ESTIMATING THE TAG-REPORTING RATE AND LENGTH-BASED SELECTIVITY OF RED DRUM (*Sciaenops ocellatus*) IN SOUTH CAROLINA USING A LONG-TERM TAG-RECAPTURE STUDY

A thesis submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

in

MARINE BIOLOGY

by

LUKAS UGLAND TROHA
AUGUST 2023

at

THE GRADUATE SCHOOL OF THE UNIVERSITY OF CHARLESTON, SOUTH CAROLINA AT THE COLLEGE OF CHARLESTON

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ABSTRACT

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Tag-recapture studies are often utilized to generate precise, externally derived, estimates of stock assessment parameters such as tag-reporting rate and selectivity. These estimates can be used to increase the accuracy of recent stock assessments for red drum (*Sciaenops ocellatus*), which have exhibited significant uncertainty and largely leave the population status in question. Using more than forty years of red drum tag-recapture data available from the South Carolina Department of Natural Resources (SCDNR) including a high-reward tagging study, we estimated the tag-reporting rate of red drum, as well as the length-based selectivity of fishery-independent sampling gears (trammel net, electrofishing, stop net, and longline) and recreational hook-and-line. Tag-reporting rate in South Carolina is high overall, approaching maximal reporting (100%) in St. Helena Sound, Charleston Harbor, and Winyah Bay, while Port Royal Sound displayed 58.9% reporting rate. The shape of fishery-independent selectivity curves depended on gear type, with each gear selecting for a different size class. A dome-shaped pattern of recreational hook-and-line selectivity was observed for harvested and released fish in nearly all management periods, though the size of maximum selectivity in South Carolina recreational fisheries varied based on fate of the fish after capture. The results of this study provide essential information to be used in future red drum stock assessments and will subsequently influence management of the species.

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CHAPTER 1

INTRODUCTION

Fisheries are a significant part of the United States (U.S.) economy, and the economic impact of recreational fisheries has been increasing through recent years (NMFS, 2023). Recreational fisheries are particularly important in the southeastern U.S., as South Carolina supports the fourth-most recreational fishery jobs among U.S. states, only behind Florida, North Carolina, and Alabama (NMFS, 2023). The red drum (*Sciaenops ocellatus*) is among the most frequently targeted fish by recreational fishers in South Carolina and the rest of the southeastern U.S., though red drum populations have been overexploited in the past. In 1987, South Carolina's red drum commercial fishery was permanently closed due to overfishing. Since 1987, all fishing pressure on red drum in South Carolina has come from the recreational fishery and landings have been managed strictly with small creel limits and the implementation of a slot limit on harvest since 1990. Despite strict management, the status of the South Carolina red drum population is still in question due to significant uncertainty in recent stock assessments (ASMFC, 2017; Murphy, 2017). Much of this uncertainty draws from the internal (i.e., within the model) estimation of key parameters used in population models addressing fish population status.

One method to improve model performance and precision is through tag-recapture studies, which are the primary techniques used to generate precise, externally derived estimates of model inputs (Myers & Hoenig, 1997; Bacheler et al., 2010; Jones & Cox, 2018). Tag-recapture studies may provide estimates of important parameters such as tag-reporting rate and selectivity (Myers & Hoenig, 1997; Hoenig et al., 1998a). However, both parameters are often estimated internal to the model, where they may be confounded with estimates of other parameters of interest (Hoenig et al., 1998a; Bacheler et al., 2010; Lauretta & Goethel, 2017). Tag-reporting rate, which is the proportion of tags caught by recreational anglers that are reported to the tagging authority, can be difficult to estimate, but if estimated accurately it can improve model performance and increase precision of parameters such as survival, exploitation rate, and the partitioning of total mortality into fishing and natural mortality (Brownie, 1985; Pollock et al., 1991; Hoenig et al., 1998b). Selectivity (i.e., population selectivity), which is the susceptibility of a certain demographic of a fish population to capture, is a principal parameter utilized in stock assessments, as errors in estimation of selectivity translate to erroneous estimates of stock abundance and harvest rate (Millar & Fryer, 1999; Maunder et al., 2014; Punt et al., 2014). Additionally, recent assessments suggest that increased precision of selectivity estimates, especially for the live-release fishery, is a critical need in future stock assessments for red drum (ASMFC, 2017; Murphy, 2017). Thus, providing external estimates of both tag-reporting rate and selectivity should increase precision of the aforementioned parameters as well as improving model performance overall.

Herein, we analyze 40+ years of tag-recapture data from the SCDNR's long-term monitoring program to provide external estimates of tag-reporting rate (Chapter 1) and selectivity (Chapter 2) for red drum in South Carolina. Tag-reporting rate is estimated through a high-reward tagging study utilizing fishery-dependent recaptures of red drum. Fishery-independent and fishery-dependent tagging data are used to provides estimates of selectivity, and selectivity is estimated separately for fishery-independent survey gears and hook-and-line recaptures from recreational anglers. The purpose of this research is to provide parameter estimates that will improve the performance of tagging models used to assess red drum populations, including the first external estimates of selectivity for red drum in South Carolina.

CHAPTER 2

TAG-REPORTING RATE

2.1. Introduction

One of the most common methods of monitoring wild animal populations is through tag-recapture experiments, which may provide information on population parameters such as abundance and mortality (Seber, 1982; Polacheck et al., 2010). Tag-recapture studies are a staple of fisheries scientists across the world, owing to their utility in directly estimating selectivity patterns, exploitation rates, and population abundances, understanding of movement patterns, and estimating of growth rates (Pollock et al., 1991; Pine et al., 2003; Pine et al., 2012). Of utility to fisheries managers interested in partitioning total mortality (Z) into fishing (F) and natural (M) mortality are tag-recapture models [a.k.a. Brownie models (Brownie et al., 1985)], with this class of tagging model being widely applied to a variety of fisheries applications (Youngs & Robson, 1975; Hoenig et al., 1998a, 1998b). The tag recovery rate (θ) parameter in tag-recapture models, which is the product of tag-reporting rate (λ) and the combined parameter of tag-shedding and tagging mortality rate (ϕ), can be used to estimate exploitation rate (Hoenig et al., 1998a). However, uncertainty in rates of tag-reporting and the combined parameter representing tag-shedding and tag-induced mortality confounds interpretation of tag-recapture data, particularly the use of such data to estimate selectivity patterns and exploitation rates.

Tag-reporting rate is among the most important parameters necessary in tag-recapture analyses when considered as part of tag recovery rate (Hoenig et al., 1998a; Sackett & Catalano, 2017). However, it is often estimated internal to the tag-recapture model, where it may be unstable and treated as a nuisance parameter and affects estimates of the other parameters of interest such as exploitation rate and fishing and natural mortality (Hoenig et al., 1998a; Bacheler et al., 2010; Lauretta & Goethel, 2017). Tag-reporting rate is typically assumed to be constant over time (Hoenig et al., 1998a; Latour et al., 2001; Denson et al., 2002) but may be variable through years (Taylor et al., 2006). The tag-reporting rate can be difficult to estimate, but if estimated accurately it can improve model performance and increase precision of parameters such as survival (Hoenig et al., 1998b). In the Brownie tag-recapture model, for example, tag-reporting rate is required to accurately estimate exploitation rate or partition mortality rates into fishing and natural mortality (Brownie et al., 1985; Pollock et al., 1991; Hoenig et al., 1998a). Researchers commonly use high-reward tagging studies to obtain external estimates of tag-reporting rate (Pollock et al., 2001; Denson et al., 2002; Pine et al., 2003). These studies consist of biologists releasing fish tagged with a standard-reward (often a novelty such as a t-shirt or hat) tag or a high-reward (commonly $100) tag, where it is assumed all high-reward tags encountered by anglers are reported. If the assumption holds, the ratio of standard-reward to high-reward tag recapture rates provides an estimate of the standard-reward reporting rate, which are the tags used in year-round biological sampling (Pollock et al., 2001; Denson et al., 2002). Such an external estimate benefits the ability of analyses using conventional tag-recapture data to estimate the uncertainty about estimates of selectivity and exploitation rates (Hoenig et al., 1998a; Jiang et al., 2007; Lauretta & Goethel, 2017).

With the goal of providing direct information on fish abundance, recreational exploitation rates, and selectivity patterns, the South Carolina Department of Natural Resources (SCDNR) and similar organizations have been monitoring fish populations through tag-recapture studies since the late 1970's. In South Carolina, red drum (*Sciaenops ocellatus*) are of particular importance to tagging studies, as they are among the most popular inshore gamefish in the southeastern U.S. (NMFS, 2023). The red drum fishery in South Carolina is primarily catch-and-release, with over 84% of captured red drum released from 2011-2020 (NMFS, 2023). However, there is a history of exploitation of red drum populations in South Carolina, as SCDNR's fishery-independent tagging began in 1986 around the closure of the South Carolina red drum commercial fishery due to concern over population status. While the tag-reporting rate of red drum has been investigated previously in South Carolina (Jenkins et al., 2000; Denson et al., 2002; Murphy, 2017), these estimates were based either on high-reward tagging studies occurring nearly 30 years ago in limited geographic areas (Jenkins et al., 2000; Denson et al., 2002) or were estimated internal to an integrated stock-assessment model and hence are confounded with other parameter estimates (Murphy, 2017). Additionally, recent stock assessments for the South Atlantic population of red drum have exhibited significant uncertainty, so much so that an overfished status could not be determined (ASMFC, 2017; Murphy, 2017). A stock assessment for the South Carolina population of red drum showed increased fishing mortality and decreased escapement to the adult population in recent years (Murphy, 2017). Thus, with the South Atlantic red drum population status in question, it is pertinent to examine external estimates of model parameters to increase precision of tag-recapture models.

Herein, the SCDNR conducted a high-reward tagging study to estimate the tag-reporting rate of red drum in South Carolina, releasing tagged fish in South Carolina's four major estuaries: Port Royal Sound, St. Helena Sound, Charleston Harbor, and Winyah Bay. The reporting estimates from this study will characterize the level of recreational angler participation in SCDNR's red drum tagging program, both in terms of fishing effort (i.e., recapture rate) and tag-reporting rate. Our tag-reporting estimate will improve precision of the overall tag recovery rate and exploitation estimates, as recent SCDNR studies have estimated tag retention (Hendrix, 2010) and tagging mortality (Ballenger & Frazier, 2020). Further, this study provides an update to previous SCDNR studies (Jenkins et al., 2000; Denson et al., 2002), and results will determine whether there have been any significant temporal changes in tag-reporting rate as a result of changes in recreational angler behavior.

2.2. Materials and Methods

Red drum tagged in the current study were produced by the SCDNR's mariculture and stock enhancement program as part of their annual efforts to supplement natural red drum reproduction across coastal South Carolina. Juvenile red drum produced via wild-captured broodstock were maintained in outdoor ponds fed by estuarine water at SCDNR's Waddell Mariculture Center in Bluffton, SC. Upon reaching legal, harvestable size [381 – 584.2 mm total length (TL; 15-23 inches TL)] during the spring and early-summer 2019, SCDNR biologists tagged all fish in the study with abdominal anchor tags (Floy Tag and MFG Co., Inc., Seattle, WA), consisting of a 26mm x 7mm plastic disk wired to a laminated 90mm streamer around a wire core, prior to releasing tagged fish across multiple sites within four South Carolina estuaries: Port Royal Sound, St. Helena Sound, Charleston Harbor, and Winyah Bay. There were, however, several individuals that were larger than the 584.2 mm maximum of the slot limit at the time of tagging (n = 51). Fish were released at three individual sites in each estuary, with fish intermittently released while boating along the bank of the site to encourage dispersal of tagged fish amongst the wild population.

