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Bridges to best management: Effects of a voluntary bycatch avoidance program in a mid-water trawl fishery

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ABSTRACT

The catch of non-target species or discarding of target species (bycatch) in commercial fisheries can result in negative species level and ecosystem wide impacts as well as adverse social and economic effects. Bycatch has become one of the foremost, global issues of fishery managers and conservationists, especially when the non-target species is from a protected or threatened population. However, the impact and spatial distribution of bycatch is frequently unknown making it difficult to develop effective, justifiable mitigation regulations. This challenge is exemplified by the bycatch of river herring (alewife, *Alosa pseudoharengus*, and blueback herring, *A. aestivalis*) and American shad (*A. sapidissima*) in the northwest Atlantic mid-water trawl fishery targeting Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*). As an alternative to immediate management action, a voluntary bycatch avoidance program was established through an industry, state government, and university partnership. Here the program is described and its impact is evaluated by comparing fleet behavior and bycatch prior to and during the program. The combined results suggest that consistent communication, facilitated by the avoidance program, positively influenced fishing habits and played a role in the approximately 60% decrease in total bycatch and 20% decrease in the bycatch ratio observed during the program. However, the success of small scale move-along strategies to reduce bycatch ratios varied greatly in different areas of the fishery and years. This suggests the program is best viewed as an intermediate or complimentary solution. Overall, this project exemplifies of how collaborative programs can help alleviate difficult management scenarios.

1. Introduction

Reducing the catch of non-target species or discarding of target species (bycatch) in commercial fisheries has become one of the foremost, global issues facing fishermen, fishery managers and conservationists. These catches can result in substantial negative species level and ecosystem wide impacts and adverse social and economic effects. To reduce bycatch, managers often mandate gear modification, time/area closures, and bycatch quotas [2,15,16]. However, if such approaches are poorly designed, mitigation tactics can result in ineffective regulations that have unintended negative impacts on the target and non-target species, in addition to lost fishery revenue [10,14,23,34]. This situation frequently occurs when protected or threatened species are caught as bycatch. In these cases limited data often prevent a thorough understanding of the patterns and impact of bycatch, but management action is still often taken because any measurable reduction in mortality is perceived as a benefit to the impacted population (see [13,26]). In addition, managers must avoid implementing contradictory or inadequate management schemes that can cause stakeholder or public resentment such as approaches that prohibit directed fisheries of threatened species, but neglect to adequately address bycatch.

The bycatch of river herring (alewife, *Alosa pseudoharengus*, and blueback herring, *A. aestivalis*) and American shad (*A. sapidissima*) in the northwest Atlantic mid-water trawl fisheries for Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus)* (hereafter the mid-water trawl fishery) exemplifies the conundrum of limiting bycatch of threatened species in the face of a poor understanding of its impact [4,18]. River herring and shad are anadromous fishes that serve important ecological roles as prey species for a variety of riverine, estuarine, and oceanic fishes, birds and mammals [8,38] and as transporters of nutrients between their freshwater and marine habitats [24]. In addition, these fishes once supported productive fisheries resulting in their cultural significance along the U.S. and Canadian Atlantic coasts [9]. Currently, river herring and American shad populations along the U.S. Atlantic coast are considered depleted, with river herring

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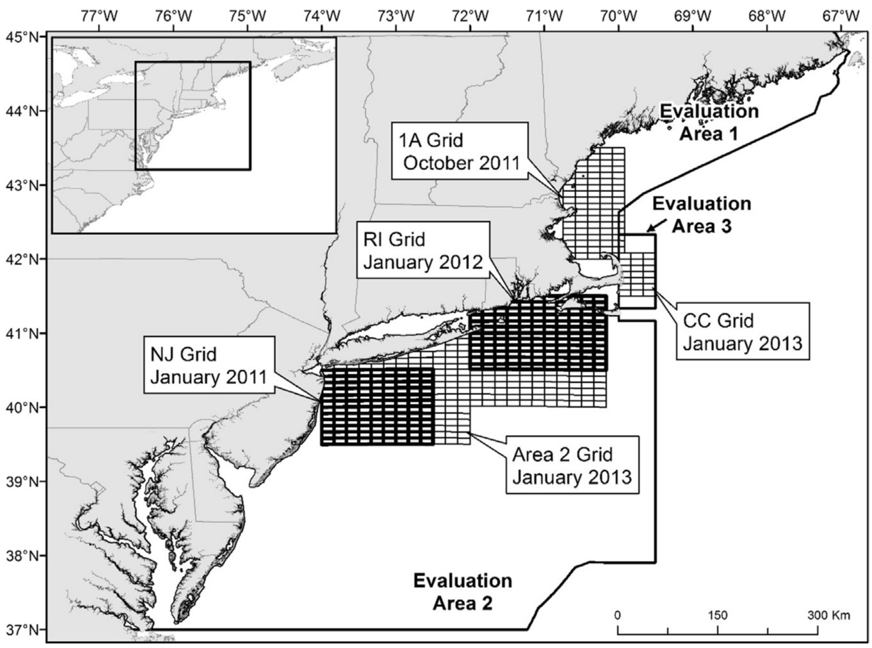

