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Novel estimation of gear selectivity using a concurrent mass mortality event: A case study using red drum (*Sciaenops ocellatus*) in the northern Gulf of Mexico

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ABSTRACT

Fishery-independent surveys are commonly used in modern stock assessment models to inform trends in abundance and these surveys may become more important when there are gaps in other data sources, such as harvest data. As a result of the federal harvest moratorium in the late 1980's, Gulf of Mexico red drum (*Sciaenops ocellatus*) remains a data-limited species with little known about its post-escapement (6 – 46-year-old fish) abundance in offshore waters, which encompasses the spawning biomass of the stock. Historically, age and growth estimates were derived from purse seine collections, which was the industry's preferred harvest technique. Recently, the addition of fishery-independent surveys, i.e. bottom longline surveys, sought to provide a potential alternative to purse seines; however, their efficacy in sampling the breadth of the offshore red drum population has not been widely evaluated. Here, we compared the age composition and selectivity of red drum collected with purse seine and bottom long line in offshore coastal waters of Mississippi and Alabama. Red drum collected in the purse seines ranged from 561 to 1018 mm total length (2–26 years old) and 770 – 1090 mm (2–36 years old) in bottom longlines. Additionally, an opportunistic sampling of red drum from a large fish kill in 2015 was used to estimate selectivity of red drum sampled by purse seine and bottom long line. Red drum selectivity generally decreased with age for the purse seine, while there was an increase in selectivity for the bottom long line survey. This novel approach using a mass mortality event to derive gear selectivity may allow fisheries scientists to refine selectivity measurements in stock assessments. Characterization of selectivity for different survey gears will allow for a more informed comparison of historic and current surveys when gear type effects change.

1. Introduction

Most stock assessments conclude with the recommendation to expand fisheries-independent monitoring of the fish stocks examined. The transition from periodic fisheries-dependent sampling to more systematic or randomized fisheries-independent surveys is a hallmark of modern fisheries assessments. This transition becomes increasingly important as commercial and recreational harvest of stocks are restricted, and the pipeline of fisheries-dependent data slows or disappears. The first stock in the Gulf of Mexico to fall under this scenario was red drum (*Sciaenops ocellatus*), a fishery which is managed cooperatively between individual states within their territorial waters (within three nautical of the coast in Alabama, Mississippi, and Louisiana and nine miles off Florida and Texas) and by the United States federal government seaward of the state water boundaries. Rapid increases in commercial harvest in the 1980's, led to a harvest moratorium in federal waters in 1987 and more restrictive state harvest regulations (Porch, 2000). The intent of these regulation changes was to rebuild the spawning biomass of the population (age 6 + red drum) by drastically reducing harvest on these age classes. Concurrently, new regulations for recreational

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fisheries (e.g., mandated slot sizes) and state closures of commercial gillnet fisheries (except Mississippi) were designed to increase escapement of juvenile red drum to the adult spawning stock populations.

After 30 years of this new management strategy, the red drum fishery in the Gulf of Mexico is considered a success story with regards to returning a once severely depleted stock to a more favorable status (Hogarth, 2004). Aggressive management in state waters resulted in higher escapement rates of subadults into the offshore population throughout the 1990's and early 2000's (Powers and Burns, 2010), which were in turn protected by a harvest moratorium. Despite evidence of recovery in state estuarine waters where juveniles occur (0 – 6 years old), the closure in offshore waters has prevented a detailed examination of the spawning stock in nearshore and offshore waters (Powers et al., 2012). For many fisheries under aggressive rebuilding strategies this is a common paradox fisheries manager must face – balancing the need to greatly reduce harvest while maintaining a consistent data series to evaluate the efficacy of changes. For red drum, the recognition that the previous management scheme with commercial harvest preferentially targeting the spawning stock was not sustainable and an entirely new management scheme adopted (focusing effort on sub-adults) further complicates any future assessment. In these cases where harvest is limited and/or major changes in management strategy are made, robust fisheries independent surveys are needed to provide a consistent (or at least comparable) long-term time series.

Unfortunately, routine fisheries-independent surveys were not established to monitor the spawning stock dynamics of red drum following the imposition of management changes. A limited number of targeted studies were conducted but repeating the methodology of the historic commercial fishery in offshore waters (purse seine collections) has proven logistically challenging as well as unpopular with recreational fishermen. Accordingly, post – 1980's data for red drum in offshore waters are sparse (Beckman et al., 1988; Wilson and Nieland, 1994; Murphy and Crabtree, 2001; Porch et al., 2002). Two studies have recently examined age composition of the offshore (seaward of the barrier islands out 100 km) sector of the red drum populations off Alabama and Tampa Bay, Florida, USA. Winner et al. (2009) conducted purse seine collections of red drum schools off Tampa Bay, Florida to repeat earlier collections of Murphy and Crabtree (2001). Older red drum were encountered in higher frequencies in 2006–2008 (mean age 11.9 ± 5.7 standard deviation) compared to 1995–1998 (9.8 ± 4.6). Powers et al. (2012) and, most recently, Hightower et al. (2022) aged red drum collected by bottom longlines collected off Mississippi and Alabama from 2005 to 2018 and also found high frequencies of older red drum (mean age 16.5 ± 0.4). However, pre-moratorium red drum (i.e. born before 1986) had a low frequency of occurrence.

The results of Powers et al. (2012) as well as Hightower et al. (2022) also suggest that bottom longlines, a survey gear used in many of the U. S. National Marine Fisheries Services (NMFS), may be suitable for long-term monitoring of abundance trends and age composition of red drum. The industry standard for red drum harvest in the northern Gulf of Mexico was purse seine fishing which was also the gear typically used in the collection of biological samples for fishery management whether fishery dependent or independent (Beckman, 1989; Murphy and Crabtree, 2001). Although efficient in collecting a large number of specimens with few gear sets, there is evidence that purse seines do not capture the oldest fish in the red drum fishery compared to hook and line-based collections (Beckman and Wilson, 1971). A similar pattern has been observed in other offshore fisheries, such as tuna (Essington et al., 2002; Medina et al., 2007; Wang et al., 2017, 2009). Consistently, in offshore fisheries that target catch with both purse seines and longlines, younger fish are collected in purse seines when compared to older and larger fish collected with longlines. This trend has been hypothesized to be a function of reproductive periodicity (Medina et al., 2007), predator avoidance, and collective feeding strategies (Essington et al., 2002). Knowledge of the gear selectivity of both bottom longlines and purse seine would allow for better comparisons of trends between historic (purse seine) and current (bottom longline) stock parameters as well as evaluate assumptions of previous stock assessments regarding gear selectivity. Differences in gear selectivity have the potential to skew growth and fecundity estimates that use samples collected exclusively from single-gear fisheries, increasing the need for orthogonality among fishery-dependent samples and increased fishery-independent sampling.

Here, we evaluate a novel estimation of gear selectivity of historic (purse seine) and modern (bottom longline) collection methods using a sample, assumed to be unbiased, of the spawning stock of red drum. The preferred method to estimate the selectivity of a fishing gear is to compare the catch composition with the composition of a known population (e.g., compare the composition of tagged fish recaptured by anglers with the composition of the fish that were tagged, Myers and Hoenig, 1997). Another approach is to compare the catch of one sampling gear with that of another gear believed to be non-selective (e.g., Millar and Fryer, 1999). Here, we use aspects of both approaches. We compared the age, growth parameter estimates, and length composition of two survey techniques and measure these metrics to samples opportunistically collected from fish killed during a harmful algae bloom, which we assume to be non-selective. Selectivity analyses like those presented here are critical in progressing current and future assessments of red drum in the Gulf of Mexico as well as fulfilling the broader mandate to incorporate rigorously designed fisheries-independent surveys into future stock assessments (Powers et al., 2018).

