DRAFT FOR SSC REVIEW

Depletion-Corrected Average Catch Estimates for U.S. South Atlantic Wreckfish
NOAA Fisheries Service
Southeast Regional Office
October 23, 2011

Introduction

Wreckfish *Polyprion americanus* is large bass distributed globally in temperate waters, including the U.S. South Atlantic (Heemstra 1986). They constitute a single genetic stock across the north Atlantic ocean (Sedberry et al. 1996). Significant catches are reported off Spain, Portugal, and the Blake Plateau of the U.S. South Atlantic (Sadovy 2003). Wreckfish are caught at depths ranging from 1,500-2,400 feet over high relief and flat hard bottom habitat (Sedberry et al. 1999). Spawning occurs in late winter and early spring, and juveniles are pelagic to 20-24 inches total length (TL), associating with floating seaweeds and wreckage.

In 1990, the South Atlantic Fishery Management Council (SAFMC) added wreckfish to the Snapper-Grouper Fishery Management Plan due to a rapid increase in landings and effort that resulted in overfishing (SAFMC 1990; Vaughn et al. 2001). In 1991, the SAFMC approved an individual transferable quota (ITQ) program for commercial wreckfish to address excess capacity and economic inefficiency in the wreckfish fleet (SAFMC 1991). The ITQ program allocated shares of quota to eligible participants; initial allocations were partially based on landings histories. Since the 1992/93 fishing year, wreckfish have been managed under an ITQ program, a two-million pound quota, and a fishing season from April 16-January 14 each year. A fixed seasonal closure from January 15-April 15 each year is in effect to protect wreckfish during peak spawning.

The Magnuson-Stevens Reauthorization Act of 2006 requires regional fishery management councils to implement annual catch limits (ACLs) and accountability measures (AMs) for all stocks under federal management by 2011. In August 2010, the SAFMC's Scientific and Statistical Committee (SSC) established an acceptable biological catch (ABC) for wreckfish of 0.250 million pounds (mp) whole weight (ww). The SAFMC later allocated 95% of the ABC to the commercial wreckfish sector and set a commercial quota of 0.2375 mp ww (SAFMC 2011). This quota is 88% less than the current 2 mp ww commercial quota and is based on recent, non-confidential average catches (SAFMC 2010). At their August 2010 meeting, the SSC recommended conducting Depletion-Corrected Average Catch (DCAC) or Depletion-Based Stock Reduction Analysis (DB-SRA) in 2011 to compare with their 2010 catch-only recommendation (SAFMC 2010). The intent of this analysis is to estimate a sustainable yield level for the U.S. segment of the north Atlantic wreckfish stock using DCAC analysis (MacCall 2009) as recommended by the SSC.

Methods

Depletion-Corrected Average Catch Formula

MacCall (2009) developed the DCAC formula to estimate sustainable yield in data poor situations. The formula is an extension of the potential-yield formula developed by Alverson and Pereyra (1969) and (Gulland 1970). DCAC divides landed catches over an extended period of time into a sustainable yield

component and a windfall component associated with a reduction in stock biomass (MacCall 2009). The DCAC formula requires the following input parameters: 1) sum of catches; 2) number of years in the catch time series; 3) estimated reduction in biomass (Δ; expressed as a ratio); 4) natural mortality rate (M); and, 5) an assumed relationship (*c*) between the fishing mortality rate at maximum sustainable yield (F_{msy}) and M. The model also requires inputs on the coefficient of variation surrounding the sum of catches and standard deviations for M, *c, and* Δ. Users can also specify the type of distribution for *c* (lognormal or normal) and Δ (beta bounded, lognormal, or normal).

Sustainable yield (Y_{sust}) is calculated as:

$$Ysust = \frac{\sum C}{n + W / Y_{pot}} \tag{1}$$

where *C* is the sum of catches, *n* is the number of years in the catch time series, and W/Y_{pot} is the windfall ratio. The windfall ratio is calculated as:

$$\frac{W}{Y_{pot}} = \frac{(B_{fyr} - B_{lyr}) / B_0}{0.4cMB_0} = \frac{\Delta}{0.4cM} \tag{2}$$

where *Δ is the relative decline in biomass relative to the unfished level, c is the tuning adjustment for setting* F_{msy} *relative to M, M is the natural mortality rate,* B_{fyr} is biomass in the first year of the time series, B_{lyr} is biomass in the last year of the time series, and B_0 is the unfished biomass level.

Uncertainty in DCAC estimates is accomplished by Monte Carlo simulation. The distribution of sustainable catches is conditioned on the distribution of input parameters.

For further details regarding the DCAC formula see MacCall (2009). The model, as well as reference manual for using DCAC, can be downloaded from the NOAA Fisheries Service stock assessment toolbox at: http://nft.nefsc.noaa.gov.

Model Inputs

Sum of Landings (C)

Wreckfish landings in whole weight (ww) were obtained from the Accumulated Landings System for 1987-1990 and from wreckfish ITQ logbooks for 1991-2010 (Gloeckner, pers. comm.). Table 1 summarizes total landings reported from 1987 through present and from 1989 through present. Two catch time periods were used in the DCAC analysis to explore the sensitivity of model results to the total sum of catches. Because DCAC calculates a windfall reduction in biomass, 1989 was chosen for sensitivity runs because landings significantly increased between the 1988 and 1989 fishing seasons. The highest reported annual landings were in 1990 (3.812 mp ww).

Table 1. Total wreckfish commercial landings (million pounds whole weight) for two different time periods and the number of years included in the sum of catches.

Years	Sum of Landings (mp ww)	Number of Years of Landings
1987-2010	15.556	24
1989-2010	15.220	22

Natural Mortality (M)

Vaughn et al. (2001) estimated wreckfish M from life history characteristics using the approaches of Pauly (1979) and Hoenig (1983). M ranged from 0.06-0.09 using Pauly (1979) and 0.11-0.14 using Hoenig (1983). Estimates of M for Hoenig (1983) were based on maximum ages of 30-39 years. More recent age and growth data from Peres and Haimovici (2004) indicate wreckfish may live considerably longer (up to 76 years). Based on Hoenig (1983) and Hewitt and Hoenig (2005) and a maximum age of 76 years, M ranged from 0.04-0.06. Vaughn et al. (2001) recommended 0.1 be used as the preferred estimate of M. This analysis evaluated the sensitivity of DCAC estimates for M = 0.025, 0.05, 0.075, and 0.1. A coefficient of variation (CV) for M of 0.5 was used for all sensitivity runs. MacCall (2009) indicated a CV of 0.5 should be used as a minimal default value and there appears to be no justification for assuming a CV<0.5 for data poor stocks.

Change in Biomass (Δ)

MacCall (2009) indicates that it is difficult to estimate the fractional depletion in biomass (Δ) and that informed judgment or expert opinions from fishermen may be useful in estimating Δ. To assess the depletion in wreckfish stock biomass, nominal and standardized catch per unit effort (CPUE) indices were developed using wreckfish logbook data from 1992 to 2010. The top 3 vessels reporting landings during the entire catch time series were selected for developing the CPUE index since these were the only vessels reporting landings continuously during the catch time series. These three vessels accounted for approximately 30% of the annual landings from 1992-1995 and 50% or more of the landings since 1996.

Variables reported in the wreckfish logbook data set include, but are not limited to: wreckfish permit number, vessel identification number, dealer number, state, day, month, and year of landing, days fished, lines fished, hooks per line, hours fished, pounds and numbers of wreckfish landed, area fished, and depth of fishing. A fixed-effects general linear model (using PROC GLM; SAS Institute 2008) was used to develop the CPUE index. The dependent variable was pounds landed per day. Other dependent variables were also explored, including numbers landed per day, pounds landed per hook-hour fished, and pounds landed per hook fished. Because DCAC requires specification of a windfall reduction in biomass, CPUE based on pounds caught per day was considered a better representation of changes in biomass than numbers caught per day. Hook-hours and hooks fished provided more temporally-refined metrics of effort, but were not used because plots of CPUE versus effort revealed decreasing catchability with increasing effort. In contrast, there was no trend in CPUE versus days-fished.

Wreckfish logbooks allow landings to be entered in both numbers and pounds for of up to five additional species. If snapper-grouper, dolphin, wahoo, or mackerels are caught while fishing for wreckfish, than landings and effort for those species must be reported via separate coastal logbooks to the Southeast Fisheries Science Center. Landings (in pounds) of species other than wreckfish were summed from wreckfish logbooks. Landings of species other than wreckfish were also summed for trips reported in coastal logbooks and trip records were merged with wreckfish logbook data using vessel identification number and month, day, and year of landing. Of the 701 wreckfish logbook records, 22 had matching coastal logbook records. For each wreckfish trip, the ratio of wreckfish landings to total landings was determined. Total landings were determined using the maximum landings reported for all other species in either the wreckfish logbook or coastal logbook. Trips were then eliminated if less than 90% of the trip's total landings were not wreckfish. Of the 701 wreckfish trips, 44 were eliminated from

CPUE analysis. These trips were eliminated to ensure only directly trips targeting wreckfish were included in CPUE calculations.

Log transformation of the dependent variable failed to satisfy GLM assumptions. A square root transformation of the dependent variable was performed to satisfy assumptions of normality and constant variance. Six factors were considered as possible influences on CPUE: fishing year, season (Apr-Jul, Aug-Oct, Nov-Jan) nested within fishing year, vessel ID, total hooks (i.e. lines fished*hooks per line), area fished, and depth fished. Factors were added to the base model using a forward stepwise procedure (α=0.05). Factors included in the final model were: fishing year, vessel ID, total hooks, and season nested within fishing year (Appendix 1). These variables explained 57.4% of the variation in CPUE. To facilitate visual comparison, a relative index and relative nominal CPUE series were calculated by dividing each value in the series by the mean CPUE of the series.

Figure 1 shows the nominal and standardized trend in catch per day from 1992-2010. Nominal and standardized catch rates declined from 1992-1997. From 1998 through 2005, standardized catch rates were stable, while nominal catch rates gradually declined. Since 2007, standardized and nominal catch rates have increased. The reduction in CPUE from 1992 to 2010 was 35% for nominal and standardized indices. Reductions in CPUE from 1992 to 2006 were ~57-58%. A 35% change in biomass was used as the lower bound for model runs and a 60% change in biomass was used as the upper bound for model runs. A middle run was also conducted using a 50% change in biomass. This run was based on personal communication with Paul Reiss (September 9, 2011), a wreckfish shareholder who currently lands a significant portion of the annual wreckfish landings. Mr. Reiss indicated that a 50% reduction in his CPUE has likely occurred since landings peaked in the early 1990s. Mr. Reiss also indicated that his CPUE has been increasing in recent fishing years.

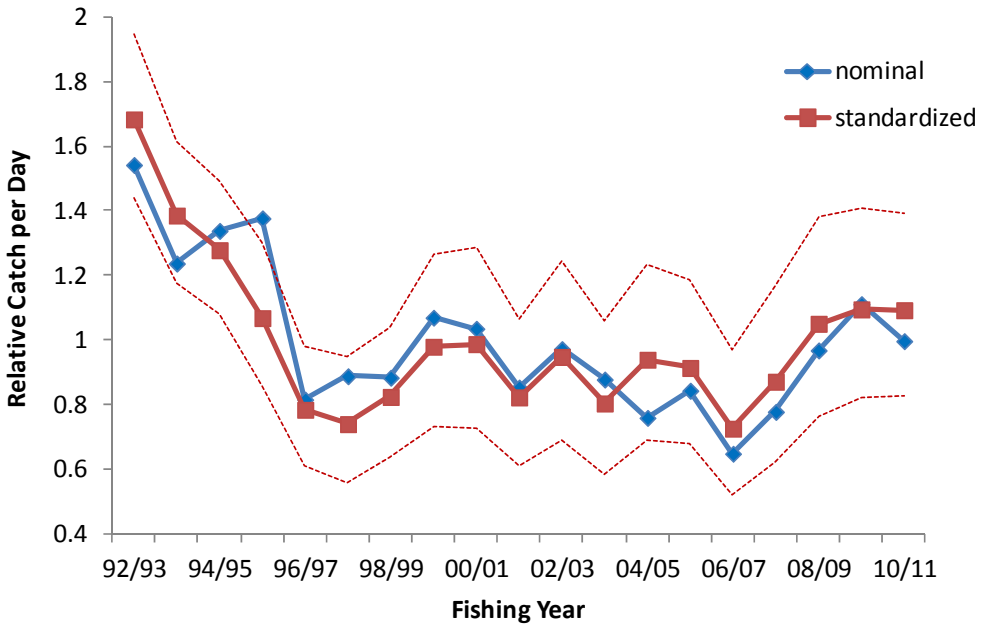


Figure 1. Nominal and standardized index of wreckfish abundance (± 80% confidence intervals) for High-3 fishing vessels, 1992-2010.

