Assessing the Population Dynamics and Sampling Efficacy of Skipjack Herring (*Alosa Chrysochloris*) in Oklahoma's Arkansas River: Growth, Mortality, and Recruitment

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Abstract: Skipjack Herring (*Alosa chrysochloris*) can be found throughout the Atlantic coastal waters of North America along with several inland river systems. In Oklahoma, Skipjack Herring are found in the Arkansas River and the Red River drainages. Little is known about the population dynamics of Skipjack Herring across their range and no information is available for populations occurring in Oklahoma. Therefore, our objectives were to: (1) qualitatively evaluate hook-and-line sampling to capture Skipjack Herring, and (2) assess population dynamics (i.e., age and growth, length-weight relationship, size structure, recruitment) of Skipjack Herring in the Arkansas River, Oklahoma. Targeted angling using Sabiki rigs was conducted in July and August 2023 to capture Skipjack Herring in active feeding areas, resulting in the collection of 157 individuals. Age estimates ranged from 0.5 to 3.5 years, and lengths ranged from 107 to 485 mm TL. The von Bertalanffy growth model estimated an asymptotic length of 430.5 mm TL, a Brody growth coefficient (*k*) of 1.1, and a theoretical length at age zero (t_0) of 0.0. The annual survival rate was 47.8%, and the instantaneous total mortality rate was 0.7. Recruitment stability, indicated by a Recruitment Variability Index of 0.8, suggests a relatively stable recruitment pattern. This study confirms that hook-and-line sampling, with Sabiki rigs, is an effective method for capturing Skipjack Herring, and may outperform previously reported traditional gears such as gill nets and electrofishing. Our study provides the first detailed demographic data for

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Skipjack Herring in Oklahoma, including growth rates, mortality, and recruitment patterns. These findings are crucial for managing Skipjack Herring populations and highlight the need for further research into sampling methods and population trends of this species, particularly in the context of climate change and its potential effects on the species.

Introduction

Skipjack Herring (*Alosa chrysochloris*; Figure 1) are members of the Clupeidae family, which comprises herrings, shads, menhaden, sardines, and other economically important species (Page and Burr 2011, Bloom and Lovejoy 2013). The Clupeidae family contains ~210 species, of which seven are found within or along the contiguous United States, and four species reside in Oklahoma (Waldman 2003, Miller and Robison 2004, Page and Burr 2011). North American Clupeids are broadly distributed and found in marine and freshwater environments across the majority of the United States (Page and Burr 2011). Skipjack Herring inhabit the Atlantic coastal waters of North America, ranging from the Gulf of St. Lawrence to the Gulf of Mexico; including river systems along the Atlantic coast, such as the St. Lawrence River, Hudson River, and Mississippi River (Pigg et al. 1991, Pflieger 1997, Miller and Robison 2004). In Oklahoma, Skipjack Herring are known to inhabit the Arkansas River and the Red River drainages (Pigg et al. 1991, Miller and Robison 2004).

Figure 1. Picture of a Skipjack Herring captured from the Arkansas River in Oklahoma (photo courtesy of Brandon Brown).

There is currently a lack of information about the population dynamics of Skipjack Herring across their range (Waldman and Limburg 2003), however; there is some research available regarding their growth, fecundity, and diet (Mettee and O'Neil 2003). There has been no research conducted on Skipjack Herring population dynamics and vital rates in Oklahoma. However, Pigg et al. (1991) suggested their abundance appeared to be increasing within Oklahoma based on their increased relative abundance in standardized samples. This coincides with the observation that they are generally abundant in Tennessee and the Missouri River (Pflieger 1975, Etnier and Starnes 1993), though their populations appear to be decreasing in far inland portions of the Mississippi River (Mette and O'Neil 2003). In May of 2023, a Skipjack Herring weighing 1573.4 g with a length of 517.5 mm was captured by an angler using hook and line and declared a new Oklahoma state record fish (ODWC 2023). This state record fish highlighted the need for additional information on their population dynamics (i.e. age and growth, mortality, and recruitment) and life history in Oklahoma.