2. Methods

2.1. Study species

Red drum occur in the Gulf of Mexico and along the US Atlantic coast to Massachusetts (Murphy and Taylor, 1990) and is an important recreational fishery in almost every state where it is found. The red drum life cycle encompasses both estuarine habitats including saltmarshes, oyster reefs, seagrasses, and small creeks as juveniles (Wenner, 1996; Rooker et al., 1998; Stunz et al., 1999; Stunz and Minello, 2001) and offshore habitats as adults (Beckman et al., 1988; Hightower et al., 2022). As adults, red drum migrate from the estuaries into offshore waters, typically between 3 and 6 years of age (Beckman et al., 1988; Murphy and Taylor, 1990). Once offshore, these fish are thought to occupy shallow to mid-depth areas (< 30 m) along the continental shelf. During spring and fall periods adult red drum can be found closer to shore compared to their wider shelf distribution in the summer (Hightower et al., 2022). Maximum age of red drum have been reported as 50 yrs (Ross et al., 1995) with red drum between 20 and 35 years old common in the Gulf of Mexico (Powers et al., 2012). There is substantial evidence for meta-population structure along the U.S. Gulf of Mexico. Based on otolith microchemistry results, Rooker et al. (2010) suggested that recruitment into Texas bays may be linked to discrete spawning areas in offshore waters directly proximate to those bays with limited mixing. Using a combination of genetic profiling and acoustic telemetry Lowerre-Barbieri et al., (2016, 2019) also found substantive evidence for strong annual spawning site fidelity and limited straying of older, reproductively active red drum in Florida. Further, Burnsed et al. (2020) concluded that natal homing (returning to the habitat off their estuarine nursery for subsequent reproductive periods) was present in two metapopulations of red drum. The possibility that recruitment is a function of regional spawning aggregations suggests that any Gulf-wide assessment should target red drum aggregations over a large geographic scale to incorporate these discrete subpopulations.

Because of ontogenetic changes in habitat requirements, fisheries management of red drum is dependent on cooperation among coastal states and the federal government. Harvest of red drum by both the commercial and recreational sectors has seen a marked change since the implementation of the Fishery Management Plan (FMP) in 1987. Prior to the 1980's, the harvest was primarily commercial, with catches typically around 1–2 million kg yr^{-1}, and by the mid 1980's harvest increased to

~7 million kg yr^{-1}. This expedited reduction in the adult stocks led to a decrease in the spawning stock biomass and resulted in the implementation of an FMP that required a total cessation of red drum harvest in federal waters. Since that time, commercial red drum harvest has primarily been incidental in other fisheries and remained low in most states; recreational harvest of red drum has been limited to state waters and remains heavily regulated (Porch, 2000). Mortality estimated for red drum during the last stock assessment (SEDAR, 2016) was at 0.16 – 0.18 year^{-1}, while Hightower et al. (2022) estimated mortality based on fisheries-independent collected specimens as 0.15 year^{-1}.

2.2. Red drum collections

Purse seine collections were planned during peak spawning aggregations in the fall (October and November) in coastal waters of Alabama (Fig. 1). Red drum were collected in Alabama coastal waters in 2014 and 2017. To collect samples in a manner like historic methods, we employed skilled spotter pilots alongside commercial purse seine vessels and crew. The purse seine net measured 549 m (600 yds) long and 40 m (130 ft) deep and was constructed of 2.54 cm (1 in) mesh. Once a red drum school was spotted by pilots, the mothership was contacted, and a striker boat was used to set the net. The net was then pursed, and fish were left in the water (< 1 hr) until they were collected by scientists and transferred to ice on a transport vessel. All red drum were collected unless the school was more than 100 red drum. In this case, a sample size of ~100–200 fish were culled from each school.

Bottom longline collections were performed during April-November off the coast of Alabama and Mississippi from 2006 to 2017 (Fig. 1). All longline set locations were randomly generated in pre-defined depth strata detailed in Powers et al. (2018). Drymon et al. (2013) effort varied among years with an average of 48 longline sets per year. Each longline set used Southeast Area Monitoring and Assessment (SEAMAP) standardized bottom longline gear. Briefly, a 1.85 km (1 nmi) monofilament mainline (4 mm, 545 kg test), was deployed off the stern through a block. Highflier buoys were used at the start and end of each set. Five kg weights (start, mid-set, end set), and 3.66 m (12 ft) gangions (3 mm, 320 kg test) with 15/0 circle hooks were clipped to the mainline during deployment. Bottom longline effort was 100 hooks fished for one hour. Soak time (60 min) was determined from the time the last highflier buoy was deployed until the first highflier buoy was retrieved to begin the haul back. Hooks were baited with Atlantic mackerel (*Scomber scombrus*) cut to fit the circle hooks (Drymon et al., 2010; Powers et al., 2012). All fish were identified, measured and weighed.

For all red drum, morphometrics and gonads were collected. Standard length (SL), fork length (FL), natural total length (NTL) defined as the longest length of the fish flat on its side, and maximum total length (TL) defined as the total length of the fish stretched to its maximum length were recorded to the nearest mm and mass was recorded to the nearest 0.1 kg. Sex was determined by examination of the gonads and all gonads were weighed to the nearest 0.1 g. Red drum were sacrificed to obtain otoliths for age determination.

In addition to purse seine and bottom longline collections, a unique opportunity was presented after a large fish kill in 2015 that was coincident with a large harmful algal bloom (*Karenia brevis*). Fish kills associated with *K. brevis* have been documented to have indiscriminate, guild-wide effects on populations of marine and estuarine fishes (Gannon et al., 2009). Measurements were made and otoliths were collected from 112 adult red drum carcasses; sampled on 30 November, 14 December, 16 December, and 18 December, 2015 from ocean front beaches from Gulf Shores, AL to the west end of Dauphin Island, AL. The poor condition of internal organs prevented accurate sex determination; however, these data were included in subsequent analyses to provide a

