POPULATION DEMOGRAPHICS OF SOUTHERN FLOUNDER IN THE NEW
RIVER, NORTH CAROLINA GILL NET FISHERY

William E. Smith

A Thesis Submitted to the
University of North Carolina Wilmington in Partial Fulfillment
of the Requirements for the Degree of
Master of Science

Department of Biology and Marine Biology

University of North Carolina Wilmington

2007

Approved by

Advisory Committee

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Chair

Accepted by

_____
Dean, Graduate School

This thesis has been formatted

for submission

in the journal,

Transactions of the American Fisheries Society

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ABSTRACT

The North Carolina (NC) fishery for southern flounder (*Paralichthys lethostigma*) is currently listed as overfished by the North Carolina Division of Marine Fisheries, and in 2005 management changes were enacted in the fishery in order to achieve a 2005 reduction in fishing mortality. Virtual Population Analysis models are currently used to assess fishing mortality (F) in the NC southern flounder stock, but direct estimates may be more accurate. Direct estimates of F in the New River, NC gill net fishery for southern flounder were obtained for years 2005 and 2006 using tag-returns and accounting for return rate, tag retention, and mortality due to tagging. Annual estimates of F and their probability distributions, $F_{2005} = 1.02$ (SE = 0.095) and $F_{2006} = 1.54$ (SE = 0.222), indicated a high probability that F attained the targeted fishing mortality of $F_{target} = 0.95$ in 2005 and a very low probability (p=0.0068) that F attained the target in 2006 in the New River gill net fishery. High interannual variability in F was found, which agrees with recent stock assessments. The results suggest that under the current regulations, F will potentially continue to exceed the target in some NC estuaries, and additional management measures may be necessary in order to reduce F to the target in all systems in which the fishery is executed.

Recoveries of previously tagged fish were used in a catch composition analysis of the length frequency, size at age, and maturity of southern flounder harvested in the New River gill net fishery, demonstrating the potential effects of the fishing strategy on long-term yield. Examination of the length frequency distribution indicates that approximately 36% of the catch is composed of sub-legal southern flounder that are discarded, with unknown consequences on mortality. It appears that the fishery is targeting age-1

southern flounder (88% total catch), and all age-0 and age-1 fish exhibited above average growth for southern flounder in NC. 28% of females captured in the months previous to the spawning season were distinguishable as mature, and approximately 19% of the catch may have had the opportunity to spawn in the spawning season previous to their capture, suggesting that much of the catch is immature. Recent evidence suggests that a high removal rate of fast-growing, immature animals can have deleterious effects on long-term yield in the fishery. Yield per recruit analysis and maturity schedules demonstrated that delaying age at entry into the fishery until age-2 may potentially provide higher, more stable yields that are robust to interannual variability in fishing mortality, while also allowing more fish to spawn before becoming subject to the fishery.

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CHAPTER 1. FISHING MORTALITY IN NORTH CAROLINA'S SOUTHERN FLOUNDER FISHERY: TAG-RETURN ESTIMATES FROM THE NEW RIVER, NC

INTRODUCTION

Modern stock assessment scientists have several tools that allow them to estimate the level of fishing mortality experienced by a population. Common methods for determining mortality rates include catch curve analysis, virtual population analysis (VPA), and statistical catch-at-age analysis, all of which are variations of depletion models. One common depletion model in use today, VPA, uses landings data that are often "tuned" with fisheries-independent estimates of relative abundance to reconstruct past levels of biomass or stock size which must have existed to produce the current age structure and landings (Gulland 1983; Hilborn and Walters 1992). Depletion models make assumptions concerning both population and observation dynamics, or the relationship between observed data (landings) and biomass or stock size. When inaccuracies in stock assessments have been closely scrutinized, violations have often been noted in observation dynamics assumptions, particularly those related to changes in gear selectivity and catch per unit effort (catchability) through time and space (Hutchings and Meyers 1994; Swain et al 1994; Walters and Maquire 1996). Observation dynamics are incorporated into VPA models through "tuning" parameters, which correct for statistical, retrospective biases in the data that can make VPA unreliable for the most recent years of an assessment (Gulland 1983; Hilborn and Walters 1992). Violations of population dynamics assumptions, including incorrect estimates of natural mortality rate and lack of understanding about patterns of migration, are also common (Hilborn and Walters 1992).

Inaccurate estimates by some stock assessments that have contributed to the collapse of marine fisheries have been attributed mainly to violations of observation dynamics assumptions, specifically in parameters used to "tune" VPA models. For instance, reviews of cod stock assessments from the 1980's and early 1990's have concluded that misspecified "tuning" parameters, specifically age-specific fishing mortalities in the most recent year of the VPA, led to grossly overestimated stock sizes and underestimated fishing mortality; a problem which has since been ascribed to changes in gear selectivity and catchability as stock sizes declined. Changes in catchability violate the typical observation dynamics assumption of constant catchability. Although it appeared that stock size was increasing and fishing mortality was declining during the 1980's and early 1990's in the cod fishery, in reality, catchability had increased, due to technological advances in fishing techniques coupled with changes in fishing behavior (Hutchings and Meyers 1994), stock size was declining, and fishing mortality was rapidly escalating (Swain et al. 1994). Thus, the "tuning" parameters used in the VPA models, in addition to severe retrospective biases, likely played a key role in the cod fishery collapse (Walters and Maquire 1996). Moderately updated versions of the VPA models that were used to assess cod populations are currently considered state of the art; however, several authors have argued that direct estimates of fishing mortality may be more accurate (Hilborn and Walters 1992; Myers et al. 1996; Walters and Martell 2002). Indeed, Myers et al. (1996) used tag-return data available at the time of the cod collapse to estimate higher fishing mortality than was estimated by the VPA models. In hindsight, the tag-return data may have provided a more accurate estimate of fishing mortality in the cod fishery than the VPA models that were used.

Tag-return models can directly estimate fishing mortality while making fewer and simpler assumptions that are easily met with adequate study design. At the least, tagging studies allow estimates of fishing mortality that have different biases than those generated from VPA models. Some general assumptions of tagging models include: (1) tagged fish are representative of the entire population and are randomly distributed; (2) tagged fish experience the same mortality as untagged fish; and (3) no tags are lost, overlooked, or unreported (Ricker 1975). Tag-return models also have the advantage of providing current estimates of mortality that are free of the retrospective biases that plague VPA estimates of fishing mortality in the most recent years. Unbiased and current estimates of fishing mortality are critical for fishery managers who must often make rapid management decisions based on recent trends in the fishery.

North Carolina's commercial fishery for southern flounder (*Paralichthys lethostigma*) has been characterized by extremely high levels of fishing mortality for the last twenty years. Harvest mortality began to trend upward in the early 1980's when many fishermen shifted to inshore gillnets to target southern flounder in the estuaries in response to more restrictive regulations in the summer flounder (*P. dentatus*) fishery offshore. The increased effort resulted in highly elevated rates of fishing mortality for southern flounder by the early 1990's. The rate of instantaneous fishing mortality (F) in North Carolina waters was estimated to have ranged between 1.77 and 3.43 during 1991 - 2002, based on the most recent stock assessment performed by the North Carolina Division of Marine Fisheries (NCDMF 2004) (Figure 1). The NCDMF currently lists the southern flounder stock as overfished (stock biomass below target), and indicates that overfishing (F above target) is still occurring. To reduce annual harvest rates, several management changes were initiated in 2005 that included an increase in the minimum

size limit to 356 mm (14 inches) TL, closure of the fishery each year during December, an eight fish recreational bag limit, and specific gear restrictions for gill nets targeting southern flounder (NCDMF 2004). In the most recent southern flounder fishery management plan, a long-term target of 25% spawning potential ratio (SPR) was specified, with a threshold SPR set at 20% (NCDMF 2004). Age-structured model projections predicted that a 30% reduction in the discrete rate of fishing mortality ($u = 0.52$, $F = 0.95$) would achieve 25% SPR by 2008, and a 20% reduction in the discrete rate of fishing mortality ($u = 0.60$, $F = 1.19$) would nearly reach the threshold of 20% SPR by 2009 (NCDMF 2004).

The southern flounder fishery in North Carolina has several features which may act to confound analyses of fishing mortality that are based on depletion models. First, the population is not closed to migration, which is a violation of one of the population dynamics assumptions of depletion models. A previous large-scale tagging study found that many southern flounder tagged in North Carolina migrate south to South Carolina, Georgia, or Florida (Monaghan 1992); so the North Carolina stock should not be treated as a closed population. Further, the North Carolina southern flounder fishery exhibits a complex pattern of gear selectivity, which complicates and may violate observation dynamics assumptions of depletion models. The fishery is executed with several gear types, including large-mesh gill nets, pound nets, gigs, trawls, and hook and line, each of which has a different gear selectivity (NCDMF 2004). Finally, the fishery is characterized by a pulse of elevated landings and high catch per unit effort in the fall, when fishermen target flounder as they migrate offshore prior to spawning (Watterson and Monaghan 2001). Therefore, the observation dynamics assumption of constant catchability may be violated. Because the nature of the fishery may cause fishery-

dependent data to violate several assumptions of depletion models, direct estimates of fishing mortality from a tag-return experiment may generate more reliable estimates of F. Tag-return models do not require the assumption of a closed population, and make no assumptions about variation in catch per unit effort.

Here we report on the results of a large tag-return experiment conducted in the New River, NC. The objectives were to characterize the levels of fishing mortality that may be experienced by southern flounder subject to the gill net fishery in the estuarine nursery areas of southeastern NC, assess the level of interannual variability in harvest rates, and evaluate the predicted short-term effects of recent management changes enacted to reduce harvest. These estimates represent the first direct estimates of fishing mortality in the North Carolina southern flounder fishery.

METHODS

Study system

The New River was selected for this study because it is representative of the several coastal plain rivers in the southeastern region of North Carolina and it has many features that make it particularly suited to conduct a tag-return experiment. The system is a semi-enclosed estuary with the intracoastal waterway and a single primary connection to the ocean as the only corridors for movement into and out of the system. Therefore, only limited mixing with southern flounder from other systems is likely during the fishing season. The end of the fishing season each year is marked by a large emigration event as mature southern flounder move offshore for spawning during late fall and early winter (Watterson and Monaghan 2001). The New River is also characteristic of many of the other river systems in southeastern NC in the execution of the southern flounder

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fishery. Monofilament gill nets, the predominant gear currently used in these systems, are generally fished overnight from small vessels. Historically, pound nets were also utilized by southeastern NC fishermen; however, the use of pound nets has declined in recent years and their current use in North Carolina is mainly restricted to larger bays (e.g., Pamlico Sound) in the northern region of the state (NCDMF 2004).

Tagging

Sampling was designed to tag and release at least 1000 southern flounder in the New River during both 2005 and 2006 fishing seasons. To capture fish, partnerships were formed with three New River commercial gill netters who each fished different areas of the river in order to evenly distribute releases of tagged fish throughout the river. Flounder were captured in 14cm (5½ inch) stretched mesh gill nets that were soaked for approximately twenty-four hours. Only fish in good condition (not wounded and behaviorly responsive) and of legal size ($\geq$ 356 mm TL) were used in the tagging experiment. After net retrieval, fish were held in insulated coolers for 5 - 15 min, then tagged and released at least 200 meters from the area where the fish was captured, in water of at least two meters depth. Fish were tagged in the dorsal region of the caudal peduncle with bright orange cinch-up tags (Floy Tag, Inc.) that were printed with a cash reward amount, a unique identification number, and contact information. Twenty percent of fish were tagged with high reward (US$50) tags and the remaining fish were tagged with standard reward (US$5) tags. Although other studies have suggested that rewards up to $100 may be necessary to ensure 100% reporting (Nichols et al. 1991), we believed that a $50 reward would be sufficient in the New River fishery based on the socioeconomic landscape of the community. Among the fish tagged with standard

reward tags, approximately 200 fish were double tagged each year to assess the potential

for tag loss. Recoveries of tagged flounder were solicited from fishermen via fliers at gas

stations and boat ramps, press releases in local newspapers, and through face to face

meetings with the investigators.