Fig. 1. River herring bycatch avoidance program grids and evaluation areas. The date of establishment is listed for each bycatch grid. The Area 2 grid includes the RI and NJ grids. Grid cells were 10' longitude by 5' latitude.

considered Species of Concern by the National Marine Fisheries Service (NMFS) [33]. Due to this status, many states have implemented moratoria on commercial and recreational harvest and marine fisheries for river herring and American shad are banned [3]. The coast-wide decline of these fishes was likely caused by a myriad of factors including overfishing, habitat loss, pollution, increases in predator populations, environmental factors, and at-sea bycatch [3,33]. Inconsistent signs of recovery despite significant freshwater-focused restoration have led to an increased focus on limiting bycatch by commercial fisheries in the northwest Atlantic.

Of the U.S. northwest Atlantic fisheries, the Atlantic herring and Atlantic mackerel fisheries have been identified as the most likely to have substantial river herring and shad bycatch [41]. Neither Atlantic herring nor Atlantic mackerel are considered overfished, and the two species have considerable economic importance, with annual landing values averaging about US$27 million and $2.6 million, respectively, from 2010 to 2014 [29]. Atlantic herring are also the primary bait species used in the lucrative U.S. fishery for American lobster (*Homarus americanus*) [28]. The dominant gear type of both fisheries is the mid-water trawl, which has accounted for over 70% of all landings over the past five years (NMFS vessel trip report data 2011–2015). While the overall bycatch ratio of the mid-water trawl fishery is less than 0.01 [43], hundreds of metric tons of fishes can be caught per trip, making the fishery the focus of management actions regarding the bycatch of river herring and American shad at sea [25,28].

Though the impact of river herring and American shad bycatch in the mid-water trawl fishery is still unknown, regulations have been created to limit this bycatch. In 2015, fleet wide bycatch limits in three areas of the Atlantic herring fishery were implemented based on past river herring and shad bycatch levels in each area [27]. Prior to this, with support from fishery managers, a voluntary bycatch avoidance program was established through an industry, state government, and university partnership [25,28]. The program aimed to intensively sample landings of mid-water trawl vessels and assist fishermen in identifying and avoiding areas with river herring and American shad bycatch [5].

Bycatch avoidance programs in the form of near-real time fleet communications have been implemented in a variety of fisheries with varying success and, in general, these programs have been most effective when coupled with existing or impending regulations [1,17,23,34]. Thus, voluntary programs could play an important role in limiting bycatch of threatened species, while economically and biologically appropriate bycatch mitigation regulations are developed [21]. However, positive impacts of a program must be shown to justify their use as a bridge solution. Though the bycatch avoidance program in the mid-water trawl fishery has been reviewed favorably in the past [21,23,34], this study represents an in-depth, program-specific evaluation of its impact on the mid-water trawl fleet. Here the impact of the program is evaluated by comparing fleet behavior, total bycatch and bycatch ratios prior to (2007–2010) and during the program (2011–2014), before the creation of bycatch limits. The results of these comparisons are then discussed to determine if they suggest the program influenced fishing behavior and if observed behavioral changes could explain variations in bycatch levels.

2. Methods

2.1. Program background

In October 2010, the Massachusetts Division of Marine Fisheries (MA DMF), the University of Massachusetts Dartmouth School for Marine Science and Technology (SMAST), and several members of the mid-water trawl fishery designed a program with the goal of reducing river herring and shad bycatch in the mid-water trawl fishery. A general overview of the program is provided in this manuscript, but details about the initial design and functionality of the program are described in [5].