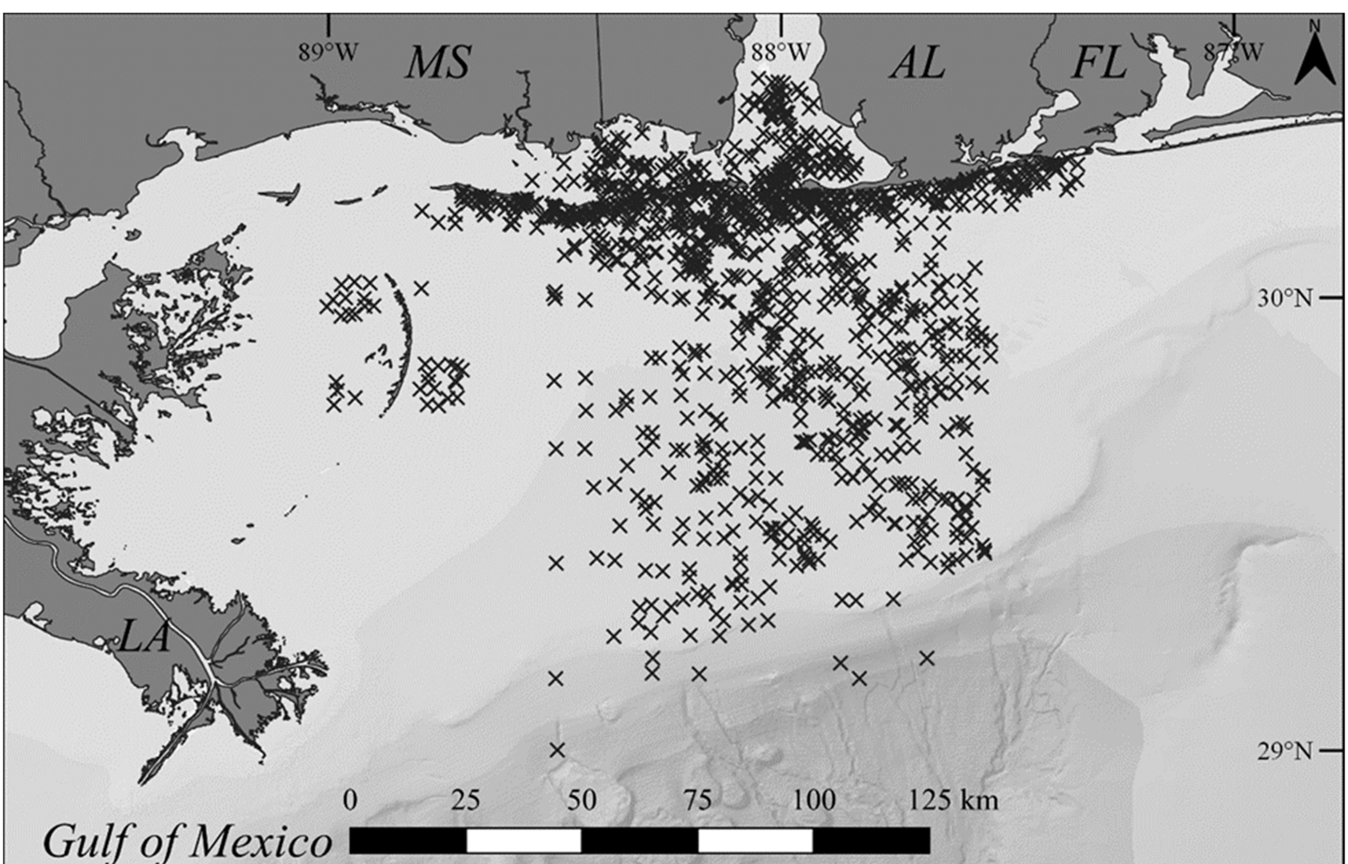

Fig. 1. Locations of red drum collected by bottom longline in this study.

presumed representative sample of age composition and determine purse seine and bottom longline selectivity curves.

2.3. Age and growth determination

Following extraction, sagittal otoliths were used to estimate red drum ages which has been found to be a reliable proxy for red drum age (Murphy and Taylor, 1991). Otolith processing for this study was conducted according to the methods for thin sectioning described in the Gulf of Mexico Marine Fisheries Commission (GSMFC) otolith handbook (VanderKooy and Guindon-Tisdel, 2003) and Beckman et al. (1988). All otoliths were aged independently by two readers. The left otolith was processed, leaving the right otolith for use when the left was not available or when there was a disagreement between otolith readers (Beckman et al., 1988). Otoliths used for aging were processed following procedures in Powers et al. (2012). Integer age was determined by counting number of opaque annuli based on methods from the GSMFC otolith handbook (VanderKooy and Guindon-Tisdel, 2003) and Beckman et.al (1988). Margin codes (1−4) were also assigned based on methods by the GSMFC aging workshop where a 1 or 2 in October or November would result in a − 1 year, based on winter annulus deposition. This adjusted age distribution was then compared to the integer count using Kolmogorov–Smirnov tests. Year at birth was estimated for all red drum by subtracting opaque zone count from year of capture with the assumption that the initial annulus was deposited during the winter of year two (Beckman et al., 1988). All red drum were aged by two independent readers. The percentage agreement was 99.99%.

To estimate growth parameters for red drum in this study, von Bertalanffy growth curves were fit to both males and females for the complete data set (von Bertalanffy, 1938). The von Bertalanffy growth curve can be written as:

$$L_t = L_\infty \,[1 - e^{K(t-t_0)}] \quad (1)$$

where L_t is total length at age t, L_∞ is the asymptotic length, e is the base of natural logarithm, K is the von Bertalanffy growth coefficient, and t_0 is the age at which the curve crosses the age axis. To better characterize growth, we supplemented the dataset with data from the Alabama Department of Conservation and Natural Resources, Marine Resources Division's (AMRD) for juvenile red drum (n = 1540) collected by the Alabama fishery-independent gillnet survey of Alabama coastal waters from 2006 to 2017. The survey uses a stratified random design to sample estuarine areas of Alabama (Livernois et al., 2020). To confirm that multiple individual models for each gear type were appropriate we compared five models. The first model was built using a single set of parameters for all samples combined, the next three models were built with two sets of parameters 1) for each gear type and 2) for the remaining samples. The last model included three sets of parameters calculated for each gear type individually. We built the models using the function "growthmultifit" in the R add-on package *fishmethods* (Nelson, 2014) and compared them using AIC. The growth models were fit using the R (4.2.0) statistical software package with the add-on packages *FSA* (Ogle, 2018) and *nlstools* (Baty et al., 2015). All analyses were conducted in R 4.2.0 (R Computing Team, 2013).

2.4. Data analysis

Length frequency and age composition were plotted by gear type for fisheries-independent bottom longline, purse seine, as well as data collected during the 2015 fish kill. All total lengths were reported as maximum total length (TL; tail pinched) for this study. Comparison between size and age distributions by collection method were performed using a two-sample Kolmogorov–Smirnov test with a significance level of α = 0.05, which was confirmed using a concurrent Anderson-Darling test using the same significance level.

2.5. Age selectivity

We assume that the age- and size-selectivity of the fish kill in 2015 was constant and non-selective due to the nature of the event. In this case, the selectivity of both the purse seine and bottom longline can be estimated by comparing the relative numbers of each cohort caught in 2013 and 2014 with the relative number of the cohort in 2015 as obtained from the fish kill.

To account for spatial (ontogenetic habitat shifts) and temporal (year class strength) effects on estimating gear selectivity, we elected to use red drum collected within the same region and three-year period. All fish collected with purse seines were captured in waters < 10 m. To facilitate accurate comparisons between gears, we only analyzed red drum from bottom longlines set in < 10 m. We directly compared age/length across gears by matching/offsetting sample years and selected purse seine samples from 2014 and bottom longline samples in 2013 and 2014 (Supplemental Table 1). In order to avoid the the confounding effects of availability and selctivity as well as low sample sizes, we truncated our data to only include fish older than 8 years and younger than 32 years to make accurate comparisons across all three sampling measures. Fish younger than age 8 have most likely not fully left the estuary into offshore habitats and are sampled in very low numbers using both purse seines and bottom longlines. Fish older than age 32 are uncommon which results in low sample sizes across the two sampling gears and makes comparisons among gears unreliable.

