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MANAGEMENT BRIEF

A Simulation-Based Evaluation of Commercial Port Sampling Programs for the Gulf and Atlantic Menhaden Fisheries

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Abstract
Biological data that are collected in commercial port sampling programs are a critical component of the assessment and management of Gulf Menhaden *Brevoortia patronus* and Atlantic Menhaden *Brevoortia tyrannus*. The menhaden port sampling program represents one of the longest continuous commercial sampling efforts in the United States; however, this sampling program has not been evaluated recently to determine whether the program adequately characterizes the size and age structure of the catch despite significant changes in the spatial extent and magnitude of the fisheries in the last three decades. We conducted a simulation study to evaluate current menhaden fishery sampling targets and to examine the relative performance of a suite of alternative targets. To simulate data collection, we conducted a bootstrap analysis of the observed port sampling data. These observations were resampled with replacement across a range of current and alternative combinations of number of trips and fish sampled per trip. At the current target for sampling intensity and allocation, the mean sample weight and proportions at age for ages 2 and 3 are well characterized in both the Gulf and Atlantic menhaden fisheries. The proportions of age-1 fish in the catch differed by stock and region, with samples from the northern Atlantic regions displaying the greatest uncertainty overall. The proportions of age-4 and older fish were poorly characterized in both fisheries, which is likely due to their rarity in the population (Gulf) and lack of spatial overlap between the fishery and the stratified distribution of menhaden by age along the coast (Atlantic). Our results indicate that reducing the number of fish that is sampled per trip from the current target of 10 to as few as four would have a minimal effect on estimates of mean size and proportions at age in the catch. Increasing the number of sampled trips will not greatly improve the characterization of catch size or age composition.

The goal of commercial port sampling programs is to collect life history information that can be used to characterize the catch (e.g., age and size composition) for use in stock assessment and management (Cotter and Pilling 2007; Thorson and Haltuch 2018). Individual fish weight is often collected from a subset of the catch to enable the conversion of landings in biomass (*t*) to numbers of fish landed. In addition, fishery-dependent age and length composition data can provide information about year-class strength and age- or size-specific fishing pressure that

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allows for the estimation of selectivity and fishing mortality by age or length, gear, and sector (Quinn and Deriso 1999).

Biological data that are collected in commercial port sampling programs are a critical component of the assessment of menhaden, which represent the second largest component of U.S. wild-capture commercial fisheries by weight, with total annual landings of more than 1.4 billion pounds in 2017 (NMFS 2018). Regionally, the Gulf Menhaden *Brevoortia patronus* stock supports the largest commercial fishery in the Gulf of Mexico and the Atlantic Menhaden *Brevoortia tyrannus* stock supports the largest commercial fishery on the East Coast of the United states (NMFS 2018). Each fishery is composed of a purse-seine reduction sector and a mixed-gear bait sector. In the Gulf of Mexico, the reduction sector accounts for the majority (approximately 99%) of the landings (SEDAR 2018). In contrast, the bait sector comprises a larger and increasing portion of the Atlantic Menhaden fishery on the East Coast, accounting for approximately 24% of coastwide landings in recent years (ASMFC 2017).

The port sampling programs for Atlantic and Gulf menhaden represent two of the longest continuous commercial data collection efforts in the USA (Smith et al. 1987; Smith 1991). The port sampling program for the reduction fishery began in 1955 for Atlantic Menhaden and in 1964 for Gulf Menhaden; both programs are conducted by the National Marine Fisheries Service Beaufort Laboratory (ASMFC 2017; SEDAR 2018). Port sampling of menhaden catch is conducted throughout the fishing season and across all ports of landing to account for seasonal growth (i.e., length at age) and migration patterns. A two-stage cluster sampling scheme is employed in which the primary sampling unit is the last set of each fishing trip that is intercepted (hereafter, “trip”) and the secondary sampling unit is the individual fish (June and Reintjes 1959; Chester 1984). Agents randomly select vessels dockside and retrieve a bucket of fish from the top of the hold (SEDAR 2015). A subset of fish is then selected by the agent at random from the bucket. Each fish is measured (fork length in mm) and weighed (g), and a collection of scales ($n = 6$ for Atlantic Menhaden, $n = 10$ for Gulf Menhaden) are removed, cleaned, and mounted on a glass microscope slide for aging (June and Roithmayr 1960; Nicholson and Schaaf 1978).

Sampling targets for the port sampling program for the menhaden reduction fishery have changed over time as understanding of menhaden biology and ecology has improved. Soon after port sampling of the Atlantic Menhaden reduction fishery began, June and Reintjes (1959) evaluated the adequacy of the sampling design. Given that menhaden purse-seine fisheries operate by surrounding and capturing all or portions of a single school, each set represents samples that are collected from the same school. June and Reintjes (1959) found that Atlantic Menhaden port samples that were collected in the same set were highly homogeneous with respect to both size and age and that variability in length, weight, and age among trips was much greater than within a trip. In the 1980s, the port sampling program for Atlantic Menhaden was reexamined (Chester 1984; Chester and Waters 1985) and it was determined that a sample size of 20 fish/trip provided adequate precision for determining the mean length of Atlantic Menhaden in a purse-seine set to within ±2%. To better capture the among-trip variance, the sampling target was changed in 1971 from a minimum of 10–15 trips·port^{-1}·week^{-1} with 20 fish sampled per trip to a new target of 20–25 trips·port^{-1}·week^{-1} and 10 fish/trip. Chester (1984) conducted an updated analysis of the port sampling program for Atlantic Menhaden in the 1980s and suggested that the minimum sampling target should be 10 trips·port^{-1}·week^{-1} to adequately characterize the size and age composition of the catch by port and week. At present, a minimum target of 10–15 trips·port^{-1}·week^{-1} and 10 fish/trip has been used on both coasts. However, the port sampling program for the reduction fishery has not been evaluated in recent decades to determine whether the sampling program still adequately characterizes mean size and age structure of the catch despite significant declines in the spatial extent and magnitude of the reduction fisheries for both Gulf and Atlantic menhaden (SEDAR 2015, 2018).

