River Herring Monitoring and Pilot Stocking Evaluation in the Chowan River, 2012–2019

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Abstract. Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis* populations in three Chowan River tributaries (Bennett's, Dillard's, and Vaughan's creeks) were surveyed with boat-mounted electrofishing during spring 2018 and 2019. Mean relative abundance of Alewife increased in Dillard's Creek in 2018 and through 2019 in Bennett's Creek. Catch rates of Alewife in Vaughan's Creek in 2018 and 2019 were higher than any other tributary sampled 2012–2019. Blueback Herring mean relative abundance has been increasing in Dillard's Creek and was the highest in 2019. Blueback Herring mean relative abundance in Bennett's Creek peaked in 2017 but declined in 2018 and 2019 likely due to low dissolved oxygen events. Catch rates of Blueback Herring in Vaughan's Creek in 2018 were the highest catch rates observed during sampling. In all three creeks, Alewives were primarily age-2 and age-3 fish, and Blueback Herring samples were predominated by age-3 and age-4 fish. In Dillard's and Bennett's creeks, Alewife with multiple spawning marks made up 7%, while 8% of Blueback Herring had multiple spawning marks. In Vaughan's Creek, repeat spawning Blueback Herring and Alewife comprised 11% and 12% of the sample, respectively. Approximately five million Blueback Herring fry were stocked into three Chowan River tributary creeks 2012–2014 as part of a pilot stocking project, but no returning adults were identified as hatchery origin. Increases in population abundance and the lack of contribution by hatchery fish support the cessation of herring stockings. Evidence of gradual population increases since the harvest moratorium supports consideration of management options that would allow for future recreational harvest opportunities.

Stocks of anadromous Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis* (collectively known as river herring) were once abundant throughout the Atlantic coast but are severely depleted throughout much of their geographic range (ASMFC 2009). Causes for the declines have been attributed to overfishing, habitat degradation, and lost or impaired access to historic spawning habitat by dam and culvert construction. To protect and rebuild current stocks, multiple coastal states have enacted harvest moratoria in waters under state jurisdiction; a harvest moratorium was implemented in North Carolina in 2006/2007 and in coastal waters of Virginia flowing into North Carolina in 2008. Except for states with an approved sustainable fishery management plan, all anadromous river herring fisheries were closed effective 1 January 2012 as mandated by Amendment 2 to the Interstate Fishery Management Plan for Shad and River Herring (ASMFC 1985; ASMFC 2009). In recent years growing concern regarding the status of herring populations resulted in a multiyear review by the National Marine Fisheries Service (NMFS) which determined listing river herring as endangered or threatened was not necessary under the Endangered Species Act (NOAA 2019).

The North Carolina Wildlife Resources Commission (NCWRC) annually monitors river herring in coastal rivers in North Carolina as required by the Atlantic States Marine Fisheries Commission under Amendment 2 of the Interstate Fishery Management Plan for Shad and River Herring (ASMFC 2009). In the Albemarle Sound area, the North Carolina Division of Marine Fisheries (NCDMF) staff conducts annual spring gill net and pound net surveys in the Chowan River, a major tributary to Albemarle Sound, and NCWRC personnel have conducted river herring electrofishing surveys in Chowan River tributaries since 2006. Amendment 2 of the North Carolina Fishery Management Plan for River Herring established three stock status indicators for Blueback Herring: a 3-year average juvenile abundance index of at least 60 fish per haul, at least 10% repeat spawners, and a female spawning stock biomass threshold of 1.8 million kilograms (NCDMF 2015). The juvenile abundance index in 2019 was 33 fish per haul, which was the highest value since 1993, but the 3-year average (12.5 fish/haul) remained below the status indicator (NCDMF 2020). The proportion of repeat spawners was 42.6% in 2019 and was above the threshold (NCDMF 2020). The most recent spawning stock biomass estimate was completed during the 2017 stock assessment with a terminal year of 2015. The female spawning stock biomass has been increasing since 2010 but was well below the threshold at 227,333 kg in 2015, roughly 12% of the target biomass of 1.8 million kg (ASMFC 2017).

In addition to a harvest moratorium, NCWRC explored experimental stocking as a recovery tool for river herring in the Chowan River basin. The Chowan River Blueback Herring fry stocking pilot project started in 2012. The objectives of the pilot project were to investigate the feasibility of a river herring stocking project and to develop genetic microsatellite markers for parentage-based tagging (PBT) evaluations of hatchery contribution of returning Blueback Herring adults to the study area (NCWRC 2015). The benefits of this approach include use of early life stages that can imprint to the targeted stream and genetic identification to facilitate non-lethal identification of returning hatchery fish. Initially, broodfish were collected from Bennett's and Dillard's creeks, and in 2013 Sarem Creek was added. All broodfish were genotyped in discrete batches allowing for specific cohorts to be identified in future surveys. Between 2012 and 2014, approximately five million Blueback Herring fry were stocked into their respective natal creek. In 2013, geneticists at the North Carolina Museum of Natural Sciences (NCMNS) developed five new population-specific microsatellite markers using NexGen

sequencing to further establish proof-of-concept for PBT analysis (Evans et al. 2018). Fry from 2014 hatchery spawning were unavailable to be used for proof-of-concept evaluations, but in 2015, fry were produced but not stocked to obtain additional known source broodfish and fry pairings (Potoka and McCargo 2015). Fifty fry samples from the 2015 broodfish were conclusively matched with parent pairs from appropriate spawning tanks, effectively establishing proof-of-concept for the use of techniques in evaluating the efficacy of stocking hatchery-reared river herring (Evans 2016). During this survey period, hatchery contribution of returning adults was evaluated by collecting fin clips from adult Blueback Herring in Dillard's, Bennett's, and Sarem creeks to be genotyped and evaluated using PBT analysis to determine hatchery or wild origin.

The objectives of the survey were to identify trends in abundance, sex ratio, age structure, and size structure of river herring in each creek across the time series (2012–2019) and to assess the pilot stocking project in three tributary creeks of the Chowan River. We summarized river herring survey results from 2018 and 2019 and compared those results across the 2012–2019 time series.

Methods

Alewife and Blueback Herring collections. River herring were collected from Dillard's and Bennett's creeks during weekly electrofishing surveys 2012–2019 and Vaughan's Creek in 2018 and 2019 (Figure 1). A boat-mounted electrofishing unit (Smith-Root 7.5 GPP; 170–1000 V pulsed DC; 2–5A) with one dip-netter was used to capture river herring during daylight hours at four fixed sites in Dillard's and Bennett's creeks and one site in Vaughan's Creek. River herring were collected as encountered and held in an oxygenated live well with a recirculating current until each site was completed. A suite of environmental variables was recorded at each survey site, including dissolved oxygen (mg/L), percent saturation, specific conductivity (µS/cm), salinity (ppt), water temperature (°C), pH, and secchi depth (m). Following site completion, river herring were identified to species, measured for total length (TL, mm) and weighed (g). Sex was determined by applying directional pressure to the abdomen toward the vent and observing the presence of milt or eggs. In 2018, scales were obtained for aging from a subsample of up to 5 fish per 10 mm length group per sex for each creek during each sampling day. Scales were taken by applying anterior, directional pressure between the dorsal fin and the lateral line; scale samples were then stored in numbered envelopes.

Relative abundance. Relative abundance was indexed as catch-per-unit-effort (CPUE), expressed as the number of fish captured per hour of electrofishing (fish/h). Annual trends in relative abundance were assessed using weekly total CPUE for Alewife and Blueback Herring in each of the three creeks. Interannual trends in river herring abundance were assessed by comparing mean relative abundance for both species in each creek 2012–2018. Annual mean relative abundance was calculated by averaging weekly total CPUE from the first day a species was collected to the last for each creek. Length frequencies were created to determine sex ratio and size-structure of river herring in each creek. Maximum and mean female and male total length was calculated and compared over the entire time series.

Age, growth, and mortality. A subsample of up to 10 scales per 10 mm group for Alewife and Blueback Herring collected from each creek in 2018 was aged and spawning marks were

identified using an EyeCom 3000 microfiche reader. Roughly 10% of aged scales were then read a second time by the same reader for age and spawning mark validation. The percent of each species that were either virgin spawners or had one or multiple spawning marks was calculated. Sex specific age length keys were created for each species using FAMS software, and ages were assigned to unaged Alewife and Blueback Herring. Annual survival (S) and instantaneous total mortality rates (Z) from the age frequency (i.e., scale ages and assigned ages) were created using Chapman-Robson methods and were evaluated using the Fishmethods package agesurvey (V 1.11; Nelson 2019) in Program R (R Core Team 2013).

Blueback Herring pilot stocking project. During weekly electrofishing surveys in 2016 through 2018, fin clips were obtained from Blueback Herring from Bennett's, Dillard's, and Sarem creeks each sampling day. Additional fin clips were collected from other Chowan River tributary creeks by NCWRC and NCDMF. Fin clips were stored in pre-labeled vials filled with non-denatured, spectrophotometric grade ethanol and recharged with new ethanol one week after collection; all fin clips were stored in the freezer. Fin clips from Blueback Herring were sent to the genetics laboratory at the NCMNS for genotyping and PBT analysis to determine any individuals of hatchery origin following Evans et al. (2018).

Results

Alewife collections from Dillard's Creek. Alewives were first collected in Dillard's Creek on February 21, 2018, when water temperature averaged 13°C and on February 15, 2019, when water temperature was 10.2°C (Table 1). A total of 188 Alewives was collected in 2018, and 73 were collected in 2019 (Table 1). The highest number of Alewives in the time series (2012–2019) occurred in 2018 (Table 2). The mean relative abundance of Alewife in 2018 was the highest in the time series (48.4 fish/h; SE = 12.4) but declined in 2019 to 17.4 fish/h (SE = 10.9; Table 2 and Figure 2). This decline in relative abundance appears to be a result of fewer male Alewife less than 250 mm collected in 2019. Mean relative abundance showed an upward trend 2012–2018 followed by a decline in 2019 (Figure 2). Peak daily relative abundance of Alewives occurred on March 19, 2018 (78.2 fish/h) and March 13, 2019 (60 fish/h). The highest catches of both male and female Alewives in this time series were observed in 2018 (Table 2). The 2018 catch of Alewives was comprised of smaller males and females (TL ≤ 250 mm), but these same size classes were not observed in 2019 and may represent a strong year-class (Figure 3).