Initially 9 mid-water trawl vessels were recruited, with 5 additional vessels joining the program by the end of 2012. Collectively, these 14 vessels accounted for over 95% of the total landings by mid-water trawl gear during the study period (2007–2014 NMFS vessel trip report data). Working collaboratively, the MA DMF, SMAST, mid-water trawl captains, crew members, and on-shore personnel designed and implemented coded grids that overlapped fishing areas with historical river herring interaction. These grids facilitated the communication of the location and timing of bycatch events (Fig. 1). An initial grid was introduced in January 2011 in a 60 × 70 nmi area off of New Jersey, within herring Atlantic herring Management Area 2 (NJ Grid). In October 2011, a second grid was established in a portion of Atlantic herring Management Area 1A (1A Grid). In 2012, an additional grid was added to herring Management Area 2 in the vicinity of Rhode Island Sound (RI Grid). In January 2013, the NJ and RI grids were merged into a single grid encompassing a broad region of herring Management Area 2 (Area 2 Grid). An additional bycatch grid was added to the eastern side of Cape Cod in January 2013 (CC grid). All cells within each grid were assigned an identification code and measured 10' longitude by 5' latitude [5].

Participating mid-water trawl vessel captains or crew provided the MA DMF and SMAST with trip and tow level locations, estimated target species catch, Northeast Fisheries Observer Program (NEFOP) bycatch data collected at-sea and access to all landings for sampling upon return to port. Portside sampling was conducted by the MA DMF portside sampling program. Both portside and NEFOP observer data were utilized to generate bycatch estimates for each sampled trip within 48 h of landing. Details about these two sampling methods and their application towards river herring bycatch estimates can be found in Bethoney et al. [4].

Trip level bycatch thresholds of “high” (river herring and American shad catch > 1.25% landings), “moderate” (0.2–1.25% landings), and “low” (< 0.20% landings) were created based on past patterns of river herring and American shad bycatch in the fishery and used to classify sampled catches within grid cells [5]. Bycatch advisories, based on aggregated data, containing cell classifications less than 7 days old, were communicated to participating vessels through onboard Boatracs® Vessel Monitoring Systems. When real-time observations of “high” bycatch were available, immediate bycatch alerts were sent based on single vessel data. Vessel names and catches remained confidential within the program, and observed areas containing zero bycatch were often withheld from fleet-wide distribution, acknowledging the competitive nature of the fishery. Discretion was used when determining urgency of communications; taking into consideration factors such as fleet spatial distribution, historical bycatch trends and weather events. During seasons of high activity, vessel-specific weekly sampling summaries were sent to vessel captains and managers, allowing for comparison to fleet-wide bycatch ratios. In addition to these communications, information indicating that river herring and American shad bycatch was unlikely to occur at depths greater than 73 m in the 1A grid was circulated prior to the start of the fishery in that area each year. Further, a shallow inshore area of the 1A Grid, known as Ipswich Bay, was highlighted as an area to avoid.

2.2. Program evaluation

The effects of the program on the fishery were evaluated by comparing fleet behavior and bycatch from the four years preceding the program (2007–2010) to the first four years of the program (2011–2014). After the first year of the program all active vessels in the mid-water trawl fishery participated, thus comparisons could not be made to a control group of non-participating vessels. Though the program is still active, data after 2014 were excluded due the implementation of river herring and shad catch limits in 2015, because these limits were much lower than estimated bycatch from 2007 to 2010 [27]. To quantify the effects of the program on fleet behavior, effort distribution during the two time periods was quantified and reentry into classified grid cells and bycatch-related communications were tracked. A 50% reduction in total bycatch from the years prior to the implementation of the program was the level set forth by the initial program funding source, The National Fish and Wildlife Foundation, to determine if the program had contributed towards river herring and American shad conservation. To supplement this metric and account for changes in effort, bycatch ratios during the two time periods were also compared.

All analyses were conducted in three evaluation areas that reflect the nature of the mid-water trawl fishery. The three evaluation areas were 1) Atlantic herring management area 1A, 2) Atlantic herring management area 2 south to 37°00’N and to the western half of National Oceanic and Atmospheric Administration (NOAA) statistical areas 526 and 541 from 70°00’ to 69°30’E, and 3) the western portion of NOAA statistical area 521 (south to 41°20’N) from 69°30’E to the western boundary (Fig. 1). Evaluation area 2 was extended into NOAA statistical areas 526 and 541 to allow for the inclusion of several fishing trips that occurred within this area throughout the study period. It was truncated at 37°00’N since all trips occurred north of this latitude during the study period. The boundary of evaluation area 3 was established around the inshore area off the eastern side of Cape Cod that encompassed Atlantic herring management Areas 1B and 3.