We assume that all age groups of red drum that were present from 2013 to 2014 experienced the same rate of mortality so that the age composition of the fish sampled by both purse seine and bottom longline are the same as if all red drum would have been sampled with the same fishing gear in 2015 (except that the ages are shifted one-year and two-years upward for fish caught in 2014 and 2013, respectively). Additionally, we assume that the age and size structure of red drum across the region is unchanged and that there is no net emigration, immigration, or changes to natural mortality related to size-class or age. Our assumption of relatively constant fishing mortality across this period is supported by the consistency of fishing regulations and stability of annual catches.

We used a simple estimator based on sample ratios to get a preliminary look at the shape of the selectivity curve. We then used maximum likelihood estimation to obtain final estimates of selectivity assuming a logistic model.

To estimate the age selectivity of purse seines, define the ratios r_a as follows:

$$r_a = \frac{m_{a-1,2014}}{n_{a,2015}} \quad (2)$$

where $m_{a-1,2014}$ is the number of fish of age a-1 in the purse seine sample from 2014, and $n_{a,2015}$ is the number of fish of age a from the fish kill in 2015. The estimated selectivity, $\widehat{sel}_a$, of the purse seine for fish of age a is:

$$\widehat{sel}_a = \frac{r_a}{\max_a r_a} \quad (3)$$

where $max\ r_a$ is the maximum ratio among all age groups. The procedure for bottom longlines is similar except that there are two years of sampling that have to be projected forward to 2015. Thus,

$$r_a = \frac{m_{a-2,2013} + m_{a-1,2014}}{n_{a,2015}} \quad (4)$$

where $m_{a-1,2014}$ is the number of fish of age a–1 from the bottom longline sample from 2014 and $m_{a-2,2013}$ is the number of fish of age a-2 from the bottom longline sample from 2013. Selectivity is then estimated from Eq. 3 as before. To increase the robustness of selectivity estimates among the three gear types, ages were binned. We evaluated multiple bin sizes from 2 to 4; to optimize sample size, as well as populate all bins with samples, we selected 3-year age bins.

Selectivity was then modeled using the GLM function in R (4.2.0) using a binomial error structure and a logit link to estimate and derive coefficients for the relationship between age and gear selectivity for both bottom longlines and purse seines. The formula for the modeled selectivity is a standard logistic function:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \quad (5)$$

where x is the age of the red drum, L is the curve maximum value (set at 1, indicating 100% selectivity), k is the logistic growth rate and x_0 is the midpoint age (or age at 50% selectivity).

We make the assumption that the nature of the fish kill was not age selective; however, to confirm that this assumption does not alter our selectivity curves we devised a sensitivity test. This tested the hypothesis that changes in the proportion of red drum collected in the fish kill affected the selectivity estimated for each gear type. Changes in selectivity for a given age-bin in excess to the change in the proportional age in each bin would indicate that age class is sensitive to the fish kill data and could result in a miscalculation of selectivity if the fish kill was indeed age selective. For the test, the number of fish in the age bins of the fish kill data were incrementally increased between 3% and 25% with a mean increase of 13.5% across all age bins modeled in four scenarios; 1) a linear increase from young to old, 2) a linear increase from old to young, 3) an increase around the mean age decreasing to the tails (steepening the curve), and 4) an increase in the tails decreasing to the mean age (flattening the curve). Our goal with these incremental increases in variability was to exaggerate the data beyond naturally

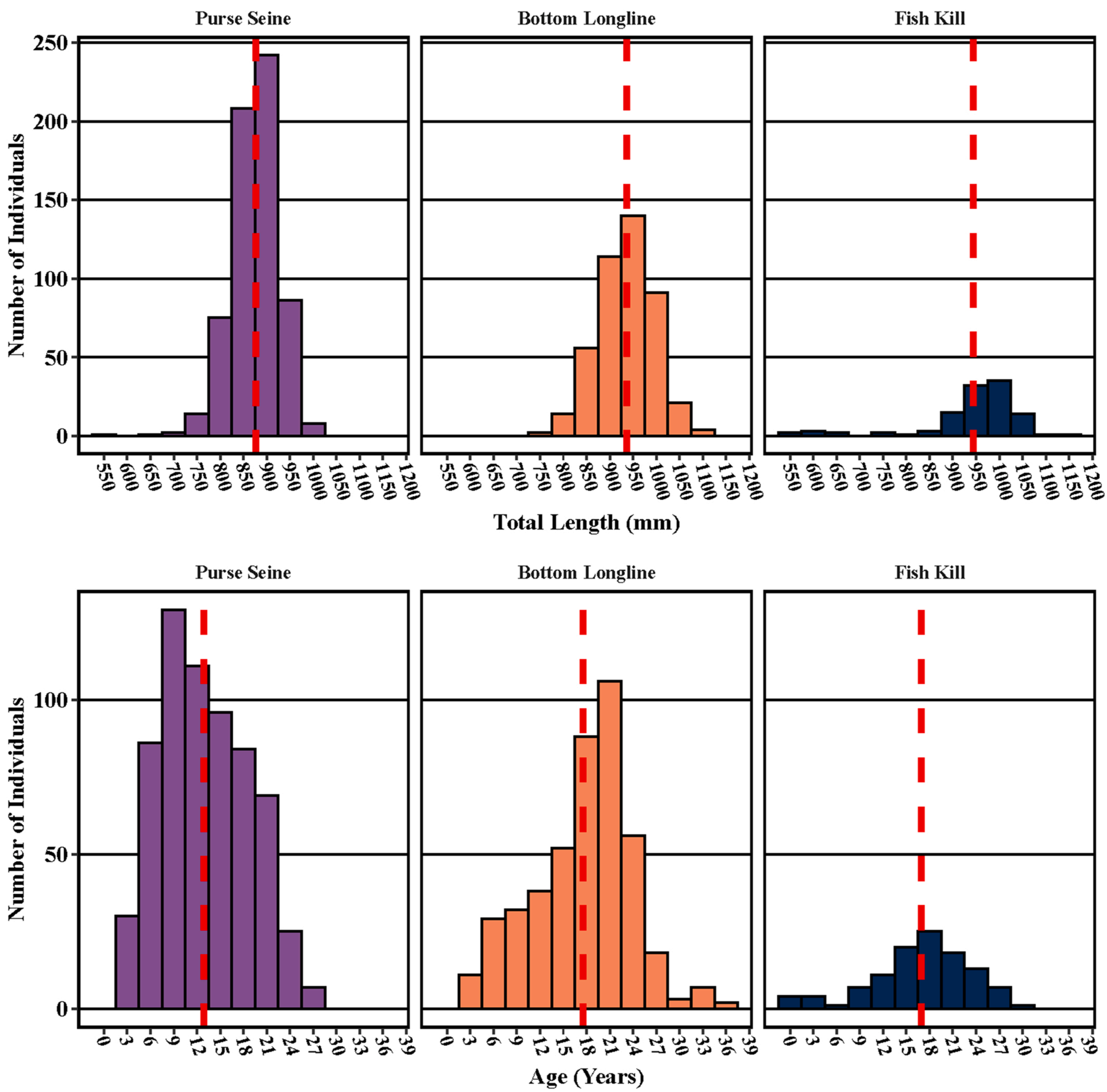

Fig. 2. Histograms of total length (mm) and ages (years) of red drum collected during purse seine collections, bottom longline surveys (BL), and from the 2015 fish kill in Alabama waters, the dashed vertical red line in each plot indicates the mean total length and age, for each gear type and fish kill red drum.

occurring variability to assess if the low sample sizes among age bins may affect our selectivity model robustness. Modeled data from each scenario was used to create new selectivity estimates for each gear type which were then compared to our selectivity estimates created using real data. We then calculated the average absolute percent difference between modeled and real data to estimate if any given scenario resulted in percent differences that exceeded the mean increase incrementally added to the fish kill age bin data (> 13.5%).