Fmsy relative to M (c)

There is currently no estimate for F_{msy}. M is often considered a conservative proxy for F_{msy} (Restrepo et al. 1998) and MacCall (2009) noted that a ratio of F_{msy} to M = 1 may be considered a target or upper limit for many stocks. Walters and Martell (2004) indicated ratios = 0.75-0.8 may be appropriate in data poor situations and that the ratio of F_{msy} to M may be as low as 0.6 for highly vulnerable stocks. For this analysis, sensitivity runs were conducted using F_{msy} to M ratios of 0.8 and 1.0.

Sensitivity Runs

Eighteen sensitivity runs were performed to evaluate how changes to various model parameters affect estimates of sustainable yield (Table 2). Runs 1-3 explored how changes in biomass affected yield estimates (35%, 50%, and 60%). Runs 4-6 explored how estimates of yield were affected by a different landing time series (1987-2010 vs. 1989-2010). Runs 7-15 evaluated how estimates of yield were affected by higher and lower assumed natural mortality rates (0.05 vs. 0.025, 0.075, and 0.10). Runs 16-18 evaluated how estimates of yield were affected by a lower F_{msy} to M ratio (0.8 vs 1.0).

Length-frequencies

Wreckfish lengths were obtained from the Trip Interview Program to evaluate trends in wreckfish length over time. A total of 16,962 length measurements collected between 1988 and 2010 were available. Lengths were reported as total length, fork length, or standard length in both centimeters and millimeters and were converted to total length in inches using length conversions summarized in Vaughn et al (2001). Sample sizes varied greatly over time, with most length measurements collected prior to 2000 (n = 14,984 lengths 1988-1999; n = 1,978 lengths 2000-2010). Most wreckfish length measurements were from South Carolina (52.6%) and Florida (36.1%), followed by North Carolina (10.3%) and Georgia (1.0%). Lengths were aggregated across years (1988-1991, … , 2008-2010) to determine if changes in length-frequency distributions have occurred over time. A two factor general linear model ($\alpha = 0.05$) was used to test if the mean size of wreckfish was significantly affected by time period, state landed (Florida, Georgia, and other South Atlantic states), and the interaction between state landed and time period. Bonferroni t-tests were used to conduct multiple comparisons of main effects and summary statistics were generated to facilitate comparisons of mean, median, minimum, and maximum lengths over time by state of landing.

Results

Estimated DCAC yields

Figure 2 and Table 2 summarize estimated yields from Monte Carlo simulations using eighteen different DCAC model parameterizations for wreckfish. Estimated sustainable yields ranged from 0.175 to 0.449 mp ww. The lowest yield was based on model run 9, which assumed a 60% windfall reduction in biomass and an M of 0.025. The highest yield was based on model run 13, which assumed a 35% windfall reduction in biomass and an M = 0.1. Of the 18 model runs, 11 estimated a higher mean annual yield for wreckfish than the current 0.250 mp ABC, four estimated a lower mean yield than the current ABC, and three estimated a mean yield comparable to the current ABC. Mean annual yields for model runs 1-3 and 4-6 were nearly identical, indicating the time series of catch data had little influence on model results. Higher assumed M increased the estimated mean annual yields (runs 10-15), while lower M (runs 7-9) and an F_{msy} to M ratio equal to 0.8 decreased the estimated yields (runs 16-18).

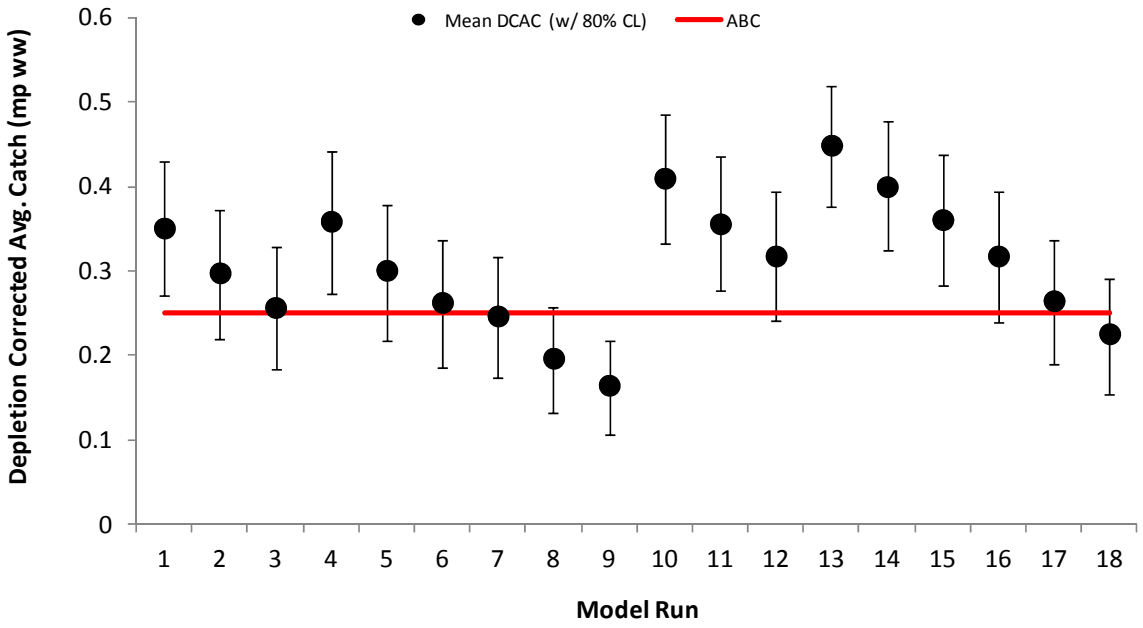


Figure 2. Mean yields (± 80% CL) estimated for eighteen different DCAC model parameterizations for wreckfish.

Length-frequencies

Length-frequency distributions of wreckfish were significantly different for time period ($F = 78.6$, $p < 0.0001$), state landed ($F = 90.45$, $p < 0.0001$), and the interaction of time period by state landed ($F = 61.7$, $p < 0.0001$). Multiple comparison tests indicated that significant differences in mean length between time periods were no greater than 0.8 inches TL and significant differences in mean length between states of landing were no greater than 0.4 inches TL. There were no discernable trends in mean length over time by state of landing (Table 3, Figure 3). Lengths of 38 to 42 inches TL were the most frequent in all six aggregated time periods. Lengths collected during 2000-2003 showed the broadest distribution and highest proportion of fish above 44 inches TL, while lengths collected during 2004-2007 showed the largest proportion of fish collected below 28 inches TL.

Table 2. Estimated yields resulting from Monte Carlo simulations using eighteen DCAC model parameterizations for wreckfish.

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12
Fishery performance												
Catch (mp ww)	15.556	15.556	15.556	15.220	15.220	15.220	15.556	15.556	15.556	15.556	15.556	15.556
Number of years	24	24	24	22	22	22	24	24	24	24	24	24
CV of sum of catch	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Average catch (mp ww)	0.648	0.648	0.648	0.692	0.692	0.692	0.648	0.648	0.648	0.648	0.648	0.648
DCAC												
Assumed M (yr^{-1})	0.05	0.05	0.05	0.05	0.05	0.05	0.025	0.025	0.025	0.075	0.075	0.075
Standard deviation ln(M) (yr -1)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Assumed Biomass Change (Δ)	0.35	0.5	0.6	0.35	0.5	0.6	0.35	0.5	0.6	0.35	0.5	0.6
Standard Deviation Δ	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Assumed c	1	1	1	1	1	1	1	1	1	1	1	1
Standard Deviation c	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Monte Carlo results (n=10,000)												
Monte Carlo mean (mp ww)	**0.351**	**0.298**	**0.269**	**0.359**	**0.301**	**0.275**	**0.247**	**0.197**	**0.175**	**0.410**	**0.356**	**0.330**
Percentiles (%)												
5	0.203	0.161	0.140	0.205	0.158	0.141	0.122	0.092	0.078	0.262	0.209	0.188
20	0.271	0.219	0.194	0.274	0.218	0.197	0.174	0.132	0.114	0.333	0.277	0.253
50	0.351	0.293	0.262	0.356	0.296	0.269	0.240	0.188	0.166	0.411	0.354	0.328
80	0.429	0.373	0.341	0.441	0.379	0.351	0.316	0.258	0.230	0.485	0.436	0.407
95	0.502	0.450	0.419	0.521	0.463	0.433	0.395	0.334	0.306	0.556	0.509	0.482

Table 2 (cont.) Estimated yields resulting from Monte Carlo simulations using eighteen DCAC model parameterizations for wreckfish.

Parameter	Run 13	Run 14	Run 15	Run 16	Run 17	Run 18
Fishery performance						
Catch (mp ww)	15.556	15.556	15.556	15.556	15.556	15.556
Number of years	24	24	24	24	24	24
CV of sum of catch	0.1	0.1	0.1	0.1	0.1	0.1
Average catch (mp ww)	0.648	0.648	0.648	0.648	0.648	0.648
DCAC						
Assumed M (yr^{-1})	0.1	0.1	0.1	0.05	0.05	0.05
Standard deviation ln(M) (yr -1)	0.5	0.5	0.5	0.5	0.5	0.5
Assumed Biomass Change (Δ)	0.35	0.5	0.6	0.35	0.5	0.6
Standard Deviation Δ	0.2	0.2	0.2	0.2	0.2	0.2
Assumed c	1	1	1	0.8	0.8	0.8
Standard Deviation c	0.2	0.2	0.2	0.2	0.2	0.2
Monte Carlo results (n=10,000)						
Monte Carlo mean (mp ww)	**0.449**	**0.400**	**0.373**	**0.318**	**0.265**	**0.237**
Percentiles (%)						
5	0.307	0.254	0.228	0.175	0.136	0.116
20	0.377	0.324	0.295	0.239	0.190	0.165
50	0.450	0.401	0.372	0.316	0.259	0.229
80	0.520	0.477	0.449	0.395	0.337	0.305
95	0.583	0.545	0.517	0.472	0.414	0.386

Table 3. Mean, median, minimum, and maximum wreckfish total lengths (in) by state landed for six time periods between 1988 and 2010.

State	Time Period	n	Mean	Median	Min	Max
eFL	1988-1991	718	37.9	37.8	26	60
	1992-1995	4,002	38.3	38.2	25.2	57.6
	1996-1999	781	38.2	38.3	25.2	52
	2000-2003	30	39.4	40	29.8	47.1
	2004-2007	509	38.7	38.9	23.9	55.1
	2008-2010	79	39.5	39.6	28.3	49.1
SC	1988-1991	2,376	38.9	38.6	25.6	58.7
	1992-1995	3,047	38.9	38.6	25.2	57.5
	1996-1999	2,178	38.1	38.2	23.6	57.6
	2000-2003	1,043	38.9	38.7	24.8	57.6
	2004-2007	172	39	38.5	24.8	59.6
	2008-2010	110	37.6	38.3	27.2	49.4
GA/NC	1988-1991	1,476	38.9	38.6	26.8	55.1
	1992-1995	406	38.8	38.6	27.6	55.5
	1996-1999	0	--	--	--	--
	2000-2003	5	26.4	24.8	21.5	32.6
	2004-2007	30	23.6	23.1	22.1	28.7
	2008-2010	0	--	--	--	--

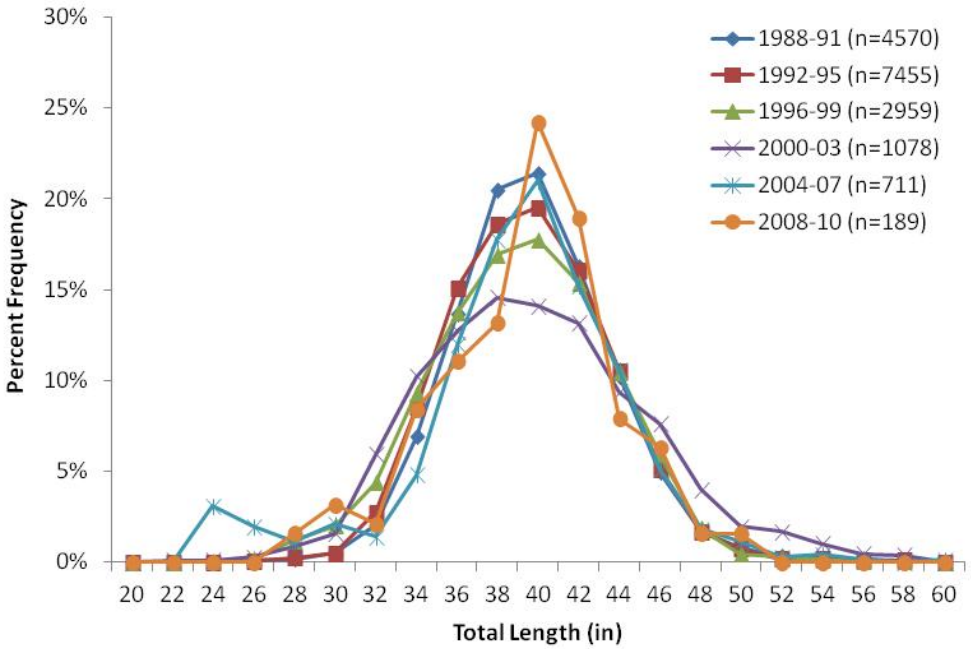


Figure 3. Frequency of wreckfish total lengths during six different time periods between 1988 and 2010.

