Fisheries Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Impact of codend mesh sizes on selectivity and retention of Acadian redfish *Sebastes fasciatus* in the Gulf of Maine trawl fishery

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ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 10 June 2016
Accepted 11 June 2016
Handled by Prof. George A. Rose
Available online xxx

Keywords:
Acadian redfish
Sebastes fasciatus
Bottom trawl
Size selectivity

ABSTRACT

A trouser trawl was used to determine the size selectivity of three sizes of mesh opening (114, 140 and 165 mm double 5 mm twine diamond) on a commercial fishing vessel fishing off Provincetown, Massachusetts, USA. Fifty-six tows were completed in March and April 2013, catching over 42,000 kg of Acadian redfish (*Sebastes fasciatus*) and about 6000 kg of other species. 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. *L*50 and selection ranges were determined for the nominal 114 mm (*L*50:22.3 cm; SR:3.3 cm), 139 mm (*L*50:29.2 cm; SR:4.4 cm), and 165 mm (*L*50:33.6 cm; SR:5.0 cm) codends. 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. Additionally, simulation of fishing of the three tested codends on the observed population indicated that substantial escape of redfish through codend meshes occurs (51–96%), 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.

1. Introduction

Acadian redfish (*Sebastes fasciatus* – “redfish”) is one of three groundfish species in the Northeast United States with Annual Catch Limits (ACL) in excess of 10,000 t (Greater Atlantic Regional Fisheries Office (GARFO, 2014a). However, the ACL has not been fully utilized over the last few years because the mandatory minimum codend mesh size is too large to effectively retain redfish.

Historically, redfish represented a sizeable fishery and income in the region. The directed commercial fishery for redfish in the Northeast US began in the 1930s with the advent of freezing technology (Mayo et al., 2006). Total landings from the Gulf of Maine and Georges Bank rose from 100 t (mt) to a peak of 56,000 t in 1942 and then steadily declined (Mayo et al., 2006). By comparison, annual landings in the 1930–40 period of the iconic Atlantic cod (*Gadus morhua)* averaged approximately 9000 t (Mayo et al., 2006). By 1989, the total US landings of redfish fell below 1000 t, and remained at that level throughout the 2000s (Mayo et al., 2006). Research vessel survey indices begun in 1963 showed a 90% decline in redfish per tow between 1968 and 1985 during which time the catch rates reached their lowest point (Collette and Klein-MacPhee, 2002; Mayo et al., 2006). Since 1995, survey catches have steadily increased and remain high to this day (Mayo et al., 2006; Northeast Fisheries Science Center (NEFSC), 2012). Based on the most recent assessment, the stock has reached and exceeded its target biomass for maximum sustainable yield of 238,000 t and the exploitation rate remains below its target of 0.04 (NEFSC, 2012).

Mesh restrictions, combined with low biomass levels between 1980 and 1995, eliminated the directed redfish fishery in the Northeastern United States. The decline in abundance of redfish likely resulted from overexploitation, and recovery was likely encouraged by a mismatch between mandatory minimum mesh sizes for the multispecies fishery and the smaller size of redfish compared to other target species in the groundfish complex. In 1977, the minimum codend mesh size for redfish (and all groundfish species) was increased from 114 to 130 mm (Anthony, 1990) and increased again in 1994–152 mm (Fogarty and Murawski, 1998; Murawski et al., 2000). Currently, the mandated minimum codend mesh size is 165 mm. This minimum mesh size is applied to all managed

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http://dx.doi.org/10.1016/j.fishres.2016.06.013
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Table 1
Codend mesh measurements.

Mesh Size (mm)	Diameter (mm)	Length (meshes)	Circumference (meshes)	Mesh opening (mm)					
				Pre-experiment		Post-experiment		Average	
				Mean	SD	Mean	SD	Mean	SD
64	Double 4	125	125.5	64	1.6	67.2	1.6	65.6	2.3
114	Double 5	70	70.5	106.3	2.5	110.6	2.8	108.4	3.4
140	Double 5	60	60.5	141.1	3	142.7	3.1	141.9	3.1
165	Double 5	50	50.5	163.4	3.1	163.1	4.1	163.2	3.6