Since sufficient numbers of fish could not be captured and tagged before the

primary part of the fishing season began, fish were tagged during each month of the

fishing season (June to November in 2005 and January to November in 2006). A

monthly time step was then incorporated into the tagging model to better meet model

assumption 6 listed below. Monthly instantaneous rates of fishing mortality, F, and their

95% confidence intervals were calculated and then summed across months each year to

generate annual rates.

Estimating Fishing Mortality

To estimate F using a tag-return experiment, several specific assumptions must be

met (Ricker 1975; Youngs and Robson 1975):

1.   The mortality of tagged fish does not differ from the mortality of untagged fish

2.   No tags are lost

3.   All tags are recognized and reported upon recovery

4.   Tagged fish randomly mix with untagged fish

5.   Tagged fish are caught at the same rate as untagged fish

6.   All fish are released instantaneously at the start of each (monthly) interval

Each of the assumptions was accounted for in our estimation of fishing mortality.

External estimates of tagging-related mortality (assumption 1), tag loss (assumption 2),

and incomplete reporting (assumption 3) were used to relate the return rate, f, to the discrete rate of fishing mortality, u:

$$f = \Phi s \lambda u \qquad \text{(Equation 1)}$$

where Φ was the proportion of fish that retained their tag, s was the estimate of short-term tagging survival, and λ was the rate at which recovered tags were reported (modified from Hoenig et al. 1998a). We included an empirical estimate of survival related to the tagging process (s) that resulted in a modification to the original equation presented by Hoenig et al. (1998a).

A common approach to assess tag loss involves placing two tags (double tagging) in a subset of fish and estimating tag loss by observing the proportion of double tagged fish recovered with only one tag intact (Beverton and Holt 1957). To estimate tag loss using double tagged fish, three assumptions must be met: (1) tags attached to the same animal can be regarded as a random sample from all tags; (2) shedding of one tag occurs independently of the shedding of other tags, including those attached to the same animal; and (3) natural mortality, migration, catchability, and reporting rate are independent of the number of tags attached to an animal (Hearn et al. 1991, Wetherall 1982). An estimate of Φ, the probability that a fish retains its tag, was calculated using:

$$\Phi = 2n_2/(2n_2 + n_1) \qquad \text{(Equation 2)}$$

where n_2 was the number of doubled tagged fish recovered with both tags intact and n_1 was the number of double tagged fish recovered with only one tag intact (Chapman et al. 1965). Thus, the probability that a fish survived the tagging process (s), with tag intact was estimated by the product Φs. Southern flounder were tagged and held in laboratory tanks for one year in order to estimate s. Some double tagged fish, n_0, may have been recovered after having lost both tags. An estimate of n_0 was generated using

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$n_0 = n_1^2/4n_2$　　　(Hearn et al. 1991) (Equation 3).

When a fisherman recovers a tagged fish, they may or may not report the tag.
Incomplete reporting of recovered tags has been recognized as a shortcoming in tag-
return studies dating back to the 1940's (Bellrose 1945). One method for assessing the
reporting rate (λ) involves releasing a subset of tags labeled with a high reward for the
return of the tag. Bellrose (1955) was the first to document this approach while studying
mallard harvest mortality, and the approach has been reviewed recently by Pollock et al.
(2001). To estimate λ using high reward tags, it is necessary to assume a 100% reporting
rate for high reward tags. If a difference in the return rate of high reward and standard
tags is found, the return rate of standard tags must be adjusted by a factor of λ, calculated
as

$\lambda = f_{standard}/f_{high\ reward}$　　(modified from Henny and Burnham 1976) (Equation 4).

The model's sensitivity to Φ, s, and λ was analyzed by either increasing or decreasing all
three parameters by 10% in the tagging model.

The traditional approach to modeling tag-return data uses the Brownie (1985)
model, which estimates the number of expected recoveries based on the number of
individuals tagged during each time period (N_i), the return rate (f), and the rate of
survival (S) from one time period to the next (Table 1A). The Brownie model is a
discrete rates model; however, an instantaneous rates formulation was more appropriate
for modeling the southern flounder tag-return data that we collected. Instantaneous rates
are commonly used in fisheries stock assessments and have the advantage of additivity.
Therefore, our estimates of fishing mortality generated on a monthly time step could be
summed into annual instantaneous rates of fishing mortality, which are easily
incorporated into stock assessments. The instantaneous rates formulation of the Brownie

model (Table 1B) (Ricker 1975; Hoenig et al. 1998a) generates the number of expected

recoveries, R_{ij}, of fish tagged at time i = 1, 2, 3 … I and recovered at time j = i, i + 1, i +

2 … J. R_{ij} is equal to $E(R_{ij}) = N_i P_{ij}$. The individual cell probabilities of recovery at time

j, P_{ij}, were given by

$$P_{ij} = \begin{cases} \left(\prod_{v=i}^{j-1} S_v \right)(1-S_j)(F_j/Z_j)\Phi\lambda & \text{(when } j > i) \\ (1-S_j)(F_j/Z_j)\Phi\lambda & \text{(when } j = i) \end{cases} \qquad \text{(Equation 5)}$$

where $Z_j = F_j + M_j$. The full likelihood, L, of the model was given by

$$L \propto \prod_{i=1}^{I} \left(\prod_{j=i}^{J} P_{ij}{}^{R_{ij}} \right)(P_{iJ^*})^{N_i - \Sigma_j R_{ij}} \qquad \text{(Equation 6)}$$

and

$$P_{iJ^*} = 1 - \sum_{j=i}^{J} P_{ij} \qquad \text{(Hoenig et al. 1998a). (Equation 7)}$$

P_{iJ^*} is the probability that a fish from cohort i is not recovered. The program SURVIV

(White 1992) was used to generate maximum likelihood estimators of all model

parameters, given the above model structure and observed recoveries. The SURVIV

software maximizes cell probabilities to iteratively fit parameter values.

There were some months during year 2005 (January – July) and 2006 (January -

April) in which little or no tagging occurred. Since an annual estimate of F was desired

for both years, monthly estimates of F had to be generated for the missing months to

calculate annual Fs. To estimate F during January – July 2005 and January - April 2006,

linear regression analysis was performed using New River monthly commercial landings

(NCDMF commercial harvest statistics) as an explanatory variable and tag-return model

estimates of monthly F's from August - November 2005 and May - November 2006 as a

response variable. If monthly Fs estimated by the tagging model were strongly related to monthly fishery landings trends, then the regression model parameters and their standard errors could be used to predict F estimates and 95% confidence intervals for months in which we lacked data.

The annual estimate of F for 2005 was estimated as the sum of monthly SURVIV-estimated F's from August - November 2005 and the monthly regression-estimated F's from January - July 2005. The annual estimate of F for 2006 was estimated as the sum of monthly SURVIV-estimated F's from May - November 2006 and the monthly regression-estimated F's from January - April 2006. Based on the annual F estimates, their degrees of freedom, and the standard errors of the estimates, t-tests were performed in order to determine the probability that the target ($F = 0.95$) may have been achieved in either 2005 or 2006. The t-score for each year was calculated as $(\tilde{y} - u_o)$/(model standard error), under the assumption $u_o = 0.95$ and where $\tilde{y}$ was each annual F estimate. The one-tailed probability distribution indicates the probability that the F estimate was greater than the target F.

Model Selection

A full model and four reduced models, with different groupings of natural mortality, were tested in SURVIV. In the full model, F was allowed to vary by month, and M was allowed to vary by year, while being held constant over all months within a year. It is not feasible to estimate a separate F and M for each period (Hoenig et al. 1998a), but monthly estimates of F were required to characterize the highly seasonal nature of the fishery and to evaluate the effects of the recently amended management regulations. Four reduced models were tested: (1) a single M was estimated for both

years 2005 and 2006, (2) M was fixed across both years at the rate determined in the most recent southern flounder stock assessment (M=0.404) (NCDMF 2004), (3) M was fixed across both years at the lowest rate calculated through common life history methods, and (4) M was fixed across both years at the highest rate calculated through common life history methods. The best models were selected based on the lowest Aikake's Information Criteria (AIC). AIC is commonly used in model selection because it provides a balance between the fit of the model and the number of parameters in the model, and is calculated as

$$AIC = 2k - 2\ln(L) \qquad \text{(Equation 8)}$$

where k equals the total number of parameters in the model and L is the likelihood given in Equation 6.

Models that did not deviate significantly from the lowest AIC appeared to perform equally well given the data and were not significantly different in model fit. F estimates were averaged over these candidate models to reflect uncertainty in model selection. All candidate models from 1 to R were assigned a normalized weight, w_r, scaled by the model with the lowest AIC (AIC_{min}):

$$w_r = \frac{\exp(-(AIC_r - AIC_{min})/2)}{\sum_{r=1}^{R} \exp(-(AIC_r - AIC_{min})/2)_r} \qquad \text{(Equation 9)}.$$

The weighted average monthly fishing mortalities F_θ over all candidate models were

$$F_\theta = \sum_{r=1}^{R} w_r F_r \qquad \text{(Equation 10)}$$

with estimated variance

$$\text{var}(F_\theta) = \left[\sum_{r=1}^{R} w_r \sqrt{\text{var}(F_r) + (F_r - F_\theta)^2} \right]^2 \qquad \text{(Equation 11)}$$

where var(F_r) is the variance of F estimated by candidate model r (Hightower et al. 2001).

For tagging models in which M was fixed, several estimates of natural mortality were calculated using common life history methods. The methods for estimating natural mortality of Hoenig (1983), Lorenzen (1996), and Pauly (1980) were explored. A detailed summary of these methods for estimating natural mortality can be found in Hilborn and Walters (1992). The Hoenig (1983) method estimates natural mortality based on the maximum observed age, using a regression equation relating maximum age and total mortality rate for lightly exploited and unexploited stocks. The oldest southern flounder aged in North Carolina was eight years old (NCDMF 2004). Lorenzen (1996) estimated age-specific natural mortality based on the average weight at age. Average weights at age for age-1 and age-2 southern flounder in North Carolina, collected from a combination of fisheries-independent and fisheries-dependent sources, are listed in the most recent fishery management plan (NCDMF 2004). Fish tagged in this study consisted of a majority age-1 and age-2 fish (Smith and Scharf, unpublished data). The Pauly (1980) method estimates natural mortality using the asymptotic maximum length (L_∞), the Brody growth coefficient (K), and average ambient water temperature. Long-term ambient water temperature data, available online from the NOAA National Oceanographic Data Center, indicated that $20^{o}C$ represented the approximate average ambient water temperature to which southern flounder in North Carolina may be exposed. L_∞ and K can be found in the von Bertalanffy growth model that is commonly used to describe fish growth. Von Bertalanffy growth model parameters were compiled from peer-reviewed sources that describe southern flounder growth in Texas (Matlock 1991a; Matlock 1991b; Stuntz et al. 2000) and Louisiana (Fischer and Thompson 2004) and from management agency reports describing southern flounder growth in South

Carolina (Wenner et al. 1991) and North Carolina (NCDMF 2004). Nine estimates of natural mortality were calculated, and the highest and lowest estimates of natural mortality were used to fix natural mortality across a likely range of M in the tagging models described above.

Assessing Potential for Violations of Tag-Return Model Assumptions

The model residual matrix was examined for violations of the basic tag-return model assumptions outlined above. Latour et al. (2001) demonstrated that an examination of the model residual matrix, the observed recoveries matrix minus the predicted recoveries matrix, can reveal violations of model assumptions. The model residual matrix is organized similarly to the Brownie model outlined in Table 1A, with numbers of recoveries of cohorts tagged in the same month arranged in rows and month of recovery arranged in columns. The potential existence of non-mixing (Hoenig et al. 1998b), emigration from the study area, and a change in the rate of natural mortality can be detected by a thorough investigation of the model residuals. Non-mixing produces a pattern of negative residuals along the main diagonal, combined with positive residuals along the super diagonal. This pattern results from a lower than expected rate of recovery during the initial time period of release, resulting in higher than expected survival in the initial time period, and thus, higher than expected recoveries in the subsequent time period. Emigration from the study area generates a cluster of negative residuals in the upper right corner of the model residual matrix, as fish move out of the study area and are never seen again. Changes in natural mortality create patterns of positive or negative residuals in the columns of the matrix, because either fewer (negative residual) or more

(positive residual) individuals than expected survive from one time period to the next, regardless of the time period of release.