The evaluation areas reflected the seasonality of the mid-water trawl fishery due to target species movement and spatial regulations prior to the implementation of the avoidance program [4,27]. In the winter (December-April), effort was concentrated in Atlantic herring management area 2, but also occurred in the portion of Atlantic herring management area 3 within evaluation area 3. In May, as target species migrated into the Gulf of Maine or to Georges Bank for the summer, effort shifted from Atlantic herring management area 2 to evaluation area 3. In addition, during this time and until September the majority of the fishery occurred offshore in Atlantic herring management area 3 on Georges Bank. Offshore bycatch on Georges Bank was not analyzed because river herring and American shad bycatch within this region was rare and inconsequential in magnitude relative to bycatch within the evaluation areas [4,12,27]. In October, effort shifted to Atlantic herring management area 1A when seasonal mid-water trawl restrictions in the area ended. Although avoidance grids did not always encompass entire evaluation areas (Fig. 1), evaluating these entire areas allowed for a more holistic examination of the fishery and the comparison of bycatch levels and vessel behavior inside and outside the avoidance grid areas.

To quantify the extent to which fishing behavior of participating vessels was impacted by the program, the total number of direct responses to bycatch advisories that indicated active avoidance of high bycatch areas was tracked and the rate of vessel re-entry into low, moderate, and high bycatch cells was calculated. Using NEFOP at-sea observer data, all observed tows that were conducted within existing bycatch avoidance grid cells were assigned a bycatch level as defined in the program overview section. For the period prior to the implementation of the program (2007–2010), the full Area 2, CC, and 1A grids were used to establish a baseline level of re-entry trips at each bycatch level (Fig. 1). A re-entry trip was classified as any NEFOP observed trip during which at least one tow was conducted in a grid cell that had been fished within the previous 7 days. A 7-day window was chosen to match the extent of the program's bycatch advisories. The total number of re-entry trips was then tallied and a re-entry rate was calculated by dividing the total number of re-entry trips by the total number of observed trips during each period at each bycatch level.

To examine the distribution of fishing effort by participating vessels prior to and following the implementation of the program, trip locations were compiled from NMFS Vessel Trip Reports and subjected to a kernel density estimator. Vessel Trip Reports are federally required reports of catch and location for every trip and are used to track the catch of Atlantic herring and Atlantic mackerel. Core areas of fishing effort (50% kernel density estimator; the area with a 50% probability of containing a trip) were plotted for each period to examine spatial trends in fishing effort within each evaluation area and between time periods. All kernel density estimators were calculated using the same smoothing parameter (k = 100 m) with the ‘Kernel Density’ function in the Spatial Analyst tool in ArcGIS (version 10.2). The location of tows with ≥ 2000 kg of river herring and shad observed in each period were plotted along with each kernel density estimator to investigate the relationship between core fishing effort and observed high bycatch tows [5].

Total bycatch and bycatch ratios before and during the program for each evaluation area were generated using a ratio estimator [11]. Similar to Standardized Bycatch Reporting Methodology, alewife, blueback herring, American shad, and combined river herring and shad bycatch ratios (R_A)were calculated based on Wigley et al. (2007, 2009) following the equation:

Table 1
The rates of re-entry into grid cells classified as having low, moderate and high alewife, blueback herring and American shad in the period prior to (2007–2010) and during (2011–2014) the implementation of a river herring bycatch avoidance program in the northwest Atlantic mid-water trawl fishery.

	Bycatch Classification		
	Low	Moderate	High
Prior	26.5%	8.8%	6.6%
During	32.0%	7.2%	3.2%
Change	+21%	−19%	−52%

$$R_A = \frac{\sum_i r_{A,i}}{\sum_i T_{A,i}} \tag{1}$$

where $r_{A,i}$ was the observed species-specific or combined bycatch from trip *i* in evaluation area *A*, and $T_{A,i}$ was the total trip landings from trip *i* in evaluation area *A*. River herring and shad bycatch data and total landings from these trips were obtained from the MA DMF portside sampling program and the NEFOP for trips that occurred solely within the evaluation areas. Variance was estimated as:

$$var(R_A) = \frac{1}{n_A \bar{T}_A^2} * \left[\frac{(\sum_i r^2{}_{A,i}) + R_A^2(\sum T_{A,i}^2) - 2R_A(\sum_i r_{A,i} T_{A,i})^1}{n_A - 1} \right] * \left[\frac{N_A - n_A}{N_A} \right] \tag{2}$$

where n_A was the number of sampled trips in evaluation area *A*, and N_A was the total number of vessel trip reports from participating mid-water trawl vessels landing Atlantic herring or mackerel in evaluation area *A*.

