North American Journal of Fisheries Management 31:445–454, 2011

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1080/02755947.2011.590116

ARTICLE

Postrelease Survival of Sublegal Southern Flounder Captured in a Commercial Gill-Net Fishery

William E. Smith*
Department of Biology, North Carolina State University, Campus Box 7617, Raleigh, North Carolina 27695, USA

Frederick S. Scharf
Department of Biology and Marine Biology, University of North Carolina–Wilmington, 601 South College Road, Wilmington, North Carolina 28403, USA

Abstract
Discards from commercial fisheries may be subject to high rates of mortality that vary over time and space, contributing to inaccuracies in stock assessments. We present the results from a field experiment in the New River estuary, North Carolina, designed to estimate the postrelease survival of commercially gill-netted, sublegal southern flounder *Paralichthys lethostigma*. Large, replicate field enclosures were used to monitor gill-netted southern flounder for a 3-d period after capture. The survival of observed discards showed significant variation among seasons. During fall and spring, overall survival was estimated to fall between 0.74 and 0.87, while during summer survival was estimated to fall between 0.22 and 0.30 and included fish that were dead when gill nets were retrieved. Logistic regression analysis was used to evaluate the relative effects of individual traits on the postrelease survival of southern flounder in the commercial gill-net fishery. Model selection indicated that season and fish condition were the best characteristics with which to predict postrelease survival and that body size may also influence postrelease survival. Low seasonal estimates of the survival of discarded southern flounder suggest that management measures that mitigate poor discard survival will be most effective during the summer.

Minimum size limits represent a routinely applied fisheries management tactic used to reduce or eliminate the harvest of juvenile fish. However, size limits frequently result in discarding sublegal target species, which may constitute a large proportion of the overall catch (Kennelly 2007; Rudershausen and Buckel 2007). Similar to recreational catch-and-release angling, which depends on the survival of angled fish after release, the efficacy of a size limit in a commercial fishery will be largely dependent upon the survival of sublegal-sized fish after release. Therefore, a minimum size limit will only represent an adequate management tactic if significant numbers of sublegal fish survive the capture and release experience. Studies documenting catch-and-release mortality of fish discarded after capture by commercial gill-net fisheries have estimated a wide range of postrelease survival probabilities from as low as 0.31 to as high as 0.97 (Murphy et al. 1995; Buchanan et al. 2002; Basaran and Samsun 2004; Vander Haegen et al. 2004; Rulifson 2007). Low rates of postrelease survival estimated for several species captured in gill nets confirm the importance of determining the fate of discarded individuals when considering the use of minimum size regulations to manage passive gill-net fisheries.

Fishery stock assessment results can be biased by the failure to fully account for discard mortality, resulting in less effective management policies. Williams (2002) demonstrated that target-fishing mortality rate estimates for the U.S. west coast groundfish fishery were positively biased by the failure to account for size-selective discards, such as those required (i.e., regulatory discards) owing to minimum size-limit regulations. Management policies designed to achieve the target mortality rates would not be sufficient to meet stock biomass goals,

*Corresponding author: wes2316@gmail.com
Received November 11, 2010; accepted February 17, 2011

because production lost to discarding was unaccounted for. Williams (2002) concluded that the collection of discard mortality data was sorely lacking and its incorporation would result in substantial modification to harvest policy.

Southern flounder *Paralichthys lethostigma* are harvested commercially in estuarine and marine coastal waters of North Carolina. Among several gear types used to target southern flounder, gill nets, gigs, and pound nets are collectively responsible for the majority of commercial landings. During the past 20 years, gill nets have contributed to an increasingly greater fraction of statewide landings (NCDMF 2005; Takade-Heumaker and Batsavage 2009; Smith and Scharf 2010). The gill-net fishery for southern flounder is executed mainly in shallow, upper estuary waters, which serve as nursery habitats for southern flounder and other species. Southern flounder reside in estuarine waters until reaching maturity between ages 1 and 2 (Monaghan and Armstrong 2000; Smith and Scharf 2010) and emigrating from the estuary to spawn offshore during winter (Watterson and Monaghan 2001). The execution of the gill-net fishery combined with southern flounder life history results in the inclusion of several younger and immature individuals in the gill-net harvest (Smith and Scharf 2010).

The North Carolina Division of Marine Fisheries (NCDMF) currently designates the southern flounder stock as overfished, and stock biomass estimates have been near the current low level since the early 1990s (Takade-Heumaker and Batsavage 2009). In an effort to reduce the level of exploitation in the fishery, the NCDMF adopted management changes in 2005 that are outlined in the southern flounder fishery management plan (NCDMF 2005). One major change was an increase in the minimum size limit to 356 mm, which coincided with requiring the use of mesh size of at least 140 mm stretched monofilament for large-mesh gill nets. The gear change was designed to reduce the bycatch of sublegal-sized fish. However, data collected in the New River estuary during 2005, the first full year after management changes were in place, demonstrated that nearly 36% of flounder caught in 140-mm-mesh gill nets were still below legal size (Smith and Scharf 2010). Although many fish caught in gill nets may survive the time they are entangled in the net before being retrieved, some are dead upon retrieval. Further, many of the live fish may be injured. Since many sublegal flounder may die either while entangled in gill nets or shortly after being released, an accurate estimate of postrelease survival is necessary to ensure that all fishing-related mortality is accounted for in the assessment of the stock. Here, we used field enclosures to estimate the short-term postrelease survival rate of sublegal southern flounder that were captured and subsequently released from commercial gill nets in a North Carolina estuary. We evaluated the effects of fish condition and season on survival estimates to identify individual and environmental factors that may influence postrelease survival. Our objective was to generate reliable seasonal estimates of postrelease mortality in the estuarine gill-net fishery that could be integrated into current population assessment models for southern flounder.