Over the history of these reduction fisheries, the achieved sampling effort often differed from the target levels. Sampling levels in the Gulf Menhaden fishery increased from an average of 5 trips·port^{-1}·week^{-1} at the start of the program to 10 trips·port^{-1}·week^{-1} from the 1980s to present (Figure 1). The average number of trips sampled per port per week in the Atlantic Menhaden fishery sometimes exceeded target levels; however, as the number of reduction plants and fleet size declined on the East Coast, sampling declined to minimum target levels (Figure 1). For both Gulf and Atlantic menhaden, the target number of fish sampled per trip shifted from 20 to 10 in 1971. However, the appropriateness of applying sampling targets for Atlantic Menhaden to the Gulf Menhaden fishery has never been evaluated, even though Gulf Menhaden typically live only to age 4, while Atlantic Menhaden can live to approximately age 10 (June and Reintjes 1959; SEDAR 2018).

The bait fishery port sampling program for Atlantic Menhaden has experienced large changes over time as well. Port sampling for Atlantic Menhaden that are harvested for bait began in 1985 using 10 fish/trip as a target for sampling individual fish but with no established target for the number of trips per state or gear type (Figure 2; Smith and O'Bier 2011). As the magnitude of the bait fishery increased in the late 2000s, a power analysis was conducted to determine the number of trips that should be

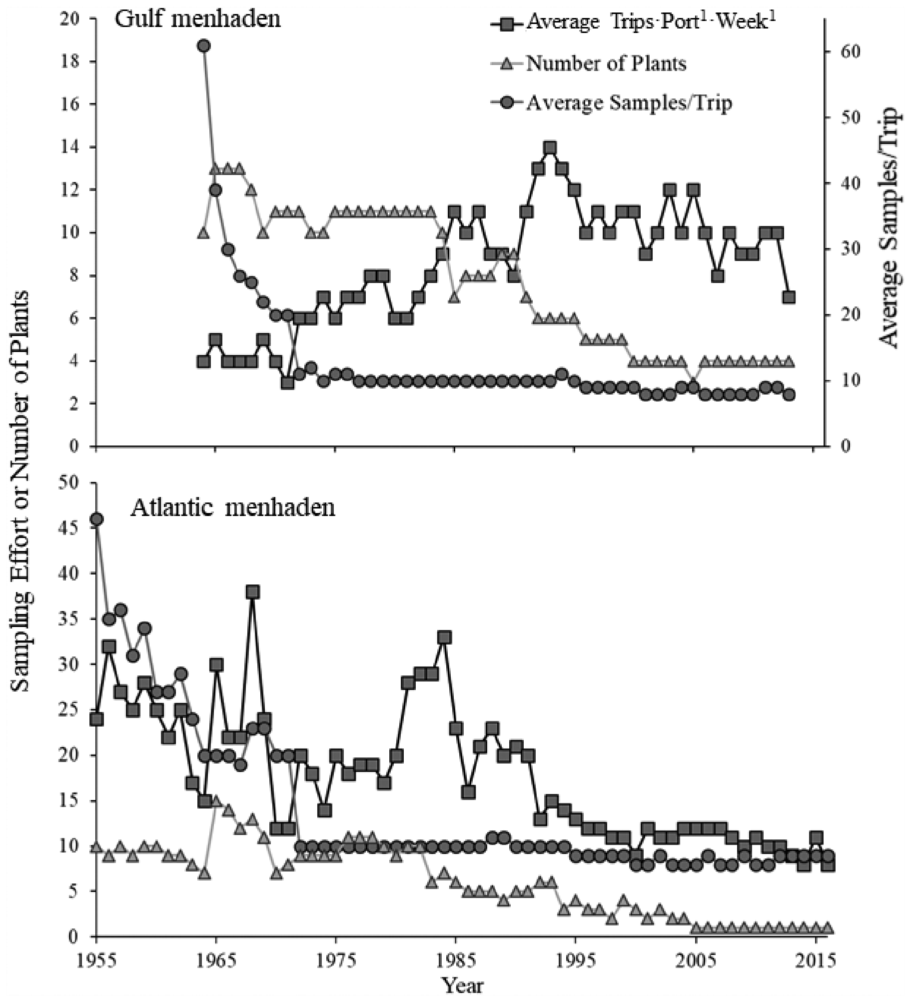

FIGURE 1. Trends in Gulf and Atlantic menhaden port sampling effort and number of reduction plants, 1955–2016.

sampled across the species' range by using the limited number of samples that had been collected to date (McNamee 2012). The results of this analysis were used to set minimum port sampling requirements for each state based on the state-specific annual bait landings from 2012 onward (ASMFC 2012). However, the adequacy of the new port sampling requirements for the bait fishery has not been evaluated since the number of trips that are sampled increased in 2012.

The objectives of our study were to (1) provide a quantitative evaluation of the current commercial port sampling programs' ability to characterize the size and age composition of menhaden catch and (2) examine the relative performance of a suite of potential alternative two-stage sampling targets. Prior to the widespread availability of high-speed computing, studies of the sampling program design were limited to analytical approaches (June and Reintjes 1959; Chester 1984; Chester and Waters 1985). Here, we adopted a simulation-based approach to examine the combined effects of alternative sampling targets for both the number of trips sampled and the number of individual fish sampled per trip in the Gulf Menhaden reduction fishery and the Atlantic Menhaden reduction and bait fisheries.