The lack of research and information on Skipjack Herring may be attributed to the difficulty of capturing individuals resulting in low catch rates using fisheries sampling gears (Miller and Robison 2004) . For example, Skipjack Herring were not captured in pre-impoundment surveys conducted by the Oklahoma Department of Wildlife Conservation (ODWC) of the Arkansas and Cimarron rivers (Linton 1961) potentially suggesting a sampling gear bias. Standardized fish surveys conducted post-impoundment by ODWC and the Oklahoma Department of Health captured 0 to 45 Skipjack Herring annually from 1979 to 1989 (Pigg et al. 1991). Over the past 40 years, ODWC has captured Skipjack Herring in 20 of their standardized sampling years using electrofishing, experimental gill nets, and seining (~18 individuals per year) indicating an irregular capture history and low per-sample abundance of this species (OFAA 2024). Due to the low sample sizes of individuals captured in standardized sampling events, researchers have been unable to quantify Skipjack Herring population dynamics (age and growth, mortality, and recruitment) and vital rates. However, local Oklahoma anglers have reported abundant Skipjack Herring catch rates using hook and line angling methods in late summer along the Arkansas Basin, indicating that increased sample sizes of these fish can be obtained with this method.

Characterizing fish population dynamics (e.g., age and growth, length-weight relationships, recruitment) is critical to understanding and properly managing fish populations (Campana et al. 1995, Neumann et al. 2012). All fishery gear types have sampling biases, so when considering sampling options it is important to identify methods that most accurately and precisely sample the fish population of interest (see Pope et al. 2010, Hayes et al. 2012, Hubert et al. 2012). Given the poor performance of traditional fishery gears in sampling Skipjack Herring and subsequent lack of population information for Oklahoma populations (Pigg et al. 1991), the objectives of this study were to: (1) qualitatively evaluate the effectiveness of hook-and-line sampling to capture Skipjack Herring, and (2) assess age and growth, length-weight relationship, size structure, and recruitment of Skipjack Herring in the Arkansas River, Oklahoma. The results of this study will provide necessary baseline population metrics that will be beneficial to fisheries managers to understand their population dynamics in Oklahoma.

Methods

Skipjack Herring were captured between July and August 2023 above Robert S. Kerr Reservoir at the confluence of the Lower Illinois and Arkansas Rivers, United States (35°29'38.9" N, 95°06'14.1" W). Local anglers reported high hook-and-line catch rates of Skipjack Herring in this location, which guided our sampling efforts. Initial hook-and-line sampling trips were conducted from a boat using small (~10 - 25 mm) soft-plastic artificial lures, but this failed to capture any Skipjack Herring. Therefore, Sabiki rigs (Ocean Cat, Quality Tackle for All Anglers, and handmade rigs) consisting of either six 1/32-oz white feather jigs (with size 4 or 6 hooks) tied in a series, with a ½ oz weight affixed to the end of the mainline were used to target groups of actively feeding (i.e. feeding and leaping near the surface) Skipjack Herring (Pflieger 1997). Sabiki rigs were most effective when casted into areas of actively feeding fish and allowed to sink to the reservoir bottom, then retrieved with a slow repetitive sweeping motion. Sampling trips were conducted for four hours on four dates with 2 to 3 anglers each trip.

Once captured, Skipjack Herring were placed into a 1:1 ice water slurry to be euthanized (Blessing et al. 2010) and transported to the ODWC office in Porter, OK. Each fish was weighed to the nearest gram and their total length (TL) was measured to the nearest millimeter. Sagittal otoliths were extracted and dried (> 24 hours) for age estimation. Whole otoliths were placed in a viewing dish concave side up, covered with water, and viewed with a dissecting microscope (4–45x) using an external light source to illuminate annuli. When illuminated, annular marks on otoliths appeared as opaque bands on a lighted background (Snow et al. 2018). Annular marks were counted to assign an age estimate to each fish. A double-blind counting approach was used to confirm age estimates from each otolith (Dunlop et al. 2023). A half-year was added to each age estimate to account for growth since annuli formation occurs in the spring, and these fish were sampled in the later summer. (*sensu* Sammons and Macenia 2009; Hanson and Stafford 2017).