METHODS

Experimental design.—Postrelease survival experiments were conducted in the New River, a moderately-sized estuarine system in southeastern North Carolina with a long history of southern flounder harvest. The hydrography in the New River is driven mainly by wind and tide, similar to other shallow estuarine systems throughout the region. The general execution of the commercial gill-net fishery for southern flounder is similar statewide. Monofilament gill nets mostly less than 90 m in length are the predominant gear used and are generally fished overnight (∼24-h soak times) from small vessels. The nets are often set parallel to shore to capture southern flounder moving between deep and shallow habitats during tidal and diurnal cycles. The nets are routinely checked each morning to retrieve any captured fish and then immediately reset. The North Carolina commercial gill-net fishery is executed throughout most estuarine waters from areas adjacent to oceanic inlets to habitats near freshwater inputs, but the majority of fish are landed in waters of moderate salinity (10–25‰). Southern flounder used in this study were collected primarily in mid to upper estuarine waters at salinities between 11‰ and 26‰.

Beginning in summer 2007, we accompanied commercial gill-net fishers on at least five fishing trips during each of four seasonal periods: summer (August) 2007, fall (November) 2007, spring (May) 2008, and summer (August) 2008. These time periods were selected to evaluate survival across a natural range of environmental conditions that occur when gill nets are typically fished in the estuary. Of primary interest were differences between summer periods that were characterized by high water temperatures and low dissolved oxygen concentrations and fall and spring periods that were characterized by low water temperatures and high dissolved oxygen concentrations. Winter is a period of relative inactivity in the North Carolina southern flounder fishery.

All southern flounder evaluated in this study were caught in commercially fished gill nets hung with 140-mm monofilament mesh (the current minimum legal mesh size in the North Carolina fishery). Gill nets were fished for approximately 24 h and retrieved each morning between 0500 and 0900 hours. Data were recorded for all live and dead gill-netted southern flounder at or below the legal minimum size limit of 356 mm total length (TL). Fish that were retrieved alive from gill nets were quickly measured and placed in a holding container filled with estuarine water. A numerical score from 1 (best) to 3 (worst) was assigned to each fish to define fish condition. Fish with no apparent injuries and only minor scale loss (less than 5% of total body area) were assigned a condition index value of 1. Fish displaying one of the following traits were assigned a condition index of 2: more than 5% scale loss, some fin loss, or lethargic behavior. Fish displaying all three of these traits or more than 50% scale loss, loss of more than 50% of fin area, visible cuts on the body, or partial evisceration were assigned a condition index of 3. The condition index was intended to encompass the broad range of fish conditions that had been observed in the New River gill-net fishery during a previous study (Smith and Scharf 2010). While a more comprehensive condition index system would have been generated by including descriptions of the physiological condition of each fish, we were interested in developing a coarse, inexpensive index that could be applied rapidly in the field to minimize handling and stress for each fish.

Each fish retrieved alive was marked by injecting a small amount of colored latex paint into a fin ray. Unique combinations of paint color and tagging location (e.g., dorsal fin, anal fin) denoted date of capture and fish condition, enabling subsequent identification of individual fish. Tagged fin rays never showed signs of irritation or infection in any fish throughout the study, suggesting that the tagging method was not associated with injury or mortality. Water in the holding container was completely exchanged with ambient estuarine water at least every 30 min, and fish were held for a maximum time of 1 h to minimize any negative effects of holding before placement into the field enclosures.

To estimate the short-term postrelease survival of sublegal discards that were alive at net retrieval, live sublegal fish were monitored in situ in net enclosures for a 72-h postrelease period. Live fish were placed in several large (2.13 × 2.13 × 0.5 m) replicate field enclosures that consisted of rigid steel frames surrounded by a nylon mesh. A zipper was sewn into the top of the nylon mesh, allowing the fish inside to be observed with minimal disturbance. The enclosures were positioned on sand bottoms at approximately 1 m depth, a habitat that typified environmental conditions where southern flounder are normally caught and discarded in the commercial gill-net fishery. The nylon enclosure consisted of 25-mm stretched mesh that allowed small prey to enter, but prevented larger crab and fish predators from entering. The maximum number of flounder per enclosure was 10, yielding a maximum fish density of approximately 1 fish/0.5 m^2. Enclosed flounder were observed daily, and any dead fish were removed and counted. Each fish was identified by TL, tag color, and location. All fish were removed after 3 d of observation. In the laboratory, the sex of each fish was determined by examining gonadal tissue, and age was estimated by counting annuli in the sectioned left sagittal otolith (GSMFC 2003).

Continuous temperature and dissolved oxygen loggers (Eureka Midge model, Eureka Environmental Engineering) were located directly adjacent to the field enclosures and provided fine-scale physicochemical data that were used to characterize the environmental conditions experienced by southern flounder in the enclosures. Dissolved oxygen values recorded by loggers were validated by means of independent measurements of dissolved oxygen taken with a Yellow Springs Instruments (YSI) model 85 multiprobe environmental meter daily at each enclosure. During the fall sampling period, one continuous environmental logger was lost during a storm, so temperature and dissolved oxygen values were not obtained during the first day of sampling. During spring sampling, equipment damage from storms resulted in the loss of all continuous data from environmental loggers. Only daily values of temperature and dissolved oxygen measured with the YSI meter were available for the spring.

Data analysis.—The use of data gathered from field enclosures to estimate postrelease survival requires that several assumptions be satisfied. First, the effects on fish of holding and transport between net retrieval and placement in the enclosures are assumed to be negligible. Second, it is assumed that the survival probability of individual fish is not influenced by containment in the enclosures (Pollock and Pine 2007). Third, fish evaluated in the enclosures are assumed to represent a random sample of the population of fish available to be caught in the fishery. To minimize holding and transport effects, the estuarine water used in the holding container was collected from the same location where fish were captured, ensuring similar physicochemical properties to avoid physiological stress, and the water was exchanged frequently. Nets were retrieved early in the morning when water and air temperatures were lowest, and fish were held onboard for a maximum of 1 h. Enclosure conditions were managed to reduce potential violations of the second assumption by maintaining low fish densities within the enclosures, placing each enclosure in typical southern flounder habitats, ensuring each location experienced sufficient tidal exchange, and restricting predator access to discarded flounder within the enclosures. We acknowledge that holding and transport effects would be best assessed by estimating mortality separately for a control group of fish that had not been exposed to gill-net capture. However, without access to laboratory-reared fish or wild fish captured with less invasive gear, it was not possible to separate the capture process from the holding and transport processes. We attempted to satisfy the third assumption by distributing our sampling effort across a large number of nets located throughout the upper portion of the estuary. A total of 7 to 12 nets were fished each day.