METHODS

We conducted a simulation study to evaluate the current sampling targets for the menhaden reduction and bait fisheries and to examine the relative performance of a suite of alternative targets. To simulate port sampling data collection, we conducted a nonparametric bootstrap analysis in which existing data were resampled with replacement across a range of current and alternative sampling schemes (i.e., with combinations of number of trips and fish sampled). This approach allowed us to account for both random sampling error and systematic error due to differences in schools caught among trips. By comparing

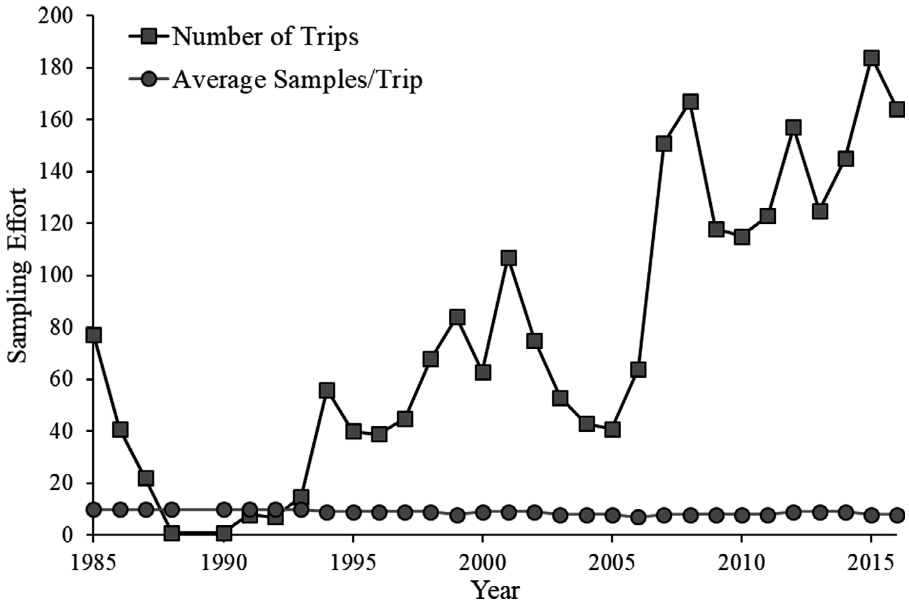

FIGURE 2. Trends in port sampling effort for Atlantic Menhaden harvested for bait, 1985–2016.

the coefficient of variation of the bootstrap distribution of size and proportions at age among the different sampling schemes, we were able to examine the trade-offs between sampling intensity and uncertainty in the current estimates of catch size and age compositions (Manly 2007).

Biological port sampling data.— We focused our analyses on the two most recent years for which data from commercial port sampling were available at the start of this study (2015 and 2016) because extensive changes have occurred in both the Gulf and Atlantic menhaden fisheries and management plans during 1955–2012 (ASMFC 2017; SEDAR 2018). Thus, the 2015–2016 data were assumed to most closely reflect current and future fishery conditions. An analysis of the data from both 2015 and 2016 allowed us to examine the influence of interannual variability in catch composition on our conclusions. We also analyzed the historical port sampling data for Atlantic Menhaden from 1969, prior to the reduction in sampling targets, for comparison with more recent years in which fewer samples were taken.

During the 2015 and 2016 fishing seasons, Gulf Menhaden reduction plants were operational at three ports in the Gulf of Mexico: Moss Point, Mississippi; Empire, Louisiana; and Abbeville, Louisiana. In the stock assessment model that is used for the management of Gulf Menhaden, inputs that are derived from the port sampling data were prepared at the port level. Therefore, we conducted the simulation analyses on a port-by-port basis.

In the stock assessment that is used for the management of Atlantic Menhaden, both the reduction and bait sectors are divided into northern and southern regional fleets to account for spatial changes in both fisheries over time relative to the extent of the coastwide stock (ASMFC 2017). Therefore, we analyzed the performance of various two-stage sampling schemes at the regional (northern versus southern) scale for each Atlantic Menhaden sector to provide the results that would be the most informative to future stock assessments. The northern region extended from Maine to coastal Maryland, and the southern region included Chesapeake Bay and the coastal regions from Virginia to Florida. During 2015–2016, only one menhaden reduction plant was operational, that in Reedville, Virginia. Therefore, the reduction samples were assigned to a region based on the set-location information that is collected in Captain's Daily Fishing Reports (SEDAR 2015). Given that Atlantic Menhaden bait operations typically operate over a much smaller geographic range than that of reduction purse-seine operations, the bait samples were assigned to a region based on port of landing, as in the assessment.

Evaluation of sampling targets.— We evaluated the performance of various sampling targets on metrics that are important to the assessment and management of menhaden, namely, accuracy of mean size and the age composition of fish landed. The mean weight of the fish that were collected in the port samples from both the Gulf and Atlantic menhaden reduction fisheries in a given port per week is used to convert landings (t) to number of fish landed at the port-per-week level to account for growth and migration effects across the fishing season (SEDAR 2015, 2018). Therefore, our simulation study evaluated the effect of sampling targets (i.e., number of trips and number of fish sampled per trip) on the mean weight of the reduction catch at the port-per-week level by year and region. For the Atlantic Menhaden bait fishery, the mean weight of the fish that are sampled is calculated after pooling the samples by gear and year because of differences in gear selectivity and the small number of samples that were collected from the bait fishery in most years (SEDAR 2015). Thus, we evaluated the effect of the sampling targets on the mean weight of the bait catch by gear, region, and year. Fork length data were treated similarly to weight for both regions and sectors. When generating catch-at-age estimates for the statistical catch-at-age assessment model that is used for each stock, the catch age composition data are pooled annually by port for the Gulf Menhaden reduction sector, by port and region for the Atlantic Menhaden reduction fishery sector, and by region for the Atlantic Menhaden bait sector. Thus, our evaluation of the influence of sampling targets on estimates of the age composition of menhaden catch was conducted at the port and year level for Gulf Menhaden and at the sector, year, and region level for both the Atlantic Menhaden reduction and bait sectors given that only one reduction plant was operational in recent years.

