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ARTICLE

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Abstract
In the U.S. northwest Atlantic, the incidental catch of river herring (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) by midwater trawl vessels targeting Atlantic Herring *Clupea harengus* and Atlantic Mackerel *Scomber scombrus* has become a concern for river herring conservation. Reduction of this incidental catch is a focus of fisheries managers, but information about river herring bycatch is limited. To improve the information available to fishery managers, we combined portside and at-sea observations to examine (1) the size of river herring, (2) the concentration of river herring with respect to the target species, and (3) the yearly contribution of different fishery areas to the total catch of river herring. We divided the fishery's spatial range into four nearshore areas and tested two null hypotheses: (1) length frequency distributions of river herring are similar between areas and between species and (2) bycatch ratios are similar among areas. We also used length frequency distributions and river herring size at maturity to infer and compare maturity status. Results showed interannual, interspecies, and intraspecies differences in bycatch among and within the four nearshore areas. Bycatch in the northern areas was mainly migratory mature or near-mature river herring from mixed origins, whereas bycatch in the southern areas was a mix of juveniles, prespawning adults from nearby areas, and migratory adults. At the levels seen in 2011 and 2012, bycatch in the midwater trawl fishery could not account for the overall decline in river herring. However, a large proportion of river herring caught in the southern areas of the fishery may be juveniles originating from New Jersey to southern New England. To better understand this impact, continued monitoring and studies examining the at-sea population dynamics of river herring are needed.

The incidental catch of river herring (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) at sea has become a concern for their conservation (ASMFC 2012). River herring are consumed by a variety of riverine, estuarine, and oceanic fishes, birds, and mammals, and they once supported productive fisheries along the U.S. Atlantic coast (Bigelow and Schroeder 2002). River herring populations are currently considered to be depleted, and river herring were recently evaluated for listing under the Endangered Species Act (ASMFC 2012; NOAA 2013a). The coastwide decline of river herring was likely caused by a combination of past overfishing, spawning habitat loss, pollution, increases in predator populations, environmental factors, and bycatch (Rulifson 1994; ASMFC 2012).

In the U.S. northwest Atlantic Ocean, river herring are incidentally caught in fisheries that target Atlantic Herring *Clupea harengus* and Atlantic Mackerel *Scomber scombrus*. Neither Atlantic Herring nor Atlantic Mackerel are considered overfished, and the two species have considerable economic importance, with landings value averaging about US$23 million and $5 million, respectively, in 2008–2011 (NOAA 2012). Atlantic Herring are also the primary bait species used in the U.S. fishery for American lobster *Homarus americanus* (NEFMC 2013a). The

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increase in landings of Atlantic Herring and Atlantic Mackerel in the 1990s coincided with a shift in gear from purse seines and weirs to midwater trawls, which now account for the majority of landings (MAFMC 2013; NEFMC 2013a). The high-volume nature of both fisheries can result in significant amounts of bycatch that are hard to quantify and classify. This uncertainty has led to concerns about the potential of the Atlantic Herring and Atlantic Mackerel fleet to capture large amounts of river herring at sea (ASMFC 2012; MAFMC 2013; NEFMC 2013a).

Managers have added regulations to address river herring bycatch in the Atlantic Herring and Atlantic Mackerel fisheries; the regulations include closing large areas of the Atlantic Herring fishery or the entire Atlantic Mackerel fishery if river herring catch limits are reached (MAFMC 2013; NEFMC 2013b). These catch limits are based upon past catch of river herring and assume that the biological characteristics and impact of bycatch are the same throughout the entire range of the fishery. However, the habits of river herring at sea suggest that this assumption is false.

Knowledge of the biological characteristics of river herring caught as bycatch is important for efficient and effective management because of the mixing of river herring life stages and populations at sea. Juvenile river herring migrate out of rivers by the late fall or winter of their first year and may spend 2 years in nearshore waters (Fay et al. 1983; Klauda et al. 1991; Limburg 1998). These nearshore areas are also utilized by adult river herring and by the midwater trawl fishery (Neves 1981; Bethoney et al. 2013a). Once the juvenile river herring become migratory, they join the adults in extensive north–south migrations along the eastern coast of North America and the continental shelf. During their ocean migrations, river herring of different natal origins share common migratory routes and feeding grounds (Neves 1981; Rulifson 1984; Rulifson et al. 1987; Stone and Jessop 1992). River herring show a high degree of spawning site fidelity, returning to the same regions (or even the same rivers) to spawn every year (Messieh 1977; Jessop 1994; Palkovacs et al. 2014). Due to these dynamics, the location of river herring bycatch may not be indicative of maturity status or origin.

The size and origin of river herring caught as bycatch from specific areas at sea have been difficult to determine due to the low frequency of large river herring catch events and the low monitoring levels during the times when river herring are encountered (Bethoney et al. 2013b; NEFMC 2013a). Length frequency combined with weight information is available only over broad regions (ASMFC 2012; MAFMC 2013; NEFMC 2013b). Our objective in the present study was to provide fishery managers with more detailed information on the characteristics (species, sizes, maturity, and origin) of river herring in various regions of the fishery and to discuss the implications that differing characteristics may have for bycatch mitigation strategies. To achieve this objective, we divided the spatial range of the fishery into four nearshore areas and Georges Bank (Figure 1). We then tested two null hypotheses: (1) length frequency distributions of river herring are similar between areas and between species; and (2) bycatch ratios are similar among areas. We also used length frequency distributions and information on river herring size at maturity to infer and compare maturity status. Testing the two null hypotheses provided a general characterization of the similarities and differences in river herring bycatch occurring within these areas and helped to clarify the potential impact of bycatch. In a broader context, we provide an example of the complexities that arise—and potential starting points to address these complexities—when trying to develop bycatch mitigation strategies for highly migratory, data-poor species. The present results also improve the general understanding of how river herring congregate at sea.