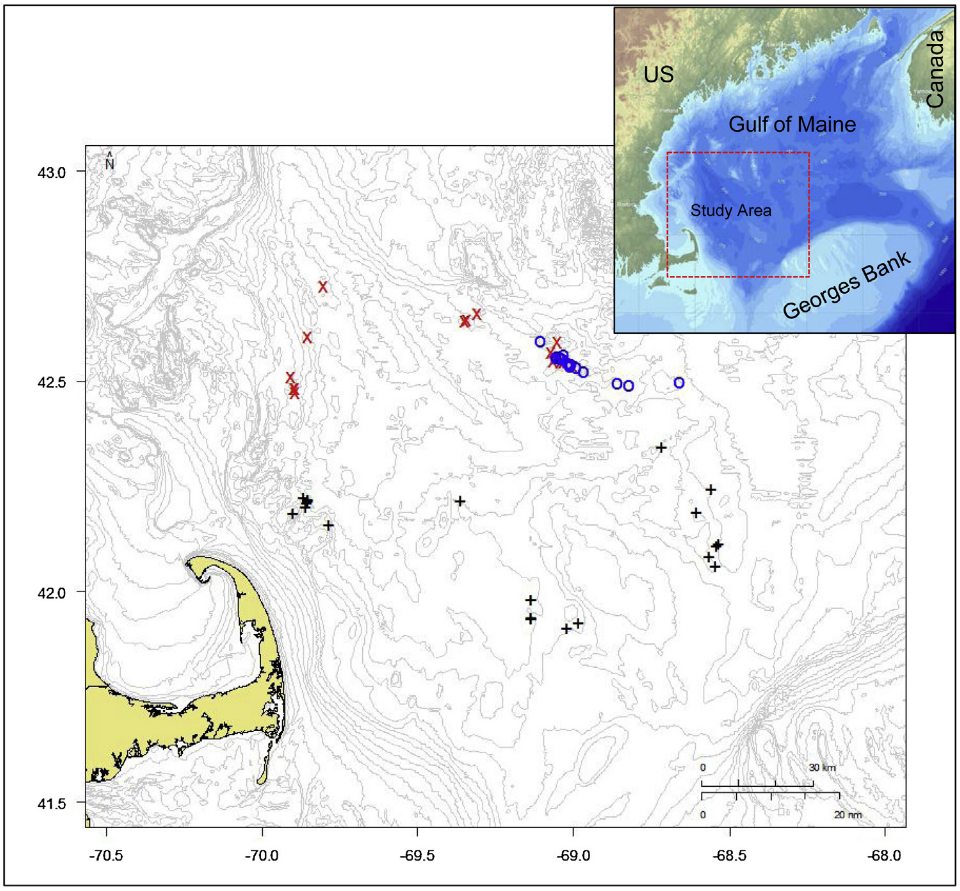

Fig. 1. Tow start locations by mesh size tested: blue circles = 114 mm; red x = 140 mm; black crosses = 165 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

groundfish species, including Atlantic cod, haddock (*Melanogrammus aeglefinus)*, and pollock (*Pollachius virens)*, as well as several species of flatfish. These species have a range of minimum landing sizes (MLS) from 30.5 to 48 cm; redfish is the smallest at 22.9 cm (recently lowered to 17.8 cm). Individual redfish are typically in the 20–30.5 cm range (Collette and Klein-MacPhee, 2002) and redfish at the minimum size are too small to be retained in a 165 mm codend. Consequently, the use of one mesh size for the multispecies fishery results in a mismatch between the mesh size and the minimum landing size for redfish. As a result, only 38.5% of the annual catch limit was landed in 2013 (GARFO, 2014b). Indeed, fishing industry collaborators within the REDNET network, a research network established to redevelop the redfish trawl fishery, have reported that the majority of redfish in the codend cannot be retained in 165 mm mesh unless the vessel maintains constant headway during retrieval of the net.

Acadian redfish is one of three Sebastes species, all very similar in morphology, exploited in fisheries across the North Atlantic (Herrmann et al., 2012). Experiments on codend mesh selectivity for these species started in the 1960s with varying levels of rigor. A recent thorough review of this topic (Herrmann et al., 2012) found 21 investigations of codend mesh selectivity, mostly for diamond-shaped meshes, and mostly for redfish congeners *Sebastes marinus* and *S. mentella.* Only three of these studies involved *S. fasciatus*, which was combined with *S. mentella* during those studies as one species group (Herrmann et al., 2012).

Our goal was to develop length retention curves for Acadian redfish to advise and to inform fishermen, processors, fishery managers, and assessment biologists on selection of an appropriate mesh size to increase codend retention and, therefore, landings while maintaining and sustaining the health of the stock. Working in collaboration with the REDNET network, three candidate mesh sizes were chosen: 114, 140, and 165 mm. This range incorporates the current minimum mesh size and the likely smallest acceptable mesh size for a special access program, with one mesh at the midpoint. Diamond meshes were preferred over square mesh due to "sticking" by redfish in square mesh codends (ICES, 2012). Sticking results when fish pass partway through meshes, and are gilled in