A common von Bertalanffy growth model was fit to the adjusted estimated ages and total lengths using the equation:

$$L_t = L_\infty\left(1 - e^{(-k(t-t_0))}\right)$$

where L_t represents estimated length at time t, $L\infty$ represents the asymptotic theoretical length, k is the Brody growth coefficient, and t_0 represents the theoretical time at which length is zero (Quist et al. 2012). The von Bertalanffy growth curve was fit via nonlinear least squares estimation using the FSA package (Ogle et al. 2023) in program R. We obtained 95% confidence intervals (95% CI) and 95% predictive intervals (95% PI) from our von Bertalanffy growth model using the propagate package (Spiess 2022) in program R (R Core Team 2022).

We estimated annual survival (S) for Skipjack Herring using the Chapman-Robson method (Chapman and Robson 1960, Robson and Chapman 1961):

$$S = \frac{T}{n + T - 1}$$

Where T represents the sum of the recorded estimated ages of fish on the descending limb of the catch curve (i.e., log(abundance) versus age) and n represents the number of fish observed on the descending limb of the catch curve. Instantaneous total mortality rate (Z) was then estimated by taking the negative natural logarithm of S (*sensu* Miranda and Bettoli 2007). Estimates of S, Z, and 95% CIs for S and Z were obtained using the FSA package (Ogle 2023) in program R (R Core Team 2022).

Variation in recruitment for Skipjack Herring was estimated using the recruitment variability index (RVI):

$$RVI = \left(\frac{S_n}{(N_m + N_p)}\right) - \left(\frac{N_m}{N_p}\right)$$

where S_n represents the sum of cumulative relative age frequencies across all age classes, N_m represents the number of missing year-classes in the sample, and N_p represents the number of present year-classes within the sample. The values of the RVI range from -1 to 1, with values close to 1 representing more stable recruitment (Maceina and Pereira 2007). The assumptions of RVI are that more year classes are present than absent (i.e., $N_p > N_m$), fish are fully recruited to the sampling gear, catch-at-age represents year-class strength, and there are no year-classes beyond the last age-group represented (Guy and Willis 1995). RVI is not recommended when there are less than three year-classes in a sample (Guy 1993).

The length-weight relationship of Skipjack Herring was estimated using a least-squares linear regression of the Log10 transformed TL (mm) and weight (g; Neumann et al. 2012). We then estimated a 95% CI and 95% PI for the weight-length regression in program R (R Core Team 2022). After this, we back transformed the length-weight regression for visual interpretation.

Results

We found that angling for Skipjack Herring was an effective sampling method averaging ~9.8 fish per hour over 16 boat-angling hours across four days (i.e., 157 individuals). Counter-intuitively, based on length at age data, size 6 Sabiki rigs anecdotally appeared to be more useful for capturing smaller individuals (107-220 mm TL), and size 4 Sabiki rigs were more useful for capturing larger individuals (>220 mm TL). Both sizes of Sabiki rigs caught multiple individuals per cast when targeting areas where Skipjack Herring were surface feeding.

Of the 157 fish captured, we successfully estimated the age of 148 and used these fish in generating our population assessments. We found that the Skipjack Herring sagittal otoliths were very small and fragile resulting in seven individuals having their otoliths damaged during the removal or aging processes (Figure 2). Skipjack Herring used for aging ranged from 0.5 to 3.5 years old (Figure 3) and TL ranged from 107-485 mm (Figure 4). Length-weight regression parameters (on Log10 scale) were log(a) = -4.9 (95% CI = -5.0 – -4.8) and b = 2.9 (95% CI = 2.9 – 3.0, Figure 6). The fit of this model was excellent (r^2 = 0.99).

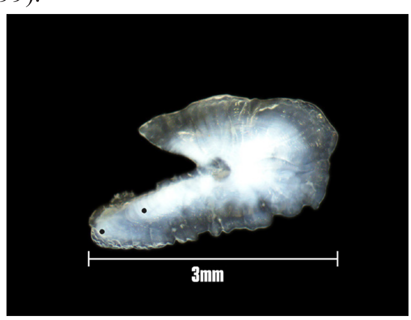

Figure 2. Image of a sagittal otolith obtained from a Skipjack Herring measuring 306 mm TL and age estimated to be 2.5 years captured from the Arkansas River, Oklahoma. Black dots indicate annuli counted.

