated by the Multispecies FMP is 165 mm (6.5”), though groundfish sector vessels may use 152 mm (6”) codends provided an observer has been assigned to the fishing trip. These mesh restrictions, combined with low biomass levels between 1980 and 1995 eliminated a directed redfish fishery in the Northeastern United States.

In recent years, the combined restrictions in the multispecies FMP have resulted in the recovered status of the redfish resource. A stock assessment of redfish was completed and reviewed at the 2008 Groundfish Assessment Review Meeting (GARM III) and updated through 2010 at a 2012 review. The assessments and reviews concluded that the redfish stock is not overfished and overfishing is not occurring.

Development of a redfish fishery in the Northeastern United States is critical to the economic survival of fishermen and to the success of groundfish sectors. Sectors were implemented through Amendment 16 to the multispecies FMP. The sectors are assigned percent allocations based on the historic catches of their members. However, the allocations of redfish could not be fully utilized under current regulations because the minimum codend mesh size is too large to effectively retain redfish. At the same time, allocations of other groundfish species are extremely small due to the very low ACLs recommended. These limiting allocations (“choke” species) will affect the fishing behavior of the sectors and potentially shut them down before more abundant allocations are realized. It is critically important to the success of sectors to find a way to allow them to access allocations of healthy stocks such as redfish while avoiding those that are depressed.

Size selection is the process that describes why the size distribution of fish caught by a fishing gear is different than the size distribution of a fish population. The concept behind size selectivity in trawls is that the retention rate of fish across lengths can be determined through a comparison of the numbers of fish caught per length in the test codend and the numbers per length in a non-selective (smaller mesh) control codend. Since the relationship is largely mechanical (what size fish can fit through a certain-sized hole?), the resulting relationship is considered robust, stable, and adequate for management purposes. Typically, the $L_{50}$ (the length at which 50% of fish in the trawl...
are retained by the codend) is used to characterize the codend performance, and can be used to set codend size limits. Other metrics (L25, for example) can also be input into the model or used as management benchmarks.

The methods, statistical model and methodology to describe this relationship have evolved, but have become fairly standardized in part due to increased computing speed and power. Trawl hauls are made simultaneously (parallel, twin, or trouser trawls) or alternatively with the test codend and the control codend with the aim of sampling the same population (one of identical or similar sizes of fish). A logistic curve that implies increasing retention, reaching a maximum of 100% (L100) is fit to individual hauls (if possible) or pooled data if not. The between and within haul variation can then be combined to produce an average curve, with error estimates or confidence limits. During this process the random effects of other factors on the size selection can be assessed. Additionally, over the years a body of research has been developed that has identified certain codend characteristics and other factors that can alter the size selection of the same mesh opening.

Size selectivity specifically for redfish species in codends has been examined across the North Atlantic since 1961 with varying levels of rigor. A recent review of this topic (Herrmann et al. 2012) found 21 trials of codend meshes, mostly diamond, mostly for redfish relatives Sebastes marinus and Sebastes mentella, with only three testing S. mentella and our species of interest, S. fasciatus, but combined. Prior to this study, we lacked vital information necessary to redevelop a sustainable trawl fishery because managers and fishermen would not be able to reliably predict the effect of different codend mesh sizes on commercial catches.

**Project Design**

REDNET is a multifaceted, comprehensive project to determine how to sustainably access the redfish ACL for the groundfish sectors in the northeast US. The goal is to execute a complete project, from conception to regulatory implementation, to marketing, that supports environmentally and economically sustainable harvesting of
redfish. REDNET includes individuals with various expertise to accomplish this vision. There are six components of the project:

Component 1: Network Meetings  
Component 2: Baseline Catch and Bycatch Evaluation  
Component 3: Codend Selectivity  
Component 4: Conservation Engineering and Bycatch Reduction  
Component 5: Processing/Marketing  
Component 6: Outreach/Implementation

This report describes experimental methods and results from Component 3: Codend selectivity. While the entire REDNET project is still ongoing, Components 2 and 3 (this report) are complete. This report should be considered the final report on the data gathered for this component.