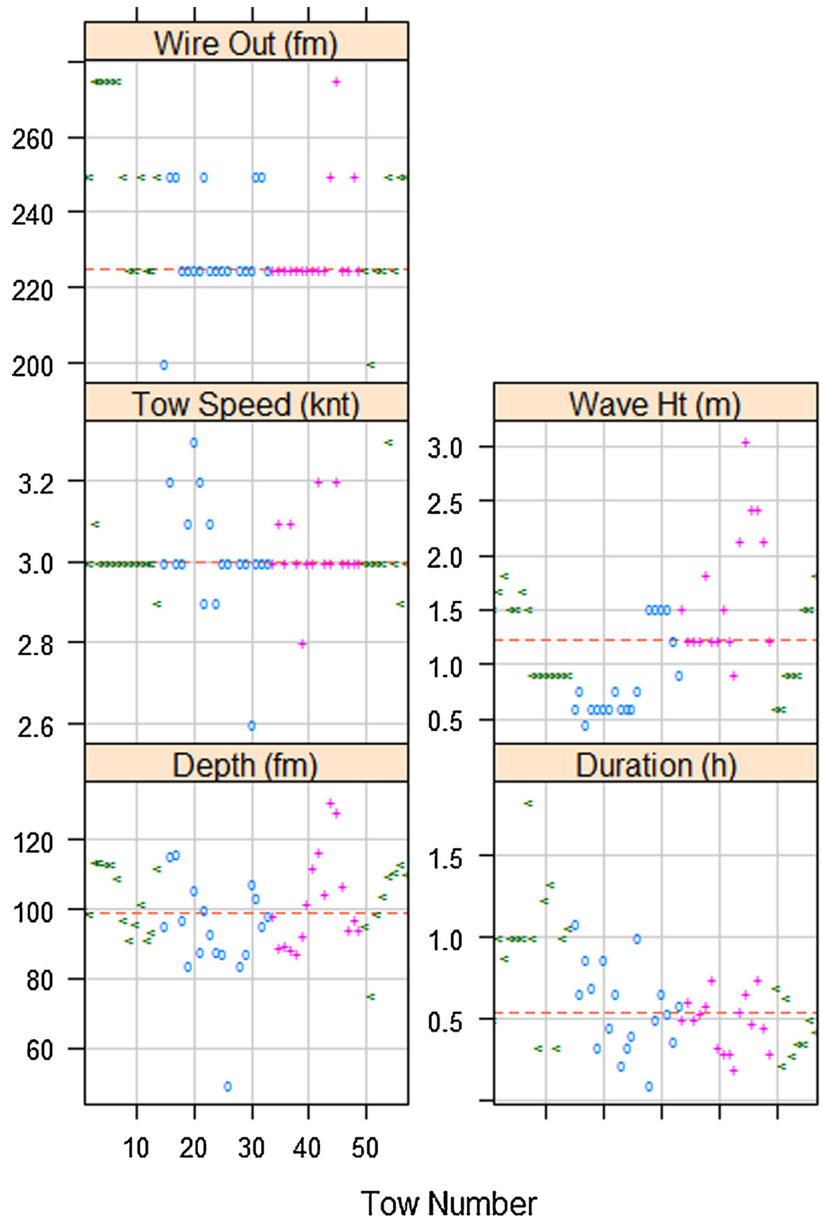

Fig. 2. Operational and environmental variables in chronological order. Green arrowheads (<) are tows testing the 165 mm codend; pink crosses is the 140 mm codend; blue circles are the 114 mm codend. Dashed red horizontal lines are panel medians. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the codend. A large number of fish sticking in the codend requires a great deal of time to remove them; many of these fish become damaged and unsalable.

2. Materials and methods

2.1. Fishing vessel and gear

The F/V Guardian (80 ft LOA; 425 hp), a commercial groundfish trawler with recent experience targeting redfish, was chosen to conduct the research. The participating vessel provided a balloon trawl front end (ground gear, wings, and net mouth) to be attached to a "trouser trawl" section. The headline of the trawl was 33.4 m in length with 100 plastic floats 20.3 cm in diameter. The footrope was 42.5 m in length and attached to a rockhopper groundgear. The front end of the net had 152 mm diamond 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 section of the trawl was also constructed of 152 mm diamond mesh, 3.6 mm diameter braided twine. It was designed with a 47.5 meshes deep common "mixing area" that was then separated uniformly into two lateral equal circumference legs (130 meshes across the bottom; 161 meshes across the top). One leg of the trouser trawl was lengthened by 25 meshes of double 4 mm 152 mm mesh to avoid contact or inhibition of escape by one codend on the other.

Mesh openings in codends were measured prior to and after the experiment using an ICES OMEGA mesh gauge and associated protocols (Fonteyne, 2005). The number of meshes for each test codend was adjusted so that the same diameter and overall length were maintained for all codends. The non-selective control codend was constructed of double 4 mm diamond shaped twine with a nominal mesh size of 64 mm, 125 meshes long and 125.5 meshes around

Table 2
Catch weights (kg) by species and by mesh size (mm) where total catch exceeded 5 kg, sorted by total weight. Note that the 64 mm mesh catches are separate for each tested codend mesh size.

		Codend Mesh Size (mm)						
Species		64	114	64	140	64	165	Total (kg)
Redfish,Acadian	*Sebastes fasciatus*	13,974.4	10,829.4	9,469.5	824.6	6,976.0	710.7	42,784.6
Pollock	*Pollachius virens*	524.1	357.1	861.6	476.3	868.9	302.6	3,390.5
Cod, Atlantic	*Gadus morhua*	62.2	94.7	67.9	96.8	233.2	85.8	640.6
Monkfish (Goosefish)	*Lophius americanus*	11.7	32.0	4.3	10.2	86.0	81.0	225.2
Lobster, American	*Homarus americanus*	17.8	24.7	11.0	12.2	43.3	87.0	196.0
Dogfish, Spiny	*Squalus acanthias*	32.5	38.8	12.9	0.7	91.8		176.7
Haddock	*Melanogrammus aeglefinus*	9.1	15.0	22.9	22.2	34.7	9.5	113.4
Skate, Nk	Rajidae	21.4	13.6	18.2	21.5	17.3	18.1	110.0
Seal, Gray	*Halichoerus grypus*	100.0						100.0
Hake, Silver (Whiting)	*Merluccius bilinearis*	11.5	4.6	24.7	0.4	44.6	1.7	87.4
Hake, White	*Urophycis tenuis*	9.2	20.8	12.7	6.5	22.8	13.4	85.4
Hake, Red (Ling)	*Urophycis chuss*	13.1	8.8	40.8	0.5	13.8	1.0	77.9
Flounder, American Plaice	*Hippoglossoides platessoides*	15.0	11.8	7.6	7.0	14.2	9.1	64.6
Herring, Atlantic	*Clupea harengus*	8.5	0.3	4.1		44.5	0.3	57.7
Herring, River, Nk*	*Alosa*	9.6	0.8	12.7		33.6	0.7	57.4
Mackerel, Atlantic	*Scomber scombrus*	4.2		2.4	0.4	35.7	0.5	43.2
Flounder, Witch	*Glyptocephalus cynoglossus*	6.0	3.6	4.1	1.7	17.5	4.7	37.7
Cusk	*Brosme brosme*	11.3	13.7	5.9	4.3	2.4		37.6
Halibut, Atlantic	*Hippoglossus hippoglossus*	9.3	0.9	1.0	6.1		17.5	34.8
Squid, Atl Long-fin	*Doryteuthis pealeii*	7.5	4.0	3.2	0.6	8.9	1.1	25.3
Sea Raven	*Hemitripterus americanus*	4.3	1.9	2.5	3.9	2.9	4.6	20.1
Shad, American	*Alosa sapidissima*	1.5		0.3		9.4		11.2
Ocean Pout	*Macrozoarces americanus*	5.4	1.9	1.9		1.0		10.2

* Blueback or Alewife.

(Table 1). The test codends (114, 140, and 165 mm nominal) were all constructed of diamond double 5 mm, and were 70, 60, and 50 meshes long and 70.5, 60.5, and 50.5 meshes around, respectively. A test codend was attached to one leg of the trouser trawl and the control codend was attached to the other side. The side of the test and control codends were switched regularly to avoid possible side-based effects. The same test codend was used for approximately three days before switching to a new mesh size.

Tow locations were based on the captain's knowledge, echo sounder signals (including bottom topography), and a goal of a mix of redfish sizes. Tows were only made in daylight hours following the practice of the fishery. Tow durations varied based on the captain's assessment of the volume of fish in the net and fishing ground conditions, and were consistent with commercial practice. Duration decreased over time as the captain narrowed the search area and successfully found fish. Very large catches were avoided due to catch processing delays that might reduce the number of tows and affect quality of fish retained and survival of fish escaped.