Discussion

In September 2011, the SAFMC approved a Comprehensive Annual Catch Limit (ACL) Amendment, which specifies ACLs for most federally managed species in the South Atlantic, including wreckfish (SAFMC 2011). The SAFMC cannot establish an ACL above the 0.250 mp ww ABC recommended by the SSC, which was based on recent average wreckfish commercial catches. The Comprehensive ACL Amendment sets the wreckfish ACL equal to ABC and allocates 95% of the ACL to the commercial sector (0.2375 mp ww) and 5% of the ACL to the recreational sector (0.0125 mp ww). Upon implementation, this amendment will reduce the commercial wreckfish quota by 88%; from 2 mp ww to 0.2375 mp ww.

During their August 2010 meeting, the SSC recommended conducting Depletion-Corrected Average Catch (DCAC) or Depletion-Based Stock Reduction Analysis (DB-SRA) in 2011 to compare with the current catch-only recommendations (SAFMC 2010), resulting in the work summarized herein. The DCAC model results appear to indicate that ABC could be set slightly higher than the SSC's current 0.250 mp recommendation; however, this result is contingent on model parameters assumed for Δ, M, and F_{msy}.

Evaluation of model parameterizations indicated that results were most sensitive to changes in natural mortality rate, followed by reductions in biomass and the assumed ratio of F_{msy} to M. An M of 0.05 is consistent with a longevity of 70+ years, as determined by Peres and Haimovici (2004), whereas an M of 0.10 is more consistent with a longevity of 30-40 years, which is the oldest known age of wreckfish sampled from the South Atlantic (Vaughn et al. 2001). An M of 0.075 is intermediate to the above-mentioned natural mortality rates and is consistent with a life-span of 50-60 years, while an M of 0.025 is representative of a maximum age greater than currently observed for wreckfish. Based upon a review of recent stock assessments in the Southeast Region and estimates of M based on Hoenig (1983) and Hewitt and Hoenig (2005), values of M at or near 0.05 are more likely given the longevity (76 years) and life history of the species (Table 4).

Table 4. Summary of Fmsy or Fmsy proxies compared to M for recent stock assessments in the Gulf of Mexico and South Atlantic.

Region	Species	Fmsy or proxy	F value	M	F to M ratio	Max Age	Source
SA	Wreckfish	Fmax	0.14-0.16	0.05	2.8-3.2	39	Vaughn et al. 2001
SA	Wreckfish	$F_{0.1}$	0.14-0.15	0.10	1.4-1.5	39	Vaughn et al. 2001
SA	Wreckfish	$F_{0.1}$	0.23-0.25	0.15	1.5-1.6	39	Vaughn et al. 2001
SA/Gulf	Black Grouper	$F_{30\%SPR}$	0.216	0.136	1.6	33	SEDAR 19 2010
SA	Red Grouper	Fmsy	0.221	0.14	1.6	26	SEDAR 19 2010
SA	Red Snapper	F30%/F40%SPR	0.104-0.148	0.078	1.3-1.9	54	SEFSC 2009
Gulf	Gag	Fmax	0.22	0.15	1.5	31	GMFMC 2010
Gulf	Yellowedge Grouper	$F_{30\%SPR}$	0.0964	0.073	1.3	85	SEDAR 22 2011
Gulf	Yellowedge Grouper	$F_{30\%SPR}$	0.092	0.055	1.7	85	SEDAR 22 2011

The change in biomass is also an important factor in determining the DCAC. CPUE indices and one fishermen interview were conducted to gauge the decline in biomass that occurred after wreckfish exploitation began and reached peak landings in 1990. CPUE trends indicated a 35-60% drop in catch rate occurred from the early 1990s through present. Catch rates declined rapidly from 1992 to 1997 then remained stable for nearly a decade, before increasing from 2007-2010. Not surprisingly, results

indicated that smaller windfall reductions in biomass resulted in higher sustainable yield estimates. A 35% reduction in biomass resulted in sustainable yields from 0.247-0.449 mp, whereas a 60% reduction in biomass resulted in sustainable yields that ranged from 0.175-0.373 mp. A 50% reduction in biomass resulted in sustainable yields that ranged from 0.197-0.400 mp. The 50% reduction level was based on expert opinion by a fisherman who has participated in the fishery since it began. This reduction in biomass is within the range of estimates provided by the CPUE index. Given that catch rates and fish lengths have remained stable for a decade or more and catch rates are showing signs of increase in recent years, a 50% reduction in biomass seems to be a reasonable proxy for the windfall reduction in biomass. This estimated reduction is considerably lower than Vaughn et al. (2001), who estimated ~85-90% reduction in biomass using wreckfish data through 1998.

Trends in CPUE are affected by a variety of factors. In this analysis, several effort metrics were evaluated and it was determined that landings in pounds per day was most appropriate for calculating CPUE. Because small changes in Δ can affect estimates of sustainable yield, estimates derived from the CPUE index are critical to how high or low sustainable yield can be set. CPUE can be affected by a variety of factors including changes in abundance, changes in fishing practices and geographic areas fished, concentration of fishing effort in areas of greatest fish abundance, environmental conditions, and many other factors. These factors can lead to CPUE not corresponding to trends in abundance. If hyperstabilization of CPUE occurs, then trends in CPUE will remain high as stock abundance declines (Hilborn and Walters 1992). Similarly, hyperdepletion may occur if CPUE declines faster than stock abundance (Hilborn and Walters 1992). Review of logbook records indicated that wreckfish were harvested from 10 different statistical areas between 1992 and 2010. Of the 10 statistical areas, three accounted for 98% of the wreckfish landings. Beginning in 2003 there was a shift to catching wreckfish in statistical areas closer to shore. The influence of this shift on CPUE is unknown. Similarly, it is unknown how fishing practices may have affected the CPUE index. Logbook records indicated trip length increased from slightly over 6 days to more than 9 days, while the number of lines fished per vessel has remained relatively stable over time and the number of hooks fished per line has declined. This latter change in gear usage was accounted for when standardizing CPUE.

Given that there is no estimate of F_{msy}, a proxy for F_{msy} must be assumed. In this analysis, F_{msy} was assumed to be equal to M or 80% of M. The lower F_{msy} is set, the less productive the stock is estimated to be; reducing the estimate of sustainable yield. Recent stock assessments from the Southeast Region were used to compare values of F_{msy} to M to assess if M is a reasonable proxy for F_{msy} (Table 4). For all assessments reviewed, the estimated ratio of F_{msy} to M was greater than 1. It should be noted that this conclusion is based on a limited number of assessments of species with differing life history characteristics and is not intended to be a comprehensive list of F_{msy} to M ratios for all species in the Southeast Region. Given these results, an F_{msy} to M ratio of 1 is considered a reasonable proxy for wreckfish.

In conclusion, the intent of this analysis was to provide additional information for SSC consideration based on their recommendation for conducting a DCAC or DBSRA analysis for wreckfish (SAFMC 2010). Given the sensitivity runs considered in this report, and the discussion above, it appears the ABC for wreckfish could be increased by 19,000 to 109,000 lbs given a windfall biomass reduction of 35-60%, M = 0.05, and an F_{msy} to M ratio of 1.0. Catch rates for wreckfish have been stable since the late 1990s and in recent years have been slightly increasing, while fish lengths have been stable since the fishery began in the late 1980s. This is evidence that a sustainable yield has been taken over a prolonged period of time without indication of a change in underlying resource abundance (MacCall 2009). Given the

stability of catch rates over time, the level of current take appears sustainable and could potentially be increased.

It should be noted that yields summarized in Table 2 represent sustainable yields but may not represent maximum sustainable yield, given that wreckfish constitutes a single genetic stock across the North Atlantic ocean (Sedberry et al. 1996) and fishing mortality in other regions of the Atlantic Ocean could affect yields from U.S. South Atlantic waters. Similar to the U.S. segment of the wreckfish stock, landings of wreckfish in Portugal and Spain peaked in the early 1990s and then declined thereafter due to overexploitation (Sadovy 2003). Fishing records from the Azores indicate wreckfish landings have stabilized in more recent years after sharply declining from 1994-1999 (Damaso 2006). For this assessment of wreckfish, it was assumed that wreckfish stocks on U.S. fishing grounds would not be affected by fishing elsewhere. However, given that the source of juvenile wreckfish is unknown and European fish hooks are frequently found in wreckfish caught in U.S. waters (Sedberry et al. 1999), this is a tenous assumption. A north Atlantic assessment of wreckfish may be more appropriate, but would require reliable landings and CPUE data from numerous fishing grounds throughout the north Atlantic. Given the complexity of conducting a north Atlantic assessment, it is recommended that the U.S. South Atlantic portion of wreckfish be managed based on a target level of depletion, thus avoiding local overfishing. Regular review of U.S. trends in catch per unit effort and fish length would ensure annual catch limits are not resulting in stock depletion.

Literature Cited

Alverson, D. and W. Pereyra. 1969. Demersal fish explorations in the northeastern Pacific Ocean – an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. Journal of Fisheries Research Board of Canada, 26: 1985-2001.

Damaso, C. 2006. Azorean Demersal Fishery Audit Report. Department of Oceanography and Fisheries. 118 pp.

Gulf of Mexico Fishery Management Council. 2010. Stock assessment of gag in the Gulf of Mexico: Report of assessment re-run webinars. GMFMC, Tampa, FL. 33 pp.

Gulland, J. 1970. Preface. *In* the Fish Resources of the Oceans pp. 1-4. Ed. By J. Gulland. FAO Fisheries Technical Paper, 97.

Hewitt, D.A., and J.M. Hoenig. 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fishery Bulletin. 103(2): 433-437.

Hilborn, R., and C.J. Walters. 1992. Quantative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York, NY. 570 pp.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin, 82: 898-903.

MacCall, A.D. 2009. Depletion corrected average catch: a simple formula for estimating sustainable yields in data poor situations. ICES Journal of Marine Science, 66: 2267-2271.

Peres, M.B., and M. Haimovici. 2004. Age and growth of southwestern Atlantic wreckfish *Polyprion americanus.* Fisheries Research, 66: 157-169.

Sadovy, Y. 2003. *Polyprion americanus.* In: IUCN 2011. IUCN Red List of Threatened Species. Version 2011.1 www.iucnredlist.org. Downloaded on 23 September 2011.

Sedberry, G.R., J.L. Carlin, R.W. Chapman, and B. Eleby. 1996. Population structure in the pan-oceanic wreckfish, *Polyprion americanus*, (Teleostei: Polyprinidae), as indicated by mtDNA variation. Journal of Fishery Biology 49 (Supplement A): 318-329.

Sedberry G.R., Andrade C.A.P., Carlin J.L., Chapman R.W., Luckhurst B.E., Manooch C.S. III, Menezes G., Thomsen B. and Ulrich G.F. 1999. Wreckfish *Polyprion americanus* in the North Atlantic: Fisheries, Biology, and Management of a widely distributed and Long lived fish. *American Fisheries Society Symposium* 23:27-50

Sedberry, G.R. 2001. Island in the stream: oceanography and fisheries of the Charleston Bump. AFS, Symposium 25, Bethesda, MD. 240 pp.

South Atlantic Fishery Management Council. 2011. Comprehensive annual catch limit amendment for the South Atlantic region. SAFMC, Charleston, SC.

Southeast Data, Assessment, and Review. 2010. Stock Assessment Report: Gulf of Mexico and South Atlantic Black Grouper. SEDAR 19, Charleston, SC. 661 pp.

Southeast Data, Assessment, and Review. 2010. Stock Assessment Report: South Atlantic Red Grouper. SEDAR 19, Charleston, SC. 612 pp.

Southeast Data, Assessment, and Review. 2011. Stock Assessment Report: Gulf of Mexico Yellowedge Grouper. SEDAR 22, Charleston, SC. 423 pp.

Southeast Fisheries Science Center. 2009. Red snapper projections V. SEFSC, Beaufort, NC. 34 pp.

Vaughn, D.S., C.S. Manooch III, and J.C. Potts. 2001. Assessment of the Wreckfish Fishery on the Blake Plateau. Pages 105-122 in G.R. Sedberry, editor. Island in the stream: oceanography and fisheries of the Charleston Bump. AFS, Symposium 25, Bethesda, MD.

Walters, C., and S. Martell. 2004. Fisheries ecology and management. Princeton University Press, Princeton, NJ. 399 pp.

