Movement and Selectivity of Red Drum and Survival of Adult Red Drum: An Analysis of 20 Years of Tagging Data

Summer M. Burdick

Joseph E. Hightower

Jeffrey A. Buckel

Lee M. Paramore

Kenneth H. Pollock

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Table of Contents

List of Tables

List of Figures

Abstract

Red drum *Sciaenops ocellatus* are an economically important species in North Carolina. Commercial landings peaked in 1998 at an estimated value of $288,000 and recreational anglers are estimated to contribute more than $13,000,000 annually to the local economy (Paramore et al. 2001). Stock assessments for red drum at the North Carolina and regional levels are planned for 2006 and 2009, respectively. The 2001 North Carolina Fishery Management Plan for red drum listed several research needs for the improvement of future stock assessments. These included estimates of adult abundance, distribution, stock delineation, and mortality. The 2000 regional stock assessment also listed length selectivity by gear type and length frequency distributions for recreation discards as data needs. Between 1983 and 2004 cooperating anglers and North Carolina Division of Marine Fisheries researchers measured and tagged 41,854 red drum in North Carolina. Tag recapture models were used to estimate patterns in gear selectivity, recreational and commercial discards, and adult survival rates. Tag returns from fish caught less than three months after their release (n=4,095) were used to examine patterns in selectivity of gill nets, pound nets, and hook and line gear using a previously described method. Our results show that current selectivity patterns using all three gear types is greatest for fish between 457 and 685 mm TL (the current slot limit for legal harvest). This differs from past selectivity patterns with these gear types which, in addition to slot-size fish, showed high selectivity for fish <400mm. Using tag returns, and supplemental data from a double-tagging study, the unadjusted model averaged estimate of adult survival (mean ±SE) was moderate prior to 1991 (0.722 ±0.086),when the bag limit was two fish; survival (1.000 ±0.095.) increased dramatically after strict commercial and recreational regulations were put into place in 1992 and remained high (1.000 ± 0.122) after further regulations in 1997. Estimates of adult survival adjusted for catch-and-release ranged from 0.722-0.723 between 1983 and 1991 but increased to 100% between 1992 and 2002. Results from this study show that fisheries regulations have been effective at selecting for slot-limit fish and reducing mortality on adults. This information will assist stock assessment biologists in accurately assessing the status of red drum in North Carolina.

Introduction

Red drum *Sciaenops ocellatus* are a recreationally and commercially important estuarine-dependent species in the U.S. South Atlantic. They were historically found from Massachusetts to Key West and along the Gulf Coast of the United States (Lux and Mahoney 1969; Mercer 1984). Landings have declined along the Atlantic coast since the 1930s with the decline being the most dramatic in the northern reaches of their range (Mercer 1984). Important red drum fisheries once existed as far north as New Jersey and red drum have been commercially harvested from North Carolina waters since before 1900 (Smith 1895). Currently, North Carolina accounts for more than 90% of all red drum landed commercially on the U.S. east coast (ASMFC 2002). Directed recreational fisheries exist throughout their range. However, they were generally caught as by-catch in other directed commercial fisheries and, since 1998, various regulations on commercial harvest of red drum in North Carolina reinforced the by-catch status of this fishery (Paramore et al. 2001).

The recreational fishery has gained considerable popularity since the 1970s and, in 2000, accounted for 60% of the harvest of this species in North Carolina (Paramore et al. 2001). The majority of reported catch consists of fish within the “slot limit” (457-685 mm TL) that establishes the size range for legal harvest. A trophy catch-and-release fishery also exists in Pamlico Sound, the mouth of the Neuse River and along the Outer Banks. Seven of the nine largest red drum on record were caught in North Carolina, including the world record (43 kg) and runner up (41 kg) (Paramore et al. 2001).

Red drum were designated “overfished” in 2000 (Vaughan and Carmichael 2000). The “overfished” designation resulted in several recommendations to further restrict harvest of red drum in North Carolina. Several research needs for the improvement of future stock assessments were also identified (Paramore et al. 2001). These included distribution, stock delineation, and mortality. The 2000 stock assessment also listed length selectivity by gear type and length frequency distributions for recreation discards as data needs. An updated stock assessment for red drum is scheduled to be completed for North Carolina in 2007 by North Carolina Division of Marine Fisheries (NCDMF) and for the entire Atlantic coast in 2009 by the Atlantic States Marine Fisheries Commission. In order to provide improved data for these upcoming assessments, we addressed several of these research needs using a 20-year tag return data set.

Understanding temporal and demographic patterns in red drum movement is vital to the interpretation of tag return data. If red drum occupy different habitats as they age, mortality may be overestimated from tag-return data (i.e., tag returns decline in an area due to emigration and not mortality). Estimates of length- or age-based gear selectivity may also be confounded with age-based movement, especially if fishing pressure varies by region. Management decisions, such as the creation of marine protected areas, depend on knowing when red drum are likely to occupy certain areas and for how long. Movement can also help us understand stock structure and rates of population mixing.

Prior studies have shown that red drum movement and habitat use varies depending upon fish length and season. During winter and spring, adult red drum (>685mm TL) commonly occupy nearshore ocean habitats up to 27 meters deep, and sub-adults (457-685 mm TL) and juveniles (< 457 mm TL) commonly occupy estuaries (Ross et al. 1983; Ross and Stevens 1992; Marks and DiDomenico 1996). During summer and fall months, large adult red drum migrate into inlets and estuaries to spawn (Ross and Stevens 1992; Marks and DiDomenico 1996). Due to relatively large estuaries in North Carolina, this migration pattern results in long migration distances, which are not seen in southern regions that have narrower estuaries (Wenner et al. 1990; Ross and Stevens 1992; Marks and DiDomenico 1996). Large adult red drum also exhibit some seasonal north-south movements along the Atlantic seaboard (Yokel 1966; Wenner et al. 1990; Ross and Stevens 1992; Marks and DiDomenico 1996). We seek to confirm these trends in habitat use and movement by examination of tag return data, which span a longer time period than in previous studies. It should be noted that the sizes used to define the three life stages of red drum (adult >685 mm TL, sub-adult 457-685 mm TL, and juvenile < 457 mm TL) throughout this report are based on a balance between changes in life history and the point where management (i.e., the slot limit) necessitates some separation in analysis. Males are only about 50% mature at 685 mm TL and females do not mature until around 800 mm TL (Ross et al. 1995), and migration patterns can be expected to vary somewhat with maturity.

Vaughan and Carmichael (2000) identified the lack of selectivity information as a major obstacle in properly assessing the red drum stock. Separable Virtual Population Analyses (SVPA) used to assess red drum stocks are sensitive to accurate estimations of age-specific fishing mortality, which is estimated using selectivity patterns. SVPAs are also sensitive to changes in length- or age-specific total harvest, which is a combination of fish kept by fishers and those that die after release. While trip tickets and creel surveys can be used to estimate harvest, selectivity patterns are required for the estimation of length-specific release mortality. Vaughan and Carmichael (2000) expressed concerns that the slot limit restrictions introduced in 1991 and other management changes led to uncertainty in the 2000 assessment; specifically, the size of fish subjected to recreational catch and release (B2-type caught fish) was unknown. As catch and release becomes a more common practice, including the number of fish at age that die from discard mortality in the stock assessment becomes important. Finally, because SVPAs rely on historical harvest estimates, understanding changes in selectivity through time is important.

The current approach for assessing the status of the red drum population in North Carolina is to estimate the spawning potential ratio (SPR), or the current spawning stock size relative to an unfished stock. Reliable information on adult survival rates is essential in estimating the SPR. Green et al. (1985) estimated very low annual survival rates for red drum ($15 \pm 2\%$) and found no significant differences between survival rates of large and small red drum. However, they did not account for tag loss, which if unaccounted for can cause survival to be underestimated. Furthermore, the size separations used by Green et al. (1985) were not based on stage of maturity, which can be a problem because maturity can drive migration and influence habitat use (Ross et al. 1995). Additionally, survival may vary by region due to differences in habitat and regulations. Therefore, it is important to estimate adult red drum survival specific to North Carolina.

Tag loss, if unaccounted for, can significantly bias estimates obtained from mark-recapture studies (Wetherall 1982; Brownie et al. 1985; Pine et al. 2003). Tag loss is commonly thought of as falling into two categories. Type I tag loss, or acute tag loss, is the initial loss of tags after tagging. Type II tag loss, or chronic tag loss, is the continual loss of tags over time (Hampton and Kirkwood 1989; Barrowman and Myers 1996; Hampton 1997; McGlennon and Partington 1997; Latour et al. 2001). In the presence of type II tag loss, survival estimates can be negatively biased (Brownie et al. 1985; Fabrizio et al. 1999). Type I tag loss can substantially bias estimates of selectivity obtained from tag return models (Myers and Hoenig 1997). Therefore, it is important to get accurate estimates of both type I and type II tag loss before attempting to analyze tagging data sets. Similar tags may have different retention rates on different species or age classes of the same species, which makes it preferable to use tag loss rates estimated specifically for red drum (Baglin et al. 1980; Hampton 1997; Fabrizio et al. 1999; Latour et al. 2001).

To address the research needs outlined in the most recent red drum stock assessment report (Vaughan and Carmichael 2000) we:

- Estimated selectivity patterns in commercial and recreational fishing gear.
- Estimated length distributions of commercial and recreational discards.
- Estimated adult survival rates.
- Examined the effect of regulatory changes on these estimates.
- Examined seasonal and length effects on red drum movement and distributions.
- Estimated tag loss within a survival model.

Methods

North Carolina Tagging Program

North Carolina Division of Marine Fisheries (NCDMF) began tagging juvenile and sub-adult red drum (< 685 mm TL) in 1983; commercial fishermen assisted with this program until 1990. In 1984, NCDMF began a cooperative tagging program with recreational anglers that targeted adult red drum (> 685 mm TL). Since 1986, an average of 20 active volunteer anglers have tagged adult red drum each year and a total of 171 anglers have volunteered since the program began.

Various methods were employed by NCDMF personnel and cooperating commercial fishers to capture sub-adult red drum throughout the project (Appendix A). Between 1986 and 1990 weekly collections from pound nets were made from early summer (June or July) to October near Gum Point (Bath, NC) on the Pamlico River. In years 1987-1990 and 1995-1996, red drum were collected using either run-around or anchored gill nets throughout North Carolina's estuaries from spring (April -May) to fall (August-December). In 1997-1998, red drum were collected using a 200-m trammel net at selected locations along the interior Outer Banks and in Core and Bogue Sounds. In all other years, red drum sampling was conducted on an opportunistic basis. Healthy fish were measured, tagged, and released (Ross and Stevens 1992).

Volunteer recreational anglers were recruited from sportfishing clubs, conservation organizations, and red drum fishing tournaments to tag adult red drum. Volunteers caught red drum by hook and line throughout most of North Carolina's marine waters, including ocean beaches, inlets, and western and eastern Pamlico Sound locations. A large portion of volunteer effort was concentrated in the mouth of the Neuse River near Point of Marsh and near Ocracoke Inlet. A tagging kit, which included tags, tagging applicator, data recording cards, tagging instructions, a tape measure and pencil were provided to volunteer taggers. Taggers were asked to record the location tagged fish were released, fork length and tag number.

Several tag types were used by NCDMF personnel to tag juvenile red drum throughout the study. From 1986 to 2004, Floy ® internal anchor tags with a monofilament streamer core were used. Between 1987 and 1998, Floy ® internal anchor tags with an extra large anchor and a 15 cm streamer (FM-89SL) were administered. Between 1999 and 2004 Floy ® internal anchor tags (FM-95W) with a wire core were used. On healthy robust red drum, scales were scraped away from a small area 0.64 cm (0.25 inches) posterior to the pelvic fin and above the mid-ventral line. An incision was made just large enough to push the internal anchor tag through. The tag was inserted into the incision and twisted 90 degrees. A gentle tug on the streamer tested proper application of internal anchor tags. In 1986 Floy ® Clinch-up tags were inserted dorsally, just posterior to the termination of the dorsal fin, using a Floy ® applicator.

Nylon dart tags were placed on juvenile and sub-adult red drum (<685 mm TL) by volunteers throughout the study and by NCDMF in the first few years. After 1995 volunteers were not given nylon dart tags, due to the perception that they had a lower retention rate than internal anchor tags or steel dart tags. However, 154 nylon dart tags were placed on juvenile red drum after 1995. Nylon dart tags were inserted behind the dorsal fin at an acute angle so that the tag would lie flat along the fish's body. Nylon dart tags were secured behind the pterygiophores and given a slight tug to insure proper placement before fish were released. Fish in poor condition were not tagged and fish were gently returned to the water.

Prior to 1999, adult (> 685 mm TL) red drum were tagged with Hallprint ® stainless steel dart tags having a monofilament streamer core. After several tags were returned without the outer streamer sheath containing the tag number and other critical text, these tags were replaced with Hallprint ® stainless steel dart tags having a stainless steel wire streamer core. The majority of all steel dart tags were placed by volunteers who were instructed to firmly insert the tag into flesh of healthy adult red drum two or three scale rows under the middle of the first dorsal fin. Taggers were instructed to test for proper application by giving the tag a slight tug to make sure it was secure.

Each tag was labeled with the tag number, and a message that read, "REWARD-SEND TAG No. DATE, LOCATION, PHONE No. TO: NCDMF, BOX 769, MOREHEAD CITY, NC". A reward of two dollars was given for returned tags until 1989. In 1990 the reward was increased to five dollars or a baseball cap. Three $100 prizes were given away in annual drawings from each year's returned tags (Ross and Stevens 1992).

North Carolina Division of Marine Fisheries personnel attempted to contact fishers who returned tags to ask about the fate of the fish. Fates included: returned to water with tag, returned to water without tag, returned to water with a partial tag (tag was clipped off but the anchor was left in the fish), retagged and returned to water, or not returned alive to water. Fishers were also asked about the type of gear used to recapture the fish and to give a detailed description of the location where the fish was captured. The distance of travel for each fish was calculated using shortest in-water route possible.

Movement

We examined seasonal differences in spatial distribution, migration rates and migration distances for juvenile (< 457 mm TL), sub-adult (458-685 mm TL), and adult (>685 mm TL) red drum. Travel distances and rates of movement were estimated for red drum that had tags returned within 90 days of tagging. This 90-day limit minimized any size-related bias caused by differences in times at large. We plotted seasonal travel rates and distances, and determined season of travel using the midpoint of each fish's time at large.

Movement rates and travel distances were examined for red drum in 100-mm length bins. We used a linear regression to examine changes in movement rate and distance with fish length. Due to heterogeneous variances, we used a two sample rank test (Zar 1984) to test for differences in distances and rates of movement between seasons (January-March, April-June, July-September, and October-December). A Dunn rank sum test for non-parametric data with unequal sample sizes (Zar 1984) was used to test the post-hoc hypothesis that movement distances and travel rates were greater in fall (October-December) than other seasons.

Seasonal changes in red drum spatial distribution were examined by mapping the number of fish captured for tagging by age class in 11 water bodies over four seasons using ArcGIS software. Volunteer taggers primarily fished in areas where they had continued success, therefore the distribution of tagging provided some information about the distribution of red drum. Water bodies were classified as either ocean or estuary. Major geographic features, such as capes or inlets were used to separate ocean water bodies. Aggregations of red drum captures helped delineate water bodies within estuaries. Four seasons were examined, winter (January-March), spring (April-June), summer (July-September), and fall (October-December).

Tagging and recapture location data on adult red drum were used to determine movement direction, extent of dispersal, and mixing within North Carolina. Data on adult red drum ocean captures from two long-term data sets, the National Marine Fisheries Service (NMFS) trawl survey and the Virginia Institute of Marine Sciences (VIMS) Shark longline survey, mapped by month using ArcGIS software, provided insight into north-south ocean migrations of adult red drum. These surveys were examined because of their long time series and coverage of multiple seasons. NMFS trawl surveys were conducted in spring (March) and autumn (September to November). Autumn trawling was initiated in 1963, and spring trawling in 1968; both spring and autumn trawling are still continuing. NMFS towed a 8.2 m (60 ft) trawl with 12.7 cm (5 in) stretch mesh at approximately 350 randomly chosen sites for a half hour each, during each research cruise. Trawling was conducted from Cape Hatteras north well beyond the Canadian boarder at ocean sites from 27-365 m (5 to 200 fathoms) deep (Despres-Patanjo et al. 1988). The VIMS longline survey began in 1974 for the assessment of shark populations and also continues through present day. Depth-stratified longline sets were made at eight standard stations plus ancillary locations each month from May or June through September or October in the Chesapeake Bay and Virginia coastal waters. At each station a 100-hook baited longline covering approximately 2 km was fished on or near the bottom for 3-4 hours (Musick et al. 1991).

Selectivity

We estimated both length-based and age-based selectivity patterns for three gear types commonly used in North Carolina using NCDMF mark-recapture data. We examined differences in selectivity between three different time periods, 1983-1991, 1992-1997, and 1998-2004. Time periods were chosen based on changes in fisheries regulations (see Table 1). For recreational and commercial tag returns, the selectivity of discards (fish released alive) and harvested fish were analyzed jointly and separately. However, data were too sparse to examine changes in harvested and released fish between time periods, therefore we combined time periods for this analysis. Here, selectivity is a combination of vulnerability and gear selectivity effects. Vulnerability is a measure of spatial overlap between fish in a particular length bin or age class and fishing effort. It is not possible to unequivocally differentiate between the two processes using this data set.

Selectivity patterns were estimated using a generalized linear model as described by Myers and Hoenig (1997). In this method, length-based (or age-based) selectivity of red drum by gear type is estimated by fitting a model for the expected tag return rate $E\lfloor C_{i,g,l} \rfloor$ of tagged fish where $E\lfloor C_{i,g,l} \rfloor = N_{i,l} R_{i,g} U_{i,g} S_{g,l}$, and $N_{i,l}$ is the number of fish tagged in experiment i in length (or age) bin *l*, $R_{i,g}$ is rate of tag recovery for gear type g for fish tagged in experiment i , $U_{i,g}$ is the exploitation rate of fish tagged in experiment i and recaptured by gear type *g*, and $S_{g,l}$ is the selectivity of gear type *g* in length (or age) bin *l*. The tag recovery rate is the product of the proportion of fish that survive tagging, the proportion of tags that are not lost (shed), and the proportion of recovered tags that is reported. For our purposes, each tag type was considered a separate experiment.