The length of warp used was set by the captain based on the water depth and the bottom topography of the tow track. The range of tow speed was also within normal operational conditions for the species and was mainly influenced by tidal conditions, as was typical in commercial operations.

2.2. Gear monitoring

A GoPro Hero2 high-definition camera (San Mateo, CA) with a deepwater underwater housing and lights was mounted to view fish reaction in the mixing area during some tows. Net geometry was measured using a trawl monitoring system (Notus Electronics, St. John's, Newfoundland) with sensors on both doors, the trawl's wing ends, just behind the headrope, and on the 64-mm codend. The sensors were set to provide bottom temperature, door spread, door heel (angle of the door to the right or left of the direction of travel), wing spread and to indicate when the control codend was full. In addition, these sensors can provide distance from the sensor to the hydrophone. Bottom temperature was also recorded with previously calibrated TidBit temperature recorders (Onset Computers, Inc., Pocasset, Massachusetts).

2.3. Catch sampling

Codends were hauled on deck one at a time, with the codend attached to the shorter "leg" hauled and emptied first. Catches from the experimental and control codends were deposited in separate areas on deck, and processed separately.

The total catch of redfish per tow was determined to 0.1 kg with subsampling when there was a large amount of catch and, on some tows, legal and sublegal catch amounts were quantified. Lengths (measured as midline length, MLL) of a random subsample of more than 100 redfish (if possible) from each codend from each tow were measured to the nearest cm. For length-frequency (LF) analysis, counts at each length were multiplied by the subsample weight divided into the total weight.

Other organisms were also identified, and weighed to the nearest 0.1 kg. Weights were directly measured or quantitatively determined; for example, by basket counts.

2.4. 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, 2013). The methods implemented in SELNET comply with accepted recommendations for the analysis of size selectivity data (Fryer, 1991; Wileman et al., 1996).

To model the size selection first we used a logistic curve described by the parameters *L50* 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 nt_l for the count of fish at each length l, and in the control codend nc_l. The pro-

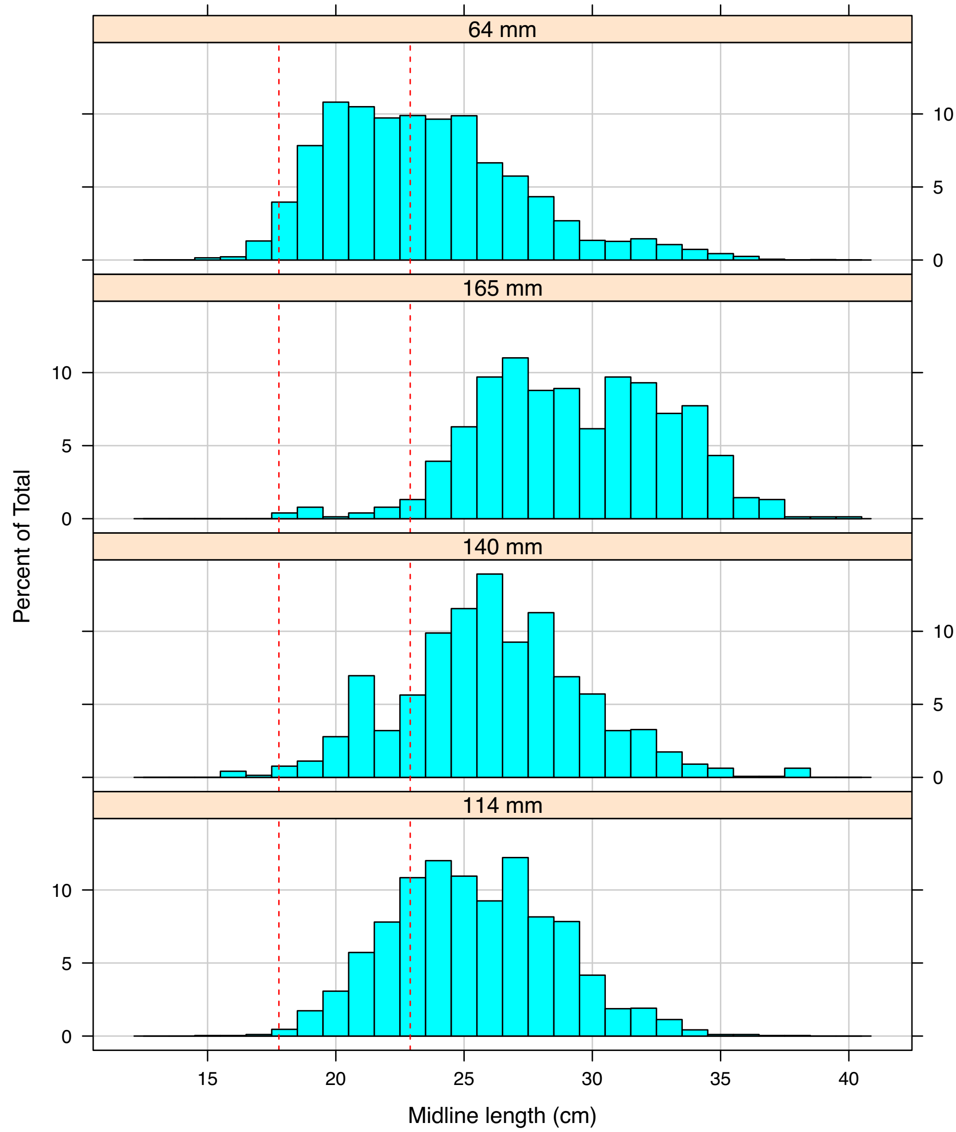

Fig. 3. Redfish length frequencies (cm) by mesh size (mm). Red dashed lines are the older (larger) and newer (smaller) minimum landing sizes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

portion of the total catch measured for lengths is described by the sampling rates *qt* (experimental) and *qc* (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:

$$-\sum_{l}\left\{\begin{array}{l} nt_l \times \ln\left(\dfrac{qt \times \varphi(l, L50, SR, SP)}{qt \times \varphi(l, L50, SR, SP) + qc \times (1 - \varphi(l, L50, SR, SP))}\right) + nc_l \\ \times \ln\left(\dfrac{qc \times (1 - \varphi(l, L50, SR, SP))}{qt \times \varphi(l, L50, SR, SP) + qc \times (1 - \varphi(l, L50, SR, SP))}\right) \end{array}\right\}$$

With:

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

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 *L*50 and SR.