**Methods**

**Fishing vessel and gear**

After a competitive bid process among REDNET active industry participants, the F/V Guardian (80 ft LOA; 425 hp) was chosen to conduct the research. An Experimental Fishing Permit was received in December 2012. Candidate mesh sizes of 4.5, 5.5 and 6.5 in diamond mesh codends were selected by REDNET members. Mesh sizes were measured prior to and after the experiment using an ICES OMEGA mesh gauge and associated protocols (Fonteyne, 2005). Square mesh codends were dismissed based on impracticality due to sticking of fish, as advised by the industry and ICES WGFTFB colleagues. Two six-day trips were made during March-April 2013 with the goal of comparing the sizes of fish caught in 3 different commercial-sized codends to the catch in a 2.5” control codend using a trouser trawl. Fishing trials were carried out in southern Gulf of Maine (Figure 1).

The participating vessel provided a balloon trawl front end (ground gear, wings, net mouth) to be attached to a “trouser trawl”; both were designed by Tor Bendiksen of Reidar’s Manufacturing (New Bedford, MA) (Figure 2). The headline of the trawl was 109
ft 10 in (33.4 m) in length with 100 plastic floats 8 in (20.3 cm) in diameter. The footrope was 138 ft 6 in (42.5 m) in length and attached with a rockhopper sweep. The front end of the net was uniformly 6.0 in (152 mm) mesh openings constructed of 4.0 mm diameter braided twine. The fishing circle was 190 meshes across the bottom panel and 240 meshes across the top. The trouser trawl was also constructed of 6.0 in (152 mm) mesh size, 3.6 mm diameter braided twine. It was designed with a 47.5 meshes deep common “mixing area” that separated uniformly into two lateral equal circumference legs (130 meshes across the bottom; 161 meshes across the top) (Figure 2). A test codend (4.5, 5.5, or 6.5 in double twine (5 mm)) was attached to one leg of the trousers and a 2.5 in diamond mesh control codend (double 4 mm) on the other side (Table 1). The side of the test and control codends was switched regularly to avoid possible side-based effects. The number of meshes for each test codend was adjusted so that the same diameter and overall length were maintained for all codends. One leg of the trouser trawl was lengthened by 25 meshes of double 4 mm 6.5 in mesh to avoid contact or inhibition between codends.

**Onboard sampling**

All regulated groundfish were counted against the sector annual catch limits (ACLs). The vessel was reimbursed for any quota purchases. Net revenue from sale of redfish was divided between the vessel and the project. The project also reimbursed the participating vessels for fuel in order to encourage the vessel to fish at different locations throughout the Gulf of Maine. Other expenses incurred by the scientific crew (insurance, food) were also reimbursed to the vessel.

Two or three scientists were on board the vessels and worked alongside the vessel crew during both trips and documented all trip, tow, environmental, catch, and bycatch data following National Marine Fisheries Service (NMFS) Fisheries Observer Program protocols. The total catch of redfish per tow was determined (on some tows, legal and sublegal catch amounts were quantified). Other organisms were also identified, and weighed. A special protocol was agreed upon between the NMFS habitat group and the project participants in the event that deep-sea corals were encountered.
Lengths (measured as midline length, MLL) of a random subsample of more than 100 redfish from each tow were commonly collected due to time constraints. Collection of pollock lengths was also prioritized. Other important species were measured opportunistically. For length-frequency (LF) analysis, counts at each length were multiplied by the subsample weight divided into the total weight. Information on net geometry and bottom temperature was collected using a trawl monitoring system (Notus Electronics, St. John’s, Newfoundland) and TidBit temperature recorders (Onset Computers, Inc., Pocasset, Massachusetts).