Blueback Herring collections from Dillard's Creek. Blueback Herring were first collected in Dillard's Creek on February 28, 2018, when water temperature averaged 15°C and March 13, 2019, when water temperature averaged 12.6°C (Table 1). Totals of 524 and 704 Blueback Herring were collected in 2018 and 2019, respectively (Table 1). The number collected and mean relative abundance for Blueback Herring in 2018 and 2019 were the highest in the time series (Table 3 and Figure 4). Blueback Herring relative abundance was 83.9 fish/h (SE = 43.5) in 2018 and 140.2 fish/h (SE = 40.3) in 2019. The relative abundance of Blueback Herring in Dillard's Creek has shown an increasing trend since 2015 (Figure 4). Peak daily relative abundance of Blueback Herring occurred on April 5, 2018, (327 fish/h) and on April 8, 2019, (256 fish/h). In 2018 and 2019, more females were collected than in any other year of the time series (Table 3). The size distributions of Blueback Herring collected in 2018 and 2019 were very

similar with a wide range of sizes classes and unimodal peaks at 260 mm for males and 280 mm for females in 2018 and 270 mm for females in 2019 (Figure 5).

Alewife collections from Bennett's Creek. Alewives were first collected on February 21, 2018, with an average water temperature of 13.8°C and February 26, 2019, when water temperature was 20.8°C (Table 4). In both 2018 and 2019, Alewives were collected on the first sampling day. Totals of 93 and 125 Alewives were collected in 2018 and 2019, respectively (Table 4). Mean relative abundance was 15.0 fish/h (SE = 13.6) in 2018 and 31.0 fish/h (SE = 13.6) in 2019. Relative abundance of Alewife throughout the 2012–2018 time series has been relatively stable (Table 2 & Figure 2). Peak relative abundance (45.5 fish/h) of Alewife occurred on February 21, 2018, the first survey day of that year, and March 13, 2019 (74.6 fish/h; Table 4). Few females were collected in 2018 and 2019, but female length distributions were similar in both years (Figure 6). Males comprised a wider range of size classes. Like Dillard's Creek, most male Alewives were less than or equal to 250 mm in 2018, but the length distribution shifted to larger fish in 2019.

Blueback Herring collections from Bennett's Creek. Blueback Herring were first collected in Bennett's Creek on March 14, 2018, with an average water temperature of 8.1°C and March 13, 2019, when water temperature averaged 19.5°C (Table 4). Totals of 35 and 87 Blueback Herring were collected in 2018 and 2019, respectively (Table 4). Blueback Herring mean relative abundance was 7.0 fish/h (SE = 2.4) in 2018 and 16.0 fish/h (SE = 9.9) in 2019. Blueback Herring relative abundance over the time series has been increasing every other year, increasing from 65.7 fish/h in 2013, then to 92.8 fish/h in 2015 and finally 158.8 fish/h in 2017 but remained low in 2018 and 2019 (Table 3 and Figure 3). The peak in Blueback Herring abundance (15.3 fish/h) occurred April 11, 2018, and April 8, 2019 (63.8 fish/h). In both 2018 and 2019, low dissolved oxygen events (less than 3 mg/L) were observed in the two weeks after peak catch rates. Low dissolved oxygen events are likely the reason for low catch rates of Blueback Herring in 2018 and 2019. In both 2018 and 2019, few females were collected, but in 2019, female lengths represented a wider range of size classes (Figure 7). In both years, males represented most of the catch and showed a wider range of size classes in 2019 (Figure 7).

Alewife collections from Vaughan's Creek. Alewives were first collected on February 19, 2018, with an average water temperature of 9.5°C, and Alewives were first collected on March 7, 2019, when water temperature was 5.8°C (Table 5). Totals of 501 and 169 Alewives were collected in 2018 and 2019, respectively. Mean relative abundance of Alewives was 143.0 fish/h (SE = 48.7) in 2018 and 71.0 fish/h (SE = 22.4) in 2019 (Table 2). Mean relative abundance of Alewives in Vaughan's Creek were the highest observed for any creek in the Chowan River basin across the time series (Figure 2). Peak daily relative abundance (538.0 fish/h) of Alewives occurred on March 28, 2018, and on March 21, 2019 (122.0 fish/h; Table 5). In both years, males were more abundant than females, and females had similar length distributions with a wide range of size classes (Figure 8). The length distribution for males in 2018 was comprised mostly of smaller individuals (≤250 mm), while 2019 length distributions were comprised mostly of males greater than 250 mm (Figure 8).

Blueback Herring collections from Vaughan's Creek. Blueback Herring were first collected in Vaughan's Creek on March 28, 2018, with an average water temperature of 8.5°C and on March 21, 2019, when water temperature averaged 10.8°C (Table 4). Totals of 413 and 216 Blueback Herring were collected in 2018 and 2019, respectively (Table 4). Mean relative abundance of

Blueback Herring was 208.0 fish/h (SE = 38.4) in 2018 and 94.0 fish/h (SE = 38.4) in 2019 (Table 3 & Figure 3). Mean relative abundance of Blueback Herring in 2018 was the highest observed for any creek in the Chowan River basin in the 2012–2019 time series (Figure 3). Peak daily relative abundance for Blueback Herring occurred April 5, 2018 (556.0 fish/h) and April 18, 2019 (298.0 fish/h; Table 5). Higher mean relative abundance in 2018 was likely driven by a large number of male Blueback Herring less than 250 mm. Similar to Alewife caught in Vaughan's creek, males in 2018 were mostly comprised of individuals less than 250 mm, while in 2019 the majority of males were larger than 250 mm (Figure 9).

Age, growth, and mortality in Dillard's and Bennett's creeks. Scales collected from Bennett's Creek and Dillard's Creek were combined for analysis due to the limited number of scales collected from Bennett's Creek. From Dillard's and Bennett's Creeks, 87 Alewife and 78 Blueback Herring scales were included for analysis. Of aged Alewives, 64% were males (n = 56) and 36% were females. Virgin fish comprised 93% of the sample, 6% had one spawning mark, and 1% had two spawning marks for a total of 7% repeat spawners. Of aged Blueback Herring, 53% were males (n = 41) and females accounted for 47% (n = 37). Virgin Blueback Herring comprised 91% of the sample, and 9% had one spawning mark and represented the only repeat spawners collected.

Annual survival and instantaneous mortality estimates were generated for both Alewife and Blueback Herring using a Chapman Robson equation. Annual survival of Alewife was 0.26 (SE = 0.23) while annual survival for Blueback Herring was 0.55 (SE = 0.01; Tables 6 and 7). Instantaneous mortality was 1.35 (SE = 0.09) for Alewife and 0.6 (SE = 0.03) for Blueback Herring (Tables 6 and 7). Using an age length-key generated from scale ages, a total of 194 and 479 ages were assigned to unaged Alewife and Blueback Herring, respectively. The majority (96%) of Alewife collected in Dillard's and Bennett's creeks were comprised of age-2 (2016 cohort) and age-3 (2015 cohort) fish (Figure 10). The majority (91%) of Blueback Herring were comprised of age-3 (2015 cohort) and age-4 (2014 cohort) fish (Figure 11).

Age, growth, and mortality in Vaughan's Creek. Totals of 76 Alewife and 44 Blueback Herring scales were aged from Vaughan's Creek. Of aged Alewives, 55% were males (n = 42) and females accounted for 45% (n = 34). Virgin Alewives comprised 88% of the sample, 11% had one spawning mark, and 1% had two spawning marks for a total of 12% repeat-spawning Alewives. Of aged Blueback Herring, 70% were males (n = 31) and females accounted for 30%. Virgin Blueback Herring comprised 89% of the sample, 7% had one spawning mark, and 4% had two spawning marks for a total of 11% repeat spawners. Annual survival of Alewives was 0.41 (SE = 0.02) and instantaneous mortality was 0.98 (SE = 0.04; Table 6). Annual survival of Blueback Herring aged from Vaughan's Creek was 0.58 (SE = 0.02) and instantaneous mortality was 0.58 (SE = 0.20; Table 7). Using an age length-key generated from scale ages a total of 423 and 366 ages were assigned to unaged Alewife and Blueback Herring, respectively. The majority (90%) of Alewife collected in Vaughan's Creek were comprised of age-2 (2016 cohort) and age-3 (2015 cohort) fish. The majority (94%) of Blueback Herring collected from Vaughan's Creek were comprised of age-3 (2015 cohort) and age-4 (2014 cohort) fish (Figure 11).

Blueback Herring pilot stocking project. From 2012 to 2014, five million Blueback Herring fry were stocked into Dillard's, Bennett's, and Sarem creeks (Table 8). Between 2016 and 2018, 181 adult Blueback Herring fin clips from Dillard's Creek, 140 adult Blueback Herring fin clips from Bennett's Creek, and 98 adult Blueback Herring fin clips from Sarem Creek were evaluated

for hatchery contribution. No fish were identified as hatchery origin (Evans et al. 2018; Table 9). An additional 232 fin clips were collected from other Chowan River tributaries, and none were found to be hatchery origin (Evans and McGrady 2019; Table 9). All Blueback Herring samples were combined from 20 Chowan River tributary creeks to evaluate genetic differences between Blueback Herring utilizing different creeks. STRUCTURE analysis was unable to detect any distinct genetic populations from any of the Chowan River creeks using the same microsatellite marker suite used for PBT analysis (Evans and McGrady 2019).