3. Results

3.1. Purse seine collections

A total of 638 red drum was sampled by purse seine for morphometrics, otoliths, and gonads from 2014 to 2017. For samples collected in 2016, we performed opportunistic sampling via menhaden purse seine discards to collect as many adult red drum as possible for age composition. Sampling occurred daily during the fall of 2016 (19 October – 17 November) when the purse vessel was fishing and was only suspended based on inoperable conditions (high seas). Year by year, 464 from three schools in 2014 and 149 were from one school in 2014 and 2017, respectively. Given the low sample size for red drum sampled in 2016, these fish were excluded from growth or selectivity analyses. Purse seine collected red drum ranged in size from 561 to 1018 mm TL with a mean total length ± 1 standard deviation (SD) of 875 ± 50 (Fig. 2).

All red drum collected in this study were assigned a final integer age agreed upon by the readers. Ages of red drum in the purse seine collections ranged from 2 to 26 years old with mean age of 13 years (Fig. 2, Table 1). Back calculated year at birth ranged from 1988 to 2015. Mean age for red drum was slightly older for males (14 years) than females (12 years).

3.2. Bottom longline collections

A total of 449 red drum were collected for age determination from the bottom longline survey off Alabama and Mississippi from 2006 to 2017. Overall mean TL of red drum was 935 ± 59 mm with a range of 766–1102 mm TL. Of the 446 red drum successfully aged, mean age was 17.6 ± 6.3 yrs with a range of 3–36 yrs. Females were slightly larger (953 ± 64 mm vs. 927 ± 43 mm) and younger (17.7 ± 5.6 vs 19.0 ± 6.5 yrs) than males.

3.3. Fish kill collections

One hundred and fifteen red drum were sampled for size and otoliths during the 2015 fish kill. The poor condition of internal organs prevented accurate sex determination. The size and age composition of these red drum were both larger and older than those sampled by purse seine. Size ranged from 530 mm to 1155 mm with a mean size 943 ± 12 mm. Ages ranged from 1 to 30 years old and was again a larger range of ages than collected by purse seine surveys. The mean age was 17 years old.

Table 1
Characteristics and mean measures of red drum collected by survey type.

Gear	N	Location	Size Range (TL mm)	Mean Size (TL mm)	Mean Age (yrs)	% Female
Purse Seine	617	AL/MS	561–1018	875	13	38
Purse Seine	25	LA	867–1000	921	13	64
Bottom Longline	449	AL/MS	766–1102	935	18	58
Fish Kill	115	AL/MS	530–1155	943	17	N/A

3.4. Age, length, and sex comparisons

Results from the two-sample Kolmogorov–Smirnov test indicated that some of the length and age distributions differed across all three sampling methods, purse seine, bottom longline, and fish kill. Length distributions of red drum differed pairwise across all three methods ($p < 0.05$); however, age distributions did not. Age distributions varied among purse seines and bottom longline ($D = 0.36$; $p < 0.05$), purse seines and the fish kill ($D = 0.33$; $p < 0.05$), but not between bottom longline and the fish kill ($D = 0.08$; $p = 0.57$). All results agreed in statistical significance with concurrent Andersen-Darling tests for length and age distributions among all three sampling methods. Fish kill samples had the largest range of sizes and ages than samples collected in purse seine surveys or bottom longlines (Fig. 2).(Fig. 3).

Sex ratios differed among the two gear types ($\chi^2 = 36.85$, $p < 0.05$), using bottom longlines of the 354 red drum that could be sexed 58% were female and 42% male. In purse seine samples of the 638 that were sexed 38% were female and 62% were male.

3.5. Growth parameters

Calculating growth models separately resulted in the lowest AIC (33984.04) compared to the combined model (34154.52) or the comparison models between each gear and the remaining samples (purse seine, 34158.15 AIC; bottom longline, 34072.19; fish kill, 34158.02). Growth parameters calculated in the independent models differed by collection method. Using all data sets combined (purse seine, bottom longline and fish kill), age at length was plotted for 753 red drum found in offshore waters of the northern Gulf of Mexico (Fig. 4). Using all adult red drum collected across gear types and the AMRD gillnet data, which collected mainly juveniles, a more realistic t_0 (−1.35) was found while L_∞ (937 mm) was similar to the previous estimate. K (0.28) was greater with the data set that included the gillnet data (Table 2). Growth parameters varied among the three models. Comparing the growth parameters for combined sexes, the smallest L_∞ (907 mm TL) and highest k (0.31) was found modeling growth with purse seine data. Modeling

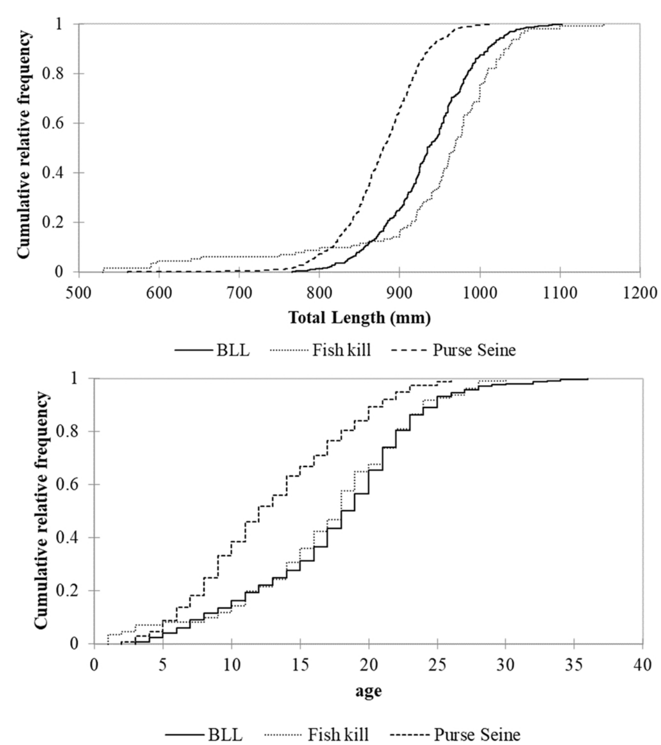

Fig. 3. Cumulative histograms by collection method (purse seine, bottom longline, or fish kill) of red drum ages (years) and total lengths (mm).