Analysis

All catch data (along with trip and gear data) were entered and uploaded into a customized relational database in Microsoft Access 2007. Collected data were analyzed using Microsoft Excel and R statistical software (R Development Core Team, 2009), primarily using the lattice package (Sarkar, 2009) and SELNET, a selectivity analysis program. SELNET was developed to acquire and analyze size selectivity and catch data for towed fishing gears, both at the haul level and for a group of hauls (Frandsen et al., 2011; Herrmann et al., 2012; Herrmann et al., 2013). The methods implemented in SELNET comply with accepted recommendations for the analysis of size selectivity data (Wileman et al. 1996; Fryer 1991).

To model the size selection first we used a logistic curve described by the parameters \( L_{50} \) and the selection range \( SR = L_{75} - L_{25} \) (Wileman et al., 1996). For each haul, the number of fish counted in the experimental codend is described as \( n_{t_i} \) for the count of fish at each length \( l \), and in the control codend \( n_{c_i} \). The proportion of the total catch actually measured for lengths is described by the sampling rates \( q_t \) (experimental) and \( q_c \) (control). The size selection in each haul can then be obtained by minimizing the following function with respect to the parameters \( L_{50}, SR \) and \( SP \):

\[
-\sum\limits_{t} \left\{ n_{t_i} \times \ln\left( \frac{q_t \times \varphi(l, L_{50}, SR, SP)}{q_t \times \varphi(l, L_{50}, SR, SP) + q_c \times \left(1 - \varphi(l, L_{50}, SR, SP)\right)} \right) + n_{c_i} \right\} 
\times \ln\left( \frac{q_c \times \left(1 - \varphi(l, L_{50}, SR, SP)\right)}{q_t \times \varphi(l, L_{50}, SR, SP) + q_c \times \left(1 - \varphi(l, L_{50}, SR, SP)\right)} \right),
\]

where \( \varphi(l, L_{50}, SR, SP) \) is the cumulative selectivity function.

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With:

$$\varphi(l, L50, SR, SP) = \frac{sp \times r_{logit}(l, L50, SR)}{1 - sp \times (1 - r_{logit}(l, L50, SR))}$$

SP is defined as the split parameter and expresses the assumed length independent relative entry of fish to the test or control side of the gear during the fishing process. SP needs to be estimated to assess the values of the selection parameters L50 and SR.

Fit statistics (i.e., the p-value and model deviance versus the DOF degrees of freedom (DOF)) were inspected for individual hauls (Wileman et al. 1996). Where the p-value < 0.05 or the deviance >> DOF, the residuals were examined for patterns or structural problems. Where no pattern was seen, the poor fit was considered overdispersion in the data and the data were included.

Our second step considered between-haul variation (Fryer 1991) using the results from all the individual hauls simultaneously for the L50, SR and SP, together with their covariance matrix and information on the values of the mesh size, m. In addition, we considered the effect of w (total control codend catch weight at end of haul in kg) and S2, which side of the twin trawl the test codend was attached to. (The trouser trawl was constructed to be longer in one leg to avoid interference underwater between the codends. Since one codend stayed in the water longer, and could potentially lose more fish, we wanted to test whether this longer hauling time might impact size selectivity.)

A model considering the potential effect of the parameters m, w and S2 was constructed with the following form and applied in SELNET for each species separately.

$$L50 = f_0 + f_1 \times m + f_2 \times w + f_3 \times S2$$
$$SR = g_0 + g_1 \times m + g_2 \times w + g_3 \times S2$$
$$SP = h_0 + h_1 \times m + h_2 \times w + h_3 \times S2$$

The parameters $$f_0...f_3$$, $$g_0...g_3$$ and $$h_0...h_3$$ are estimated while fitting the model to the data with values for L50, SR and SP based on the selectivity results from the individual
hulls. Models were selected based on the AIC value (Akaike, 1974), while considering every possible simpler sub-model following the procedure described in Wienbeck et al. (2011) and Herrmann et al. (2013). A total of 4096 model runs were completed.