Our von Bertalanffy growth model suggested asymptotic theoretical length was 430.5 mm (95% CI = 413.3 – 456.8 mm), the Brody growth coefficient (k) was 1.1 (95% CI = 0.8 – 1.3), and t_0 was 0.0 (95% CI = -0.1 – 0.1; Figure 5). The Champman-Robson estimate of annual survival was 47.8% (95% CI = 42.0 – 53.7%) resulting in an instantaneous total mortality of 0.7 (95% CI = 0.4 – 1.1). Our estimated RVI for Skipjack Herring was 0.8, suggesting recruitment in the population is relatively stable.

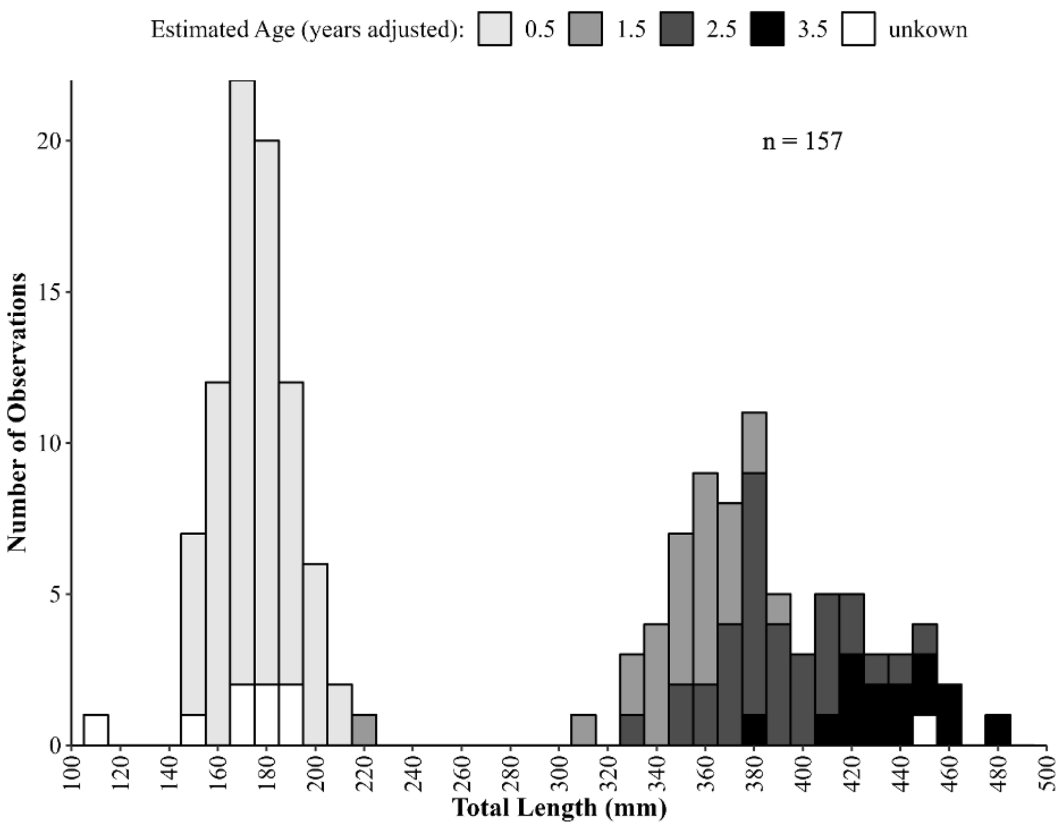

Figure 3. Length frequency histogram (10-mm bins) of Skipjack Herring collected using Sabiki rigs from the Arkansas River basin, Oklahoma in late summer and early fall of 2023. Bar height represents the number of observations for each length group and shading represents the proportion of adjusted age estimates within each length group. The unknown fish are individuals that we were unable to determine an age.