Survival of discarded fish can be considered in two parts: the fraction that initially survive capture, the live discard rate (S_c), and the fraction that survive the subsequent period after release, the postrelease survival rate (S_s). The product of these two survival probabilities equals the probability that a sublegal-sized fish will survive the capture and release experience (S_{sc}). We collected data from all live and dead sublegal fish during observed commercial gill-net trips. The fraction of fish that were alive at net retrieval during each seasonal period was considered an estimate of the seasonal live discard rate. Sublegal fish alive at net retrieval were monitored for postrelease survival in replicate field enclosures. The mean survival rate, $\hat{S}$, for each replicate enclosure (i to r) was used to estimate $\hat{S}_s$ during each of the four seasonal periods as follows:

$$\hat{S}_s = \frac{\sum_{i=1}^{r} \hat{S}_i}{r},$$

with SE calculated as:

$$\mathrm{SE}(\hat{S}_s) = \sqrt{\frac{\sum_{i=1}^{r} (\hat{S}_i - \hat{S}_s)^2}{r(r-1)}},$$

for enclosures 1 to r. All pairwise comparisons of seasonal postrelease survival were made with multiple t-tests at a Bonferroni-corrected $\alpha = 0.05$.

Individual traits and postrelease survival.—While treating the enclosure as the experimental unit helps to ensure statistical independence among replicates in an enclosure experiment, individual trait effects such as age, body size, and condition cannot be explored with this design. Therefore, we used logistic regression to assess the potential influence of each of these individual traits on survival, while acknowledging that the model is not able to account for potential nonindependence among individual fish treated as replicates. Logistic regression models are frequently applied in catch-and-release survival studies to identify factors affecting individual survival probabilities (Murphy et al. 1995; Ayvazian et al. 2002; Buchanan et al. 2002; St John and Syers 2005; Reeves and Bruesewitz 2007; Butcher et al. 2008). We used the R general linear model (glm) procedure and the option family = binomial (link = "logit") to fit all logistic models (R Development Core Team 2005). Although the potential interactive effects of condition and season were also of interest, this interaction was not explored because the high degree of correlation between condition and season indicated nonindependence between these parameters. Four a priori groupings of fixed seasonal effects were explored that included either the four unique seasonal effects for summer 2007, fall 2007, spring 2008, and summer 2008 or summer and spring–fall groupings. Within each seasonal effect subset of candidate models, all combinations of individual trait effects were explored.

Model selection was performed with Bayesian information criterion (BIC). Akaike information criterion (AIC) are commonly used to select the most parsimonious model from a set of candidate models; however, recent criticism of AIC suggests that it may lead to biased model selection that favors more highly parameterized models when large data sets are used (Link and Barker 2006). The Bayesian information criterion have been suggested as a model selection criterion to achieve parsimony when large sample sizes are used; thus, we elected to present BIC model selection results. Change in BIC (ΔBIC) was calculated for each candidate model as the change in BIC from the model with the greatest support, i.e., the lowest BIC score ($\mathrm{BIC}_{\mathrm{min}}$). We considered models with a ΔBIC score of less than 2 to be highly supported by the data, and models with greater ΔBIC were considered less likely given the data. All models with ΔBIC score less than 2 were assigned a normalized weight, scaled by $\mathrm{BIC}_{\mathrm{min}}$ (Kass and Raftery 1995) to demonstrate the relative weight of evidence for each candidate model given the data. Proportional standard errors ($\mathrm{SE}_{B(i)}/B_i \times 100$) were calculated for each non-intercept logistic regression parameter. Values of 30 or more were interpreted to indicate poor precision and thus poor predictive utility, and only models with parameter-proportional SE values less than 30 were used to predict postrelease survival probabilities.

Regression analysis can be biased by influential data points that contribute disproportionately to parameter estimation. For linear regression models, the diagnostic tool Cook's D is often used to identify influential observations. For logistic regression models, the analog to Cook's D is "C-bar", which, like Cook's D, measures the effect of removal of an individual datum from the data set on parameter estimates. Values of C-bar for the best model supported by BIC were generated with the proc logistic procedure in SAS (SAS 2000). Influential observations were identified as those with absolute C-bar values greater than two standard deviations from the mean C-bar value. The sensitivity of the logistic regression results and model selection to individual observations was assessed by individually removing each influential observation from the data set, and then repeating the model estimation and selection process. If the same model was selected with and without inclusion of an influential observation, then the regression results were considered to be robust to that observation.

RESULTS

Throughout the study, 268 sublegal southern flounder were captured in commercial gill nets; 200 of these fish were recovered alive and subsequently placed in field enclosures to monitor short-term (72-h) survival. When pooled across all seasons, the live discard rate for southern flounder was 0.75, and the postrelease survival rate for sublegal fish recovered alive and placed in enclosures was 0.67 (Table 1). After accounting for all sublegal fish that were dead when retrieved from gill nets, the overall discard survival rate was 0.50. Postrelease survival estimates were not significantly different between the two summer periods or

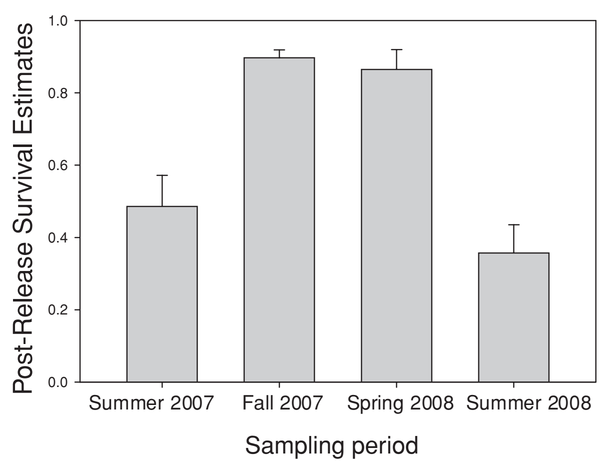

FIGURE 1. Seasonal estimates of postrelease survival of sublegal southern flounder in the New River estuary, North Carolina. Error bars indicate SEs.