Individual haul results were plotted for the $L50$ and $SR$ with 95% CI versus the mean model estimated values and the predicted 95% CI for the total variation (between-haul variation + uncertainty around the mean). The lower and upper 95% CI for the estimated between-haul variation in the selection parameters (lim $L50$, lim $SR$) were calculated by:

$$
\begin{align*}
\text{lim } L50 &= L50_{\text{mean}} \pm 1.96 \times \sqrt{(\text{Var}L50_{\text{mean}} + D_{11})} \\
\text{lim } SR &= SR_{\text{mean}} \pm 1.96 \times \sqrt{(\text{Var}SR_{\text{mean}} + D_{22})} \\
\text{lim } SP &= SP_{\text{mean}} \pm 1.96 \times \sqrt{(\text{Var}SP_{\text{mean}} + D_{33})}
\end{align*}
$$

where $L50_{\text{mean}}$, $SR_{\text{mean}}$ and $SP_{\text{mean}}$ are the predictions based on the selected submodel based on (1), and $D_{11}$, $D_{22}$ and $D_{33}$ are the diagonal elements in the estimated between haul-variation matrix for the selected model (Fryer, 1991).

These plots were inspected to see if the model predictions appeared to reflect the main trends for the effects of catch size on the results for each codend to see if it was necessary to consider the estimates of the between-haul variation and uncertainty on the means in the selection process in addition to the uncertainty of the haul results.

After successful model validation based on the above procedure the models were applied to predict size selection for codend mesh sizes between 80 and 170 mm.

**Results and Discussion**

The codend mesh sizes measured prior to and following fishing using an OMEGA mesh gauge indicated a slight change during the experiment (Table 1). All test and control codends except the largest mesh codend (6.5”) showed some increase. The average of the two measurements was used for analysis.
Fifty-six tows were completed in two trips carried out between 27 March and 1 April, and 3 April and 8 April 2013. The same test codend was used for approx. three days before switching to a new mesh size. Overall, 18 tows were completed pairing the 4.5 in mesh, with 10 on the starboard side; 16 tows with the 5.5 inch with 9 on the starboard side; 22 tows with the 6.5 in codend with 9 on the starboard side.

Tows were conducted generally east and northeast of Provincetown, Massachusetts over an area of approximately 4700 nm² (Figure 1). Tow locations were based on captains’ previous knowledge, echo sounder signals (including bottom topography), and a goal of wide coverage. Tows were only made in daylight. Tow durations varied based on the captain’s assessment of the volume of fish in the net and fishing ground conditions. Very large catches were avoided if possible due to catch processing delays that might reduce the number of tows and affect fish survival and quality. Median tow duration was 0.6 h. Median depth fished was 100 fm (Figure 3), deeper than is typical for other groundfish. Median towing speed was 3.0 knots. Median warp length was 225 fm. Median wave height experienced was 4 ft with a maximum of 10 ft; these heights are unlikely to substantially affect net performance.

Median bottom temperatures (°C) recorded by the TidBit recorder did not show differences between mesh sizes (4.5: 6.9°C (IQR: 6.7-7.0°C); 5.5: 6.9 °C (IQR: 6.7-7.0°C); 6.5: 6.7 °C (IQR: 6.5-6.7°C). Median bottom temperatures as recorded by the Notus system were very similar (4.5: 7.0 °C (IQR: 6.7-7.3°C); 5.5: 6.7 °C (IQR: 6.6-6.8°C); 6.5: 6.8 °C (IQR: 6.4-7.0°C)).

Adequate trawl monitoring sensor readings were obtained to estimate distance from a hydrophone towed off the port stabilizer to both trawl doors, one wing end, the headline and the codend (Figure 4). Additional data on door heel (angle of the door to the right or left of the direction of travel) (Figure 5), distance of the headline to the bottom, and some information on door spread (Figure 6) were collected. The distance measurements in Figure 6 are separated by wire out as the sensors are further away when there is more wire out. No anomalies are apparent; some filtering of clearly erroneous readings was used in the headline height plot. Additionally, since the split
parameter indicated good net performance (see below) and both codends were on the same net, any differences in geometry would have minimal impact.