Total bycatch for each evaluation area (B_A) was estimated by:

$$B_A = R_A * L_A \tag{3}$$

where L_A is the total landings from evaluation area *A* based on vessel trip reports.

The coefficient of variation (CV) for the bycatch ratios, which is the same as the CV for weight estimates in each area [42], was defined as:

$$CV(R_A) = \frac{\sqrt{var(R_A)}}{R_A} \tag{4}$$

The variance for the sum of bycatch in all areas was estimated following the Separate Ratio Method [42]:

$$var(\text{Sum}) = \sum_A L_A^2 * var(R_A) \tag{5}$$

The CV for the yearly sum was calculated by:

$$CV(\text{Sum}) = \frac{\sqrt{var(\text{Sum})}}{\sum_A \text{B}_A} \tag{6}$$

A Mann-Whitney-Wilcoxon (MWW) test was utilized to examine difference in bycatch ratios between the evaluation periods (2007–2010 and 2011–2014). Statistical significance was accepted at $p < 0.05$. In addition, the overall percent change in species-specific and total bycatch ratios between the two periods was calculated. All analyses were conducted in R [37], ArcGIS (version 10.2) or Microsoft Excel.

Unlike the target species, information about the abundance and distribution of river herring and American shad at-sea during the evaluation time period was not available in published literature. While some in-river counts of river herring and American shad populations exist, a measure of river herring and American shad biomass trends at-sea provides better context for evaluating the results of the program in terms of river herring and shad abundance and availability. Thus, alewife, blueback herring, and American shad biomass indices from the Northeast Fisheries Science Center spring trawl surveys prior to and following the implementation of the program were created and compared (see [36] for a complete description of the survey gear, deign, and protocols).

3. Results

All mid-water trawl vessels that were recruited for the program remained participants during their time as active vessels in the mid-water trawl fishery. Over the course of the project period, 803 emails and 564 trip logs, which detailed trip and tow level location and estimated target species catch, were received from captains. A total of 18 advisories containing high bycatch information were sent to participating vessels and twelve direct correspondences were received from vessel captains explicitly stating that they would be avoiding high bycatch cells during upcoming or ongoing trips. In addition, bycatch sampling and avoidance program results, as well as program improvements and upcoming management measures, were discussed during seven formal captain's meetings and numerous dockside conversations. Comparison of re-entry rates before and during the program indicated a 21% increase in the rate of re-entry into cells classified as low bycatch areas and a 19% decrease in the rate of re-entry into moderate cells (Table 1). The rate of re-entry into high bycatch cells was about 50% less during the avoidance program, only occurring during a total of 4 trips in evaluation area 2; two in 2011 and two in 2012.

The kernel density estimator analysis indicated that the spatial extent of core fishing effort areas varied between the two periods in evaluation areas 1 and 2 (Fig. 2), but was similar in evaluation area 3. Within evaluation area 1, core fishing effort shifted to the north and south after the implementation of the program, away from where almost all (78%) high bycatch tows had previously occurred (Ipswich Bay, Fig. 2). In evaluation area 2, prior to the program core fishing effort was focused off the coasts of Rhode Island and New Jersey, with 60% of high bycatch tows occurring off the coast of New Jersey. In contrast, during the program core fishing effort was focused in a relatively small area near coastal Rhode Island with the majority (80%) of high bycatch tows occurring outside of this core area (Fig. 2). There was an overall increase in the utilization of offshore areas and evaluation area 3 during the traditional timing of the fishery that occurs in evaluation area 2 (Table 2). Core areas of fishing effort and the location of high bycatch tows overlapped considerably within evaluation area 3 prior to and during the avoidance program (Fig. 2).

A comparison of fishing effort, sampling effort, river herring and shad bycatch weight and ratios is presented in Table 3. During the avoidance program, effort in evaluation areas 1 and 2 decreased by about 50%, while effort in evaluation area 3 increased by 20%. Overall, the number of trips within the evaluation areas declined during the avoidance program years, while the number of sampled trips increased by about 30%. Bycatch ratios during the avoidance program were significantly lower in evaluation area 1 (MWW: $W = 5932$, $p < 0.05$), significantly higher in evaluation area 2 (MWW: $W = 4611$, $p < 0.05$), and not statistically different in evaluation area 3 (MWW: $W = 2137$, $p = 0.30$). The overall bycatch ratio was not statistically different between the two periods (MWW: $W = 38460$, $p = 0.22$), but total bycatch was lower during the avoidance program.