TABLE 1. Summary statistics for all sublegal southern flounder captured in this study.

Variable	Summer 2007	Fall 2007	Spring 2008	Summer 2008	Total
Total number captured	36	70	47	115	268
Total number enclosed	22	68	40	70	200
Proportion alive at net retrieval ($\hat{S}_c$)	0.61	0.97	0.85	0.61	0.75
Postrelease survival of enclosure fish ($\hat{S}_s$)	0.49	0.90	0.86	0.36	0.67
Overall discard survival ($\hat{S}_{sc}$)	0.30	0.87	0.74	0.22	0.50

between the fall and spring periods. However, survival estimated during both fall 2007 and spring 2008 was significantly greater ($P < 0.001$) than the survival estimate for summer 2008 (Table 1; Figure 1). Although no statistically significant difference was found between summer 2007 and the fall–spring periods, a low sample size during summer 2007 ($n = 22$) may have limited our ability to detect a difference.

Logistic regression model selection indicated that season of capture and fish condition at net retrieval were the best factors among those evaluated with which to predict the postrelease survival of southern flounder (Table 2; Figure 2A). The second best model (with ΔBIC < 2) also included a body size effect that indicated a positive relationship between body size and postrelease survival (Figure 2B). Both models with high BIC support contained two seasonal groupings: the two summer periods were grouped together as were the fall and spring periods. The C-bar values indicated that only one observation was highly influential in the best BIC model. Results for BIC model selection appeared to be robust to this observation, because removing the influential datum did not result in selection of a different model set. All parameter-proportional SEs of the best BIC model were less than 30, indicating acceptable precision in the parameter estimates. The best BIC model (Table 3) predicted that the postrelease survival of southern flounder declined with poor fish condition and that postrelease survival was lower in summer compared with that of spring and fall (Table 4). The best BIC model predictions of seasonal postrelease survival agreed closely with the seasonal survival estimates generated by averaging postrelease survival across enclosures.

Both summer periods demonstrated low postrelease survival estimates that coincided with low average dissolved oxygen concentrations and high water temperatures (Table 5). Additionally, fish were exposed to episodic hypoxia (dissolved oxygen < 3 mg/mL) during both summer periods (Figure 3). Water quality data collected during summer 2008 at a nearby U.S. Geological Survey gauge station suggested that hypoxic conditions were regularly present throughout the river (Figure 3), perhaps even to a greater degree than in the shallow, well-mixed areas where our enclosures were located.

Sublegal-sized southern flounder captured in the commercial gill-net fishery were primarily female and age 0. For all southern flounder captured during observed trips, the portion of the total catch consisting of sublegal fish was consistent across sampling periods, varying from 30% to 40%. Among the 217 sublegal fish that were captured and could be sexed, 32 males (15%) and 185 females (85%) were identified. Among fish that were aged ($n = 209$), most individuals were age 0 ($n = 150$; 71.8%). The catch also included 58 age-1 fish (27.8%) and a single age-2 individual. These demographic totals included both fish used in the enclosure experiments and those that were dead upon net retrieval. Some decomposition of dead fish occurred; thus, not all southern flounder sampled were in a condition suitable for age and sex determination.

DISCUSSION

Seasonality and Postrelease Survival

Our estimates of postrelease survival of gill-netted, sublegal-sized southern flounder demonstrated significant variation across seasons. Low survival rates of discarded fish were estimated for both summer sampling periods ($\hat{S}_{sc} = 0.22$–0.30), which coincided with low dissolved oxygen concentrations and high water temperatures. Significantly higher postrelease survival was estimated during fall and spring ($\hat{S}_{sc} = 0.74$–0.87) and coincided with high dissolved oxygen concentrations and low water temperatures. Our summer discard survival estimates are in general agreement with a single previous estimate of postrelease survival for gill-netted southern flounder during summer in the Pamlico Sound (a large North Carolina estuary located north of our study area) by Montgomery (2000), who estimated

TABLE 2. Models supported by Bayesian information criterion (BIC) selection. All models with ΔBIC values less than 2 are shown.

Model	BIC	BIC weight	Seasonal grouping
Condition + season	186.3	0.80	Summer 2007–2008, fall–spring
Body size + condition + season	187.7	0.20	Summer 2007–2008, fall–spring