Fit statistics (i.e., the *p*-value and model deviance versus 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.

The second step considered between-haul variation (Fryer 1991) using the results from all the individual hauls simultaneously for the *L*50, 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 (kg)) and *S2*, which side of the twin trawl the test codend was attached to. Since one codend necessarily stayed in the water longer during haulback, and could potentially lose more fish, it is prudent 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.

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

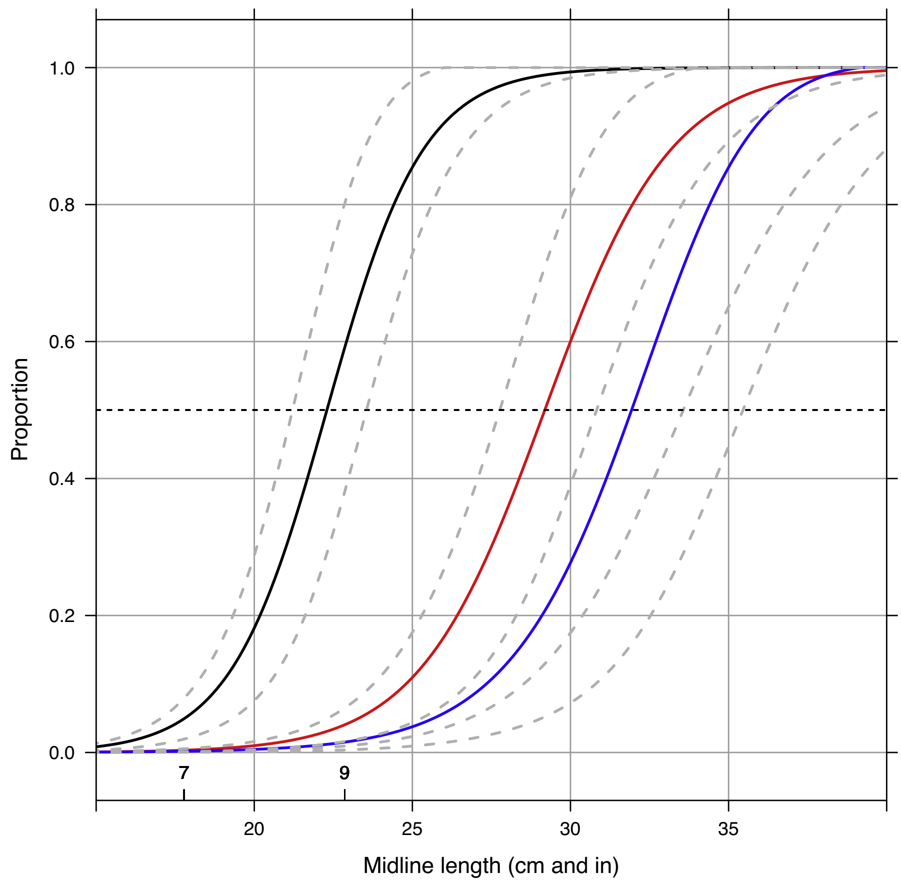

Fig. 4. Selection curves (solid lines) for 114 (black, left), 140 (red, center), and 165 (blue, right) mm codends, with 95% confidence bands in stippled lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The parameters $f_0 \ldots f_3$, $g_0 \ldots g_3$ and $h_0 \ldots h_3$ are estimated while fitting the model to the data with values for $L50$, SR and SP based on the selectivity results from the individual hauls. 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).

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:

$$\lim L50 = L50_{\text{mean}} \pm 1.96 \times \sqrt{(VarL50_{\text{mean}} + D_{11})}$$
$$\lim SR = SR_{\text{mean}} \pm 1.96 \times \sqrt{(VarSR_{\text{mean}} + D_{22})}$$
$$\lim SP = SP_{\text{mean}} \pm 1.96 \times \sqrt{(VarSP_{\text{mean}} + D_{33})}$$

where $L50_{mean}$, SR_{mean} and SP_{mean} are the predictions based on the selected submodel 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 and to inspect if the model was able to describe the results for the individual hauls, considering the estimated 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.

For further consideration of the impact of different choices of mesh sizes, we used the length distribution found in the 64 mm control codend as a representation of the overall population size structure available to trawl gear. 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 using codends ranging from 114 mm to 165 mm, in 12.7 mm steps.

3. Results

Tows were conducted generally east and northeast of Provincetown, Massachusetts, USA over an area of approximately 4700 nm^2 (Fig. 1). Fifty-six tows were completed in two trips carried out between 27 March and 1 April, and 3 April and 8 April 2013. Overall, 18 tows were completed pairing the 114 mm mesh, with 10 on the starboard side; 16 tows with the 140 mm with 9 on the starboard side; 22 tows with the 165 mm codend with 9 on the starboard side.

Tow duration ranged from 0.1 to 1.8 h with the median tow duration of 0.6 h (Fig. 2). Depth fished was 100 fm (median), and ranged from 50 to 131 fm; median towing speed was 3.0 knots (range: 2.6–3.3 knts); median warp length (wire out) was 225 fm (range: 200–275 fm). Median wave height experienced was 1.2 m with a maximum of 3 m (Fig. 2); these heights are unlikely to substantially affect net performance both based on the captain's decisions and as they are within typical commercial operational conditions.