To assess the two-stage cluster sampling design that is employed in the menhaden port sampling program, we examined the combined effects of both the number of trips sampled and the number of individual fish sampled from each trip using menhaden port sampling data that were collected in 2015 and 2016. For the reduction fishery, the data from weekly port sampling with <8 trips and fish collections with <8 fish/trip were not used in the simulation study to ensure that the sampling data were representative and adequate for resampling. Failure to meet the target number of trips per port per week is typically due to weather or plant logistics, whereas unreadable scales are the typical reason for failing to meet the target number of fish sampled per trip. Using the remaining data, we first evaluated the effect of current sampling targets for the Gulf and Atlantic menhaden reduction sector on the estimated size composition of the catch at the per-port-per-week level. The first stage of the two-stage cluster sampling design was simulated such that between 2 and 20 trips were randomly selected with replacement in each port weekly. We then simulated the random selection with replacement of between 2 and 20 individual fish from each trip that was selected. Thus, our simulated sample target combinations spanned 20 trips·port^{-1}·week^{-1} with 2 fish/trip being sampled to 2 trips·port^{-1}·week^{-1} and 20 fish/trip. This resampling procedure for each trip/fish sample-size combination was then repeated 1,000 times (Efron 1979), and the coefficient of variation for the distribution of mean weight and fork length of fish caught per port per week was calculated for the reduction fishery. The same procedure was used for the Atlantic Menhaden bait sector with the exception that data were pooled across gears within a year instead of by port per week.

Next, we evaluated the effect of the sampling targets on the estimated annual age composition of the catch by port for the Gulf Menhaden reduction fishery and by region and sector for the Atlantic Menhaden fishery using the same data inclusion criteria that were described above for size. In the first stage, a subset of trips per year was selected with replacement; the range of trips that was selected for resampling was chosen based on the reasonable fishery performance expectations for each port, sector, and region, as appropriate, spanning approximately 50% fewer to approximately 25% more trips being sampled in recent years. From each trip that was selected, we then simulated the random selection with replacement of 2 to 20 individual fish. This resampling procedure for each trip/fish sample-size combination was then repeated 1,000 times (Efron 1979), and the coefficient of variation for the distribution of proportions at age in the catch was calculated.

RESULTS

Our simulation results demonstrated a low amount of interannual variability, indicating that the same general conclusions could be drawn regardless of the year (2015 or 2016). Therefore, the summarized results that were generated using the 2016 data are presented here for brevity. More extensive 2016 and complementary 2015 results can be found in the Supplemental Materials (Table S1; Figures S1–S23 available in the online version of this article). Also, the simulation results were largely similar across all three ports of menhaden landings in the Gulf of Mexico; therefore, the results for the Abbeville, Louisiana, port are presented here and additional results for the Moss Point, Mississippi, and Empire, Louisiana, plants can be found in the Supplemental Materials. The simulation results that were generated at sampling levels of $n = 2$, 10 (current target), and 20 fish/trip are presented to demonstrate the range of estimated coefficients of variation (CVs). A complete set of simulation results that were generated at all of the sampling levels that were explored can be found in the Supplemental Materials.

Size

At the current target sampling levels, mean length and weight are well characterized on both coasts, at all plants, and in all sectors and regions. Across all of the simulations, the CV of the bootstrap distribution of mean weight was about 2 to 3 times higher than that of the CV of mean fork length; however, the overall pattern of decline in CV with increasing sample sizes for both variables was similar. Therefore, only the simulation results for mean weight are displayed here for brevity; the results of the simulation of fork length can be found in the Supplemental Materials.

At the current target sampling levels of 10 trips·port^{-1}·week^{-1} and 10 fish sampled per trip, the average bootstrap distribution CV for the mean weight of Gulf Menhaden that were sampled across ports each week at the Abbeville, Louisiana, reduction plant was approximately 3.0% (Figures 3, S1). Increasing the number of simulated trips that was sampled generally resulted in small improvements in the form of slightly lower average CVs in the range of 1.0–2.0%. Decreasing the number of simulated trips below target levels resulted in higher average CVs in the range of 4.0–7.0%. Increasing the number of fish sampled per trip to greater than 10 had little effect, whereas decreasing the number of fish to as low as two increased the average CV to 4–11% across the range of number of trips sampled.

At the current target sampling levels, the average bootstrap distribution CV for the mean weight of Atlantic Menhaden that are sampled across ports on a weekly basis (reduction) or gears (bait) was approximately 6.0–7.0% for the reduction sector and 2.0–3.0% for the bait sector in both the northern and southern regions (Figures 4, S4–S7). Increasing the number of simulated trips sampled above

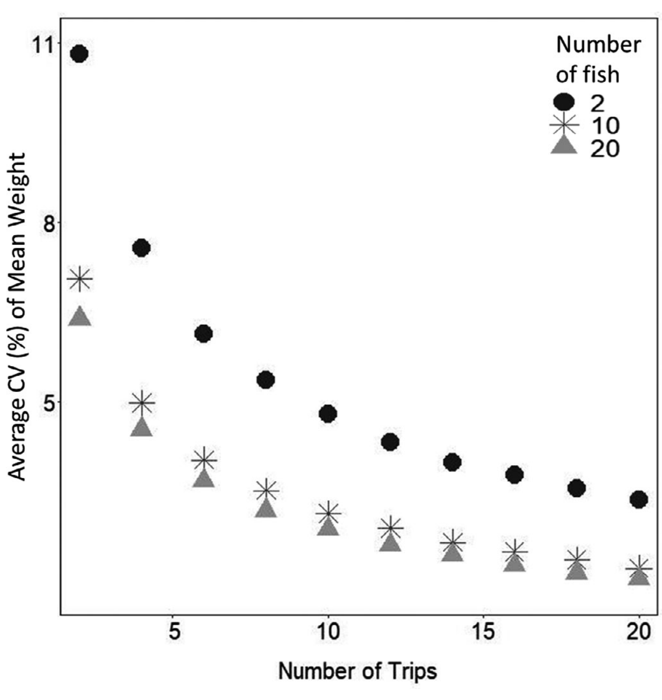

FIGURE 3. Bootstrap distribution coefficient of variation for mean weight of Gulf Menhaden by resample size for the Abbeville, Louisiana, reduction plant, averaged across ports each week, 2016.

current levels generally resulted in small improvements in the form of slightly lower average CVs in the range of 4.0–5.0% for the reduction sector and 2.0–2.4% for the bait sector. Decreasing the number of simulated trips below target levels resulted in higher average CVs in the range of 6.0–14.0% for the reduction sector and 3.5–4.0% for the bait sector. Increasing the number of fish sampled per trip to greater than 10 had little effect in both sectors and regions. In general, decreasing the number of fish to as low as two increased the average CV by 1.0–2.0% across the range of number of trips sampled. However, in the bait sector, reducing the number of fish sampled per trip had a larger effect on the estimated CVs for pound-net gear than for purse seines or cast nets (Figures S8, S9).