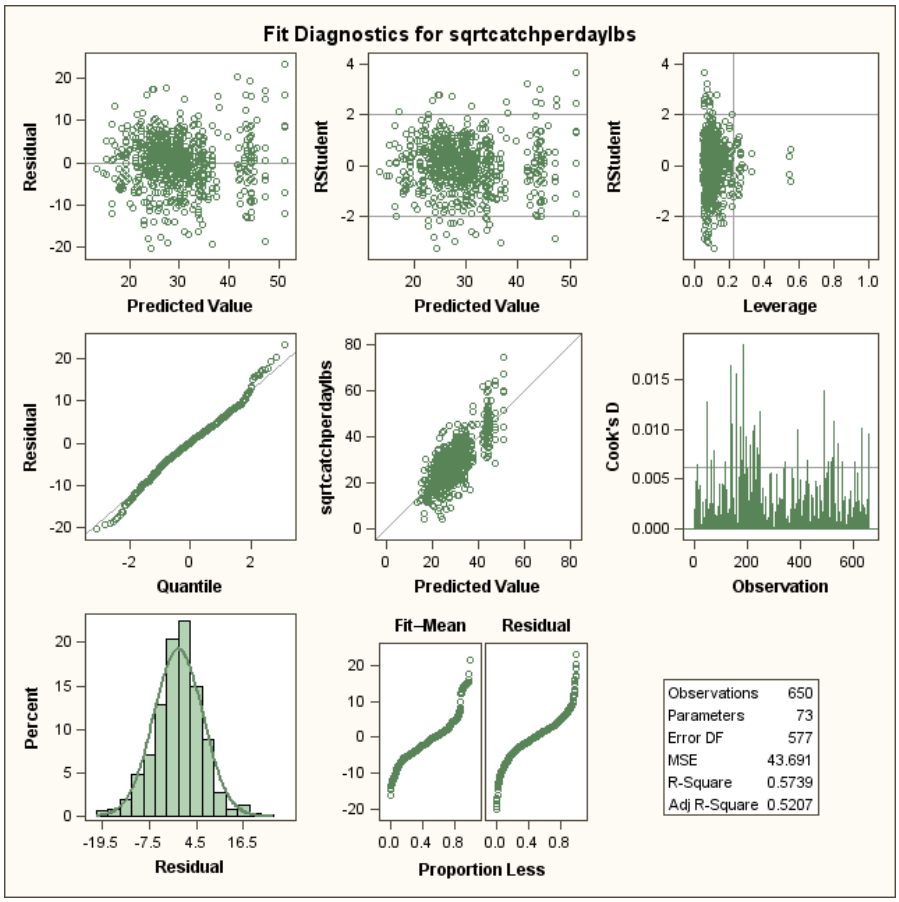
Appendix 1: GLM results and diagnostic plots for standardized pounds per day indices.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	72	33955.37356	471.60241	10.79	<.0001
Error	577	25209.94928	43.69142		
Corrected Total	649	59165.32284			

R-Square	Coeff Var	Root MSE	sqrtcatchperdaylbs Mean
0.573907	22.27010	6.609949	29.68083

Source	DF	Type I SS	Mean Square	F Value	Pr > F
vesselid	2	15950.71662	7975.35831	182.54	<.0001
fishingyear	18	11177.10363	620.95020	14.21	<.0001
seasons(fishingyear)	38	3342.52751	87.96125	2.01	0.0004
totalhooks	14	3485.02580	248.93041	5.70	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
vesselid	2	4783.766042	2391.883021	54.74	<.0001
fishingyear	18	4550.019905	252.778884	5.79	<.0001
seasons(fishingyear)	38	2769.711567	72.887146	1.67	0.0083
totalhooks	14	3485.025799	248.930414	5.70	<.0001



Available online at www.sciencedirect.com
SCIENCE DIRECT®
Fisheries Research 66 (2004) 157–169
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

Age and growth of southwestern Atlantic wreckfish *Polyprion americanus*

Mônica Brick Peres [a,*], Manuel Haimovici [b]

[a] *Região do Litoral—Departamento de Qualidade Ambiental, Fundação Estadual de Proteção Ambiental—FEPAM, Carlos Chagas 55, Porto Alegre RS 90030-020, Brazil*
[b] *Fundação Universidade Federal do Rio Grande—FURG, Cx. Postal 474, Rio Grande RS 96201-900 Brazil*

Received 6 February 2002; received in revised form 23 May 2003; accepted 10 July 2003

Abstract

Southwestern Atlantic wreckfish *Polyprion americanus* (27°56′S and 34°52′S) were aged using transverse thin sections of the sagittae otoliths of 390 individuals (44–155 cm TL, total length). The index of average percentage error for independent readings of two readers was 3%, and 10% of the sections were considered illegible. Marginal state assessment of the whole otolith's margin ($n = 406$) showed that one opaque band (annulus) is laid down each spring–summer. Supposed daily ring counts confirmed what was thought to be the first annual band. Maximum observed age was 76 years for males and 62 years for females. The von Bertalanffy growth model was significantly different ($P < 0.01$) between males ($L_\infty = 109.5$ cm, $K = 0.084$ per year and $t_0 = -4.69$ years) and females ($L = 129.5$ cm, $K = 0.0534$ per year and $t_0 = -6.80$ years). The absence of wreckfish below 44 cm TL in the samples and younger than 1.5 years means that this is the minimum size and age of recruitment to the bottom.

Keywords: Age; Growth; Whole and sectioned otolith; Wreckfish; *Polyprion americanus*

1. Introduction

Wreckfish, *Polyprion americanus* (Bloch and Schneider, 1801), of the family Polyprionidae (Eschmeyer, 1990), is a large demersal fish that inhabits continental and oceanic islands slopes of temperate and subtropical waters at both sides of the Atlantic Ocean, at the Mid-Atlantic Ridge, the Mediterranean, southern Indian Ocean and southern Pacific (Heemstra, 1986; Roberts, 1989, 1996; Sedberry et al., 1999). Recent studies using mtDNA and microsatellite, differentiated northern and southern wreckfish stocks, and allelic variation at microsatellite loci differentiated wreckfish from two southern hemisphere locations, Brazil and the south Pacific (Ball et al., 2000).

Along southwestern Atlantic *P. americanus* occurs from 23°S, near Rio de Janeiro, Brazil, to 46°S, Argentina (Cousseau and Perrota, 1998; Peres, 2000). A wreckfish fishery with handlines from small boats off southern Brazil is recorded since 1973 (Santos and Rahn, 1978; Barcellos et al., 1991). In the nineties, the fishery changed to vertical longlines and then to steel wire longlines. The number of vessels increased from around 10 in the 1970s, to more than 35 in 1997. Although fishing power grew with gear development and expansion of fishing area, estimated annual landings decreased from 2772 (1989) to 1080 t (1995). Capture (kg) per hook, per days at sea, dropped from 0.72

* Corresponding author. Tel.: +55-5132132124227; fax: +55-5132251588.
E-mail address: monica.peres@fepam.rs.gov.br (M.B. Peres).

0165-7836/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0165-7836(03)00207-8

(1989) to 0.48 (1997–1998). This suggests that this stock may be endangered and needs to be managed (Peres, 2000).

Age estimates from band counts on aging structures and validation of the periodicity of their deposition are basic requirements to obtain growth rates, ages at maturity and recruitment, longevity and natural mortality rates. These are essential data for proper management of southwestern Atlantic wreckfish.

Band patterns on otoliths sections of *Polyprion* species have been considered unreliable (Paul, 1992) or difficult to count (Francis et al., 1999). *P. oxygeneios* (New Zealand hapuku) may attain more than 60 years of age (Francis et al., 1999) and *P. americanus* (southeastern USA wreckfish) up to 39 years (Vaughan et al., 2000), but there are no age estimates for *P. americanus* stocks in the southern hemisphere.

Here, the otolith transverse sections were chosen for age determination. The development of a method to prepare and read otoliths sections and find the periodicity of band formation, made it possible to determine longevity and growth models for male and female southwestern Atlantic wreckfish *P. americanus*.

2. Material and methods

2.1. Sampling

Biological samples were obtained from commercial landings (1990–1995) with different fishing gears and from research surveys with bottom trawl (1986–1987) and longline (1996–1997) (Table 1). The study area was the continental shelf and slope off southern Brazil (27°56′S and 34°52′S), in water depths from 70 to 500 m.

In research cruise samples, fish total weight (TW in kg) and total length (TL in cm) were recorded. Length was measured between the end of the inferior jawbone and the end of the tail in natural position. Sex was determined by external examination of the gonads and both otoliths were stored dry for aging.

Wreckfishes from commercial landings are sold ice cooled and ungutted. As each fish may attain large body size and high prices, sampling procedures required fast and non-damaging techniques. Fish were measured from the posterior border of the eye orbit to the fork of the caudal fin (EF in cm) and converted to TL by the relationship $TL = -0.724 + 119.5EF$ (Peres and Haimovici, 1998). Sex was determined by extracting a small sample of the gonad with a surgical curette through the gonopore and the left otolith was obtained through the opercular openings and stored dry.

2.2. Readings on the otoliths

Whole otoliths of 406 wreckfish of both sexes (44–155.5 cm TL), immersed in 70% ethanol for 24 h, were examined with incident light over a black background. Thin transverse sections through the focus were obtained from otoliths embedded in a polyester resin with a single high concentration diamond wheel

Table 1
Sampling period, fishing gear, fishing area, TL (mm) and number (*n*) of fish examined for age and growth study of southwestern Atlantic wreckfish

Period	Gear/type[a]	Fishing area		TL (cm)	*n*
		Latitude	Water depth (m)		
1986/1987	BT/res	31°50′–34°52′S	120–450	57–115.5	43
1990	FT/com	33°55′S	70–90	44–51	22
1994	VL/com	30°45′–34°04′S	250–400	64–150.5	24
1994	BG/com	33°25′–33°43′S	220–320	44–132.5	27
1995	VL/com	28°40′–34°49′S	280–460	62–155.5	83
1995	L/com	30°05′–32°13′S	400–420	54–140.5	114
1995	BG/com	33°30′–33°50′S	90–320	44–130	31
1996/1997	BL/res	27°56′–34°29′S	130–500	49–123	62
Total		27°56′–34°52′S	70–500	44–155.5	406

[a] BT: bottom trawl; BG: bottom gillnet; BL: bottom longline; FT: fish traps; VL: vertical line and hook; L: longline; res: research cruise; com: commercial.

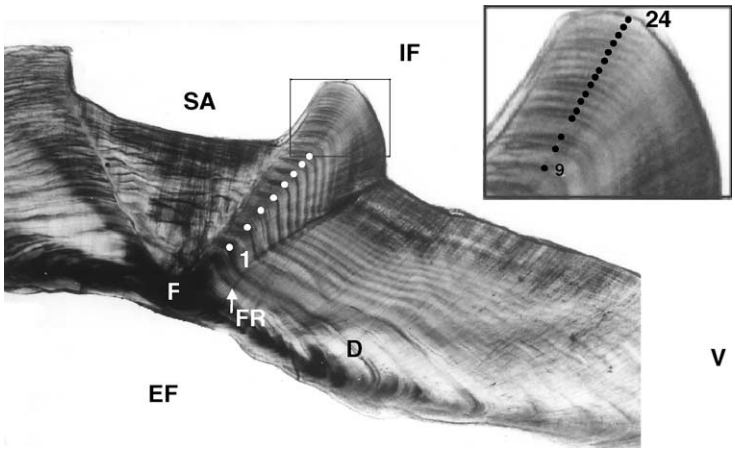


Fig. 1. Transverse otolith section, 0.18 mm thick, observed with transmitted light (32×). Otolith from a female wreckfish (127 cm TL) captured in October 1995 off southern Brazil. Counted opaque annual bands (white or black circles), sulcus acusticus (SA), internal face (IF), external face (EF), ventral margin (V), focus (F), first opaque band (1), first discontinuity (D), false ring (FR).

with a Burhler-Isomet low-speed saw. Band patterns were clearer in sections of 0.20–0.25 mm thick for the smaller fish (TL < 75 cm) and 0.15–0.20 mm thick, for larger ones. Sections with more than 30–40 bands were ground further on 1000-grade sandpaper until 0.11–0.15 mm thick. All sections were mounted on glass slides with xylol base mounting media (ENTELAN Merck).

Undamaged otolith sections ($n = 390$) were examined with transmitted light under a compound microscope (40–100×). Opaque bands were counted from the focus to the outer edge of the sulcus (Fig. 1). Thinner sections (0.11–0.15 mm thick), usually from older fish, were also examined with incident light under a dissecting microscope with low magnification to confirm the band patterns on the central area near the focus. After several preliminary readings, final individual blind counts were made independently by two readers. If band counts differed, both readers examined the section together and if no agreement could be reached the otolith was rejected.

Counts between successive readings of the same reader and between the two readers varied due to (1) high number of bands, (2) splitting of opaque bands in some portions of the section, or (3) very irregularly spaced bands. Initial agreement between independent readers was 30.5% and disagreement by only one band was 26.5%. Following a common reading and discussion 89.5% of the otoliths were considered readable. For 3.6% of them, agreement was not possible and the other 6.9% were considered unreadable by one or both readers. The index of average percentage error (IAPE, Beamish and Fournier, 1981), was calculated as

$$\mathrm{IAPE} = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{|X_{ij} - X_j|}{X_j}\right]$$

where N is the number of fish aged, R the number of times each is aged, X_{ij} the ith age determination of the jth fish and X_j the average age calculated for the jth fish. The IAPE between independent counts ($n = 2$) was 2.91%.