We used the GENMOD procedure in SAS to perform our analysis (SAS 2006). Data were log transformed and errors were assumed to have a binomial distribution. As a default the GENMOD procedure automatically scales all estimates to the last estimate in a class, which it sets to 0. Therefore, unless the last length bin had the highest selectivity, when the estimates are back-transformed some selectivities would be negative. To avoid this artifact of the default setting, we first ran preliminary tests to predict which length bin would have the highest selectivity. Then we ordered the data input so that the last length bin listed was the one with the highest selectivity. All other ln-transformed selectivity estimates were negative. Therefore, when back-transformed, all selectivity estimates were between 0 and 1. The selectivities we estimated are relative to the maximum selectivity, which equals one.

The approach we used required several assumptions (Myers and Hoenig 1997). Tag loss, tagging mortality, natural mortality, and reporting rate are assumed to be independent of fish length or age for each recapture gear type. In addition, we assumed that the exploitation and recovery rates did not change over time for a given tag type and that fish did not grow out of their length (or age) bin before they were recaptured.

For length-based analysis, we experimented with the criteria for selecting data. We varied the maximum allowed time at large and the size of length bins used in the analysis to determine the optimum combination given the data available. The smallest acceptable length bin was considered to be the amount a fish could grow given the time at large. Selectivity estimates could be biased if animals grew out of their assigned size bin by the time they were recaptured. Large length bins and time periods allowed for higher sample sizes within each length bin but resulted in a coarse selectivity curve. Small length bins and short time periods resulted in refined selectivity curve but also small sample sizes in each length bin. The optimal combination was 100-mm length bins and 90-day time periods. For consistency, we used a 90-day time window for the age-based analysis as well. However, a longer time window could be employed.

For larger red drum, tag return rates using pound and gill nets were low; therefore, a single length bin was used for fish over 600 mm. Hook and line data, which included more adult catches than other gears, were sufficient to estimate selectivity for seven length bins of adults from <300mm to 1200+mm. For age-based analyses, older fish were pooled as age-4+ for all gear types. All mesh sizes and net dimensions were considered jointly for pound nets and gill nets. Additionally, we did not discriminate between the types of hook and line rigs (hand lines, bottom rigs, and other hook and line rigs).

Total fish length was converted to an estimated age using an age-length key (Table 2). The age-length key was based on 17 years of aging data collected on North Carolina red drum by NCDMF. Rapid first year growth necessitated separate age length keys for January-June and July-December. A January 1 birthday was assumed for all red drum. Red drum are actually hatched in the fall, therefore an age-1 fish in our analysis is anywhere from 4 to 16 months old. Red drum older than age 4 were grouped together into a single age bin.

The minimum allowable number of tag returns from a particular tag type from a given gear type was examined by comparing estimates of selectivity and variances derived from data selected using the following criteria i) at least one tag return per experiment, ii) at least ten returns per experiment, iii) at least 100 returns per experiment, and iv) at least one tag return in at least 50% of the length bins per experiment. The four data selection criteria yielded similar results (see below); thus, we had a minimum of one tag return per experiment in our final analysis.

Following Myers and Hoenig (1997), we examined deviance residuals to assess model fit. Residuals were plotted by length (or age) bin and experiment. Deviance residuals are defined as the square root of the deviance contribution for the observation, with sign equal to the sign of the raw residuals (SAS 2006). The deviance is based on the difference between the log-likelihood of the fitted and the saturated models (Neter et al. 1996). We tested for overdispersion by comparing the ratio of the deviance and degrees of freedom to one. If this ratio (dispersion parameter) is greater than one, data are overdispersed. Overdispersion indicates poor model fit (high variance), which can be caused by outliers, using the wrong link function, violating the assumption that variances are binomially distributed, lack of independence among marked individuals, or omitting an important parameter. An important parameter may be omitted due to unaccounted for heterogeneity in the data.

Shifts in selectivity patterns resulting from changes in regulation (Table 1) were examined using Akaike Information Criteria (AIC). For hook and line and gill nets, we compared two models, each with two parameters for time period (before versus after the 1991 and 1998 regulation changes), to a reduced model with no parameters for time periods. For pound nets we only examined the 1991 regulation change, due to a lack of data in the most recent time period. Additionally, we estimated selectivity of live-released and harvested fish and made qualitative comparisons.

Tag Loss and Adult Survival

We estimated mortality for red drum larger than the slot limit (>685 mm TL), in the three separate regulation periods (1983-1991, 1992-1997, after 1998; see Table 1) using tag return data and a Brownie type approach modified for tag loss. By estimating adult red drum mortality separately from juveniles and slot-limit sized fish we were able to avoid complications arising from emigration and unequal fishing mortality. Additionally, since we are estimating mortality for adult red drum, which have had no legal harvest since 1998, we can reasonably make the assumption that most of the estimated mortality (other than catch-and-release and poaching) is from natural causes since that year.

Analyses were done only for red drum larger than the upper end of the slot limit (685 mm TL), and tagged with either a nylon (Hallprint ® FT-1 or FT-2) dart tag, stainless steel dart tag with a monofilament core (Hallprint ® FH-69) or Hallprint ® stainless steel dart tag with a wire core. These were the tag types for which we were able to estimate tag loss (see below). Tagging data were included in the analysis regardless of the time of year that the fish were tagged. Tag returns from red drum that were harvested or had their tag removed before release were included in our analysis, but fish re-released with tags attached were not.

We estimated survival (*S*) using a method described in detail by Brownie et al. (1985), which compares observed tag recoveries to a matrix of predicted recoveries. The expected number of tags returned after the first year is: $E(R) = N_i P_{ij}$, where N_i is the number of fish tagged in year *i*, and P_{ij} is the probability that a tag placed on a fish in year *i* is recovered in year *j*. The probability of recovering a tag within the first year (*j*=*i*) is, $P_{ij} = f_j$, where *f* is return rate in year *j*. The probability of recovering a tag in years thereafter is, $P_{ij} = \left[\prod_{i}^{j-1} S_i\right] f_j$.

We modified the basic Brownie model to account for tag loss, by adding a component to model acute tag retention (ρ_k ; type I) and exponential decline in tag retention ($e^{-L_k t_{ij}}$; type II) for each tag type (k) to the probability of tag recovery, where L is the instantaneous rate of tag loss and t is time at large. In this modified model the probability of recovering a tag within the first year (j=i) is, $P_{ij} = f_j \rho_k$. The probability of recovering a tag in years thereafter is, $P_{ij} = \left[\prod_{i}^{j-1} S_i \right] f_j \rho_k e^{-L_k t_{ij}}$. Each tag type had its own recovery matrix.

Data from a double tagging study conducted by the South Carolina Department of Natural Resources (Glenn Ulrich and Charles Wenner, SCDNR, unpublished data), were used to estimate tag loss in adult red drum. Adult red drum (N=1395; TL > 800 mm) were tagged with both a Floy ® steel dart tag, and a Floy ® nylon dart tag between 2001 and 2004. We assumed an exponential decline in tag retention over time. Using this approach the probability of retaining a tag of a particular type is $Q_k(t) = \rho_k e^{-L_k t}$ where k indicates tag type (steel (S) or nylon (N) dart tag). The probabilities for recapturing a fish with 1) both tags ($p_{SN}(t)$), 2) only a steel dart tag ($p_S(t)$), or 3) only a nylon dart tag ($p_N(t)$) are

$$p_{SN}(t) = Q_S(t) Q_N(t) \qquad (1)$$

$$p_S(t) = Q_S(t)[1 - Q_N(t)] \qquad (2)$$

$$p_N(t) = [1 - Q_S(t)] Q_N(t) \qquad (3)$$

We modeled exponential tag loss of both steel dart and nylon dart tags and survival (described above) simultaneously in program SURVIV (White 1992) using a maximum likelihood approach described by Barrowman and Myers (1996). We made several assumptions about tag loss. First, we assumed that loss of a steel dart tag was independent of the loss of a nylon dart tag on the same fish. The second assumption was that tag loss was independent between individual fish. Thirdly, we assumed that if fishers were to catch fish and cut off tags prior to the fish being recaptured by SCDNR biologist, they would consistently remove both tags. Finally, we assumed mortality was constant over time for double-tagged fish.

The Brownie et al. (1985) method makes the assumption that tagged fish are representative of the overall population. This means that tagged fish are assumed to be fully mixed within the population of red drum before the recapture period begins. It is further assumed that the fate of each tagged fish is independent of all other tagged fish and that the fate of any individual fish follows a multinomial distribution.

We fit several models to test for time period effects on survival and tag recovery and to check for differences in type I and type II tag retention between tag types (see below). The time periods were chosen based on changes in red drum management (Table 1). Akaike Information Criteria (AIC) was used to rank the models and parameters were obtained through model averaging. Model averaged estimates were derived by:

$$ave(\hat{\theta}) = \sum_{i=1}^{n} \hat{\theta}_i w_i$$

where $\hat{\theta}$ is the parameter estimate of interest (i.e., *S* or *f*) for model *i*, and normalized weights (w_i) are calculated by dividing each model weight $\left(e^{-\frac{1}{2}\Delta AIC_i}\right)$ by the sum of all model weights in a group of models (Cooch and White 2006).

Brownie type models used to estimate mortality assume that marked animals are killed upon recapture (Brownie et al. 1985). However, in many fisheries, such as the red drum fishery, at least some of the marked fish are released after recapture. Mortality will be overestimated if fish released alive are simply included in the analysis and undifferentiated from harvested fish. We define harvested fish as fish which were kept and those thrown back dead. Two studies provide methods to correct for catch-and-release fisheries in the estimation of total mortality. Smith et al. (2000) developed an equation to adjust estimates derived using both live released and harvested fish; this method requires known rates of hook-and-release mortality and tag reporting. Jiang et al. (2006) developed an alternative method, which uses separate recovery matrices for fish released alive and those that died. Using this approach, fishing mortality rates are estimated not only for fish, but also for tags that are removed from fish released alive.

The Smith et al. (2000) method was more appropriate for our analysis because we lacked enough tag return data to fit the model described by Jiang et al. (2006). We used an estimate of hooking mortality (7%) for adult red drum caught on circle hooks in the Neuse River (Aguilar 2003). Reporting rate estimates for juvenile red drum in the southeast United States range from 0.25 to 1.0, but no reporting rates are available for adult red drum (Jenkins et al. 2000; Latour et al. 2001; Denson et al. 2002; N.M. Bacheler, Department of Zoology, N.C. State University, unpublished data). Therefore, we applied a range of reporting rates between (0.2 and 1.0) to the Smith et al. (2000) adjustment to assess this parameter's influence on survival estimates.

Results

Tagging

A total of 41,852 red drum was measured and tagged between 1983-2004. Additionally, 586 red drum were tagged but not measured. On average, a total of 2,166 (range 739-5673) red drum was tagged each year since 1986 (Table 3). Fishers using hook and line gear tagged the majority of adult red drum, while most of the juvenile red drum were captured for tagging by NCDMF using pound net and gill nets (Table 4). Eleven different tag types were administered (Table 5). The largest percentage of juveniles (86%) was tagged with internal anchor tags. Most adults (92%) were tagged with stainless steel dart tags (Table 5).

There was a bimodal distribution in the length frequency data for both tagged and recaptured red drum (Figure 1). Juvenile red drum made up the majority of tagged fish (51%), followed by adults (36%) and sub-adult red drum (13%; Table 3). Large red drum (1050-1250 mm TL) were recaptured relatively less frequently than they were tagged. Small to medium sized red drum (350-750 mm TL) were recaptured relatively more frequently than they were tagged (Figure 1).

Tags were distributed throughout North Carolina in estuaries (65%) and ocean waters (35%). Most juvenile (94%) and sub-adult (66%) red drum were tagged in estuaries, but the majority of adult (76%) red drum were tagged in the ocean. The largest percentage (35%) of red drum was tagged in west Pamlico Sound, followed by Ocracoke Inlet (21%) and Roanoke and Croatan Sounds (12%). A total of 75 red drum was tagged in Chesapeake Bay, Virginia. Most estuary-tagged fish were released into west Pamlico Sound (54%), and most ocean-tagged fish were released into Ocracoke Inlet (59%; Table 6).

The recapture location was recorded for 4,544 of 4,814 recaptured red drum. Tag return rates decreased as size increased. Juvenile red drum had an 18% tag return rate, sub-adults a 13% return rate and only 2% of adult red drum tags were returned. More red drum were recaptured in estuaries (80%) than in the ocean (20%). Most recaptures occurred in west Pamlico Sound (57%). The areas with the fewest recaptures were Chesapeake Bay, Virginia (n=13) and the Core Banks (n=25; Table 7).

Movement

Location data was recorded for 556 tagged red drum recaptured within 90 days of release. Fifty percent of these red drum moved less than 3.20 km at a rate of 0.09 km/d. Twenty five percent moved more than 23 km and 5% moved more than 90 km. The top 5% of red drum recaptured within 90 days exhibiting the fastest rate of movement, traveled over 4.00 km/d. The mean ($\pm$ SE) rate of movement for red drum recaptured within 90 days was 0.83 ($\pm$ 0.12) km/d. There was no significant effect of fish length on either the distance moved (p=0.81; Figure 2) or movement rate (p=0.18; Figure 3).

Red drum traveled farther in the fall (October-December) than the winter and spring (p<0.05; Figure 4), and at a faster rate in the fall than all other seasons (p<0.05; Figure 5). There was a significant effect of season on both the distance (p<0.0001) and rate of travel (p<0.0011) for tagged red drum less than 500 mm TL and on the rate of travel for red drum longer than 600 mm TL (p=0.0035). Season did not have a significant effect on the distance that red drum greater than 500 mm TL (500-599 and 600+) moved within 90 days (Figure 4); however, this season effect for these size groups may have been difficult to detect due to small sample sizes. Similarly, we did not detect a significant difference in the rate of movement between seasons for red drum 500-599 mm TL (p=0.524; Figure 5).

Juvenile red drum were captured and tagged in estuarine waters in nearly all seasons (Figure 6) but the tagging locations of subadult and adult red drum were highly dependent on season (Figures 7-8). Sub-adult red drum, the size class having the fewest tagged fish, were tagged in inside waters from April to December, and were also tagged from ocean catches in summer and fall (Figure 7). Beginning in April, adult red drum were tagged near Cape Hatteras and in Ocracoke Inlet (Figure 8). As spring progressed, more adult red drum were tagged on the inside of the Outer Banks, and by summer the majority of large red drum were tagged in western Pamlico Sound and in the mouth of the Neuse River. From October to December, adult red drum were primarily tagged in

Ocracoke Inlet and on ocean beaches. Few sub-adult or adult red drum were tagged in the winter (Figures 7a and 8a). More juvenile red drum were tagged state wide during the summer and fall than the winter or spring.

Cape Lookout appeared to serve as a partial barrier to red drum. Most recaptures of red drum tagged south of Cape Lookout occurred south of Cape Lookout (juvenile = 98%, sub-adult=95%, and adult =83%; Tables 8-10). Similarly, there was infrequent movement from north to south with a small portion of recaptured juvenile (36%), sub-adult (21%) and adult (21%) red drum tagged north of Cape Lookout being recaptured south of Cape Lookout (Tables 8-10). A similar barrier to movement was not observed at Cape Hatteras.

Consecutive recaptures would be useful in movement analyses and can be used in mark-recapture models to estimate population abundance (Williams et al. 2002). However, the numbers of red drum that were recaptured more than once in our study was limited. Twenty-four adults, one sub-adult, and 43 juvenile red drum were recaptured twice with the same tag. One adult, and two juvenile red drum were recaptured three times with the same tag. One juvenile red drum was recaptured four times with the same tag. On 64 occasions an old tag was removed and replaced with a new tag; however, changes in tag numbers cannot be tracked in the current database. The only way to track these fish through time is to manually examine hard copies of the data sheets. Some of these fish were recaptured multiple times over many years. For example, a red drum was tagged with tag number D08102 on September 15 1990 in Ocracoke Inlet. It was recaptured

November 8 1995 and given a new tag with the number D31625. This same fish was recaptured again on July 26 2005 and given a new tag with the number D39061. It was recaptured a third time on November 2 2005. All three recaptures occurred in Ocracoke Inlet. It was at large for a total of 5,528 days (15.15 years). Systematic manual examination of all original data sheets may reveal more fish recaptured multiple times and may provide valuable insight into red drum movement.

Adult red drum caught in NMFS and VIMS surveys show latitudinal differences between seasons (Figure 9). A total of 51 adult red drum was caught in NMFS trawl surveys from 1975-2003, and 66 red drum were caught in VIMS longline surveys between 1990-2004. In March trawls, red drum were primarily caught in the ocean between Oregon Inlet and Drum Inlet. From June to September, large red drum were caught in VIMS longline surveys in Chesapeake Bay. Large red drum were caught in both surveys from coastal waters of the Delmarva Peninsula and the mouth of Chesapeake Bay south to Oregon Inlet from September to November.

Selectivity

The estimates of selectivity and corresponding variances were similar between the four data selection criteria; thus, we were able to include more experiments (tag types) when our minimum requirement was a single tag return in each experiment (Table 11). After excluding tag types which didn’t result in any returns, 41,305 tagged red drum were included in hook and line analyses, 35,381 in gill net analyses, and 37,395 in pound net analyses. Out of nine tag types used to mark red drum a total of eight different tag types (experiments) for hook and line and pound net models and seven for gill net models was included in the selectivity analysis. Recaptures of these tags within 90 days included 1,121 by hook and line, 772 by gill nets, and 1,098 by pound nets. A sufficient number of tag returns in each regulation period were available for gill nets and hook and line in order to estimate selectivity. Only three tags were recovered from pound nets after 1997, making a selectivity estimate for that gear impossible in the most recent period.