Biomass indices from the Northeast Fisheries Science Center spring trawl survey indicate a potentially higher at-sea biomass of alewife following the implementation of the program and no change in the biomass of blueback herring or American shad (Fig. 3).

4. Discussion

The combined results of this review suggest that the avoidance program influenced fishing behavior in a manner that contributed to decreased river herring and American shad bycatch. The overall project goal of a 50% reduction in total bycatch was met during a time where indices of river herring and American shad abundance at-sea suggest increased or stable abundance (Fig. 3). Though the indices are independent of mid-water trawl effort distribution, they are the best

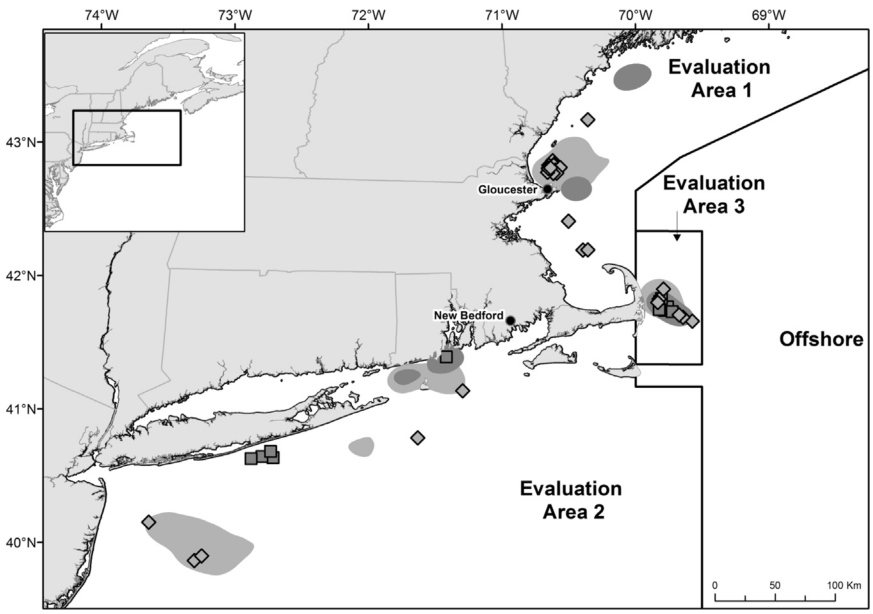

Fig. 2. The location of core fishing effort by mid-water trawl vessels participating in a river herring bycatch avoidance program prior to (2007–2010, light areas) and during (2011–2014, dark areas) the program. Core fishing effort was calculated using vessel trip reports and therefore included data from all trips conducted from 2007 to 2014. Tows with ≥ 2000 kg of alewife, blueback herring and American shad prior to (light diamonds) and during (dark squares) the program are also displayed. Tow-level location and landings data were obtained from the federal Northeast Fisheries Observer Program and are a representative subset of all tows of this nature.

Table 2
The percent of total trips conducted by participating vessels during the months of most alewife, blueback herring and American shad bycatch (December – March) in evaluation areas 2 and 3 and in offshore waters on Georges Bank in the period preceding (2007–2010) and during (2011–2014) the implementation of a river herring bycatch avoidance program in the northwest Atlantic mid-water trawl fishery.

Year	Area 2	Area 3	Offshore
2007	65%	29%	6%
2008	92%	7%	1%
2009	95%	1%	5%
2010	90%	6%	4%
2007–2010	85%	11%	4%
2011	96%	4%	0%
2012	78%	18%	4%
2013	64%	24%	12%
2014	41%	35%	24%
2011–2014	65%	23%	12%

available data to indicate river herring and American shad abundance at-sea over time [22,40]. Additionally, during the program, abundance based Atlantic herring and Atlantic mackerel quotas available to mid-water trawlers decreased by 24% and 63%, respectively and effort in the evaluation areas declined by half [31,32]. This context suggests that the decrease in total bycatch is not simply explained by decreases in