Fish released in Port Royal Sound and St. Helena Sound were tagged and released from Waddell Mariculture Center. Fish to be released in Charleston Harbor and Winyah Bay were first transported to the SCDNR Marine Resources Research Institute in Charleston, South Carolina to be tagged, held, and later transported to release locations. Regardless of tagging location, fish were anesthetized with 30 ppm of AQUI-S aquatic anesthetic (AQUI-S New Zealand Ltd., Melling, Lower Hutt, New Zealand) prior to tagging to reduce stress during the tagging process. Fish exhibiting physical ailments such as lesions were not tagged. Tagged fish were held for a minimum of seven days post-tagging in tanks prior to release at each location to ensure no short-term tag shedding or tagging mortality occurred. Fish were transitioned to well water for acclimation shortly before release. Fish lengths were recorded at time of tagging prior to the acclimation period and release.

After the holding period, approximately 100 sub-adults tagged with standard-reward tags and 50 subadults tagged with high-reward tags were released at each site within an estuary. The streamer portion of standard reward tags read "tag inside", "reward", "SCDNR", and a unique tag number, and the disk portion contained the tag number and read "reward, send tag, date, location, gear, length, phone to…" with the SCDNR mailing address on the other side of the disk. The streamer of high-reward tags contained the same text except "reward" was replaced with "$100 reward." We did not advertise the existence of the study to South Carolina recreational anglers to minimize effects the study may have on the behavior of anglers (Denson et al., 2002).

To estimate λ, we divided the return rate of conventional tags by the return rate of high reward tags (Equation 1; Jenkins et al., 2000; Pollock et al., 2001; Denson et al., 2002).

$$\lambda = \frac{\#\, standard\ tags\ returned / \#\, standard\ tags\ released}{\#\, high\ reward\ tags\ returned / \#\, high\ reward\ tags\ released} \tag{1}$$

Eq. (1) assumes anglers report high-reward tags on 100% of the occasions they are encountered, so the ratio of standard- to high-reward tag return rates approximates the reporting rate of standard-reward tags. We examined tag return rates over an approximately six-month period of accepting recaptures (recaptures through December 31, 2019). In calculating all reporting rates, we considered only the first recapture of a tagged fish so as not to confound the number of unique recapture events. We limited tag-reporting rates so they did not exceed 100% as it is not possible to report more than 100% of tags. Thus, maximal reporting is achieved when the proportion of standard-reward tags recaptured is equal to or exceeds the proportion of high-reward tags recaptured. We did not consider recaptures for which no recapture location information was provided (n = 2), so we could not confirm which estuary the recapture could be attributed to. Additionally, we ignored the few recaptures where a fish was recaptured in an estuary different from the estuary it was initially released in order to not bias the λ calculated by estuary (n = 2).

We estimated 95% confidence intervals surrounding the proportion of return rates of standard- and high-reward tags using the “BinomRatioCI” function in the “DescTools” package (Signorell, 2023) in R software (R Core Team, 2023). “BinomRatioCI” estimates the confidence interval surrounding a ratio of binomial proportions, which is the ratio of the proportion of standard-reward tags returned to the proportion of high-reward tags returned. We used the Chi-squared based Koopman asymptotic score method, which performs well in calculating confidence intervals of binomial proportions (Koopman, 1984; Aho & Bowyer, 2015).

To account for potential bias in our λ estimation induced by a few anglers reporting several tags, we also calculated a λ based only on anglers who returned one tag throughout the entire study, termed “single returns” (Denson et al., 2002). Theoretically, this should eliminate bias associated with the capture of multiple tagged fish or the interaction of different reward messages (Jenkins et al., 2000; Denson et al., 2002).

2.3. Results

From March 26, 2019 through July 11, 2019, 1,169 sub-adult red drum ranging in size from 403-645 mm TL were released across coastal South Carolina (Table 2.1). Through December 31, 2019, 192 anglers had reported tags on 213 tagged fish. Fourteen of the anglers (7.3%) reported multiple tagged fish, and six (42.9%) of those fourteen anglers recaptured multiple tagged fish in Port Royal Sound. We calculated a statewide tag-reporting rate of 89.1% (95% CI: 67.8-100.0%) with 15.0% of standard-reward tags and 16.9% of high-reward tags recaptured.

Tag-reporting rates were high overall, with St. Helena Sound, Charleston Harbor, and Winyah Bay all approaching a 100% reporting rate (Table 2.1). Port Royal Sound exhibited the lowest reporting rate at 58.9% albeit with large confidence intervals (95% CI: 33.7-100.0%; Table 2.1). Recapture rates varied with estuary, as 27.4% and 27.5% of standard- and high-reward tags, respectively, were reported in Charleston Harbor, while St. Helena Sound showed the lowest recapture rate with only 7.0% and 7.2% of standard- and high-reward tags reported, respectively (Table 2.1).

We calculated a single return reporting rate of 94.7% (95% CI: 69.5-100.0%) across the four major estuaries in South Carolina (Table 2.2). Similar to the findings when considering all returns, single return reporting rates were high overall, as Port Royal again exhibited the lowest reporting rate at 78.2%, though not significantly lower than other estuaries given the large confidence intervals (95% CI: 34.7-100.0%; Table 2.2). There were no recaptures excluded in Winyah Bay as no anglers reported multiple tags in the six-month period. Port Royal, however, required that 19 of 40 total recaptures be excluded in this single return dataset, as six anglers accounted for nearly half of the recaptures in the Port Royal area.

2.4. Discussion

Recapture rates in this study were relatively high, but our observed coastwide recapture rate of 15.7% is typical for red drum in the southeastern U.S. (Jenkins et al., 2000; Denson et al., 2002; Bacheler, 2008). However, recapture rates varied with estuary, with returns being approximately four times more likely from Charleston Harbor (~27%) than St. Helena Sound (~7%). The high recapture rates of tagged sub-adult red drum may be due to a combination of several factors, such as inhabiting estuaries easily accessible to anglers, often exhibiting schooling behavior (Overstreet, 1983; Reyier et al., 2011; Powers et al., 2012) and being a highly sought-after gamefish (NMFS, 2023). The recaptures rates observed in this study suggest high fishing mortality, which is supported by a recent stock assessment on red drum in South Carolina that found fishing mortality has increased through recent years despite being a primarily catch-and-release fishery (Murphy, 2017).

In contrast to tag-returns that varied with estuary, tag-reporting rates were high in all estuaries, with nearly equivalent tag-return rates of standard- and high-reward tags in St. Helena Sound, Charleston Harbor, and Winyah Bay resulting in near-maximal (100%) point estimates of λ in these estuaries. While Port Royal Sound displayed the lowest point estimate of λ (58.9%), the confidence intervals (33.7-100%) surrounding this estimate indicate a high degree of uncertainty in λ at this small spatial scale. That said, at the statewide scale the broad and overlapping 95% confidence intervals suggest a lack of evidence of spatial variability in tag-reporting rate across coastal South Carolina. Future studies should increase the power of λ estimates at the estuary scale by increasing sample sizes if there is need to provide estuary specific λ for fisheries management purposes. However, the cost of such a study may be prohibitive given the increased resolution in λ gained.

This is the first study to evaluate the tag-reporting rate of conventionally tagged red drum in South Carolina at any spatial scale since the 1990's (Jenkins et al., 2000; Denson et al., 2002). The coastwide estimate of λ, 89.1% (95% CI: 67.8-100.0%), from the current study is similar to the point estimates of λ estimated in Jenkins et al. (2000) and Denson et al. (2002). Jenkins et al. (2000) conducted a variable reward study using red drum released in October 1992 in Port Royal Sound where the highest reward tag was worth $50. The estimated λ of tags with the message "reward" was 81.7% and 100% based on using all returns or single returns, respectively, over approximately one year (Jenkins et al., 2000). Denson et al. (2002) used a $100 high-reward tag and estimated λ of conventionally tagged red drum released in Charleston Harbor and Calibogue Sound (Port Royal Sound area), South Carolina, and St. Simon Sound and Wassaw Sound, Georgia, using three different methods: raw tag returns, single returns, and returns adjusted to account for results of surveys regarding willingness to report tagged fish. The three methods resulted in λ estimates of 78.0%, 77.3%, and 56.7%, respectively, combining data across South Carolina. While these point estimates are somewhat lower than the current study, they generally fall within the confidence intervals for statewide λ calculated herein. Similarly, the most recent λ for sub-adult red drum in South Carolina calculated as part of an integrated stock assessment and not using high-reward tags, estimated λ as 73% based on SCDNR tag-recapture data integrated into the assessment (Murphy, 2017). These results, when combined with other studies in South

Carolina (Jenkins et al., 2000; Denson et al., 2002; Murphy, 2017), suggest temporal variation in tag-reporting rate is minimal. The lack of spatial and temporal differences in tag-reporting rate in South Carolina is significant, as tag-recapture models exhibit increased sensitivity on the estimation of parameters when λ varies over space or time (NEFSC Tagging Workshop, 2005).

High-reward tagging studies assume anglers can recognize the value of tags. To address this assumption, some researchers advocate for advertisement of high-reward tagging studies or having different colored standard- and high-reward tags so that the tags are not ignored, which would cause a positive bias in tag-reporting rate (Pollock et al., 2001; Pollock et al., 2003; Bacheler, 2008). However, our study was not advertised so that we would not influence the typical behavior of anglers, as discussed in Denson et al. (2002). While this may mean we obtained a more representative sample of typical angler behavior, it is possible some anglers may not have recognized the value on a high-reward tag. If this were the case, the assumption that 100% of high-reward tags encountered are reported may be violated, leading to a positive bias (i.e., overestimation) in our tag-reporting estimates. This is possible, especially since most tag-reporting rates in this study approach maximal reporting, though the return rates of both standard and high-reward tags are high overall and equal to or greater than tag-return rates observed in previous studies in the same geographic area (Jenkins et al., 2000; Denson et al., 2002). Another assumption of high reward tagging studies is that the "high reward" is sufficiently large to elicit a 100% reporting rate. Our study assumed $100 was sufficient to ensure a 100% reporting rate of high-reward tags, however, some authors suggest this reward may need to be increased in contemporary studies (Nichols et al., 1991; Taylor et al., 2006). Denson et al. (2002) found direct evidence, based on their angler survey, that $100 was not sufficient to elicit 100% of tag-returns by at least one South Carolina angler capturing sub-adult red drum in the late 1990's. If our high-reward tags were not sufficiently incentivizing to anglers to elicit a 100% return rate, this would lead to an overestimation of the red drum λ in South Carolina, though the degree of bias is expected to be small given the high return rates observed.

An additional consideration with any long-term tagging study is the possibility of tag fatigue, or a decrease in tag-reporting over time. Tag fatigue or satiation may be especially common when the standard reward offered is a novelty (Pollock et al., 2001), such as a hat or t-shirt. SCDNR's sub-adult red drum tagging programs provide such novelties to anglers for the standard reward tags, though there are several possible rewards to choose from and they have varied in design over the years. Denson et al. (2002) identified tag fatigue as a possible reason why they initially failed to identify significant differences in return rates and that angler fatigue could eventually lead to angler ambivalence and reduced cooperation. However, the relatively stable return rates and λ observed herein compared to early studies suggest tag fatigue is not leading to significant declines in angler participation across South Carolina.

Moreover, we designed and executed a high-reward tagging study across coastal South Carolina, releasing fish in four major South Carolina estuaries. We find no significant temporal variation in tag-reporting rate when compared to earlier studies on tag-reporting rate of red drum in South Carolina. Tag-reporting rates did not significantly vary across estuaries, primarily due to large confidence intervals surrounding each estimate. An updated, more spatially representative estimate of λ, as calculated in this study, should aid in reducing uncertainty in future tag-return and stock assessment models and allow for better informed management of red drum. Future studies should focus on increasing sample size and potentially increasing the value of high-reward tags or including an additional reward value to assess if the assumption of 100% reporting of high-reward tags is satisfied.

2.5. Tables

Table 2.1: Number of sub-adult red drum released, number of tag returns within approximately six months of the release date (December 31, 2019 return cutoff date), arranged by tag type and location. Also provided is the tag-reporting rate. Number of returns are by all anglers, regardless of number of tag-returns provided.