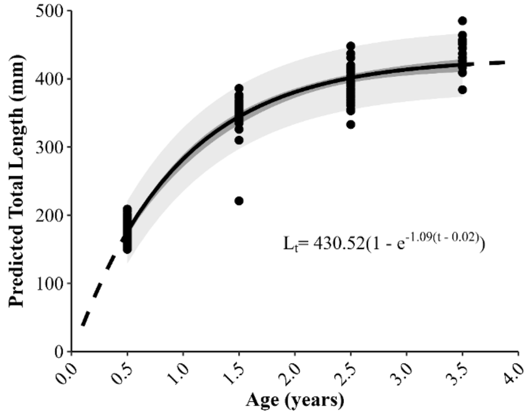

Figure 4. Mean predicted total length at age (solid and dashed black lines) for Skipjack Herring based on the von Bertalanffy growth model. The solid and dashed lines represent mean predicted total length for observed and unobserved ages, respectively. Included are 95% CI (dark grey) and 95% PI (light grey) estimates for observed ages, along with observed total length and age estimates for Skipjack Herring (black circles). Parameter estimates for the von Bertalanffy growth model are included.

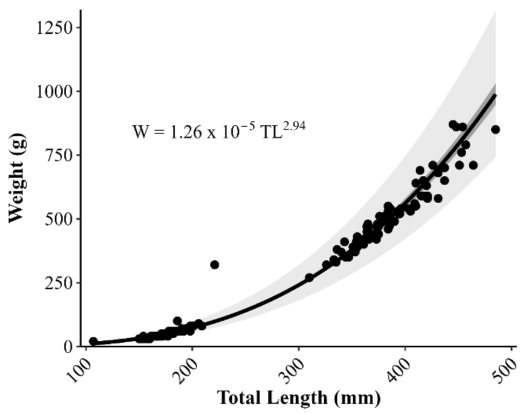

Figure 5. Mean weight-length relationship (black line) for Skipjack Herring along with the corresponding parameter estimates. Included are 95% CI (dark grey) and 95% PI (light grey) estimates for the relationship, along with observed total lengths and weights (black circles).

Discussion

This study increased our knowledge of Skipjack Herring population characteristics in Oklahoma and expanded on the limited amount life history information currently available for the species across their range (Mettee and O'Neil 2023, Waldman 2023, Waldman and Limburg 2023). To the best of our knowledge, this is the first study to estimate population dynamics and vital rates of Skipjack Herring in Oklahoma. Furthermore, this is the first study to use sagittal otoliths to estimate growth, mortality, and recruitment of Skipjack Herring whereas previous studies that have estimated ages for Skipjack Herring have used scales (Wolfe 1969). Although otoliths of Skipjack Herring have not been validated directly, other members of the family Clupeidae (e.g., American Shad [Alosa sapidissima], Duffy et al. 2012) have been validated for accuracy and used to characterize vital rates. Finally, this paper represents the first assessment of this method for sampling Skipjack Herring in Oklahoma. Hook-and-line sampling has been used to collect Skipjack Herring in Florida (Wolfe 1969) and has also been used to capture other members of the family Clupeidae (e.g., American Shad, Ely et al. 2008).

Hook-and-line sampling was effective at capturing Skipjack Herring in the Arkansas River, Oklahoma. Sabiki rigs (equipped with #4 and #6 hooks) fished near actively feeding Skipjack Herring was more effective than using soft plastics. A total of 157 Skipjack Herring were captured over 16 total angling hours using Sabiki rigs while targeting areas where they were actively feeding. In general, this method was more efficient (higher catch rates) than previous ODWC gill netting and electrofishing efforts on Robert S. Kerr reservoir (a slack-water portion of the Arkansas River formed by a lock and dam). For example, gillnet samples from 2019 yielded 18 Skipjack Herring with 15 net nights of effort, and samples from 2022 yielded 4 Skipjack Herring with 20 net nights of effort (OFAA 2024). Furthermore, the ODWC boat electrofishing standardized sampling survey on Robert S. Kerr Reservoir did not catch any Skipjack Herring. In addition, seining efforts having failed to produce any Skipjack Herring (OFAA 2024). Past collection efforts on the Arkansas River also failed to capture as many Skipjack Herring as were captured via hook-and-line angling (Pigg et al. 1991). These findings are consistent with results from Wolfe (1969), who captured 279 Skipjack Herring in 6 days of effort using hook-and-line sampling on the Apalachicola River, Florida.