Discussion

Reduction of fishing mortality, a direct result of the moratorium, in coastal waters of North Carolina has likely contributed to the increase in relative abundance of river herring observed in Dillard's Creek and the observed high abundance in Vaughan's Creek. Overall increases in both catch and relative abundance of Alewife and Blueback Herring in Dillard's Creek suggest natural population recovery is occurring. Although Blueback Herring fry were stocked into this creek, PBT analysis revealed that stocking did not contribute to the increase in numbers.

While general trends in Blueback Herring abundance appear to be increasing in Bennett's Creek throughout the time series, abundance has been highly variable. This variation can be at least partially attributed to the ineffectiveness of our sampling gear in a relatively large creek. The staging location of river herring likely has an impact on catch rates, and Bennett's Creek is wide enough that herring could be missed using current sampling techniques. Both Vaughan's and Dillard's creeks are narrow enough that river herring, when present, are more readily captured during electrofishing. Given our sampling limitations, Bennett's Creek survey results may not be effective for long term monitoring of trends in abundance. Additionally, the physical properties of Bennett's Creek make it prone to low dissolved oxygen during springtime flooding events. Bennett's Creek is wide at the mouth and is generally a slow draining creek; river herring demonstrate spawning preference for creeks that have moderate to high discharge (Walsh et al. 2005). Due to the biases associated with the electrofishing data from Bennett's Creek, sampling should be focused elsewhere in the Chowan River basin. Catherine's Creek was surveyed from 2006 to 2011; future surveys should include Catherine's Creek. Multiple researchers have found that Catherine's Creek had one of the highest abundances of larval river herring compared with other creeks in the Chowan River basin (O'Rear 1983; Butler 2012; Ezzard 2017). The inclusion of Catherine's Creek in our annual monitoring could elucidate trends in abundance from a creek where historical adult abundance has been high and more recent surveys reported high larval abundance. It will also allow for comparison with 2006–2011 surveys, which include one year before the moratorium.

Future monitoring events should start earlier in the calendar year than the 2018 and 2019 surveys. In both years Alewives were collected on the first sampling date, possibly indicating that the beginning of the Alewife run was missed. It is important to capture the entirety of the river herring run because much of the run can occur within a few days and missing these peak days can have significant effects on catch rates. Water temperature is used as a predictor of river herring runs; however, there are no active water quality loggers in the targeted creeks for this monitoring program. Placing water temperature, dissolved oxygen, and depth loggers in each creek to be surveyed may help describe water conditions in each creek before, during, and

after river herring runs. Lombardo et al. (2020) found that Alewife and Blueback Herring in the Albemarle Sound arrived on the spawning grounds earlier in the calendar year and remained on the spawning grounds for a shorter period of time during a truncated spawning period from 2001 to 2016 when compared with the 1970s and 1980s. For the sampling period 2001–2016, Alewife and Blueback Herring were observed to have a spawning period shortened by 11 days and 18 days respectively, when compared with the collections from the 1970s and 1980s.

Obtaining comprehensive water quality parameters from monitoring sites will also elucidate effects of low oxygen events on river herring runs. Low dissolved oxygen events as a result of springtime flooding occurred during the Blueback Herring run in Bennett's Creek in both 2018 and 2019. These low dissolved oxygen events could disrupt spawning activity, contract the spawning time frame, reduce egg viability, lower hatch rates, and decrease larval survival. Comprehensive water quality information in each creek will help managers identify the duration and potential impacts of low dissolved oxygen events and may help identify resulting weak year-classes. In addition to increased low dissolved oxygen events, widespread blue-green algae blooms have impacted the Chowan River in recent years. While these blooms tend to occur in the late spring and early summer when adult herring are not actively spawning, impacts on the food web and the disruption of feeding behavior of juvenile river herring could have significant effects on year-class strength (Jupitz 2017).

Annual survival estimates for Alewives were lower than Blueback Herring in all creeks sampled in this study, and instantaneous mortality rates were higher for Alewife than Blueback Herring in all three creeks. In 2018, the Alewife populations in all creeks were primarily age-2 and age-3 fish with very few age-4 or age-5 fish. The truncated age structure can likely be attributed to the high mortality rate of adult river herring. Blueback Herring also had a truncated age structure with no fish over age 5 and age-3 and age-4 fish making up the majority of the sample. Mortality estimates from this survey were much higher than those observed in the NCDMF pound net and independent gill net surveys in 2018 (White and McCargo 2019), a result of fewer age-classes represented in this survey. Additional years of age data are needed to better assess mortality of river herring in the NCWRC survey; currently 2019, 2020, and 2021 scales are available to be aged. In future surveys a subsample of herring should be retained for otolith removal and age-to-scale validation. The percent of repeat spawners collected from Vaughan's Creek exceeded the 10% repeat spawners target established in Amendment 2 to the North Carolina River Herring Fishery Management Plan for herring collected in the pound net survey (NCDMF 2015). In Dillard's and Bennett's creeks, the percent of repeat spawners was just below the 10% target. The percent of repeat spawners in this study was much lower than was reported in the 2018 NCDMF pound net survey (39.3% for Blueback Herring and 49.2% for Alewife) and the 2018 independent gill net survey (57.0% for Blueback Herring and 53.5% for Alewife; White and McCargo 2019). Both agencies should compare ageing protocols to rectify discrepancies in age-structure and spawning marks.

The pilot stocking project for Blueback Herring suggested that fry stockings at the rates applied in 2012–2014 did not contribute to population increases; no hatchery fish were collected in subsequent years of sampling. However, important advances in the utilization of parentage-based tagging as a hatchery evaluation method for river herring were gained. Microsatellite markers were developed for the identification of hatchery-produced progeny and for distinguishing between Alewife, Blueback Herring, and their hybrids. While STRUCTURE

analysis was unable to determine genetic differences between Blueback Herring from different creeks, it appears this may in fact be a limitation of the genetic techniques and not necessarily a reflection of population characteristics (personal communication, Heather Evans). Other genetic techniques such as single nucleotide polymorphism (SNP) have been used to evaluate the genetic population structure of Blueback Herring along the Atlantic Slope but were not able to distinguish intra-basin differences in population genetics (Reid et al. 2018). River herring from the Chowan River Basin were identified as part of the Mid Atlantic Stock which includes populations from the Connecticut River to the Neuse River (Palkovacs et al. 2013; Reid et al. 2018). Future discussions of fry stocking as supplementation for year-class strength should begin with the use of parentage-based tagging as the marking and evaluation technique.

Additional fin clips obtained from creeks not stocked during the pilot project were assessed for hatchery contribution to determine if fish return to creeks outside their natal origin. Since no hatchery fish were identified from the fin clips sampled, we currently do not know if fish return to their natal creeks within the Chowan River Basin. Additionally, studies have been conducted to determine the efficacy of otolith microchemistry for identifying natal homing; however, this technique is limited to sites with unique chemical signatures and may not be useful within the same river basin (Gahagan et al. 2012). It may be beneficial for future research projects to place batch tags in river herring from each creek to determine creek-level fidelity or river basin fidelity and more easily identify repeat spawners without having to process scale samples. One option to consider for discrete batch tags is visible elastomer (VIE) tags, which are color-coded, and can be placed in various ways to uniquely characterize tagging year. Other methodologies for determining site fidelity include the use of coded wire tags or passive integrated transponders.

Annual run-size estimates are recommended for monitoring abundance of river herring populations imprinted to a tributary (ASMFC 2016). Obtaining run-size estimates from annual monitoring locations could elucidate trends in abundance and would provide baseline information for comparison to relative abundances from our electrofishing surveys. In 2019 and 2020 the NCWRC started a survey to estimate run sizes of river herring in Vaughan's Creek using dual-frequency identification sonar (DIDSON). The DIDSON was placed in a narrow part of the creek where fish would be visible as they migrate upstream. Video recordings were taken for 10 minutes every hour to ensure diel migration patterns were captured. Electrofishing below the DIDSON occurred weekly to verify species composition of fish recorded. Run-size estimates were generated from the counts of each species on the video and extrapolated to cover the entire migration period. Annual run-size estimates in tributaries monitored by NCWRC will be valuable for documenting river herring recovery.

The truncated age structure of river herring collected in the spawning creeks is concerning; however, the cause is largely unknown. Age structure could be impacted by sampling bias, be indicative of poor year class production or poor recruitment to the spawning stock. An expanded age structure showing individuals greater than age 5 would indicate a wide range of age-classes that could support a sustainable fishery. Due to the migratory nature of river herring it can be difficult to determine causes of mortality; however, for a population to support recreational harvest, mortality rates must be consistently estimated. For age and mortality estimates to be reliable a time series is needed; currently scales collected in 2019, 2020, and 2021 need to be processed. The continued collection of age, mortality, and repeat

spawning information coupled with continuous water quality monitoring could help determine if poor year classes are a result of environmental variables or due to the truncated size structure of the spawning stock.

Continued data collection and evaluation of the river herring population status in the monitoring creeks would inform the decision to maintain the harvest moratorium or to develop a plan for sustainable harvest. A sustainable fishery management plan will be developed when data shows population trends are compatible with limited harvest. Metrics used to determine the sustainability of the population may include but are not limited to: electrofishing catch per unit effort, percent repeat spawners, age structure, mortality estimates, and estimates of biomass or run size.

Management Recommendations

1. Maintain the harvest moratorium on river herring in the Chowan River basin in 2021. As time-series data from NCWRC sentinel monitoring locations now approach 10 years, identify and consider management options that might allow for sustainable recreational harvest in future seasons.
2. Establish Dillard's Creek as a sentinel long-term monitoring location. Annual surveys in Vaughan's Creek and Catherine's Creek should be continued.
3. Deploy DIDSON sonar technologies in at least one monitoring location each spawning season to obtain run-size estimates of river herring.
4. Evaluate scale samples collected in 2019, 2020, and 2021 for age and spawning marks. Collect otoliths for scale age validation in 2022. Coordinate with NCDMF staff to compare ageing protocols and evaluate spawning mark identification.
5. Install water level, temperature, and dissolved oxygen loggers in Dillard's, Catherine's, and Vaughan's creeks to assess annual habitat conditions during spring river herring spawning migrations.