Trawl monitoring sensor readings indicated a median headrope height of 4.6 m (Interquartile range (IQR): 3.8-9.0 m), a door spread of 80 m, and door heel medians of 6.2° (IQR:0.5–6.25°)

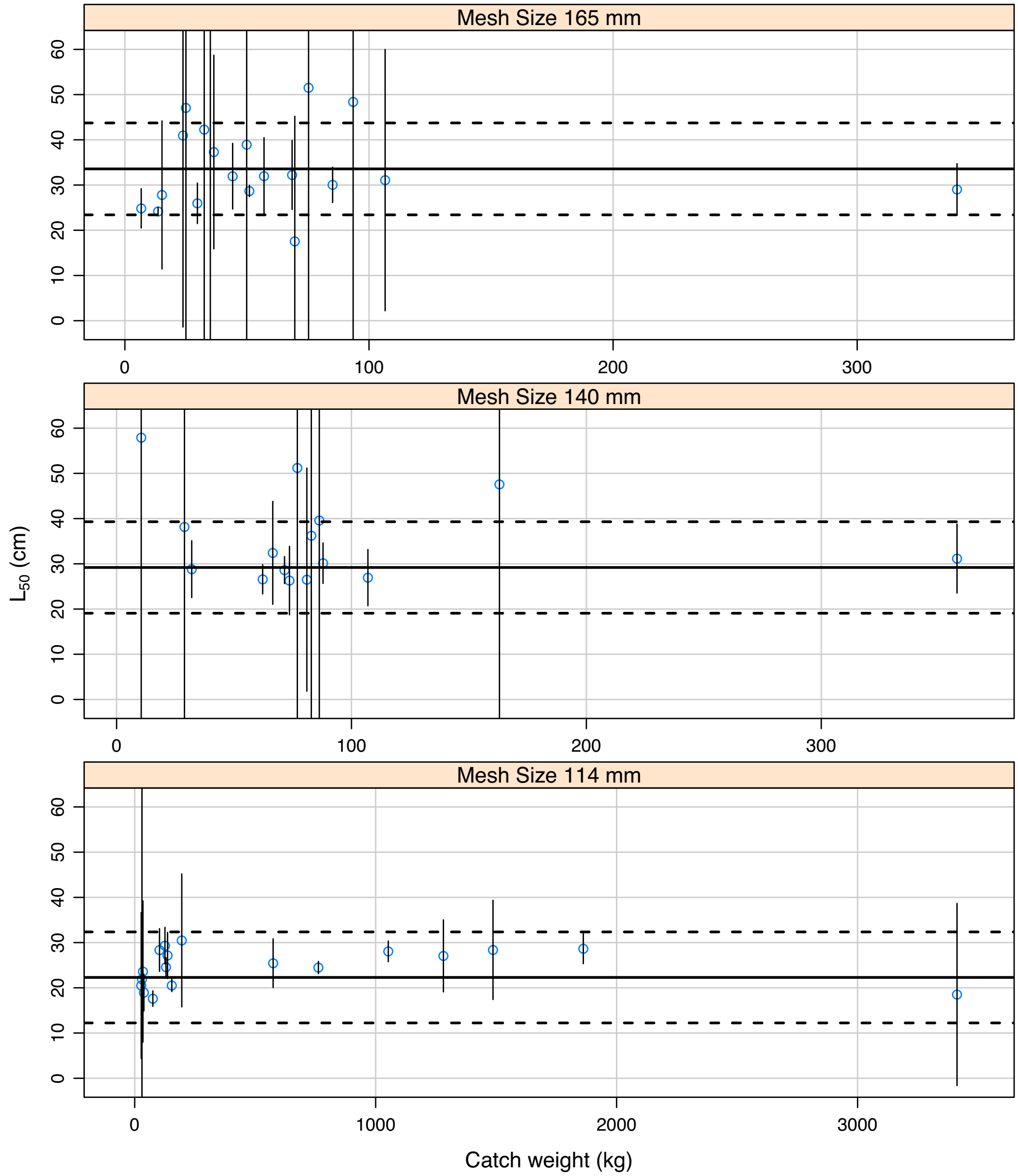

Fig. 5. *L*50 estimates by mesh size (mm) from individual hauls (blue circles) with 95% confidence intervals (error bars) compared to modeled mean *L*50 (solid horizontal line) and 95% confidence intervals (stippled lines), depicted by catch weight (kg). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(port) and 4.6° (IQR:1.5–7.25°) (starboard) inward. Median distance to doors was 423 m (IQR:420–468 m); to the headrope 555 m (IQR:553–561 m); to the codend 603 m (IQR:598–605 m) – these distances increased with depth and more wire out. Based on net geometry, no anomalous tows were identified. Median temperature was 6.7° (IQR: 6.5-7.1°) and did not differ between hauls with different codend mesh sizes.

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. Average catch per codend was 432.2 kg (range: 6.7–3412.7 kg). Pollock was the main bycatch species (3390.5 kg), with 21 other species with catches greater than 10 kg total (Table 2). Over 18,000 redfish were measured. Lengths ranged from 13 to 40 cm with distributions differing between codends (Fig. 3).

Fifty-three 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, and all simpler sub-models (4096 models in all), resulted in selection of a sub-model where the *L*50 and the SR depend only on mesh size:

$$L50 = 0.206 \times \textit{mesh size}\,(\mathrm{CI}: 0.194, 0.217)$$

$$\mathrm{SR} = 0.310 \times \textit{mesh size}\,(\mathrm{CI}: 0.027, 0.035)$$

$$\mathrm{SP} = 0.533\,(\mathrm{CI}: 0.458, 0.609)$$

The model estimated a split parameter near the ideal value of 0.5 with the 95% confidence interval (CI) overlapping 0.5, indicating that redfish were equally likely to enter either codend and that the trouser trawl was functioning properly. Video recordings collected from this area also seemed to indicate no unusual fish behavior. The effect of *w* (total control codend catch weight (kg)) and *S*2, which side of the twin trawl the test codend was attached to were not significant and were removed from the model.