METHODS

River herring bycatch information was obtained from the Massachusetts Division of Marine Fisheries (MA-DMF) portside sampling program and from the Northeast Fisheries Observer Program (NEFOP). The MA-DMF portside program samples approximately 50% of the midwater trawl landings that occur in Massachusetts waters; 60–85% of all midwater trawl landings of Atlantic Herring occur in Massachusetts (vessel trip reports for 2008–2012; National Marine Fisheries Service, unpublished data). Samplers take systematic subsamples of whole boat offloads as fish are pumped across dewatering boxes into vats or trucks. The proportion of total weight contributed by each species from all subsamples is extrapolated to the weight of the entire trip. Portside samplers collect a representative sample of river herring during offloads and record the FLs (nearest cm) for fish of each species.

The NEFOP samples about 40% of all midwater trawl trips, with about 15% of trips monitored from January to March, when most of the river herring bycatch occurs (NEFMC 2013a). At-sea NEFOP samplers gather information by taking subsamples of each tow. Samplers target a total of 10 subsample baskets of unsorted fishes taken in equal intervals from the catch as it is pumped from the net to the hold. The weight of each species within each subsample is recorded, and the species proportions are extrapolated to the weight of the entire tow. The FLs of each species in basket subsamples are recorded to the nearest centimeter (see NEFSC 2010 for further details on NEFOP midwater trawl sampling protocols).

We analyzed data on Alewife and Blueback Herring bycatch in four nearshore areas, along Georges Bank (GB; National Oceanic and Atmospheric Administration [NOAA] statistical areas 522, 525, 561, and 562), and for the overall fishery (Figure 1). The four nearshore areas were (1) waters off northeast New Jersey and Long Island (NJLI; NOAA statistical areas 612, 613, and 615); (2) southern New England (SNE; NOAA statistical areas 537, 539, and 611); (3) east of Cape Cod (CC; NOAA statistical area 521); and (4) the western Gulf of Maine (GoM; NOAA statistical areas 513 and 514). For each area except GB, results were reported for the months that accounted for greater

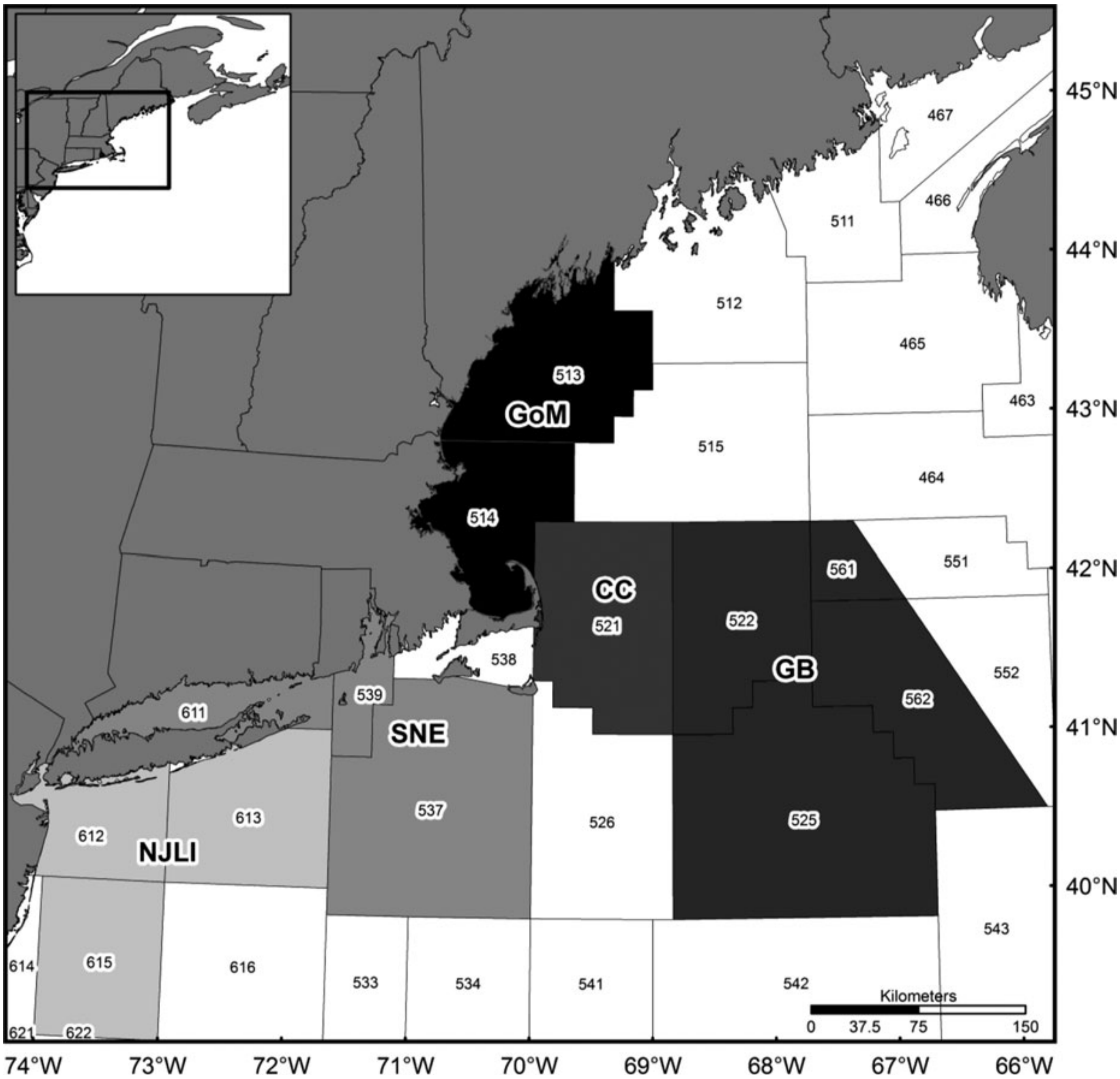

FIGURE 1. Areas for which length frequencies, weights, and numbers of river herring taken as bycatch in the Atlantic Herring and Atlantic Mackerel midwater trawl fisheries were generated (GoM = western Gulf of Maine; CC = east of Cape Cod; SNE = southern New England; NJLI = New Jersey and Long Island; GB = Georges Bank). Numbered areas are National Oceanic and Atmospheric Administration statistical areas.