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TABLE 1. Weekly electrofishing effort, Alewife and Blueback Herring catch, and CPUE (catch/effort), along with accompanying totals and daily water temperatures for Dillard's Creek, Chowan River Basin 2018 and 2019.

Date	Effort (h)	Catch Alewife	Alewife CPUE	Catch Blueback	Blueback CPUE	Water Temp	Dissolved Oxygen (mg/L)
February 21, 2018	0.83	40	48.1	0	0.0	13.0	7.5
February 28, 2018	0.82	60	73.1	5	6.1	15.0	4.1
March 6, 2018	0.68	9	13.2	4	5.9	10.6	8.4
March 19, 2018	0.68	53	78.2	29	42.8	11.6	9.9
March 27, 2018	0.88	26	29.5	41	46.5	10.6	10.5
April 5, 2018	0.93	0	0.0	305	327.3	17.8	6.8
April 11, 2018	0.89	0	0.0	115	129.4	14.4	8.5
April 18, 2018	0.85	0	0.0	25	29.6	16.1	4.2
Total	6.56	188		524			
February 15, 2019	0.71	8	11.3	0	0.0	10.2	12.7
February 26, 2019	0.66	0	0.0	0	0.0	10.3	12.1
March 7, 2019	0.7	1	1.4	0	0.0	7.6	14.0
March 13, 2019	0.85	51	60.0	15	17.7	12.6	10.0
March 18, 2019	0.91	13	14.3	80	87.8	14.3	7.4
March 29, 2019	0.85	0	0.0	159	186.9	14.0	4.0
April 3, 2019	0.88	0	0.0	206	233.9	12.9	8.7
April 8, 2019	0.80	0	0.0	205	255.9	18.2	8.1
April 16, 2019	0.66	0	0.0	39	58.9	21.1	7.1
April 23, 2019	0.84	0	0.0	0	0.0	19.3	2.6
Total	7.86	73		704			

TABLE 2. Alewife electrofishing survey results, 2012–2019.

Creek	Year	Effort (h)	Catch Males	Catch Females	M:F Ratio	Mean CPUE (fish/h)	Male Mean TL	Female Mean TL	Max TL
Dillard's Creek	2012	2.81	20	4	5.0:1	8.2 (4.1)	260	275	289
	2013	6.25	55	10	5.5:1	9.1 (3.9)	251	271	303
	2014	4.06	73	30	2.4:1	24.7 (10.9)	261	271	313
	2015	3.44	110	9	12.2:1	31.6 (11.5)	261	288	302
	2016	1.60	25	2	12.5:1	-	265	292	295
	2017	4.39	126	16	7.9:1	32.5 (8.7)	273	273	317
	2018	3.90	142	46	3.1:1	48.4 (12.4)	254	272	298
	2019	3.80	57	16	3.6:1	17.4 (10.9)	272	291	321
Bennett's Creek	2012	2.63	58	9	6.4:1	24.6 (11.7)	267	285	325
	2013	3.70	107	7	15.3:1	28.1 (14.1)	255	268	293
	2014	4.06	38	2	19.0:1	9.2 (3.6)	261	294	314
	2015	2.00	50	3	16.7:1	26.4 (23.5)	261	273	294
	2016	1.00	14	0		-	256	NA	285
	2017	2.62	84	7	12.0:1	26.1 (14.9)	272	272	311
	2018	6.10	83	10	8.3:1	14.9 (5.7)	262	282	312
	2019	3.90	117	8	14.6:1	31.2 (13.6)	267	283	318
Vaughan's Creek	2018	3.30	352	149	2.4:1	142.7 (48.7)	266	283	323
	2019	2.30	80	89	0.9:1	71.2 (22.4)	271	283	315

TABLE 3. Blueback Herring electrofishing survey results, 2012–2019. Standard errors in parentheses.

Creek	Year	Effort (h)	Catch Males	Catch Females	M:F Ratio	Mean CPUE (fish/h)	Male Mean TL	Female Mean TL	Max TL
Dillard's Creek	2012*	0.54	7	1	7.0:1	14.8 (-)	258	297	297
	2013	4.60	69	28	2.5:1	22.1 (14.4)	248	263	300
	2014	4.06	64	20	3.2:1	20.6 (10.5)	254	265	284
	2015	2.50	9	1	9.0:1	3.6 (2.7)	260	262	284
	2016	1.60	27	5	5.4:1	-	264	276	290
	2017	2.63	142	45	3.2:1	69.7 (66.2)	269	266	294
	2018	5.72	416	108	3.9:1	83.9 (43.5)	259	280	308
	2019	4.90	577	127	4.5:1	140.2 (40.3)	260	278	308
Bennett's Creek	2012*	0.98	1	0	–	1.0 (-)	237	–	237
	2013	1.89	119	12	10.0:1	65.7 (50.9)	253	278	301
	2014	1.63	9	4	2.3:1	8.5 (6.3)	257	272	298
	2015	1.87	153	8	19.1:1	92.8 (91.8)	254	264	286
	2016	1.00	13	5	2.6:1	-	262	272	287
	2017	1.60	267	23	11.7:1	158.8 (155.9)	264	263	300
	2018	4.50	29	6	4.8:1	7.4 (2.4)	265	281	289
	2019	5.00	72	15	4.8:1	15.8 (9.9)	257	282	307
Vaughan's Creek	2018	2.00	392	21	18.7:1	208.2 (95.1)	260	280	299
	2019	2.30	177	39	4.5:1	94.2 (38.4)	264	278	305

*River herring sampling was incomplete during 2012 because the weekly sampling protocol was altered to accommodate Blueback Herring broodfish collection.

TABLE 4. Weekly electrofishing effort, Alewife and Blueback Herring catch, and CPUE (catch/effort), along with accompanying totals and daily water temperatures for Bennett's Creek, Chowan River Basin 2018 and 2019.

Date	Effort (h)	Alewife		Blueback		Temperature (°C)	Dissolved Oxygen (mg/L)
		Catch	CPUE	Catch	CPUE		
February 21, 2018	0.73	33	45.5	0	0.0	13.8	7.4
February 28, 2018	0.90	30	33.4	0	0.0	14.6	6.0
March 6, 2018	0.83	3	3.6	0	0.0	11.5	7.1
March 14, 2018	0.66	3	4.5	1	1.5	8.1	11.4
March 19, 2018	0.68	9	13.3	1	1.5	9.3	9.6
March 27, 2018	0.79	11	13.9	10	12.6	11.1	9.9
April 11, 2018	0.78	3	3.8	12	15.3	13.7	5.9
April 18, 2018	0.77	1	1.3	3	3.9	16.6	4.4
May 1, 2018	0.85	0	0.0	8	9.5	19.1	3.7
Total	6.98	95		35			
February 26, 2019	0.69	3	4.4	0	0.0	9.3	13.1
March 13, 2019	0.89	49	55.1	1	1.1	12.2	10.9
March 18, 2019	1.03	49	47.7	1	1.0	16.5	7.8
March 29, 2019	0.82	22	26.8	4	4.9	14.2	2.3
April 5, 2019	0.75	2	2.7	13	17.2	16.6	8.0
April 8, 2019	0.99	0	0.0	63	63.8	9.3	7.3
April 16, 2019	0.79	0	0.0	5	2.3	12.4	7.2
April 23, 2019	0.79	0	0.0	0	0.0	14.5	3.2
Total	6.52	125		87			

TABLE 5. Weekly electrofishing effort, Alewife and Blueback Herring catch, and CPUE (catch/effort), along with accompanying totals and daily water temperatures for Vaughan's Creek, Chowan River Basin 2018 and 2019.

Date	Effort (h)	Alewife		Blueback		Temperature (°C)	Dissolved Oxygen (mg/L)
		Catch	CPUE	Catch	CPUE		
February 19, 2018	0.32	50	158.1	0	0.0	9.5	9.9
February 27, 2018	0.39	58	149.1	0	0.0	13.1	6.7
March 8, 2018	0.34	31	92.2	0	0.0	6.3	9.9
March 14, 2018	0.25	10	40.0	0	0.0	5.0	-
March 22, 2018	0.32	73	228.5	0	0.0	7.7	11.3
March 28, 2018	0.38	206	537.4	3	7.8	8.5	9.9
April 5, 2018	0.33	17	51.0	185	555.0	15.0	-
April 10, 2018	0.33	40	122.0	5	15.3	10.4	8.9
April 17, 2018	0.33	8	24.0	108	323.5	13.8	7.1
April 26, 2018	0.32	8	24.8	111	344.2	17.5	7.7
May 3, 2018	0.29	0	0.0	1	3.5	20.9	6.6
Totals	3.60	501		413			
February 15, 2019	0.19	0	0.0	0	0.0	8.9	15.1
February 26, 2019	0.22	0	0.0	0	0.0	8.0	13.8
March 7, 2019	0.24	2	8.3	0	0.0	5.8	14.4
March 14, 2019	0.34	28	81.4	0	0.0	10.8	11.4
March 21, 2019	0.35	43	121.5	3	8.5	10.8	11.5
March 28, 2019	0.33	37	111.1	32	96.0	-	-
April 3, 2019	0.34	39	116.1	7	20.8	8.9	10.4
April 9, 2019	0.33	19	57.1	39	117.1	10.0	-
April 18, 2019	0.32	1	3.1	96	298.1	20.7	7.8
April 25, 2019	0.33	0	0.0	36	108.1	-	-
April 30, 2019	0.29	0	0.0	3	10.5	17.9	7.1
May 9, 2019	0.29	0	0.0	0	0.0	23.3	5.0
Totals	3.57	169		216			

TABLE 6. Discrete annual survival and instantaneous total morality estimates and standard error (SE) using the Chapman-Robson mortality estimator for Alewives collected from Dillard's and Bennett's creeks, and Vaughan's creek in 2018.