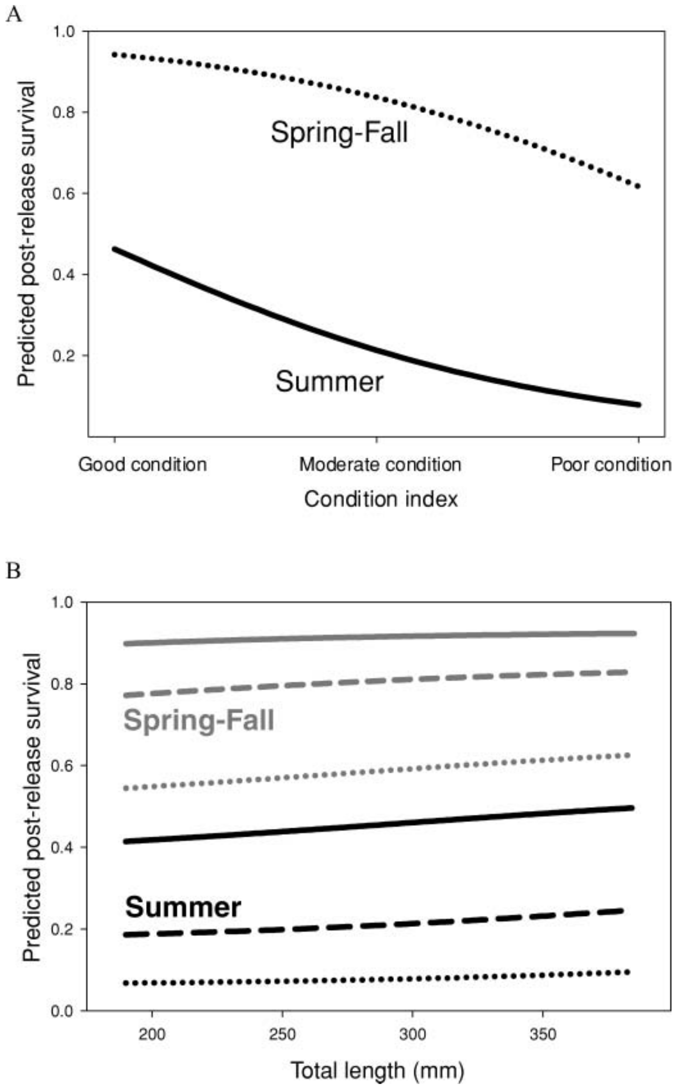

FIGURE 2. Logistic regression model predictions of **(A)** the model with the most Bayesian information criterion (BIC) support (which contained only season and fish condition) and **(B)** the model with the second-greatest BIC support (which contained season, fish condition, and body size). The predictions for fish in good condition are indicated by the solid lines, those for fish in moderate condition by the dashed lines, and those for fish in poor condition by the dotted lines. Note that the differences in predicted postrelease survival were minor across the range of body sizes examined.

overall discard survival at 0.304 during a study extending from July to October.

We identified three factors associated with the postrelease survival of gill-netted southern flounder: season of capture, fish condition at net retrieval, and body size. Numerous previous studies designed to quantify postrelease survival in hook-and-line, trawl, and gill-net fisheries have identified environmental conditions (Murphy et al. 1995; Ross and Hokenson 1997; Reeves and Bruesewitz 2007) and the severity of gear interactions, such as hooking depth or trawl tow duration (DuBois et al. 1994; Murphy et al. 1995; Purbayanto et al. 2001; Buchanan et al. 2002; Davis and Olla 2002; Fabrizio et al. 2008), as good predictors of postrelease survival. However, most previous studies have not identified a strong association between body size and postrelease survival (Vander Haegen et al. 2004; St John and Syers 2005; Stunz and McKee 2006; Alos and Palmer 2009). Generally, body size has been positively correlated with postrelease survival when this relationship is evident (Neilson et al. 1989; Ross and Hokenson 1997; Davis and Olla 2002; Reeves and Bruesewitz 2007). The data presented here indicate that season of capture and fish condition at net retrieval are the strongest predictors of southern flounder postrelease survival. Furthermore, fish condition was correlated with season; fewer fish in poor condition were captured in the fall and spring. Predicted postrelease survival was lower for smaller fish, but relative to the effects of season and fish condition, body size effects were minor across the length range examined. Our findings suggest that the implementation of management tactics designed to minimize gill-net discards (e.g., larger minimum mesh sizes) or to improve fish condition (e.g., shorter soak times) during the summer should reduce fishing-related mortality on sublegal juvenile southern flounder.

TABLE 3. Logistic regression parameter estimates for the model with the most Bayesian information criterion support.

Parameter	Estimate	SE
Intercept	1.01	0.46
Condition	−1.16	0.33
Season	2.94	0.44

Data Limitations and Interpretation

Seasonal variation in the postrelease survival probabilities of southern flounder was clearly demonstrated in this study; however, equipment design limited exploration of the spatial patterns in survival. Our original study was designed to include stratified sampling across a salinity gradient, but the field enclosures were not well suited to the high energy environments that typify high salinity habitats in North Carolina estuaries. During pilot work, we discovered that placement of enclosures in these habitats resulted in high mortality since fish movement within the enclosures was restricted by high flow rates. Thus, we placed enclosures in moderate and low salinity habitats where tidal currents were not as strong. Habitat use in the estuary is stratified

TABLE 4. Predictions of the postrelease survival of sublegal southern flounder by the model with the most Bayesian information criterion support.

	Season	
Fish condition	Summer	Fall–spring
Best	0.46	0.94
Moderate	0.21	0.84
Worst	0.08	0.62

TABLE 5. Average environmental conditions during each seasonal sampling period. Measurements were made using continuous data loggers positioned directly adjacent to the field enclosures except during spring 2008, when data were collected daily using a handheld meter.

Variable	Summer 2007	Fall 2007	Spring 2008	Summer 2008
Water temperature (°C)	30.1	13.7	26.4	31.0
Dissolved oxygen (mg/L)	4.31	5.62	4.63	3.73

by age, with younger fish on average using lower salinity areas as nursery habitats (Wenner et al. 1990; NCDMF 2005). Since this study was conducted in mesohaline waters in a fishery characterized by high proportions of young fish in the catch (Smith and Scharf 2010), the postrelease survival estimates generated here should be interpreted as broadly representative of southern flounder gill-net fisheries executed in upper-estuary nursery habitats throughout North Carolina.

We were unable to test for the effects of several potential factors that could influence postrelease survival, including salinity, net soak time, and mesh size. Currently, the gill-net sector of the North Carolina commercial southern flounder fishery is executed primarily using gill nets hung with the minimum legal mesh size and set for roughly 24-h soak times. Therefore, we limited our experiments to fish captured by these methods. However, directly quantifying the effects of net soak time and mesh size on postrelease survival could prove useful for predicting the outcomes of potential alternative management measures, such as requiring reduced soak durations or larger mesh sizes in the gill-net fishery.