Narrow opaque bands, assumed to be daily rings (Campana, 1992), were examined on the otoliths sections of four wreckfish (45–90.5 cm TL, 2–22 years old). The sections were hand ground until 0.04–0.09 mm thick and mounted on glass slides with mounting media. They were counted from the focus to the first discontinuity (Fig. 1), along the external face, on a compound microscopy (400–1000×). This discontinuity was similar to the ultra structures in the otoliths of the eel *Anguilla anguilla* (Lecomte-Finiger, 1992). Differences of maximum and minimum counts for three readings of each section by the same reader did not exceed 9.9% (Table 2).

The terminology used to otolith description was adapted from Wilson et al. (1987) and Moralis-Nin (1992) (Table 3).

Table 2
Number of narrow opaque bands, considered daily, on wreckfish otolith sections[a]

TL (cm)	Age	Sex	FC	FD(1)	FD(2)	FD(3)	FD(mean)	%
49	3	Female	137	373	356	362	363.7	4.78
90.5	22	Male	155	387	372	384	381	4.03
54	3	Male	141	393	382	386	387	2.88
45	2	Unknown	–	400	364	368	377.3	9.89

[a] For each section, length, age and sex of the fish, number of daily bands from the focus to the end of the central opaque area (FC), number of daily bands from the focus to the first discontinuity (FD) for three counts (first, second and third), the mean number of daily bands and the percent difference (%) between the minimum and maximum number counted on each section.

2.3. Validation

The periodicity of band depositions was assessed by monthly proportions of opaque margins in sectioned and whole otoliths. The posterior end of the whole otoliths was chosen for younger fish and the edge of the rostrum for older ones (Fig. 2).

2.4. Growth

Length at age data was fitted with non-linear iterative procedure (Gauss–Newton) to the von Bertalanffy growth model (von Bertalanffy, 1938), VBGM: $Lt = L_\infty(1 - e^{-K(t-t_0)})$, where Lt is the length (cm) at age t (years), L_∞ the assintotic length (cm), K the growth coefficient (per year) and t_0 the theoretical age at zero length (years). Growth curves between sexes were compared with a likelihood ratio test (Kimura, 1980; Cerrato, 1990), for immature (TL $<$ 75 cm), adults (TL $>$ 75 cm) and for all wreckfish together.

Length–weight regression for sexes combined (n = 207, 44–145.5 cm TL, 1.2–53 kg TW, $r^2 = 0.98$) was $W = (6.29 \times 10^{-6})L^{3.21}$ (Peres and Haimovici, 1998). Weight at age was calculated using this relationships and estimated length at age.

Ages were assigned based on annuli counts, assuming 1 September as the theoretical birthday,

Table 3
Terminology used to otolith description of southwestern Atlantic wreckfish, adapted from Wilson et al. (1987) and Moralis-Nin (1992)

Annulus (opaque band)	A concentric mark on any ageing structure that allows interpretation of growth in terms of age. In whole and sectioned wreckfish otolith, concentric and continuous opaque bands with a discontinuity, white under incident light and dark with transmitted light were counted as annual bands
Central area	In the wreckfish otolith it is an area between the focus and the first translucent annual band (associated with a depression on the external face). It is predominantly opaque. In whole otolith, it can be large and diffuse, or composed by one to three opaque areas, considered false rings. On the sections, it was the most difficult portion to interpret the growth band pattern
Discontinuity	This was the main criterion used to identify the first annual band on wreckfish otolith sections. It is a concentric and continuous structure like "thin crack" when viewed under a compound microscope (50–100×) in otolith sections of less than 0.15–0.17 mm thick. It is found, usually, between the end of the translucent band and the beginning of the opaque one
Daily ring	On wreckfish otolith sections (0.04–0.09 mm thick), narrow concentric and continuous opaque bands, with smooth transition in width and contrast were counted as "daily" bands
Area, region, zone, mark	Auxiliary terms used to describe the ageing structures, with no relation with a temporary scale
False ring	Any opaque area similar to an annual band but interrupted or without a "discontinuity" (if in the central area of the section)
Focus	Real or hypothetical origin of the whole or sectioned otolith, used as a reference to begin counts or measurements of growth bands. On wreckfish otolith the focus is opaque. Under incident light and dark bottom, the focus appears as a small brilliant white circle in the central area of the lateral face (concave). In the sections, under transmitted light, it is a dark circular area in the central area, near to the margin of the lateral face

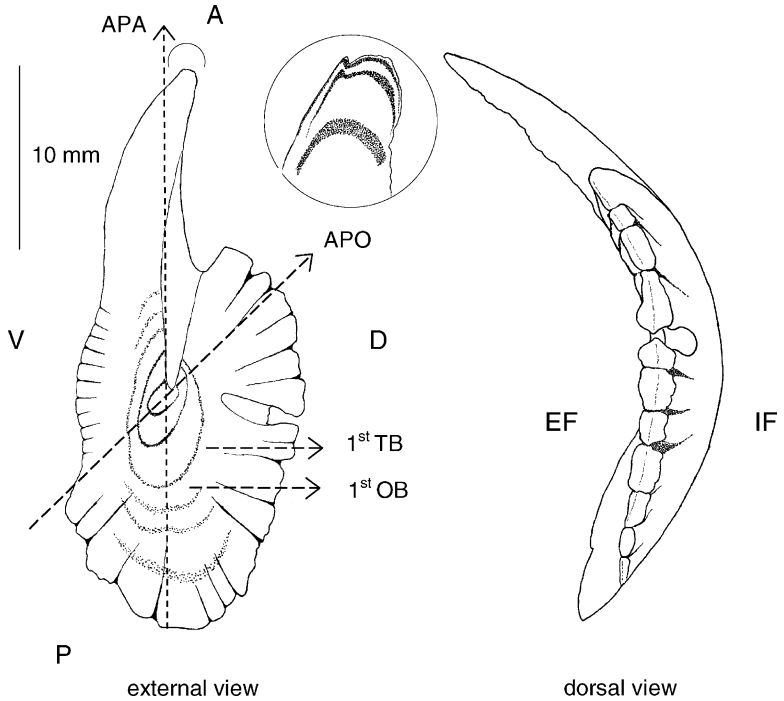


Fig. 2. View of the left otolith from a female wreckfish, 145.5 cm TL and 51 years old, captured in November 1994 off southern Brazil. Otolith external face observed with reflected light over a dark background. Ventral margin (V), dorsal (D), posterior (P), anterior (A), first translucent band (first TB), first opaque band (first OB), antero-posterior axis (APA), original antero-posterior axis (APO). Magnified opaque otolith rostrum's edge (10×). Otolith dorsal view showing the otolith curvature, external face (EF), and internal face (IF).

considering the spawning season in the region (Peres, 2000).

3. Results

3.1. Otolith structure

In wreckfish, the sagittae otoliths are elongated, laterally compressed, curved and very fragile (Fig. 2). Their surfaces are irregular, with many mounts and crenellations. The external face of the otolith is concave with grooves and ridges radially disposed. With age, the rostrum becomes conspicuous and curved, the sulcus acusticus gets deeper and the irregularities on the surface get strongly marked. The antero-posterior axis rotates during otolith growth and for older fish it may be up to 30° or 40°. Due to this rotation, transverse sections through the focus changed planes with ages.

3.2. Band patterns on sectioned and whole otoliths

Viewed with transmitted light, otolith sections have a dark central area (opaque) around the focus and a dark line that radiates along the external face surface (Figs. 1 and 3a). Translucent bands were wider than the opaque ones near the focus but this width difference progressively diminished from the focus to the border. For the same otolith, width of the translucent bands increased with thinner sections.

On the sections thinner than 0.15 mm, it was possible to observe a structure like a "thin crack", the discontinuity, between the end of the first translucent band and the beginning of the first opaque band. Thin transverse otolith sections (0.04–0.09 mm) showed pairs of opaque and translucent narrow bands (Fig. 3b). The mean number of these bands, considered daily rings, from the focus to the first discontinuity was 377.3, almost 1 year (Table 2). Thus, for wreckfish, the discontinuity and the end of the first

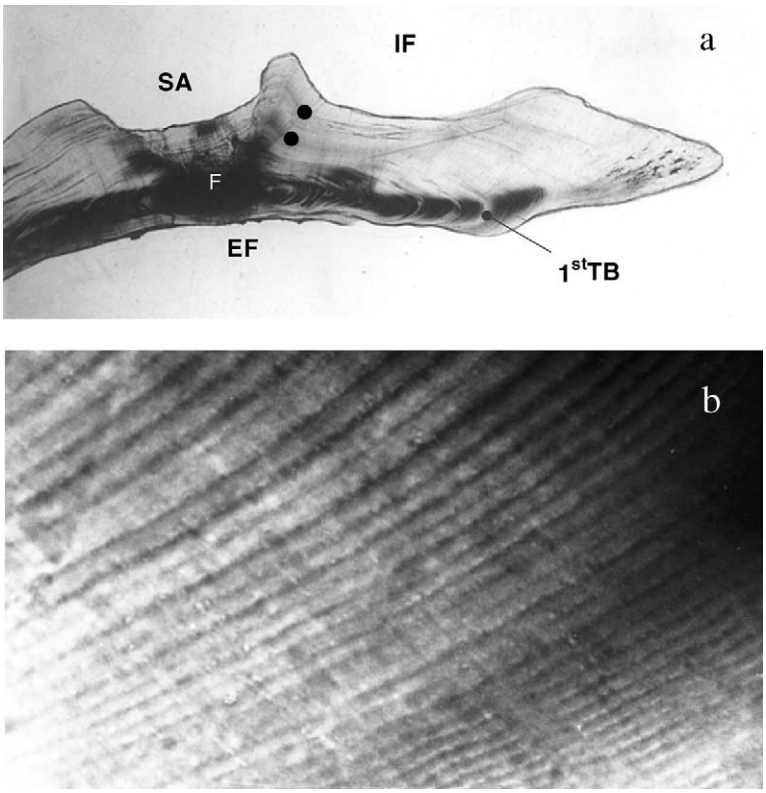


Fig. 3. Transverse otolith section (0.04 mm thick) of a 54 cm TL wreckfish, captured in September 1994 off southern Brazil. (a) Observed with transmitted light (32×). Annual opaque bands (black circles), sulcus acusticus (SA), internal face (IF), external face (EF), first translucent band (first TB), focus (F). (b) Observed in higher magnification (1000×) showing general aspect of the narrow opaque bands, considered daily rings, in the opaque otolith central area, adjacent to the external face near to the first annual translucent band.

crest on the external surface of the otolith were both used as criteria to detect the first annual band. One to three translucent narrow translucent rings were frequently observed before the first annual band, and were considered false (Fig. 3a).

The following continuous opaque bands were considered annual and counted on the dorsal margin of the sulcus (Fig. 1). Some were very irregularly spaced and this was considered the main cause of low precision of preliminary readings. Although they were frequent, for each section their number was never more than 1–5. Counting every band, independent of their spacing resulted in lower IAPE.

The border type was inconsistently classified between successive readings for 62.2% of the 390 otolith sections. Sometimes, even sequential sections of the same otolith had different classifications. This was due to either extremely thin opaque bands at the border or misinterpretation of the border type caused by optical distortions.

Examined with incident light over a black background, the central area of whole otoliths is brilliant white and may show one to three false rings. The first translucent band is always associated with a depression. The central area is surrounded by a clear and distinct opaque band, the first annual band (Fig. 2). The following 6–12 bands could be easily observed in the posterior and dorsal region of the otoliths and the others along the rostrum. The border type, opaque or translucent, was consistently classified between two independent readings of the same reader for 80.3% of the 406 otoliths.

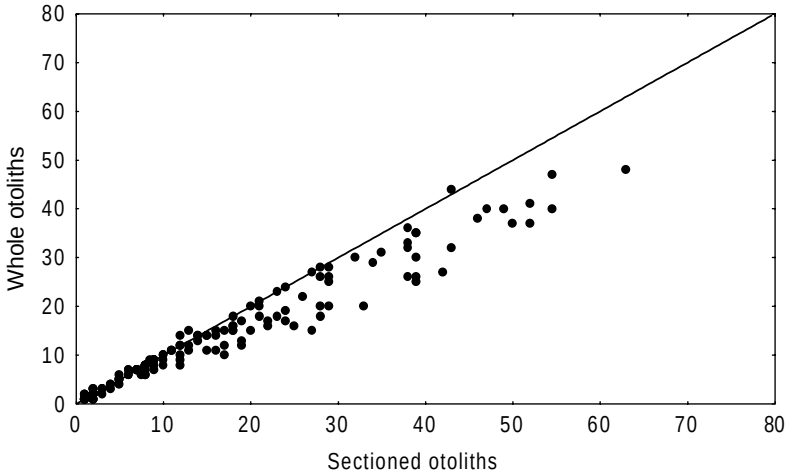


Fig. 4. Number of opaque bands counted on whole and sectioned otoliths of southwestern Atlantic wreckfish. It also shows the bisection line.