RESULTS

In total, 1008 southern flounder were tagged in 2005 and 962 fish were tagged in 2006. Recoveries of 2005 tags numbered 293 during the 2005 fishing season and an additional 46 fish that were recovered during 2006. Recoveries of 2006 tags numbered 486 during the 2006 fishing season (Table 2). Twenty flounder were tagged and held in laboratory tanks for up to one year, with only three mortalities related to the tagging process. Therefore, the probability of surviving the tagging process (s) was estimated as 0.85. Although no fish held in laboratory tanks experienced tag loss, some double tagged fish were recovered with only one tag intact. Of 383 total double tagged fish released, 155 double tagged fish were recovered. Only 4 fish had only one tag intact (n_1), while 151 had both tags intact (n_2). The probability of retaining the tag (Φ) was estimated to be 0.974 (eq. 2), and the probability of surviving and retaining the tag intact (Φs) was then estimated as 0.828 for this study. n_0 was estimated to be 0.026 (eq. 3), so it is unlikely that any double tagged fish lost both tags and were recovered. Of 1583 standard tags that were released 601 were returned ($f_{standard} = 0.380$), compared to 152 returns out of 385 high reward tags that were released ($f_{high reward} = 0.395$), resulting in a reporting rate, λ, estimate of 0.985 during the study (eq. 4).

Due to sparse returns of tagged fish after the overwinter period, recoveries of fish in the second year after tagging (recoveries of 2005 tags in 2006 and recoveries of 2006 tags in 2007) were not included in the model. Many recoveries of tags in the second year after tagging occurred at substantial distances south of the New River. For instance, one

fish tagged in 2005 was recovered near Hilton Head Island, SC in 2007. Due to the high probability that fish migrated to areas with different reporting rates and natural and fishing mortalities after the year of their tagging, leading to lower than expected recoveries, only recoveries within the year of tagging were considered in the model.

Natural mortality estimates used in tagging models with fixed Ms ranged from M = 0.20 to M = 0.58. The difference in AIC scores among all models tested in SURVIV was less than four, indicating that no model had a significantly improved model fit relative to any other model. Thus, all five candidate models were averaged to yield partial annual estimates of F. All models generated point estimates of F that were very similar (Table 3), which demonstrated that the F estimates were generally robust, regardless of how natural mortality parameters were estimated. Sensitivity analysis revealed that the model estimate of F were extremely sensitive to the parameters Φ, s, and λ (Table 4). Assuming that all three parameters were underestimated, a 10% increase in Φ, s, and λ resulted in a 29% decrease in the F_{2005} estimate and a 21% decrease in the F_{2006} estimate. Assuming that all three parameters were overestimated, a 10% decrease in Φ, s, and λ resulted in a 50% increase in the F_{2005} estimate and a 75% increase in the F_{2006} estimate.

Regression analysis indicated that 44.8% of the variation in F estimates during August - November 2005 and May - November 2006 could be explained by the trend in monthly commercial landings of southern flounder in the New River (Fig. 2). The sum of the regression model predictions of F for months during which inadequate numbers of fish were tagged and released, January - July 2005 and January - April 2006, were $F_{2005} = 0.46$ (SE = 3.10 x 10^{-5}) and $F_{2006} = 0.018$ (SE = 1.77 x 10^{-5}). This sum was added to the tagging model estimate of F, $F_{2005} = 0.57$ (SE = 0.095) and $F_{2006} = 1.52$ (SE = 0.222),

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yielding total F estimates of 1.02 (95% CI = 0.84 - 1.21; SE = 0.095) for 2005 and 1.54

(95% CI = 1.10 - 1.97; SE = 0.222) for 2006 (fig. 3). Given the annual F estimates of the

averaged model and the standard errors of the estimates, t-tests indicated that the

probability of F being equal to or exceeding the target F of 0.95 in the New River gill net

fishery was about 76% (p= 0.24) during 2005, and was over 99% (p = 0.0068) during

2006.

Examination of the model residual matrix revealed the potential for non-mixing of

tagged and untagged flounder during the study. A consistent pattern of negative residuals

along the main diagonal followed by positive residuals along the super diagonal was

apparent (Table 5). This pattern may have been generated by the continual release of

tagged fish throughout each month, which may have subjected fish to less than the full

mortality during the initial month of their release. Assumptions related to the continuous

release of tags, non-mixing, and their effects on model output should be examined further

in future modeling of this data.

DISCUSSION

Estimates of Fishing Mortality

The results of our tagging experiment indicate that the short-term goal of a 30%

reduction in southern flounder harvest may have been achieved in 2005, but was not

likely attained in 2006 in the New River gill net fishery. Examination of the error

associated with our estimates of F in the New River demonstrated a moderate probability

that F did not exceed the target F (0.95) during 2005, but a very low probability that this

goal was met in 2006 (Fig. 3). Although estimates of F varied between years, it was very

likely that fishing mortality in the New River exceeded the short-term goal of F = 0.95

during one of the study years (2006), implying that, at least in New River, it may take longer than 2008 before the management goal of 25% SPR is achieved. More importantly, our direct estimates of F revealed that, despite recent management changes, the potential for overfishing may still be high for the gill net component of the southern flounder fishery in the southeastern region of the state.

Sensitivity analysis revealed that the model was sensitive to the parameters estimating reporting rate, tagging survival, and tag retention; however, a 10% perturbation of these parameters did not alter the conclusion that fishing mortality likely exceeded the target in 2006. As tag reporting (λ) and tag retention (Φ) estimates were relatively high for this study, these parameters were more likely to be overestimated than underestimated, resulting in a negative bias in F and conservative estimates. We believe that λ and survival of the tagging process (s) may have varied across months, but lack the data at present to confirm either of these possibilities. It is possible that the model's accuracy and precision would be improved by better estimates of variation in λ and s. It is likely that reporting rate was underestimated in this study due to an inadequate reward amount for the high reward tags. In this case, the actual fishing mortality may have been higher than estimated in this study. Although fishing mortality was the parameter of interest during this study, better estimates of natural mortality would also likely have improved the precision and accuracy of our F estimates. Determining the fate of individuals using telemetry, when combined with traditional tag-return designs, offers a promising approach to obtain accurate estimates of natural mortality (see Pollock et al. (2004) for methodological details). Although the method of combining tag-return and telemetry studies has yet to be field tested and documented in the literature, Hightower et al. (2001) used telemetry methods to estimate fishing and natural mortality of striped bass

in Gaston Lake, NC, and Thompson et al. (2007) used the same technique to estimate fishing and natural mortality of striped bass in Badin Lake, NC.

Future tag-return studies in the North Carolina southern flounder fishery could avoid potentially biased data by tagging fish throughout the state in order to better understand migration patterns, regional variation in reporting rates, and seasonal and spatial variability in tag loss. More substantial (e.g., US$100) rewards for high reward tags may yield reporting rates closer to 100%, and an assessment of seasonal variability would improve estimates of the probability of surviving the tagging process. Natural mortality was poorly estimated by the tag-return model - models in which natural mortality was not fixed estimated M with low precision; therefore, more accurate estimates of natural mortality, such as through telemetry methods, are in order.

Data Limitations and Interpretation

Our estimates of F in the New River gill net fishery for southern flounder may be conservative. Both F_{2005} and F_{2006} estimates may have been negatively biased by a violation of the mixing assumption (assumption 6), the potential for which was revealed by analysis of model residual error (Table 5). Spatial non-mixing or the continual release of fish throughout each month could have produced a lower than expected recovery rate, and thus a negatively biased F estimate, because fish that were released later in the time period were available to be recovered for a shorter length of time. Furthermore, if reporting rate was underestimated, then the standard model estimates of fishing mortality would be negatively biased. Therefore, we conclude that the fishing mortality rates estimated in this study may be conservative and that the true values of F could have been greater during both years.

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The estimate of F generated by our models for 2005 may not be representative of fishing mortality under the new regulations. By all accounts, 2005 was a poor year in the North Carolina southern flounder fishery. The newly instituted regulations required many fishers to purchase new gill nets, since the minimum stretched mesh size increased from 133 mm (5¼ inches) to 140 mm (5½ inches). We believe that the required gear changes, coupled with poor catch per unit effort (Fig. 4A), led to a decline in participation in the New River southern flounder fishery during 2005. This was reflected in the unusually low number of commercial trips targeting southern flounder during 2005 relative to other years (Fig. 4B). Both effort and catch per unit effort were lower during the 2005 fishing season than any other year between 1998 and 2006. A combination of environmental and regulatory factors appeared to operate synergistically to generate the moderate level of fishing mortality observed during 2005 that may not accurately reflect average conditions in the fishery. Effort and landings during 2006 were more in line with long term averages suggesting that the level of fishing mortality estimated for 2006 is a more likely representation of expected fishing pressures under the new regulations.

We acknowledge that the fishing mortality estimates generated during this study represent fishing mortality for only a single system occupied by the North Carolina southern flounder stock. Among several reasons, the New River was chosen for this study because it is representative of the small river systems located in the central and southern regions of the state, where the southern flounder fishery is executed primarily with gill nets in shallow nursery habitats. Commercial fisheries for southern flounder in many of the larger systems (e.g., Pamlico Sound) in the northern region of the state are executed using different fishing gears (e.g., pound nets) and practices. Our estimates of F in the New River are probably best interpreted as a regional estimate of fishing mortality

within an estuarine nursery habitat that experiences moderately high fishing pressure on a consistent annual basis.

Management Implications

The results of this study suggest that fishing mortality in the North Carolina southern flounder gill net fishery has the potential to greatly exceed targeted levels. In spite of recently amended regulations in this fishery, fishing mortality still approached the 1991 - 2002 average level of $F = 1.91$ for the North Carolina stock (NCDMF 2004). If the levels of fishing mortality that we found are common throughout the state and if the fishery continues to exert this degree of pressure on the stock, short-term SPR recovery targets are unlikely to be met, SPR will probably remain low, and recovery from overfishing could be delayed for several years. In terms of spawning stock biomass, the NCDMF (2004) estimated that if fishing mortality remains at the 1991 - 2002 level, only 5.4 % percent of the virgin stock biomass would be retained, which is well below what is considered sustainable in most fisheries (25 - 40% virgin spawning stock biomass). Our estimates of fishing mortality indicate that further reductions in harvest may be necessary to achieve management goals.

Extended periods of high fishing mortality in nursery areas could have severe consequences for the overall health of the stock. We observed that 88% of all recovered flounder in this study were age-1 fish, which also appeared to be above average size for their age (Smith and Scharf unpublished data). During the fall months, October and November, leading up to the winter spawning season only 28% of the recoveries were distinguishable as mature, and, based on age at recapture, only 19% of all recoveries throughout the study likely had the opportunity to spawn in the previous spawning season

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(Smith and Scharf, unpublished data). Furthermore, approximately 36% of fish captured

during tagging consisted of sub-legal discards, for which mortality is unknown.

Therefore, the New River gill net fishery imposes a very high level of fishing mortality

on predominantly young, fast-growing, and immature members of the southern flounder

stock. Recent findings indicate that fish stocks may rapidly evolve in response to

selective harvest, producing life history traits (e.g., slow growth and early maturation)

that may eventually compromise long term yield (Heino 1998; Conover 2000; Hutchings

2000; Law 2000). Given historical fishing patterns within the North Carolina southern

flounder fishery, alternative management strategies may be necessary to reduce harvest

pressure in estuarine nurseries and conserve life history traits that influence stock

productivity.