Creek		Estimate	Standard Error
Dillard's/Bennett's creeks	s	0.26	0.23
	z	1.35	0.09
Vaughan's Creek	s	0.41	0.20
	z	0.98	0.04

TABLE 7. Discrete annual survival and instantaneous total morality and standard error (SE) using the Chapman-Robson mortality estimator for Blueback Herring collected from Dillard's and Bennett's creeks, and Vaughan's creek in 2018.

Creek		Estimate	Standard Error
Dillard's/Bennett's creeks	s	0.55	0.01
	z	0.60	0.03
Vaughan's Creek	s	0.58	0.02
	z	0.58	0.20

TABLE 8. Number of Blueback Herring fry stocked 2012–2014.

Stocking Year	Dillard's Creek	Bennett's Creek	Sarem Creek
2012	696,653	14,430	NA
2013	859,999	1,264,161	156,409
2014	NA	984,500	1,033,500
Total	1,556,652	2,263,091	1,189,909

TABLE 9. Locations and number of fin clips collected from Blueback Herring in the Chowan River Basin and results of parentage-based tagging analysis for identifying hatchery origin.

Collection Site	Number Fin Clips	Number Hatchery Origin
Dillard's Creek	181	0
Bennett's Creek	140	0
Sarem Creek	98	0
Vaughan's Creek	40	0
Queen Anne's Creek	19	0
Pembroke Creek	30	0
Warwick Creek	9	0
Trotman Creek	3	0
Brooks Creek	4	0
Wiccacon River	16	0
Deep Swamp Creek	13	0
Salmon Creek	11	0
Catherine's Creek	37	0
Rockyhock Creek	10	0
Beef Creek	9	0
Deep Creek	10	0
Hodges Creek	2	0
Mud Creek	4	0
Goose Creek	8	0
Somerton Creek	7	0
Total	651	0

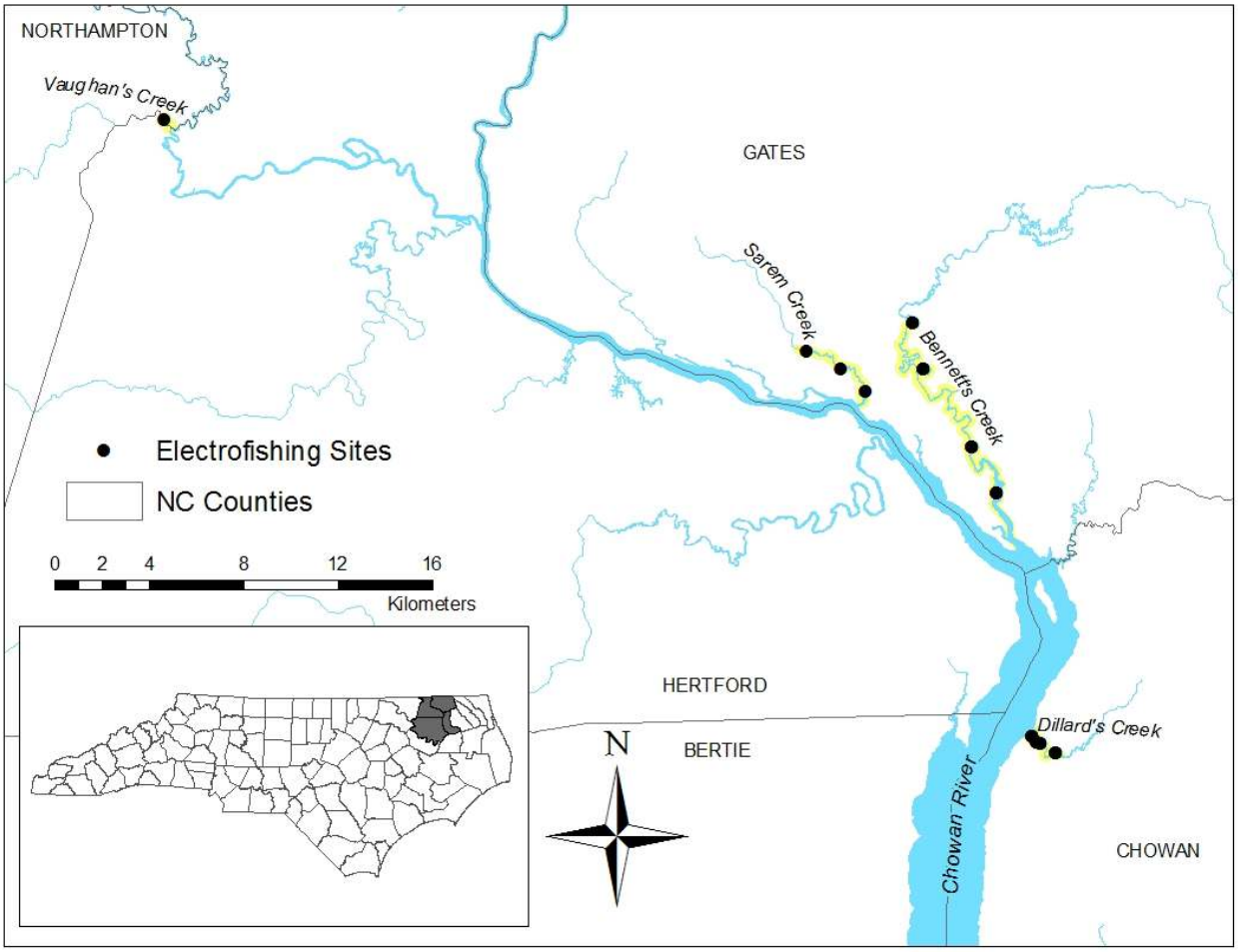

FIGURE 1. River herring sampling sites on the Chowan River, spring 2012–2019

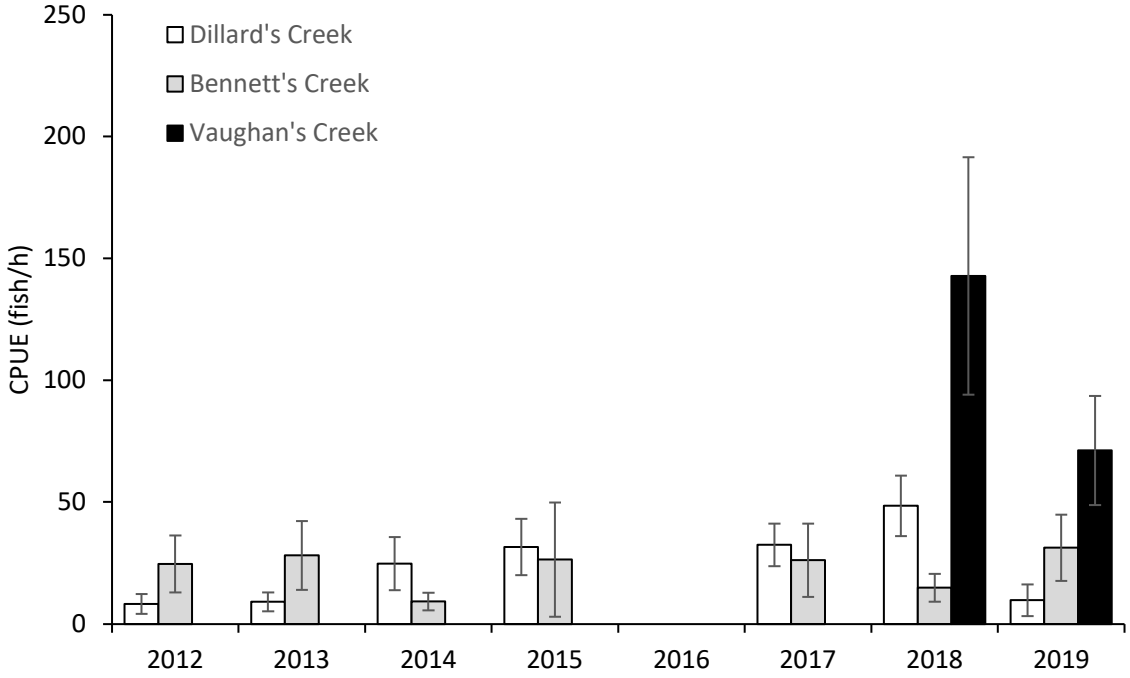

FIGURE 2. Relative abundance of Alewife collected from Dillard's and Bennett's creeks from 2012 to 2019 and Vaughan's Creek in 2018 and 2019. Error bars represent standard error.