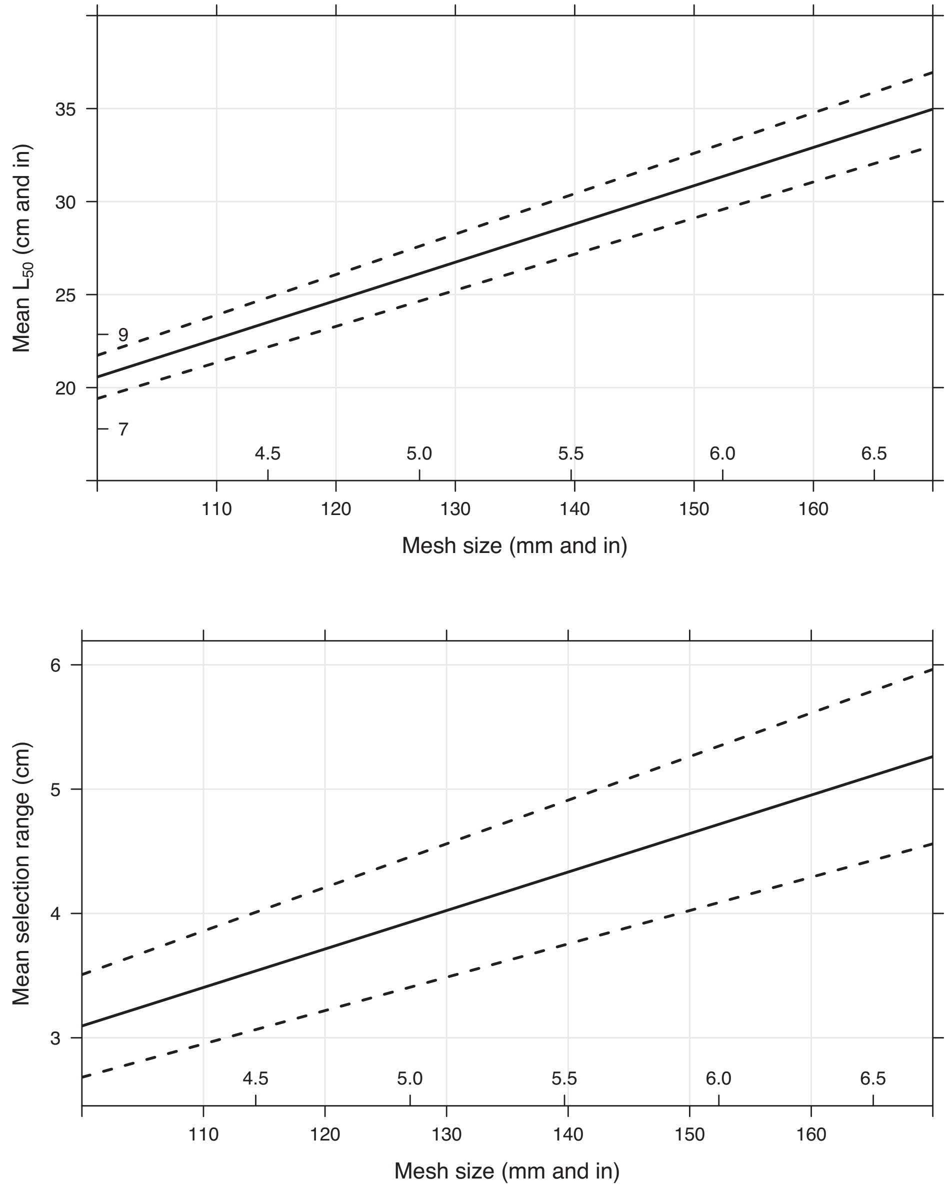

Fig. 6. Predicted mean *L*50 (top) and SR (bottom) v mesh size for redfish (solid line) with 95% confidence intervals (stippled lines).

Full logistic curves with 95% confidence intervals illustrating the catch curves for the codends as measured were constructed from model results (Fig. 4). *L*50 and selection ranges were determined for the nominal 114 mm (*L*50: 22.3 cm; SR: 3.3 cm), 139 mm (*L*50: 29.2 cm; SR: 4.4 cm), and 165 mm (*L*50: 33.6 cm; SR: 5.0 cm) codends. Further validation of the selectivity model was demonstrated by plotting *L*50 (Fig. 5) and SR values (not shown) for each individual haul, with 95% confidence intervals as error bars, along with overall mean values predicted by the final model, against the size of the codend catch (Fig. 5). 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. 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 was excellent.

Model results were used to produce estimates of mean *L*50 and SR (Fig. 6) 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.

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 (Fig. 7). It is predicted that only 3.6% (36/1000) of redfish in numbers would be retained by a 165 mm codend, 14.9% (149/1000) for a 140 mm codend, and 49.2% (492/1000) by a 114 mm codend.

4. Discussion

Testing and analysis of the selectivity of the codends provided results that by all and multiple measures are robust. These results support observations by industry members and others that the current mandatory minimum mesh size of 165 mm is a mismatch to the MLS. These results should be used to identify appropriate codend mesh sizes for sustainable harvesting of the species and for incorporating into stock assessment models.