	Standard Reward Tags			High Reward Tags			
Location	**Released**	**Reported**	**Return Rate**	**Released**	**Reported**	**Return Rate**	**Tag-Reporting Rate (95% CI)**
Port Royal Sound	189	22	12.2%	91	18	19.9%	58.9% (33.7-100.0%)
St. Helena Sound	186	13	7.0%	97	7	7.2%	96.9% (41.4-100.0%)
Charleston Harbor	201	55	27.4%	102	28	27.5%	99.7% (68.4-100.0%)
Winyah Bay	202	27	13.4%	101	13	12.9%	100.0% (57.1-100.0%)
South Carolina	**778**	**117**	**15.0%**	**391**	**66**	**16.9%**	**89.1% (67.8-100%)**

Table 2.2: Number of sub-adult red drum released, number of tag returns within approximately six months of the release date (December 31, 2019 return cutoff date), arranged by tag type and location. Also provided is the tag-reporting rate. Returns by only anglers who returned one tag throughout the entire study were considered.

Location	Standard Reward Tags			High Reward Tags			Tag-Reporting Rate (95% CI)
	Released	Reported	Return Rate	Released	Reported	Return Rate	
Port Royal Sound	189	13	6.9%	91	8	8.8%	78.2% (34.7-100.0%)
St. Helena Sound	186	10	5.4%	97	6	6.2%	86.9% (34.0-100.0%)
Charleston Harbor	201	50	24.9%	102	25	24.5%	100.0% (67.7-100.0%)
Winyah Bay	202	27	13.4%	101	13	12.9%	100.0% (57.1-100.0%)
South Carolina	**778**	**100**	**12.8%**	**391**	**52**	**13.3%**	**94.7% (69.5-100.0%)**

CHAPTER 3

SELECTIVITY

3.1. Introduction

Selectivity is a principal parameter utilized in stock assessments, as errors in estimation of selectivity translate to erroneous estimates of stock abundance and harvest rate (Bacheler et al., 2010; Maunder et al., 2014; Punt et al., 2014). Selectivity (i.e., population selectivity) is defined generally as the susceptibility of a certain demographic (i.e., age or length class) of a fish population to capture and can be thought of as the sum of gear selectivity (a.k.a. contact selectivity) and availability (Millar & Fryer, 1999; Sampson & Scott, 2011; Cadrin et al., 2016). Gear selectivity is the probability that a particular gear catches a fish if it is present (Fauconnet & Rochet, 2016). For example, hook and/or bait size can discriminate among size of target fishes, as smaller fish may not be able to be hooked on a large hook or are less likely to attempt to consume a large bait, and vice versa (Hilborn & Walters, 1992; Millar & Fryer, 1999; Bacheler & Buckel, 2004). Similar gear selectivity issues plague other gears used either in commercial fisheries or fishery-independent surveys. For example, entangling gear such as gill nets and trammel nets, such as those used by the SCDNR trammel net survey, will be most successful targeting certain sizes of fish (Hamley, 1975; Saadet Karakulak & Erk, 2008; Lucchetti et al., 2020). Despite its significance, gear selectivity is often neglected in analyses due to complicating factors such as differences in movement and wariness/avoidance of gear with fish size (Hillborn & Walters, 1992; NEFSC Tagging Workshop, 2005). While gear selectivity addresses the properties of the fishery, availability relates to the spatial position of different size fish to the fishing gear (Millar & Fryer, 1999). For example, environmental conditions affecting detectability of the gear or the fishes' behavior can alter availability (Fauconnet & Rochet, 2016). Additionally, fish populations that are not well-mixed can exhibit selectivity patterns driven by availability (Sampson, 2014), which could be an important factor for schooling species like red drum that tend to segregate by size (Bacheler et al., 2012). This can manifest in different size classes being available to fisheries seasonally within a given area (e.g., salt-marsh edge habitats) or across space (e.g., small tidal creeks, lower estuary salt-marsh edge habitats, versus coastal ocean). Such spatial and seasonal changes in availability of different size classes are clearly important in understanding selectivity patterns; ignoring the availability component of selectivity could result in biased estimates of fishing mortality, abundance, and escapement (Latour et al., 1998).

Estimation of age- or length-based selectivity is often expressed via selectivity curves where the age/size with peak selectivity has a value of 1.0, and these curves are used to describe the pattern of fishing mortality applied to a stock (Millar & Fryer, 1999; Sampson & Scott, 2012; Vasilakopoulos et al., 2020). Gear selectivity of age classes of fishes should ideally change with the age of the fish to preferentially catch large adults and let juveniles and subadults avoid capture (MacLennan, 1992); this results in the well-known and generally assumed flat-top selectivity (i.e., maximum selectivity reached before largest sizes and remains at maxima throughout largest size classes) of many commercial fishing gears regardless of species. Alternatively, dome-shaped selectivity occurs when maximum selectivity is observed at intermediate sizes, which is common when harvest restrictions define both a minimum and maximum length (i.e., a slot or window limit; Bacheler et al., 2010). Dome-shaped selectivity also may result from larger fish being able to avoid or escape the fishing gear or non-uniform fishing (Sampson & Scott, 2011; Sampson & Scott, 2012). Additional selectivity curve shapes include increasing (and decreasing) and saddle-shaped or multi-peaked (Sampson & Scott, 2012). Selectivity is often estimated within assessment models (i.e., internally), though internally generating estimates is confounded with other important parameters such as abundance and fishing mortality (Punt et al., 2014; Cadrin et al., 2016), often resulting in greater uncertainty in stock status and individual parameters.

Tag-recapture studies, such as SCDNR's long-term tag-recapture program which utilizes both fishery-independent and fishery-dependent data, are an effective method of generating precise, externally derived, selectivity estimates (Myers & Hoenig, 1997; Bacheler et al., 2010; Jones & Cox, 2018). The primary species monitored by this program is red drum, *Sciaenops ocellatus*, which are among the most popular inshore gamefish in the southeastern U.S., generating significant economic impacts within these states (Matlock, 1986; NMFS, 2023). They inhabit coastal and estuarine waters of the Atlantic Ocean on the southeastern coast of the United States, ranging from Massachusetts to Florida and the Gulf of Mexico until northeastern Mexico (Lux & Mahoney, 1969; Mercer, 1984; Wenner, 1999). Along the U.S. Atlantic coast, the red drum population is separated into northern and southern stocks, with the southern stock ranging from South Carolina through the east coast of Florida (Vaughan & Carmichael, 2000; SEDAR, 2015). Red drum tolerate a wide range of salinities, and the estuarine and coastal habitats they occupy are largely dictated by life history stage (Wenner et al., 1990; Latour et al., 1998). Juveniles (0-203 mm total length (TL); 0-10 months of age) primarily use small estuarine creeks as nurseries, while sub-adults (203-838 mm TL; 10 months – 5 years of age) venture into deeper bodies of water and the lower estuarine habitat. Red drum in South Carolina transition from sub-adults to adults by approximately 711 mm TL in males and 838 mm TL in females while reaching maximum age of 41.7 years, and these adults primarily occupy nearshore coastal waters (Wenner et al., 1990; Latour et al., 1998; SEDAR, 2015). The harvest of red drum in South Carolina has been regulated with a slot limit since 1993 which allows the harvest of immature fish. As sub-adult red drum occupy estuarine waters easily accessible to fishers and are harvestable if within the slot limit, the sub-adult phase of a red drum's life cycle represents a period of high susceptibility to exploitation.

Due to concerns of red drum populations being overfished along the U.S. Atlantic coast during the 1980's, several recreational harvest restrictions were instituted in South Carolina (McGurrin, 1991; ASMFC, 2002; SEDAR, 2015), as well as a complete ban on commercial harvest in 1987. Since then, there has been evidence to encourage adjustments to the size and creel limits to further reduce fishing mortality to levels needed for recovery (Vaughan & Carmichael, 2001; SEDAR, 2015), with the most recent adjustment to the slot limit on South Carolina red drum enacted in 2007. Furthermore, though the 2017 regional stock assessment on red drum conducted by the Atlantic States Marine Fisheries Commission (ASMFC) determined overfishing was not occurring, there was significant uncertainty in the assessment and minimal available data on the adult population (ASMFC, 2017). Due to the inability to use the region-wide assessment for management advice, the South Carolina Department of Natural Resources (SCDNR) completed a separate, state-specific stock assessment for the South Carolina population of red drum, with the results indicating that red drum populations increased in abundance from 1982-2010, but then began declining through 2015, with constantly decreasing recruitment (Murphy, 2017). Moreover, fishing mortality (F) increased from the early 2000's through 2015 and suggested a change in the age structure of the South Carolina population over the years, with a general juvenescence of the population due to decreased numbers of older, and presumably larger, fish. Though providing critical information, the accuracy of both the 2017 ASMFC and South Carolina stock assessment models could be improved by reducing variation on key estimated parameters, incorporating more information on the lengths of caught-and-released fish, and further investigating tag-recapture datasets (Murphy, 2017). Furthermore, both assessment models relied on internal estimation of key parameters, such as selectivity. External estimation of selectivity (e.g., using a parametric equation) could improve not only the precision of selectivity estimates but also the accuracy of the assessment model itself (ASMFC, 2017).

Herein, we attempt to ameliorate uncertainty surrounding internal estimates of selectivity by using 40+ years of tag-recapture data to provide length-based selectivity of red drum in South Carolina, utilizing the methodology of Bacheler et al. (2010). Our primary objective was to characterize selectivity patterns for fishery-independent sampling gears (trammel net, electrofishing, stop net, and longline) as well as the recreational hook-and-line fishery in South Carolina. By comparing the selectivities of fishery-independent gears, we can assess if SCDNR sampling methods are achieving adequate coverage of the red drum population (e.g., each gear selecting for a different length class). Additionally, we compared selectivity of hook-and-line across regulation periods and fates (i.e., harvested or released) to determine if harvest restrictions and angler behavior are influencing the selectivity of red drum. As recent assessments have shown increasing fishing mortality of red drum, we want to determine if there are differences in selectivity of harvested and caught-and-released fish and whether changes in regulations shift the length of maximum selectivity (and potentially fishing mortality). It is of particular importance to determine size of maximum selectivity in the catch-and-release fishery, as characterization of the live-release fishery is a critical need in proper assessment of the red drum recreational fishery

(ASMFC, 2017; Murphy, 2017). The results of this study yield the first external estimates of red drum selectivity in South Carolina, providing estimates of parameters that will increase precision in future stock assessments and tagging models.

3.2. Materials and Methods

3.2.1 South Carolina Tag-Recapture Program

We used tag-recapture data available from two SCDNR tagging programs spanning more than 40 years, 1) the Marine Game Fish Tagging Program (MGFTP) and 2) the SCDNR Inshore Fisheries tagging program. The MGFTP (1978-present) is a fishery-dependent tagging program which works with select recreational anglers to tag species of recreational importance with conventional tags (i.e., spaghetti tags), that includes a unique identifying number and SCDNR contact information. The SCDNR Inshore Fisheries tagging program is designed to complement these data, by tagging multiple species of recreational importance encountered in long-term fishery-independent surveys of stop nets (1986-1996), trammel nets (1987-present), longlines (1993-present), and electrofishing (2001-present) across coastal South Carolina. Recaptures of tagged fish, either by SCDNR surveys or recreational anglers, are reported back to SCDNR.

Several different tag types were used throughout the history of the MGFTP and Inshore Fisheries tagging program when tagging red drum. We considered tag types used by the MGFTP as different from tag types used by Inshore Fisheries due to possible differences in tag retention and tagging mortality based on tagging techniques of recreational anglers versus biologists. The MGFTP utilized t-bar tags, nylon dart tags, steel dart tags, and cinch tags with yellow streamers over the course of the tagging program. All variations of each tag type were categorized broadly as that same tag type (i.e., nylon dart tags with 146 mm streamer and nylon dart tags with 95 mm streamer were considered the same tag type). The Inshore Fisheries program deployed nylon dart tags, steel dart tags, and two types of internal anchor tags with orange streamers. Inshore Fisheries tagged red drum 350-550 mm total length (TL) with belly anchor tags and those >550 mm with steel dart tags, though large red drum caught on the longline survey were often tagged with nylon dart tags as well. All tag streamers included "REWARD," "SCDNR", and a tag number, with novelties (e.g., hat, t-shirt, towel, etc.) as a reward for reporting a tag.