Criticism of studies using enclosures to estimate postrelease survival often focuses on the potential effects of containment. Confined fish may be unable to escape episodic intrusion of low quality (e.g., hypoxic) water. Restricted fish movement and extended observation periods in the enclosure can result in cumulative effects that negatively bias survival probabilities; however, short observation periods may not capture delayed effects on survival that may manifest several days after release. Finally, survival of individuals within an enclosure may be autocorrelated. Careful study design is required to generate unbiased

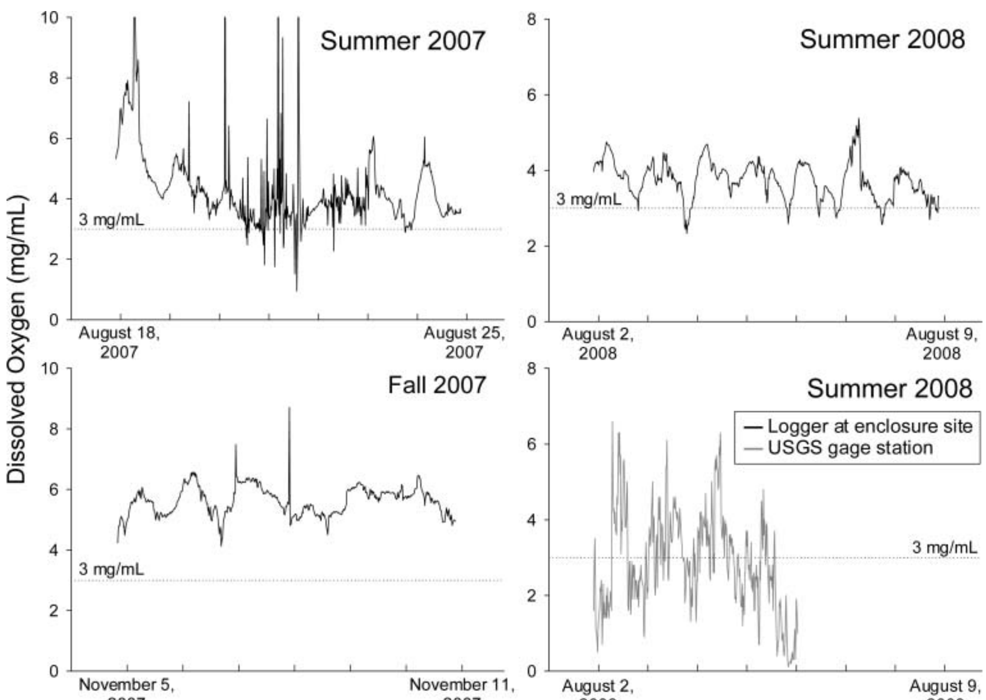

FIGURE 3. Dissolved oxygen concentrations in the New River estuary in summer 2007, fall 2007, and summer 2008, as measured by continuous data loggers positioned directly adjacent to the field enclosures and by a nearby U.S. Geological Service (USGS) gauge station (summer 2008 only, bottom right panel; this gauge was installed in summer 2008, so these data were only available during the final sampling period). Spring 2008 data are not shown because only data collected once daily were available. During both summer periods, dissolved oxygen concentrations periodically fell below 3 mg/mL at the enclosure site, and during summer 2008 much lower dissolved oxygen concentrations were observed in the deeper waters at the nearby USGS gauge station. When hypoxic conditions were present at the enclosures, they appeared to be more severe in deeper regions of the river, and fish may not have been able to escape hypoxic conditions even if not confined.

estimates of postrelease survival of enclosed fish. To ensure that fish in enclosures were exposed to optimal environmental conditions, we placed our enclosures in shallow, well-mixed areas that were likely to have higher-than-average dissolved oxygen concentrations relative to other parts of the estuary. In fact, we determined that when hypoxic conditions did occur at our enclosure sites, they were also prevalent and perhaps even more severe in deeper regions of the estuary. Thus, even if not enclosed, fish may not have been able to escape hypoxic conditions during these episodes.

Field enclosure estimates of postrelease survival can also be influenced specifically by the effects of containment. To reduce the effects of containment, Wassenberg and Hill (1993) recommended a containment duration of 96 h or less. We restricted our postrelease observation period to 72 h. The pattern of survival we observed over a 3-d period did not indicate that postrelease survival estimates for southern flounder were biased by any cumulative effects of containment. If fish did succumb to containment effects that accumulated during the observation period, we would expect to have observed higher mortality rates during the latter days of containment. We observed the opposite pattern, with most postrelease mortalities during the summer occurring during the first day of containment. In general few mortalities were observed during the fall and spring. The short observation period we employed did not account for potential delayed mortality effects, which can generate positive bias in postrelease survival estimates. Exhaustively exercised fish may suffer delayed mortality associated with osmoregulatory challenges and extended recovery after anaerobic exercise (e.g., capture in a gill-net) (Wood et al. 1983; Bourke et al. 1987; Kieffer 2000). In addition, energy used to recover from the stress of capture cannot be allocated toward growth or reproduction, yielding further potential long-term effects that are unknown. Enclosure studies can effectively capture patterns in postrelease survival over short periods; however, tag-return or telemetry experiments may be more appropriate for estimating total survival rates and other long-term effects associated with capture and discarding.

We were also unable to estimate potential handling and transport effects separately by using a group of control fish (Pollock and Pine 2007); however, it is unlikely that handling and transport effects significantly biased our estimates of postrelease survival. Individual southern flounder retrieved alive from commercial gill nets were held on board for less than 1 h in ambient estuarine water that was exchanged at regular intervals. Further, length measurements and marking with acrylic paint required fish to be held out of the water for less than 1 min.