Proportions at Age

At the 2016 target sampling levels, the bootstrap distribution CV for proportions at age of Gulf Menhaden that were sampled in 2016 at the Abbeville, Louisiana, reduction plant ($n = 199$) was low for fish at ages 1–3 (3.0–9.0%) relative to age-4 fish (39.0%; Figures 5, S8). Increasing the number of simulated trips that was sampled generally resulted in small reductions in CVs, whereas decreasing the number of simulated trips to below the current levels resulted in higher CVs in the range of 3.0–13.0% for ages 1–3 and 39.0–45.0% for age-4 fish. Increasing the number of fish sampled per trip to greater than 10 had little effect, whereas decreasing the number of fish to as low as two increased the CV to a range of 7.0–20.0% for ages 1–3 and 30.0–70.0% for age-4 fish across the range of number of trips sampled.

At the 2016 target sampling levels, the CV for proportions at age of Atlantic Menhaden that were sampled in the northern reduction sector ($n = 70$) was high for ages 1 (30.0%) and 4 (25.0%) relative to ages 2 (13.0%) and 3 (11.0%), shown in Figures 6 and S11. At the 2016 target sampling levels, the CV for proportions at age sampled in the southern reduction sector ($n = 180$) was high for age 4 (40.0%) relative to ages 1 (10.0%), 2 (5.0%), and 3 (11.0%). In both regions, increasing the number of simulated trips that was sampled resulted in small reductions in the CV. Decreasing the number of simulated trips that was sampled in the southern reduction sector had little effect on the CV for proportions of age-2 fish; in contrast, the CVs increased from 13.0% to between 14.0% and 30.0% in the northern reduction sector. Notably, decreasing the number of trips in the northern reduction sector resulted in CVs for age-1 fish ranging as high as 70.0%. Decreasing the number of simulated trips to below the current levels for both sectors resulted in moderate increases in CVs to between 12.0% and 29.0% for age-3 fish and 25.0% and 75.0% for age-4 fish in the northern region. In the southern region, the CVs increased to between 10.0% and 14.0% for age-3 fish and 45.0% and

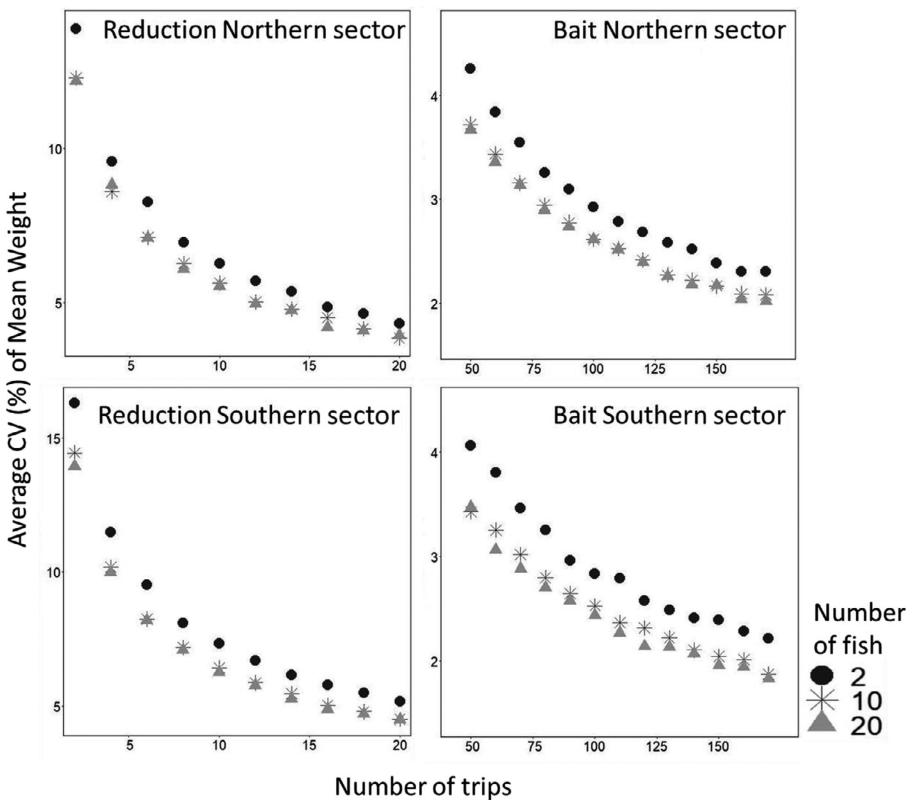

FIGURE 4. Bootstrap distribution coefficient of variation for mean weight of Atlantic Menhaden by resample size, averaged across ports each week by sector and region, 2016. The sampling targets in 2016 were 10 fish sampled per trip with 10 trips·port^{-1}·week^{-1} for the reduction sector and 10 fish sampled per trip with 83 and 90 total trips sampled for the northern and southern bait sectors, respectively.