Codends were hauled on deck one at a time, with the codend attached to the shorter “leg” hauled first. Catches from the experimental and control codends were deposited in separate areas on deck, and processed separately. All bycatch and incidental catches were identified; weights (kg) were directly collected or quantitatively determined; for example, by basket counts. The total catch of all species was just over 47,900 kg, with redfish comprising 42,482.9 kg or 89.7% of all catch (Table 2.) Pollock (*Pollachius virens*) was the main bycatch species (3390.5 kg), with 21 other species with catches greater than 10 kg total. One porbeagle shark was captured with no reported weight.

Approx. 19,600 kg of redfish were sold, combined over both trips, at $0.50 per pound. Discards were not a primary focus during the study. They were quantified on some tows during the trip, and were primarily driven by a market that discourages the smaller legal-sized fish.

Over 18,000 redfish were measured. Lengths ranged from 13-40 cm with distributions differing between codends (Figure 7). Sufficient numbers of pollock were caught to construct length frequencies and to conduct selectivity analyses. Over 1800 pollock were measured; sizes ranged from 18-86 cm (Figure 8). Size selectivity analysis for pollock will be reported separately.

Fifty-four hauls were included in redfish size selectivity analyses; two hauls could not be included due to zero catches of redfish in one of the codends (experimental or control). Testing of the full model revealed a simplified version where the $L_{50}$ and the $SR$ depend only on mesh size ($p>>0.001$; AIC = 1467.35).

\[
\begin{align*}
L_{50} &= 0.209 \times \text{mesh size} (\text{CI}: 0.206, 0.216) \\
SR &= 0.0315 \times \text{mesh size} (\text{CI}: 0.029, 0.034) \\
SP &= 0.556 (\text{CI}: 0.509, 0.602)
\end{align*}
\]

The model estimated a split parameter near the ideal value of 0.5 with the 95% confidence interval (CI) overlapping 0.5. This result, together with the lack of significant
impact of catch size or which side the codends were on, provided evidence for good functioning of the gear and random distribution of fish between the test and control codends. The absence of any intercept terms in the L_{50} and SR provided the logical result that as the mesh size is reduced to zero, the fish length would similarly be reduced to zero.

Full logistic curves that illustrate the catch curves for the codends as measured are shown in Figure 9, along with 95% confidence intervals. Also included in the figure are the current and recent minimum landing sizes (MLS). L_{50} and selection ranges were determined for 4.5 in (L_{50}: 22.3 cm (8.8 in); SR: 4.5 cm), 5.5 in (L_{50}: 29.2 cm (11.5 in); SR: 4.4 cm), and 6.5 in (L_{50}: 33.6 cm (13.2 in); SR: 5.1 cm) codends. Further validation of the selectivity model was demonstrated by plotting L_{50} and SR values for each individual haul, along with 95% confidence intervals as error bars, along with overall mean values predicted by the final model, against the size of the codend catch (Figure 10). Only six hauls were found to have values of L_{50} outside the 95% CIs; all of these hauls overlapped their error bars with the confidence band indicating that the model is an excellent fit to the data.

A similar comparison was made for the selection range (Figure 11); eight individual hauls had SR values outside the overall CI for the mean SR. All of these also had error bars overlapping the CI band. These combined results indicated that the fit of the individual hauls to the overall results were excellent.

Model results were used to produce estimates of mean L_{50} (Figure 12) and SR (Figure 13) across a broad range of mesh sizes to support the choice of appropriate mesh sizes. Model results can be used to estimate these values for both larger and smaller meshes, but expansion outside the tested range is less reliable and likely unnecessary.