Deviance residuals demonstrated good overall fit for the hook and line models, but gill net and pound net models did not fit the data as well. When separated out by tag type, deviance residuals from hook and line analysis were all negative in longer length bins (TL > 600 mm) for red drum tagged with internal anchor and nylon dart tags. This tag type effect was not noticeable in gill net and pound net selectivity in which there was only one length bin for fish greater than 600 mm TL. We detected no bias from deviance residuals in period-specific selectivity analysis in any of the gear types. Deviance residuals also indicated there was no bias in selectivity estimates of recreational discards and harvested fish. Data were overdispersed for gill net and pound net estimates, but evenly dispersed for hook and line caught fish (Tables 12-13). Overdispersion may have resulted from lack of independent fates among marked fish caught in gill nets or pound nets, since these gears are more apt to catch multiple individuals from a single school.

Based on AIC values, the best model for estimating hook and line length-based and age-based selectivity (harvested and catch-and-release fish) was one that included parameters for time periods before and after 1991, followed by a model that included parameters for time periods before and after 1998 (Tables 14-15). After an increase in the minimum size limit in 1991, hook and line selectivity on fish less than 400 mm TL decreased (Table 16); Figure 10a). Selectivity was highest on age-1 and age-2 red drum in both time periods (Table 17; Figure 10b). Examination of selectivity before and after 1998 revealed a dramatic decrease in hook and line selectivity on red drum less than 500 mm TL (Figure 10c); this decrease in selectivity was also observed in the age based analysis (Figure 10d; Table 17). However, there was no substantial change in the selectivity for red drum greater than 500 mm TL between these two time periods (Figure 10c).

Over all periods, hook and line selectivity was greatest for age-1 and age-2 red drum between 500 and 699 mm TL (Figure 10 a-d; Tables 16-17) and there was a rapid decline in hook and line selectivity between the 600-699 mm and 900-999 mm length bins. Red drum less than 500 mm TL were about half as vulnerable to capture by hook and line gears as those 500-599 mm TL (Figure 10 a, c). In all periods, there was a steady decline in selectivity between age-2 and age-4+ for hook and line gear (Figure 10 b, d). Relative probabilities of recapture were substantially different for red drum harvested by hook and line and fish released alive (Figure 11a). When data were pooled over all time periods, red drum 500-599 mm TL were most likely to be retained by anglers, whereas fish less than 500 mm TL were most likely to be released alive.

A model containing parameters for time periods before and after the 1991 regulation change, followed by a model with time period parameters before and after the 1998 regulation change, had the lowest AIC when estimating length-based and age-based gill net selectivity (Tables 14-15). Gill nets selected primarily for red drum larger than 400 mm TL after 1991. Before the 1991 increase in minimum size limit, gill net selectivity was highest for red drum 300-499 mm TL and red drum larger than 500 mm TL were selected against (Table 16; Figure 12a). A shift from age-2 to age-3 red drum, after 1991 was also observed (Table 17; Figure 12b). After the 1998 rule change, red drum greater than 300+ mm TL were selected for (Figure 12c). There was a shift in maximum selectivity from age-1 to age-2 red drum in gill net catches, after 1998 (Figure 12d). Based on a comparison of selectivity patterns, red drum retained by gill net fishers tended to be larger and older than those released alive (Figure 11c-d).

Pound nets tended to catch smaller and younger red drum than gill nets or hook and line fisheries (Figure 13). A model containing time period parameters for before and after 1998, had the lowest AIC values of the models used to estimate length-based pound net selectivity. However, for age-based selectivity of pound nets, a model with additional parameters for time period before and after 1991 did not fit better than a model without time period parameters, when parsimony was taken into account. From 1983-1991, pound nets selected for red drum less than 300 mm TL; however, pound nets selected for red drum in the 300-399 mm TL size bin from 1992-2004 (Table 16; Figure 13a). This size selective shift did not cause a substantial shift in age selectivity (Table 17; Figure 13b). In both time periods examined, red drum < 400 mm TL had the highest probability of recapture in pound nets (Table 16; Figure 13a) and pound nets had high selection for age-1 fish with age-2+ fish selected for less than 13% as often (Table 17; Figure 13b). For all years combined, age-2 red drum were most likely to be harvested from pound nets, whereas age-1 red drum were most likely to be caught and released (Figure 11f). However, this pattern was not observed when data were binned by size (Figure 11e).

Tag Loss and Adult Survival

Tag recovery rates were low for adult red drum tagged in North Carolina with steel and nylon dart tags. Only 10 (1.9%) tags were returned from 517 adult red drum with tag type FT-1 Dart (nylon dart tags); nine out of 10 of these fish were kept by anglers (Table 18). For stainless steel dart tags, 298 (mono and wire core combined) were returned from 12,625 tagged red drum. However, 97 of these were re-released with their tags intact and could not be used in our analysis (Table 18). Therefore, only 201 fish recaptured with steel dart tags (1.5% of fish tagged with steel dart tags) could be used in our analysis.

The fate of recaptured adult red drum and their tags varied dramatically with time (Figure 14; Table 19). The percentage of recaptured adult red drum that was harvested was 100% prior to 1987 but decreased almost linearly since that time. After 1997, only 12% of all recaptured adult red drum were killed. Of the re-captured adult red drum that were re-released before 1997, 43% were returned to the water with their old tag, 9% had their tag clipped and were given a new tag, 3% were given a new tag with out having the old tag clipped, 23% were given two new tags, and 23% were released without a tag. After 1997, 46% of re-released adult red drum were returned to the water with their old tag, 29% had their tag clipped and were given a new tag, and 25% were released without a tag (Table 19). No recaptured fish were double tagged or given a new tag without cutting off an old tag after 1997.

In the double-tagging study conducted by South Carolina DNR, 72 tagged red drum were recaptured by their biologists. Fish were recaptured with one of three tag combinations i) both the steel dart and nylon dart tag, ii) only a steel dart tag, or iii) only the nylon dart tag. Six of these were recaptured twice; for these fish, we used only the second recapture in our analysis.

The best-fit model, as determined by AIC, had separate estimates for survival $\left(\hat{S}\right)$ in each regulation period and tag return $\left(\hat{f}\right)$ in each year (Table 20). The unadjusted model averaged estimate of adult survival (mean ± SE) was moderate prior to 1991 (0.722 ± 0.086), with a bag limit of two fish, but high (1.000 ± 0.095) between 1992 and 1997, when the bag limit was reduced, and between 1997 and 2002 (1.000 ± 0.122) when the bag limit was further reduced and the minimum size limit increased (Table 21). Estimated survival adjusted for catch-and-release was 0.72 before 1991, 1.00 between 1991 and 2002. The Smith et al. adjustment had no affect on survival estimates for any level of reporting rate (Table 22).

We were unable to detect a difference in tag loss between nylon and steel dart tags from SCDNR data. The best fit model according to AIC had 58.7% of the model weights (w_i), and indicated that the most appropriate model was one that also had a single value for $\hat{L}$ (0.253 ± 0.068) and $\hat{\rho}$ (1.000 ± 0.011). However, the second best fit model, which carried 28.2% of the model weights, had a delta AIC of 1.5 and indicated tag loss rates were different between types. For steel dart tags, the model averaged estimate of L

was 0.252 (SE= 0.075) and for nylon dart tags it was 0.312 (SE=0.100). These values indicate rapid chronic tag loss. Using the model averaged estimates, we estimate that only 28% of steel dart tags and 21% of nylon dart tags are retained after 5 years, and after 10 years only 8% of steel dart tags and 4% of nylon dart tags are estimated to be retained (Table 23; Figure 15).

Discussion

Movement

Our results generally corroborate findings in previous studies on red drum movement. Two previous studies, which analyzed a subset of the mark-recapture data that we examined, also found that adult red drum occupied ocean habitats in the winter and spring, and estuaries in the summer and fall (Ross and Stevens 1992; Marks and DiDomenico 1996). Additionally, an autumn migration is suggested by our analysis of movement rates and distances by season. The distributions of distance and rate of travel appear skewed, which is in agreement with the findings of Wenner et al. (1990). They observed that while the majority (85%) of tagged red drum (210-860 mm TL) in South Carolina moved less than 24 km, a greater number of fish moved longer distances than would be expected based on a normal distribution. Wenner et al. (1990), who included all recaptured fish in their analysis regardless of the fish's time at large, observed minimum average red drum swimming speeds for tagged fish between 1.4 km/day and 4.0 km/day depending on the direction of travel. This is faster than the average speed we observed for fish at large 90 days or less (0.8 km/day). Red drum in both studies were predominantly collected in the summer and fall, therefore seasonal effects are not responsible for the differences in observed red drum movement rates. The discrepancy between our findings and Wenner et al. (1990) may be a result of the time at large used in analysis.

We found no significant difference in the distance or rate of travel with fish length. Using a subset of the same data, Marks and DiDomenico (1996) found a significant difference in the distance of travel with length. The discrepancy between our findings and Marks and DiDomenico (1996) is a result of the time at large used in analysis. Marks and DiDomenico (1996) examined tag returns for all fish regardless of time at large. We analyzed tag returns only for red drum at large for less than 90 days. The short time period used in our analysis was chosen to reduce effects of varying times at large. Comparison of the results from both studies suggests that large red drum do not move faster but farther given longer periods of time.

Fisheries biologists and recreational fishers have long wondered where large adult red drum overwinter. The collection of data from several sources in this report suggests that adult red drum are overwintering in deep offshore habitats. Catches from the NMFS trawl survey and VIMS long-line survey show that red drum were caught well over 20 kilometers off shore in March, but close to shore and in inside waters during other months (Figure 9). The lack of red drum caught in inside waters or near-shore ocean habitats in our study in winter further corroborates the hypothesis that adult red drum overwinter offshore. Very few adult red drum were caught in January-March (136 tagged and 46 recaptured), throughout our study. Low fishing effort by cooperating anglers and sampling effort by DMF personnel during these months may be a factor, but effort is somewhat scaled by availability. As angler success decreases in the winter, less effort is put into catching large adult red drum. Therefore small winter sample sizes are still somewhat representative of availability.

Tagging studies, which examine movements of individuals, are complementary to genetic studies, which examine gene flow. Our examination of tag returns and long-term trawl and longline data suggests there are seasonal north-south movements between Virginia and North Carolina but little north-south movement past Cape Lookout. Chapman et al. (2002) found a high degree of genetic homogeneity among red drum all along the Atlantic seaboard. Thus, the low rate of exchange north and south of Cape Lookout appears sufficient for genetic mixing.

Selectivity

In the most recent time periods, selectivity by hook and line and gill net gears was highest for red drum within the slot limit. This is similar to selectivity patterns observed in Florida, where hook-and line caught red drum in the slot limit are heavily selected for but age-4+ red drum are selected against (Murphy 2005). The rapid decline in selectivity probably results from the spatial overlap between red drum and fishing effort as red drum reach maturity. Age-1 and -2 red drum remain in the estuaries before they reach maturity where fishermen can easily target them. Adult red drum spend winter and early spring months in deep water or offshore ocean waters, making them more difficult for fishers to access (Pafford 1990; Ross and Stevens 1992).

Age and size selectivity patterns were affected by gear and regulation period. Selectivity patterns (harvested and discard combined) in all three gear types shifted dramatically to larger and older fish after the 1991 increase in minimum size limit from 14 inches (356 mm TL) to 18 inches (457 mm TL). Murphy (2005) documented a similar shift in selectivity patterns for hook-and-line caught red drum in Florida after size limits were instated. These selectivity patterns indicate that regulation rule changes were effective in shifting the size class targeted by fishers. This shift may have resulted from changes in the spatial overlap of fishing effort and red drum, as fishers narrowed their targeted size range (shift in vulnerability). Our failure to detect a reduction in selectivity of large red drum (>700 mm TL) in North Carolina after 1998, was likely due to low vulnerability prior to the moratorium on adult harvest.

Changes in size selectivity may also be a result of modifications in gear (shift in selectivity); we did not statistically examine for effects of mesh or hook size modifications within a gear type. Substantial gear modifications were made in both the commercial and recreational fisheries since the inception of this study. In 1998 rule changes were implemented requiring attendance of gill nets with mesh of 5 inches (0.127 m) or less in all nursery areas and also within 200 yards of any shoreline from May 1 through October 31 (Paramore et al. 2001). These regulations likely resulted in increases in mesh size. Hook and line fishers have gradually switched from using J hooks to circle hooks, which have a lower mortality rate associated with their use (Aguilar 2003).

Our results indicate that hook and line caught and released red drum tended to be smaller compared to those killed, which is likely the result of anglers only keeping fish in the legal slot limit. The length distributions we observed support the assumptions for the DELTA and PROP models (see description below) used in the 2000 stock assessment. Gillnet fishers catch a relatively large number of red drum smaller than the slot limit, some of which are likely dead discards (Figure 11c). For example, Buckel et al. (2006) found that 33% of all red drum caught in gill nets were dead when the nets were retrieved and 10% of these fish were smaller than the slot limit.

The selectivity results presented here from a generalized linear model approach complement those estimated for all gears combined from a mark-recapture model by Bacheler et al. (in prep). Based on data needs from prior assessments, these two independent estimates of selectivity along with our information on the size distribution of live discards should substantially improve future stock assessments for red drum in at least two different ways. First, the post-1998 selectivity patterns for red drum can be used to calibrate the SVPA models. Secondly, length- or age-frequency data of live discards are essential in accurately partitioning numbers of discards into size or age bins for size or age-based assessment models.

In the most recent stock assessment on red drum in North Carolina, Vaughan and Carmichael (2000) compared two assumptions about red drum selectivity. First they assumed that selectivity was equal for age-2 and -3 fish for both the recreational and commercial. Second, through examination of the size distribution of red drum relative to the slot limit they estimated selectivity of age-3 fish legally available relative to age-2 fish to be 0.43 in North Carolina. They speculated the second approach was more accurate despite a lack of direct evidence. Our results corroborate the 2nd approach.

Information on length- or age-frequency of live discards of red drum were unavailable for red drum in the last assessment. In lieu of this data, Vaughan and Carmichael (2000) used four models with different sets of assumptions. First they assumed complete survival of all recreational and commercial discards (BASE0). The other three models assumed a 10% discard mortality but differed in how sizes of discarded fish were determined. In the second model, length frequency of discards was assumed to be the same as harvested fish (BASE1). Recreationally and commercially harvested fish sizes are available from MRFSS and NCDMF, respectively. In the third model, estimates of discard size were derived by comparing length frequency of fish harvested recreationally before and after 1991 (DELTA). The final model used a weighted average to proportion the lengths from the BASE1 and DELTA approaches (PROP). The DELTA and PROP models imply a higher frequency of smaller, and hence younger, fish in the discards. Vaughan and Carmichael (2000) speculated that the DELTA and PROP options were the most accurate; however, they were unable to validate this. The lengths of live discards determined in this study corroborate their speculations.

Overdispered data, which may have caused increased variance in our selectivity analyses, can occur in the presence of unaccounted-for heterogeneity. Such heterogeneity may be present in the data if the assumption of independence between individual fish was violated, such as in the presence of schooling behavior. Red drum are frequently observed in schools (Yokel 1966). However, the rate of mixing between schools is unknown. High overdispersion estimates in truncated data used to examine time dependent effects, such as in estimates of pound nets after 1992 (Tables 12-13), may indicated a large number of tag returns from relatively few schools of red drum. Therefore, time dependent selectivity estimates should be viewed with caution.

It is unlikely that assumptions made for selectivity analysis were severely violated. If fishers are less likely to see tags on fish that are released compared to harvested fish, then tag reporting rate may have been lower on red drum outside the slot limit. Also adult red drum, which are primarily caught at night, may have had lower tag reporting rates if fewer tags were seen in low light situations. We have no evidence to suggest reporting rates were influenced by either of these situations; however, future research should be conducted to confirm homogenous reporting rates across size classes. The assumption that tag loss is independent of fish length could have been violated by uneven distribution of tag types between length bins, if tags of different types had different short-term (i.e., <90 days) rates of loss. For example, most internal anchor tags (95%) were placed on red drum less than 600 mm TL. We believe this was not a complicating factor in our analysis because all tag types used in our analysis have high short-term retention rates.

The low tag recovery rate led to low precision in our selectivity analysis. A greater number of recaptures across all length bins and years would have reduced the standard errors. More tag recoveries would also have allowed us to reduce the size of the length bins thus giving us finer detailed information on size selectivity. Also, more tag recoveries would have allowed us to reduce the length of allowable time at large, which would have increased our confidence in the assumption that red drum do not grow out of their length bin before recapture. Finally, if there were more recaptures across years, we could have examined annual or seasonal changes in selectivity.

Tag Loss and Adult Survival

Our estimates of adult survival (≥0.72) are higher than most published estimates on juvenile and adult red drum. Using both a catch curve and tag recovery model, Ross et al. (1995) estimated a combined annual survival rates for juvenile and adult red drum in North Carolina of 6-24%. However, these estimates may be biased low due to adult emigration from bays. Green et al. (1985) estimated annual survival of 400-950 mm red drum at 15% in several bays along the Gulf of Mexico, but did not account for tag loss. Murphy and Taylor (1990) estimated annual survival for red drum age 2-4 on the Gulf Coast (2-13%) and ages 2-6 on Atlantic Coast (24-50%), using a modified Heincke approach. Latour et al. (2001) found annual survival rates for age-1 red drum between 19-23%, and for age-2 red drum 33-39%, but did not estimate survival for adult red drum.

We found that adult red drum survival increased after 1991 management regulations were put into place. Similar responses to management actions were reported by two studies on red drum in Florida. Murphy and Crabtree (2001) used length frequency plots to show that a complete prohibition on red drum harvest in 1987-1988 increased sub-adult survival dramatically. Murphy (2005) observed similar increases in survival for juvenile red drum in Florida after a moratorium on commercial fishing in 1997. Survival rates found in our study in the period before 1991 (0.722-0.723) likely contributed to the declining population during that period. Survival increased with size and bag limits instated in 1991 and 1992, and remained high after more restrictive regulations were put into place in 1997.