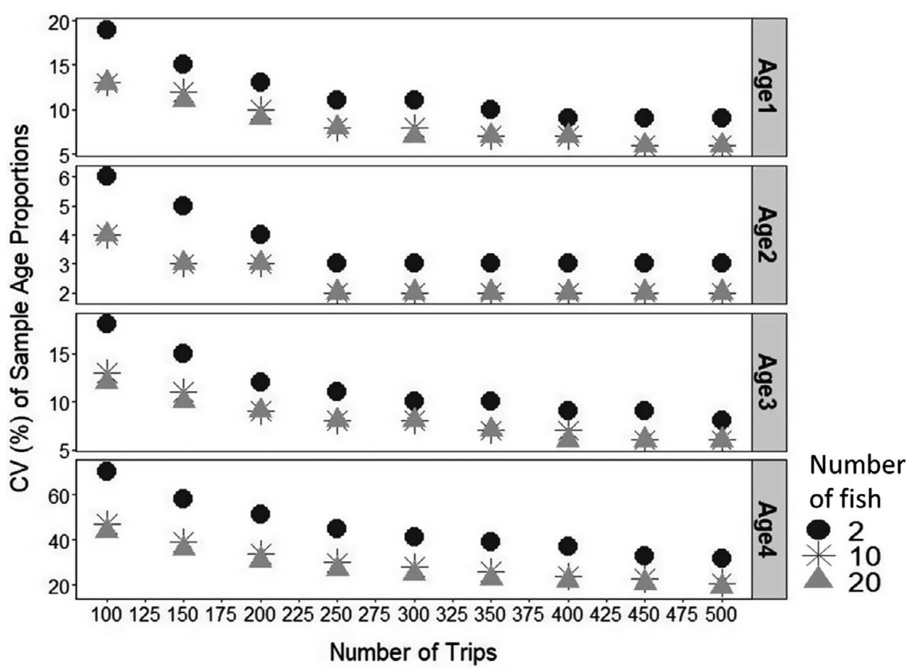

FIGURE 5. Bootstrap distribution coefficient of variation for Gulf Menhaden catch sample proportions at age by resample size for the Abbeville, Louisiana, reduction plant, 2016. The target sampling levels in 2016 were 10 trips·port^{-1}·week^{-1} (170 total trips) and 10 fish/trip.

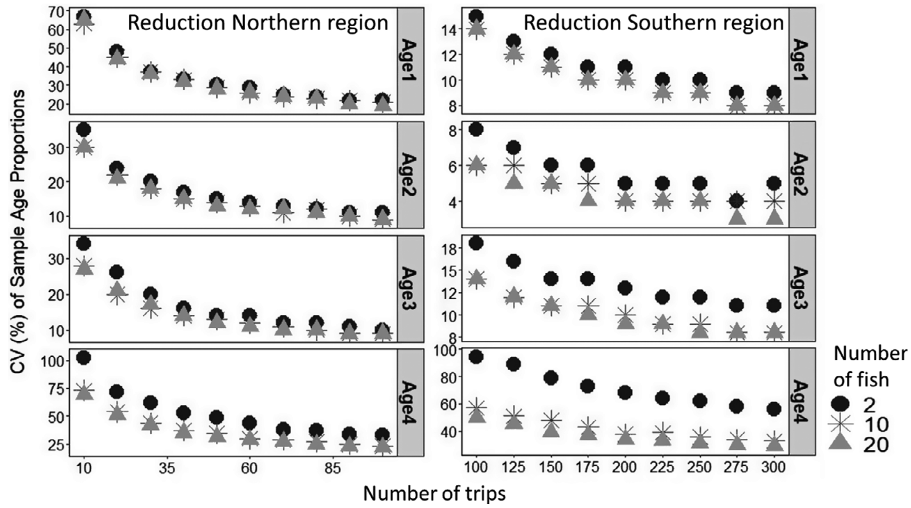

FIGURE 6. Bootstrap distribution coefficient of variation for Atlantic Menhaden reduction catch sample proportions at age by resample size and region, 2016. The sampling targets in 2016 were 70 (in the northern region) and 180 (in the southern region) trips per year and 10 fish/trip.

60.0% for age-4 fish. Both increasing and decreasing the number of fish that was sampled per trip from the current target of 10 generally had little effect, with the exception of increasing the CVs for fish at ages 3 and 4 in the southern region to between 12% and 18% and 60.0% and 100.0%, respectively. Although fish that were older than age 4 were encountered by the fishery, there were insufficient samples to provide reliable simulation results.

At the 2016 target sampling levels, the CV for proportions at age of Atlantic Menhaden that were sampled in the northern bait sector was relatively high for ages 1 (30.0%), 4 (30.0%), and 5 (75.0%) relative to ages 2 (7.0%) and 3 (7.0%), shown in Figures 7 and S12. At the 2016 target sampling levels, the CV for proportions at age for fish that were sampled in the southern bait sector was relatively high for ages 4 (25.0%) and 5 (50.0%) relative to ages 1 (15.0%), 2 (7.0%), and 3 (10.0%), shown in Figures 7 and S12. In both regions, increasing the number of simulated trips that was sampled resulted in minor reductions in the CVs. Decreasing the number of simulated trips that was sampled resulted in slight increases in the CVs for proportions at age in both regions. In contrast to the reduction fishery, though, decreasing the number of fish that was sampled per trip in the bait sector increased the CVs noticeably, in particular for fish that were ages 4 and 5 in both regions. For example, the CVs for age-5 fish in the northern bait sector (where they are most likely to be encountered by any fishery) increased from a range of 60.0–90.0% at 10 fish sampled per trip to 90.0–150.0% at two fish sampled per trip. Increasing the number of fish that was sampled per trip to above the current target of 10 had little effect. Although fish that were older than age 5 were encountered by the fishery, there were insufficient samples to provide reliable simulation results.

DISCUSSION

This study evaluated the ability of current and alternative port sampling targets to characterize the size and age composition of the Gulf and Atlantic menhaden commercial fishery catch. The current sampling targets appear to be adequate for characterizing the mean weight and fork length of fish that are caught in both the Gulf and Atlantic menhaden fisheries and across all of the Atlantic Menhaden sectors and regions (Figures 3, 4, S1–S7). Our results demonstrated similar performance of sampling program targets for overlapping ages (1–4), indicating that applying Atlantic Menhaden targets to Gulf Menhaden is appropriate. Also, both Gulf and Atlantic menhaden reduction purse-seine sets that were sampled (which are representative of schools sampled) were found to be highly homogeneous with respect to size, confirming historical Atlantic Menhaden studies (June and Reintjes 1959; Chester 1984; Chester and Waters 1985). Given that our simulations generated consistently low CVs for the bootstrap distribution of fork length compared with weight or age (Figures S1–S7), our results also suggest that both Gulf and Atlantic menhaden school primarily by length rather than by age. This conclusion is supported by the fact that there is considerable overlap in length among ages for both species (Schueller et al. 2014). Also, menhaden sets can contain a mixture of ages, which is likely due to a combination of multiple ages schooling together and aging error.