than 80% of the observed river herring bycatch from 2000 to 2012 (Table 1). These areas and times reflect the known overall spatial and temporal patterns of river herring bycatch in the midwater trawl fishery and allow for inferences to be made based upon the seasonal distributions of river herring (Cieri et al. 2008; Cournane et al. 2013). Portside and at-sea data were pooled for all analyses. For trips that were sampled by both MA-DMF and NEFOP, portside data were used. Previous analyses found no significant difference between co-sampled portside MA-DMF and at-sea NEFOP estimates of river herring bycatch (Cieri et al. 2008; NEFMC 2013c). Other tests confirming the consistency in length frequencies and data quality between MA-DMF

TABLE 1. Percentage of total river herring (Alewife and Blueback Herring) bycatch by weight in the Atlantic Herring and Atlantic Mackerel midwater trawl fishery within the four nearshore areas (NJLI = New Jersey and Long Island; SNE = southern New England; CC = east of Cape Cod; GoM = western Gulf of Maine), as documented by the Northeast Fisheries Observer Program during 2000–2012.

Area	Period	Percentage of bycatch
NJLI	Jan–Mar	99
SNE	Jan–Mar	81
CC	Dec–Mar	95
GoM	Oct–Nov	99

sampling and NEFOP sampling have also been conducted (Bethoney 2013).

The length frequency distribution within each sampling area was determined by

$$X_{A,s,i} = \frac{W_{A,s,i}}{w_{A,s,i}},$$

where $X_{A,s,i}$ is an expansion factor used to relate the total number of fish measured to the total number of fish caught during trip i in area A; $W_{A,s}$, is the total weight of species s caught during trip i in area A; and $w_{A,s,i}$ is the weight of individuals of species s caught during trip i in area A that were measured and weighed (Roman et al. 2011).

The proportion of species s in area A and length-class l ($P_{A,s,l}$) was determined as

$$P_{A,s,l} = \frac{\sum_i X_{A,s,i} \times n_{A,s,l,i}}{\sum_i X_{A,s,i} \times n_{A,s,i}},$$

where $n_{A,s,l,i}$ is the number of measured individuals of species s in length-class l on trip i in area A; and $n_{A,s,i}$ is the number of sampled fish of species s on trip i in area A. Sampled trips from 2008 to 2012 were summed, excluding trips in which only a single length-class was observed. If the weights of measured fish were not available, then the number of Alewives or Blueback Herring measured at each length was multiplied by an estimated weight at length by using an Alewife or Blueback Herring weight-at-length table (MA-DMF, unpublished data). Intraspecies length frequency distributions between areas and interspecies distributions within areas were compared using Kolmogorov–Smirnov tests with α adjusted based on the number of independent samples (trips) taken for each comparison (Siegel and Castellan 1988).

The number of river herring taken as bycatch from each area during 2011 and 2012 was estimated by

$$\frac{\sum_i X_{A,s,i} \times n_{A,s,l,i}}{\left[\frac{N_A - n_A}{N_A}\right]},$$

where n_A is the number of sampled trips and N_A is the total number of vessel trip reports (reports of catch required by the federal government for every fishing trip) from midwater trawl vessels targeting Atlantic Herring or Atlantic Mackerel in area A.

River herring bycatch estimates for 2011 and 2012 were generated using a ratio estimator (Cochran 1977). Estimates were generated for each sampling area and for all other areas (including the four nearshore areas during the months not listed in Table 1). Grouping catch on GB with the rest of the fishery creates results that are less representative of overall bycatch. On GB, the midwater trawl vessels capture a large portion of their yearly Atlantic Herring quota but almost no river herring (Cieri et al. 2008; Cournane et al. 2013). Therefore, the sum of estimates from all of these areas was used to estimate total bycatch for the fishery. Similar to the standardized bycatch reporting methodology (Wigley et al. 2007, 2009), an Alewife and Blueback Herring bycatch ratio for each area (R_A) was calculated by

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

where $r_{A,i}$ represents the observed river herring landings (Alewife or Blueback Herring) from trip i in area A; and $T_{A,i}$ represents the observed target species landings (Atlantic Herring and Atlantic Mackerel) from trip i in area A. Variance was estimated as

$$var(R_A) = \left(\frac{1}{n_A \bar{T}_A{}^2}\right) \times \left[\frac{\left(\sum_i r_{A,i}^2\right) + R_A^2\left(\sum_{A,i}^{T^2}\right) - 2R_A\left(\sum_i r_{A,i} T_{A,i}\right)}{n_A - 1}\right] \times \left(\frac{N_A - n_A}{N_A}\right).$$

Total river herring bycatch for each area (B_A) was calculated as

$$B_A = R_A \times L_A,$$

where L_A is the total target species landings from area A based on vessel trip report data. The coefficient of variation (CV) for the ratios, which is the same as the CV for the area, was defined as

$$\mathrm{CV}(R_A) = \frac{\sqrt{var(R_A)}}{R_A}.$$

The variance for the sum of bycatch in all areas (Sum) was estimated by following the separate ratio method (Wigley et al. 2007):

$$var(\mathrm{Sum}) = \sum_A L_A^2 \times var(R_A).$$

The CV for the yearly sum was calculated as

$$\mathrm{CV}(\mathrm{Sum}) = \frac{\sqrt{var(\mathrm{Sum})}}{\sum_A B_A}.$$

Confidence intervals around ratio estimates were compared between areas, between years, and between species by graphing mean estimates with their associated 95% confidence intervals. Although overlapping confidence intervals do not necessarily indicate nonsignificant results, only means with nonoverlapping confidence intervals were considered to be significantly different (Sokal and Rohlf 2012).