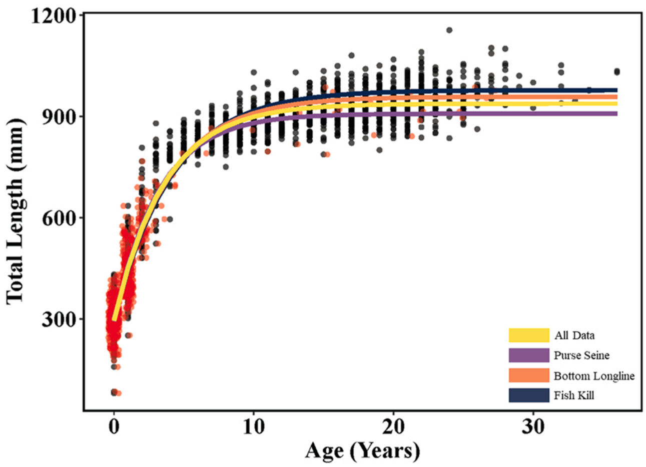

Fig. 4. Length at age for red drum collected during purse seine, bottom longline and fish kill surveys (black points) during this study as well as gillnet surveys by the Alabama Department of Conservation and Natural Resources (red points) used to gain better resolution for juvenile stages.

Table 2
Estimated growth parameters by collection methods: bottom longline (BL), purse seine (PU), fish kill (FK), and gillnet (GN). Note the table only presents results of fish collected in Alabama and Mississippi waters.

		L_∞	±SE	k	±SE	t_0	±SE
ALL (BL,FK,GN, PU)	Combined	937.44	2.09	0.28	0.01	-1.35	0.03
	Female	952.60	3.41	0.28	0.01	-1.43	0.07
	Male	912.59	2.87	0.29	0.01	-1.49	0.08
PU + GN	Combined	907.77	2.77	0.31	0.01	-1.26	0.03
	Female	921.58	4.60	0.31	0.01	-1.28	0.07
	Male	897.72	3.40	0.31	0.01	-1.37	0.08
BL + GN	Combined	957.96	3.10	0.26	0.01	-1.44	0.04
	Female	974.82	4.56	0.26	0.01	-1.48	0.09
	Male	941.72	5.26	0.23	0.01	-1.93	0.15
FK + GN	Combined	977.38	6.24	0.24	0.01	-1.54	0.06

growth at age using bottom longline data, the L_∞ parameter increased to 958 mm and k decreased to 0.28. Growth models based on the fish kill data had the largest L_∞ (977 mm) and smallest k (0.24). For purse seine and bottom longline sampling that also collected sex data allowing for males and females to be modeled separately, females had a slightly larger L_∞ (~ 30 mm) than males with similar k values (Table 2).

3.6. Gear selectivity

Age selectivity based on sample ratios (Eq. 1) differed among gear types, with younger fish having higher selectivity than older fish in purse seines, and the reverse occurring in bottom longline sampling (Fig. 5). Peak selectivity occurred in purse seine samples at age 8 years (1.00) and declined for each subsequent age group (Table 3). Bottom longline sampling exhibited the opposite selectivity with the lowest selectivity ratio for ages 11–13 (0.02) and the highest for the oldest fish, greater than or equal to 29 years (1.00) (Table 3).

The logistic model for purse seining had an accurate model fit with the selectivity ratios ($r^2 = 0.79$), with greater error in the younger age bins (11 – 16 years) (Fig. 5). The logistic model agrees slightly better with the sample ratio estimates for bottom longlines ($r^2 = 0.81$) with a majority of the difference between modeled data and actual occurring at the oldest ages where sample sizes are low. The estimate of the age at 50% selection for purse seines is ~ 12.5 years while for bottom longlines it is ~ 23 years (Table 4).

The selectivity curve for purse seines is:

$$f(x) = \frac{1}{1 + e^{0.2882(x-12.534)}} \tag{6}$$

while the selectivity curve for bottom longline is:

$$f(x) = \frac{1}{1 + e^{-0.2637(x-22.539)}} \tag{7}$$

Regarding our sensitivity analysis, across all four scenarios, the average mean change in modeled selectivity was lower than the mean proportional change made to the modeled fish kill data (Fig. 6). The greatest proportional change in selectivity, between modeled and real selectivity, occurred for scenario 3 (steepening the curve) which differed by 8.8% on average (max, 20.4%; min, 3%), indicating that it is unlikely that our selectivity estimates are confounded by age selectivity of the

Table 3
Age selectivity for bottom longline (BL) and purse seine (PU) sampling estimated using sample ratios for three-year age bins and Eqs. (2) or (3). Included also are sample sizes (N) for each gear type and from the fish kill (FK) within each age bin.

Age (yrs)	BL (*N*)	PU (*N*)	FK (*N*)	Selectivity (BL)	Selectivity (PU)
8 – 10	1	106	7	0.07	1
11 – 13	1	91	12	0.04	0.5
14 – 16	3	63	20	0.08	0.21
17 – 19	10	55	26	0.19	0.14
20 – 22	7	53	18	0.19	0.19
23 – 25	18	21	13	0.69	0.11
26 – 28	9	4	8	0.56	0.03
29 – 31	2	0	1	1	0

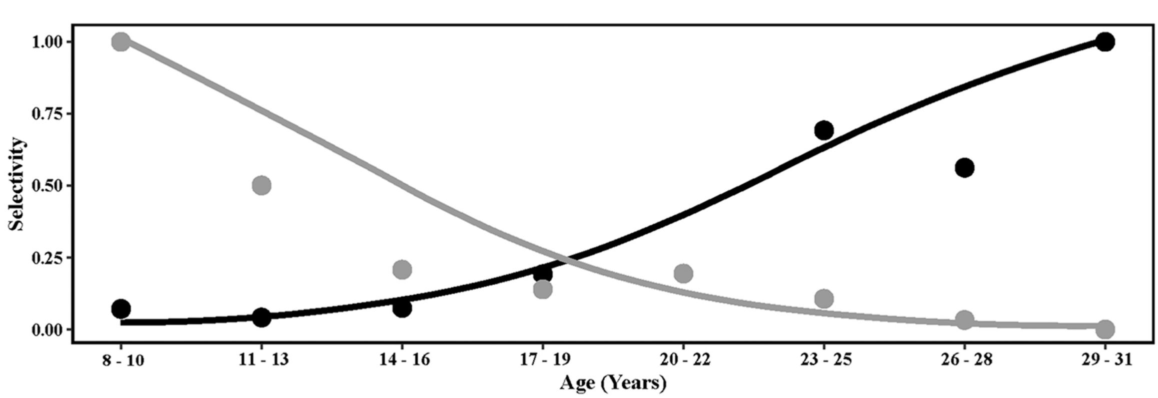

Fig. 5. Selectivity curves for bottom longline (BL) and purse seine (PU) surveys. Modeled selectivity is denoted with solid lines, while sample selectivity ratios are denoted by points. Purse seine selectivity is conveyed in grey lines and shapes, bottom longline selectivity is conveyed in black lines and points.

Table 4
Model parameters for GLM's used to generate selectivity curves. Models were run using binomial error structure and a logit link. P-values indicate low statistical significance, in part due to the low degrees of freedom df = 8 for both the purse seine and bottom longline curves.