Age determinations were similar for sectioned and whole otoliths, although the number of opaque bands on otolith sections was progressively higher for older fishes (Fig. 4). This indicates that the best age estimates are on sectioned otoliths. Co-linearity between readings on whole and sectioned otoliths means that the band patterns are the same and the used criteria for band counts are consistent.

3.3. Validation

Periodicity of band depositions was validated by monthly proportions of opaque margins of whole otoliths (Fig. 5, Table 4). For adult wreckfish (n = 290, 75–155.5 cm TL) almost 100% of the legible borders were opaque from November to February and less than 5% from April to June. Despite the smaller

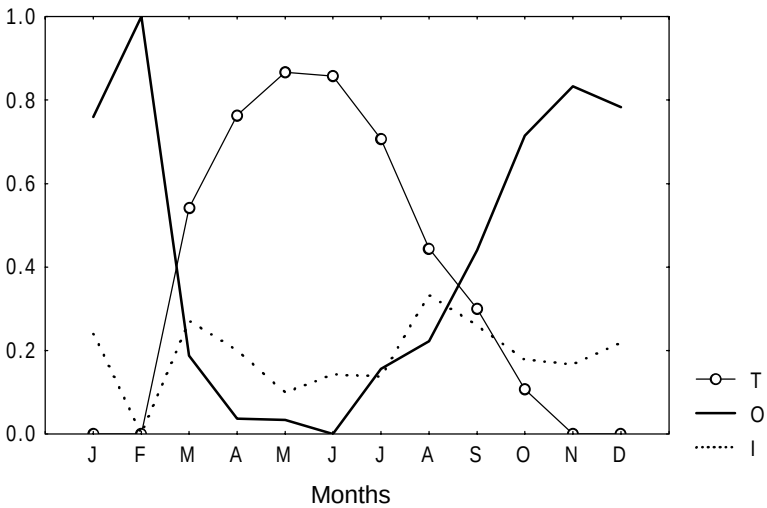


Fig. 5. Monthly proportion of border type, translucent (T), opaque (O) and illegible (I) observed in whole otoliths (n = 406) of southwestern Atlantic wreckfish.

Table 4
Number of opaque margins (O), translucent (T) and illegible (I) observed per month, on whole wreckfish otoliths[a]

Month	Immature			Adults A			Adults B			%			*n*
	T	O	I	T	O	I	T	O	I	T	O	I	
January	–	–	–	–	5	3	–	14	3	–	76.0	24.0	25
February	–	1	–	–	–	–	–	–	–	–	100.0	–	1
March	14	4	6	8	3	2	4	2	5	54.2	18.8	27.1	48
April	16	2	–	23	–	10	3	–	1	76.4	3.6	20.0	55
May	–	–	1	14	–	2	12	1	–	86.7	3.3	10.0	30
June	1	–	–	4	–	–	1	–	1	85.7	–	14.3	7
July	17	1	3	31	14	8	29	2	4	70.6	15.6	13.8	109
August	4	3	2	1	–	–	3	1	4	44.4	22.2	33.3	18
September	5	12	2	6	7	4	4	3	7	30.0	44.0	26.0	50
October	–	4	–	1	7	3	2	9	2	10.7	71.4	17.9	28
November	–	6	–	–	–	–	–	4	2	–	83.3	16.7	12
December	–	10	2	–	1	1	–	7	2	–	78.3	21.7	23
Total	57	43	16	88	37	33	58	43	31			19.7	406

[a] Immature wreckfish (TL < 75 cm), adults A (75 cm < TL < 100 cm) and adults B (TL > 100 cm). Percentage of translucent, opaque and illegible margins within total number of examined otoliths per month (*n*).

sample size, the same pattern was observed for immature fish (45–75 cm TL, $n = 116$). It is concluded that, annually, one opaque band is laid down from late winter to summer. Higher proportions of illegible margins (non-coincident or doubtful) occurred during transitional months, when fishes are beginning to deposit opaque (August–September) or translucent (March) material on the otoliths (Fig. 5, Table 4).

3.4. Growth

As growth differences were not observed between sexes for immature fish (Table 5), 22 unsexed wreckfish (44–55 cm TL, 1–3 years old) were included in the VBGM for males, females and gathered sexes. Growth was significantly different between sexes, of adults and of all wreckfish together (Table 5). So, growth

Table 5
Maximum likelihood comparison for the VBGM parameters between sexes of southwestern Atlantic wreckfish[a]

H_0	Equal L	Equal K	Equal t_0	All equal
Immature (TL < 75 cm) ($n = 53$)				
Observed F	0.4182	0.2131	0.2359	0.4461
Fixed F (0.05)	4.05	4.05	4.05	2.8
Probability	0.4932	0.6243	0.6064	0.685
	Accepted	Accepted	Accepted	Accepted
Adults (TL > 75 cm) ($n = 265$)				
Observed F	9.33	4.43	2.02	22.12
Fixed F (0.05)	3.88	3.88	3.88	2.64
Probability	0.0022	0.03409	0.1509	<0.00001
	Rejected	Rejected	Accepted	Rejected
All ($n = 328$)				
Observed F	131.88	9.04	2.44	22.25
Fixed F (0.05)	3.87	3.87	3.87	2.63
Probability	<0.00001	0.0026	0.1156	<0.00001
	Rejected	Rejected	Accepted	Rejected

[a] The curves were adjusted and compared for immature fish (TL < 75 cm), adult (TL > 75 cm) and all together. The observed F, fixed F ($P = 0.05$), the probability that the null hypothesis (H_0) is accepted or rejected.

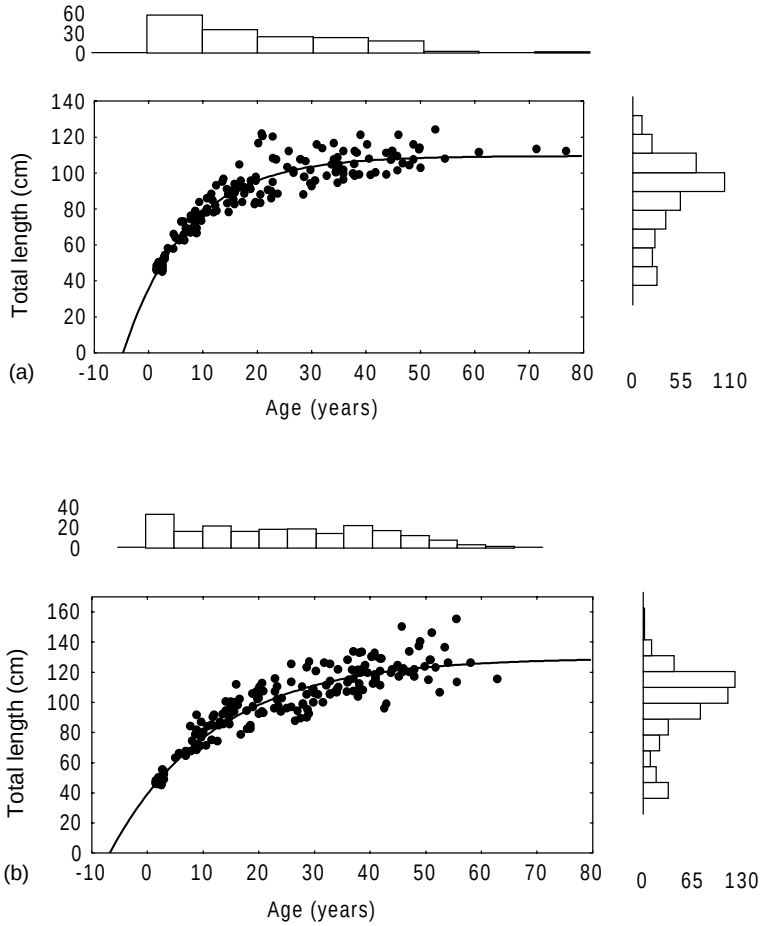


Fig. 6. Age at length data and fitted VBGM for southwestern Atlantic wreckfish. Frequency distributions of ages and lengths are shown at respective axes. (a) Males ($n = 141$) and unsexed fish smaller than 55 cm TL ($n = 22$). (b) Females ($n = 174$) and unsexed smaller than 55 cm TL ($n = 22$). See text for parameter values.

rates between sexes become different after sexual maturation. Females attain larger sizes than males of the same ages (Fig. 6). Ages varied from 1 to 76 years old for males ($n = 141$, 47–126 cm TL), 1–62 years for females ($n = 174$, 45.5–155.5 cm TL) and the fitted VBGM were

$$Lt_{\text{males}} = 109.5(1 - e^{-0.084(t+4.69)})$$
$$(n = 163, \text{S.E.} = 6.886, r^2 = 0.90)$$

$$Lt_{\text{females}} = 129.5(1 - e^{-0.053(t+6.80)})$$
$$(n = 196, \text{S.E.} = 9.129, r^2 = 0.88)$$

$$Lt_{\text{both sexes}} = 121(1 - e^{-0.063(t+6.30)})$$
$$(n = 337, \text{S.E.} = 9.207, r^2 = 0.85)$$

Growth equations in weight were

$$Wt_{\text{males}} = 21.8(1 - e^{-0.084(t+4.69)})^{3.21}$$

$$Wt_{\text{females}} = 37.5(1 - e^{-0.053(t+6.80)})^{3.21}$$

4. Discussion

The difficulties to get consistent reading criteria leading to low counting precision were described for

New Zealand hapuku, *P. oxygeneios* (Francis et al., 1999). USA wreckfish, *P. americanus* have been considered one of the most difficult fish species to age (Potts, 2000). Aging southwestern Atlantic wreckfish, *P. americanus*, was possible by counting the opaque bands (annulus) in transverse sections of the sagittae otoliths. It was shown that one opaque band is deposited each spring–summer. The number of bands increased with body size and spacing between them decreased gradually from the focus to the margins, confirming their adequacy for age and growth studies (Brennan and Cailliet, 1989; Casselman, 1990).

Here, when wreckfish otoliths were sectioned at usual thickness (0.3–0.5 mm), band patterns were unreliable. The lack of sharpness of the growth bands observed in several age and growth studies of *Polyprion* species is probably caused by the irregularities on the otolith surface. Narrow deposition layers on these irregular surfaces and sectioned in different planes (in part, caused by the torsion of the antero-posterior axis) may produce "ghosts" of adjacent bands, making it difficult to delineate the limits of each band, and therefore, count them. This is why thinner sections (0.11–0.15 mm) resulted in clearer band patterns, specially for older fish where annual bands are narrower spaced and the irregularities on the otolith surface are strongly marked.

Besides thinner sections, aging was much improved by clear definition of the criteria used to identify the first annual band, because the otolith central area may show one to three false rings. These criteria included the observation of growth features on the surface of whole and sectioned otolith (the ridge, associated with the central area, and the groove, associated with the first translucent annual band) and the presence of a "discontinuity". Ridges on the otolith surface have been used as an auxiliary criterion to define annual rings of *Seriola dumerili* (Thompson et al., 1999) and *Istiophorus platypterus* (Prince et al., 1986).

Daily rings of other fish species (Stevenson and Campana, 1992) are very similar to the narrow opaque bands counted on wreckfish otolith microstructure (400–1000×). Wreckfish spawning season in the study area is from late July to early October (Peres, 2000) and coincides with the beginning of the deposition of the opaque material on the otolith. The mean number of these bands from the focus to the end of the otolith central area (the opaque portion before the assumed first annual band) was 144. This is about the number of days of the opaque deposition period observed for older wreckfish. The mean number of narrow bands, from the focus to the first annual opaque band (discontinuity) was 377, almost the number of days in 1-year period. These results together indicate that (1) the narrow bands might be considered daily marks; (2) the criteria used to identify the first annual band are adequate; (3) the deposition of opaque material during the first year follows the observed pattern for older fish. Even with circumstantial evidence that the narrow bands are daily growth marks, we emphasized the need for a further validation of wreckfish daily rings.

The difficulty to assess marginal state in otolith sections was also observed for New Zealand hapuku (Francis et al., 1999). The monthly proportion of opaque margins in whole otoliths permitted us to validate the periodicity of band deposition on southwestern Atlantic wreckfish otoliths. Except for very young fish, the clearer margin pattern was at the edge of the otolith rostrum, presumably because it has a high rate of deposition (the fastest growth axis) and its surface is more regular than the rest of the otolith. This method might be applied to other species with irregular otolith surfaces and unreliable margins on otolith sections, such as the Serranidae species, to which *Polyprion* has traditionally been aligned.

Processes controlling otolith growth are still not completely explained. Some authors believe that opaque or translucent band formation is linked with external factors as water temperature, photo period or food availability. Others, associate the type of band deposition with endogenous events as reproduction, migration or physiological stress. Fishes inhabiting temperate waters usually deposit fast growing—opaque bands—in summer months and slow growing–translucent bands—in winter (Pannela, 1980; Chilton and Beamish, 1982). Secor and Dean (1989) observed that when otolith growth is fast, the deposition is opaque, lightweight and contains more protein. During slower growing period, the deposition is translucent, heavier than the opaque one and has less protein and more calcium. Wright (1991) showed that the otolith growth of *Salmo salar* is related to a high metabolic rate and not to fish body growth.