One potential alternative may be to manage for optimum yield by maximizing

yield per recruit (YPR). Age-structured, YPR models assume that each cohort

simultaneously experiences both growth and mortality (Deriso 1987). YPR models then

combine age-specific natural mortality with growth trajectories of fish in the harvested

population to estimate the age at entry and fishing mortality that optimize yield in the

fishery (Ricker 1975). We constructed YPR models using the average weight at age for

female southern flounder in North Carolina and the range of natural mortality rates

calculated using life history methods, which were used in the tagging model. While

historical landings data and observations during this study indicate that many age-1 fish

are captured in this fishery (NCDMF 2004; Smith and Scharf unpublished data), our YPR

modeling revealed that, given the average growth rate of southern flounder in North

Carolina waters, the population could sustain relatively high fishing mortality rates while

maintaining yield if entry into the fishery was delayed until age-2. Across the range of

natural mortalities examined, the fishing mortality associated with maximum YPR (F_{max})

when fish enter the fishery at age-2 was higher than the F_{max} when fish enter the fishery at

age-1 (Fig. 5). In models with a low assumed rate of natural mortality, as F increased

beyond F_{max} yield declined more gradually when age-at-entry was delayed until age-2

compared with age-1. Furthermore, when intermediate levels of natural mortality were

assumed, the YPR for age-2 at entry reached an asymptote after F_{max} while the YPR for

age-1 at entry declined at fishing mortality rates greater than F_{max}. Within the range of

fishing mortalities estimated in this study (F = 1.02 - 1.54), it would appear that yield in

the fishery is more robust to variation in fishing mortality when age at entry is delayed

until age-2. However, if a higher rate of natural mortality is assumed, the difference

between age-1 and age-2 at entry appears to be less pronounced, with inconsequential

differences in yield at F_{max}. Although natural mortality was not well estimated by the

tagging model, the marginally better performance of models in which a low natural

mortality was assumed suggest that natural mortality is better characterized by the lower

estimates. In this study, we observed considerable interannual differences in fishing

mortality within a single estuary. Our observations agree with the highly variable fishing

mortality estimates during 1991 to 2002 contained in the most recent stock assessment

for southern flounder (Fig. 1), and suggest that large interannual fluctuations in fishing

mortality may be characteristic of the southern flounder fishery throughout the state .

Consequently, it would appear that the North Carolina southern flounder fishery might

realize greater protection from growth overfishing if age at entry were delayed until age-

2. In addition, such a management strategy could also protect against the effects of large

annual variations in fishing mortality by producing greater consistency in annual yields.

The incorporation of an age-2 at entry could easily be accomplished by increasing the minimum size limit to the average size at age-2 (406 mm or 16 inches TL).

We hesitate to conclude, however, that an alternative to reducing fishing mortality in the North Carolina southern flounder fishery is simply to delay age at entry into the fishery until age-2. YPR analyses do not incorporate the spawner-recruit relationship, nor do they account for the possibility of recruitment overfishing, which occurs when the spawning stock biomass is fished to a level which cannot provide adequate recruitment to replenish itself. From the available data, there is no apparent trend in the spawner-recruit relationship for southern flounder (NCDMF 2004), a common problem in fisheries science that limits the ability of stock assessments to accurately predict future recruitment levels, given estimates of current or future biomass. Until a relationship can be derived from the available data, it will be impossible to determine the likelihood of recruitment overfishing under a given harvest strategy. Williams and Shertzer (2003) recommend a Bayesian approach to estimate the stock-recruitment function, especially the steepness parameter, in order to set appropriate biological reference points for recruitment overfishing. The steepness parameter measures the maximum reproductive rate, and is critical for estimating the ability of the stock to respond to harvest (Williams and Shertzer 2003).

Our findings implicate that, under the current regulations for the southern flounder fishery in North Carolina, it is very likely that fishing mortality will continue to exceed the target fishing mortality (F = 0.95) in the New River. Importantly, this may extend to many of the other small river estuarine fisheries throughout the state. If current harvest rates in other systems are similar to those estimated for the New River (F = 1.54 in 2006), it is possible for the fishery to remove as much as 68% of the stock each year.

Considering that the gill net fishery targets mostly young, fast-growing, and immature fish, continued fishing at these rates could have long term consequences on stock health and, ultimately, yield potential. While the current high levels of fishing mortality do not appear to be sustainable, fishery yield may be more robust to these levels of fishing mortality if age-2, rather than age-1, southern flounder were targeted. However, until a spawner-recruit relationship can be identified, the maximum levels of fishing mortality that can be sustained while still providing adequate recruitment cannot be determined. Thus, a conservative approach may require alternative management strategies to both decrease harvest rates and reduce selection for young fish to maintain stock productivity into the future.

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Table 1A. - A: Expected recovery matrix after Brownie (1985). N = number tagged during each time period; f = return rate; S = survival. B: Instantaneous rates formulation of the Brownie model. $Z_j = F_j + M_j$; F_j = the instantaneous rate of fishing mortality; M_j = the instantaneous rate of natural mortality. s, Φ, λ, and u are defined in the text (Ricker 1975; Hoenig et al. 1998a).

A. Brownie model formulation.

Time Period	Number Tagged (N_i)	Expected Recoveries		
		j = 1	j = 2	j = 3
i = 1	N_1	$N_1 f_1$	$N_1 S_1 f_2$	$N_1 S_1 S_2 f_3$
i = 2	N_2		$N_2 f_2$	$N_2 S_2 f_3$
i = 3	N_3			$N_3 f_3$

B. Instantaneous rates formulation.

Time Period	Number Tagged (N_i)	Expected Recoveries		
		j = 1	j = 2	j = 3
i = 1	N_1	$\dfrac{N_1 s\lambda\phi F_1}{Z_1}(1-e^{-(Z_1)})$	$\dfrac{N_1 s\lambda\phi F_2}{Z_2}(1-e^{-(Z_2)})(e^{-(Z_1)})$	$\dfrac{N_1 s\lambda\phi F_3}{Z_3}(1-e^{-(Z_3)})(e^{-(Z_1+Z_2)})$
i = 2	N_2		$\dfrac{N_2 s\lambda\phi F_2}{Z_2}(1-e^{-(Z_2)})$	$\dfrac{N_1 s\lambda\phi F_2}{Z_2}(1-e^{-(Z_3)})(e^{-(Z_2)})$
i = 3	N_3			$\dfrac{N_1 s\lambda\phi F_1}{Z_1}(1-e^{-(Z_3)})$

Table 2. - Observed recoveries matrix of all fish tagged and recovered during 2005 and 2006. Only underlined data was used in the tagging models.

Month of tagging (i)	Number tagged (N_i)	Month of Recovery (j)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
June-2005 (1)	27	<u>1</u>	<u>2</u>	<u>0</u>	<u>0</u>	<u>1</u>	<u>1</u>	0	0	0	0	0	0	0	0	0	0	0	0
July-2005 (2)	9		<u>1</u>	<u>0</u>	<u>0</u>	<u>1</u>	<u>0</u>	0	0	0	0	0	0	0	0	0	0	0	0
Aug-2005 (3)	208			<u>24</u>	<u>10</u>	<u>19</u>	<u>4</u>	0	0	0	0	0	0	1	0	1	0	0	0
Sept-2005 (4)	229				<u>8</u>	<u>44</u>	<u>10</u>	0	0	0	1	0	1	0	2	0	0	2	0
Oct-2005 (5)	214					<u>25</u>	<u>19</u>	0	1	0	0	0	3	1	2	1	0	1	0
Nov-2005 (6)	321						<u>26</u>	0	0	0	2	6	3	4	5	3	4	1	1
Dec-2005 (7)	0							0	0	0	0	0	0	0	0	0	0	0	0
Jan-2006 (8)	2								0	0	0	0	0	0	0	0	0	0	0
Feb-2006 (9)	3									0	0	0	0	0	0	0	0	0	0
Mar-2006 (10)	11										0	0	1	0	1	0	0	0	0
Apr-2006 (11)	0											0	0	0	0	0	0	0	0
May-2006 (12)	98												<u>8</u>	<u>38</u>	<u>17</u>	<u>5</u>	<u>2</u>	<u>1</u>	0
June-2006 (13)	254													<u>43</u>	<u>78</u>	<u>31</u>	<u>7</u>	<u>1</u>	0
July-2006 (14)	473														<u>97</u>	<u>72</u>	<u>46</u>	<u>9</u>	1
Aug-2006 (15)	38															<u>5</u>	<u>2</u>	<u>2</u>	0
Sept-2006 (16)	44																<u>8</u>	<u>2</u>	2
Oct-2006 (17)	29																	<u>3</u>	4
Nov-2006 (18)	10																		<u>0</u>

Table 3. - All tagging models listed in order of AIC score. F includes both regression estimates (January - July 2005 and January - April 2006) and SURVIV estimates (August - November 2005 and May - November 2006). AIC scores only represent SURVIV model fits.

Model	AIC	F_{2005} (95% CI)	F_{2006} (95% CI)
Full	256.2	1.06 (0.85 - 1.27)	1.50 (1.05 - 1.96)
Constant M estimated across 2005 and 2006	259.3	0.97 (0.81 - 1.14)	1.50 (1.06 - 1.94)
M fixed at M = 0.20	257.8	0.98 (0.82 - 1.14)	1.55 (1.15 - 1.95)
M fixed at M = 0.404	258.8	0.99 (0.83 - 1.16)	1.60 (1.19 - 2.02)
M fixed at M = 0.58	260.1	1.00 (0.83 - 1.17)	1.65 (1.22 - 2.08)

Table 4. - Sensitivity analysis of the parameters Φ, s, and λ. Maxima for these parameters was reached at 1.0.

	Φ	s	λ	F_{2005} (% change from baseline)	F_{2006} (% change from baseline)
Baseline	0.974	0.85	0.962	1.02	1.54
10% increase	1.0	0.935	1.0	0.72 (-29%)	1.21 (-21%)
10% decrease	0.877	0.765	0.866	1.53 (+50%)	2.70 (+75%)

Table 5. - Model matrix residuals of the best fit model (lowest AIC score; F model 1/M model 6). Note the pattern of negative residuals along the main diagonal (italicized) and positive residuals along the superdiagonal (underlined).

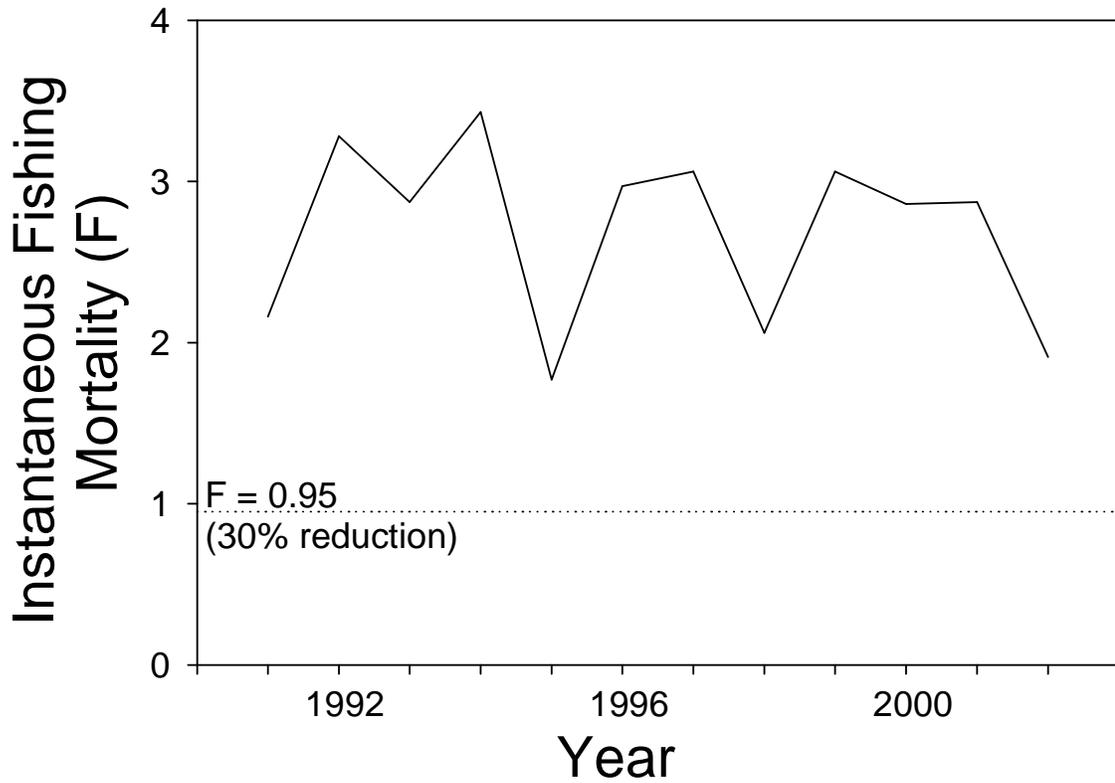|	Month of recovery (j)											
	Year 2005					Year 2006						
Aug	Sept	Oct	Nov	Not seen again	May	June	July	Aug	Sept	Oct	Nov	Not seen again
-0.3	8.4	18.6	4.0	-30.6								
	-2.7	41.2	9.7	-48.2								
		-7.4	15.7	-8.3								
			1.8	-1.8								
Main diagonal mean					*0.4*	35.6	16.2	4.8	2.0	1.0	0.0	-59.9
-6.1						*-16.6*	57.3	25.0	5.7	0.9	0.0	-72.4
							-34.0	34.1	38.0	8.5	1.0	-47.5
Superdiagonal mean								*-3.8*	0.1	1.9	0.0	1.8
17.7									*0.6*	1.5	2.0	-4.1
										1.4	4.0	-5.4
											-0.2	0.2