Gear Type	x_0	x_0 + SE	x_0 - SE	k	SE	z	p
Purse Seine	12.534	16.672	8.3938	-0.288	0.218	-1.325	0.185
Bottom Longline	22.539	26.630	18.452	0.264	0.182	1.435	0.146

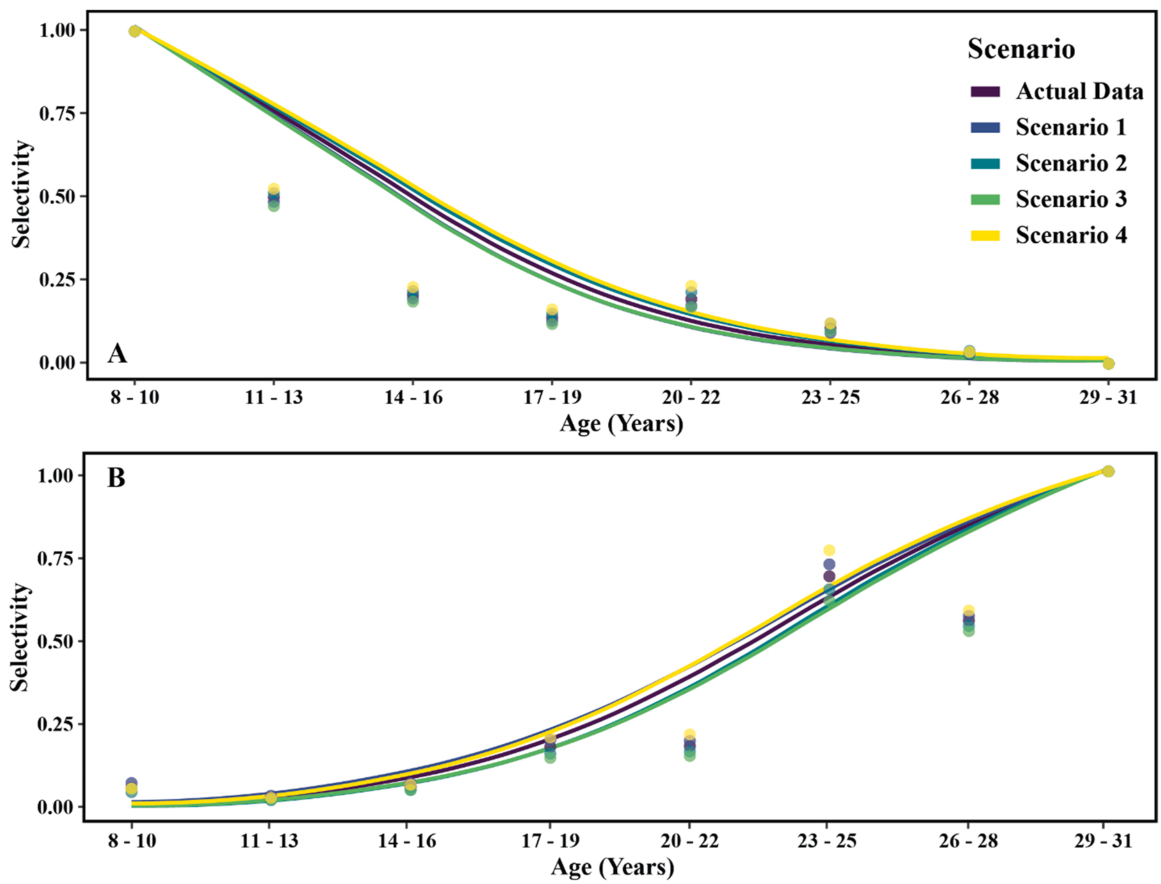

Fig. 6. Selectivity curves for actual data and modeled scenarios (1 − 4) used in out sensitivity analysis to determine whether fish kill age selectivity is likely to have substantial influence on the estimates of gear selectivity for A) purse seine and B) bottom longline.

fish kill.

4. Discussion

Red drum remain one of the most popular recreational fisheries species in the southeastern United States. Aggressive rebuilding was needed to end overfishing and overcome an overfished status in the early 1990's. By halting the commercial purse seine harvest, fishing mortality on the adult spawning stock (+ 6 year-old fish) was substantially reduced. While the reduction was key to rebuilding the stock, a consequence of the total moratorium was the end of any fisheries-dependent data to assess the current conditions of the spawning stock population and a change in the gear type available for fisheries- independent surveys. Transitioning from fisheries-dependent sampling to a rigorously designed fisheries-independent survey can be helpful for assessing stocks when data from the fishery becomes unavailable or is greatly reduced as stocks undergo aggressive rebuilding programs that limit harvest. However, when, as in the case for red drum, the survey gears and methods change, adequate characterization of selectivity of each gear on the targeted population must be conducted. Here, we illustrate how this can be achieved for Gulf of Mexico red drum and allow comparison of historic surveys and fisheries-dependent data to current survey methods.

The most simplistic approach for continuing a survey program through a fishery closure would be to maintain the gear and methods used by previous scientific surveys or the most widely used commercial gear. This approach could allow for the direct comparisons between fishery-dependent and independent surveys because selectivity could be assumed to be comparable. In our case these comparable surveys would have been in the form of annual purse seine collection of offshore red drum. However, reproducing the methodology of a fishery becomes more difficult over time as fishermen and vessels that were once common in the fishery transition to other fisheries with dissimilar gear. Additionally, there are times when gear cannot be used because of environmental concerns (e.g., high discards, or habitat impacts) (Kaiser et al., 2002). The most cost-effective fisheries-independent surveys use methods that can collect data on multiple fisheries and perhaps serve more broader ecosystem-based goals (e.g., trawl surveys, longlines). Further preventing the continued use of purse seines as a monitoring tool for red drum is the disdain of the technique by recreational stakeholders who witness the decline in red drum following the very efficient use of spotter planes and purse seiners.

The logistics and costs associated with conducting purse seines and bottom longlines differed considerably. In the 1980's and 1990's, the ability to secure purse seine boats and spotter planes with crews that were familiar with targeting red drum populations was relatively easy since the commercial fishery had just closed and capacity in the fishing fleet for these types of surveys existed. Currently, purse seine fisheries are now limited to bait fish (primarily Gulf menhaden) with most crews having little experience capturing schools of red drum. Although we were able to secure a spotter plane, vessel, and crew, our field operation had to fit into time periods around the menhaden fishery leading to decreased opportunities to survey populations. Further, there was considerable reluctance on the part of many potential vessels and crews to purse red drum given fear of bad publicity associated with capturing the highly popular fish in large numbers. In contrast, bottom longline surveys were logistically easier to establish since the gear does not require spotter planes or highly specialized vessels and crews. Moderate size vessels (12 m) can be fitted with the 100-hook gear, and haul-back requires a relatively small winch. Further, several standardized bottom longline surveys (e.g. SEAMAP) are now established, and hence scientific crews with experience are available to train others. Costs differed between the two surveys with vessel and crew cost, including spotter plane, for the purse seine operations ranging from $12,000 – $14,000 per day and the bottom longline approximately $2600 per day (in 2018 USD).

Size and age distributions differed between purse seine and bottom longline collections. Red drum collected from purse seines were generally smaller and younger than red drum collected from bottom longlines. Purse seines and bottom longlines both captured relatively few small specimens (< 800 mm TL). Because many red drum don't recruit to the offshore adult population until sexual maturity at age 6 or above, the absence of most red drum below < 800 mm TL is likely more of a reflection of low availability then selectivity of either gear. Further confirmation of this pattern is seen in the low frequency of red drum < 800 mm TL in the fish kill collections which, it is assumed, have constant gear selectivity with age. The relative frequency of large red drum (> 900 -mm TL) compared to smaller fish was higher in the bottom longline collections than in the purse seine collections. Age distribution followed the same pattern with the relative frequency of older age classes higher in bottom longlines than purse seines.