For further consideration of the impact of different choices of mesh sizes, we used the length distribution found in the 2.5 in codend as a representation of the overall population size structure available to trawl gear. (This distribution was compared to NMFS NEFSC Groundfish Survey data and found to be similar). A simulation using our model results was then developed using SELNET that estimated the distribution and number of fish predicted to be caught from a similarly structured theoretical population.
of 1000 redfish (Figure 14) using codends ranging from 4.5 in to 6.5 in, in 0.5 in steps. Intermediate mesh sizes can also be extrapolated using this procedure.

Additionally, the estimated escape of fish through the codend meshes can be inferred from the difference between the predicted number of fish caught and the theoretical population of 1000 fish. It is predicted that only 5.1% redfish in numbers would be retained by a 6.5” codend, 19.5% for a 5.5” codend, and 51.3% by a 4.5” codend. It is not known whether these fish would escape during fishing at the depth, during hauling in midwater, or at surface. Mortality rates of escapees that exit the net during different stages of fishing (towing, hauling, at surface) are likely different. It is generally agreed that fish that escape during towing may suffer less mortality than during hauling or at surface (Madsen et al. 2008). Escape at the surface increases mortality due to predation by other fish and by seabirds (Grimaldo et al. 2009; Madsen et al. 2008). Redfish may be unable to leave the surface for some time, if at all, due to eversion of swim bladders.

The simulations illustrate challenges associated with sustainable harvest of this species. First, the size distribution of redfish *S. fasciatus* is truncated compared to its near relatives *S. mentella* and *S. marinus*. This limitation may prevent exploitation of certain markets.

The current minimum landing size of 7 in (18 cm) represents the tail of the distribution of redfish, even when using the 2.5 in mesh control codend. Any mesh size larger than 2.5 will result in legal-sized fish passing through the codend meshes, and becoming subject to escape mortality.

The simulation results also suggest that some mesh sizes, while yielding larger sized fish, may result in catches that are too small in size to be economical. Additionally, the simulation emphasizes that substantial numbers of fish are passing through codend meshes and not being caught. The process of pursuit, exhaustion, and mesh passage has a definite, but difficult to quantify, level of mortality on fish. The range of possible escape mortality is quite wide; however, even at mortality rates of 10%, a significant number of redfish would die and be wasted as a result of the capture process.
Conclusions and Recommendations

Testing of the selectivity of the codends provided model results that by all, multiple measures appear robust. These results should be used to identify appropriate codend mesh sizes for sustainable fishing and for incorporation into stock assessment models.

The relatively small amount of bycatch in this experiment, even using a very small mesh control codend, indicates the power of choosing appropriate time, depth, and areas to sustainably target redfish with minimal bycatch.

The relatively small size range of this species of redfish should be a consideration in determining sustainable strategies for harvesting redfish. Unlike species with a larger maximum size, implementation of larger mesh sizes will not yield substantially greater growth.

The biology and population dynamics of this species should be used to help identify an appropriate size of redfish to be targeted, including whether this target should be at the L25, L50, or other retention level.

The results of this study should be communicated to processors and marketers, in addition to the fishing fleet and managers, to emphasize the catch size and volume of fish at length available to the market.

Emphasis should be placed on determination of when escapement occurs. Research on other species has indicated that substantial escape could occur at the surface with all trawl gears. Unobserved escape mortality can be minimized by investigating when or if escape occurs in the codend during towing, and further if the use of a sorting grid, similar to the Nordmøre grate used in shrimp trawl fisheries, can be used to efficiently and effectively exclude small fish during the capture process with minimal mortality.
**Acknowledgements**

Primary thanks are due to the F/V Guardian captain and crew: Capt. Bradford Horrell, Bobby Blethen, José Garcia, Séan Farren, and Richard Walsh, and its owner, Mike Walsh, for their wisdom, patience, friendship, and participation. Our thanks also go to biologists who collected data onboard from DMF: David Chosid, and SMAST: Chris Rillihan and to Mark Szymanski of DMF for contract and other support. We acknowledge the extensive involvement of the REDNET network, which at present includes over 30 members. Bent Herrmann of SINTEF Fisheries and Aquaculture is kindly thanked for the use of SELNET and his instruction and analysis. Funding was provided by the National Marine Fisheries Service Cooperative Research Partnership Program.