Figure 1. - Estimates of instantaneous fishing mortality, F, estimated for the years 1991-2002 by the NCDMF using retrospective VPA. The dotted line represents the management target F (0.95) which translates to a 30% reduction in the discrete harvest rate (u).
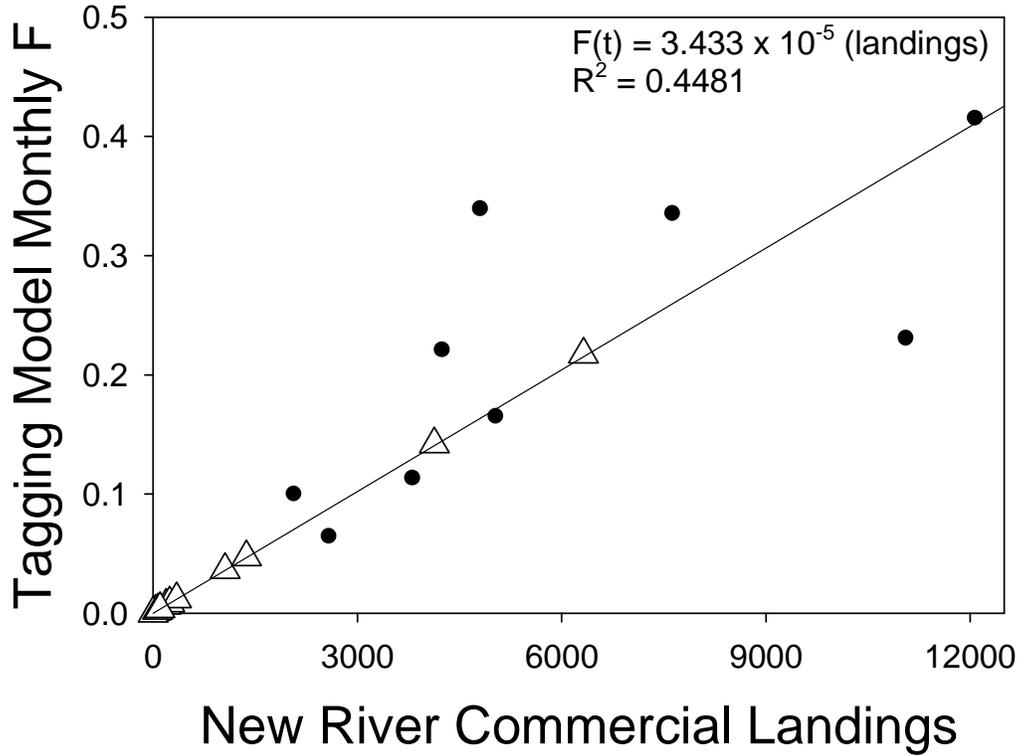
Figure 2. – Linear relationship between New River commercial landings and monthly F estimates generated by the tagging model for August 2005 through November 2006. The reference line indicates the fitted regression model. Filled circles denote tagging model F estimates vs. landings; open triangles illustrate the predictions of F for January - July 2005.
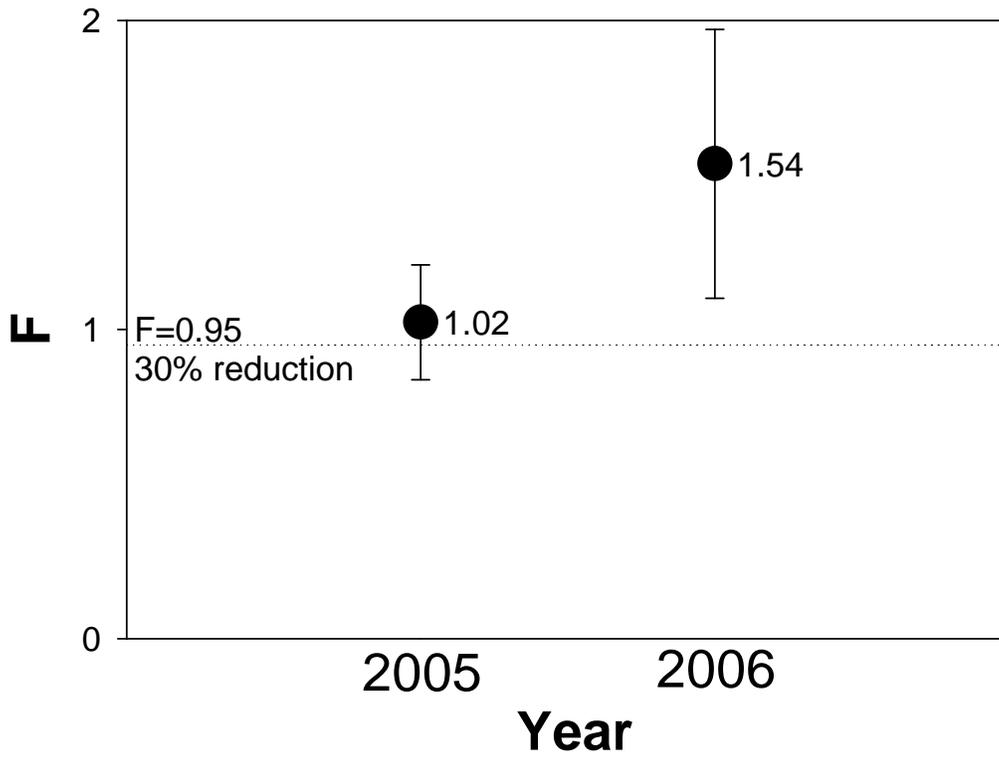
Figure 3. – F estimates and 95% confidence intervals during years 2005 and 2006.
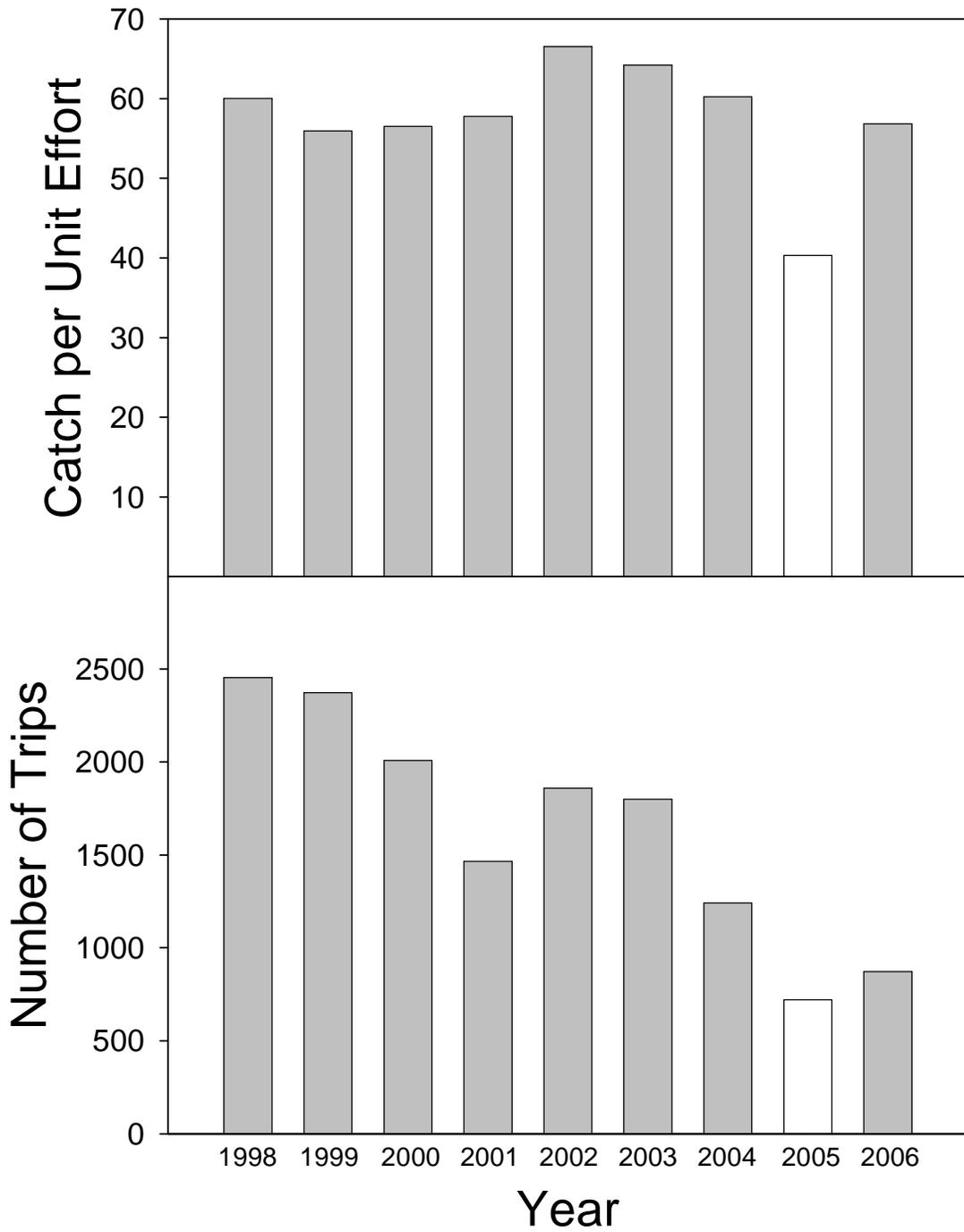
Figure 4. - Gill net catch per unit effort for 1998 - 2006 in the New River (A) and the number of gill net trips targeting southern flounder (effort) during the same time period (B) The first year of the new regulations, 2005, is indicated by the white bars.

Figure 5. – Estimates of southern flounder YPR for age-1 and age-2 at entry, across a range of fishing and mortality rates. Solid vertical reference lines indicate F_{max} at age-1 at entry, for natural mortality rates tested, and dashed vertical references lines indicate F_{max} at age-2 at entry.