3.2.2. Generalized Linear Models to Estimate Selectivity

A length-based approach was used to estimate the selectivity of harvested and released red drum in South Carolina (see Bacheler et al., 2010) with a generalized linear model (GLM):

$$E\left[C_{i,l,g,f,p}\right] = N_{i,l}R_{i,g}\mu_{i,g}S_{l,g,f,p} \tag{1}$$

Where $E\left[C_{i,l,g,f,p}\right]$ is the expected return rate of fish that are tagged, $N_{i,l}$ is the number of fish tagged in experiment i in length bin l, $R_{i,g}$ is the product of proportion of fish surviving the tagging process, proportion of tags not shed, and the proportion of recovered tags reported for gear type g for fish tagged in experiment i, $\mu_{i,g}$ is the exploitation rate of fish tagged in experiment i and recovered by gear type g, and $S_{l,g,f,p}$ is the selectivity of gear type g in regulation period p in length bin l for fish of fate f (Myers & Hoenig, 1997; Bacheler et al., 2010). Previous SCDNR studies on red drum showed tag retention rates differ with tag type (Hendrix, 2010). As such, herein we define an "experiment" as any releases of fish with a given tag type to account for any differences between tags in shedding, mortality, or reporting (Bacheler et al., 2010). Bacheler et al. (2010) did not provide true estimates of R and μ, treating them as constant (within a given age a, experiment i, and gear g) nuisance parameters. We follow the same methodology. We fit the GLM to available data using the log link function and binomial error structure (Myers & Hoenig, 1997; Bacheler et al., 2010) using program R (R Core Team, 2023; version 2023.03.1+446).

For selectivity estimates, we mirrored the approach proposed by Bacheler et al. (2010) and used 100-mm wide length bins using fish TL at tagging (<300 mm, 300-399 mm, 400-499 mm, 500-599 mm, 600-699 mm, 700-799 mm, 800-899 mm, 900-999 mm, 1000-1099 mm, 1100-1199 mm, and ≥1200 mm). Time between tagging and recapture (i.e., days-at-large) was limited to 120 days after the initial tagging event to minimize the chance of a fish growing out of its length bin, to ensure natural mortality would have minimal effect, and to ensure differences in tag retention are negligible (Myers & Hoenig, 1997). Only the first recapture of a fish was considered if multiple recaptures of that fish occurred within the 120-day period. Among other assumptions, the GLM method assumes fish do not grow out of their length bin between tagging and recapture, which influences choice of length bin size and days-at-large maxima. We examined the sensitivity of the length-based models by comparing model selection results where the days-at-large maxima is increased to 240 days and/or the length bin size is reduced to 50 mm. We excluded any recaptures that occurred on the same day as tagging, as this violates the assumption of adequate mixing of the tagged fish back into the wild population. See Bacheler et al. (2010) for a complete list of assumptions.

3.2.3. Fishery-Independent Analysis

We analyzed SCDNR's fishery-independent sampling gears separately from the fishery-dependent hook-and-line data. Fishery-independent gears include a trammel net (1987-2022), electrofishing (2001-2022), stop net (1986-1996), and adult red drum and shark longline (1993-2022) surveys. The trammel nets are 183.9 meters long and 2.4 meters tall with 35.6- and 6.4-

centimeter stretch mesh. Trammel nets are deployed along shorelines in the lower estuary. Electrofishing is conducted from a boat with electrodes attached to the front of the hull and attached to booms hanging in front of the boat. The boat is driven along shorelines for 15-minute sets in the upper estuary, where the salinity does not exceed 7 parts per thousand (ppt) during sampling and is generally <5 ppt. Stop nets were 366 m long and 3 m tall with 51 mm stretch mesh, and the nets were stationed outside of creek mouths through the ebbing tide with the net being picked up at low tide. Multiple variations of longline gears have been used in sampling efforts and all were included in the analysis to increase sample size of recaptures for the longline survey. The longline was 1.6 km long until 2005 and then shortened to 0.5 km, and the longline contained both circle hooks and J hooks in 2005 for a concurrent post-release mortality study (circle hooks used on all other deployments). Longline bait was changed from Spanish mackerel (*Scomberomorus maculatus*) to striped mullet (*Mugil cephalus*) in 2007.

We conducted the fishery-independent analysis using two methodologies, each of which has its benefits in the interpretation of results. In the first methodology, we analyzed all gears together in a GLM that includes tag type, length bin, and recovery gear as categorical variables in order to determine if gear is a significant predictor variable affecting expected recovery at a given size. For selectivity estimation the full model (Eq. 1) could be simplified as there was no effect of regulation period (same gear used throughout) or fate (all fish released), resulting in Equation 2:

$$E\left[C_{i,l,g}\right] = N_{i,l} R_{i,g} \mu_{i,g} S_{l,g} \quad (2)$$

where terms are defined as previously except dropping the subscripts for regulation period and fate.

In the second methodology, we analyzed all fishery-independent gears separately, only using tag type and length bin as categorical variables which allows closer examination of the length-based effects of each gear without being confounded by other gear types, as shown in Equation 3:

$$E\left[C_{i,l}\right] = N_{i,l} R_i \mu_i S_{l,} \tag{3}$$

with different GLMs developed independently based on individual fishery-independent survey recapture gears.

When there were less than ten recaptures within a length bin for a particular gear, we pooled length bins so that each length bin had at least ten recaptures (e.g., creating a <800 mm TL bin for the longline survey). Pooling allows for smoothing of the selectivity curve within a gear type, removing length bins with zero recaptures, reduction of the variance in those length bins less commonly encountered in a particular survey, and minimizing the number of parameters and length bins in the final model. The pooling was not used in the first methodology, as pooling in this case would have diminished the effect of differences between gears. Additionally, the length bins that were pooled were different within each gear, making it more difficult to compare gears within one model.

3.2.4. Longline Survey

The SCDNR longline survey samples seasonally from August-November each year, so there was less opportunity for recapture events compared to the year-round effort of other fishery-independent sampling gears. To increase sample size for the longline survey, we assumed an asymptotic length of red drum starting at 900 mm total length and removed the 120-day restriction on recaptures, instead accepting the first recapture for fish ≥900 mm at tagging regardless of days-at-large. Wenner et al. (1990) estimated an asymptotic length of 979 mm TL for otolith-aged red drum in South Carolina, so we applied a conservative approach and used 900 mm as the asymptotic length for our analysis.

3.2.5. Fishery-Dependent Analysis

For selectivity estimation of the fishery-dependent recreational fishery all recaptures were assumed to occur via hook-and-line fishery with no discrimination amongst different fishing/rigging techniques. While a small percentage of harvested fish may have derived from non-hook-and-line gear (e.g., gigging) and terminal tackle of hook-and-line gear likely varied, reported recaptures did not contain this level of detail. Based on this assumption, the full model (Equation 1) could be simplified resulting in Equation 4:

$$E\left[C_{i,l,f,p}\right] = N_{i,l} R_i \mu_i S_{l,f,p} \tag{4}$$

where terms are defined as previously except dropping the subscript for gear. Tag type, length bin, regulation period, and fate were retained as categorical predictor variables. We considered five regulation periods that represent changes in recreational fishing creel limits and/or length restrictions in South Carolina (1986-1992, 1993-2000, 2001-2006, 2007-2017, 2018-2022; Table 3.1). In addition to evaluating the sensitivity of length-based selectivity using the 100 mm TL and 50 mm TL bins and the 120- and 240-days-at-large restriction, we also estimated selectivity with 100-mm wide length bins set at different minima and maxima (i.e., length bins of <250, 250-349, 350-449, etc.) to account for the possible effect of length-based regulations on selectivity, particularly for harvested fish. For example, the lower end of the slot limit for red drum harvest in South Carolina has been 381mm since 2001, so fish in the 300-399mm length bin are only available for harvest for a short duration near the upper end of the length bin. After an initial analysis with the full GLM, we then analyzed the selectivity of harvested and released fish separately to emphasize differences in selectivity based on fate and provide selectivity estimates for the catch-and-release fishery. Additionally, estimating selectivity by fate provides a clearer estimate of selectivity, as it mitigates the effect of multiple interactions and the potential effect of length on fate in the full GLM. Pooling was not necessary for the fishery-dependent analysis, as there were more recaptures via hook-and-line than fishery-independent surveys and only one gear type in this analysis.

3.2.6. Model Selection

We defined full models for each analysis as including all relevant categorical predictor variables and compared these full models to reduced models based on Bacheler et al. (2010) and *a priori* knowledge of the fishery-independent sampling methods and the recreational fishery for red drum in South Carolina. We selected the most parsimonious model for each analysis through Quasi-Akaike's Information Criterion (Quasi-AIC or QAIC), an adjusted version of AIC (Akaike, 1973), as overdispersion can be an issue in tag-recapture datasets, particularly when analyzing our fishery-independent gears with smaller sample sizes (Anderson et al., 1994). Using the QAIC method, we estimated a variance inflation factor ($\hat{c}$) based on the full model that was used to compare the fit of all models (Equation 5; Lebreton et al., 1992; Burnham & Anderson, 2002; Bacheler et al., 2010):

$$QAIC = -\left[\frac{2\log\left(L(\hat{\theta})\right)}{\hat{c}}\right] + 2K \tag{5}$$

where $L(\hat{\theta})$ is the likelihood of model θ and K is the number of parameters in the model. The model with the lowest QAIC value was considered the most parsimonious, and we ranked models by using the difference between the QAIC of the model in question ($QAIC_i$) and the QAIC of the model with the lowest QAIC value ($QAIC_{min}$) to assess model fit (Equation 6):

$$\Delta QAIC = QAIC_i - QAIC_{min} \tag{6}$$

Additionally, we calculated Akaike weights (w_i) to assess the relative likelihood of each model, with all candidate models cumulatively summing to a likelihood of 1.00 and assuming the model with the largest w_i has the highest probability of being the model of best fit (Equation 7; Burnham & Anderson, 2004):

$$w_i = \frac{\exp\left(-(1/2)\Delta_i\right)}{\sum_{r=1}^{R} \exp\left(-(1/2)\Delta_r\right)}. \tag{7}$$

Here Δ_i is the ΔQAIC value for the *i*th model and Δ_r is the ΔQAIC value of each respective value of the models in question, with the best model exhibiting a ΔQAIC = 0 (Burnham & Anderson, 2002). Burnham & Anderson (2004) define a rule of thumb when interpreting the ΔAIC (and hence ΔQAIC) rankings: models with a $\Delta_i < 2$ have considerable support as the best model, models where $4 \leq \Delta_i \leq 7$ have less support but are still relevant, and any models with a $\Delta_i > 10$ have minimal to zero support. We used this theory when interpreting model selection, assuming any models with a $\Delta_i < 10$ have at least a minute amount of support. The Akaike weights generally corroborate with this rule, as models with a $\Delta_i > 10$ display $w_i < 0.01$ in our study, corresponding to a relative likelihood < 1%.

Selectivity is typically expressed on a relative scale of zero to one, so we scaled the estimated marginal means (EMM) of the most parsimonious model in each analysis so that the length bin with the highest EMM displayed a selectivity of one and all other EMMs were scaled relative to this maximum selectivity of one. We conducted all analyses using R software (R Core Team, 2023). We used the “glm” procedure in R to create each of the models, the “MuMIn” package (Bartón, 2022) to create a model selection table based on QAIC, and the “emmeans” package (Lenth, 2023) to estimate EMMs and hence selectivity within each model. The "emmeans" package estimated confidence intervals as the asymptotic upper and lower control limits, and these were re-scaled along with the selectivity estimates on a relative scale.