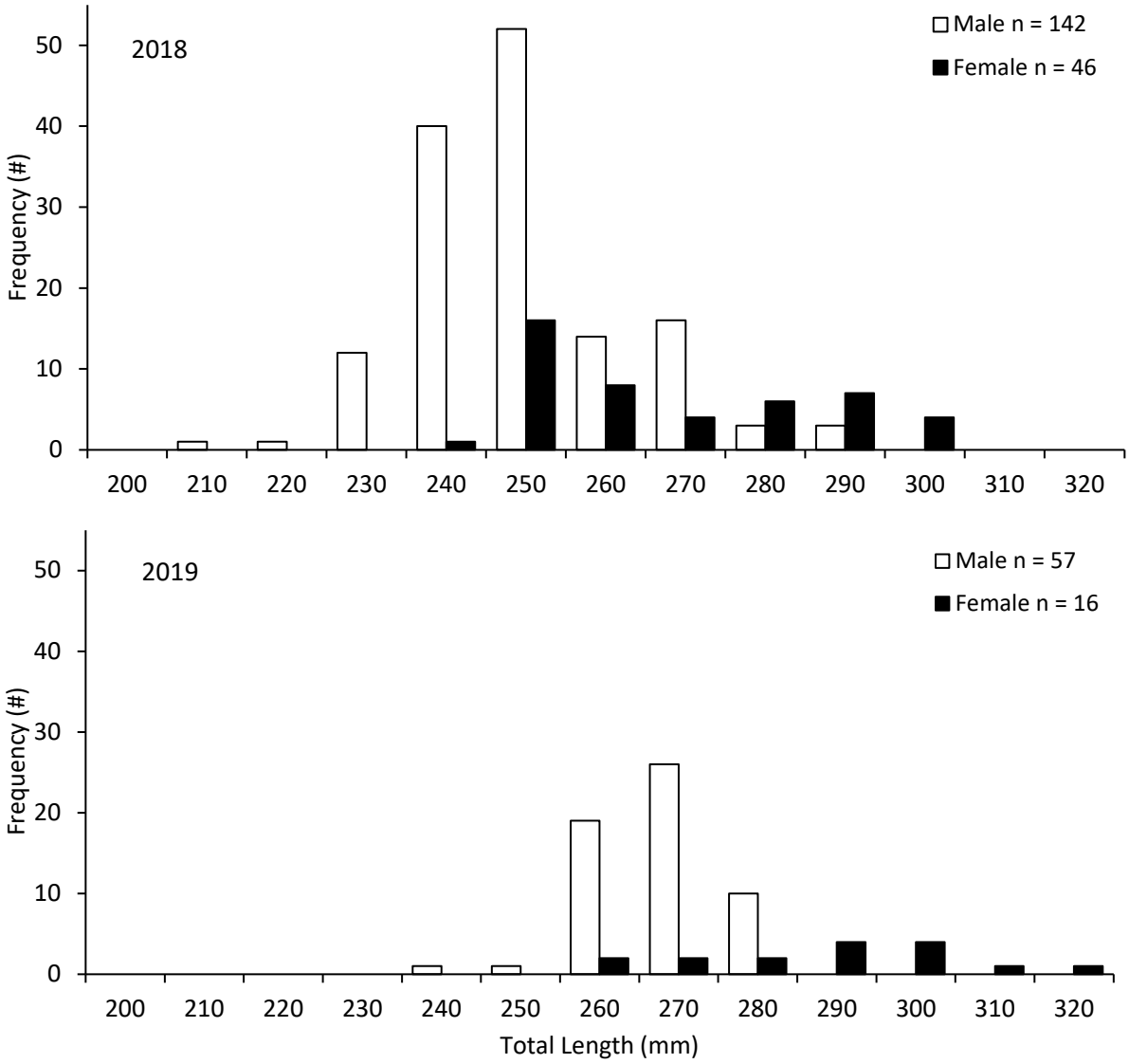

FIGURE 3. Length frequency histogram for Alewives collected from Dillard's Creek, spring 2018 and 2019.

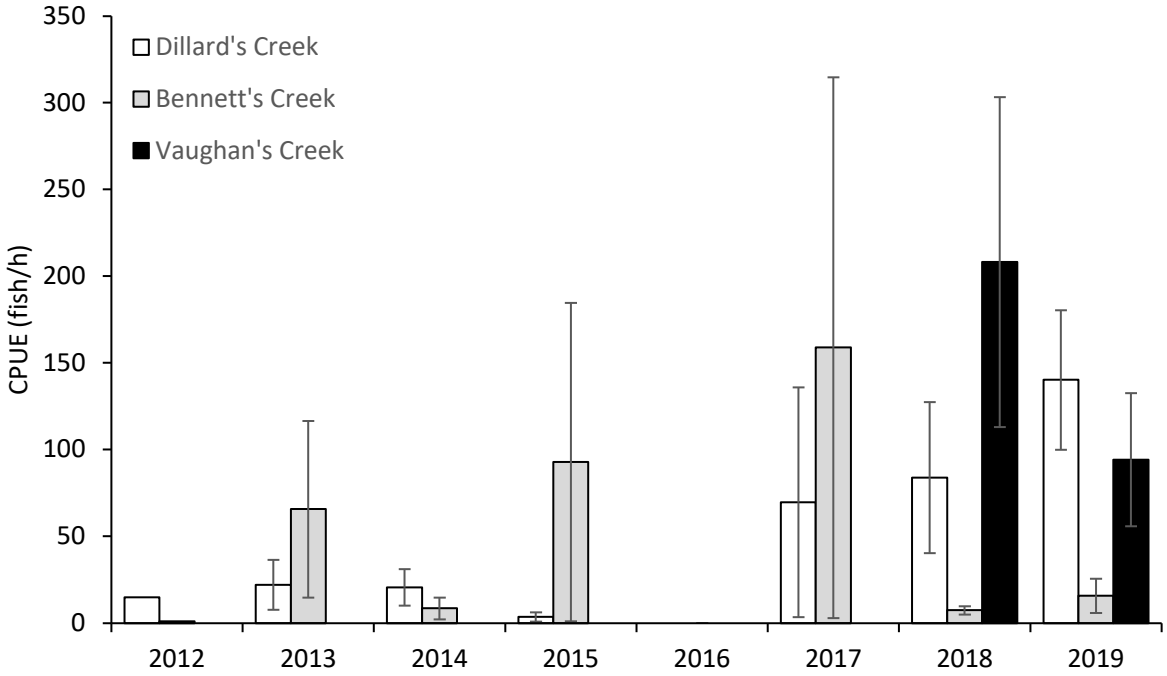

FIGURE 4. Relative abundance of Blueback Herring collected from Dillard's and Bennett's creeks from 2012 to 2019 and Vaughan's Creek in 2018 and 2019. Error bars represent standard error.

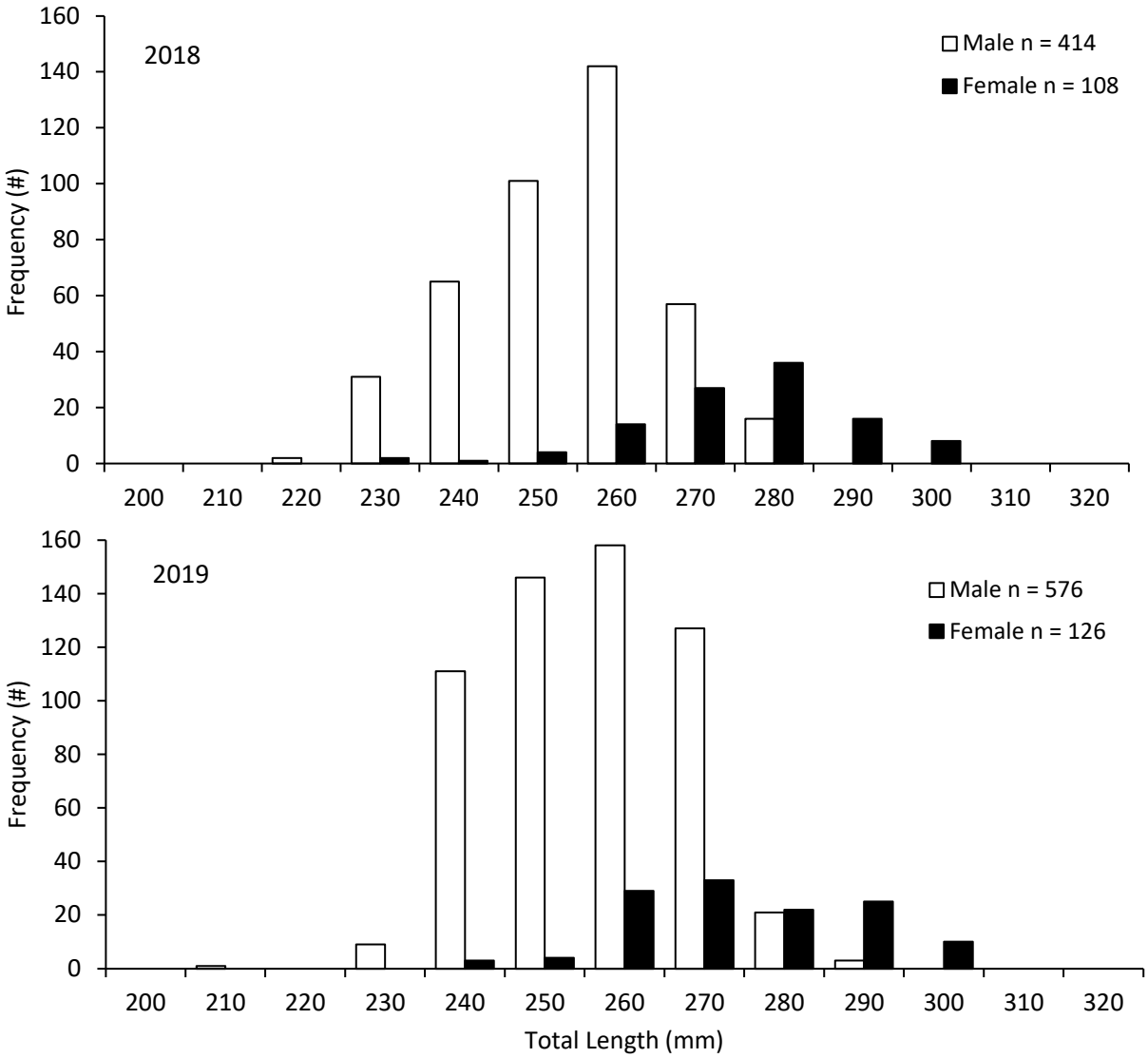

FIGURE 5. Length frequency histogram for Blueback Herring collected from Dillard's Creek, spring 2018 and 2019.