CHAPTER 2. AGE STRUCTURE AND MATURITY OF SOUTHERN FLOUNDER
IN NORTH CAROLINA'S GILL NET FISHERY

INTRODUCTION

Gill netting for southern flounder has been an important fishing industry in coastal

North Carolina (NC) since at least the 1980s. In addition to pound nets, gigs, and trawls,

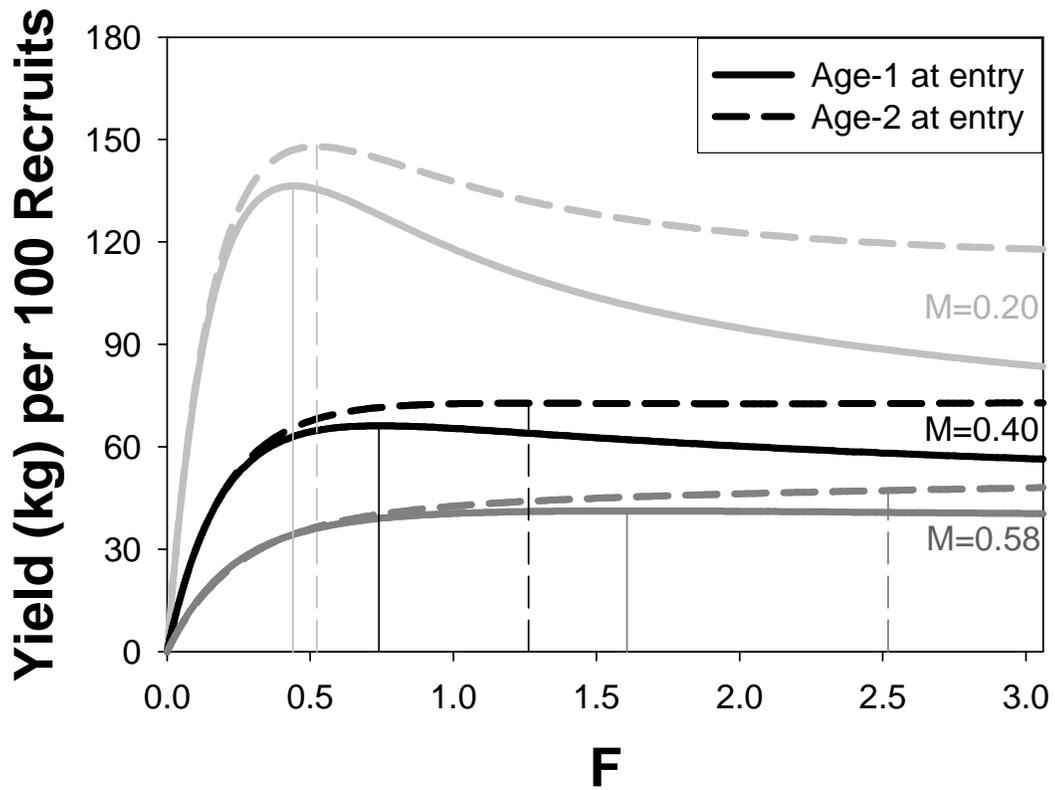commercial harvest of southern flounder with gill nets has contributed heavily to recent

landings, helping to make the southern flounder fishery the most economically valuable

inshore finfish resource in NC during the last decade (NC Division of Marine Fisheries

[NCDMF] commercial harvest statistics 1997-2006). In spite of foreboding stock

assessments, which indicate that the extremely high fishing mortalities that have

characterized this fishery for the past several years are unsustainable in the long term

(NCDMF 2004), regulatory changes in the commercial southern flounder fishery in NC

have not effectively reduced fishing mortality or eliminated young fish from the catch.

Previous management regulations have not included commercial gear reductions or time

and area closures, which each can indirectly reduce fishing mortality through effort

restrictions, but, instead have been strictly technical measures. The minimum size limit

was increased from 280 mm (11 inches) in 1979 to 331 mm (13 inches) in 1988, and gear

restrictions for pound nets, trawls, and gill nets applied mostly to minimum mesh sizes.

The only management restrictions that were intended to directly reduce harvest of

southern flounder were effected in other fisheries that captured southern flounder as

bycatch (Mumford 1999).

Despite many technical measures instituted prior to 2005, assessment models

estimate that harvest exceeded the current target fishing mortality (F = 0.95) every year

from 1991 through 2002. During this period, fishing mortality rates were estimated to

range between 1.77 and 3.43, and young, age-0, fish were documented in the catch every year (NCDMF 2004). The most recent regulatory changes, enacted in 2005, included a 25.4 mm (1 inch) increase in the minimum size limit to 356 mm (14 inches), a recreational bag limit of 8 fish, a complete fishery closure during the month of December, and several specific commercial gear limitations. Despite these new regulations, a recently completed tag-return study found that fishing mortality rates imposed by the gill net fishery in one of the smaller estuarine systems likely exceeded the target fishing mortality rate during the first two years of the new regulations (Smith et al. in prep).

Although numerous examples have illustrated the potential for gill nets to generate negative ecosystem-level impacts due to the bycatch of megafauna such as sea turtles and marine mammals (Gearhart 2001; Gearhart 2002; Read et al. 2006), the potential effects on the target fish species from the methods of gill net harvest have been largely ignored. In addition to the direct effects of harvest rate, fishing practices, including factors other than gear choice, can often have considerable impacts on the target species. For instance, the pattern of harvest was demonstrated to have a potential effect on the evolutionarily stable life history strategy of Northeast Arctic cod (Heino 1998). Law (1991) had speculated that the spatial distribution of the fishery may have resulted in declining size at maturity, a pattern also observed by others (Oosthuizen and Daan 1974; Heino 2002). Historically, cod were only harvested from inshore waters on the spawning grounds, and the optimal reproductive strategy for cod was to delay maturation as long as possible before risking a trip to the spawning grounds. With the advent of technology, fishing on the deeper, offshore feeding grounds became possible, resulting in a shift in the optimal reproductive strategy to spawn as early as possible before being harvested. The net effect of the shift in fishing toward the feeding grounds

was a change from late maturation to early maturation, a result which Heino (1998) concluded could have a long-term negative effect on sustainable yield.

Juvenile southern flounder have been found to initially settle and remain in oligohaline estuarine habitats (Burke et al. 1991; Walsh et al. 1999). They are commonly found in waters with salinities as low as 1-2 ppt and they have been found to be highly tolerant of low salinity (Daniels 2000). The gill net sector of the commercial fishery for southern flounder operates extensively in low salinity, nursery habitats within estuaries, although gill nets are also fished in high salinity waters inshore. Other gears such as gigs and trawls are generally restricted from low salinity nursery habitats. Gigging is limited to low turbidity waters, which are uncommon in oligohaline habitats that tend to have higher rates of sediment deposition, and trawling is not permitted in primary nursery habitats (NCDMF 2007). The execution of a fishery primarily in nursery habitats is cause for concern. The harvest of immature fish has been shown to have negative repercussions on yield-determining traits in several fish stocks (Heino 1998; Hutchings 2000; Law 2000).

Here, we characterize the age structure, size distribution, and size at age of southern flounder captured in the commercial gill net fishery operating in the New River during two consecutive years. We also determine the maturity status of the catch, and predict the percentage of the targeted population that may be available to spawn during the reproductive season. Using our age structure data and previously published data on age at maturity for NC southern flounder (Monaghan and Armstrong 2000), we then estimate the proportion of the catch that may have spawned prior to being harvested. The combination of the age composition of the catch and the age-based maturity schedule provides evidence of the potential impact of the fishing strategy utilized in the

commercial gill net fishery on the long-term growth potential of the NC southern

flounder stock.

METHODS

All southern flounder examined in age and maturity analyses were captured

during a large tag-return study conducted in the New River, NC (Fig. 1) between 2005

and 2007 (Smith et al. in prep). Commercial fishers captured fish for tagging throughout

the river using 14-cm (5½ inch) stretched mesh gill nets, the current minimum mesh size

allowed for large mesh gill nets in the state. Only fish of legal size (356 mm) or greater

were tagged; however, all fish caught, including sub-legal southern flounder were

measured for total length. After tagged fish were released they were exposed to

commercial and recreational harvest and were recaptured by fishers utilizing gill nets,

gigs, and/or hook and line. Recovered fish were considered to represent a random subset

of the original group of all fish caught, tagged, and released. Further, the pool of all

tagged fish was assumed to represent a random sample of southern flounder captured in

the New River commercial gill net fishery.

Recaptured southern flounder were retrieved from fishers and returned to the

laboratory for processing. The total length (mm) was recorded for all fish and the left

sagittal otolith was removed, sectioned, mounted, and aged according to methods

established for southern flounder in the Gulf of Mexico (GSMFC 2003). Although the

use of whole otoliths is regarded as an acceptable method for aging southern flounder, the

use of sectioned otoliths is considered to be the least error-prone method (GSMFC 2003).

Therefore, we used sectioned otoliths in an attempt to reduce measurement error as much

as possible. Marginal increment analysis of southern flounder in Louisiana indicates

opaque increment formation from January - May (Fishcher and Thompson 2004); therefore, all recoveries (all were collected after May each year) had likely deposited annuli by the time of their capture. Only female fish were included in age analyses, because southern flounder exhibit sexually dimorphic growth patterns (Stokes 1977; Music and Pafford 1984; Wenner et al. 1990; NCDMF 2004) and also because females comprise the vast majority of the catch (NCDMF 2004).

The frequency distribution of total lengths of fish captured was calculated to determine the sizes of southern flounder targeted in the commercial gill net fishery, and the percentage of sub-legal flounder (<356 mm TL) captured. Since both age and length of recovered fish that were previously tagged were positively biased by time at large (all fish had the opportunity to grow during time at large between tagging and recovery), the total length at tagging and the backcalculated age at tagging were used in our analysis of age structure and size-at-age. The relative frequency of southern flounder ages (in years) harvested was used to assess the relative fishing pressure on different age groups within the New River gill net fishery. To estimate the size-at-age of the catch, age in fractional years was assigned based on the date of capture, the number of annuli present, and an assumed February 1 birth date. February 1 represented the midpoint of the spawning period for southern flounder, which has been found to extend from late December to early March (Gilbert 1986). Age estimates were then plotted against total length and compared to a previously estimated von Bertalanffy growth curve for southern flounder in North Carolina (NCDMF 2004).

Catch-at-age estimates were combined with an age-specific maturity schedule generated during a previous study by Monaghan and Armstrong (2000) to evaluate the proportion of fish that were likely to have spawned prior to capture. The products of the

fraction of the catch at each age and the percent mature at each age during the previous year's spawning season (% mature at age - 1) were summed for all represented ages. The sum estimates the percentage of the catch that may have had the opportunity to spawn during the previous spawning season.

Only fish harvested during the months of October and November, just prior to the spawning season, were used to analyze the maturity status of the catch. Fish in pre-spawning condition were first encountered in October; prior to that time, mature and immature individuals were indistinguishable. No fish were recovered in December due to the current management regulations which include a December closure. Also, due to very low commercial landings in the estuary during the winter (Fig. 2), no fish were recovered in January or February. As no sampling occurred during the actual spawning season (December - February), a complete length- or age-based analysis of maturity was not possible. However, the pre-spawn maturity status of southern flounder captured during October and November was analyzed to quantify the fraction of the catch composed of mature fish.

The gonads of previously tagged fish recovered in October and November during both 2005 and 2006 were removed and macroscopically staged. Because these fish were a sample from the catch, the analysis is based on fish greater than or equal to the minimum size limit (356 mm TL). Females were grouped into five maturity stages according to a macroscopic ovarian staging guide developed previously for southern flounder (Wenner et al. 1990) (Table 1). The ovaries of 31 females (17% of all fish used in the maturity analysis) were preserved and histologically staged in order to validate the macroscopic staging classifications. Histological examination of prepared tissues is

considered to be the most accurate ovarian staging method, and is commonly used to validate macroscopic staging techniques (West 1990).

For histological preparation, ovaries were preserved in 10% buffered formalin, rinsed in a series of ethanol, acetone, and toluene solutions, and then infiltrated with paraffin. The paraffin-infiltrated tissues were then embedded in paraffin blocks, from which 4 μm thick sections were extracted. Sections were mounted on glass microscope slides and stained with eosin-Y and hematoxalin. Histological staging of the stained ovarian tissues followed West (1990) (Table 3).

RESULTS

A total of 3,203 southern flounder were caught in gill nets during observed trips in 2005-2006. The mean TL of these fish was 362 mm, with 95% of all fish caught in the range 244-459 mm TL, and 35.7% were sublegal and discarded (Fig. 3). Of all southern flounder caught in gill nets, 1970 were of legal size and in good condition for tagging and release, resulting in 743 recoveries with 627 recovered intact for additional analyses. The sagittal otoliths of all intact, recovered female southern flounder were removed and aged. Most fish captured in the commercial gill net fishery were age-1 (87.7%), 7.5% were age-0, 4.6% were age-2, and only 0.16% were age-3. The age structure of the catch indicates that the New River gill net fishery was targeting primarily age-1 southern flounder during 2005 and 2006 (Fig. 4). The size-at-age of all age-1 and age-0 fish appeared to fall above the average expected growth curve for southern flounder in NC (Fig. 5). Thus, the young fish harvested in this fishery represented the fastest growers in their respective age classes.

Of all previously tagged fish which were recovered and sexed (n = 621) only 2.0% were male. Among all fish captured during the months of October and November and subsequently examined for maturity (n = 185), only one male was discovered; therefore, only females were considered in the maturity analysis. Distinguishing between developing and fully developed maturity stages macroscopically proved difficult, and, indeed, histological validation confirmed that many developing ovaries were initially misclassified macroscopically as fully developed. All nine ovaries macroscopically staged as fully developed, and then examined histologically, were in fact, developing (stage I or II, Table 3) or otherwise indistinguishable from immature ovaries. The net result of histological staging was to shift all fish staged macroscopically as fully developed back one stage to developing. Histological validation also confirmed that all developing ovaries were correctly classified macroscopically as immature and all running ripe ovaries were correctly classified as mature, based on macroscopic staging.