3.3. Results

3.3.1. Tag-Recapture Dataset Summary

Through the joint efforts of the SCDNR Inshore Fisheries and MGFTP 182,077 red drum have been tagged and 46,761 recaptures have subsequently reported since 1978 (Figure 3.1; Tables 3.2, 3.4, and 3.5). When only considering gears examined in this study and no days-at-large restriction, there were 34,720 unique recaptures (i.e., excluding multiple recaptures of the same fish) of tagged red drum, amounting to a recapture rate of 19.1%. Of the recaptures, anglers and SCDNR fishery-independent sampling personnel reported 11,614 and 4,324 (trammel net: n = 3,093, electrofishing: n = 115, stop net: n = 977, longline: n = 139) recaptures of tagged red drum within 120 days of tagging, respectively (Tables 3.3, 3.6, and 3.7). The most commonly tagged length bin of red drum was 300-399 mm TL with 39,056 tagging events while fish 600-699 mm TL were the most frequently recaptured with 12,291 recaptures, with 84.1% and 88.1% of all red drum tagged and recaptured occurring on fish between 300 and 799 mm TL. The most tags and recaptures occurred within the 1993-2000 regulation period with 51,696 tagging events and 14,366 recaptures. The least tags and recaptures occurred during the 2018-2022 regulation period (22,030 tags and 4,963 recaptures). There were 9,743 harvests and 21,566 releases of red drum caught by hook-and-line through the course of the tagging program (68.9% catch-and-release rate). The catch-and-release rate has increased from 24.2% in the 1986-1992 regulation period to 88.5% in the 2018-2022 regulation period.

3.3.2. Fishery-Independent Analysis

We estimated the length-based selectivity of fishery-independent sampling gears in a GLM model including length and gear variables (Equation 2; Table 3.8) in addition to estimating selectivity for each gear separately to further investigate the effect of length (Equation 3; Table 3.9). For the combined fishery-independent analysis, the most parsimonious model included gear as a variable but excluded length as a predictor of selectivity. Given gear was included in the most parsimonious model, we then analyzed the length-based selectivity of each gear separately (Table 3.9). For the trammel net survey, the length-based model was the most parsimonious model (Table 3.9), with length-based selectivity being dome-shaped with maximal selectivity of 700-799 mm TL red drum (Table 3.10; Figure 3.2). Selectivity remained relatively high for length bins 400-499 to 600-699 mm up until peak selectivity at 700-799 mm. Selectivity then decreased sharply for fish >800 mm in the trammel net survey. The electrofishing survey displayed length-based effects on selectivity, though not significant, as the model without length still received relevant support and confidence intervals were large (Table 3.9). Maximum selectivity of the electrofishing survey occurred at 400-499 mm TL with relatively high selectivity at 300-399 mm and 500-599 mm TL (Table 3.11; Figure 3.2). Upper and lower asymptotic control limits were larger on the electrofishing survey than any other survey, owing to the smallest sample size among gears (n = 115 recaptures). The stop net survey suggested a strong effect of length on selectivity (Table 3.9), with maximum selectivity occurring on red drum <300mm TL (Table 3.12; Figure 3.2). Selectivity generally decreased with increasing length.

Before proceeding with the analysis of the longline survey using 900 mm TL asymptotic length, we inspected whether this days-at-large extension would lead to too many fish growing out of its initial length bin. We compared the number of fish growing out of its length bin at time of tagging when the asymptotic length was 900 mm TL versus 1000 mm TL, to determine the best minimum length in which days-at-large can be extended to all-time instead of 120 days. We found that 0.0% (0/59) of fish recaptured by the longline survey were recaptured in a length bin different than the length bin they were tagged in when the asymptotic length was 1000 mm TL (i.e., there are 59 recaptures in the longline survey when the days-at-large restriction was removed for fish >1000 mm TL, and zero fish grew out of its length bin). However, 7.4% (10/136) of fish grew out of their length bin with an asymptotic length of 900 mm TL. The percentage of fish growing out of their length bin with 900 mm TL asymptotic length (7.4%) was less than the percentage of fish growing out of their length bin across all length bins and fishery-independent survey gears (15.6%). In other words, though some fish grow out of their length bin when 900 mm TL asymptotic length is used, the percentage of fish growing out of the length bin in the longline survey is still smaller than the percentage of fish that grew out of their length bin in the other survey methods. Thus, we compromised few fish growing out of the length bin at tagging in order to more than double the sample size of the longline survey. The best fit GLM for the longline survey rejected the inclusion of length as a significant predictor of selectivity. This suggests full selectivity of this gear for red drum greater than approximately 800 mm TL overall, while peak selectivity on red drum appears at ≥1000 mm TL in a flat-topped selectivity curve (Table 3.13; Figure 3.2).

3.3.3. Fishery-Dependent Analysis

We estimated the selectivity of recreational hook-and-line through GLMs including length, regulation period, and fate as categorical variables (Equation 3). The full model without the interaction between length and regulation period was the most parsimonious model, with no other models receiving support (Table 3.14). When estimating selectivity of red drum by fate after recapture, the most parsimonious model depended on whether the fish was harvested or released. For released fish with 100-mm length bins, the most parsimonious model was the full model without the length and regulation period interaction (Table 3.15). For display purposes, the full model for released fish is included on graphs and in tables, as the full model without the interaction between length and regulation period produces the same selectivity estimates (and hence same selectivity curve) for each regulation period (Table 3.16). Maximum selectivity for released fish was primarily focused on fish below the slot limit, with maximum selectivity at <300 mm TL in every regulation period except for the 2001-2006 period where maximum selectivity is at 800-899 mm TL (Tables 3.18, 3.20, 3.22. 3.24, 3.26; Figure 3.3). We found a decrease in selectivity of caught-and-released red drum ≥700 mm in length in South Carolina through the three most recent regulation periods, which has created a flattening of the dome-shaped selectivity curve. We also observe consistently high selectivity of released slot-sized fish over time even as harvest restrictions became stricter.

For harvested fish, the full model including all interactions was the most parsimonious, receiving full support from Akaike weights (Table 3.15). Maximum selectivity of harvested fish occurred within the length restrictions of that regulation period, with highest selectivity on 300-399 mm TL red drum from 1986-2000, and then increasing to 500-599 mm TL fish from 2001-2022 (Tables 3.17, 3.19, 3.21, 3.23, 3.25; Figure 3.3). The selectivity curve for harvested fish appears similar in shape across regulation periods except for the 1986-1992 regulation period, when red drum harvest restrictions were first enacted in South Carolina and the slot limit was not put into effect until 1990, explaining the high selectivity on fish in the 800-899mm length bin. However, the size of maximum selectivity of harvested red drum shifts slightly towards the upper end of the slot limit in later regulation periods (2001-2006, 2007-2017, and 2018-2022) corresponding with decreases in bag limit and narrowing of the slot limit.

3.3.4. Sensitivity to Length Bin Size and Days-at-Large Restrictions

In order to test the effect of length bin size and days-at-large length on model selection, we created 50-mm length bins and 240-day days-at-large restriction for each gear and examined whether this changed the best model fit. Reducing the length bin size to 50 mm generally decreased the relative support for length-based models, most likely due to the increased number of parameters, but increasing the days-at-large maxima to 240 days did not produce a consistent trend in model selection. Model selection for the trammel net survey was not affected by length bin size or days-at-large maxima. For electrofishing, all other combinations of length bin size and days-at-large period (i.e., not 100-mm length bin and 120 days-at-large) exhibited $\Delta QAIC \leq 3.2$, meaning both models have significant support and thus we conclude that there is not enough evidence to detect a length effect for those models. For the longline survey, there is a stronger leniency towards the model without length as a variable when using 50-mm length bins. Length bin size did not have an effect on model selection for the stop net survey, but increasing the days-at-large maxima to 240 days caused the models without a length effect to be the most parsimonious. Neither length bin size nor days-at-large maxima affected the choice of most parsimonious model for the fishery-dependent analyses.

3.4. Discussion

Selectivity is a critical component in stock assessments and aids in connecting the lengths of captured fish to the length distribution of the wild population (Bacheler et al., 2010; Vasilakopoulos et al., 2020). However, selectivity is not often estimated external to a model (e.g., tag-recapture experiments) and instead is treated as an unknown or nuisance parameter (Maunder et al., 2014; Sampson, 2014; Dean et al., 2021). Thus, an external estimate of selectivity, as provided in this study, would improve the precision of selectivity estimates and other parameters that may be confounded with selectivity (e.g., stock abundance, harvest rate) within a stock assessment model (Bacheler et al., 2010). This is especially critical for the red drum population in South Carolina, as recent stock assessments have had difficulty generating precise estimates of parameters, such as abundance, that can be confounded with selectivity estimation. Our study proves the SCDNR fishery-independent surveys each select for a different length class, and hence life history stage, of red drum. The length at maximum selectivity for the South Carolina recreational fishery depends on whether the fish was harvested or released, and the fishery exhibits slight changes in selectivity through regulation periods. The observed dome-shaped selectivity of red drum combined with minimal data on the adult population could be a significant contributor to uncertainty in recent assessments, as it may be difficult to determine if declines in recaptures of older/larger fish are due to decreasing selectivity or decreasing abundance (Jones & Cox, 2018).

There is minimal research on the selectivity of red drum using the fishery-independent sampling gears (trammel net, electrofishing, stop net, and longline) examined in this study, with the only published studies being on bottom longline gear (e.g., Powers et al., 2023). The fishery-independent gears show adequate sampling coverage of the red drum population, as trammel net, electrofishing, stop net, and longline each display maximum selectivity at different length classes (trammel net: 700-799mm, electrofishing: 400-499mm, stop net: <300mm, longline: 1000+mm). However, there is a small gap in coverage for the SCDNR's fishery-independent gears, with relatively low selectivity for red drum at 800-999mm TL in any survey. Powers et al. 2023 found that purse seines may be the best sampling method for this length class, and thus additional gear types may need to be implemented in order to sample this length class of the red drum population in South Carolina. Additionally, the SCDNR stop net sampling was discontinued in 1997, so current sampling methods may not be obtaining representative samples of the juvenile red drum population. As the utilization of multiple sampling gears ameliorates gear selectivity bias to obtain a more representative sample, including additional gear types in SCDNR's fishery-independent sampling may improve coverage of the red drum population, particularly the juveniles and adults as sub-adults are represented well by the electrofishing and trammel net surveys (Pine et al., 2012). Current SCDNR surveys display adequate coverage of length classes of red drum most vulnerable to harvest, though surveys targeting juvenile (maximum selectivity in the stop net survey which has since been discontinued) or young adult red drum (800-999 mm TL) may be beneficial to fill in data gaps. The maximally selected length classes for each gear align with expected results based on both gear selectivity and availability of red drum according to ontogenetic habitat use. For example, red drum begin their lives in low salinity habitats and move into the lower estuary with increasing age until leaving the estuary for nearshore coastal waters as adults (Wenner et al., 1990; Latour et al., 1998; Bacheler et al., 2009). Thus, it is not surprising that the size of maximum selectivity increases as gear deployment locations move into more saltwater-dominated habitats, corresponding with red drum age-dependent movement. Herein, we use long-term sampling to provide comprehensive selectivity estimates to assess the probability that these gears may capture red drum. This information is essential for applying fishery-independent capture data to estimate the length composition of the wild population and address data gaps.

Though each fishery-independent gear displays maximum selectivity at different lengths, it is important to note that not all gears exhibited a significant length-based effect on selectivity. Specifically, our results indicated there was not support for length-based effects in the longline survey. The longline survey selects for the largest length class of red drum which is consistent with other studies (Powers et al., 2012; Powers et al., 2023). There was no detectable effect of electrofishing on length-based selectivity, and we estimated three consecutive length classes with selectivity >0.75. That said, while the selectivity curve appears as a slight dome-shape, the large error bars indicate significant uncertainty in this shape. Additionally, the electrofishing survey recorded the least recaptures (115) of the fishery-independent gears and there was much lower probability of recapture in this survey (e.g., the recapture probability for 400-499mm red drum is approximately 20x higher in the trammel net versus electrofishing). Sample size likely influenced model selection results, as both electrofishing and longline show support for non-length-based models and recorded the least recaptures (115 and 139, respectively). While testing different asymptotic sizes for the longline survey, we found that the length-based model gained more support each time the sample size increased. However, using the 120-day days-at-large restriction and the 100-mm length bins results in minimal violations of assumptions, whereas smaller length bins lead to more fish growing out of length bins and increased days-at-large prompts fish growing out of length bins and increased probability of tag loss over time.