**References**


TABLES
Table 1: Codend mesh measurements

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<tr>
<th>Mesh Size (in)</th>
<th>Diameter (mm)</th>
<th>Length (meshes)</th>
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<td>60</td>
<td>60.5</td>
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<td>142.7</td>
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<td>141.9</td>
<td>3.1</td>
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<td>6.5 Double 5</td>
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<td>4.1</td>
<td>163.2</td>
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</table>

Table 2: Catch weights (kg) by species and by mesh size (in) where total catch exceeded 5 kg, sorted by total weight. Note that the 2.5 in mesh catches are separate for each tested codend mesh size.

<table>
<thead>
<tr>
<th>Species</th>
<th>2.5</th>
<th>4.5</th>
<th>2.5</th>
<th>5.5</th>
<th>2.5</th>
<th>6.5</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redfish, Acadian</td>
<td>13.974</td>
<td>10,829.4</td>
<td>9,469.5</td>
<td>824.6</td>
<td>6,976.0</td>
<td>710.7</td>
<td>42,784.6</td>
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<tr>
<td>Pollock</td>
<td>524.4</td>
<td>357.4</td>
<td>386.3</td>
<td>476.6</td>
<td>868.9</td>
<td>302.6</td>
<td>3,390.5</td>
</tr>
<tr>
<td>Cod, Atlantic</td>
<td>62.2</td>
<td>94.7</td>
<td>67.9</td>
<td>96.8</td>
<td>233.2</td>
<td>85.8</td>
<td>640.6</td>
</tr>
<tr>
<td>Monkfish (Goosefish)</td>
<td>11.7</td>
<td>32.0</td>
<td>4.3</td>
<td>10.2</td>
<td>86.0</td>
<td>81.0</td>
<td>196.0</td>
</tr>
<tr>
<td>Lobster, American</td>
<td>17.8</td>
<td>24.7</td>
<td>11.0</td>
<td>12.2</td>
<td>43.3</td>
<td>87.0</td>
<td>225.2</td>
</tr>
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<td>Dogfish, Spiny</td>
<td>32.5</td>
<td>38.8</td>
<td>12.9</td>
<td>0.7</td>
<td>91.8</td>
<td>196.0</td>
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</tr>
<tr>
<td>Haddock</td>
<td>9.1</td>
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<td>22.9</td>
<td>22.2</td>
<td>34.7</td>
<td>9.5</td>
<td>113.4</td>
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<td>18.2</td>
<td>21.5</td>
<td>17.3</td>
<td>18.1</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Hake, Silver (Whiting)</td>
<td>11.5</td>
<td>4.6</td>
<td>24.7</td>
<td>0.4</td>
<td>44.6</td>
<td>1.7</td>
<td>87.4</td>
</tr>
<tr>
<td>Hake, White</td>
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<td>20.8</td>
<td>12.7</td>
<td>6.5</td>
<td>22.8</td>
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<td>85.4</td>
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<td>13.8</td>
<td>1.0</td>
<td>77.9</td>
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<tr>
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<td>7.0</td>
<td>14.2</td>
<td>9.1</td>
<td>64.6</td>
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<tr>
<td>Herring, Atlantic</td>
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<td>0.3</td>
<td>4.1</td>
<td></td>
<td>44.5</td>
<td>0.3</td>
<td>57.7</td>
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<tr>
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<td>0.8</td>
<td>12.7</td>
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<td>33.6</td>
<td>0.7</td>
<td>57.4</td>
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<tr>
<td>Mackerel, Atlantic</td>
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<td></td>
<td>35.7</td>
<td>0.5</td>
<td>43.2</td>
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<tr>
<td>Flounder, Witch</td>
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<td>4.1</td>
<td>1.7</td>
<td>17.5</td>
<td>4.7</td>
<td>37.7</td>
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<tr>
<td>Cusk</td>
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<td>13.7</td>
<td>5.9</td>
<td>4.3</td>
<td>2.4</td>
<td></td>
<td>37.6</td>
</tr>
<tr>
<td>Halibut, Atlantic</td>
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<td>0.1</td>
<td>6.1</td>
<td></td>
<td>17.5</td>
<td>34.8</td>
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<tr>
<td>Squid, At Long-fin</td>
<td>7.5</td>
<td>4.0</td>
<td>3.2</td>
<td>0.6</td>
<td>8.9</td>
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<td>1.9</td>
<td>2.5</td>
<td>3.9</td>
<td>2.9</td>
<td>4.6</td>
<td>20.1</td>
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<td>0.3</td>
<td>9.4</td>
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<td></td>
<td>11.2</td>
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<tr>
<td>Ocean Pout</td>
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<td>1.9</td>
<td></td>
<td>1.0</td>
<td></td>
<td>10.2</td>
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</table>