After all misclassified ovaries were corrected according to the results of the histological validation process, 134 ovaries of the total 185 examined were concluded to be in an immature condition, and only 51 were in a mature condition. Therefore, as many as 72.4% of all southern flounder caught the New River gill net fishery during 2005 and 2006 were immature. Ignoring the results of histological validation, when fully developed females (n = 41) were considered mature, it appeared that 50.3% of the 2005 and 2006 catch was immature. Based on the catch-at-age patterns observed in this study and a previously constructed age-specific maturity schedule (Monaghan and Armstrong 2000), we estimated that only 19.4% of the catch may have had the opportunity to spawn during the reproductive season prior to the year of their capture (Table 3).

DISCUSSION

Several recently published studies have documented the potential for the harvest of natural populations to result in irreversible genetic changes. Theoretical modeling (Heino 1998), laboratory studies (Conover and Much 2002), and empirical data (Oosthuizen and Daan 1974; Heino 2002) each indicate that the selective removal of fast-growing, immature fish can lead to reduced growth potential within a harvested stock. Heino (1998) constructed age-structured population dynamic models to reveal that, when the harvest included both immature and mature fish, selection favored earlier maturation. The model illustrated how a population of early maturing fish, with a gene pool altered by fishing, could produce a lower annual yield than a population of late maturing fish. Thus, Heino (1998) concluded that the harvest of immature fish could lead to altered gene pools that would lower sustainable yields. Conover and Munch (2002) used a series of laboratory experiments with Atlantic silversides (*Menidia menidia*) to show that, after four consecutive generations exposed to size-selective harvest, the average growth rate was significantly reduced in populations from which the largest, fastest growing individuals had been harvested. Further, in populations from which the smallest individuals were removed, the average growth rate was significantly greater after four generations (Conover and Munch 2002). In the field, Heino (2002) found that North Sea cod, after several decades of intense exploitation, were maturing at smaller sizes, observable as a reduction in the length at 50% maturity. This finding agreed with previous observations of changes in the size at maturity resulting from selective harvest (Oosthuizen and Daan 1974); however, the effects of reduced population size coupled with elevated growth rates could not be separated from the effects of potential genetic changes in maturation.

Our results bring to light causes for concern related to the age, growth, and maturity of southern flounder caught in the New River gill net fishery and the potential population-level effects of the fishing strategy employed. The maturity analyses depict the potential past and future contributions of the fished stock to the spawning stock. By combining catch-at-age and the percent mature at age during the previous spawning season (Monaghan and Armstrong 2000), we estimated that only 19.42% of the catch may have had the opportunity to spawn during the previous spawning season. This analysis is appropriate because most southern flounder landings in the New River commercial fishery occur pre-spawn, between May and November (Fig. 2). Therefore, when considering the consequences of fishing on the spawning stock for this fishery, it is important to determine the fraction of the catch may have already had the chance to spawn. The maturity status of the catch reveals that nearly three quarters (72.4%) of all southern flounder captured in the New River in the months leading up to the spawning season are immature. Regardless of whether fully developed females are considered mature or immature, at least half of the total catch in the New River gill net fishery may be immature. If trends in fishing practices continue as present, it appears that few fish in the catch will have spawned during the previous reproductive season and only about one quarter of fish targeted by the fishery will be likely to spawn if they escape the fishery. The data presented in this study clearly demonstrate that the New River commercial gill net fishery is harvesting a predominantly immature fraction of the population, many members of which may never contribute to the spawning stock.

Our findings related to the size and age at maturity varied somewhat from southern flounder maturity schedules previously described in South and North Carolina. In this study, the smallest mature female captured in the New River was 367 mm TL, and

the largest immature female was 472 mm TL. In South Carolina, Wenner et al. (1990)

observed mature females as small as 320 mm TL, and immature females were only

found as large as 360 mm TL. In a previous study in North Carolina, Monaghan and

Armstrong (2000) also found mature females as small as 320 mm TL, but did capture

immature females up to 430 mm TL. The discrepancies in size at maturity among studies

may be explained by the potential for younger (and thus smaller) southern flounder to

become reproductively active later in the spawning season compared to larger (and thus

older) fish. Age effects on the timing of spawning have been found in other species,

including halfbeaks (Berkeley and Houde 1978), herring (Lambert 1987), and Atlantic

cod (Hutchings and Myers 1993). We were only able to examine fish captured during the

two months before the spawning season began, so we cannot discount the possibility that

younger, smaller fish may have matured later in the spawning season, thus resulting in

few small, mature fish represented in our sample. The findings of Wenner et al. (1990)

contain some evidence to support this hypothesis. In South Carolina, the average TL of

female southern flounder in pre-spawn condition declined from 430 mm in September, to

400 mm in October, and then to approximately 380 mm in November, indicating that

smaller females may have begun to enter a reproductively active stage later than larger

females. Alternatively, spawning related emigration from the estuary may be size

dependent, with larger fish moving offshore earlier in the fall compared to smaller fish.

The majority of the New River gill net catch was composed of age-1 fish, with

low percentages of age-0 and age-2 fish. Moreover, size-at-age analysis revealed that the

age-0 and age-1 fish in the catch were among the fastest growers in their respective age

classes. All sizes-at-age of age-0 and age-1 fish were above the average growth

trajectory for fish of their age in NC (Fig. 3). Furthermore, sub-legal discards

represented 35.7% of all gill netted flounder in this study, with unknown consequences on the mortality of discarded fish. Although the age-structure of discarded flounder was not examined, based on the average age of southern flounder at the minimum size limit (356 mm TL), most discarded flounder were likely age-0 or age-1 females or males. A separate study is currently underway which will estimate mortality, as well as the age and sex composition of sub-legal discards captured in gill nets constructed of the current minimum mesh size (140 mm stretched mesh).

Given the documented effects of harvesting fast-growing and immature fish, our findings should be interpreted with concern by fishery managers. Although the time scale may be debatable, it is likely that the harvesting practices common in the inshore gill net fishery are slowly eroding the yield-generating capacity of the North Carolina southern flounder stock. If the gill net fishery were instead to target older age classes, allowing for sufficient escapement of immature fishes, most potentially detrimental effects may be alleviated. One means of accomplishing this goal without drastically altering the current regulatory framework include increasing the minimum size limit to the average size at age-2 (406 mm or approximately 16 inches TL) (NCDMF 2004). Based on the maturity schedule calculated by Monaghan and Armstrong (2000), targeting age-2 fish would afford approximately 74% of females the chance to spawn in the reproductive season previous to becoming subject to the fishery. Under the current scenario, in which age-1 fish are targeted, only approximately 18% of females may have the chance to spawn before entering the fishery. Additional tactics to minimize the harvest of immature fish include further technical measures related to gear restrictions, or the introduction of spatial closures to remove the gill net fishery for southern flounder from low salinity nursery habitats. Technical measures that change gear selectivity by

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increasing gill net mesh sizes have been shown to reduce the bycatch of small fish in other many other fisheries (Psuty-Lipska et al. 2006; Revill et al. 2007; Sabrana et al. 2007). Indeed, data from fishery-independent studies included in the most recent fishery management plan for southern flounder (NCDMF 2004) demonstrated that an increase in the stretched mesh size from 140 mm, the current minimum mesh size, to 152 mm considerably reduced the bycatch of small, sub-legal fish (Table 4). Increasing the minimum size limit and changing the selectivity pattern of gill nets by increasing the minimum stretched mesh size represents a minimal measure to reduce the catch, including bycatch and discarding, of juvenile southern flounder. At the least, long-term monitoring of the average growth rate, size at maturity, and age at maturity is imperative in the North Carolina fishery for southern flounder. Monitoring population demographics can help to alert fishery managers to changes and minimize any irreversible effects on the stock's yield-determining traits.

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TABLES

Table 1. - Macroscopic ovarian stage criteria (modified from Wenner et al. 1990).

Reproductive stage	Description
Immature	
Immature	ovaries very small and thin
Developing	ovaries rotund, yellowish-orange and turgid
Mature	
Fully-developed	similar to developing but with oocytes visible
Running ripe	ovaries large and soft with many large, free-flowing (with slight pressure) hydrated oocytes
Spent	ovaries flaccid and bloodshot; few hydrated oocytes if any
Resting	ovaries small, flaccid, translucent with no visible oocytes

Table 3. - Microscopic ovarian stage criteria (West 1990).

Reproductive stage	Description
Immature	
I Early perinucleolis	One or few large nucleoli, basophilic ooplasm, no cytoplasmic inclusions
II Late perinucleolis	Less basophilic ooplasm, a cortical alveolus and/or a lipid droplet
Maturing	
III Cortical alveolar	Many small lipid droplets and cortical alveoli dispersed in cytoplasm
IV Late lipidogenic	Lipid droplets fill ooplasm and coalesce centrally, cortical alveoli at follicular envelope
Mature	
V Vitellogenic	Yolk protein globules present
VI Final maturation	Germinal vesicle breakdown, lipid and yolk coalesced, may hydrating
VII Postspawning	Postovulatory follicles, atretic oocytes

Table 3. - Percent catch at age of southern flounder during this study and the percent mature during the previous spawning season (age - 1) based on the maturity schedule presented in Monaghan and Armstrong (2000). An estimate of the proportion of the total catch that may have spawned during the previous spawning season is obtained by multiplying these two quantities.

Age	% Catch at age	% Mature$_{age-1}$	% of catch spawning in previous year
0	7.5	0	0
1	87.7	18.1	15.9
2	4.6	73.5	3.4
3	0.16	90.7	0.15
Total			**19.4**

Table 4. - Frequency of capture of sub-legal southern flounder in gill nets constructed of three different mesh sizes (modified from NCDMF 2004).

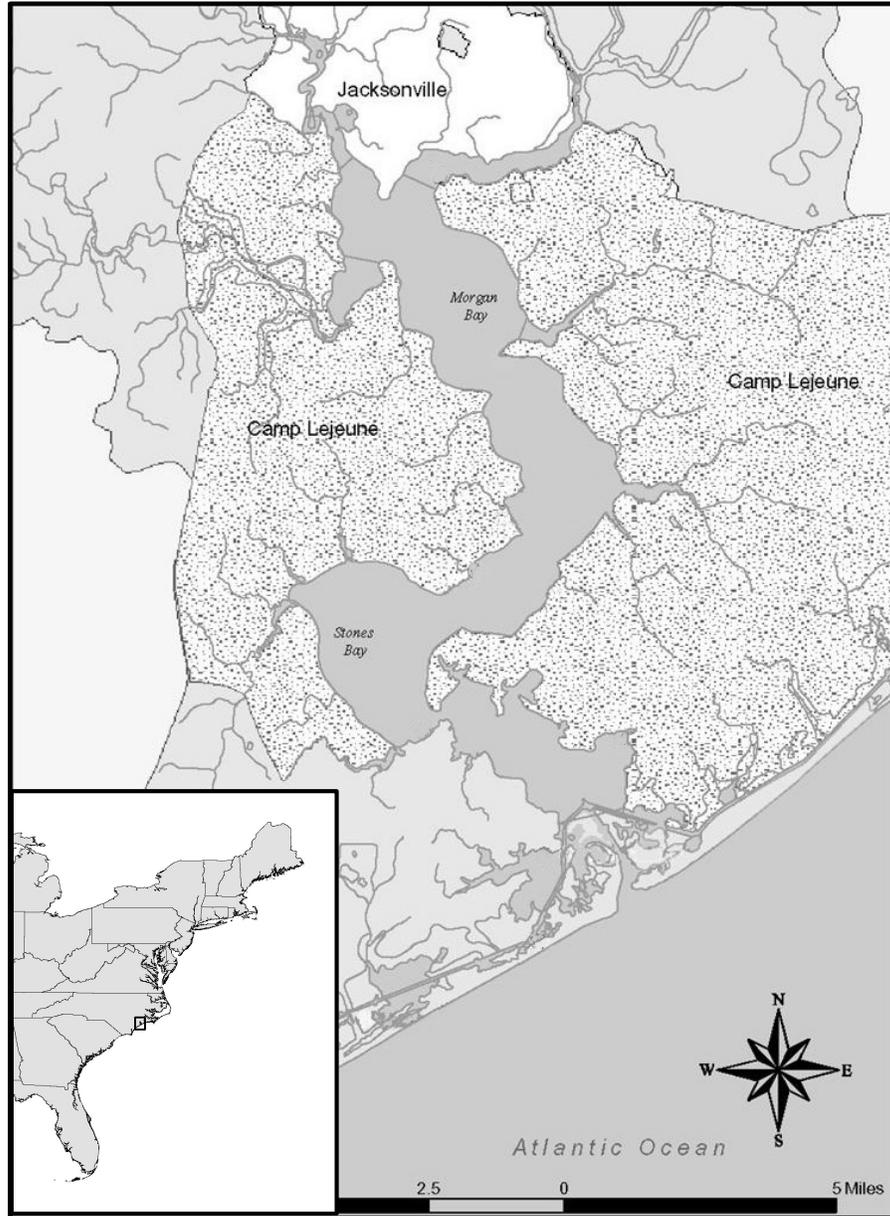| Stretched mesh size	Number of fish captured	% catch below size limit (<356 mm TL)
140 mm	3121	21%
146 mm	2621	15%
152 mm	4005	9.3%