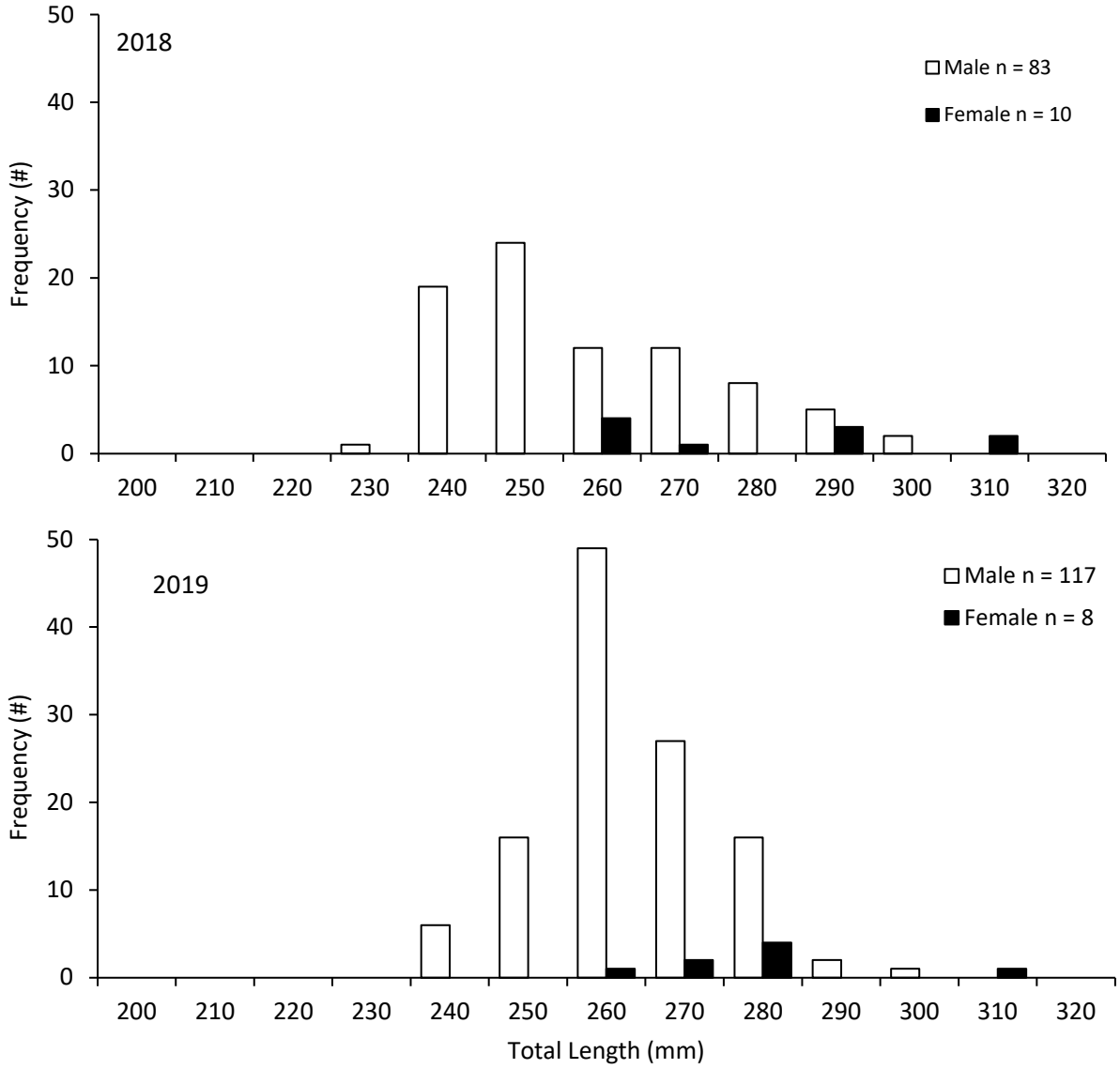

FIGURE 6. Length frequency histogram for Alewives collected from Bennett's Creek, spring 2018 and 2019.

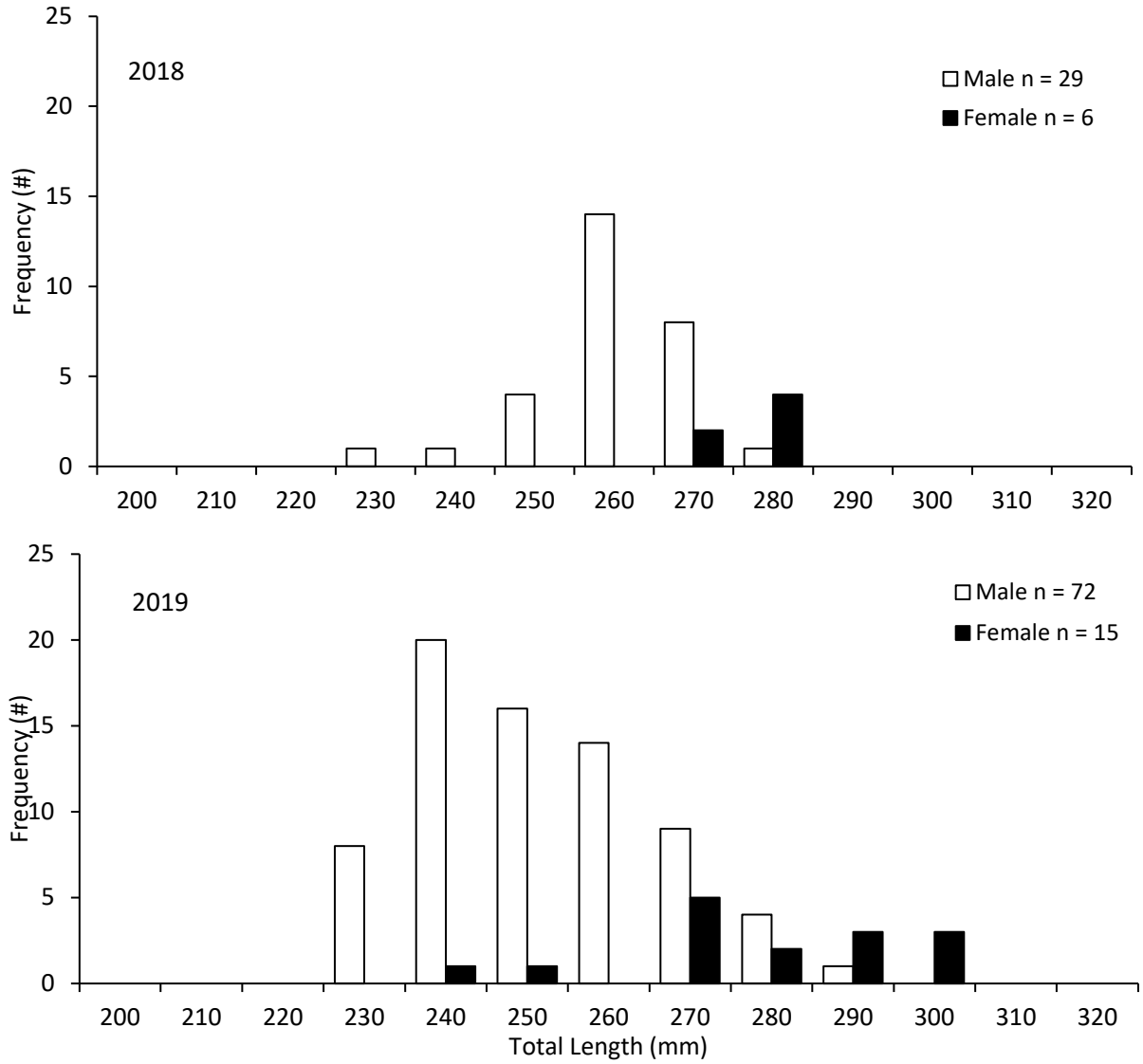

FIGURE 7. Length frequency histogram for Blueback Herring collected from Bennett's Creek, spring 2018 and 2019.

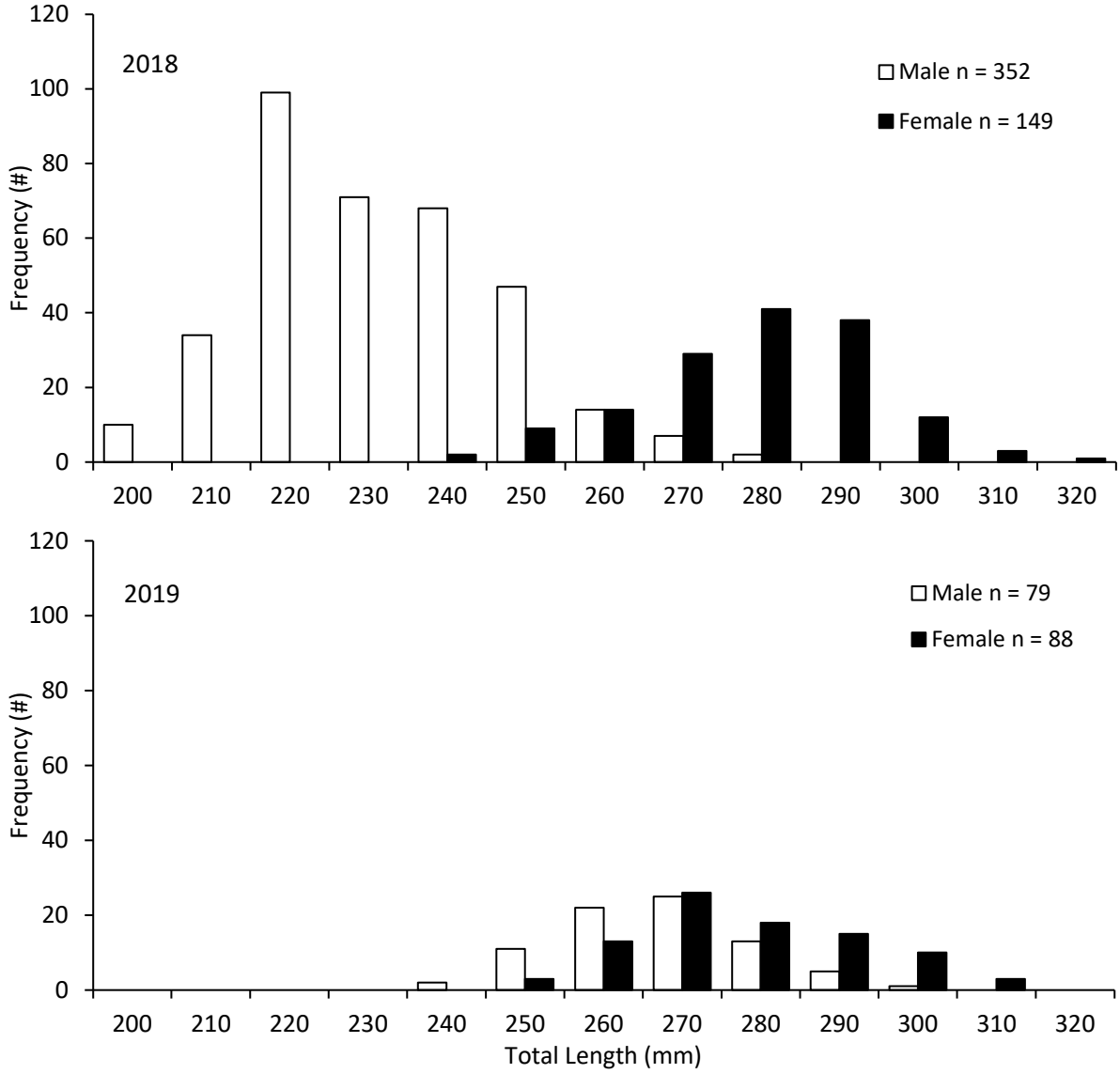

FIGURE 8. Length frequency histogram for Alewives collected from Vaughan's Creek, spring 2018 and 2019.

