Why are river herring disappearing?
Early life stage dynamics of blueback herring and alewife near Cape Cod, Massachusetts

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Abstract: River herring populations have been declining over the past several decades, including in ecosystems around Cape Cod, Massachusetts. Early life stage development is critical for sustaining and growing populations, as it is necessary to have surviving juvenile river herring to develop into the reproductive adult population. By comparing length at time of migration, $\delta^{13}C$, and proxies for larval growth rate between early and late migrating juvenile river herring, between ecosystems, and between species, a more holistic view of the early life stage dynamics of river herring near Cape Cod, Massachusetts can be created. This study shows that there are differences in length at time of migration, $\delta^{13}C$, and larval growth rate between early and late migrators. There are also differences between ecosystems in terms of $\delta^{13}C$ and larval growth rates and between species in terms of $\delta^{13}C$. These results suggest that it may be beneficial to have monitoring and management strategies target specific times of year and ecosystems and that individual species of river herring may need distinct monitoring and management strategies.

Key words/phrases: River herring, blueback, alewife, otolith
Introduction

River herring, a collective term for alewife, *Alosa psuedoharengus*, and blueback herring, *Alosa aestivalis*, are experiencing population levels as low as 1% of historic sizes (Figure 1) (Limburg and Waldman 2009). Despite a 2013 revision to the Massachusetts river herring management plan (Diodati 2013), populations of river herring remain relatively low. River herring are listed as a species of concern by the National Marine Fisheries Service and the Atlantic States Marine Fisheries Commission (Limburg and Waldman 2009), and were petitioned to be covered under the Endangered Species Act in 2013 (NOAA 2013). While it is evident that dramatic declines have been occurring over the past several decades, the major contributing factors to these declines remain unclear (Hall et al. 2012).

River herring are anadromous species, which means that they spend the majority of their life in the open ocean, but migrate into freshwater ecosystems to spawn. Their offspring spend roughly the first two to three months of their lives developing from larvae to juveniles in these fresh water systems before beginning emigration towards the open ocean (Turner and Limburg 2012). Due to the variability in habitat over the life stages of river herring, it remains unclear in which habitats and in which life stage river herring populations are being the most impacted. This study examines the larval and juvenile life stages of river herring, as the survivors of these populations are the fish that will ultimately develop into the reproducing, mature adults. Without successful development in the larval and juvenile life stages that allows for survival into the reproductive adult river herring population, river herring populations cannot grow.

The variability in habitat of river herring throughout their life cycle is what also makes understanding contributions to their rapid population decline so critical. River herring are components to a number of different food webs and serve as a link between the lowest and
highest trophic levels (Limburg and Waldman 2009). Most notably, river herring serve as a form of prey for cod, a fish that brought in an estimated $18.6 million for Massachusetts in 2012 (NOAA 2012). River herring also have cultural significance for both indigenous and nonindigenous peoples (Limburg and Waldman 2009). Thus, river herring are ecologically, economically, and culturally significant.

This study aims to begin understanding the early life stage dynamics of river herring by comparing early and late emigrants, emigrants out of three spawning sites around Cape Cod, and blueback herring and alewife. By examining distinctions between early and late emigrants, we can begin to understand factors that may influence the decision to emigrate. Looking at three different spawning sites around Cape Cod allows us to see if river herring emigration shows similar trends across ecosystems or if ecosystems, in terms of river herring emigration, are distinct. Comparing blueback herring and alewife helps show if the early life stage dynamics between species are similar or different. Initiating an understanding of the early life stage dynamics of river herring allows an understanding of how population recruitment may change as factors critical to larval and juvenile river herring change. It can also help inform changes that should be made to river herring monitoring and management techniques.

The three spawning sites studied were Great Herring Pond, Johns Pond, and Coonamessett Pond (Figure 2). Great Herring Pond is one of the most productive spawning grounds for river herring near Cape Cod. The Monument River connects Great Herring Pond to the Cape Cod Canal. The Quashnet River connects Johns Pond to Waquoit Bay, while the Coonamessett River connects Coonamessett Pond to Great Pond, an estuarine system that has a channel connecting it to Vineyard Sound.
Methods

Juvenile river herring from the Monument River were collected on June 17th, 18th, 24th and 30th, 2014 and October 6th, 14th, 20th, 24th, 27th, and 31st, 2014. Samples from the Quashnet River and Coonamessett River were collected on November 4th and 11th, 2014, respectively. Samples were immediately placed in labeled plastic Ziploc bags and then on ice. Back in the lab, the bags were placed in a -20°C freezer.