Our best model according to AIC suggested no difference in tag retention between steel and nylon dart tags, although model averaged estimates were slightly different. Baglin et al. (1980) also found no detectable differences between tag retention of steel dart and single barbed nylon dart tags on Atlantic bluefin tuna. Our estimates of tag retention are similar to those of other studies on dart tags. Our estimates of type I tag retention (ρ=1.0) match estimates by Latour et al. (2001) for steel dart tags on red drum less than three years old, and McGlennon and Partington (1997) for nylon dart tags used on sparid snapper. Adams and Kirkwood (2000; ρ=0.97) and Baglin et al. (1980; ρ=0.96) also found high rates of type I tag retention. Our estimate of instantaneous annual tag loss ($0.25<L<0.31$) was within the range of previously published estimates for nylon dart tags ($0.02<L<0.69$) and similar to the highest published estimates for steel dart tags

(0.05<*L*<0.29; Baglin et al. 1980; Hearn et al. 1991; McGlennon and Partington 1997; Adam and Kirkwood 2000; Latour et al. 2001).

Rapid tag loss may have resulted from tag type and construction, inexperienced taggers, or red drum rubbing tags off on reefs or other structure. Several researchers have noticed that the construction of the streamer may cause tags with similar anchor mechanisms to have different tag loss rates (Prince et al. 2002; Lee Paramore, NCDMF, personal communication). We assumed that tags had equal retention rates regardless of streamer core construction. Prior to 1999, the streamer sleeves were held in place with shrink-wrap plastic. After several tags were returned with only a monofilament streamer core and no external sleeve containing the tag number and other vital information, a change was made to a tag having a wire core in hopes of correcting this problem. Since the modification, no tags have been returned without their sleeves. Tags used in the SCDNR double tagging data study had wire cores. If wire core tags are more durable than monofilament core tags, tag loss and survival estimates before 1999 may be negatively biased.

Tagging technique and experience of taggers (tagger skill) may have an effect on tag retention. Prince et al. (2002) noticed substantial differences in the retention rates of dart tags applied by different volunteer taggers on four large pelagic species (blue marlin *Makaira mazara*, white marlin *Tetrapturus albidus,* swordfish *Tetrapturus audax*, sailfish *Istiophorus platypterus*). Hearn et al. (1991) found no tagger effect on tag loss in two out of three regions they examined and only a slight tagger effect in the third region. In a tag retention study on three species of tuna, Hampton (1997) detected no significant effects of individual volunteer taggers on retention rates of single barbed Hallprint ® nylon dart tags. Tag returns in our study were too sparse and too widely distributed to adequately assess the effect of tagger skill on retention. However, the wide range of experience among taggers in our North Carolina volunteer tagging program is cause for concern. In the future, efforts should be made to reduce the variance between tagging methods and skill. This may be accomplished by providing standardized training to all taggers.

Recommendations

North Carolina's red drum mark-recapture program provides valuable long-term data and should be continued. However, modifications to the study design should be made to meet future research objectives. Movement analyses were limited by the precision of both tagging and recapture locations and could be improved if GPS coordinates were collected for each tagging event.

Multiple fates of recaptured red drum and their tags caused complications in estimating survival. In theory, red drum released with the tag intact could be used in open capture-recapture models to estimate abundance (Pine et al. 2003). In practice, however, we believe it is not feasible to mark or recapture enough adult red drum to meet the data requirements for estimating abundance. Therefore, we suggest modifying the study design to improve estimates of mortality by encouraging all tags to be cut off of recaptured fish. To accomplish this, the text "CUT OFF TAG" or "REWARD FOR TAG" could be added to all tags. Also, because few adult red drum were recaptured, we resorted to using the Smith et al. (2000) equation to adjust for fish released after removing the tag. A preferred method is to separately model the declines in tags and tagged fish (Jiang et al. 2006). When some fish are caught and released but the tags are clipped, it results in a higher fishing mortality rate for the cohort of tags than for the cohort of tagged fish. This approach was not possible in our case because of the limited number of tags returned.

Currently, there are no estimates of tag reporting available for adult red drum in North Carolina. Reporting rate can be used to estimate fishing and natural mortality and to adjust mortality estimates for catch and release activity when data are sparse (Pollock et al. 1991; Smith et al. 2000). Reporting rate for red drum could be estimated using a high-reward method, angler surveys, or observers (Pollock et al. 2001). End of the season lotteries could be discontinued to make funding available for a high-reward study.

A low rate of tag recovery was a limiting factor in this study. The double-tagging data obtained from the SCDNR were likely adequate for estimating tag loss rates for the steel and nylon dart tags used in our study. The red drum tagged by SCDNR were similar in size and life stage and were tagged using similar methods to the fish in our study. However, a double-tagging study in North Carolina would greatly improve our analysis by offering region-specific estimates. A greater number of tag returns could be achieved by increasing advertising, using tags with higher retention rates, and increasing the number of tagged fish.

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Table 1.- Regulation periods used in comparative analysis.

Period	Year of regulation change	Regulation Change
	1976	First regulations instated. Minimum size limit of 356 mm TL. Two fish recreational bag limit on red drum > 812 mm TL
1983-1991	1990	Bag limit on red drum > 812 mm TL decreased to one fish. A five fish bag limit was instated on red drum 356-812 mm TL. 300,000 lb commercial cap put into place.
	1991	Minimum size limit increased to 457 mm TL.
1992-1997	1992	The five fish bag limit was applied to fish 457-685 mm TL. Sale of red drum > 685 mm TL was prohibited. Commercial cap reduced to 250,000 lb.
1998-2004	1998	Bag limit on red drum 457-685 mm TL was reduced to one fish. Possession of red drum > 685 mm TL made illegal.

Table 2. – Age-length key for red drum in North Carolina, for fish collected in 1987-2004.

January - June		June - December	
Age	Total Length mm	Age	Total Length mm
1	0-253	1	0-507
2	254-558	2	508-710
3	559-761	3	711-812
4+	>761	4+	>812

Table 3.- Number of red drum measured and tagged by year and size class (Juveniles <457 mm TL, Sub-Adults - 457-685 mm TL, and Adults >685 mm TL).

	Size Class			
Year	Juvenile	Sub-adult	Adult	Total
1983	68	7	17	92
1984	14	52	238	304
1985	35	22	242	299
1986	1609	113	161	1883
1987	450	50	239	739
1988	729	100	364	1193
1989	291	117	612	1020
1990	122	135	612	869
1991	2179	288	596	3063
1992	1165	344	479	1988
1993	1334	780	663	2778
1994	4344	280	1049	5673
1995	499	349	714	1562
1996	287	128	734	1149
1997	2048	147	778	2973
1998	2366	673	781	3820
1999	1718	445	1193	3356
2000	986	635	1310	2931
2001	396	380	1071	1847
2002	191	98	1177	1466
2003	107	249	981	1337
2004	267	37	1207	1511
Total	21205	5429	15218	41852

Table 4.- Gears used to collect red drum for tagging, and the number of fish measured and tagged in each size class (Juveniles <457 mm TL, Sub-Adults 457-685 mm TL, and Adults >685 mm TL).

	Size Class			
Gear Type	Juvenile	Sub-adult	Adult	Total
Crab pot	5	1	0	6
Pound net	8810	711	18	9539
Fyke net	1	0	0	1
Drop net	104	5	1	110
Gill net	6685	1521	293	8501
Trammel net	2447	258	25	2730
Seines	207	122	52	381
Cast net	4	0	0	4
Hook and line	2872	2681	14785	20339
Trawl	8	12	37	57
Electric shocker	61	114	4	179
Unrecorded	0	4	3	7
Total	21205	5429	15218	41852

Table 5. – Number of fish measured and tagged with each tag type, in each of three size classes (Juveniles <457 mm TL, Sub-Adults 457-685 mm TL, and Adults >685 mm TL).

	Size Class			
Tag Type	Juvenile	Sub-adult	Adult	Total
FT-1 dart tag	1543	931	517	2992
FT-2 dart tag	45	1	0	46
FT-4 clinch up tag	1237	25	1	1263
FM-66 dart tag	0	0	4	4
FTSL-73 shrimp tag	2	10	4	16
Internal anchor tag / monofilament core	13758	1926	335	16019
FH-69 stainless steel dart tag	93	798	8428	9320
Conical prince plastic dart tag 170mm	0	0	4	4
Big head internal anchor tag 26 mm	1958	175	105	2238
Stainless steel dart tag / wire core	1	235	5688	5924
Internal anchor tag /wire core	2510	1318	118	3946
Unrecorded	58	10	14	82
Total	21205	5429	15218	41852

Table 6.- Number of red drum measured and tagged by area and size class (Juveniles <457 mm TL, Sub-Adults 457-685 mm TL, and Adults >685 mm TL).

Area	Juveniles	Sub-Adults	Adults	Total
Estuary				
Chesapeake Bay and Virginia	3	16	56	75
Albermarle Sound	390	54	2	446
Roanoke and Croatan Sounds	4167	697	45	4909
East Pamlico Sound	2539	852	450	3841
West Pamlico Sound	10768	1071	2991	14830
Sounds South of Cape Lookout	2022	898	160	3080
Estuary Total	19887	3586	3655	27128
Ocean				
North of Cape Hatteras	535	303	1410	2248
Cape Point to Hatteras Inlet	162	187	1433	1782
Ocracoke Inlet	59	813	7931	8803
Core Banks	270	142	409	821
South of Cape Lookout	290	396	331	1017
Ocean Total	1318	1843	11563	14724
Grand Total	21205	5429	15218	41852

Table 7. – Number of red drum recaptured by area and size class (Juveniles <457 mm TL, Sub-Adults 457-685 mm TL, and Adults >685 mm TL).

Estuary	Juveniles	Sub-Adults	Adults	Size Unknown	Total
Chesapeake Bay and Virginia	0	2	7	2	13
Albermarle Sound	25	27	5	18	75
Roanoke and Croatan Sounds	109	64	4	44	221
East Pamlico Sound	83	164	31	82	360
West Pamlico Sound	1262	399	119	801	2581
Sounds South of Cape Lookout	130	152	32	78	392
Estuary Total	1609	807	195	1025	3636
Ocean					
North of Cape Hatteras	41	114	28	11	194
Cape Point to Hatteras Inlet	21	67	55	17	160
Ocracoke Inlet	31	95	131	58	315
Core Banks	4	7	7	7	25
South of Cape Lookout	58	99	38	15	210
Ocean Total	155	383	262	108	908
Location Unknown	79	137	28	26	270
Grand Total	1843	1327	485	1159	4814

Table 8.- Number of recaptures by area for red drum tagged and recovered as juveniles. A total of 13 red drum measured as juveniles at the time of recapture were measured as sub-adult fish at the time of tagging. These fish are not included in this table.

Tagging Area	Recapture Area											
	Estuary						Ocean					
Estuary	Chesapeake Bay and Virginia	Albermarle Sound	Roanoke and Croatan Sounds	East Pamlico Sound	West Pamlico Sound	Sounds South of Cape Lookout	North of Cape Hatteras	Cape Point to Hatteras Inlet	Ocracoke Inlet	Core Banks	South of Cape Lookout	Unknown
Chesapeake Bay and Virginia	0	0	0	0	0	0	0	0	0	0	0	0
Albermarle Sound	0	4	3	0	1	0	0	0	0	0	0	0
Roanoke and Croatan Sounds	0	17	100	12	16	2	15	3	5	0	3	0
East Pamlico Sound	0	1	3	59	15	9	5	9	10	3	7	0
West Pamlico Sound	0	2	2	8	1221	26	9	3	8	1	6	2
Sounds South of Cape Lookout	0	0	0	0	1	74	0	0	1	0	22	76
Ocean												
North of Cape Hatteras	0	1	0	3	2	1	11	2	1	0	1	0
Cape Point to Hatteras Inlet	0	0	0	0	0	2	0	4	1	0	0	0
Ocracoke Inlet	0	0	0	0	1	1	0	0	1	0	0	0
Core Banks	0	0	0	0	0	6	0	0	3	0	7	0
South of Cape Lookout	0	0	0	0	0	7	0	0	0	0	10	1

Table 9. - Number of recaptures by area for red drum tagged and recovered as sub-adults. Of the 1327 red drum recovered as sub-adults, 832 were tagged as juveniles. Three red drum were measured as adults during tagging and as sub-adults when recaptured. These fish are not included in this table.

Tagging Area	Recapture Area											
	Estuary						Ocean					
Estuary	Chesapeake Bay and Virginia	Albermarle Sound	Roanoke and Croatan Sounds	East Pamlico Sound	West Pamlico Sound	Sounds South of Cape Lookout	North of Cape Hatteras	Cape Point to Hatteras Inlet	Ocracoke Inlet	Core Banks	South of Cape Lookout	Unknown
Chesapeake Bay and Virginia	1	0	0	0	0	0	0	0	0	0	0	0
Albermarle Sound	0	0	0	0	0	0	1	2	1	0	0	0
Roanoke and Croatan Sounds	0	6	15	13	6	1	15	6	2	0	0	1
East Pamlico Sound	0	0	3	29	5	0	9	5	4	0	1	1
West Pamlico Sound	0	1	0	8	96	6	6	0	10	0	3	0
Sounds South of Cape Lookout	0	0	0	0	0	36	0	0	14	0	15	51
Ocean												
North of Cape Hatteras	0	0	0	4	3	2	5	5	2	0	2	0
Cape Point to Hatteras Inlet	0	0	0	1	0	3	4	6	0	0	0	0
Ocracoke Inlet	0	0	0	3	3	4	0	2	16	2	2	2
Core Banks	0	0	0	0	0	3	0	0	2	1	0	0
South of Cape Lookout	0	0	0	0	0	13	0	0	1	0	35	3

Table 10. – Number of recaptures by area for red drum tagged and recovered as adults. Of the 485 red drum recovered as adults, 84 were tagged as juveniles and 116 were tagged as sub-adults. These fish are not included in this table.

Tagging Area	Recapture Area											
	Estuary						Ocean					
Estuary	Chesapeake Bay and Virginia	Albermarle Sound	Roanoke and Croatan Sounds	East Pamlico Sound	West Pamlico Sound	Sounds South of Cape Lookout	North of Cape Hatteras	Cape Point to Hatteras Inlet	Ocracoke Inlet	Core Banks	South of Cape Lookout	Unknown
Chesapeake Bay and Virginia	0	0	0	0	0	0	0	0	0	0	0	0
Albermarle Sound	0	1	0	0	0	0	0	0	0	0	0	0
Roanoke and Croatan Sounds	0	0	1	1	0	0	0	0	0	0	0	0
East Pamlico Sound	0	0	0	6	2	0	2	3	5	0	0	0
West Pamlico Sound	0	0	0	1	36	1	3	2	5	0	0	0
Sounds South of Cape Lookout	0	0	0	0	0	4	0	0	4	0	3	0
Ocean												0
North of Cape Hatteras	4	0	0	2	3	0	6	4	1	0	0	0
Cape Point to Hatteras Inlet	0	0	0	1	6	0	0	3	4	0	0	0
Ocracoke Inlet	1	0	0	8	40	3	4	13	78	4	1	0
Core Banks	0	0	0	0	2	0	0	1	2	2	0	0
South of Cape Lookout	0	0	0	0	0	3	0	0	0	0	9	0

Table 11. – Number of experiments (tag types) resulting from one of four selection criteria in selectivity analysis. Criteria were, i) at least one tag return per experiment, ii) at least ten returns per experiment, iii) at least 100 returns per experiment, and iv) at least one tag return in at least 50% of the length bins per experiment.

	Gear Type		
Selection Criteria	hook and line	gill nets	pound nets
i	8	7	8
ii	7	6	5
iii	3	2	2
iv	5	5	3

Table 12.- Dispersion estimates for length-based selectivity. Estimates (deviance/degrees of freedom) greater than one indicate overdispersed data, and less than one indicates underdispersed data.

	Hook and Line	Gill Net	Pound Nets
Overall	1.92	5.52	5.92
1983-1991	0.86	3.05	4.85
1992-2004	2.06	2.01	14.54
1983-1997	1.26	7.51	7.76
1998-2004	0.64	0.81	-
Released Alive	1.16	-	-
Harvested	1.04	1.87	0.56

Table 13.- Dispersion estimates for age-based selectivity. Estimates (deviance/degrees of freedom) greater than one indicate overdispersed data, and less than one indicates underdispersed data.

	Hook and Line	Gill Net	Pound Nets
Overall	2.61	3.54	1.65
1983-1991	0.91	2.83	0.53
1992-2004	2.79	2.92	13.54
1983-1997	2.69	2.59	2.32
1998-2004	1.58	0.40	-
Released Alive	1.37	0.54	2.18
Harvested	1.65	1.28	0.50

Table 14. – AIC values for length-based selectivity models from best to worst fit for each of three gear types. Models had either two parameters for time period before and after regulation changes (Table 1), or no time period parameters. The log likelihood, number of parameters (K), and delta AIC are also given.

Gear	Time Periods Used in Model	Log Likelihood	K	AIC	Delta AIC
Hook and Line	1983-1991 and 1992-2004	-4821.92	15	9673.84	0
	1983-1997 and 1998-2004	-4831.23	15	9692.46	18.62
	1983-2004	-4848.54	13	9723.07	49.23
Gill Nets	1983-1991 and 1992-2004	-3350.11	14	6728.23	0
	1983-1997 and 1998-2004	-3431.63	14	6891.26	163.04
	1983-2004	-3453.28	12	6930.56	202.33
Pound Nets	1983-1991 and 1992-2004	-4072.83	15	8175.65	263.68
	1983-2004	-4087.93	13	8201.87	289.89

Table 15. - AIC values for age-based selectivity models from best to worst fit for each of three gear types. Models had either two parameters for time period before and after regulation changes (Table 1), or no time period parameters. The log likelihood, number of parameters (K), and delta AIC are also given.

Gear	Time Periods Used in Model	Log Likelihood	K	AIC	Delta AIC
Hook and Line	1983-1991 and 1992-2004	-4760.76	22	9565.53	0
	1983-1997 and 1998-2004	-4765.86	22	9575.72	10.19
	1983-2004	-4781.58	20	9603.16	37.64
Gill Nets	1983-1991 and 1992-2004	-3279.27	15	6588.54	0
	1983-1997 and 1998-2004	-3353.31	15	6736.63	148.08
	1983-2004	-3375.4	13	6776.8	188.26
Pound Nets	1983-2004	-4225.5	14	8479.01	403.94
	1983-1991 and 1992-2004	-4224.52	16	8481.04	405.98

Table 16.- Length-based selectivity estimates and standard errors for red drum caught by hook and line, gill nets, and pound nets 1983-2004. Red drum greater than 600 mm TL were combined into one length bin in gill and pound net analysis.