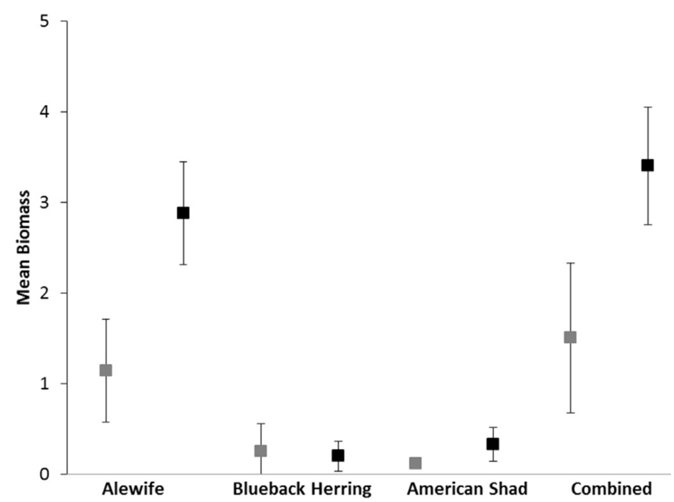

Fig. 3. Alewife, blueback herring, American shad and combined mean biomass per tow (+/− 1 SD) prior to (2007–2010, grey) and during (2011–2014, black) a river herring bycatch avoidance program based on the NOAA Northeast Fisheries Science Center spring trawl survey catch.

Table 3
Number of total fishing trips, the percent sampled by fisheries-independent observers, total catch, and total bycatch landings and ratios of alewife, blueback herring, and American shad for each evaluation area in period prior to (2007–2010) and during (2011–2014) the implementation of a river herring bycatch avoidance program in the northwest Atlantic mid-water trawl fishery. Coefficients of variation are presented in parentheses and are the same for catch and ratios in the same strata. All landings are in metric tons.

	Area 1		Area 2		Area 3		Combined	
	Prior	During	Prior	During	Prior	During	Prior	During
Trips	341	156	605	278	129	153	1075	587
Sampled	29%	56%	15%	48%	34%	58%	22%	53%
Total Catch	67,480	29,770	118,970	48,750	19,110	27,780	205,560	108,300
Total Bycatch	481 (0.18)	24 (0.17)	466 (0.29)	389 (0.16)	203 (0.51)	137 (0.23)	1266 (0.18)	524 (0.13)
Alewife	225 (0.24)	6 (0.21)	154 (0.31)	240 (0.23)	128 (0.47)	72 (0.26)	589 (0.21)	300 (0.18)
Blueback Herring	207 (0.18)	13 (0.16)	285 (0.41)	142 (0.21)	72 (0.62)	63 (0.23)	587 (0.21)	211 (0.14)
American Shad	50 (0.26)	5 (0.38)	27 (0.34)	6 (0.29)	3 (0.42)	2 (0.26)	89 (0.21)	13 (0.21)
Bycatch Ratio	0.71%	0.08%	0.39%	0.80%	1.06%	0.49%	0.62%	0.49%
Alewife	0.33%	0.02%	0.13%	0.49%	0.67%	0.26%	0.29%	0.28%
Blueback Herring	0.31%	0.04%	0.24%	0.29%	0.38%	0.23%	0.29%	0.20%
American Shad	0.07%	0.02%	0.02%	0.01%	0.02%	< 0.01%	0.04%	0.01%

bycatch species availability or increases in target species abundance, but may be due to overall effort. However, fishing behavior or bycatch ratio results from each evaluation area show that the avoidance program contributed to bycatch reduction.

In evaluation area 1, communication with vessel captains resulted in a shift of fishing effort away from the inshore area where the majority of high bycatch events occurred prior to the implementation of the avoidance program (Ipswich Bay, north of Gloucester, MA in Fig. 2). While this spatial shift was small in scale (10's of nmi) and there is a partial overlap between the core fishing effort areas before and during the program, core fishing effort during the program did not occur in Ipswich Bay, which was repeatedly highlighted by the avoidance program as an area to avoid due to historically high bycatch. Based on personal communications with captains and the observation of overall effort in evaluation area 1, this area was not avoided due to a lack of target species. For example, in 2011 tows were made in this inshore area by vessels leaving from Gloucester, MA in response to the impending area closure due to Atlantic herring catch limits being reached. Prior to the closure notice the fleet had fished in a less bycatch-prone area approximately 10 nmi away for approximately two weeks [6,7,39]. Assuming a large scale shift in the biomass of target species did not occur over this time period, this suggests that vessels actively passed over fishable densities of target species in a bycatch prone area, and fished in part of the avoidance grid where bycatch ratios were low. Additionally, the decline in total bycatch or the bycatch ratio are not explained by changes in total target species catch (Table 1). Thus, the avoidance program is the best explanation for the shift in effort and subsequent reduction in the bycatch ratio observed in evaluation area 1.