There has been an increase in hook-and-line sampling in the scientific literature because this gear can be an effective way to collect specimens when traditional fisheries sampling gears are unable to capture them (i.e., size and species selectivity, Gabelhouse and Willis 1986, Pope et al.2005, Bonvechio and Rydell 2016, Hall et al. 2019). Fisheries managers are relying more on angler catch data because these data can be collected passively and cost effectively compared to biased electrofishing sampling surveys (e.g., Gabelhouse and Willis, 1986; Bonvechio and Rydell 2016). For instance, Hall et al. (2019) found that angling collected 8 times more trophy bass than the creel methods and 24 times more than electrofishing methods. Bonvechio and Rydell (2016) used angling to encounter larger fish due to relative scarcity of this size class in electrofishing samples. Furthermore, hook-and-line sampling is commonly used and widely accepted for obtaining information on the size, structure, and abundance of Rainbow Trout *Oncorhynchus mykiss* in southwest Alaska (Heterick and Bromghin 2006) and Largemouth Bass *Micropterus nigricans* in central Illinois (Santucci and Whal 1991).

Hook-and-line sampling efficiently captured Skipjack Herring, although there is potential for bias in our samples. The use of different sized Sabiki rigs allowed for the capture of different sized Skipjack Herring, which is not surprising as hook size is known to influence catchability of fishes via angling (e.g., Cooke et al. 2005). Anecdotally, observations from our targeted angling suggest Skipjack Herring feeding groups consisted of similarly sized individuals. Therefore, to obtain a broad range of sizes some active feeding events were ignored, or abandoned, to seek feeding events with larger individuals. To the best of our knowledge, no investigations into size bias between feeding schools of Skipjack Herring exists. Though anecdotal information on separation of age groups exists for the species (see Wolfe 1969), further study is needed to determine its potential effects on catchability and the implications for standardized sampling designs.

All fisheries sampling gears are have biases associated with them. Therefore it is important to identify the biases present within each gear to either account or correct for its influence (Shoup and Ryswyk 2016, Montague and Shoup 2022). While choosing a sampling gear with high sampling efficiency may be beneficial for collecting demographic information (Zentner et al. 2023), it does not guarantee relative abundance estimates reflect true population size, size structure is accurately represented, or that fisheries metrics are precise enough to monitor populations (Montague and Shoup, 2022). Given the age structure present in our samples reflects all but the highest recorded age for Skipjack Herring (i.e., Age 4, Wolfe 1969), it is unlikely strong bias was present in our size structure data. Furthermore, prior comparisons of size structure indices and relative abundance obtained via angling and electrofishing for Largemouth Bass found angling and electrofishing to provide statistically similar estimates of both metrics (Santucci and Whal 1991, Isaak et al. 1992). Given the difference between species, a multi-gear (e.g., angling, electrofishing, seining) approach would likely be needed to confirm that these findings translate to Skipjack Herring. Regardless, even if a size bias exists for capturing Skipjack Herring with hook-and-line angling, so long as sampling precision is high this method may be accurate enough to track changes in relative abundance of the species (Pope et al. 2010) as size bias is present across a multitude of fisheries sampling gears (Hubert and Fabrizio 2007). Future work should focus on understanding bias and precision for hook-and-line sampling for Skipjack Herring to quantitatively assess its potential as a sampling gear and to provide information needed to develop standardized sampling protocols. However, we currently recommend the use of hook and line angling with methods described in this study to sampled Oklahoma populations of Skipjack Herring.