For New Zealand hapuku, austral winter–spring is the time of opaque band formation (Francis et al., 1999), about the same period observed for southwestern Atlantic wreckfish, late winter to summer. In the study area (1) water temperatures in the summer (below 80 m) are 3 °C higher than in winter (18.5–15.5 °C) (Bakun and Parrish, 1991); (2) due to slope upwellings in winter–spring (Garcia, 1997), ocean productivity and food availability are higher (Ciotti et al., 1995); (3) in winter–spring, adult wreckfish does a northern migration to spawn and has a higher food uptake (Peres, 2000). These events may all be related to higher metabolic rates of southwestern Atlantic wreckfish.

Body sizes of USA wreckfish captured with line and hook were 75–146 cm TL (Sedberry et al., 1999). New Zealand hapuku captured with bottom trawl were 41–147 cm TL, but most fish were less than 85 cm (Francis et al., 1999). The size range of aged southwestern Atlantic wreckfish (44–155.5 mm TL), captured with several fishing gears was about the same as in other studies. Despite having just a few large fish, the maximum observed age for hapuku was 63 years, not far from the maximum ages observed for southwestern Atlantic wreckfish (62 years for females and 76 years for males). Maximum age for USA wreckfish stock was 39 years (Vaughan et al., 2000), about half of the other studies. Here, counting all continuous opaque bands, even some which could be false rings (very irregularly spaced), might have generated some overestimated readings. But this cannot explain the observed differences because the number of these bands was never more than one to five for each otolith section.

The K values obtained here (0.053 females, 0.084 males) were similar to those of hapuku, 0.061–0.079 gathered sexes (Francis et al., 1999) and USA wreckfish, 0.073 also for sexes together. The t_0 values of the VBGM obtained for all *Polyprion* species were strongly negative: −6.80 and −4.69 years for southwestern Atlantic wreckfish; −12.48 and −16.56 years for USA wreckfish (Vaughan et al., 2000); −4.06 to −5.75 for New Zealand hapuku (Francis et al., 1999). This might indicate that VBGM does not fit the data for small fish or may be due to the absence of small fishes in the samples.

Juveniles of *Polyprion* species are pelagic, live associated with floating objects and capturing them is extremely difficult (Roberts, 1996; Sedberry et al., 1996; Francis et al., 1999). Francis et al. (1999) estimated for New Zealand hapuku a pelagic phase of 3–4 years (about 50 cm TL). From a sample of 7654 southwestern Atlantic wreckfish, caught with different gears, no fish were smaller than 44 cm TL, only 5 were below 45 cm TL (0.07%) and 50 fishes were 45–50 cm TL (0.7%) (Peres, 2000). All sampled fish below 55 cm TL were aged. Wreckfish from 44 to 45 cm TL were 1.5–2.5 years old, so this is the size and age of the recruitment to the bottom in the study area.

Negative values of t_0 are frequent among species with rapid growth during the first year and reduced growth rates in the following years (Sadovy et al., 1992; Newman et al., 1996; Craig et al., 1997). There are no data on the 1-year-old wreckfish in the study area, but the results indicate that their lengths should be around 35 or 40 cm. The growth rate of southwestern Atlantic wreckfish in its pelagic phase must be faster than the observed after the settlement to the bottom. Fit two VBGM, one for the pelagic and one for demersal phase, could be a solution (Vooren, 1977; Craig et al., 1997). However, there are no catches of wreckfish juveniles (<1.5 years) off southern Brazil. So, we consider that the fitted VBGM describes body growth with age, for male and female, for the size range recruited to the bottom and commercially exploited.

Acknowledgements

This work was originally submitted as part of a Ph.D. thesis to the Biological Oceanography Pos-Graduation, Universidade de Rio Grande (FURG)—Brazil, and was supported by grants from Brazilian Ministry of Education (CAPES). Thanks to Antonio Bianchi for access to his wreckfish catches and to many fishers during biological sampling. We thank Lucio Waengertner Pires, who developed the technique to extract wreckfish otoliths from commercial landings and for field assistance, and to Carolina Araújo who photographed otoliths sections. Many thanks to Carolus Maria Vooren and Sandro Klippel for critical reviews and helpful comments on earlier versions of the manuscript. Special thanks to Beatrice Padovanni Ferreira for advice, reviews of the manuscript and much fruitful discussion.

References

Bakun, A., Parrish, R.H., 1991. Comparative studies of coastal pelagic fish reproductive habitats: the anchovy *Engraulis anchoita* of the southwestern Atlantic. ICES J. Mar. Sci. 48, 343–361.

Ball, A., Sedberry, G., Zatcoff, M., Chapman, R., Carlin, J., 2000. Population structure of the wreckfish *Polyprion americanus* determined with microsatellite genetic markers. Mar. Biol. 137 (5/6), 1077–1090.

Barcellos, L., Peres, M., Wahrlich, R., Barison, M., 1991. Optimização bioeconômica dos recursos pesqueiros marinhos do Rio Grande do Sul. Editora da FURG, Rio Grande, 58 pp.

Beamish, R., Fournier, D., 1981. A method for comparing the precision of a set of age determinations. Can. J. Fish. Aquat. Sci. 38, 982–983.

Brennan, J., Cailliet, G., 1989. Comparative age-determination techniques for white sturgeon in California. Trans. Am. Fish. Soc. 118, 296–310.

Campana, S., 1992. Measurement and interpretation of the microstructure of fish otoliths. In: Stevenson, D., Campana, S. (Eds.), Otolith Microstructure Examination and Analysis. Canadian Special Publication of Fisheries and Aquatic Sciences 117, pp. 59–71.

Casselman, J., 1990. Grow and relative size of calcified structures of fish. Trans. Am. Fish. Soc. 119, 673–688.

Cerrato, R.M., 1990. Interpretable statistical tests for growth comparisons using parameters in the von Bertalanffy equation. Can. J. Fish. Aquat. Sci. 47, 1416–1426.

Chilton, D., Beamish, R., 1982. Age determination methods for fishes studied by the groundfish program at the Pacific Biological Station. Canadian Special Publication of Fisheries and Aquatic Sciences 60.

Ciotti, A., Odebrecht, C., Fillmann, G., Möller, O., 1995. Freshwater outflow and subtropical convergence influence on phytoplankton biomass on the southern Brazilian continental shelf. Cont. Shelf Res. 15 (14), 1737–1756.

Cousseau, M., Perrota, R., 1998. Peces marinos de Argentina: biología, distribución, pesca. INIDEP, Mar del Plata, Argentina.

Craig, P., Choat, J., Maxe, L., Saucerman, S., 1997. Population biology and harvest of the coral reef surgeonfish *Acanthurus lineatus* in American Samoa. Fish. Bull. US 95, 680–693.

Eschmeyer, W., 1990. Catalog of the Genera of Recent Fishes. California Academy of Sciences, San Francisco.

Francis, M., Mulligan, K., Davies, N., Beentjes, M., 1999. Age and growth estimates for New Zealand hapuku, *Polyprion oxygeneios*. Fish. Bull. US 97, 227–242.

Garcia, C., 1997. Physical oceanography. In: Seeliger, U., Odebrecht, C., Castello, J.P. (Eds.), Subtropical Convergence Environments: The Coast and Sea in the Southwestern Atlantic. Springer, Berlin.

Heemstra, P., 1986. Family No. 165: Polyprionidae. In: Smith, M.M., Heemstra, P. (Eds.), Smith's Sea Fishes, 6th ed. Springer, Berlin.

Kimura, D.K., 1980. Likelihood methods for the von Bertalanffy growth curve. Fish. Bull. US 77 (4), 765–776.

Lecomte-Finiger, R., 1992. The crystalline ultrastructure of otoliths of the eel (*A. anguilla* L. 1758). J. Fish Biol. 40, 181–190.

Moralis-Nin, B., 1992. Determination of growth in bony fishes from otolith microstructure. FAO Fisheries Technical Paper, vol. 322. FAO, Rome, 51 pp.

Newman, S., William, D., Russ, G., 1996. Age validation, growth and mortality rates of the tropical snappers (Pisces: Lutjanidae) *Lutjanus adetti* (Castelnau, 1873) and *L. quinquelineatus* (Bloch, 1790) from the Central Great Barrier Reef, Australia. Aust. J. Mar. Freshwater Res. 47, 575–584.

Pannela, G., 1980. Growth patterns in fish sagittae. In: Rhoads, D.C., Lutz, R.A. (Eds.), Skeletal Growth of Aquatic Organisms. Plenum Press, New York, pp. 519–560.

Paul, L., 1992. Age and growth studies of New Zealand marine fishes, 1921–1990: a review and bibliography. Aust. J. Mar. Freshwater Res. 43, 983–1013.

Peres, M., 2000. Dinâmica populacional e pesca do cherne-poveiro *Polyprion americanus* (Bloch e Schneider, 1801) (Teleostei: Polyprionidae) no sul do Brasil. Ph.D. Thesis. Fundação Universidade Federal do Rio Grande, Rio Grande, Brazil, 151 pp.

Peres, M., Haimovici, M., 1998. A pesca dirigida ao cherne-poveiro, *Polyprion americanus* (Polyprionidae, Teleostei) no sul do Brasil. Atlântica, Rio Grande 20, 141–161.

Potts, J., 2000. Personal communication. Center for Coastal Fisheries and Habitat Research—NOAA, Road Beaufort, NC, USA.

Prince, E., Lee, D., Wilson, C., Dean, J., 1986. Longevity and age validation of tag-recaptured Atlantic sailfish, *Istiophorus platypterus*. Fish. Bull. US 84, 493–502.

Roberts, C., 1989. Reproductive mode in the percomorph fish genus *Polyprion* Oken. J. Fish Biol. 34, 1–9.

Roberts, C., 1996. Hapuku and bass: the mystery of the missing juveniles. Seafood NZ 4 (1), 17–21.

Sadovy, Y., Figuerola, M., Román, A., 1992. Age and growth of red hind *Epinephelus guttatus* in Puerto Rico and St. Thomas. Fish. Bull. US 90, 516–528.

Santos, A., Rahn, E., 1978. Sumário das explorações com espinhel de fundo ao longo da costa do Rio Grande do Sul. Relatório Síntese 4, SUDEPE/PDP, Brasília, Brazil, 41 pp.

Secor, D., Dean, J., 1989. Somatic growth effects on the otolith—fish size relationship in young pond-reared striped bass, *Morone saxatilis*. Can. J. Fish. Aquat. Sci. 46, 113–121.

Sedberry, G., Carlin, J., Chapman, R., Eleb, B., 1996. Population structure in the pan-oceanic wreckfish, *Polyprion americanus* (Teleostei: Polyprionidae) as indicated by mt-DNA variation. J. Fish Biol. A 49, 318–329.

Sedberry, G., Andrade, C., Carlin, J., Chapman, R., Luckhurst, B., Manooch III, C., Menezes, G., Thomsen, B., Ulrich, G., 1999. Wreckfish *Polyprion americanus* in the North Atlantic: fisheries, biology and management of a widely distributed and long-lived fish. Am. Fish. Soc. Symp. 23, 27–50.

Stevenson, D., Campana, S. (Eds.), 1992. Otolith Microstructure Examination and Analysis. Canadian Special Publication of Fisheries and Aquatic Sciences 117, Ottawa, 126 pp.

Thompson, B., Beasley, M., Wilson, C., 1999. Age distribution and growth of greater amberjack, *Seriola dumerilli*, from north-central Gulf of Mexico. Fish. Bull. 97, 362–371.

Vaughan, D., Manooch III, C., Potts, J., 2000. Assessment of the wreckfish fishery on the Blake Plateau. In: Proceedings of the Charleston Bump Symposium, Charleston, SC.

von Bertalanffy, L., 1938. A quantitative theory of organic growth (inquiries on growth laws. II). Hum. Biol. 10 (2), 181–213.

Vooren, C., 1977. Growth and mortality of Tarakihi (Pisces: Cheiloactylidae) in lightly exploited populations. NZ J. Mar. Freshwater Res. 11 (1), 1–22.

Wilson, C., Beamish, R., Brothers, E., Carlander, K., Casselman, J., Dean, J., Jearld, A., Prince, E., Wild, A., 1987. Glossary. In: Summerfelt, R.C., Hall, G.E. (Eds.), Age and Growth of Fish. Iowa State University Press, pp. 527–530.

Wright, P., 1991. The influence of metabolic rate on otolith increment width in Atlantic salmon parr (*Salmo salar* L.). J. Fish Biol. 38, 929–933.

Reprinted from American Fisheries Society Symposium, number 25, 2001, pp. 105-120. Vaughan et al.: Assessment of the Wreckfish Fishery on the Blake Plateau. In: Sedberry, George R. (ed.), Island in the stream: oceanography and fisheries of the Charleston Bump. With permission from the American Fisheries Society.