In evaluation area 2, the reallocation of effort to offshore areas and evaluation area 3 during the winter fishing season resulted in similar total bycatch weight before and during the avoidance program despite a significant increase in the bycatch ratio. Though target species quota in evaluation area 2 was decreased during the program period, movement of effort offshore was not driven by quota restrictions as the Atlantic herring quota was fully harvested only in 2012 [30]. However, there is evidence that the avoidance program influenced this spatial shift in effort. For example, in 2012 effort after a high bycatch advisory shifted out of the RI grid towards the NJ grid, where only low bycatch was observed [6]. Further, with knowledge of high bycatch occurring in evaluation area 2 and target species availability in evaluation area 3 and offshore, several captains communicated their intent to avoid fishing in evaluation area 2 (personal comm. Mid-water trawl captains). This is supported by an increase in the utilization of evaluation area 3 and offshore areas during the avoidance program period (Table 1), particularly since New Bedford, MA, the primary landing port during the winter fishery, has similar proximity to traditional fishing grounds in evaluation area 2 and 3 (Fig. 2). Given the higher overall bycatch ratio within evaluation area 2 during the avoidance program, if a similar percentage of effort was allocated to the area as was prior to the program total bycatch would have likely increased.

In evaluation area 3, increased effort in the same core fishing area utilized prior to the avoidance program led to no significant change in the total bycatch or bycatch ratios. However, the bycatch ratio during the avoidance program was less than half of its pre-program value. This lack of statistically significant difference between bycatch ratios from the two time periods is likely attributable to the lower sampling levels, and subsequently higher error estimates, that were evident in the pre-program period (Table 3). Once the CC avoidance grid was established in 2013, rather than moving to adjacent cells in reaction to high bycatch advisories, vessels typically avoided the CC area all together and returned to the formerly high cells after one week with little subsequent bycatch [39]. This behavior could be attributed to the concentration of target species into a few cells within the area. This explains why total bycatch remained similar despite increased effort and no re-entries into high bycatch cells were observed. At worst, stable bycatch levels in evaluation area 3 despite increased effort can be explained by exploitation of temporal bycatch patterns. In addition, the lower bycatch ratio in evaluation area 3 compared to evaluation area 2 supports the notion that effort displaced from evaluation area 2 into evaluation area 3 decreased overall bycatch in the mid-water trawl fishery.

The assertions made regarding the influence of the program on fishing patterns in each area are supported by consistent industry participation and the results of the re-entry analysis. Since the second year of the program all active vessels participated, which evolved into the signing of a responsible fishing agreement committing vessels to reporting and avoidance standards that qualify them for additional research set-aside Atlantic herring quota [39]. Though the overall number of trips that returned to the spatial extent of a grid cell was low prior to the avoidance period, a substantial drop in the rate of re-entry into high bycatch cells (−52%) was still observed during the avoidance program period, and no such re-entries occurred after 2012. The program was framed as an opportunity for participants to demonstrate to fishery managers that an agreed upon response to high bycatch areas was a viable alternative to impending bycatch regulations, which included broad seasonal closed areas [25,28]. Further, industry input was a valued component of the program design, helping to foster end-user ownership. The small size of the fleet also aided in this mentality by limiting the dispersion of benefits [1,35]. Overall, the rationale for fleet utilization of avoidance program information can be found in the core components of collective action [35].

While the avoidance program did not significantly reduce bycatch ratios in all areas, it is clear the approach yielded positive results that can be improved upon to make the program more effective. The expansion of the spatial coverage of the program beginning in 2013, the implementation of real-time reporting at-sea by all vessels in 2014, and the establishment of management area-specific river herring and shad catch limits should enhance the overall effectiveness of the program. Further, research into river herring habitat forecasts [40] could facilitate a more proactive approach towards bycatch avoidance, as seen in other pelagic fisheries [19,20], or help refine the spatial scale of mitigation tactics. In a larger context, the success of this program serves as an example of how collaborative programs can help alleviate difficult management scenarios and serve as a viable alternative to highly restrictive policies (e.g., area closures) that will negatively impact a fishing industry without clear conservation benefits.

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