Maturity of river herring was inferred from length. River herring size at maturity increases with spawning latitude (Bigelow and Schroeder 2002). The smallest spawning Blueback Herring observed in the St. Johns River, Florida (the southern extent of the species' range), was approximately 17 cm FL (McBride et al. 2010). Although a relatively small number of fish were measured in these runs (<250 fish), examination of length data from river herring spawning runs in Rhode Island, Massachusetts, New Hampshire, and Maine for 2008–2012 also revealed a minimum size of 17 cm FL, with the vast majority of fish exceeding 20 cm FL (Rhode Island Department of Environmental Management, MA-DMF, New Hampshire Fish and Game Department, and Maine Department of Marine Resources, unpublished data). In the lower St. John River, New Brunswick, spawning female Blueback Herring are seldom less than 21 cm FL (Jessop 2001). In the Gaspereau River system, Nova Scotia, spawning female Alewives are rarely less than 24 cm FL (McIntyre et al. 2007). For this study, river herring smaller than 17 cm FL were categorized as "most likely immature." Alewives larger than 22 cm FL and Blueback Herring larger than 20 cm FL were categorized as "most likely mature." The maturity of river herring between these lengths was classified as "unknown." The addition of the "unknown" category makes this approach more conservative than the approach of Stone and Jessop (1992), who used a cutoff of 19 cm FL to distinguish between mature and immature river herring caught at sea.

RESULTS

Significant differences in Alewife length frequency distributions were found between the GoM and SNE (Kolmogorov–Smirnov test: $D_{16,33} = 0.41$, $P < 0.05$), the GoM and NJLI ($D_{16,20} = 0.63$, $P < 0.01$), and the CC and NJLI ($D_{10,20} = 0.67$, $P < 0.01$). Alewives were generally larger in the GoM than in the other nearshore areas, and the highest percentage of Alewives that were most likely mature (just over 35%) was caught in this area (Figure 2; Table 2). The CC area exhibited the smallest Alewife length range of any area, and about 90% of Alewives were within the size range of unknown maturity (Figure 2; Table 2). The CC area also contained the lowest percentage (about 1%) of Alewives that were most likely immature (Table 2). About 30% of Alewives caught in SNE were most likely immature, while 9% were most likely mature. Close to 60% of Alewives caught in NJLI were smaller than 17 cm FL and most likely immature (Figure 2; Table 2); this represented the highest percentage of juvenile Alewives present in any area.

The Alewife bycatch rate significantly differed between areas and between years (Figure 3). Compared with the other areas, bycatch of Alewives in the GoM was minimal during 2011 and 2012 despite about three times as much fishing effort in the GoM during 2011 relative to 2012 (Tables 3, 4). The bycatch rate, weight, and number of Alewives removed from the CC area could only be estimated for 2012 (Tables 3, 4). From 2011 to 2012, the Alewife bycatch rate increased in SNE and decreased in NJLI (Figure 3).

TABLE 2. Percentage of river herring (Alewife and Blueback Herring) caught as bycatch at specific times and areas (NJLI = New Jersey and Long Island; SNE = southern New England; CC = east of Cape Cod; GoM = western Gulf of Maine) that were estimated to be mature, immature, or of uncertain/unknown maturity based on FLs measured from 2008 to 2012.

Maturity status	NJLI (Jan–Mar)	SNE (Jan–Mar)	CC (Dec–Mar)	GoM (Oct–Nov)
		Alewife		
Immature	59	31	1	4
Uncertain	30	60	93	60
Mature	11	9	6	36
		Blueback Herring		
Immature	20	9	1	3
Uncertain	40	64	76	39
Mature	40	27	23	58

For Blueback Herring, significant differences in the length frequency distributions were only found between the GoM and SNE ($D_{24,27} = 0.39$, $P < 0.05$). Blueback Herring caught in the GoM area were generally larger than those caught in SNE (Figure 4). The GoM area also contained the highest percentage (about 60%) of Blueback Herring that were most likely mature (Table 2). As was observed for Alewives, the length range of Blueback Herring in the bycatch was smaller in the CC area than in any other area, and over 75% of Blueback Herring in the CC area were classified as being of unknown maturity (Figure 4; Table 2). About 65% of Blueback Herring caught in SNE were of unknown maturity, but the percentage of Blueback Herring that were most likely mature (27%) was higher than the percentage that were most likely immature (9%; Figure 4; Table 2). In NJLI, most of the Blueback Herring caught were larger than 17 cm FL, but this area contained the highest percentage of immature individuals (Table 2).

The bycatch rate of Blueback Herring significantly differed between areas and between years (Figure 3). Blueback Herring bycatch in the GoM decreased from 2011 to 2012, whereas the bycatch rate did not (Tables 3, 4). In contrast to the results for Alewives, the Blueback Herring bycatch rate significantly increased in both SNE and NJLI from 2011 to 2012.

Overall, fishery effort and river herring bycatch increased from 2011 to 2012 (Tables 3, 4). Approximately 30% of all trips and target species catch came from the four nearshore areas in 2011, and almost 40% of all trips and target species catch came from these areas in 2012 (Tables 3, 4). Within the areas, river herring constituted 0.18% of the catch by weight in 2011 and 0.71% of the catch by weight in 2012. Bycatch rates of Alewives and Blueback Herring were much more variable in 2012 than in 2011 (Figure 3). Compared with the other three nearshore areas, the GoM had significantly lower river herring

TABLE 3. Catch and effort information for midwater trawl vessels targeting Atlantic Herring and Atlantic Mackerel at specific times and areas during 2011 (NJLI = New Jersey and Long Island; SNE = southern New England; CC = east of Cape Cod; GoM = western Gulf of Maine; GB = Georges Bank). The “Other” column includes trips that occurred in the sampling areas during the months not shown in parentheses. Catch weight is presented with the coefficient of variation (CV; %) in parentheses. Asterisks denote numbers of fish that were not within 1 CV of catch estimates when a weight was extrapolated from length frequencies. Blueback Herring numbers with asterisks are probably overestimates, whereas Alewife numbers with asterisks are probably underestimates.