*Blueback or Alewife
FIGURES
Figure 1: Tow start locations.
Figure 2: Net diagram of trouser trawl.
<table>
<thead>
<tr>
<th>Wire Out (fm)</th>
<th>Tow Speed (knt)</th>
<th>Wave Ht (ft)</th>
<th>Depth (fm)</th>
<th>Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>10</td>
<td>10</td>
<td>200</td>
<td>0.5</td>
</tr>
<tr>
<td>240</td>
<td>4</td>
<td>8</td>
<td>150</td>
<td>1</td>
</tr>
<tr>
<td>220</td>
<td>2</td>
<td>4</td>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>220</td>
<td>1</td>
<td>2</td>
<td>50</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3: Operational and environmental variables in chronological order. Green dots are tows testing the 6.5 in codend; pink is the 5.5 in codend; blue dots are the 4.5 in codend. Dashed red horizontal lines are panel medians.
Figure 4: Distance (m) to net sensors by amount of wire out (fm)
Figure 5: Door heels (negative = ; positive = ) in degrees, separated by trip and wire out (fm)
Figure 6: Headline height (m) and door spread (m) shown for each amount of wire used during selectivity trials. Insufficient readings were obtained when 275 fm of wire was used. Red horizontal line is the overall median. Sample sizes proportional to box width.
Figure 7: Redfish length frequencies (cm) by mesh size (in). Red dashed lines are the older and newer minimum landing sizes
Figure 7: Pollock length frequencies (cm) by mesh size (in). Red dashed line is the minimum landing size.
Figure 9: Selection curves for 4.5 (blue), 5.5 (red), and 6.5 (black) (nominal inches) codends, with 95% confidence bands in stippled lines.
Figure 10: L50 estimates by mesh size (in) from individual hauls (blue circles) with 95% confidence intervals (error bars) compared to modeled mean L50 (solid horizontal line) and 95% confidence intervals (stippled lines), depicted by catch weight (kg).
Figure 11: Selection range (cm) estimates by mesh size (in) from individual hauls (blue circles) with 95% confidence intervals (error bars) compared to modeled mean L50 (solid horizontal line) and 95% confidence intervals (stippled lines), depicted by catch weight (kg).
Figure 12: Predicted mean L50 v mesh size for redfish (solid line) with 95% confidence intervals (stippled lines).
Figure 13: Predicted mean selection range (cm) v. mesh size for redfish (solid line) with 95% confidence intervals (stippled lines).
Figure 14: Simulated catch distributions based on selectivity analysis using five different mesh sizes (4.5; 5.0; 5.5; 6.0; 6.5 in) from the observed population distribution, scaled to 1000 fish. Numbers indicate the estimated number of fish retained by that codend mesh size.