Please cite this article in press as: Pol, M.V., et al., Impact of codend mesh sizes on selectivity and retention of Acadian redfish *Sebastes fasciatus* in the Gulf of Maine trawl fishery. Fish. Res. (2016), http://dx.doi.org/10.1016/j.fishres.2016.06.013

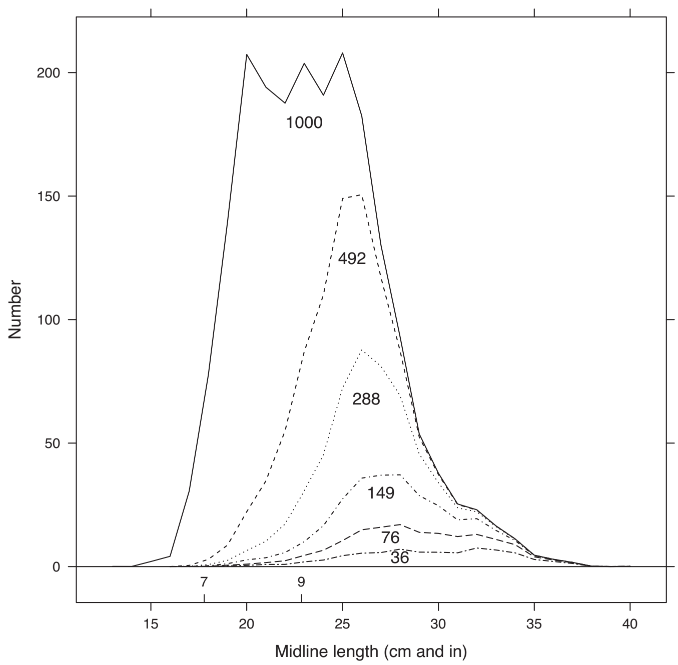

Fig. 7. Simulated catch distributions based on selectivity analysis using five different mesh sizes (from bottom: 114; 127; 140; 152; 165 mm) from the observed population distribution, scaled to 1000 fish. Numbers indicate the estimated number of fish retained by that codend mesh size.

Additionally, this study provides information on potential bycatch in smaller mesh fisheries. Despite the use of a non-selective codend much smaller than the mandatory minimum (64 mm), bycatch levels were very low. Since the gear used is substantially similar to groundfish trawls that target Atlantic cod, haddock, and pollock, our results illustrate the power of choosing appropriate time, depth, and areas to sustainably target redfish with minimal bycatch.

The lack of substantial variation in geometry, geographical area, weather conditions, depth, and temperature further suggests that uncontrollable sources of variability were limited during the testing, and that the comparability of the codends was high. Additionally, since each tow consisted of a selective and a non-selective codend, the results are consistent and accurate within each tow. The lack of significant impact of catch size or which side the codends were on also provided evidence for good functioning of the trouser trawl and randomization of the distribution of fish between the test and control codends. The absence of any intercepted 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. Wileman et al. (1996) recommend the use of a trouser trawl with a full vertical split, but our design avoids a vertical panel based on the gear designer's recommendation and our prior experience (He and Balzano 2011). Vertical panels are very difficult or impossible to rig without causing deformity or distracting motion in the net and panel.

Selectivity studies relate mesh opening to fish length, which serves as a proxy for fish girth, a more important morphological characteristic for determining codend escape. Fish girth can vary due to condition and breeding status, and thus the retention probabilities can vary over time (Wileman et al., 1996; Özbilgin et al., 2006). Additionally, twine type and thickness and other gear parameters may also influence retention probabilities (Wileman et al., 1996). Variation in selection between seasons, gears, weather and other factors is therefore expected (Pope et al., 1975; DeAlteris and Grogan 1997). While this potential for variability presents a challenge for selecting an appropriate mesh size for this fishery, Herrmann et al. (2012) identified two cross-sections of Sebastes encompassing the hard parts of the skull as important to codend selectivity; their work suggests that size selectivity of Sebastes species may be subject to less variation attributable to changes in girth. Nevertheless, consideration of possible variation in retention curves should be given.

We originally considered use of a covered codend method. In consultation with industry partners and others in the network, it was felt that a trouser trawl avoided some deck-handling problems associated with covers, reduced risk of masking of codend meshes, and risk of over-filling the cover, since we did not know what size catches might result from using a 64 mm mesh. Few difficulties were encountered using the trouser trawl, as the crew was adaptable to the hauling of two codends, and operationally it was not difficult to retrieve, and empty two codends in a controlled and safe manner.

The size distribution of redfish *S. fasciatus* available to the fishery, as determined by the catch in the 64 mm codend, is truncated compared to its near relatives *S. mentella* and *S. marinus* (Robins and Ray, 1986). This limitation may prevent exploitation of broader markets as the processing costs are higher and price lower for smaller fish. The relatively small size range of this species of redfish should be a consideration in determining sustainable strategies for harvesting and marketing redfish. Unlike species with a larger maximum size, implementation of larger mesh sizes will not yield substantially greater growth with age.

Also, the current minimum landing size of 7 in (18 cm) represents the tail of the available size distribution of redfish. Any mesh size larger than 64 mm will result in potentially large numbers of legal-sized fish passing through the codend meshes, and becoming subject to escape mortality. It is not currently known whether these fish would escape during fishing at the depth, during hauling in midwater, or at surface, although some escape was observed at surface during our fieldwork. Mortality rates of redfish 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). Redfish are notably more vulnerable than many other species to capture and escape (Benoît et al., 2013). Escape at the surface increases mortality due to predation by other fish and by seabirds and injury due to barotrauma and solar radiation (Grimaldo et al., 2009; Madsen et al., 2008). Exposure and associated risk are also elevated by the impacts of barotraumas; everted stomachs and inflated swim bladders result in an inability to control buoyancy and extend the period of time at the surface.

The small maximum size of the population also suggests that larger mesh sizes, while yielding larger sized fish, may result in catch rates too low to be commercially viable due to escape through the codend meshes. 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 L_{25}, *L*50, or other retention level. The results of this study are also useful to processors and marketers, in addition to the fishing fleet and managers, in terms of 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 while the net is still on the seabed, resulting in 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. Thanks are also go to Sally Sherman, Co-PI of the REDNET project, for her support and advice. We appreciate assistance from Division of Marine Fisheries staff biologists David Chosid for data collection and Mark Szymanski for contract and other support. We acknowledge and appreciate the extensive involvement of the REDNET network, which at present includes over 30 members. Funding was provided by the NOAA Fisheries Northeast Cooperative Research Partners Program and an NOAA Interstate Fisheries Management Support Grant. This is Massachusetts Division of Marine Fisheries Contribution No. 67.

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