The simulation results indicate that the sampling targets (both number of trips and fish per trip) could be lowered on both coasts if the primary goal were characterizing the mean size of fish in the catch (Figures 3, 4). However, the models used to assess both stocks require catch-at-age information. Our results suggest that characterizing the

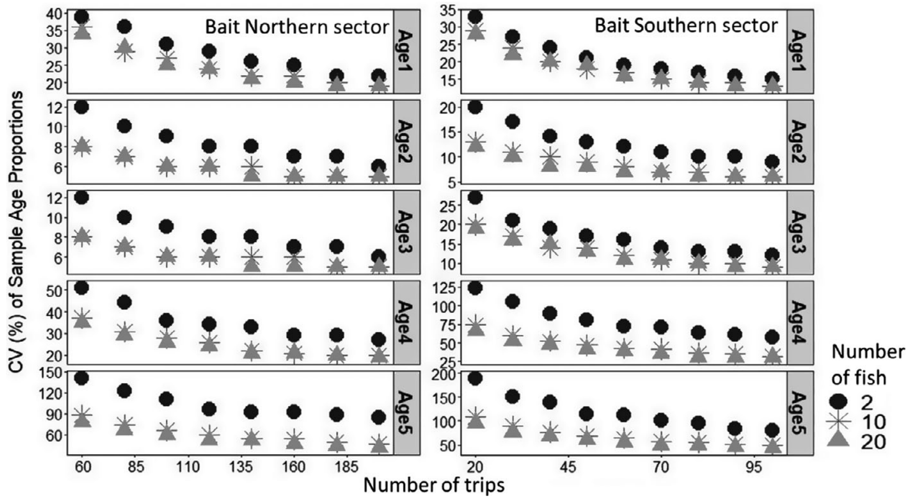

FIGURE 7. Bootstrap distribution coefficient of variation for Atlantic Menhaden bait catch sample proportions at age by resample size and region, 2016. The sampling targets in 2016 were 10 fish sampled per trip, with 83 and 90 total trips, sampled for the northern and southern bait sectors, respectively.

age composition of both Gulf and Atlantic menhaden catch requires higher sampling intensity than does characterizing size alone (Figures 5, 6), as initially suggested by Chester (1984) for the Atlantic Menhaden reduction fishery. In general, the current fishery sampling levels achieved low CVs for the bootstrap distribution of annual catch proportions at age for ages 2 and 3 in both the Gulf and Atlantic menhaden fisheries (Figures 5, 6). Fish that are ages 2 and 3 are an important component of these fisheries, and they are thought to make up the majority of the catch in the northern Atlantic Menhaden reduction and bait sectors; in addition, age-2 fish are thought to comprise the majority of fish caught in the southern Atlantic Menhaden fisheries (ASMFC 2017; SEDAR 2018).

However, the characterization of the proportions of age-1 fish in the catch differed by plant, region, and sector (Figures 5, 6). Across all of the sampling levels, the CVs for proportions of age-1 Gulf Menhaden were lower at the more eastern reduction plants in Louisiana and Mississippi than at the westernmost reduction plant in Abbeville, Louisiana, indicating a potential longitudinal effect of the availability of age-1 fish in the western Gulf of Mexico, as was suggested by Ahrenholz (1991; see Figures S19–S21). For Atlantic Menhaden, the CVs for proportions of age-1 fish at the current sampling levels were lower in the southern reduction and bait sectors compared with both sectors in the northern region (Figures 5–7). Given that Atlantic Menhaden exhibit age-based northward migration behavior that stratifies fish by age along the East Coast during the fishing season (Dryfoos 1973; Nicholson 1978; Liljestrand et al. 2019), the higher CVs for proportions of age-1 fish in northern-sector catches is likely due to the lack of overlap between the locations of fishing activities and locations of high concentrations of age-1 Atlantic Menhaden. The proportions of age-1 Atlantic Menhaden were well characterized in the southern region where they are more likely to reside prior to migrating northward as they age (Liljestrand et al. 2019).

Proportions of fish at ages 4 and older were characterized with much greater uncertainty than were those at younger ages in both fisheries and across all sectors and regions. Both species exhibit dome-shaped selectivity (SEDAR 2018, 2020), which is thought to be driven by a combination of fisher choice and annual migration patterns for both species. Gulf Menhaden have a shorter life span (maximum age 6; SEDAR 2018) than Atlantic Menhaden (maximum age 10; June and Reintjes 1959); thus, higher uncertainty in estimating proportions of fish at ages 4+ in the catch is likely due to their rarity in the population. The proportions of age-4 and older fish in the Atlantic Menhaden fishery were poorly characterized by the sampling program likely due to their rarity in the catch, not in the population itself. It is possible that there is little spatial overlap between the location of older Atlantic Menhaden and the locations in which the fishery is prosecuted. Evidence from commercial sea samples indicates that age-4+ Atlantic Menhaden are typically encountered farther offshore and in more northerly portions of their range, where they are not often encountered by most trips that are taken by the current reduction sector (SEDAR 2015). However, biological data that are collected from the very limited offshore-directed midwater trawl and other offshore bycatch fisheries frequently encounter older Atlantic Menhaden (SEDAR 2015), indicating that these fish are present but are not encountered by the majority of