Variable	NJLI (Jan–Mar)	SNE (Jan–Mar)	CC (Dec–Mar)	GoM (Oct–Nov)	GB (all months)	Other (see caption)	All areas (all months)
Target catch	5,047	1,776	327	10,130	32,017	9,871	59,168
Trips	29	16	2	49	194	66	356
Sampled trips	21	8	0	21	97	18	165
Alewife catch weight (metric tons)	14.0 (15)	1.3 (26)	NA	0.9 (26)	0.8 (35)	6.4 (53)	23.4 (17)
Alewife number	273,257	40,607	NA	2,200*	NA	200,431	516,495
Blueback Herring catch weight (metric tons)	8.6 (20)	0.1 (57)	NA	5.4 (30)	0	4.8 (52)	19.0 (18)
Blueback Herring number	359,005*	NA	NA	37,568	0	141,574	538,147

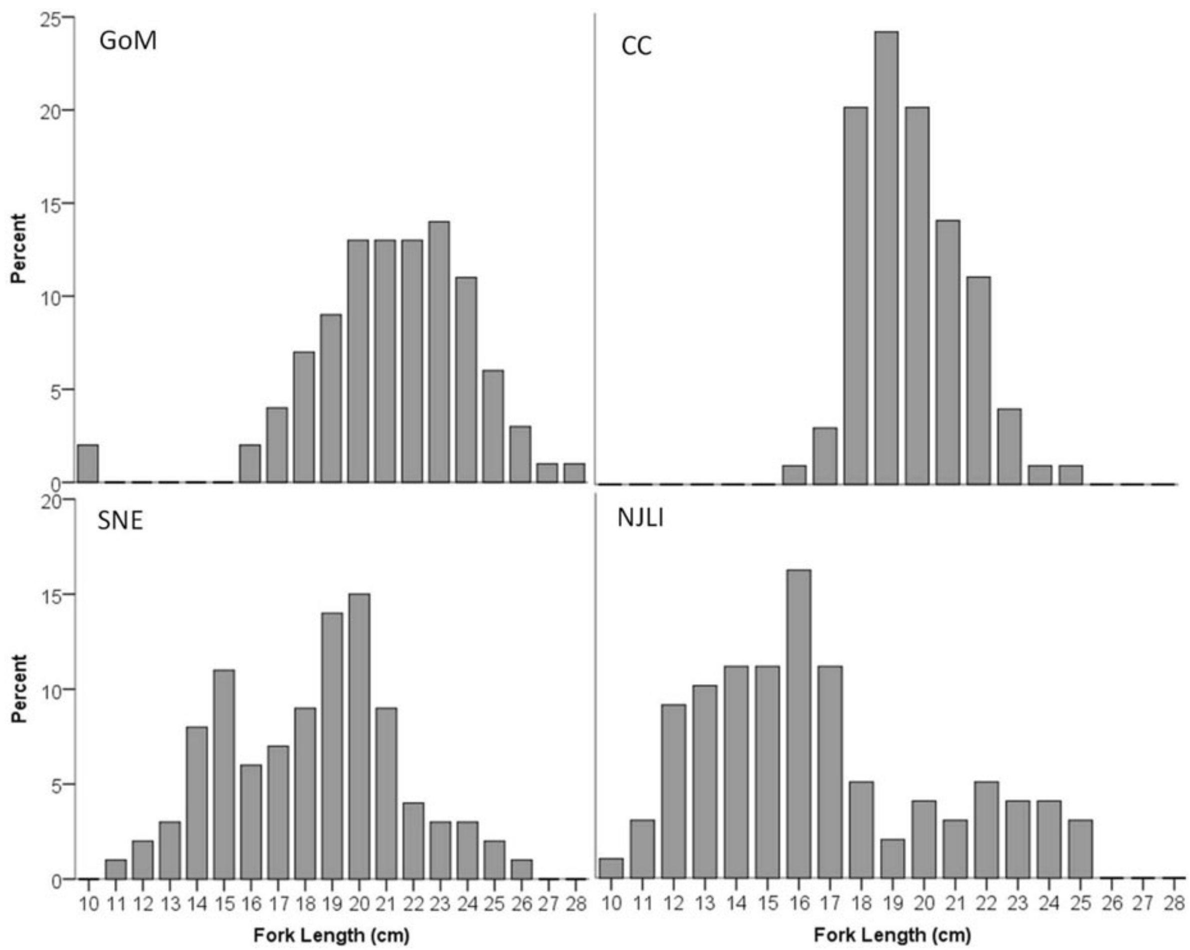

FIGURE 2. Length frequencies of Alewives caught by midwater trawl vessels in the four nearshore areas (GoM = western Gulf of Maine; CC = east of Cape Cod; SNE = southern New England; NJLI = New Jersey and Long Island) from 2008 to 2012.