As we found that fate of the fish after capture is a significant variable in the estimation of selectivity in the red drum recreational fishery, it was most appropriate to analyze harvested and released fish separately given the different behaviors of fishers based on fate of the fish. Length, regulation period, and the interaction between length and period were significant variables for the model describing the selectivity of harvested fish, which is not surprising given the lengths of harvested fish should shift with changes in harvest restrictions (Burdick et al., 2007). Bacheler et al. (2010) also found a clear dome-shaped selectivity for fish harvested via hook-and-line, with the peak of the dome within the slot limit for more recent regulation periods. There are multiple factors that may cause a dome-shaped selectivity that we see in South Carolina red drum, such as the spatial distribution of fishing effort and ontogenetic movement (Bacheler et al., 2010; Sampson & Scott, 2011; Maunder et al., 2014). However, the observed dome-shaped selectivity is likely being driven by minimum and maximum length restrictions on harvest, meaning peak selectivity must be at intermediate sizes. The peak selectivity shifting towards larger fish within the slot limit in more recent regulation periods shows that as anglers are allowed to keep less fish with stricter length regulations, they are more likely to keep larger fish within the slot limit to maximize fishing efforts.

Though selectivity of harvested fish falls within the legal limit for each regulation period, the selectivity of released fish can be complicated by the intentions of the fishers when releasing red drum. For example, an angler may release a red drum because a) the angler intends to harvest a fish but this fish did not fall within the slot limit or b) the angler is catch-and-release fishing without intent to harvest. This theory can be observed in the dome-shaped selectivity curve of released fish in recent regulation periods. Generally, we found a selectivity peak at the smallest length classes, where fish are too small to harvest, and there is an additional peak in the 700-899mm range, which is likely the result of anglers targeting fish well above the slot limit for catch-and-release fishing. For red drum that were released after being captured via hook-and-line in North Carolina, Bacheler et al. (2010) showed that selectivity had increased on the largest red drum (except for the 800-899mm length class) through regulation periods, with the highest relative selectivity in the most recent regulation period and the dome-shape becoming more pronounced with subsequent regulation periods. The flattening of the dome-shaped selectivity through the last three regulation periods in our study may be cause for concern and further investigation, as selectivity on subadult red drum remains high throughout 300-799mm in length. The rapid decrease in selectivity for 800-899mm red drum in the current regulation period represents the lowest relative selectivity for fish of that size through all regulation periods. While the cause behind the observed shifts in selectivity through regulation periods is not apparent, it could be related to the increase in fishing mortality and decrease in abundance and recruitment of the red drum population in South Carolina in recent years (Murphy, 2017). However, given the regulation period beginning in 2018 covers a shorter timespan than other regulation periods, the selectivity of the 2018 regulation period can be assessed more appropriately as more recaptures are reported and the sample size increases.

In this study, we provide the first comprehensive estimates of selectivity for red drum in South Carolina for both fishery-independent sampling and fishery-dependent activities using the methodology of Bacheler et al. (2010). We restricted our dataset by limiting the number of days-at-large between tagging and recapture and only considering the first recaptures of tagged fish, though this was required to minimize assumptions, reduce the number of parameters estimated, and fit the generalized linear model framework. Additional information could be extrapolated by including more recapture events, though this may require the use of a different analytical approach. The fishery-independent gears are not equal in terms of number of recaptures, as electrofishing and longline gears recorded significantly less recaptures than the trammel net and stop net, resulting in smaller sample size, large confidence intervals, and failure to fully support length-based models. Since doubling the days-at-large period did not significantly affect results, the smaller sample size is likely a product of gear selectivity, as electrofishing and longline were more restrictive in the number of length classes encountered than trammel net and stop net. Despite minor limitations, we were able to estimate selectivity for each of the fishery-independent gears and hook-and-line using a robust long-term tagging program to assess the efficiency of red drum population sampling and detect shifts in selectivity based on changes in the recreational fishery. Our fishery-dependent selectivity estimates include characterization of the live-release fishery, which is a critical need in proper assessment of the red drum recreational fishery (ASMFC, 2017; Murphy, 2017). Importantly, the selectivity estimates generated in this study represent the first derived from external data sources for the South Carolina red drum population and provide improved parameters estimates to potentially be used in future stock assessments.

3.5. Figures

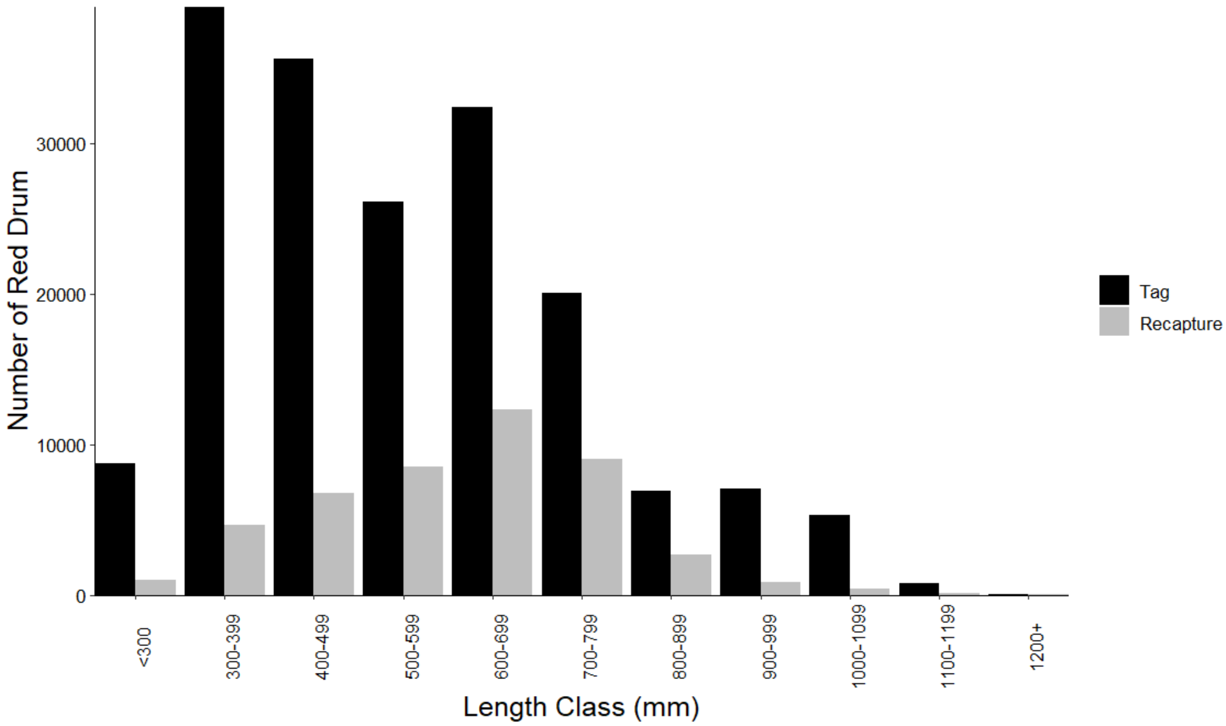

Figure 3.1. The number of red drum tagging and recapture events across all gears, grouped according to length class at time of tagging.

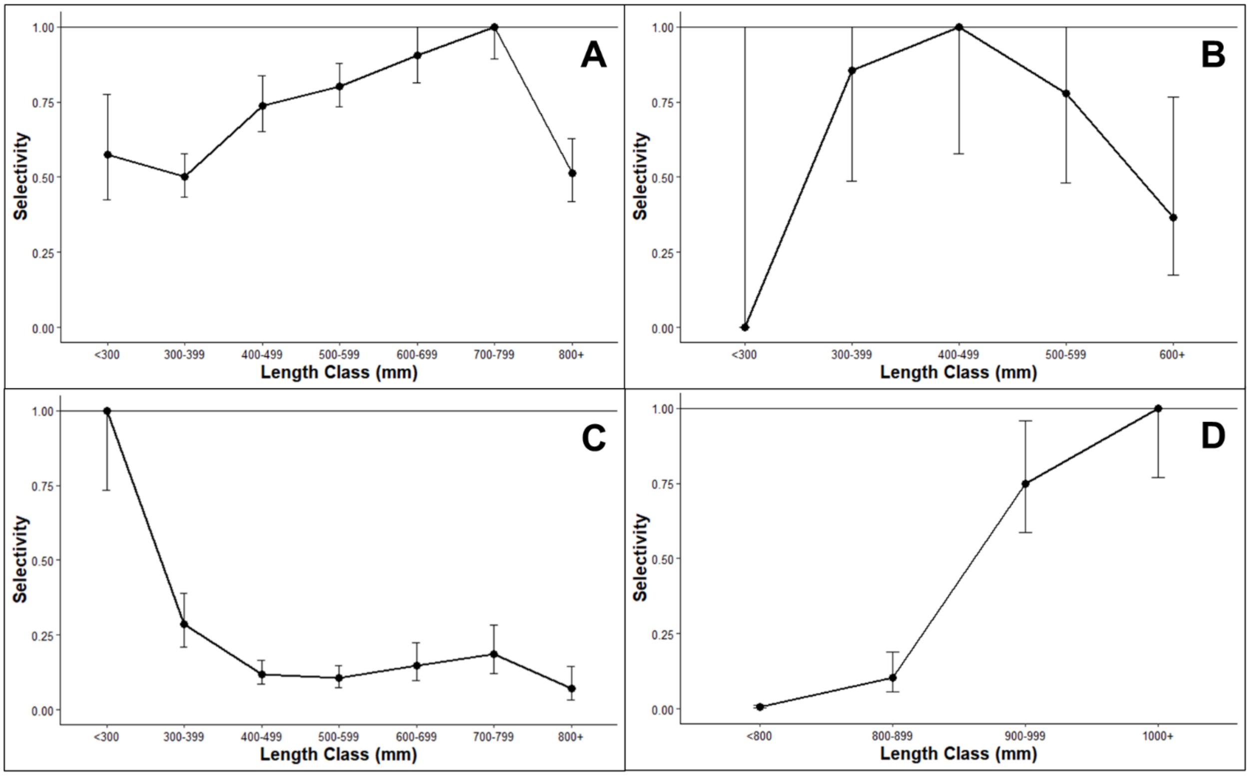

Figure 3.2. Selectivity of red drum captured in the A) trammel net survey (n = 3,086), B) electrofishing survey (n = 115), C) stop net survey (n = 977), and D) longline survey (n = 139) based on 100-mm length bins and a 120-day days-at-large limit. The error bars represent the asymptotic control limits, with the upper limit restricted to a maximum of 1.0. Length bins were pooled until each length bin had at least ten recaptures. For the longline survey, recaptures of all individuals ≥900mm at tagging were considered, regardless of the number of days-at-large.