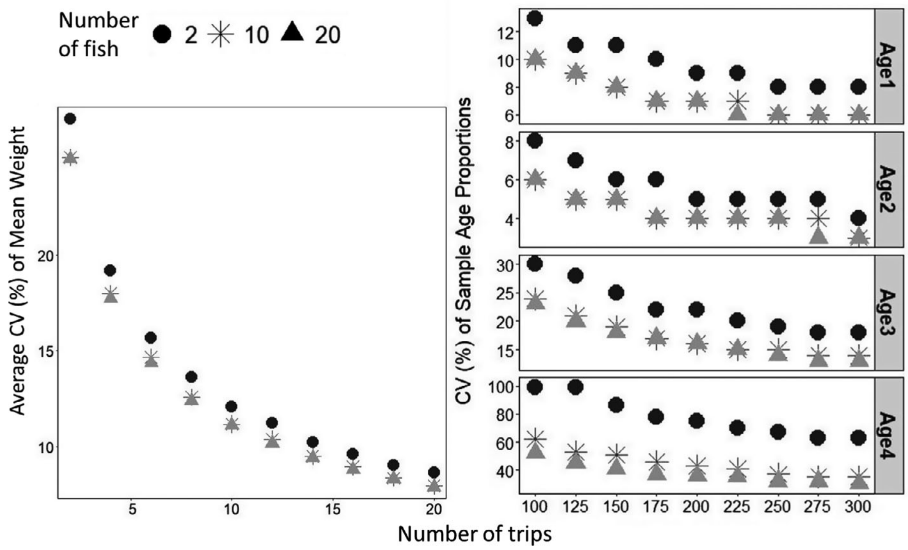

FIGURE 8. Bootstrap distribution coefficient of variation for Atlantic Menhaden reduction catch sample size (left) and proportions at age (right) by resample size and region, 1969.

fishing trips that target menhaden. In addition, aging error may be contributing to higher uncertainty in the estimation of proportions of age-4 and older fish for both stocks given that uncertainty in age determination for menhaden increases with age (ASMFC 2015, 2017; SEDAR 2018). It is also possible that older menhaden have greater variability in size at age, so schools of larger fish may be more heterogeneous in age composition, which would make the estimates of proportions at age in the catch more uncertain.

Our results suggest that reducing the number of fish that is sampled per trip from the current target of 10 to as few as four would have a minimal effect on estimating mean size or proportions at age (Figures 3–7, S1–S23). Thus, it may be possible to increase the efficiency of the sampling program by sampling fewer fish per trip. Our results also indicate that increasing the number of trips that is sampled to above the current levels will not greatly improve the characterization of age composition of the catch, particularly for age-4 and older fish. In some situations, such as in the northern reduction sector for Atlantic Menhaden, the port samplers are already sampling nearly all of the available trips per port per week. Given the limited number of trips that is taken in the northern region in both sectors of the Atlantic Menhaden fishery, increasing sampling may not be feasible. Also, it may not be possible to improve sampling for age-4 and older fish in the Gulf Menhaden fishery given their shorter life span. Similarly, given the lack of spatial overlap between their locations and current fishing activities, it may not be possible to improve sampling for age-4 and older fish in the Atlantic Menhaden fisheries.

The conclusions that are drawn from this simulation study assume that the port sampling data that were collected from the 2016 and 2015 Gulf and Atlantic menhaden fisheries represent the full range of sizes and ages that is typically encountered by the fishery (Manly 2007). If current sampling levels are insufficient to fully characterize the size and age range of fish that are caught, our results could be biased. Therefore, we performed our resampling simulation procedures on reduction fishery data for Atlantic Menhaden that were collected in 1969 prior to the sampling effort reductions when the number of trips per port per week and fish per trip was approximately 20 (Figure 1). The CVs for the bootstrap distributions of mean size and age composition in 1969 were largely similar to those that were generated by using data that were collected in 2016 (Figure 8), demonstrating that our results are not unique to recent years and the current sampling scheme is adequate to produce representative data for this resampling study. However, if significant shifts in the geographic distribution of the fish or fishery occur in the future, this analysis should be repeated to provide updated advice to menhaden scientists and managers. Unlike the Atlantic Menhaden port sampling program, which underwent a period of very high sampling effort prior to establishing current targets, the Gulf Menhaden sampling program does not have a comparable reference period during which both a larger number of trips and fish sampled per trip were collected for comparison. That being said, all sizes and ages are likely represented in the 2016 port samples given the shorter life span of Gulf Menhaden. The bait fishery for Atlantic Menhaden, however, is not as closely monitored as the reduction fishery. Amendment 2 to the Atlantic Menhaden Fishery Management Plan recommends, but does not require, that port samples from the bait fishery be distributed among gear types. Without requirements to sample each bait gear in proportion to its landings, it is possible that the port samples that are collected by the states are not truly representative of the size and age composition of the bait catch.

Large uncertainty in the proportion of age-4 and older menhaden in the Gulf and Atlantic commercial catch has implications for the assessment of both stocks. The current model for stock assessments tracks ages 0–4+ for Gulf Menhaden and ages 0–6+ for Atlantic Menhaden (ASMFC 2017; SEDAR 2018). If proportions of age-4 and older fish are as difficult to estimate well as our study suggests, the statistical catch-at-age models that are used in the Gulf and Atlantic menhaden assessments may be chasing noise in the catch-at-age matrix rather than tracking real information about trends in older fish that are encountered. Thus, the adoption of a Dirichlet likelihood function (Thorson et al. 2017) for fitting proportions at age in the most recent Gulf (SEDAR 2018) and Atlantic menhaden (SEDAR 2020) assessments appears to be warranted. In general, though, caution should be used in interpreting and fitting assessment models to menhaden catch-at-age data that include age-classes 4 and older until the influence of plus-group selection on both Gulf and Atlantic menhaden assessments can be quantified with further simulation studies.

Our simulation study can be used to guide decisions regarding any proposed future changes to the port sampling programs for Gulf and Atlantic menhaden. However, in order to examine the effect that sampling has on model estimates and management, our resampled data sets would need to be passed through the complete data preparation and modeling processes that are unique to each stock assessment. Future research will include a full exploration of the potential effect that current and alternative sampling targets have on assessment model estimates and the resulting management advice.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.