		Before and After 1991 Comparison				Before and After 1998 Comparison			
		1983-1991		1991-2004		1983-1997		1998-2004	
Gear	Length	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Hook and line	<300	0.65	0.18	0.52	0.09	0.74	0.12	0.11	0.04
	300-399	0.76	0.14	0.55	0.08	0.75	0.10	0.11	0.03
	400-499	0.72	0.07	0.40	0.06	0.60	0.08	0.12	0.03
	500-599	1.00	0.07	1.00	0.00	1.00	0.16	0.64	0.18
	600-699	0.68	0.12	0.90	0.16	0.71	0.12	1.00	0.00
	700-799	0.20	0.06	0.37	0.12	0.27	0.07	0.52	0.27
	800-899	0.10	0.04	0.12	0.09	0.10	0.05	0.35	0.29
	900-999	0.02	0.02	0.04	0.05	0.01	0.02	0.12	0.14
	1000-1099	0.01	0.02	0.02	0.03	0.02	0.01	0.00	0.08
	1100-1199	0.05	0.02	0.07	0.03	0.06	0.02	0.12	0.08
	1200 +	0.05	0.03	0.12	0.07	0.06	0.03	0.29	0.20
Gill Nets	<300	0.44	0.07	0.41	0.13	0.38	0.07	0.44	0.27
	300-399	1.00	0.04	0.76	0.20	0.93	0.08	0.92	0.46
	400-499	0.82	0.11	0.95	0.25	1.00	0.00	0.75	0.38
	500-599	0.54	0.14	1.00	0.00	0.78	0.16	1.00	0.00
	600+	0.42	0.13	0.47	0.18	0.46	0.10	0.94	0.74
Pound Nets	<300	1.00	0.07	0.25	0.03				
	300-399	0.93	0.12	1.00	0.00				
	400-499	0.36	0.07	0.23	0.03				
	500-599	0.09	0.10	0.25	0.07				
	600+	0.21	0.06	0.04	0.03				

Table 17.- Age-based selectivity estimates and standard errors for red drum caught by hook and line, gill nets, and pound nets before and after the 1991 and 1997 regulation changes.

		Before and After 1991 Comparison				Before and After 1998 Comparison			
		1983-1991		1991-2004		1983-1997		1998-2004	
Gear	Age	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Hook and line	1	0.98	0.14	1.00	0.00	0.92	0.09	0.70	0.14
	2	1.00	0.00	0.84	0.08	1.00	0.00	1.00	0.00
	3	0.46	0.11	0.48	0.14	0.50	0.10	0.62	0.34
	4+	0.07	0.02	0.07	0.02	0.07	0.01	0.15	0.06
Gill Nets	1	0.89	0.22	0.93	0.12	1.00	0.00	0.25	0.08
	2	0.56	0.16	1.00	0.00	0.71	0.10	1.00	0.00
	3	1.00	0.00	0.24	0.19	0.92	0.22	0.00	0.04
	4+	0.05	0.04	0.03	0.04	0.05	0.03	0.00	0.04
Pound Nets	1	1.00	0.00	1.00	0.00				
	2	0.07	0.10	0.13	0.02				
	3	0.00	0.05	0.04	0.05				
	4+	0.02	0.04	0.01	0.01				

Table 18.- The number of adult red drum (>685 mm TL) tagged with each tag type and the fate of these fish at time of recapture. Only fish with steel or nylon dart tags and fate codes 3, 4, or 6 were used in survival analysis. Tags that have monofilament streamer cores are indicated by with the code mc, where as tags that have wire streamer cores are indicated with the code wc.

Tag Type	Number of fish released	Returned to water with tag (code 2)	Fish re-released with tag and then re-caught at a later date (code 2*)	Not returned to water (code 3)	Retagged and returned to water - without old tag (code 4)	Retagged and returned to water - with old tag (code 4*)	Fish double tagged and then re-released (code 5)	Fish re-released without tag (code 6)	Fish re-released with partial tag (code 7)	Total recaptured
FT-1 Dart	517	0	0	9	1	0	0	0	0	10
Stainless Steel Dart mc	335	49	2	104	36	1	8	33	0	233
Stainless Steel Dart wc	5688	37	0	3	11	0	0	14	0	65
Internal Anchor mc	335	1	0	9	1	0	0	0	0	11
Big Head Internal Anchor	105	1	0	3	0	0	0	0	0	4
Internal Anchor wc	118	3	0	5	0	0	0	0	1	9
Total	7098	91	2	133	50	1	8	47	1	332

Table 19.- Fate of recaptured adult red drum (>685 mm TL) tagged with steel or nylon dart tags by year. Only fish with fate codes 3, 4, or 6 were used in survival analysis.

Year of tag return	Returned to water with tag (code 2)	Fish re-released with tag and then re-caught at a later date (code 2*)	Not returned to water (code 3)	Retagged and returned to water - without old tag (code 4)	Retagged and returned to water - with old tag (code 4*)	Fish double tagged and then re-released (code 5)	Fish re-released without tag (code 6)	Total
1983	0	0	0	0	0	0	0	0
1984	0	0	2	0	0	0	0	2
1985	0	0	0	0	0	0	0	0
1986	0	0	2	0	0	0	0	2
1987	0	0	5	0	0	0	0	5
1988	3	0	3	0	0	0	0	6
1989	1	0	15	0	0	0	0	16
1990	0	1	14	0	0	0	1	16
1991	0	0	9	0	1	1	0	11
1992	0	0	5	1	0	0	1	7
1993	0	0	7	2	0	0	0	9
1994	3	1	10	0	0	2	3	19
1995	2	0	19	0	0	5	1	27
1996	4	0	4	0	0	0	2	10
1997	5	0	6	0	0	0	1	12
1998	9	0	6	10	0	0	1	26
1999	10	0	2	12	0	0	3	27
2000	16	0	1	6	0	0	11	34
2001	13	0	2	7	0	0	9	31
2002	13	0	2	5	0	0	11	31
2003	7	0	2	5	0	0	3	17
Total	86	2	116	49	0	8	47	308

Table 20.- AIC values for 20 models from best to worst fit. Subscript *y* indicates individual parameters were estimated for each year. Subscript *p* indicates three parameters were estimated, one for each period (Table 1). When the parameter for immediate tag retention (rho) or long-term instantaneous tag loss rate (L) is subscripted with an *i* separate parameters were estimated for stainless steel (mono and wire core) and FT-1 nylon dart tags (Table 16). A dot indicates only one parameter was estimated. In model seven survival was estimated for two time periods (1983-1991 and 1992-2002). In model twelve survival was also estimated for two time periods (1983-1997 and 1998-2002). The subscript in these models indicates the year that separates the two time periods. The total numbers of parameters for each model (K), degrees of freedom (NDF), log likelihood values, model weights (w_i), and delta AIC are also given.

Model	Model Number	K	Log-likelihood	NDF	AIC	Delta AIC	w_i
$S_p f_y L_. \rho_.$	1	26	-234.2	625	520.4	0.0	0.587
$S_p f_y L_i \rho_i$	2	28	-232.9	623	521.9	1.5	0.282
$S_p f_p L_i \rho_i$	3	10	-252.0	641	524.0	3.6	0.096
$S_{91} f_. L_. \rho_.$	4	5	-259.5	646	529.1	8.7	0.008
$S_. f_y L_. \rho_.$	5	24	-240.8	627	529.6	9.2	0.006
$S_. f_. L_. \rho_.$	6	4	-260.9	647	529.9	9.5	0.005
$S_. f_p L_i \rho_i$	7	8	-257.0	643	530.0	9.6	0.005
$S_. f_y L_i \rho_i$	8	26	-239.3	625	530.6	10.2	0.004
$S_p f_. L_. \rho_.$	9	6	-259.5	645	531.0	10.6	0.003
$S_. f_. L_i \rho_i$	10	6	-259.9	645	531.7	11.3	0.002
$S_{97} f_. L_. \rho_.$	11	5	-260.9	646	531.8	11.4	0.002
$S_p f_. L_i \rho_i$	12	8	-258.6	643	533.2	12.8	0.001
$S_y f_y L_. \rho_.$	13	43	-226.4	608	538.8	18.4	0.000
$S_y f_p L_. \rho_.$	14	25	-244.5	626	538.9	18.5	0.000
$S_y f_y L_i \rho_{i.} (FULL)$	15	45	-225.0	606	540.0	19.6	0.000
$S_y f_p L_i \rho_i$	16	27	-245.1	624	544.3	23.9	0.000
$S_y f_. L_. \rho_.$	17	23	-249.6	628	545.3	24.9	0.000
$S_y f_. L_i \rho_i$	18	25	-248.8	626	547.6	27.2	0.000
$S_p f_p L_. \rho_.$	19	8	-655.3	643	1326.7	806.3	0.000
$S_. f_p L_. \rho_.$	20	6	-660.5	645	1333.0	812.6	0.000

Table 21.- Unadjusted model averaged annual adult survival rate estimates and average estimates of tag recovery rate for each regulation period.

Regulation Period	Annual Survival	Survival Standard Error	Tag Recovery Rate	Tag Recovery Standard Error
1983-1991	0.722	0.086	0.002	0.364
1992-1997	1.000	0.095	0.001	0.411
1998-2002	1.000	0.122	0.001	0.504

Table 22.- Model averaged annual adult survival rate estimates for three regulation periods, adjusted for catch-and-release using the Smith et al. (2000) adjustment and a range of reporting rates. Reporting rates for juvenile red drum from the literature are marked with an *.

Reporting Rates	Regulation Periods		
	1983-1991	1992-1997	1997-2003
0.20	0.72	1.00	1.00
*0.25	0.72	1.00	1.00
0.30	0.72	1.00	1.00
0.40	0.72	1.00	1.00
0.50	0.72	1.00	1.00
*0.57	0.72	1.00	1.00
*0.60	0.72	1.00	1.00
*0.63	0.72	1.00	1.00
0.70	0.72	1.00	1.00
*0.80	0.72	1.00	1.00
0.90	0.72	1.00	1.00
*1.00	0.72	1.00	1.00

Table 23. – Estimated portion of tags retained each year at large after release for both steel and nylon dart tags. Model averaged estimates of *L* for steel (*L*=0.253) and nylon dart tags (*L*=0.312) were used for estimates.

Years	Steel Dart Tags	Nylon Dart Tags
1	0.78	0.73
2	0.60	0.54
3	0.47	0.39
4	0.36	0.29
5	0.28	0.21
6	0.22	0.15
7	0.17	0.11
8	0.13	0.08
9	0.10	0.06
10	0.08	0.04
11	0.06	0.03
12	0.05	0.02
13	0.04	0.02
14	0.03	0.01
15	0.02	0.01

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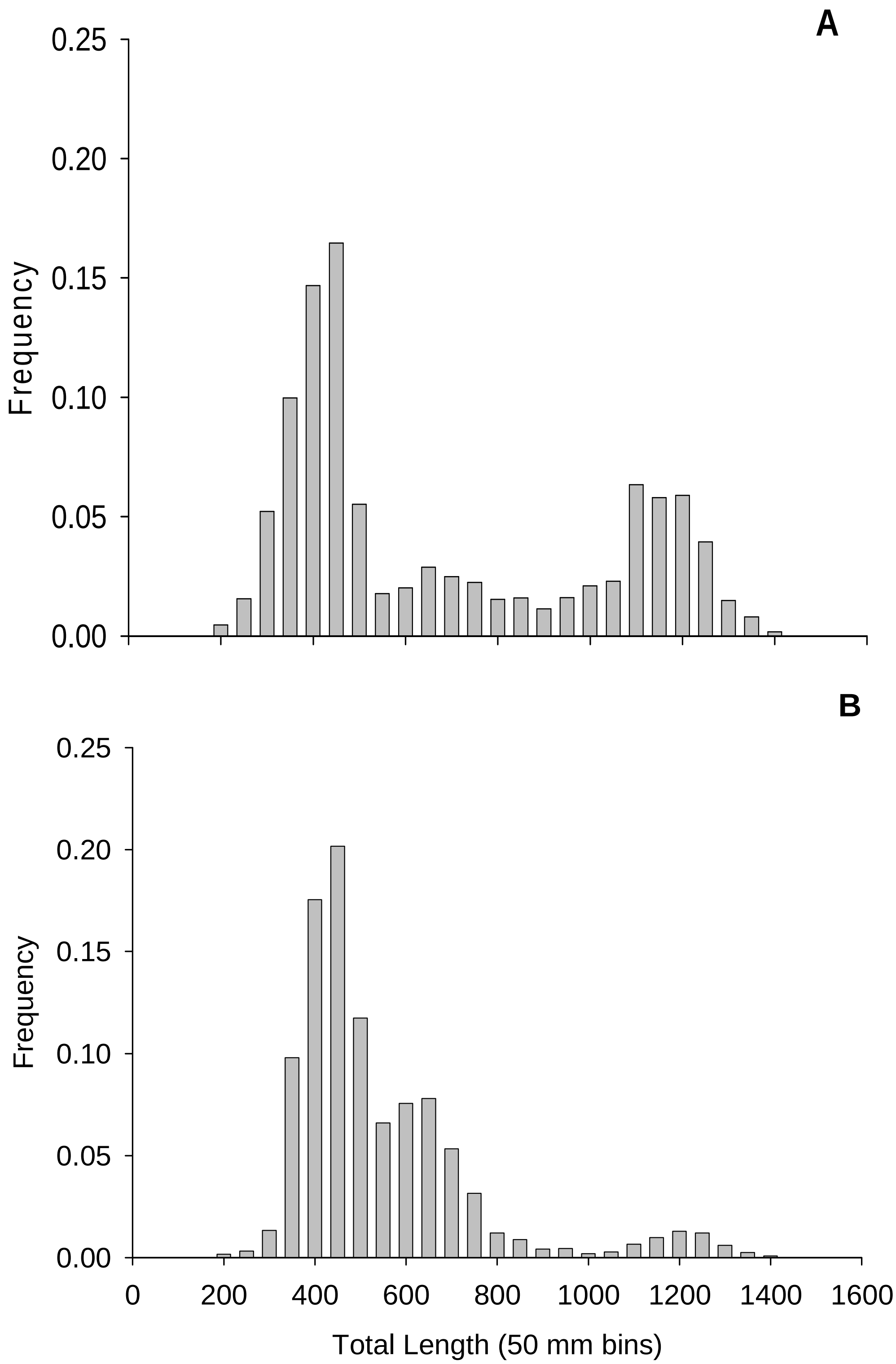

Figure 1.- Percent frequency of A) tagged and B) recaptured red drum, by length, for years 1983-2003.

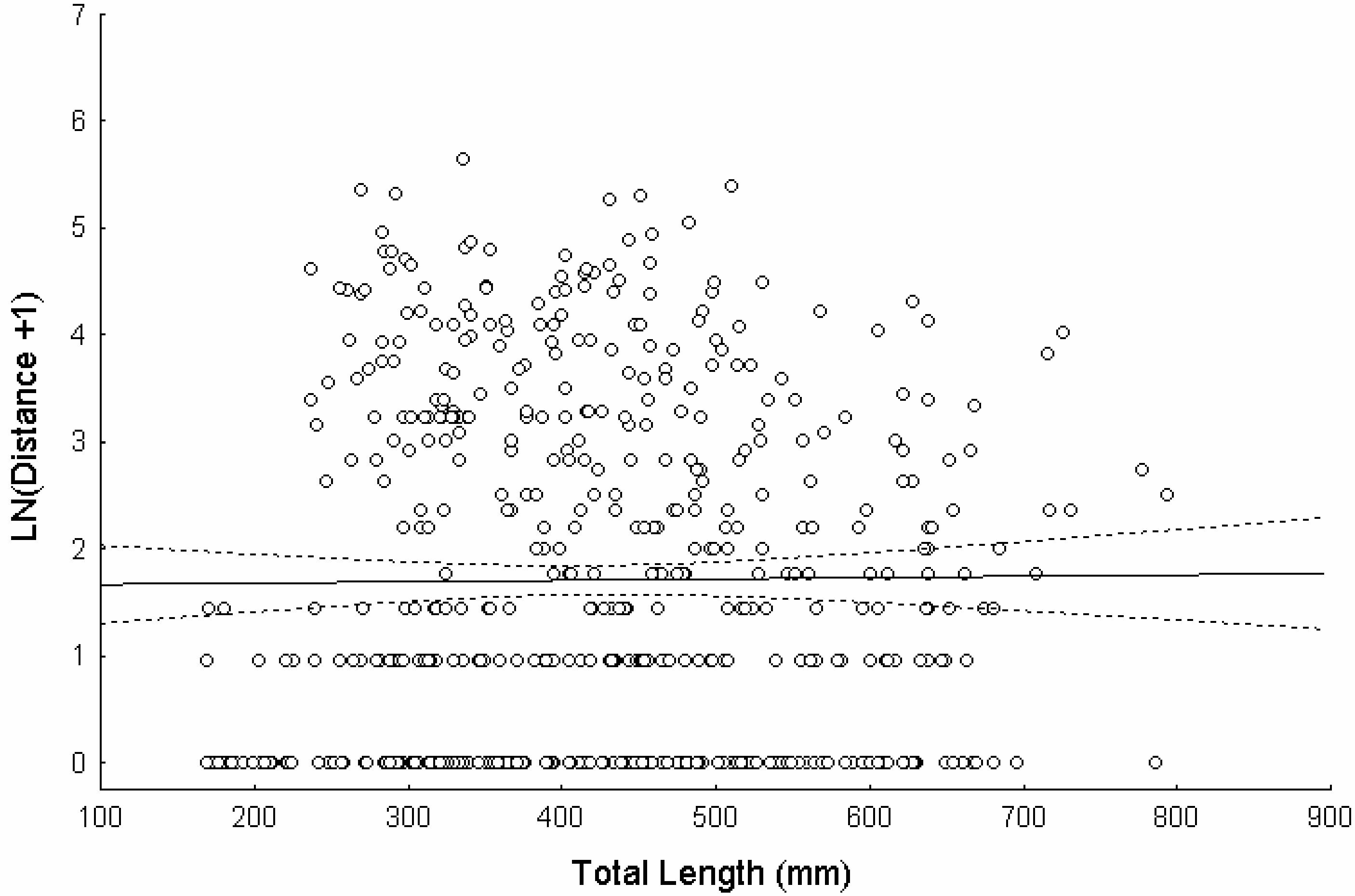

Figure 2.- Regression line (solid) and 95% confidence intervals (dotted) for linear regression of natural log transformed distance of travel (for red drum recaptured within 90 days) versus total length. There was no significant effect of length on the distance traveled (p=0.81).