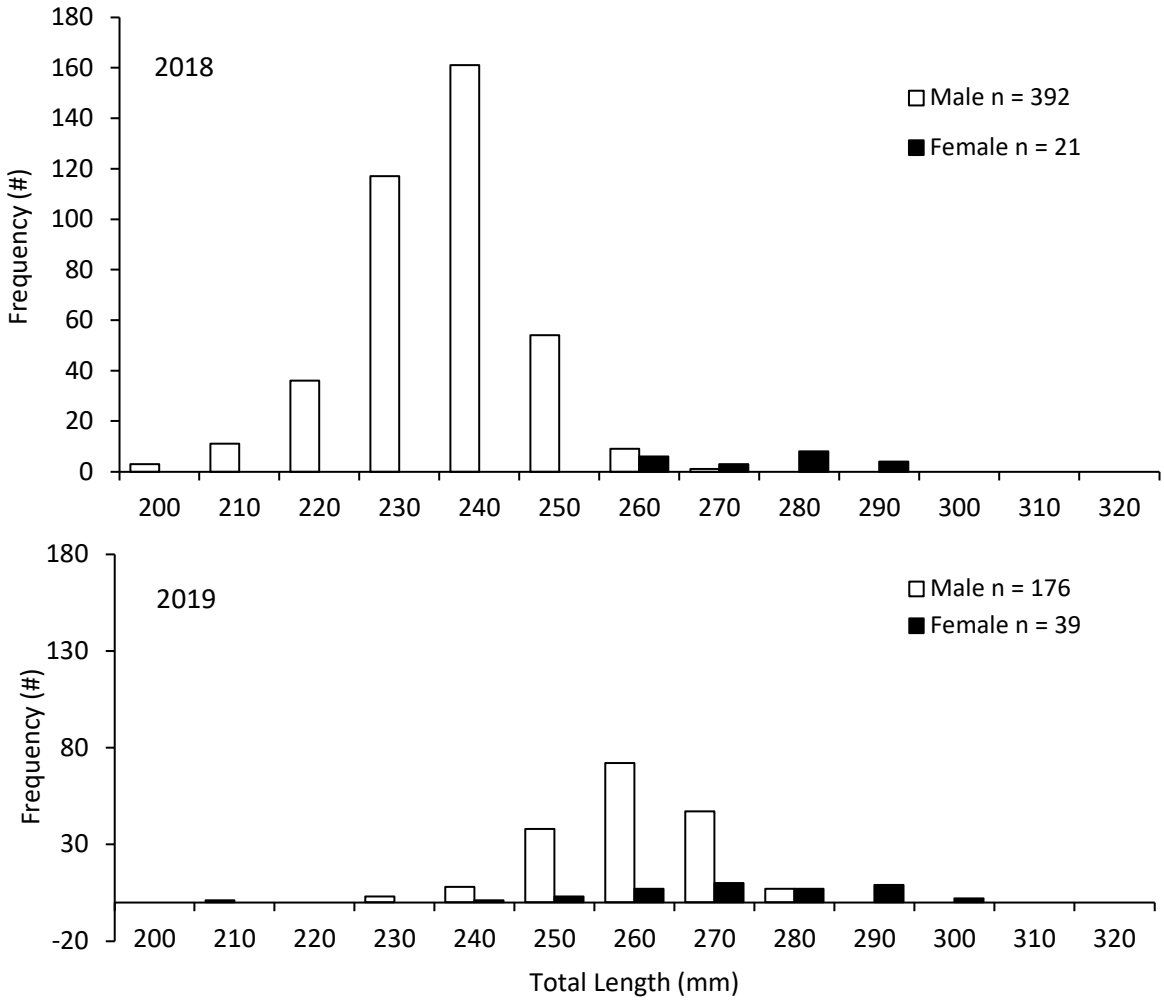

FIGURE 9. Length frequency histogram for Blueback Herring collected from Vaughan's Creek, spring 2018 and 2019.

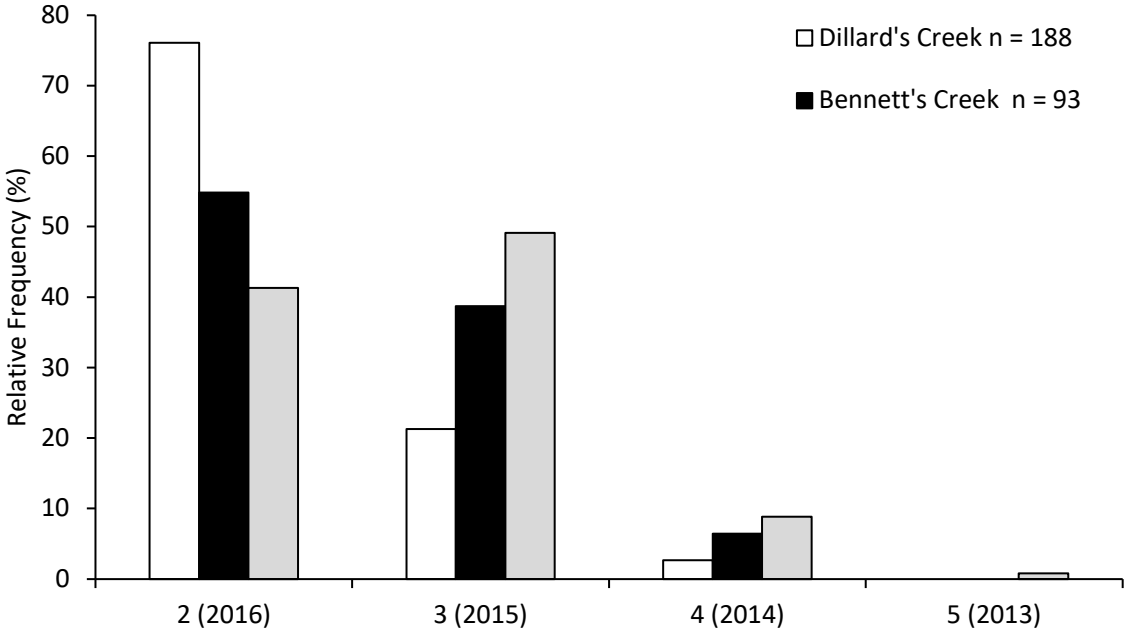

FIGURE 10. Age frequency of Alewives collected from Dillard's, Bennett's, and Vaughan's creeks in 2018.

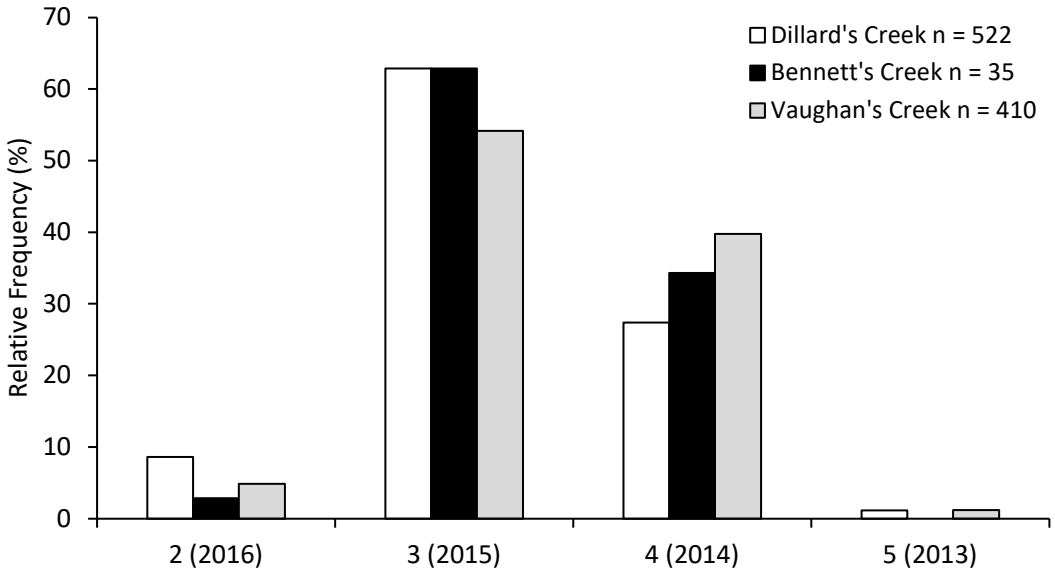

FIGURE 11. Age frequency of Blueback Herring collected from Dillard's, Bennett's, and Vaughan's creeks in 2018.