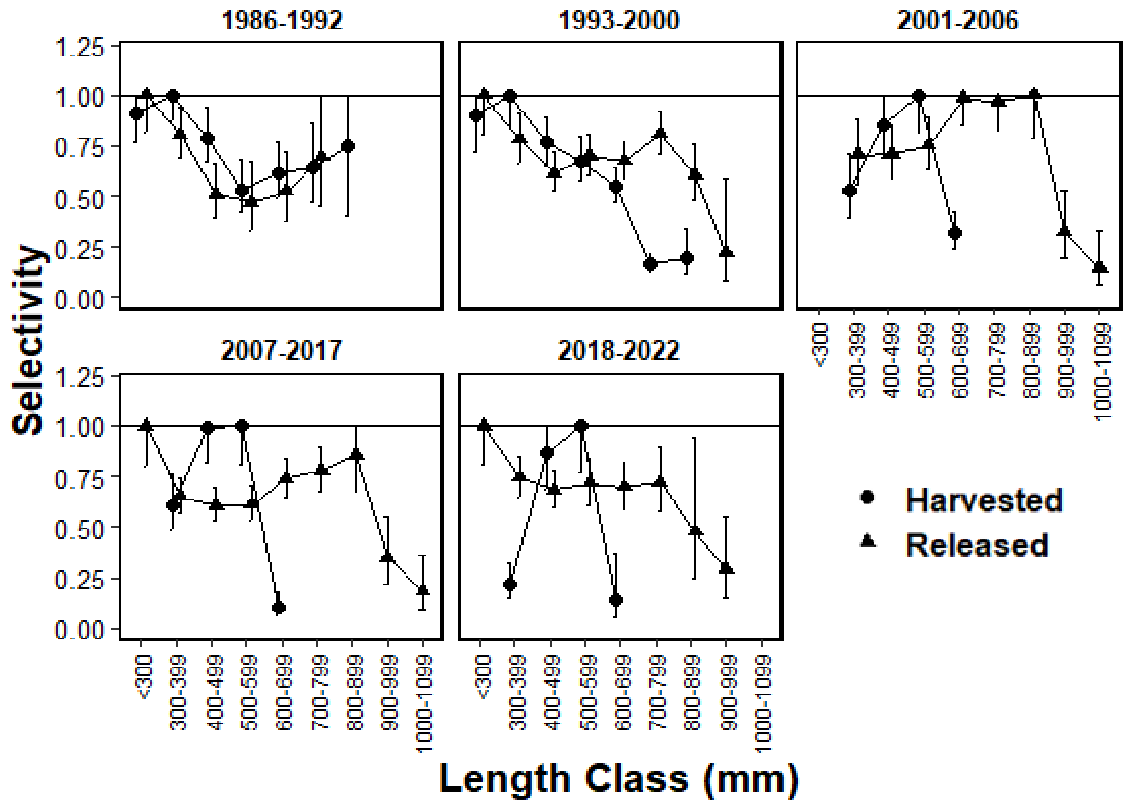

Figure 3.3. Selectivity of red drum captured via hook-and-line based on 100-mm length bins and a 120-day days-at-large limit. Selectivity curves for both harvested and released fish are graphed as the full models. Selectivity was analyzed separately for harvested versus released fish, and the selectivities are grouped according to regulation period. The horizontal line represents maximum selectivity at 1.0, and vertical error bars do not extend beyond this maximum. Symbols within a length bin are jittered to avoid overlap of symbols and error bars.

3.6. Tables

Table 3.1. History of recreational fishing regulations for red drum in South Carolina. Size limits are in mm total length (TL) and creel limits are in number of fish. The 1986-1992 regulation period is divided into two separate periods as regulations changed mid-period.

Regulation Period	Size Limit	Creel Limit
1986-1992 (1986-1989)	Minimum = 356mm Keep 1 fish > 813mm	20
1986-1992 (1990-1992)	Minimum = 356mm Maximum = 813mm	5
1993-2000	Minimum = 356mm Maximum = 686mm	5
2001-2006	Minimum = 381mm Maximum = 610mm	2
2007-2017	Minimum = 381mm Maximum = 584mm	3
2018-2022	Minimum = 381mm Maximum = 584mm	2

Table 3.2. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via fishery-independent sampling gears. Length bins are based on the fish total length at tagging. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. There are no restrictions on days-at-large and there may be multiple recaptures of the same fish included in this summary.

		Number Recaptured			
Length Bin (mm)	**Number Tagged**	**Trammel Net**	**Electrofishing**	**Stop Net**	**Longline**
<300	8,760	4	0	77	0
300-399	39,056	302	29	683	0
400-499	35,578	775	104	378	0
500-599	26,093	2,103	122	352	1
600-699	32,399	4,154	84	402	2
700-799	20,063	3,523	26	325	34
800-899	6,876	682	4	37	83
900-999	7,055	27	1	1	176
1000-1099	5,278	1	0	0	163
1100-1199	757	0	0	0	20
>1200	58	0	0	0	0
N/A	*104*	*16*	*1*	*2*	*15*
Total	182,077	11,587	371	2,257	494

Table 3.3. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via fishery-independent sampling gears within 120 days of the initial tagging event. Length bins are based on the fish total length at tagging. Recaptures from the longline survey include the extended days-at-large period for fish >900 mm total length. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. Only the first recapture of a fish is considered; subsequent recaptures are not counted in this summary.

		Number Recaptured			
Length Bin (mm)	**Number Tagged**	**Trammel Net**	**Electrofishing**	**Stop Net**	**Longline**
<300	8,760	45	0	179	0
300-399	39,056	284	38	358	0
400-499	35,578	451	48	161	0
500-599	26,093	581	18	82	1
600-699	32,399	972	9	107	1
700-799	20,063	649	1	80	7
800-899	6,876	105	1	9	11
900-999	7,055	6	0	1	64
1000-1099	5,278	0	0	0	48
1100-1199	757	0	0	0	7
>1200	58	0	0	0	0
N/A	*104*	*0*	*0*	*0*	*0*
Total	182,077	3,093	115	977	139

Table 3.4. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via hook-and-line for the 1986-1992, 1993-2000, and 2001-2006 regulation periods. Length bins are based on the fish total length at tagging. The number of tags and recaptures are grouped by the regulation period in which the event occurred, and recaptures are separated by fate of the fish after capture. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. There are no restrictions on days-at-large and there may be multiple recaptures of the same fish included in this summary. There was 1 recapture before the beginning of regulations in 1986, and the fish was released.

	Regulation Period								
	1986-1992			**1993-2000**			**2001-2006**		
	Tagged	**Recaptured**		**Tagged**	**Recaptured**		**Tagged**	**Recaptured**	
Length Bin (mm)		**Harvest**	**Release**		**Harvest**	**Release**		**Harvest**	**Release**
<300	4,495	256	95	2,028	139	97	244	10	61
300-399	11,648	809	398	7,218	481	351	3,675	28	94
400-499	4,459	638	135	9,319	845	485	5,628	256	253
500-599	2,430	341	80	8,315	990	691	5,740	544	540
600-699	2,467	350	102	11,232	1,301	1,283	8,053	194	1,339
700-799	980	142	59	8,055	149	1,410	4,980	12	1,120
800-899	253	38	12	2,454	49	509	1,741	4	413
900-999	72	6	1	1,353	10	75	1,990	1	186
1000-1099	60	1	0	1,419	3	11	1,429	0	72
1100-1199	15	0	0	254	0	7	267	0	17
>1200	2	0	0	23	1	1	15	0	3
N/A	*10*	*242*	*19*	*26*	*35*	*29*	*26*	*15*	*55*
Total	26,891	2,823	901	51,696	4,003	4,949	33,788	1,064	4,153

Table 3.5. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via hook-and-line for the 2007-2017 and 2018-2022 regulation periods. Length bins are based on the fish total length at tagging. The number of tags and recaptures are grouped by the regulation period in which the event occurred, and recaptures are separated by fate of the fish after capture. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. There are no restrictions on days-at-large and there may be multiple recaptures of the same fish included in this summary.

	Regulation Period					
	2007-2017			2018-2022		
	Tagged	Recaptured		Tagged	Recaptured	
Length Bin (mm)		**Harvest**	**Release**		**Harvest**	**Release**
<300	926	10	138	855	0	72
300-399	9,841	66	617	6,001	32	679
400-499	9,900	474	990	5,965	239	1,058
500-599	6,616	687	968	2,896	256	670
600-699	7,981	33	1,937	2,600	16	882
700-799	4,746	5	1,545	1,255	2	506
800-899	1,769	3	630	639	2	190
900-999	2,486	3	275	1,146	1	90
1000-1099	1,761	0	142	605	1	44
1100-1199	165	0	28	54	0	8
>1200	14	0	9	3	0	2
N/A	*31*	*23*	*65*	*11*	*0*	*17*
Total	46,236	1,304	7,344	22,030	549	4,218

Table 3.6. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via hook-and-line within 120 days of the initial tagging event for the 1986-1992, 1993-2000, and 2001-2006 regulation periods. Length bins are based on the fish total length at tagging. The number of tags and recaptures are grouped by the regulation period in which the event occurred, and recaptures are separated by fate of the fish after capture. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. Only the first recapture of a fish is considered; subsequent recaptures are not counted in this summary. There was 1 recapture before the beginning of regulations in 1986, and the fish was released.

	Regulation Period								
	1986-1992			1993-2000			2001-2006		
	Tagged	Recaptured		Tagged	Recaptured		Tagged	Recaptured	
Length Bin (mm)		Harvest	Release		Harvest	Release		Harvest	Release
<300	4,495	252	123	2,028	102	94	244	0	2
300-399	11,648	745	272	7,218	412	258	3,675	55	94
400-499	4,459	249	67	9,319	399	264	5,628	130	146
500-599	2,430	85	33	8,315	284	295	5,740	136	185
600-699	2,467	98	41	11,232	304	397	8,053	57	371
700-799	980	43	22	8,055	67	358	4,980	4	231
800-899	253	10	5	2,454	15	82	1,741	0	74
900-999	72	0	0	1,353	2	8	1,990	0	18
1000-1099	60	1	0	1,419	0	3	1,429	0	9
1100-1199	15	0	0	254	0	0	267	0	2
>1200	2	0	0	23	0	0	15	0	1
N/A	*10*	*0*	*0*	*26*	*0*	*1*	*26*	*0*	*0*
Total	26,891	1,483	563	51,696	1,585	1,760	33,788	382	1,133

Table 3.7. Number of red drum tagged by biologists and anglers and the number of recaptures of red drum via hook-and-line within 120 days of the initial tagging event for the 2007-2017 and 2018-2022 regulation periods. Length bins are based on the fish total length at tagging. The number of tags and recaptures are grouped by the regulation period in which the event occurred, and recaptures are separated by fate of the fish after capture. A length bin of "N/A" corresponds to a tagging or recapture event where fish length was not recorded. Only the first recapture of a fish is considered; subsequent recaptures are not counted in this summary. There was 1 recapture before the beginning of regulations in 1986, and the fish was released.

	Regulation Period					
	2007-2017			2018-2022		
	Tagged	Recaptured		Tagged	Recaptured	
Length Bin (mm)		Harvest	Release		Harvest	Release
<300	926	2	90	855	0	110
300-399	9,841	118	519	6,001	29	555
400-499	9,900	193	476	5,965	123	482
500-599	6,616	124	322	2,896	73	227
600-699	7,981	17	490	2,600	5	214
700-799	4,746	1	301	1,255	0	98
800-899	1,769	0	77	639	0	11
900-999	2,486	0	23	1,146	0	12
1000-1099	1,761	1	10	605	0	3
1100-1199	165	0	1	54	0	0
>1200	14	0	1	3	0	0
N/A	*31*	*0*	*0*	*11*	*0*	*0*
Total	46,236	456	2,310	22,030	230	1,712

Table 3.8. Generalized linear models fit to red drum tag-recapture data investigating whether the length of the fish at recapture and recovery gear are significant variables in calculating selectivity of fishery-independent sampling. Length bin size is 100-mm and the days-at-large maxima is 120 days. The base model includes the tag type, length bin, and gear type variables, as well as the interaction between length bin and gear type. The "experiment" variable (tag type) was included in all models. The variables are: K = number of parameters, w_i = normalized Akaike weights.

Model	K	QAIC	ΔQAIC	w_i
Base except length	7	48.7	0.0	0.993
Base	26	59.7	11.0	0.004
Base except length x gear	15	60.4	11.7	0.003
Base except gear	12	128.8	80.1	0.000

Table 3.9. Generalized linear models fit to red drum tag-recapture data investigating whether the length of the fish at recapture is a significant variable in calculating selectivity of the trammel net, electrofishing, longline, and stop net surveys. The "experiment" variable (tag type) was included in all models. The variables are: K = number of parameters, w_i = normalized Akaike weights.