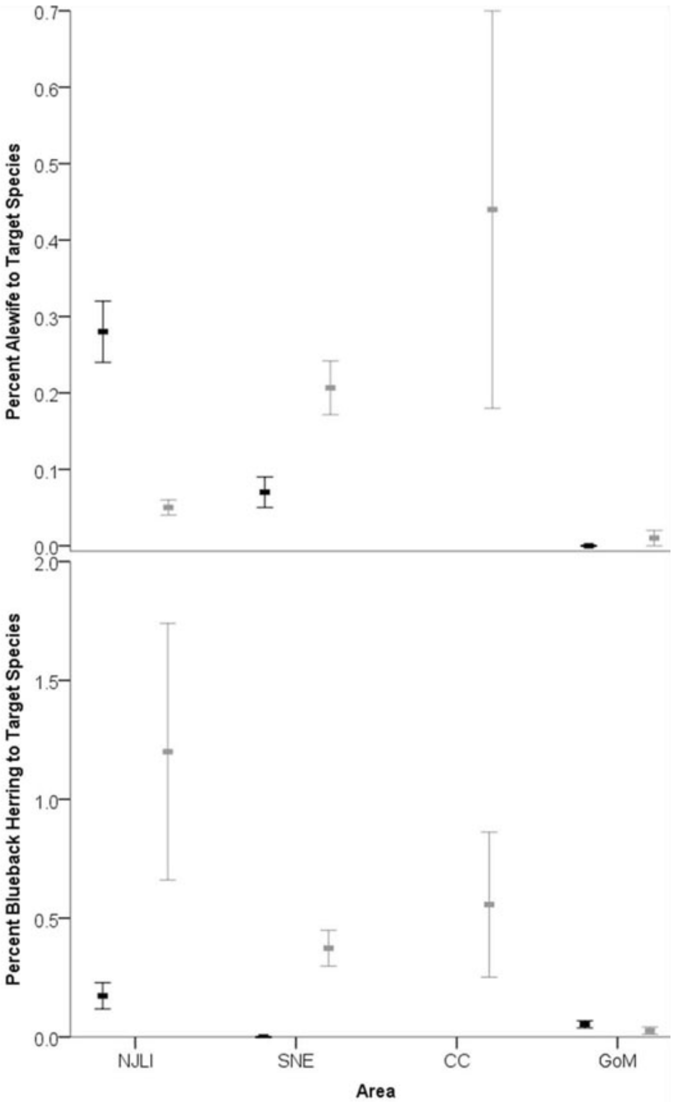

FIGURE 3. Mean bycatch rates (±95% confidence interval) for Alewives (upper graph) and Blueback Herring (lower graph) in the four nearshore areas (NJLI = New Jersey and Long Island; SNE = southern New England; CC = east of Cape Cod; GoM = western Gulf of Maine) during 2011 (black symbols) and 2012 (gray symbols). Mean bycatch rates for Alewives in the GoM and for Blueback Herring in SNE were less than 0.01% in 2011. Due to small sample size, no ratio was calculated for the CC area in 2011.

bycatch rates during both study years. In 2011, 70% of Alewife bycatch and 75% of Blueback Herring bycatch came from the nearshore areas; in 2012, the four nearshore areas contained nearly 100% of river herring bycatch. Despite the increase in weight of Alewife bycatch from 2011 to 2012, the number of Alewives caught was similar between the 2 years (Tables 3, 4). The number of Blueback Herring caught increased between years, but the increase was not proportional to the increase in bycatch weight (Tables 3, 4). The NJLI area was the only area for which the length frequency distributions of Alewives and Blueback Herring were significantly different ($D_{20,\,19} = 0.47$, $P < 0.05$).

DISCUSSION

Bycatch Description

River herring that were caught in the GoM appeared to be larger and more mature than river herring that were caught in the other nearshore areas. The length frequencies of river herring bycatch in this area are consistent with those of spawning runs throughout the U.S. range of river herring (McBride et al. 2010; ASMFC 2012), and they lack the presence of the larger mature fish that are more commonly found in the Canadian portion of the species' range (Jessop 2001; McIntyre et al. 2007). However, based on river herring life history, the Alewives and Blueback Herring observed in this area most likely consist of mature fish from mixed U.S. stocks that are migrating south to wintering grounds rather than juveniles from northern stocks. In the late summer or early fall, river herring begin to leave their summer feeding grounds in the Bay of Fundy and migrate to wintering areas in SNE and the mid-Atlantic (Neves 1981; Rulifson 1984; Rulifson et al. 1987; Stone and Jessop 1992). This timing would result in river herring passage through the GoM at the same time that midwater trawl vessels are active in the area.

The results from the CC area are unclear, but based on migratory and life history patterns the river herring caught in the CC area may also be mostly migratory. Although length samples in the CC area were from trips taken throughout the time range examined, the Alewife length frequency was derived from 10 trips and the Blueback Herring length frequency was derived from six trips; in all other areas, at least 19 trips were used to create length frequencies. The smaller sample sizes for the CC area may explain (1) the truncated range of length frequencies and (2) the statistical similarity in length frequency distributions between the CC area and most other areas despite this truncated range. However, there may be a biological explanation for this distribution. The fishery within the CC area is concentrated at depths between 50 and 100 m, which exceed the depths at which small, nonmigratory, age-2 or younger river herring are expected to be found, thereby explaining their absence from length frequencies (Bigelow and Schroeder 2002). At some point prior to their first spawning event, immature river herring join the older fish as they undergo north–south migrations. Forage fishes such as river herring school with fish of similar size (Fréon and Misund 1999; Krause et al. 2000), and large-scale migrations may be a learned behavior (McKeown 1984). Thus, it is plausible that when migrating for the first time, juveniles school with the smaller migrating fish. Like the closely related American Shad *Alosa sapidissima*, the movement of river herring from summer feeding grounds to wintering sites may be triggered by environmental cues (Leggett and Whitney 1972; Dadswell et al. 1987; Stone and Jessop 1992). If all size-classes of river herring begin their migrations based on the same cues, then schools of

TABLE 4. Catch and effort information for midwater trawl vessels targeting Atlantic Herring and Atlantic Mackerel at specific times and areas during 2012 (see Table 3 for definition of area codes). The "Other" column includes trips that occurred in the sampling areas during the months not shown in parentheses. Catch weight is presented with the coefficient of variation (CV; %) in parentheses. Asterisks denote numbers of fish that were not within 1 CV of catch estimates when a weight was extrapolated from length frequencies. Blueback Herring numbers with asterisks are probably overestimates, whereas Alewife numbers with asterisks are probably underestimates.

Variable	NJLI (Jan–Mar)	SNE (Jan–Mar)	CC (Dec–Mar)	GoM (Oct–Nov)	GB (all months)	Other (see caption)	All areas (all months)
Target catch	4,856	11,662	4,027	3,157	29,538	9,314	62,554
Trips	30	65	19	16	179	51	360
Sampled trips	13	28	10	7	134	34	226
Alewife catch (metric tons)	2.4 (29)	24.6 (17)	17.6 (59)	0.4 (57)	0.2 (20)	0	45.3 (25)
Alewife number	12,162	304,800	184,707	NA	393*	0	502,062
Blueback Herring catch (metric tons)	56.0 (45)	43.6 (21)	22.4 (55)	0.8 (59)	0	0	122.8 (27)
Blueback Herring number	613,009	792,130*	150,204	11,087	0	0	1,556,430

larger fish would reach the wintering grounds first (Weihs 1987; Jobling 1995a). Larger river herring may pass through the CC area prior to December, resulting in the fishery catch of only the smaller, mixed-maturity schools.