Seventeen blueback herring and 15 alewife were identified from the June collections in the Monument River, 23 blueback herring and 7 alewife were identified from the October collections in the Monument River, 17 blueback herring were analyzed from the Quashnet River (no alewife were collected from this ecosystem), and 8 blueback herring and 8 alewife were analyzed from the Coonamessett River.

River herring samples were measured for standard length to the nearest mm with an electronic digital caliper. Excess moisture was then patted off of the fish, and the fish were weighed on an electronic balance to the nearest 0.01 g. Fish were then sliced open along the underbelly and identified by species by looking for the dark blue body cavity lining (i.e. peritoneum) in the blueback herring. All river herring without this dark blue lining were assumed to be alewife. These identifications reflect the sample sizes indicated above.

Muscle tissue was then cut out for isotopic analyses. Samples came from four bluebacks and three alewife from June, two bluebacks and three alewife from October in the Monument River, six bluebacks from November in the Quashnet River, and three bluebacks and three alewife in the Coonamessett River. Skin and scales were scraped off of the muscle tissue before placing the samples in the drying oven. Samples were dried for 48 hours at roughly 60°C. Once dried, samples were ground up using a mortar and pestle and then roughly one milligram of each
sample was weighed out and packed into tin capsules (Otter). A mass spectrometer was used to analyze for $\delta^{13}C$ and $\delta^{15}N$.

Each herring’s head was cut off using a scalpel and was then placed under a dissecting microscope to extract one sagitta otolith. The otolith allows us to calculate the age, larval growth rate, and hatch date of the fish from the daily rings. The number of rings indicates the age in days of the fish, while the distance between rings indicates the daily growth rate. The hatch date can be back calculated from the date of collection and age. The sagitta otolith was then placed on a labeled slide with the concave side up and was covered in immersion oil. Immersion oil helps clear the otoliths to make the rings more visible. Otoliths sat in immersion oil for roughly one week before the first read and two weeks before the second read.

Otoliths were read using a Leica DM 2500 compound microscope and were analyzed using the LAS W3 computer program. Otoliths were analyzed at 20x or 40x magnification for age and growth rate. Age was calculated by counting the number of daily growth rings seen along the clearest axis of the otolith, starting in the center of the otolith and moving outwards. Growth rate was calculated along the longest axis using the two-point line and parallel line tools within the LAS W3 computer software. The two-point line draws a line perpendicularly out of the center of the otolith so that the rings can more easily be followed. The parallel line tool was used to mark the outer edge of the first 15 to 20 dark rings, which allowed us to get the larval growth rate, after some additional calculations. The otoliths were read once all the way through and then were all read a second time. The second read was considered the official read, and all data are based off of the second read.

In Microsoft Excel, length and age were plotted against one another to look for trends between early and late migrators. $\delta^{13}C$ and $\delta^{15}N$ were plotted against one another in Microsoft
Excel as well. $\delta^{13}C$ can give indication of food source, while $\delta^{15}N$ can give an indication of trophic level. By plotting early and late migrators, between ecosystem, and between species against one another, comparisons and contrasts between these groups in terms of food source and trophic level can be made. The Mann Whitney U-Test, for pairwise comparison, was used to test for statistical significance. This is a nonparametric test.

The LAS W3 computer program produced a Microsoft Excel spreadsheet with increment radii data. By calculating the difference between radii (i.e. increment widths), larval growth rate data was produced. To correct for inconsistency and the possibility of having missed some of the most inner rings, no increment radii smaller than seven microns were counted. Past research indicates that rings beginning at seven microns represent around six days of age (Price 2014). Both larval growth rate and increment radii were plotted against age. Increment radii against age serves as another proxy for larval growth rate, termed size-at-age. These data were compared between early and late migrators and between ecosystems. Again, the Mann Whitney U-Test, for pairwise comparison, was used to analyze for statistical significance.

Results

Length versus age was plotted to look for trends between early and late migrators (Figure 3). Early migrators were both smaller and younger than late migrators at time of migration.

$\delta^{15}N$ and $\delta^{13}C$ were plotted for comparisons between early and late migrators (Figure 4), between ecosystems (Figure 5), and between species (Figure 6). Late migrators were more enriched in $\delta^{13}C$ than late migrators, but had comparable $\delta^{15}N$ values (Figure 4). Fish from the Quashnet River and Monument River had more enriched $\delta^{13}C$ than fish from the Coonamessett River (Figure 5). Fish from the Quashnet River were more enriched in $\delta^{15}N$ than fish from the Monument River and Coonamessett River (Figure 5). Bluebacks were more enriched in $\delta^{13}C$
than alewife within the same ecosystem, while bluebacks and alewife had comparable $\delta^{15}N$ values (Figure 6).