Model	K	QAIC	ΔQAIC	w_i
Trammel Net				
Length	8	85.0	0.0	1.00
No Length	2	171.6	86.7	0.00
Electrofishing				
Length	6	36.0	0.0	0.96
No Length	2	42.4	6.4	0.04
Longline				
No Length	2	11.9	0.0	0.61
Length	5	12.8	0.9	0.39
Stop Net				
Length	9	26.1	0.0	1.00
No Length	3	37.0	10.9	0.00

Table 3.10. Scaled selectivity of the trammel net survey. Length bins with less than ten recaptures were combined until the pooled length bin contained at least ten recaptures.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	0.57	0.09	0.42-0.78
300-399	0.50	0.04	0.43-0.58
400-499	0.74	0.05	0.65-0.84
500-599	0.80	0.04	0.73-0.88
600-699	0.90	0.05	0.81-1.00
700-799	1.00	0.06	0.89-1.00
>800	0.51	0.05	0.42-0.63

Table 3.11. Scaled selectivity of the electrofishing survey. Length bins with less than ten recaptures were combined until the pooled length bin contained at least ten recaptures.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	0.00	0.00	0.00-1.00
300-399	0.86	0.25	0.49-1.00
400-499	1.00	0.28	0.58-1.00
500-599	0.78	0.19	0.48-1.00
>600	0.37	0.14	0.17-0.77

Table 3.12. Scaled selectivity of the stop net survey. Length bins with less than ten recaptures were combined until the pooled length bin contained at least ten recaptures.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.16	0.74-1.00
300-399	0.28	0.05	0.21-0.39
400-499	0.12	0.02	0.08-0.17
500-599	0.10	0.02	0.07-0.15
600-699	0.15	0.03	0.10-0.22
700-799	0.18	0.04	0.12-0.28
>800	0.07	0.03	0.03-0.14

Table 3.13. Scaled selectivity of the longline survey. Length bins with less than ten recaptures were combined until the pooled length bin contained at least ten recaptures.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<800	0.00	0.00	0.00-0.01
800-899	0.10	0.03	0.06-0.19
900-999	0.75	0.09	0.59-0.96
>1000	1.00	0.13	0.77-1.00

Table 3.14. Generalized linear models fit to red drum tag-recapture data investigating whether the length of the fish at tagging, regulation period, and fate of the fish (e.g., harvested or released) at recapture are significant variables in calculating selectivity of fishery-dependent hook-and-line activity (100-mm length bins and 120 days-at-large). The base model includes the tag type, length bin, regulation period, and fate variables, as well as all interactions. The "experiment" variable (tag type) was included in all models. The variables are: K = number of parameters, w_i = normalized Akaike weights.

Model	K	QAIC	ΔQAIC	w_i
Base except length x period	31	297.1	0.0	1.00
Base	58	331.1	34.0	0.00
Base except length x fate	52	376.4	79.2	0.00
Base except period x fate	54	541.7	244.6	0.00
Base except period	23	542.1	245.0	0.00
Base except all interactions	21	559.7	262.6	0.00
Base except fate	47	623.7	326.5	0.00

Table 3.15. Generalized linear models fit to red drum tag-recapture data investigating whether the length of the fish at tagging and regulation period are significant variables in calculating selectivity of fishery-dependent hook-and-line activity, separated by fate of the fish at recapture (100-mm length bins and 120 days-at-large). The base model includes the tag type, length bin, and regulation period variables, as well as all interactions. The "experiment" variable (tag type) was included in all models. The variables are: K = number of parameters, w_i = normalized Akaike weights.

Model	K	QAIC	ΔQAIC	w_i
Released				
Base except length x period	19	183.7	0.0	0.994
Base except length	11	194.0	10.3	0.006
Base except period	15	225.9	42.2	0.000
Base	45	228.8	45.1	0.000
Harvested				
Base	32	192.4	0.0	1.00
Base except length x period	17	233.9	41.4	0.00
Base except length	11	287.4	95.0	0.00
Base except period	13	446.2	253.8	0.00

Table 3.16. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture across all regulation periods, using the full model without the interaction between length and regulation period. All regulation periods exhibit the same selectivity curve in this model. Standard errors and asymptotic confidence levels show minimal variation, so the range of observed standard errors and confidence levels across regulation periods are included. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.07-0.08	0.86-1.00
300-399	0.72	0.04-0.05	0.63-0.81
400-499	0.62	0.04	0.54-0.71
500-599	0.64	0.04-0.05	0.56-0.74
600-699	0.71	0.04-0.05	0.62-0.81
700-799	0.77	0.04-0.05	0.67-0.88
800-899	0.70	0.05-0.06	0.59-0.84
900-999	0.27	0.04	0.20-0.37
1000-1099	0.14	0.04	0.08-0.24

Table 3.17. Scaled selectivity of hook-and-line fishing when the red drum is harvested post-capture in the 1986-1992 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	0.91	0.08	0.77-1.00
300-399	1.00	0.07	0.87-1.00
400-499	0.79	0.07	0.67-0.94
500-599	0.53	0.07	0.42-0.68
600-699	0.61	0.07	0.49-0.76
700-799	0.64	0.10	0.47-0.87
800-899	0.75	0.24	0.41-1.00

Table 3.18. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture in the 1986-1992 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.10	0.82-1.00
300-399	0.80	0.06	0.69-0.94
400-499	0.51	0.07	0.39-0.66
500-599	0.47	0.09	0.33-0.67
600-699	0.52	0.09	0.38-0.72
700-799	0.69	0.15	0.46-1.00

Table 3.19. Scaled selectivity of hook-and-line fishing when the red drum is harvested post-capture in the 1993-2000 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	0.90	0.10	0.72-1.00
300-399	1.00	0.08	0.86-1.00
400-499	0.77	0.06	0.66-0.89
500-599	0.68	0.06	0.57-0.79
600-699	0.55	0.04	0.47-0.64
700-799	0.16	0.02	0.13-0.21
800-899	0.20	0.05	0.12-0.34

Table 3.20. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture in the 1993-2000 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.11	0.80-1.00
300-399	0.78	0.06	0.67-0.91
400-499	0.61	0.05	0.53-0.72
500-599	0.70	0.05	0.60-0.81
600-699	0.67	0.05	0.59-0.77
700-799	0.81	0.05	0.71-0.92
800-899	0.61	0.07	0.48-0.76
900-999	0.22	0.11	0.08-0.58

Table 3.21. Scaled selectivity of hook-and-line fishing when the red drum is harvested post-capture in the 2001-2006 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
300-399	0.53	0.08	0.40-0.71
400-499	0.85	0.09	0.69-1.00
500-599	1.00	0.10	0.82-1.00
600-699	0.32	0.05	0.24-0.43

Table 3.22. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture in the 2001-2006 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
300-399	0.71	0.08	0.56-0.89
400-499	0.71	0.07	0.58-0.86
500-599	0.75	0.06	0.64-0.89
600-699	0.98	0.07	0.86-1.00
700-799	0.97	0.08	0.83-1.00
800-899	1.00	0.12	0.78-1.00
900-999	0.32	0.08	0.20-0.53
1000-1099	0.15	0.06	0.07-0.33

Table 3.23. Scaled selectivity of hook-and-line fishing when the red drum is harvested post-capture in the 2007-2017 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
300-399	0.61	0.07	0.49-0.76
400-499	0.99	0.09	0.82-1.00
500-599	1.00	0.11	0.81-1.00
600-699	0.10	0.03	0.06-0.18

Table 3.24. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture in the 2007-2017 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.11	0.80-1.00
300-399	0.65	0.04	0.57-0.74
400-499	0.61	0.04	0.53-0.69
500-599	0.61	0.04	0.53-0.70
600-699	0.74	0.05	0.65-0.84
700-799	0.78	0.06	0.68-0.90
800-899	0.85	0.10	0.68-1.00
900-999	0.35	0.08	0.22-0.55
1000-1099	0.18	0.06	0.09-0.36

Table 3.25. Scaled selectivity of hook-and-line fishing when the red drum is harvested post-capture in the 2018-2022 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
300-399	0.22	0.04	0.15-0.33
400-499	0.87	0.10	0.69-1.00
500-599	1.00	0.13	0.77-1.00
600-699	0.14	0.07	0.05-0.37

Table 3.26. Scaled selectivity of hook-and-line fishing when the red drum is released post-capture in the 2018-2022 regulation period. Length bins with N/A values for selectivity are excluded from the table.

Length Bin (mm)	Selectivity	Standard Error	Asymptotic Confidence Level
<300	1.00	0.11	0.81-1.00
300-399	0.74	0.05	0.65-0.85
400-499	0.68	0.05	0.59-0.78
500-599	0.72	0.06	0.61-0.84
600-699	0.70	0.06	0.59-0.82
700-799	0.72	0.08	0.59-0.89
800-899	0.48	0.17	0.24-0.94
900-999	0.29	0.09	0.15-0.55

CHAPTER 4

CONCLUSIONS

Through evaluation of a long-term tag-recapture study, we estimated critical parameters utilized in stock assessments and other tag-recapture models. Tag-reporting rate was consistent with previous SCDNR studies (Jenkins et al., 2000; Denson et al., 2002), though this research presents the most expansive estimate of tag-reporting rate in South Carolina. The lack of spatial and temporal variation in tag-reporting rate is significant for future tagging analyses, as there is increased sensitivity in parameter estimation when tag-reporting rate varies over space and/or time (NEFSC Tagging Workshop, 2005). The high tag-reporting rates throughout the state are a product of significant participation by recreational anglers in the SCDNR tagging program as exemplified by the high recapture rates, although it also may suggest that the $100 reward should be investigated as an asymptotic reward value (Nichols et al., 1991; Denson et al., 2002; Taylor et al., 2006). The high recapture rates of tagged red drum (e.g., approaching 30% in Charleston Harbor) may be indicative of high exploitation rate of red drum, which should be investigated in future studies given the increase in red drum fishing mortality in recent years (Murphy, 2017).

The length of maximum selectivity of red drum in South Carolina depended on the fishing gear used to capture the fish, indicating that SCDNR's fishery-independent sampling gears exhibit ample coverage of red drum length classes. Given the minimal research on the interaction of red drum with the fishery-independent survey gears examined in this study, apart from longline (Powers et al., 2012; Powers et al., 2023), our study provides novel selectivity estimates for the South Carolina red drum population that could potentially be applied to the southern stock of red drum in the Atlantic Ocean in future stock assessments. Hook-and-line selectivity of red drum has changed through regulation periods and depends on the fate of the fish after capture. This study shows that red drum fishing regulations in South Carolina have significantly affected the length-based selectivity of harvested fish, though we found no interaction between fish length and regulation period for caught-and-released fish. The dome-shaped selectivity observed for red drum caught on hook-and-line could be a product of many factors, including the minimum and maximum length restrictions on harvest, ontogenetic movement, and the spatial distribution of fishing effort (Bacheler et al., 2010; Sampson & Scott, 2011; Maunder et al., 2014).

The tag-reporting rate and selectivity parameters estimated in this study may be of utility in future stock assessments and other tag-recapture models to increase the precision of other important parameters typically estimated internal to the model, such as abundance and exploitation rate (Pollock et al., 1991; Pine et al., 2003; Pine et al., 2012). External estimates of selectivity are of particular importance to the southern stock of red drum, as recent assessments contained significant uncertainty (ASMFC, 2017; Murphy, 2017). The assessments suggest using a parametric equation to estimate selectivity (i.e., external estimation; ASMFC, 2017) and providing a more comprehensive description of the lengths of caught-and-released fish (Murphy, 2017), both of which are accomplished in this study. Future studies may explore an external estimation of the exploitation rate and/or fishing mortality of red drum in South Carolina or the southern stock (e.g., Jiang et al., 2007; Bacheler et al., 2008), as the increase in catch-and-release fishing through time and high recapture rates show that red drum are experiencing high fishing pressure despite changes in size and creel limits.

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