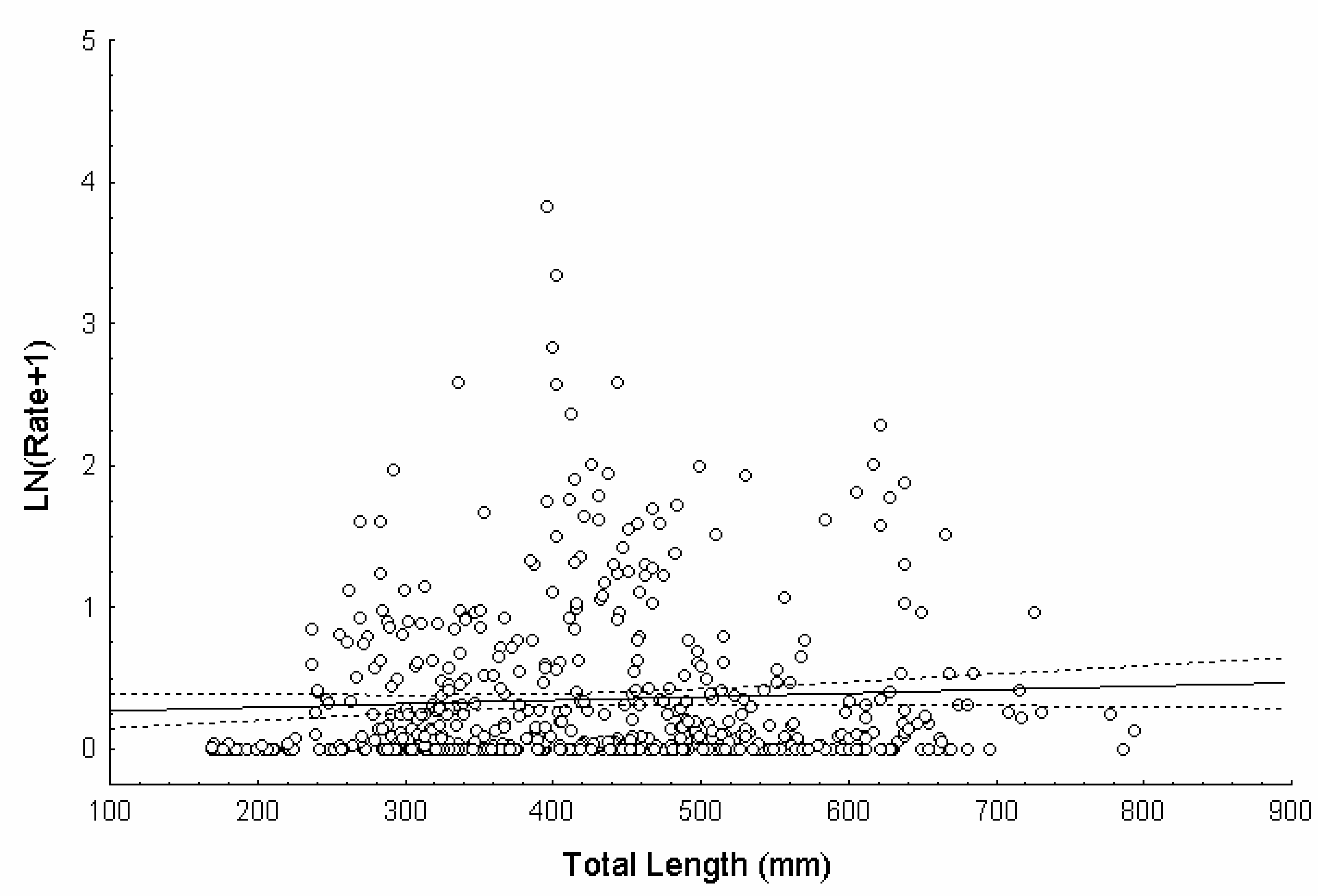

Figure 3.- Regression line (solid) and 95% confidence intervals (dotted) for linear regression of natural log transformed rate of travel (for red drum recaptured within 90 days) versus total length. There was no significant effect of length on the rate of travel (p=0.81).

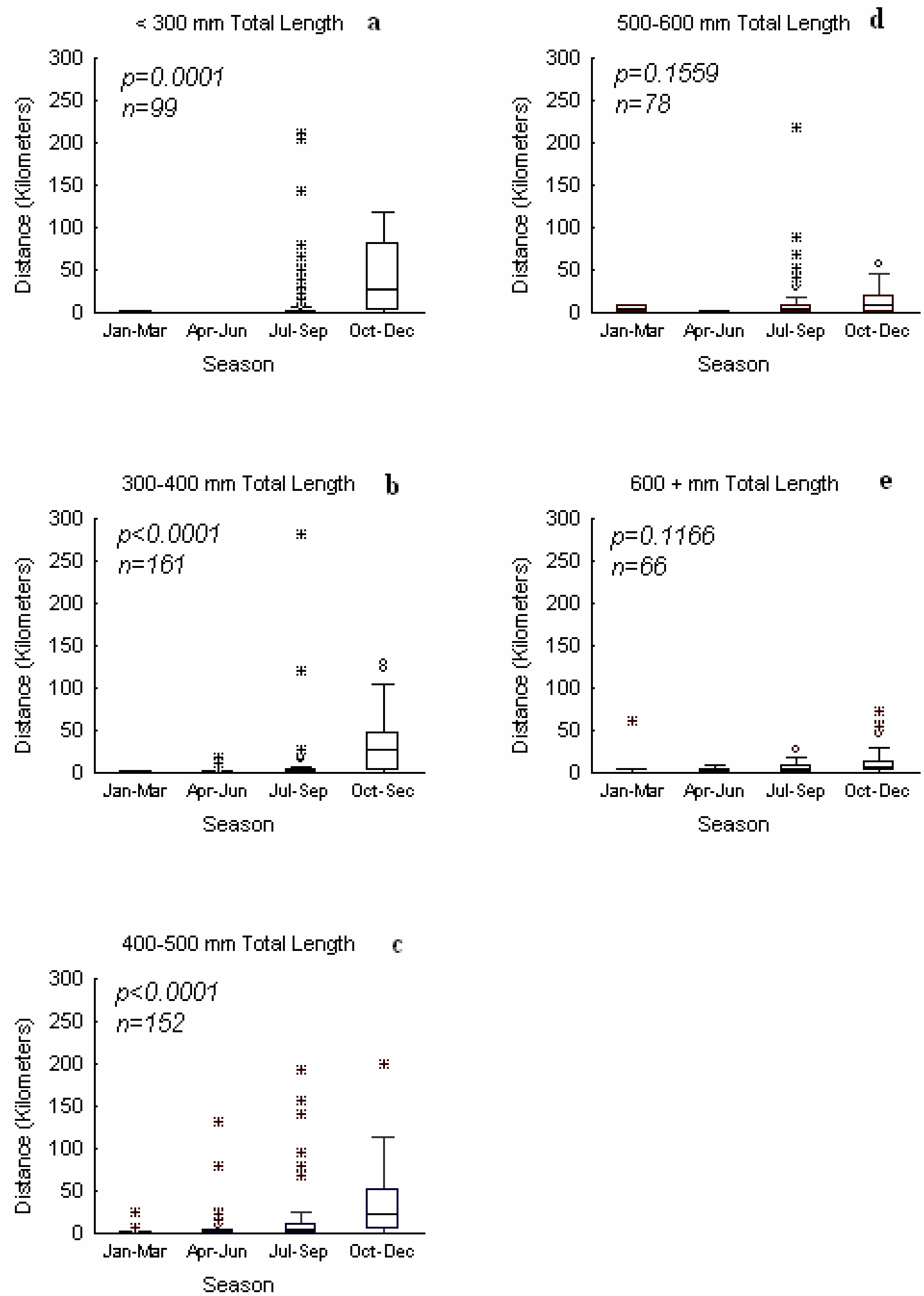

Figure 4. – Distance traveled by size and season for red drum at large less than 90 days. Season was determined by the mid-point in the fish's travel. Boxes show 25th, 50th and 75th percentiles, and error bars show 10th and 90th percentiles. Circles indicate outliers and asterisks indicate extreme outliers (>95th percentile). P-values are from Kruskal-Wallis test for differences in distances of movement between seasons.

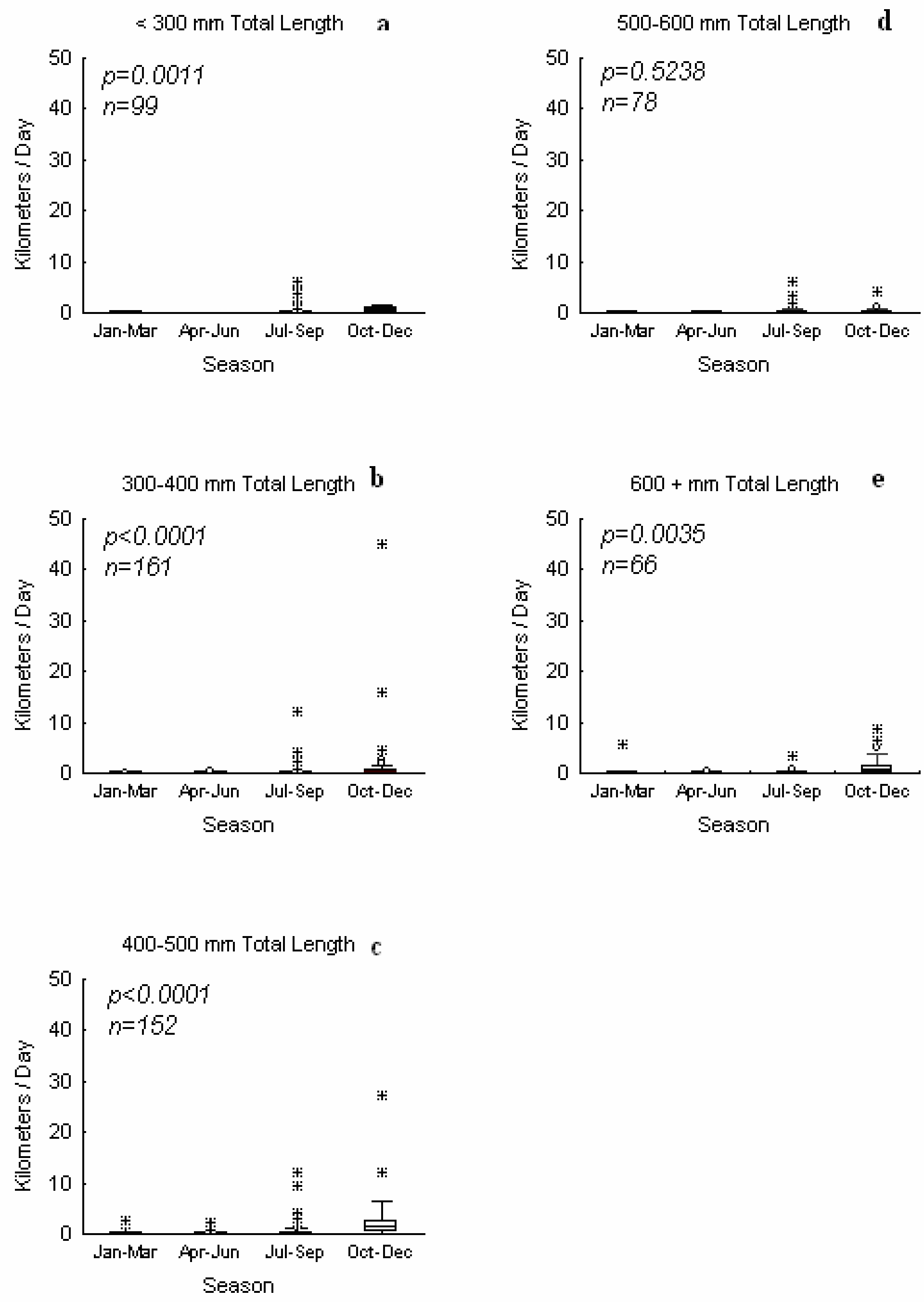

Figure 5. – Rate of travel by size and season, for red drum at large less than 90 days. Season was determined by the mid-point in the fish's travel. Boxes show 25th, 50th and 75th percentiles, error bars show 10th and 90th percentiles. Circles indicated outliers, and asterisks indicate extreme outliers (>95th percentile). P-values are from Kruskal-Wallis test for differences in rate of movement between seasons.

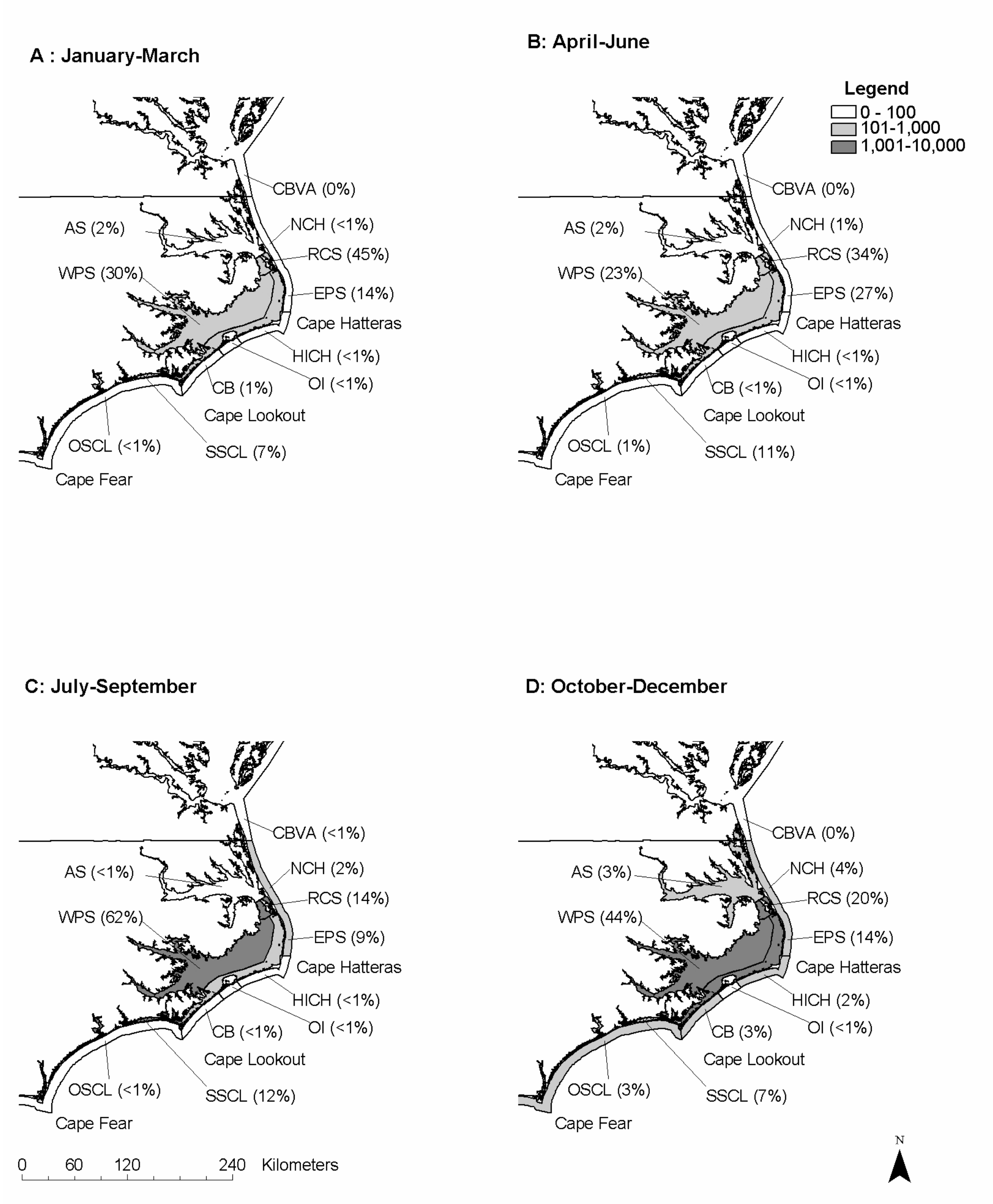

Figure 6. - Juvenile red drum (TL < 457 mm) tagged by area in months A) January-March, B) April-June, C) July-September, D) October-December, combined over all years. Percentages of fish tagged in each area are given in parenthesis. Areas include, Chesapeake Bay and Virginia (CBVA), ocean beaches north of Cape Hatteras (NCP), Roanoke and Croatan Sounds (RCS), Eastern Pamlico Sound (EPS), Hatteras Inlet to Cape Hatteras (HICH), Ocracoke Inlet (OI), Core Banks (CB), sounds south of Cape Lookout (SSCL), ocean beaches south of Cape Lookout (OSCL), Western Pamlico Sound (WPS), and Albermarle Sound (AS).