There was a significant difference in $\delta^{13}C$ values between early (n=3) and late migrating alewife (n=3) ($p=0.05$, Mann Whitney U-Test), but not for $\delta^{13}C$ between early (n=4) and late migrating bluebacks (n=2) ($p=0.165$).

There was a significant difference in $\delta^{13}C$ values between the Coonamessett River (n=2) and Quashnet River (n=6) ($p=0.05$, Mann Whitney U-Test) when $\delta^{13}C$ was averaged between bluebacks and between alewife in the Coonamessett River. There was no significant difference in $\delta^{13}C$ values between the Coonamessett River (n=2) and Monument River (n=2) ($p=0.1$) or between the Monument River (n=2) and Quashnet River (n=6) ($p=0.1$).

There was a significant difference in $\delta^{13}C$ between bluebacks (n=3) and alewife (n=3) in the Coonamessett River ($p=0.05$, Mann Whitney U-Test) and early migrating bluebacks (n=4) and alewife (n=3) in the Monument River ($p=0.03$), but not for $\delta^{13}C$ between bluebacks (n=2) and alewife (n=3) that migrated late in the Monument River ($p=0.6$).

Larval growth rate and size-at-age were compared between early and late migrators (Figures 7, 8, 9, and 10) and between ecosystems (Figures 11, 12, 13, and 14). Both larval growth rate and size-at-age for early and late migrating bluebacks and alewife showed that early migrators are slower growing than late migrators during the larval period, regardless of species (Figures 7, 8, 9, and 10). The Coonamessett River has slower growing larvae compared to larvae in the Monument and Quashnet Rivers, regardless of species (Figures 11, 12, 13, and 14).

There was also a statistical difference in larval growth between early (n=14 at age 14 days; n=10 at age 16 days) and late (n=17 at age 14 days; n=14 at age 16 days) migrating river herring ($p=0.03$; $p=0.04$, Mann Whitney U-Test). There was no statistical difference for early
versus late migrating alewife for the larval growth proxy at any age, and no statistical difference for bluebacks or alewife using the size-at-age proxy at any age.

Finally, there was a statistical difference between the larval growth rates of bluebacks in the Monument River (n=19) versus in the Coonamessett River (n=4) at age 12 days (p=0.05, Mann Whitney U-Test). There was no statistical difference between the Quashnet River and Coonamessett River for bluebacks or alewife at any age and no statistical difference between any ecosystems with the size-at-age proxy at any age.

**Discussion**

Early migrating river herring were shown to be smaller and younger than late migrators at time of migration, which suggests that river herring near Cape Cod may not be trying to reach a certain level of nutritional condition or a certain age before migration. When examining hatch and migration dates of early and late migrators in the Monument River, early migrators are still living in the spawning site, Great Herring Pond, when the late migrators are hatched. This raises the question of whether competition for resources and space may be driving early migrators out of Great Herring Pond, despite being smaller and younger than what may be optimal for their survival in the open ocean. As the late migrators hatch and density in Great Herring Pond increases, early migrators may chose to leave because of the increased competition. Examining gut contents of the early migrating juveniles versus the late migrating larvae and gathering data on density of river herring and carrying capacity in Great Herring Pond would help support this theory.

Early migrators, across both species and both proxies for growth rate, are slower growing than late migrators. When we look at water temperatures during the first two to three weeks after the mean hatch dates for early and late migrators, early migrators were growing in water
temperatures around 8°C, while late migrators were growing in water temperatures around 22°C. This temperature difference suggests that early migrators may be slower growing and smaller than late migrators because of water temperature, suggesting that warmer water temperatures are more conducive to river herring growth during their early life stages. This may mean that warming water temperatures as a result of climate change may actually be positive for river herring larval growth.

The difference in δ¹³C between early and late migrators suggests that early migrators may have a more pelagic diet, while late migrators may have to rely on a more littoral diet as the year progresses. Literature suggests that δ¹³C values approaching -30‰ in ponds suggest pelagic reliance, while δ¹³C values approaching -24‰ suggest littoral consumption (Zanden et al. 1999). River herring are naturally pelagic consumers (Jordan and Evermann 1900), so it makes sense that the early migrators would have δ¹³C values that reflect the ability to exploit pelagic resources. The more littoral δ¹³C values of late migrators may reflect the eventual depletion of pelagic resources as the year progresses, forcing late migrators to rely on more littoral resources during the last weeks of their time in Great Herring Pond. However, studies have also shown that baseline δ¹³C values can change as the year progresses, and these changes can propagate up the food web, in ecosystems influenced by seasonal flow. Gathering zooplankton samples from Great Herring Pond, comparing the δ¹³C values between pelagic and littoral zooplankton, and sampling earlier in the year versus later in the year would help explore these two theories.