Interpretation of the size and age class distribution of red drum collected during the fish kill is dependent on the cause of the fish kill. In order for the fish kill sampling to be non-age-selective, the following conditions need to be met: 1) the effect of the conditions causing the fish kill is non-selective among size or age classes, 2) all carcasses (regardless of size or age) have an equal likelihood of washing to shore and being found, and 3) scavenging of carcasses also did not influence the ages of red drum sampled on the beaches. Not all fish kills will meet these criteria, specifically the first criteria. Fish kills resulting from low dissolved oxygen may affect large fish more than small fish, due to the decrease of gill surface area to relative body size as the fish grows (Pan et al., 2016). However, support for the fish kill in question being a result of a brevitoxin is strong. Red drum were collected on the Gulf-facing beaches indicating an offshore origin of red drum carcasses on the beach. The timing of the fish kill (Fall) also coincides with a period where adult red drum form large schools in nearshore waters for feeding and spawning (Powers et al., 2012). The fish kill, which contained several species in addition to large red drum, was coincident with the advection of a *K. brevis* bloom westward from the Florida panhandle to the Mississippi Bight - MS and AL coastal waters (Soto et al., 2018). Based on satellite-derived imagery and concomitant water samples, *K. brevis* appeared off Alabama from November 3, 2015 until December 4, 2015 (Soto et al., 2018) when the bloom was disrupted by high river discharge in the region (Dzwonkowski et al., 2017). Given the highly coincidental timing between the fish kill and the *K. brevis* bloom in the area and the lack of any documentation of alternative explanation (chemical or oil spill, fisheries bycatch, or rapid intrusion of low dissolved oxygen water), we conclude the kill was most likely the result of the bloom of *K. brevis* – an issue of growing prominence in the region.

Assuming fish kill collected specimens was a natural unbiased sample, the selectivity curves indicate that purse seines select for younger red drum and bottom longlines select for older red drum. The curve obtained by logistic regression for the bottom longline data is very similar to that observed in the fish kill except at the oldest ages where low sample sizes became an issue. The logistic regression curve for the purse seine data shows the opposite pattern in selectivity with age, but there is some disagreement in observed data with the curve shape specifically at younger ages (11 – 14 years). The authors feel that the logistic curve is most appropriate because it uses all of the data and allows for estimation of each age rather than having to bin ages to achieve suitable sample sizes. However, it is not clear that the logistic model is the most appropriate for the shape of the selectivity curve. The sample ratios calculated using each gear type and the corresponding fish kill are free from the constraints arising from assuming a particular parametric form for the selectivity curve. Due to limitations of sample sizes and list of assumptions regarding the non-selectivity of the fish kill, it is not possible to objectively resolve the shape of the selectivity curve but instead use the best subjective fit. This is because any calculation of variance is conditional on the model, and the model assumptions, which are not objectively verifiable.

Although we cannot evaluate all the assumptions of the method for estimating selectivity, we believe this novel approach is likely to provide approximate values for selectivity among the two gear types and, as such, is a valuable addition to the methods for estimating selectivity. In comparison to our opportunistic use of the fish kill, a more traditional mark and recapture study to establish a known population would have required tagging over 1100 adult red drum, assuming a very high recapture rate of 10%, an effort that would have been extremely costly given the low catch rates and large sampling area. In ideal circumstances, these type of non-selective fish kills will happen concurrently with fishery-dependent and independent sampling. Additionally, fish kill caveats must be met for use in selectivity estimation, 1) observing a broad range of fish sizes and fish species, 2) the cause of the fish kill is understood non-selective, and 3) fish are sampled soon after the fish kill to avoid a potential biased loss of samples. The latter point could be confirmed by repeating collection of fish in the fish kill over several days to observe changes in size and age composition.

The underestimation of older red drum in the purse seine collections may have substantial consequences for how reproductive capacity and growth parameters of the stock are viewed. Between our gear-specific growth models L_∞ was estimated to be 50 mm longer for the bottom longline collected red drum than purse seine. Additionally, mean age was 5 years older for bottom longline collected red drum compared to purse seine collected red drum. Because fecundity increases disproportionally with increased size and age in most fish (Berkeley et al., 2004a, Berkeley, 2004b), the reproductive capacity (as measured by number of eggs) of the offshore population could be estimated to be much higher based on the higherproportion of larger red drum collected in the bottom longline compared to the purse seine. Similarly, comparisons of our growth parameters with other studies (e.g. Table 2, Bennetts et al., 2019) demonstrate that growth curves estimated using bottom longline collected red drum tend to be at the high end of the L_∞ and have mid-range k values, while the opposite trend was observed using purse seine collected fish which estimated smaller L_∞ and higher k values. In the context of future stock assessments, a lack of reliable estimation of fecundity and growth using biased fishery-independent sampling is especially concerning for management. Wells et al. (2013) in their age and growth study of Pacific albacore (*Thunnus alalunga)* demonstrated how variation in age and growth models yielded substantial differences in estimates of spawning stock biomass.

Assessments conducted in the 1990's and early 2000's assumed a logistic (flat-top) selectivity curve for the purse seine collections. The updated selectivity curve we derived may have led to slightly different conclusions relative to the abundance of older age class red drum although the assessment would likely have not changed (overfishing and an overfished condition) given the rapid increase in harvest of spawners. We do note that while biased selectivity may have resulted in the overestimation of fishing mortality of larger fish. We conclude that a safer assumption would be that bottom longline collections have a flat-top selectivity curve. Several assessments (e.g., Red Snapper, Sharks, Groupers in the Gulf of Mexico) have assumed a flat-top selectivity curve for fisheries-independent bottom longline captured fishes which we also found support for in our study.

As more fisheries stocks undergo changes in management scheme and necessary harvest restriction, fisheries-independent surveys will become increasingly important to measure recovery. Often, sampling methods and gears may change as the transition from fisheries-dependent to fisheries-independent data sources become necessary. For species like red drum that are long lived and show ontogenetic habitat shifts, differing gears may also be necessary for a full assessment of all age groups. Hence, knowledge of gear selectivity and performance is critical for accurate assessments. Because of their logistic difficulty as well as the possibility of killing large numbers of fish, purse seine collections will remain difficult to accomplish. Based on public testimony at the Gulf of Mexico Fishery Management Council as well as position statements from the Coastal Conservation Association (which represents thousands of recreational fishermen), resumption of purse seine collection, even for scientific studies, would be widely unpopular with recreational fishermen who fought hard for the cessation of such activities in the late 1980's early 1990's. Our study demonstrates that bottom longline collections are closer to the fish kill samples in both age composition and growth parameter determination, which have important implications to survey design for red drum if the fish kill is indeed non-selective. While the cost of fisheries-independent collections is often higher than fisheries-dependent collections, the cost per fish can be decreased by using gears that sample multiple stocks of interest, such as bottom longlines. Managers should carefully consider whether adequate fisheries independent sampling programs are in place or need to be adopted to monitor stock condition if fisheries dependent data sources are stopped or substantially altered. This consideration should be a component of stock rebuilding plans.

CRediT authorship contribution statement

Sean P. Powers: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization, Funding acquisition. **Crystal L. Hightower:** Data curation, Methodology, Writing – review & editing, Project Administration. **John M. Hoenig:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Jeffrey D. Plumlee:** Formal analysis, Writing – review & editing, Visualization. **T. Reid Nelson:** Formal analysis, Writing – review & editing. **J. Marcus Drymon:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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