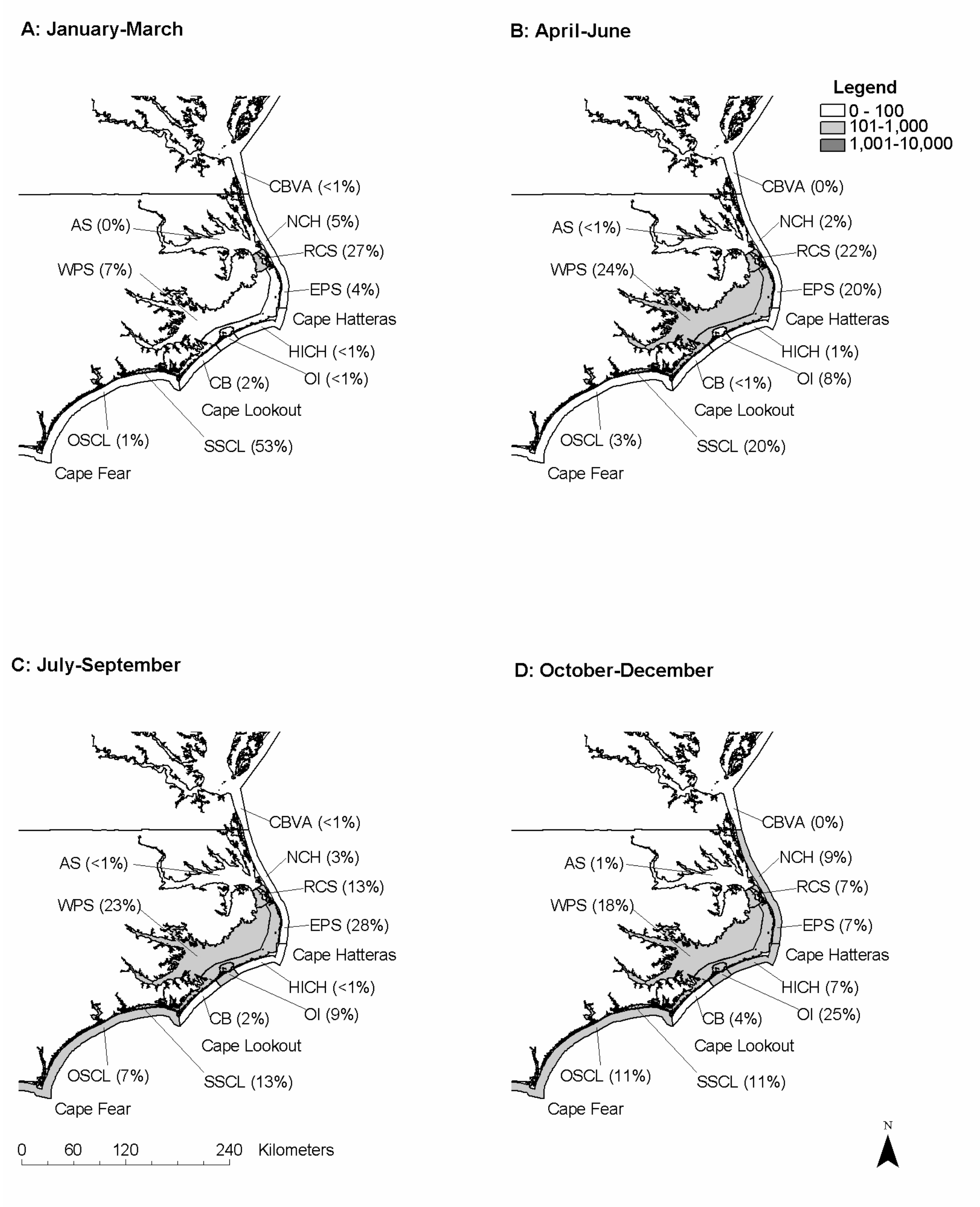

Figure 7. – Sub-adult red drum (TL 457-685 mm) tagged by area in months A) January-March, B) April-June, C) July-September, D) October-December, combined over all years. Percentages of fish tagged in each area are given in parenthesis. Areas include, Chesapeake Bay and Virginia (CBVA), ocean beaches north of Cape Hatteras (NCP), Roanoke and Croatan Sounds (RCS), Eastern Pamlico Sound (EPS), Hatteras Inlet to Cape Hatteras (HICH), Ocracoke Inlet (OI), Core Banks (CB), sounds south of Cape Lookout (SSCL), ocean beaches south of Cape Lookout (OSCL), Western Pamlico Sound (WPS), and Albermarle Sound (AS).

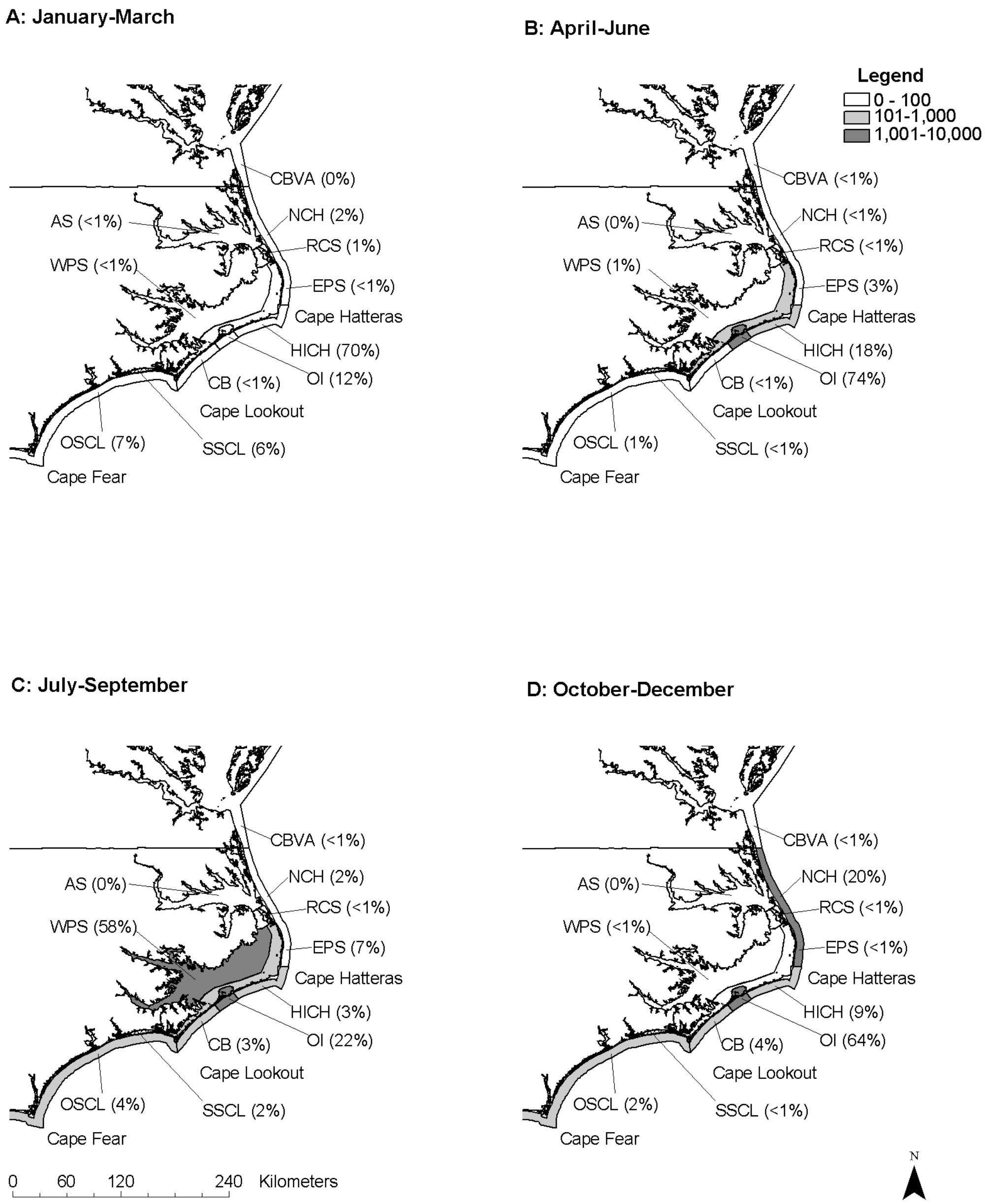

Figure 8. – Adult red drum (TL >685 mm) tagged by area in months A) January-March, B) April-June, C) July-September, D) October-December, combined over all years. Percentages of fish tagged in each area are given in parenthesis. Areas include, Chesapeake Bay and Virginia (CBVA), ocean beaches north of Cape Hatteras (NCP), Roanoke and Croatan Sounds (RCS), Eastern Pamlico Sound (EPS), Hatteras Inlet to Cape Hatteras (HICH), Ocracoke Inlet (OI), Core Banks (CB), sounds south of Cape Lookout (SSCL), ocean beaches south of Cape Lookout (OSCL), Western Pamlico Sound (WPS), and Albermarle Sound (AS).

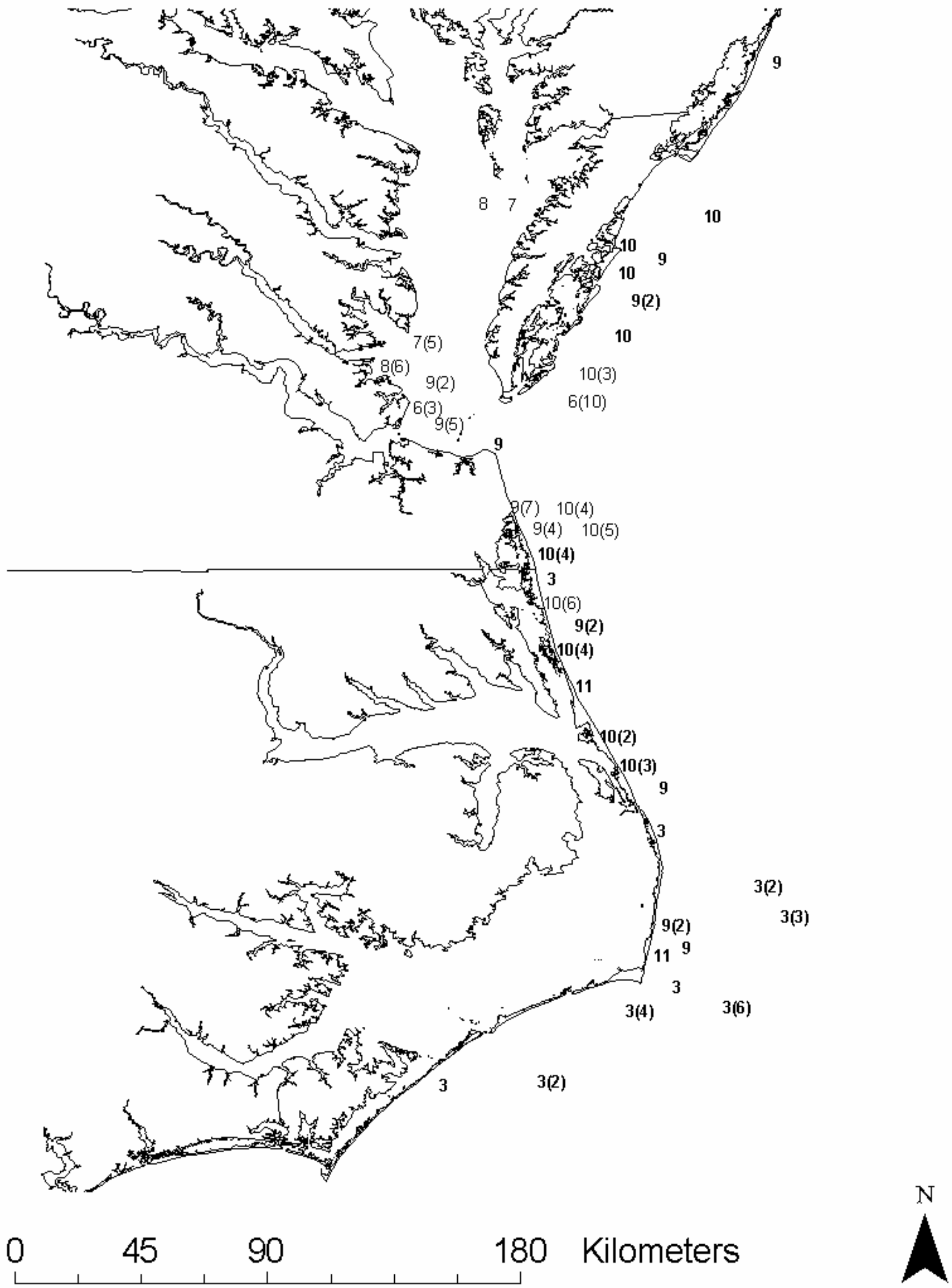

Figure 9. – Locations of adult red drum (TL > 685) caught in the National Marine Fisheries Service Trawl Survey (bold) and the Virginia Institute of Marine Sciences Shark Long-line Survey (regular) by month. Numbers indicate the month red drum were caught. The number of red drum caught at a particular location is given in parentheses.

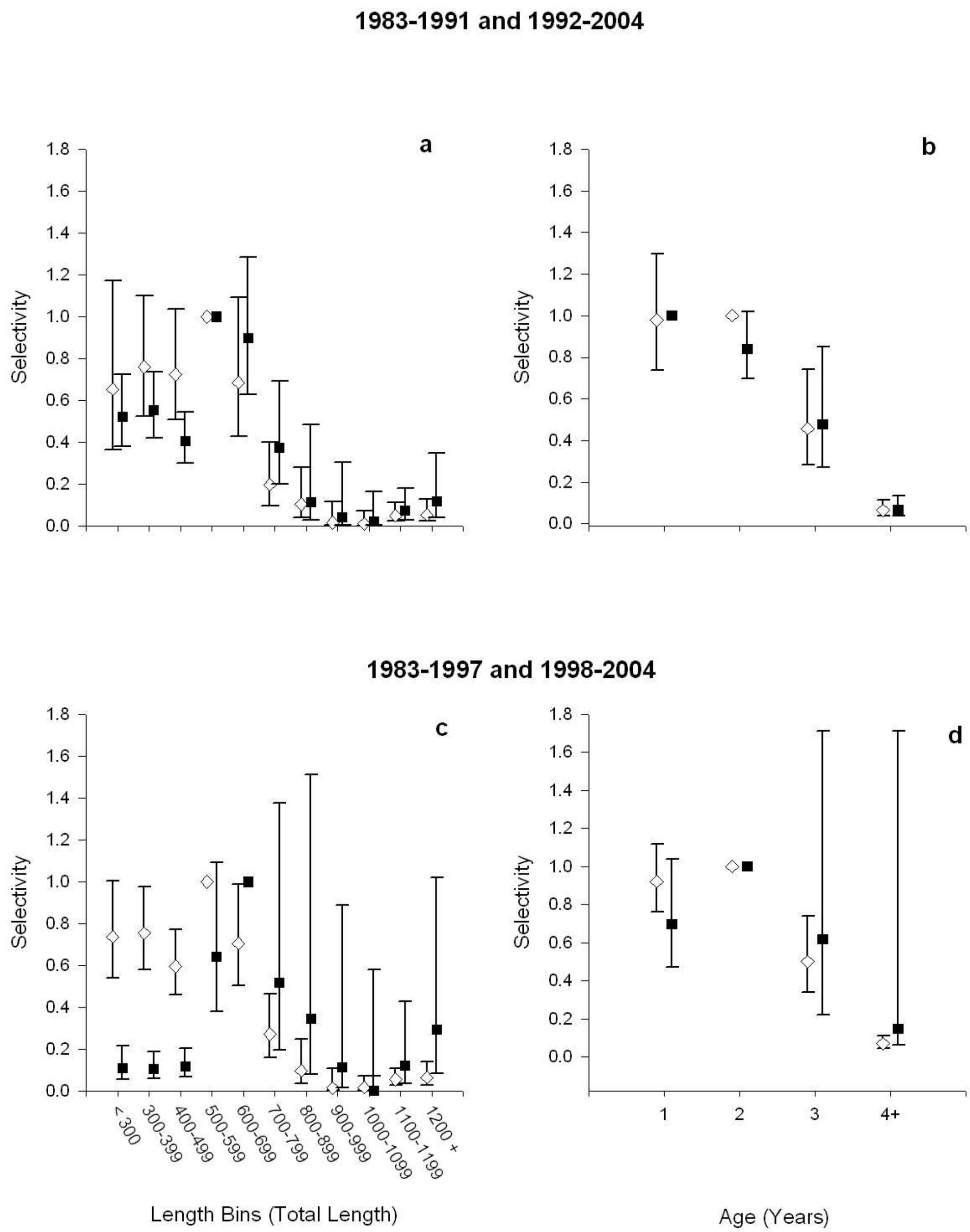

Figure 10.- Length (left) and age (right) selectivity patterns of hook and line gears on red drum. Comparisons are made for selectivity before (open diamonds) and after (solid squares) regulation changes made in 1991 (a and b) and 1998 (c and d). Error bars indicate 95% Wald confidence intervals. All selectivities are scaled to be relative to the maximum selectivity, which were set equal to one. There is no error associated with this maximum selectivity.