FIGURES

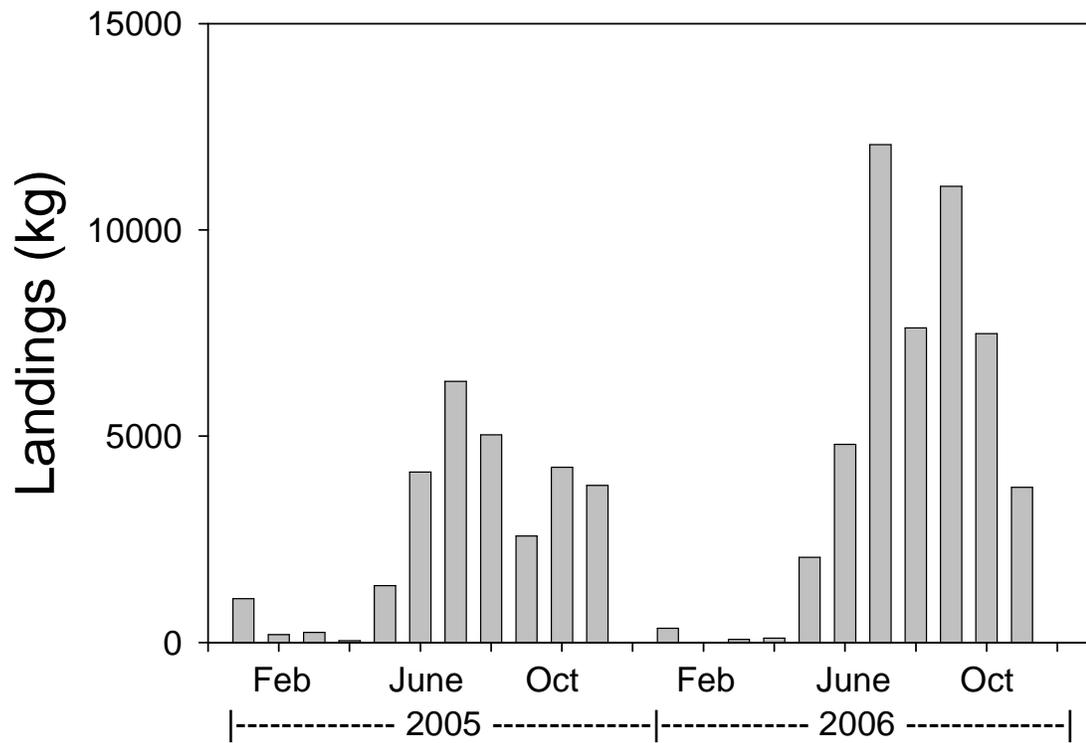Figure 1. - Map of the US East Coast (box indicates the location of the New River) and the New River, NC.

Figure 2. - New River commercial landings for 2005 and 2006 (*courtesy of Alan Bianchi, NCDMF*).
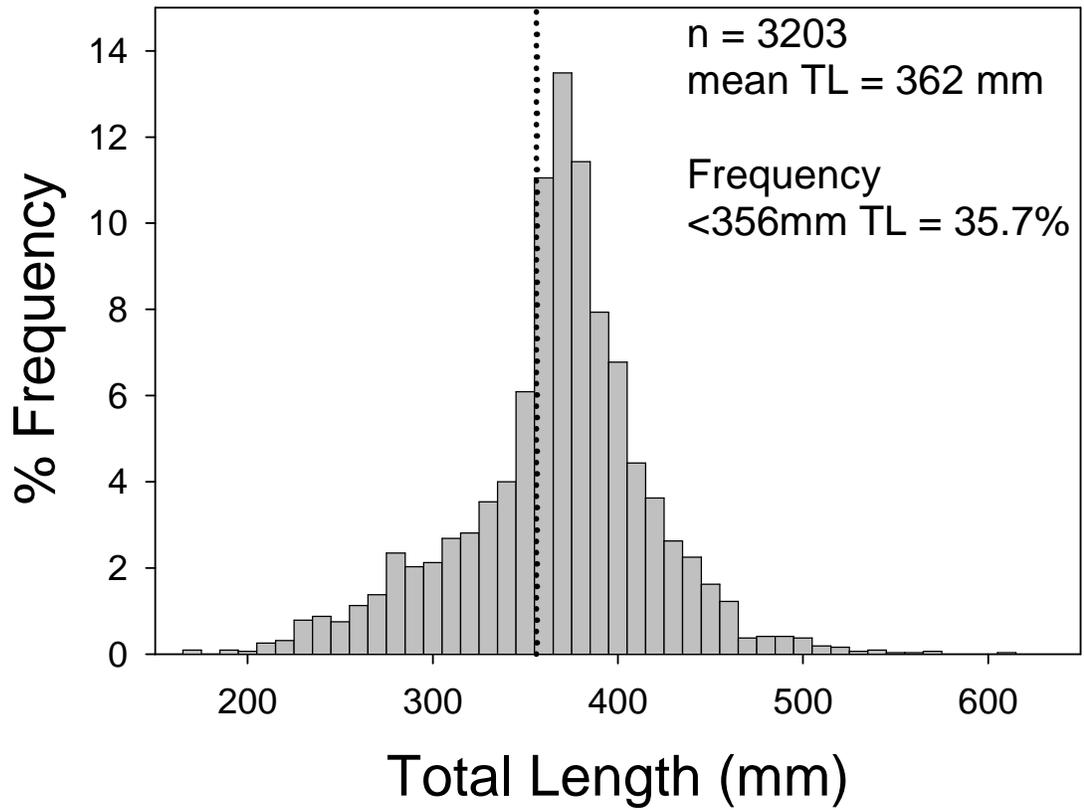
Figure 3. - Total length distribution of all southern flounder captured in 140 mm (5½ inch) stretched mesh gill nets. The dotted reference line indicates the size limit, 356 mm (14 inches).
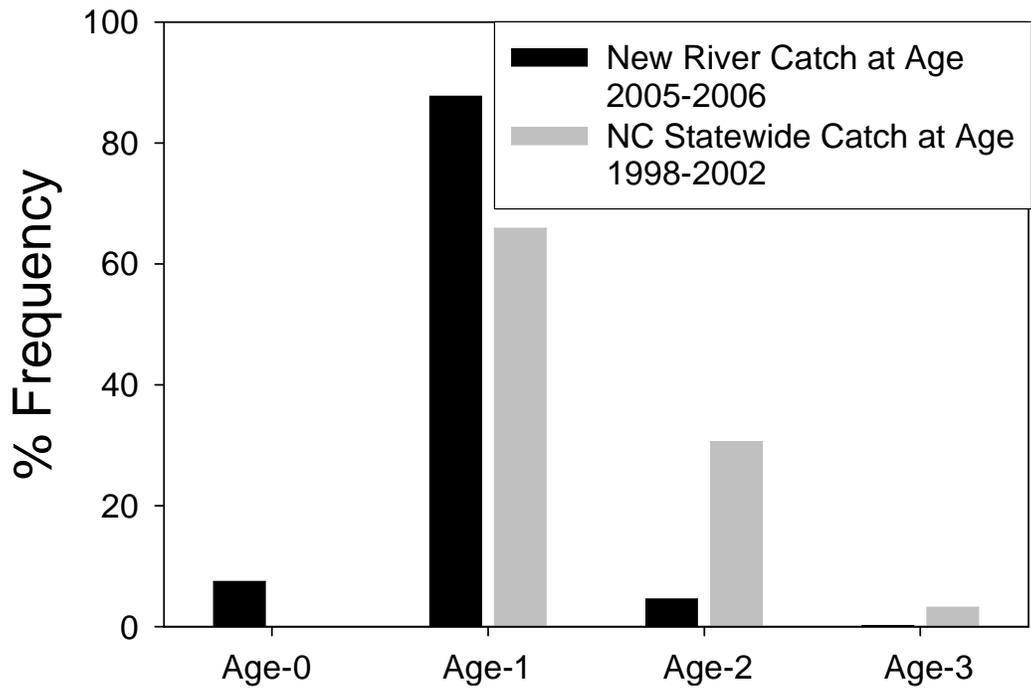
Figure 4. - Catch at age of the New River southern flounder gill net catch and the statewide gill net catch at age for years 1998 - 2002 (NCDMF 2004).
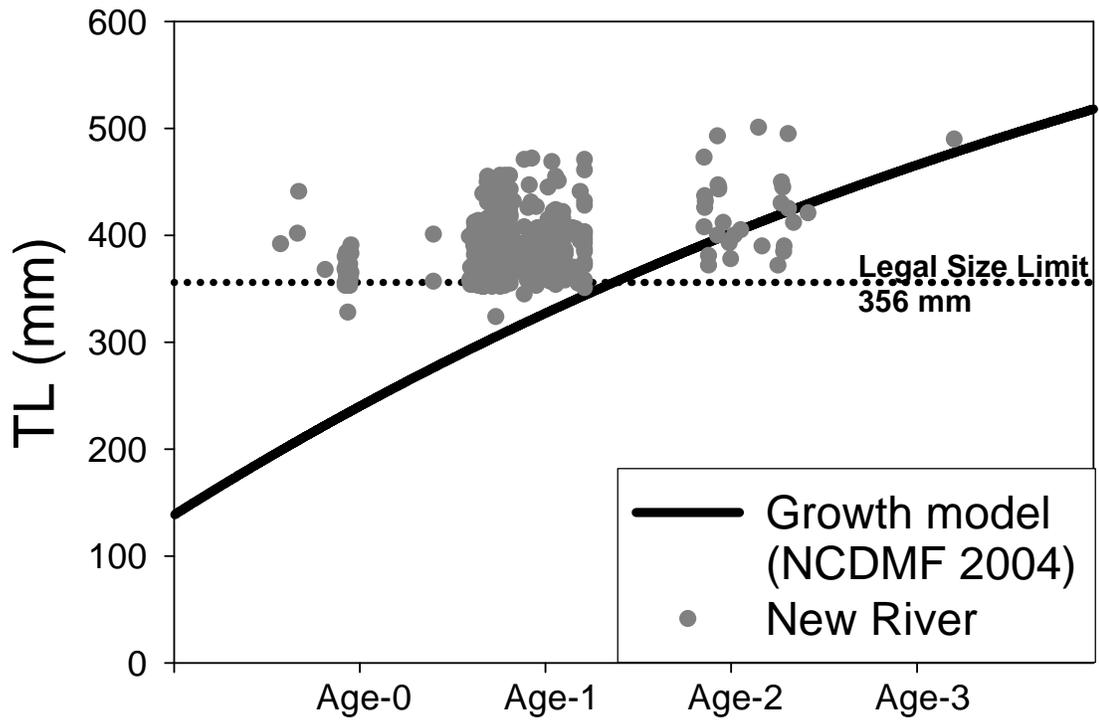
Figure 5. - Size-at-age of the New River southern flounder gill net catch and von Bertalanffy growth curve derived for all female southern flounder in North Carolina (NCDMF 2004).