The intraspecies size distributions in SNE and NJLI were similar, suggesting that these areas contain a complex mix of juveniles, prespawning adults from nearby rivers, and migratory adults. In both areas, fishing effort was concentrated at depths

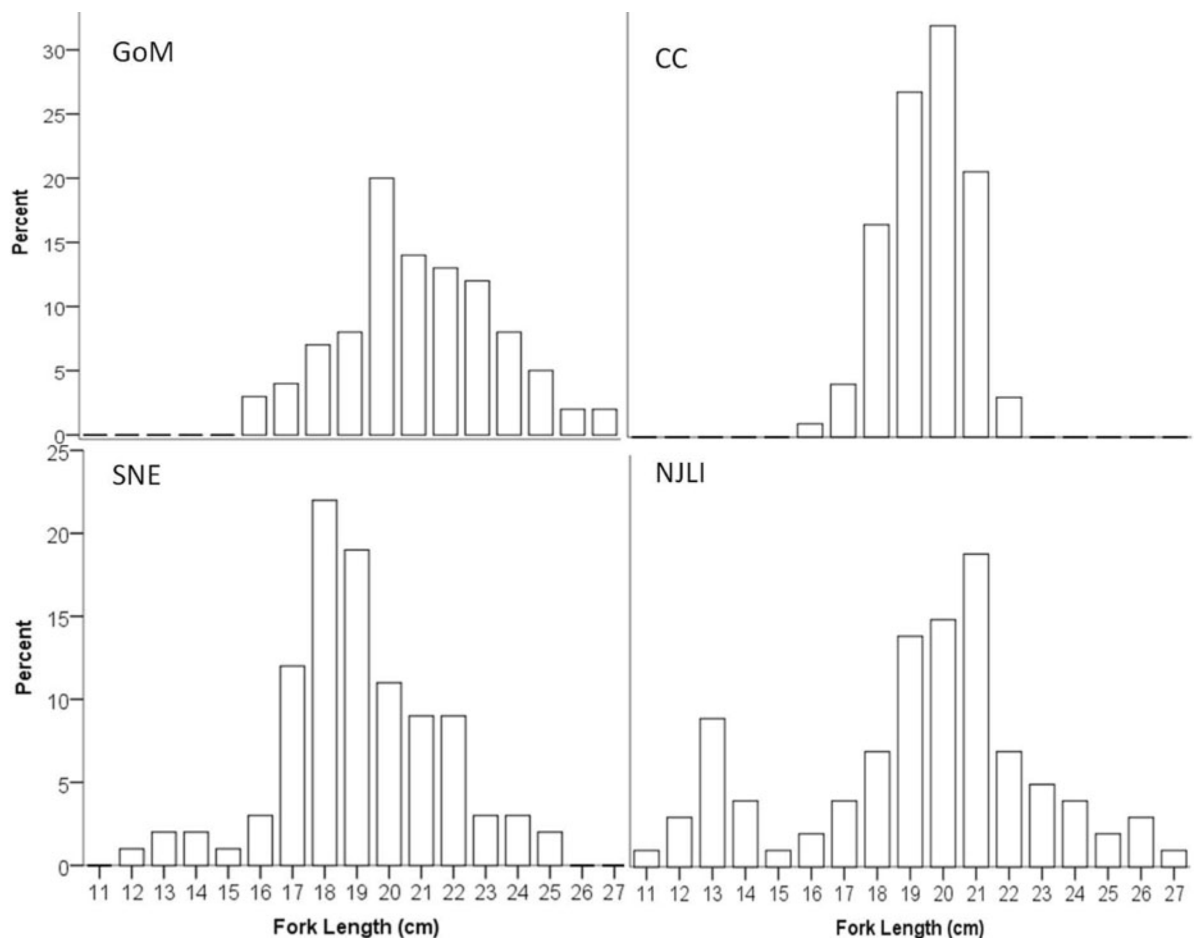

FIGURE 4. Length frequencies of Blueback Herring caught by midwater trawl vessels in the four nearshore areas (GoM = western Gulf of Maine; CC = east of Cape Cod; SNE = southern New England; NJLI = New Jersey and Long Island) from 2008 to 2012.

less than 50 m, leading to overlap with immature and adult river herring (Neves 1981; Fay et al. 1983; Bethoney et al. 2013a). The presence of mature river herring, especially during March, could indicate the capture of prespawning fish of local origin or river herring moving along the coast toward northern spawning areas. Recent spawning runs of Blueback Herring in Rhode Island and Connecticut have been extremely small in comparison with Alewife run sizes (ASMFC 2012); this difference suggests that Blueback Herring caught in SNE are more likely to be migratory than Alewives.

The NJLI area was the only area in which the size distributions of Alewives and Blueback Herring were significantly different. The difference may be due to interannual shifts in the location of fishing effort within NJLI and river herring wintering sites. During the winter, adult Alewives are located in deeper waters than adult Blueback Herring (Neves 1981; Bethoney et al. 2013a). However, juveniles of both species co-occur in nearshore areas (Fay et al. 1983; Klauda et al. 1991; Limburg 1998). Fishing effort in the NJLI area is concentrated at depths shallower than 50 m, which therefore may explain the overall lower proportion of larger Alewives. The shift from nearly equal bycatch of Alewives and Blueback Herring in 2011 to predominantly Blueback Herring bycatch in 2012 supports this explanation. In 2011, most of the bycatch occurred off the northern coast of New Jersey around the Hudson Canyon (NOAA statistical area 612; Figure 1). This area is known habitat for immature river herring from the Hudson River and nearby rivers (Fay et al. 1983; Limburg 1998). In contrast, most of the bycatch in 2012 occurred in NOAA statistical area 613 (Figure 1) from nearshore Long Island to depths of 50 m, which has been identified as Blueback Herring wintering grounds (Neves 1981; Bethoney et al. 2013a). Thus, in 2011, juveniles of both species were caught in the Hudson Canyon, while in 2012 the midwater trawl vessels primarily caught larger Blueback Herring.