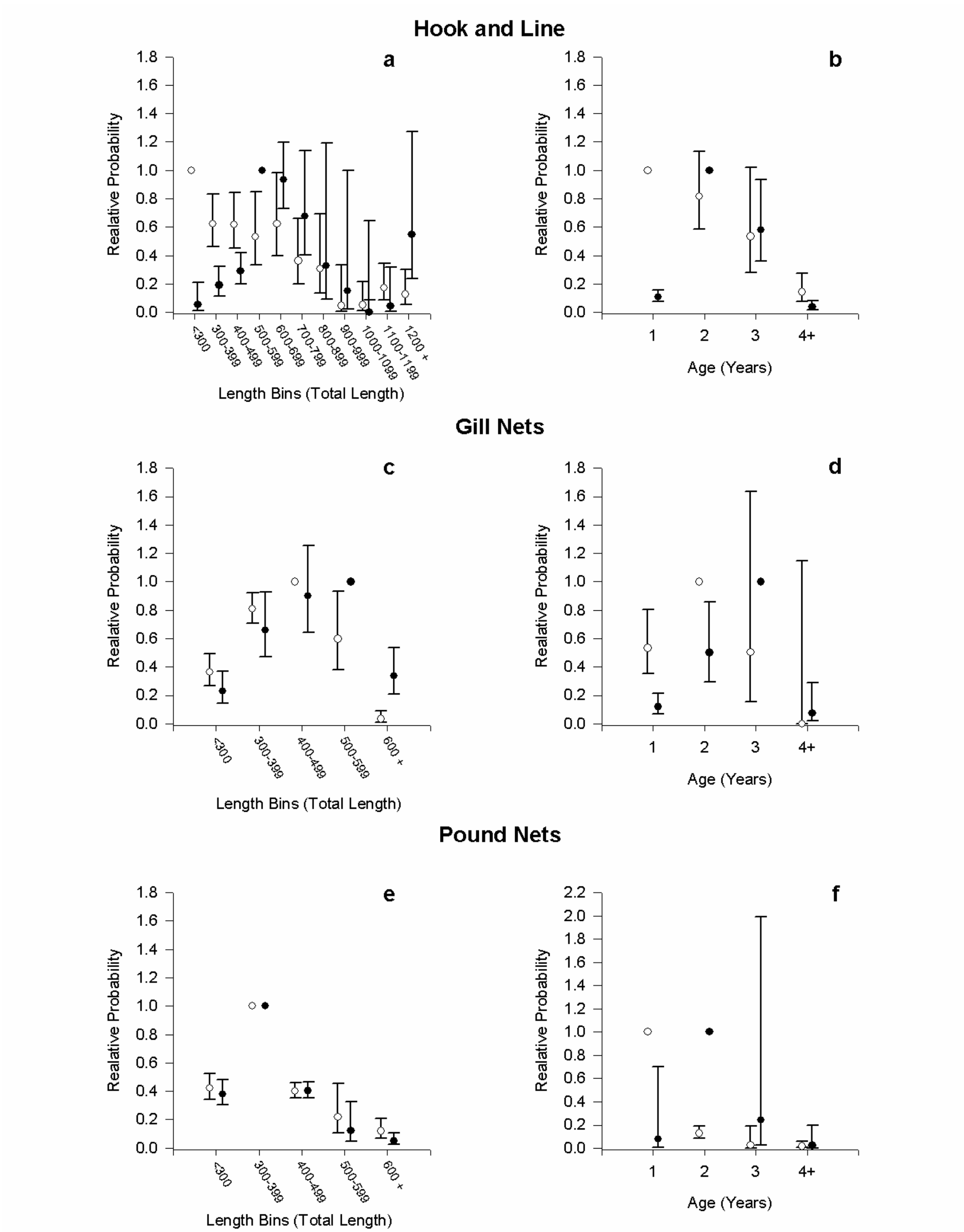

Figure 11.- Probability of tagged fish in each length bin (left) or age group (right) being recaptured by hook and line (top), gill nets (middle) or pound nets (bottom) and either released alive (open circles) or harvested (filled circles). Error bars indicate Wald 95% confidence intervals. All return proportions are scaled to be relative to the maximum for each fate (released or harvested), which were set equal to one. There is no standard error associated with this maximum selectivity.

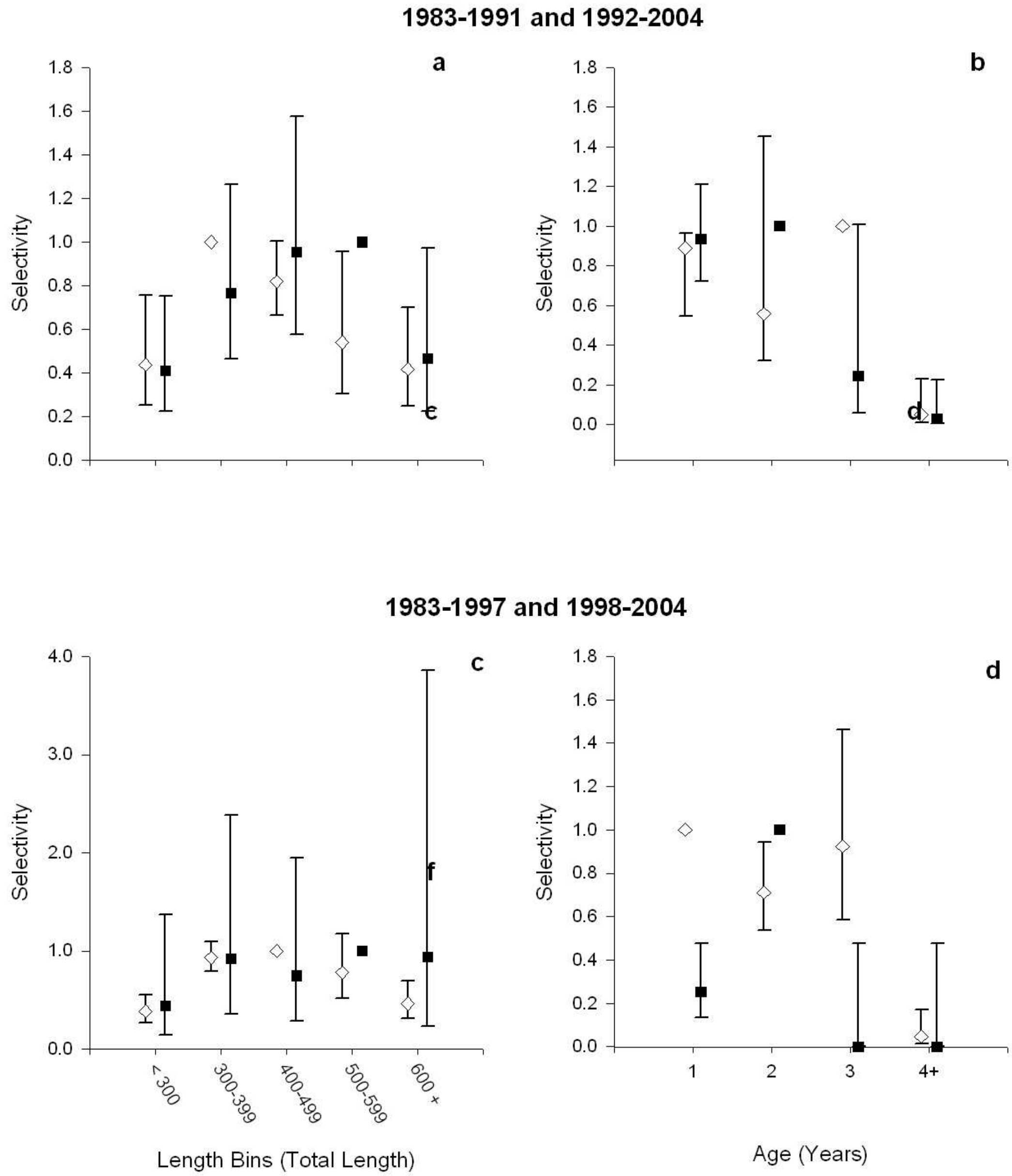

Figure 12.- Length (left) and age (right) selectivity patterns of gill nets on red drum. Comparisons are made for selectivity before (open diamonds) and after (solid squares) regulation changes made in 1991 (a and b) and 1998 (c and d). Error bars indicate 95% Wald confidence intervals. All selectivities are scaled to be relative to the maximum selectivity, which were set equal to one. There is no error associated with this maximum selectivity.

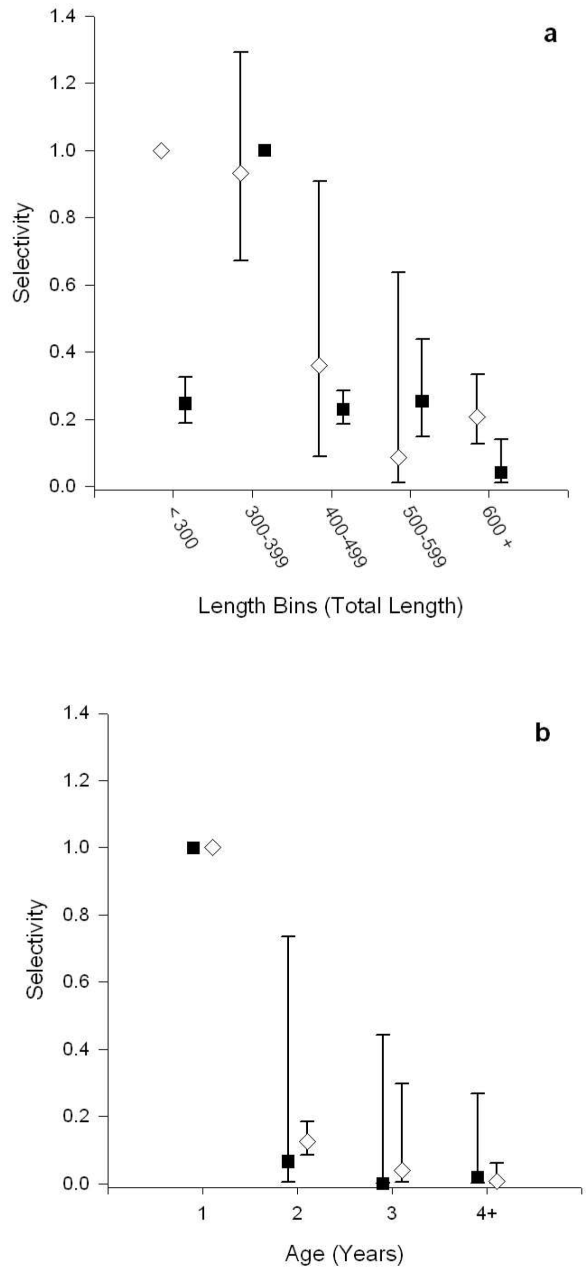

Figure 13.- Length (a) and age (b) selectivity patterns of pound nets on red drum. Comparisons were made for selectivity before (open diamonds) and after (solid squares) regulation changes made in 1991. Error bars indicate 95% Wald confidence intervals. All selectivities are scaled to be relative to the maximum selectivity, which were set equal to one. There is no error associated with this maximum selectivity.

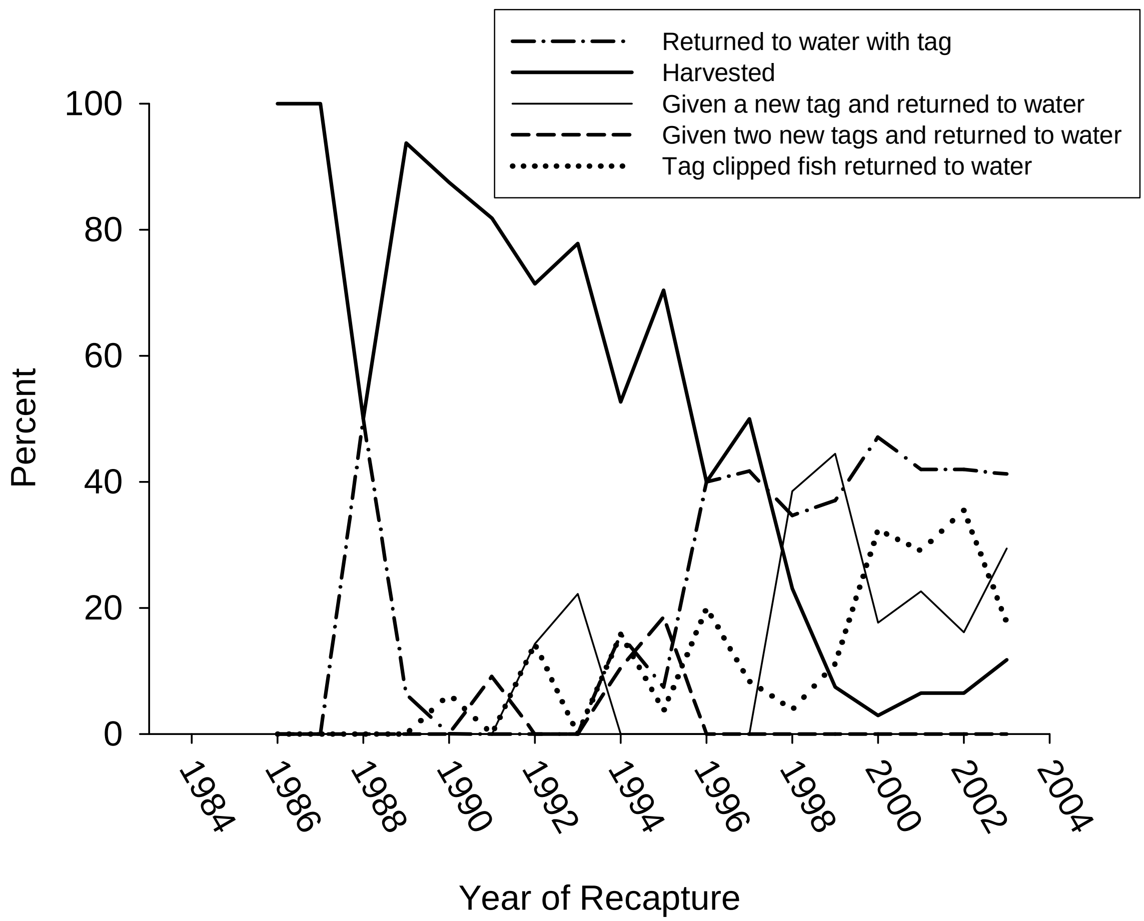

Figure 14. – Portion of recaptured adult red drum (>685 mm TL) tagged with a steel or nylon dart tags to receive one of five fates. Fates include, released alive with tag (dot-dash), killed (thick solid), given a new tag and released alive (thin solid), given two new tags at the same time and released alive (dash), and having tag clipped and released alive (dotted).

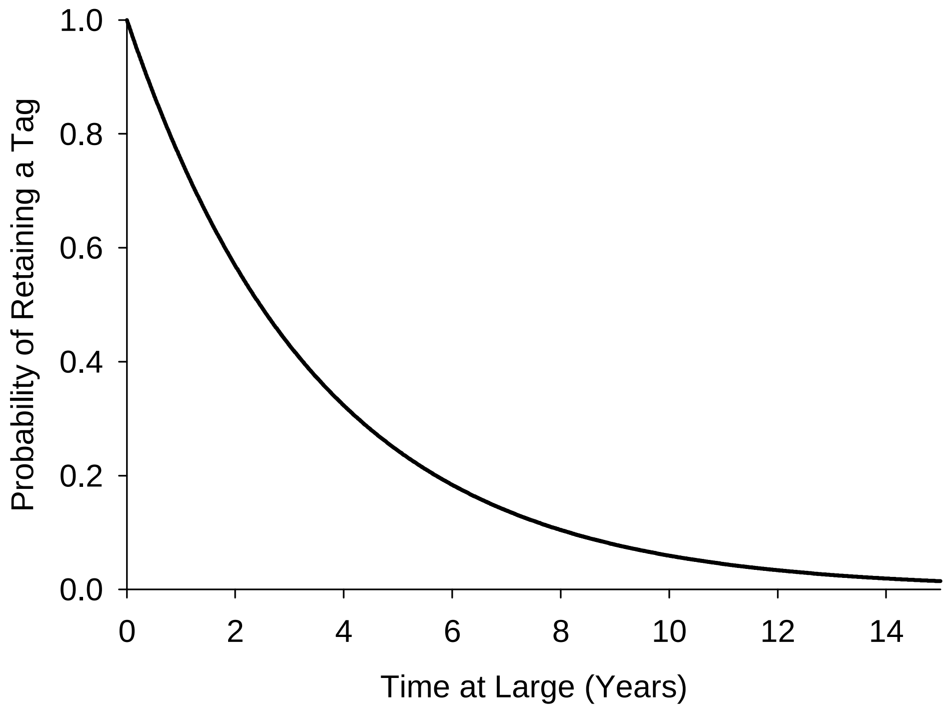

Figure 15.- Probability of tag retention for steel dart and nylon dart tags by the number of years a tagged fish is at large, from the best fit model ($S_p f_y L_. \rho_.$; Table 18). The probability of tag retention is modeled using the equation $Q(t) = \rho e^{-L t}$, where acute tag retention $(\rho \pm SE)$ is 1.000 ± 0.011 and the instantaneous rate of tag loss (L ± SE) is 0.253 ± 0.068.

Appendix A

Methods of capture used in North Carolina red drum tagging program

Various methods were employed by NCDMF personnel and cooperating commercial fishers to capture sub-adult red drum throughout the project. Some methods were described in Ross and Stevens (1992). However, prior to this report many of the details about capture methods were only described in notes and memorandums between NCDMF personnel. This appendix contains a detailed description of red drum sampling protocols used by NCDMF personnel since 1986.

Between 1986 and 1990 weekly collections from pound nets were made from early summer (June or July) to October near Gum Point (Bath, NC) on the Pamlico River. Red drum were obtained from pound nets and transferred to either a floating holding net or 35 gallon tank to await tagging. Fish were measured, tagged, then transported 1.6 km to the other side of Pamilco River before being released (Ross and Stevens 1992).

Between 1987 and 1990 NCDMF personnel accompanied commercial fishers seeking striped mullet *Mugil cephalus*, spotted seatrout *Cynoscion nebulosus,* and red drum using run-around gill nets over grass flats in the Pamlico Sound behind Ocracoke and Hatteras Islands. NCDMF also accompanied commercial fishers employing anchored gill nets in Hatteras Inlet, Wilson Bay on the New River, and the Newport River (Ross and Stevens 1992). The fork length was measured for all red drum collected in these gill nets and healthy fish were tagged and released.

With the help of a federal MARFIN Grant awarded in 1996, NCDMF initiated fishery independent red drum sampling. During the 1995 and 1996 sampling seasons, a run-around gill net was used to capture red drum in three predetermined areas; 1) Albermarle, Croatan, and Roanoke Sounds, 2) Pamlico Sound, 3) Pamlico River. These areas were selected based on input gathered from commercial fishermen and NCDMF staff. The three areas were sampled on a rotational basis with a target goal of four days per month devoted to each area. Three to five randomly chosen primary stations in each area were sampled on any given day, with one set per station. Randomness was achieved by selecting stations using a random numbers table.

In 1997 and 1998, red drum were collected for tagging using a 200-m trammel net. Sampling stations were chosen in the Outer Banks and Morehead City regions. The Outer Banks region included the eastern Pamlico Sound from Hatteras Inlet north to Roanoke Sound. The Morehead City region included Core and Bogue Sounds and the Newport River. Five stations within each area were randomly sampled each month from May-December in 1997 and April-August in 1998. Additional non-random sets using various gears were conducted to maximize the probability of capturing red drum in a wide range of size classes. Locations of non-random sets were determined from input of NCDMF staff, commercial and sport fishermen, and by the presence of schooling fish. Since 1999 NCDMF tagged red drum opportunistically, using a variety of gears.