The Quashnet and Monument Rivers have enriched δ¹³C values compared to the Coonamessett River. Again, gathering zooplankton samples and running isotopic analyses would help explain whether river herring may be eating different zooplankton in different ecosystems or whether the differences in their δ¹³C values are simply reflections of baseline
differences in $\delta^{13}$C between ecosystems. Isotopic analyses would also help show whether the more enriched $\delta^{15}$N in the Quashnet River is actually a trophic level difference or simply a baseline difference. A baseline difference could be explained due to the high amount of development, and thus potentially higher use of fertilizers and septic tanks, around Johns Pond.

River herring in the Coonamessett River, across both species and both proxies, appear to be growing slower than river herring from the Monument River and Quashnet River. Similar to how the difference in growth rates between early and late migrators may have been an effect of significantly colder water temperatures during the larval period of early migrators, river herring in the Coonamessett River may be experiencing colder water temperatures than river herring in the Monument and Quashnet Rivers. Deploying a YSI sonde during the spring months in these three ecosystems would help provide support for whether water temperature may be a driver of these slower growth rates in the Coonamessett River.

Finally, the differences in $\delta^{13}$C values between bluebacks and alewife in the same ecosystem may be a reflection of spatial and dietary partitioning between species of river herring that would otherwise be forced to share the same habitat and resources. Based on a study by Zanden et al. (1999), alewife appear to be more pelagic consumers, while bluebacks appear to be more littoral consumers within the same ecosystem. We know that bluebacks and alewife are coexisting in the spawning sites from the mean hatch and migration dates. Thus, bluebacks and alewife may be choosing to occupy slightly different habitats or to consume prey from slightly different habitats to reduce competition between the two species. Again, collecting zooplankton samples from spawning sites and comparing $\delta^{13}$C values between pelagic and littoral zooplankton would help explain or refute this theory.
Overall, many interesting trends arose from this preliminary research on the early life stage dynamics of blueback herring and alewife in three spawning sites around Cape Cod, Massachusetts. Continuing this research by increasing sample sizes, gathering zooplankton data, and collecting year-round water quality data for all three spawning sites would help support or disprove many of the potential theories that arose from this initial research.

**Conclusions**

Similar research on the early life stage dynamics of river herring with increased sample size is necessary to help validate trends seen in this study. With validation of these trends may come support for monitoring and management techniques that target specific times of year and specific spawning grounds near Cape Cod. Additionally, trends may show that blueback herring and alewife need distinct management techniques, particularly if it appears that they may occupy different habitats within spawning grounds. Finally, it is important to continue to understand how distinctions between groups of migrating juvenile river herring ultimately affect one group’s ability to develop into the reproducing adult population over the other group.

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Figure 1: Historic commercial landings of river herring in North America
Figure 2: River herring spawning sites and their connections to the open sea

1. Great Herring Pond and Monument River
2. Coonamessett Pond and River
3. Johns Pond and Quashnet River
Figure 3: Length at age for early versus late migrators
Figure 4: $\delta^{15}$N versus $\delta^{13}$C for early versus late migrators
Figure 5: $\delta^{15}\text{N}$ versus $\delta^{13}\text{C}$ for late migrators by ecosystem
Figure 6: $\delta^{15}\text{N}$ versus $\delta^{13}\text{C}$ for bluebacks versus alewife
Figure 7: Larval growth rate of early versus late migrating bluebacks
Figure 8: Larval growth rate of early versus late migrating alewife
Figure 9: Size at age of early versus late migrating bluebacks
Figure 10: Size at age of early versus late migrating alewife
Figure 11: Larval growth rates for late migrating bluebacks by ecosystem
Figure 12: Larval growth rate for late migrating alewife by ecosystem

![Graph showing larval growth rates for alewife in different ecosystems. The graph plots age (days) on the x-axis and increment width (microns) on the y-axis. Three ecosystems are compared: Quashnet River, Monument River, and Coonamessett River. Each ecosystem is represented by a different line color and marker style. The graph shows fluctuations in growth rates over the age range of 6 to 18 days.]
Figure 13: Size-at-age for late migrating bluebacks by ecosystem
Figure 14: Size-at-age for late migrating alewife by ecosystem