The survival probabilities of fish within an enclosure can be correlated if, for example, proximity to moribund fish increases the chance of infection in other injured fish in the same enclosure. By treating the enclosure as the experimental unit, we have accounted for enclosure-to-enclosure variation in postrelease survival probabilities (Pollock and Pine 2007). Effects of this type are left unaccounted for in logistic regression modeling; however, close agreement between the logistic regression and enclosure-averaged models presented here indicates that enclosure effects did not bias regression results.

Management Implications

Identifying factors that influence the postrelease survival of discarded fish allows fishery managers to explore management strategies that may reduce discard mortality by limiting the fishery during specific temporal periods or mandating the use of gears that limit the incidental take of nontarget fish. Factors such as ambient water temperature, fish condition upon retrieval, body size, gear soak time, and gear type have each been identified as potentially significant factors influencing the probability of postrelease survival (Murphy et al. 1995; Ross and Hokenson 1997; Davis 2002; Buchanan et al. 2002; Vander Haegen et al. 2004; Reeves and Bruesewitz 2007). For southern flounder in a North Carolina estuarine gill-net fishery, we estimated postrelease survival rates to be much less than 1, particularly during summer months. If the New River can be considered representative of other upper estuarine gill-net fisheries throughout North Carolina, then under current southern flounder management regulations, a considerable level of fishing mortality may be imposed upon young, age-0, and age-1 fish below the minimum size limit, even though these fish are not landed.

The high rate of discarding (35% in this study) and low mean rate of surviving capture in gill nets (50%) in the New River estuary indicate that the North Carolina gill-net fishery may be able to alter fishing tactics to harvest the southern flounder resource more efficiently. One management option for reducing the bycatch of sublegal fish in gill nets is to increase the minimum legal mesh size. Data contained in the most recent fishery management plan for southern flounder in North Carolina demonstrated that increasing the minimum stretched mesh size of gill nets from 140 mm (current minimum) to 152 mm could achieve as much as a 50% reduction in the bycatch of sublegal fish (NCDMF 2005). Furthermore, our logistic regression model predicted that fish in poor condition had an extremely low probability of survival during the summer. Requiring shorter soak times or net attendance during the warm summer months could reduce fish stress and injury, providing for greater postrelease survival.

When combined with estimates of direct fishing mortality, our estimates of postrelease mortality for sublegal fish suggest that total fishing-related mortality for southern flounder is very high during summer months in North Carolina's upper-estuary waters. Smith et al. (2009) demonstrated high monthly instantaneous fishing mortalities of 0.53–0.59 during the summers of 2005 and 2006 in the New River southern flounder gill-net fishery. At the same time of year we also estimated discard survival to be very low (0.22–0.30). The combination of high fishing mortality and low postrelease survival of sublegal discards leads us to conclude that total mortality in this fishery may be exceedingly high during summer months. Seasonal closures have already been implemented in the North Carolina southern flounder fishery to increase fish escapement to offshore spawning grounds at the end of the fall. Our findings suggest that some form of a summer closure of the gill-net fishery may have considerable positive effects. Elevated fishing mortality during the past two decades has been identified as the primary factor responsible for reductions of southern flounder stock biomass in North Carolina waters (NCDMF 2005). The information presented here suggests that alternative management strategies that account for seasonally high discard mortality in the gill-net sector of the fishery could effectively limit total fishing-related mortality on southern flounder.

ACKNOWLEDGMENTS

Funding for this research was provided by North Carolina Sea Grant through the Fishery Resource Grant Program. The expertise of New River commercial fisher Bobby Padgett was essential for capturing southern flounder and selecting sites for placement of our field enclosures. Helpful discussions with Ken Pollock and Howard Bondell (North Carolina State University) facilitated the modeling of this data. Two anonymous referees and the Associate Editor provided several suggestions that considerably improved the manuscript.

REFERENCES

Alos, J., and M. Palmer. 2009. Mortality of *Diplodus annualris* and *Lithognathus mormryus* released by recreational anglers: implications for recreational fisheries management. Fisheries Management and Ecology 16:298–305.

Ayvazian, S. G., B. S. Wise, and G. C. Young. 2002. Short-term hooking mortality of tailor (*Pomatomus saltatrix*) in western Australia and the impact on yield per recruit. Fisheries Research 58:241–248.

Basaran, F., and N. Samsun. 2004. Survival rates of black turbot (*Psetta maxima*, L. 1758) broodstock captured by gill nets at different depths and their adaptation culture conditions. Aquaculture International 12:321–331.

Bourke, R. E., J. Brock, and R. M. Nakamura. 1987. A study of delayed capture mortality syndrome in skipjack tuna, *Katsuwonus pelamis* (L). Journal of Fish Diseases 10:275–287.

Buchanan, S., A. P. Farrell, J. Fraser, P. Gallaugher, R. Joy, and R. Routledge. 2002. Reducing gill-net mortality of incidentally caught coho salmon. North American Journal of Fisheries Management 22:1270–1275.

Butcher, P. A., M. K. Broadhurst, and S. C. Cairns. 2008. Mortality and physical damage of angled-and-released dusky flathead *Platycephalus fuscus*. Diseases of Aquatic Organisms 81:127–134.

Davis, M. 2002. Key principles for understanding fish bycatch discard mortality. Canadian Journal of Fisheries and Aquatic Sciences 59:1834–1843.

Davis, M. W., and B. I. Olla. 2002. Mortality of lingcod towed in a net as related to fish length, seawater temperature, and air exposure: a laboratory bycatch study. North American Journal of Fisheries Management 22:1095–1104.

DuBois, R. B., T. L. Margenau, R. S. Stewart, P. K. Cunningham, and P. W. Rasmussen. 1994. Hooking mortality of northern pike angled through ice. North American Journal of Fisheries Management 14:769–775.

Fabrizio, M. C., F. S. Scharf, G. R. Shepherd, and J. E. Rosendale. 2008. Factors affecting catch-and-release mortality of bluefish. North American Journal of Fisheries Management 28:533–546.