Skipjack Herring showed rapid growth in their first year, achieving a mean total length of 176 mm at the end of their first summer and three-quarters of their predicted TL by the time they reached age 1. Wolfe (1969) found Skipjack Herring TLs on the Apalachicola River were approximately 197-205 mm at age 1, 240-378 mm at age 2, 293-445 mm at age 3, and 310-482 at age 4. Wolfe (1969) estimated age using scales whereas we used sagittal otoliths to derive age estimates. Currently the accuracy (i.e., bias and reader precision) of otoliths has not been validated for Skipjack Herring. Nevertheless, sagittal otoliths have been found to have high precision and accuracy between readers for other members of the family Clupeidae (Maceina 1988, Hendricks et al. 1991, Lessa et al. 2008, Duffy et al. 2012). This combined with the fact that similar estimates were obtained from scales by Wolfe (1969) suggest our results are robust. Scales are commonly used because they are easy to sample and inexpensive to analyze compared to other structures (e.g., otoliths, spines, vertebrae), the removal of scales is generally non-lethal. Furthermore, the process of preparing sagittal otoliths is time-consuming and sometimes requires advanced equipment (Davies et al. 2017, Davies et al. 2015, Koch and Quist, 2011). Regardless, future studies should compare the scale and otolith derived age estimates for Skipjack Herring especially considering scales often over-age young fish and under-age older fish (Lowerre-Barbieri et al. 1994, McBride et al. 2005, Maceina and Sammons 2006). The accuracy of age estimates from scales can be negatively influenced by periods of nutritional scarcity during which fish will resorb nutrients present in scales (Kerr and Campana 2014).

Our study provided information into length-weight, mortality, and recruitment information for Skipjack Herring in Oklahoma. To the best of our knowledge, no prior study has produced a length-weight relationship for any Skipjack Herring population. However, Wolfe (1969) observed fishes from 197 – 482 mm TL exhibited weights ranging from 58 – 1,078 g. Recruitment and mortality of Skipjack Herring has not been documented prior in the peer reviewed literature. Our results suggest that less than half of the population survives each year. However, Skipjack Herring within the Arkansas River, Oklahoma exhibit relatively stable recruitment as indicated by the derived RVI index. This information combined with the growth rates observed for the species suggest Skipjack Herring may be a fast-growing shorter-lived species (see Winemiller and Rose 1992, Winemiller 2005), though more information is needed to confirm this hypothesis.

This study provides baseline population dynamics information for Skipjack Herring from the Arkansas River basin, the first use of otoliths to derive population dynamics for Skipjack Herring, and a novel method of capturing this species. Due to a lack of available literature, we cannot say whether this represents a typical population within their range, although our results are similar to the Skipjack Herring population described by Wolfe (1969). Future research should focus on additional validation of the findings from this study and the applicability of these estimates for other populations of Skipjack Herring in Oklahoma. This is especially important as information on Skipjack Herring is lacking statewide and is critical to understanding and properly managing this species. Future research efforts should focus on quantifying the sampling biases associated with hook and line sampling for Skipjack Herring and aim to identify a standardized sampling protocol for these fish where they are found. Developing a standardized sampling survey will also provide insights into Skipjack Herring range and whether this species can inhabit various systems throughout Oklahoma (Pigg et al. 1991, Galat et al. 2005, Neebling and Quist 2008, Dunn et al. 2018). For example, Skipjack Herring are a euryhaline species thought to be anadromous in the Gulf of Mexico that is also capable of completing its life cycle solely in freshwater (Etnier and Starnes 1993), therefore the increase in salinity in the Mississippi River basin caused by climate change may create a competitive advantage for Skipjack Herring over other native species, thereby increasing their range. Given this species is native to the Gulf of Mexico, it may also benefit from increasing water temperatures caused by climate change.

Acknowledgments

We thank Matt Pallet, Drew Wallace, Jon West, and Matt McElroy, who helped in the field and lab for assisting in field sampling and laboratory sampling. We want to thank Graham Montague, Dr. Dan Shoup, and Jonathan West for reviewing a prior draft of this manuscript. We thank Smokey Solis, Don Brown, and Brandon Brown (ODWC) for providing pictures and improving figure quality. We would also like to thank Dr. Mostafa Elshahed and the anonymous reviewers for providing edits that improved this manuscript. The Sport Fish Restoration Program grant F-112-D-3 to the Oklahoma Department of Wildlife Conservation provided financial support for this publication.

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Submitted September 6, 2024 Accepted November 3, 2024