Bycatch Implications and Mitigation Strategies

Despite the uncertainties surrounding the coastwide impact of river herring bycatch, strategies for bycatch mitigation should be consistent with the differing impacts of bycatch in different areas of the fishery. Limits based only upon historical bycatch, which have been implemented in the Atlantic Mackerel and Atlantic Herring fisheries, do not recognize the potential varying impact that bycatch may have throughout the range of the fishery and could fail to benefit river herring populations, could overly restrict the midwater trawl fishery, or both. The results from this research, coupled with river herring life history data, indicate that the impact of bycatch in the GoM and CC may be less significant than the impact of bycatch in SNE and NJLI.

Based on the size of river herring caught in the GoM and the seasonal movements of river herring in the GoM and CC areas, bycatch in the two areas most likely consists of migratory mature or near-mature river herring representing mixed origins. Under this scenario, the impact of bycatch in the GoM and CC areas is dispersed among a large number of stocks. This dispersion of bycatch, along with the restrictions on the midwater trawl fleet in the GoM and CC areas (lower Atlantic Herring quotas and spawning closures) and the low bycatch rate in the GoM, may reduce the impact of bycatch in these areas relative to the SNE and NJLI areas (ASMFC 2006; NOAA 2013b). In the GoM and CC areas, where river herring appear to be passing through aggregations of target species, fleet communication may be an effective mitigation strategy (Gilman et al. 2006; O'Keefe et al. 2014). Vessels could be alerted when large numbers of river herring begin to pass through or when circumstances arise that are likely to indicate river herring presence. Implementation of a fleet communication system coupled with environmental data has begun in the GoM, with promising results (Bethoney 2012). The lower bycatch rate in the GoM than in other areas during 2011 and 2012 differs from patterns observed from 2005 to 2009 (Cieri et al. 2008; Cournane et al. 2013). In early January 2013, midwater trawl vessels were alerted of high river herring bycatch occurring within the CC area. Vessels avoided this area for 1 week, and no further high-bycatch events were observed (SMAST 2013).

The larger proportion of river herring in the immature size range within SNE and NJLI than within the GoM indicates a greater potential for bycatch in these areas to affect a smaller subset of nearby rivers and year-classes. In populations with small spawning stocks, strong year-classes can lead to substantial increases in overall population size (Jobling 1995b). Fewer year-classes are likely represented in juvenile aggregations. Furthermore, anadromy may have evolved due to improved fitness through increased survival of early life history stages (Dodson 1997). Thus, a reduction in juvenile bycatch mortality may be most beneficial to river herring populations. However, many factors can determine year-class strength before juvenile river herring can be caught as bycatch (Gibson and Myers 2003; Gahagan et al. 2010; ASMFC 2012). Although the magnitude of river herring removals is notable in comparison with estimated run sizes for several rivers adjacent to the SNE and NJLI areas, an evaluation of these removals is impossible given the current method of river herring stock assessment and the resolution of the information collected (ASMFC 2012).

Regulations that limit the amount of river herring taken in the SNE and NJLI areas may be justified given (1) the depleted state of river herring runs in northern mid-Atlantic and SNE rivers and (2) our conclusion that bycatch in SNE and NJLI likely comprises a considerable percentage of less-migratory juveniles (ASMFC 2012). Given the uncertainties surrounding the impact of bycatch on local populations and the seasonal importance of these areas to the midwater trawl fishery, closure of the SNE and NJLI areas would be unjustified. Static, smaller-scale closures would also be problematic due to the interannual variability in bycatch patterns within these areas (Bethoney et al. 2013b). Similarly, the development of intra-annual patterns that can be exploited via a fleet communication system varies from year to year (Bethoney et al. 2013b; SMAST 2013). Thus, a biologically based limit on the amount of river herring taken in

SNE and NJLI may be the best approach. To achieve this, river herring that are caught at sea must be linked to their populations of origin, possibly through genetic (Palkovacs et al. 2014) or morphometric (Rulifson 1984) analysis. At-sea removals could then be linked to index river mortality rates, and limits could be set based on bycatch amounts that would cause notable declines in the run sizes of index rivers.

At the levels seen in 2011 and 2012, bycatch in the midwater trawl fishery cannot account for the overall decline in river herring. For example, in 2011, the number of river herring estimated to have passed the Benton River fishway, Maine (ASMFC 2012), was similar to the number we estimated as taken by midwater trawl vessels in 2011 and 2012 combined. Furthermore, a consistent decline in the oceanic biomass of river herring has been documented since 1976, long before the establishment of the current midwater trawl fishery (i.e., in the 1990s; ASMFC 2012). A comprehensive review of rangewide threats to river herring (NOAA 2013a) identified dams and other barriers as the most significant threat to river herring populations, while water quality, climate change, predation, water withdrawal, dredging, and several other threats were also identified in addition to bycatch. The midwater trawl fishery is not the only fishery in which river herring are incidentally caught (Wigley et al. 2009). Bycatch in the midwater trawl fishery is highly variable from year to year, and the greatest potential impact on river herring appears to be for rivers from New Jersey to SNE. To better understand this impact, continued monitoring and studies examining the at-sea population dynamics of river herring are needed. Small improvements to existing monitoring programs, such as prioritization of length frequencies and further coordination among the NEFOP, MA-DMF, and other state agencies, will also allow for improvements (e.g., creation of intra-annual length frequencies and a reduction in CVs for weight estimates).

Basic biological measurements of bycatch species in conjunction with life history knowledge can greatly aid in the development of bycatch mitigation strategies. The composition of fish assemblages, especially those that are highly migratory, can differ over the range of a fishery. False assumptions about the similarity in bycatch among different areas can lead to ineffective strategies, while identifying where the impact of bycatch may be the greatest and focusing mitigation on these areas can increase the benefit to bycatch species and minimize the impact on the fishery. In areas characterized by great uncertainty, collaboration with fishery participants is an effective way to increase available data and potentially reduce bycatch (Roman et al. 2011; Bethoney et al. 2013b; O'Keefe et al. 2014).

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