GSMFC (Gulf States Marine Fisheries Commission). 2003. A practical guide for determining the age of Gulf of Mexico fishes: section 5.5. Available: www.gsmfc.org/. (November 2005).

Kass, R. E., and A. E. Raftery. 1995. Bayes factors. Journal of the American Statistical Association 90:773–795.

Kennelly, S. J. 2007. By-catch reduction in the world's fisheries. Springer-Verlag, New York.

Kieffer, J. D. 2000. Limits to exhaustive exercise in fish. Comparative Biochemistry and Physiology 126A:161–179.

Link, W. A., and R. J. Barker. 2006. Model weights and the foundations of multimodel inference. Ecology (Washington, D.C.) 87:2626–2635.

Monaghan, J. P., and J. L. Armstrong. 2000. Reproductive ecology of selected marine recreational fishes in North Carolina: southern flounder, *Paralichthys lethostigma*. North Carolina Department of Environment and Natural Resources, Division of Marine Fisheries, Project F-29, Study 3B, Morehead City.

Montgomery, F. 2000. What percentage of southern flounder survive for three days after being caught in a gill net for up to 12 hours. North Carolina Sea Grant, Fisheries Resource Grant Program, Grant 00-FEG-10, Raleigh.

Murphy, M. D., R. F. Heagey, V. H. Neugebauer, M. D. Gordon, and J. L. Hintz. 1995. Mortality of spotted seatrout released from gill-net or hook-and-line gear in Florida. North American Journal of Fisheries Management 15:748–753.

NCDMF (North Carolina Division of Marine Fisheries). 2005. North Carolina fishery management plan: southern flounder, *Paralichthys lethostigma*. North Carolina Department of Environment and Natural Resources, Elizabeth City.

Neilson, J. D., K. G. Waiwodd, and S. J. Smith. 1989. Survival of Atlantic halibut (*Hippoglossus hippoglossus*) caught by longline and otter trawl gear. Canadian Journal of Fisheries and Aquatic Sciences 46:887–897.

Pollock, K. H., and W. E. Pine. 2007. The design and analysis of field studies to estimate catch- and-release mortality. Fisheries Management and Ecology 14:123–130.

Purbayanto, A., A. Tsunoda, S. Akiyama, T. Arimoto, and T. Tokai. 2001. Survival of Japanese whiting *Sillago japonica* and by-catch species captured by a sweeping trammel net. Fisheries Science 67:21–29.

R Development Core Team. 2005. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available: www.R-project.org. (October 2010).

Reeves, K. A., and R. E. Bruesewitz. 2007. Factors influencing the hooking mortality of walleyes caught by recreational anglers on Mille Lacs, Minnesota. North American Journal of Fisheries Management 27:443–452.

Ross, M. R., and S. R. Hokenson. 1997. Short-term mortality of discarded finfish bycatch in the Gulf of Maine fishery for northern shrimp *Pandalus borealis*. North American Journal of Fisheries Management 17:902–909.

Rudershausen, P. J., and J. A. Buckel. 2007. Discard composition and release fate in the snapper and grouper commercial hook-and-line fishery in North Carolina, USA. Fisheries Management and Ecology 14:103–113.

Rulifson, R. A. 2007. Spiny dogfish mortality induced by gill-net and trawl capture and tag and release. North American Journal of Fisheries Management 27:279–285.

SAS (SAS Institute). 2000. SAS statistical software, version 8. SAS Institute, Cary, North Carolina.

Smith, W. E., and F. S. Scharf. 2010. Demographic characteristics of southern flounder, *Paralichthys lethostigma*, harvested by an estuarine gill-net fishery. Fisheries Management and Ecology 17:532–543.

Smith, W. E., F. S. Scharf, and J. E. Hightower. 2009. Fishing mortality in North Carolina's southern flounder fishery: direct estimates of instantaneous fishing mortality from a tag-return experiment. Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science [online serial] 1:283–299.

St John, J., and C. J. Syers. 2005. Mortality of the demersal West Australian dhufish, *Glaucosoma hebracium*, (Richardson 1845) following catch and release: the influence of capture depth, venting and hook type. Fisheries Research 76:106–116.

Stunz, G. W., and D. A. McKee. 2006. Catch-and-release mortality of spotted seatrout in Texas. North American Journal of Fisheries Management 26:843–848.

Takade-Heumaker, H., and C. Batsavage. 2009. Stock status of North Carolina southern flounder (*Paralichthys lethostigma*). North Carolina Department of

Environment and Natural Resources, Division of Marine Fisheries, Morehead City.

Vander Haegen, G. E., C. E. Ashbrook, K. W. Yi, and J. F. Dixon. 2004. Survival of spring Chinook salmon captured and released in a selective commercial fishery using gill nets and tangle nets. Fisheries Research 68:123–133.

Wassenberg, T. J., and B. J. Hill. 1993. Selection of the appropriate duration of experiments to measure the survival of animals discarded from trawlers. Fisheries Research 17:343–352.

Watterson, J. C., and J. P. Monaghan Jr. 2001. Flounder pound net fishery: in assessment of North Carolina commercial finfisheries, 1997–2000. North Carolina Department of Environment and Natural Resources, Division of Marine Fisheries, Grant F-71 Segments 1–2, Morehead City.

Wenner, C. A., W. A. Roumillat, J. E. Moran Jr., M. B. Maddox, L. B. Daniel III, and J. W. Smith. 1990. Investigations on the life history and population dynamics of marine recreational fishes in South Carolina: part 1. South Carolina Wildlife and Marine Resources Department, Marine Resources Research Institute, Charleston.

Williams, E. H. 2002. The effects of unaccounted discards and misspecified natural mortality on harvest policies based on estimates of spawners per recruit. North American Journal of Fisheries Management 22:311–325.

Wood, C. M., J. D. Turner, and M. S. Graham. 1983. Why do fish die after severe exercise? Journal of Fish Biology 22:189–201.