American Fisheries Society Symposium 25:105–120, 2001

Assessment of the Wreckfish Fishery on the Blake Plateau

DOUGLAS S. VAUGHAN, CHARLES S. MANOOCH, III, AND JENNIFER C. POTTS
National Oceanic and Atmospheric Administration, Beaufort Laboratory
101 Pivers Island Road, Beaufort, North Carolina 28516, USA

Abstract.—The status of the wreckfish *Polyprion americanus* stock caught on the Blake Plateau in the southeastern United States Atlantic was analyzed by calibrated virtual population analysis (VPA) to estimate trends in fishing mortality and population (or stock) biomass. Calibration of the FADAPT VPA program was to fishery-dependent catch-per-unit effort (CPUE) for a range in assumed values for natural mortality (M). Age-length keys were developed from two aging studies of wreckfish (1988–1992 and 1995–1998). Keys were developed annually (pooled across seasons to create three "annual" age-length keys to represent 1988–1990, 1991–1993, and 1994–1998) and seasonally (pooled across years to create three seasonal age-length keys to represent April–June, July–September, and October to end of fishing year on 15 January). Analyses based on both annual and seasonal catch matrices showed similar patterns and values, with the seasonal catch matrix producing slightly lower estimates of fishing mortality rates (F) and higher estimates of biological reference points based on F. Fishing mortality rates peaked in 1989, as did the maximum annual U.S. landings (4.2 million pounds). Subsequently, both landings and fishing mortality rates have generally declined. Although stock biomass has generally declined over the study period, recruitment at age 7 has risen since about 1994. Meanwhile, annual estimates of static spawning potential ratio (SPR), which are inversely related to F, have risen since 1994. Fishing mortality rates from recent low landings are at or near the South Atlantic Fishery Management Council's threshold definition of overfishing (static SPR of 30%), while the process of rebuilding with improving recruitment appears to be underway. Concern persists because the assessment is based on the underlying assumption that wreckfish from the Blake Plateau form a single stock separate from the eastern North Atlantic and genetic evidence suggests the stock encompasses the entire North Atlantic.

Wreckfish *Polyprion americanus* is a large grouper-like fish, distributed globally in temperate waters, including both sides of the North Atlantic Ocean (Heemstra 1986; Sedberry et al. 1994, 1996). Juveniles are rare in the western Atlantic, but common in the eastern Atlantic. Juveniles are pelagic to a length of about 24 in (60 cm), and are associated with seaweed and wreckage, hence their common name. Adults are found at depths of 138–3,280 ft (42–1,000 m). Wreckfish spawn off the southeastern United States on the Blake Plateau between December and March. The Charleston Bump comprises a small portion of this plateau. It is characterized by extensive bottom relief at a depth of 1,476–1,968 ft (450–600 m), where the Gulf Stream waters are deflected, resulting in a region of upwelling that concentrates food. Based on recent genetic work by Sedberry et al. (1996), the North Atlantic wreckfish are believed to constitute one stock that drifts or migrates across the North Atlantic. Since 1991 (SAFMC 1991), wreckfish on the Blake Plateau have been managed under an annual quota (two million pounds) through an Individual Transferable Quota (ITQ) system, with a spawning season closure between 15 January and 15 April. Although the fishing year is from 16 April through 15 April of the following calendar year, the effective fishing year is now from 16 April through 14 January of the following calendar year. During 1990, the quota of two million pounds was reached and the fishery was closed at the end of August.

This paper updates information provided annually to the South Atlantic Fishery Management Council's (SAFMC) Snapper Grouper Assessment Group. Included are a summary of landings and length frequency data from the fishery for 1988 through 1998 fishing years, analyses of length-at-age data, application of a calibrated virtual population analysis approach (FADAPT) to catch-in-numbers-at-age matrices (referred to hereafter as catch matrices), and a summary of F-based biological reference points obtained from analyses of yield per recruit (YPR) and static spawning potential ratio (SPR). Re-aging of wreckfish samples collected during 1988–1992 and new aging of wreckfish samples collected during 1995–1998 were used to develop age-length keys from which catch matrices were estimated.

Methods and Results

Data included in these analyses were: 1) historical landings, 2) annual length-frequency distributions, and 3) annual or seasonal age-length keys. These data were combined to estimate annual catch in numbers

at age, which were then used in virtual population analysis to estimate age- and year-specific population numbers and fishing mortality rates. Biological reference points were estimated from analytical methods based on yield and spawning stock biomass per recruit to evaluate the status of the fishery.

Historical landings

Commercial wreckfish landings (in whole weight) by fishing year (16 April through 15 April of following year) are summarized in Table 1. Estimates of monthly and total U.S. landings in whole weight given in the 1992 Snapper Grouper Assessment Group Wreckfish Report were used for the 1988–1990 fishing years, and total U.S. landings in numbers were estimated using seasonal mean weight per fish from biological samples collected at dockside. Landings in weight and numbers, and effort in trips, days, and hours, for 1991–1998 are from the logbook data file (Hardy 2000). Logbook landings suggest that about 51% were made in South Carolina ports, 42% in Florida ports, 6% in North Carolina ports, and less than 1% in Georgia ports. Landings have only been made in South Carolina and Florida ports beginning with 1995. Estimates of wreckfish landings for the eastern North Atlantic (FAO 1999) are shown for comparison (Table 1). Eastern North Atlantic landings rose from 1.0 million pounds in 1988 to a high of 2.0 million pounds in 1993–1994, with landings in 1997 of about 1.1 million pounds.

Catch-per-unit effort (CPUE) was estimated from the logbook data file using three potential measures of effort (trips, days fishing, and hours fishing). Discussions within the SAFMC Snapper Grouper Advisory Panel have led to catch per hour being excluded from further analyses. The panel, which included wreckfish fishermen, felt that hour fished was not an accurate estimate of effort. Using fishery-dependent CPUE raises questions of a tautological nature. Because the catch matrix and CPUE are based on the same data, little additional information is gained. To reduce this tautological quandary, calculation of CPUE was limited to five vessels that were active continuously between 1991 and 1997 (referred to as "High 5"). The total number of vessels active in the wreckfish fleet

TABLE 1. Wreckfish U.S. landings in pounds and numbers, sample size for length frequency, and percent of fish landed that were sampled during 1988–1998. Also included are landings for the eastern North Atlantic through 1997 (FAO 1999). Logbook information on number of vessels, total trips, days fished, number of "High 5" vessels, landings by "High 5" vessels, and percent of total landings are presented for 1991–1998.

Fishing year	U.S. landings		Number sampled	Percent sampled	FAO landings[a] (pounds)
	Pounds	Numbers			
1988	617,662	16,137	498	3.1	1,038,376
1989	4,161,965	107,389	308	0.2	1,236,792
1990	1,970,299	58,621	1,267	2.2	1,197,109
1991	1,926,088	57,704	10,381	18.0	1,139,789
1992	1,270,557	38,205	6,394	16.7	1,514,574
1993	1,144,726	33,803	7,231	21.4	1,966,521
1994	1,203,265	35,770	4,100	11.5	1,995,181
1995	644,997	19,256	4,579	24.8	1,673,307
1996	396,868	11,657	2,605	22.3	1,578,508
1997	249,715	7,299	1,197	16.4	1,082,468
1998	210,800	6,172	2,089	35.4	

Fishing year	Number of vessels[b]	Total trips[b]	Days fished[b]	High 5 vessels[c]	High 5 landings[c] (pounds)	Percent of total landings
1991	38	308	2,164	5	703,361	36.5
1992	20	222	1,516	5	737,521	58.0
1993	19	210	1,531	5	713,479	62.3
1994	17	201	1,602	5	686,652	57.1
1995	13	140	946	5	460,463	71.4
1996	9	95	762	5	370,269	93.3
1997	7	56	403	5	241,715	96.8
1998	3	36	268	3	210,800	100.0

[a] Landings from FAO for Eastern North Atlantic, not available for 1998.
[b] From Table 1 in Hardy (2000).
[c] From logbook data provided by L. Hardy (NMFS SEFSC, Beaufort Laboratory).

declined from 38 in 1991 to 7 in 1997 (Table 1). However, only three of the "High 5" vessels fished in 1998, and none of the remaining permitted vessels were active that year. The contribution of landings in pounds from the "High 5" vessels increased from 37% in 1991 to 100% in 1998 (Table 1). The reduction in fleet size to just "High 5" vessels has negated to some extent the premise on which the "High 5" vessels were selected originally.

A nested fixed-effects analysis of variance (ANOVA) model (using PROC GLM, General Linear model; SAS Institute 1985) was used to develop annual estimates of CPUE for the calibration process, restricted to data from the "High 5" vessels. The dependent value was catch in numbers-per-unit effort. Model effects were fishing year, season nested within fishing year, vessel (nested within state), and the cross product of year and state. Model fits were all highly significant (based on *P*-values) with R^2 of 0.51 for catch per trips and 0.55 for catch per days (see Table 2 for ANOVA details). The estimates for both indices show a downward trend since about 1994, with a slight upturn in 1998 for catch per trip (Figure 1).

Length-frequency distributions

Commercial length data were obtained from the National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center (SEFSC) Trip Intercept Program (TIP) data file for Florida, Georgia, South Carolina, and North Carolina; and additional length data were obtained from North Carolina's Division of Marine Fisheries for January 1991 through January 1992. Length-frequency distributions were developed from biological samples of commercial landings in terms of total lengths in 1-in increments. With most landings made in Florida and South Carolina ports, length-frequency data sampled from these ports were compared. Only minor differences were noted between the length-frequency distributions from Florida and South Carolina, since fishermen from these two states fished in the same general geographic area (Blake Plateau); hence, samples from the different states were pooled together. Length-frequency distributions were developed by season within fishing year (April–June, July–September, and October to end of fishing year for 1988–1998) and annually (assigned weights by seasonal landings in numbers). These length-frequency distributions were used with either annual or seasonal age-length keys to estimate catch-in-numbers-at-age matrices (referred to hereafter as annual or seasonal catch matrices). The sample size of lengths has been excellent since 1991, with over 35% of the wreckfish landed in 1998 were measured (Table 1). Only the relatively low sampling in 1989 (308 fish measured or 0.2%) raised some concern over sampling adequacy. A comparison of these annual length-frequency distributions for 1992–1998 showed a flattening of the peak or modal value, with greater proportion of lengths in the left-hand tail of the distribution for 1997 and 1998 (Figure 2).

Both annual and seasonal mean total lengths and mean weights of individual fish were estimated from the biological samples (Table 3). Monthly estimates of mean weight of fish from the logbook data

TABLE 2. Analysis of variance (ANOVA) results for nested fixed effects model applied to "High 5" wreckfish catch in numbers per unit effort (CPUE in trips or days).

Source	DF	Sum of squares	Mean square	F Value	Pr > F
		Catch in numbers per trip			
Model[a]:	30	4860656.7	162021.9	21.65	0.0001
Fishing year	7	443385.8	63340.8	8.46	0.0001
Season (year)	16	269038.0	16814.9	2.25	0.0036
Vessel (state)	7	4148233.0	592604.7	79.17	0.0001
Error	623	4663052.1	7484.8		
Corrected total	653	9523708.9			
		Catch in numbers per day			
Model:	37	165776.9	4480.5	20.33	0.0001
Fishing year	7	19492.0	2784.6	12.64	0.0001
Season (year)	16	14498.0	906.1	4.11	0.0001
Vessel (state)	7	127854.9	18265.0	82.90	0.0001
Year*state	7	3932.0	561.7	2.55	0.0136
Error	616	135728.1	220.3		
Corrected total	653	301504.9			

[a] Year*State factor was not significant.

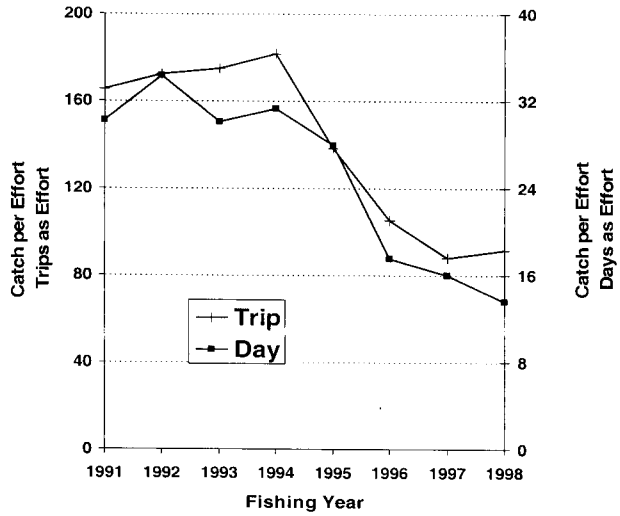


FIGURE 1. Wreckfish catch-per-unit effort based on catch in numbers per trip and per day estimated from ANOVA models applied to logbooks from "High 5" (continuously active) vessels.

file were compared with those calculated from the biological samples (Figure 3), with generally higher means obtained from the logbook data file. No temporal trends were noted in these estimates between 1991 and the present.

Age, growth, and reproduction

Wreckfish otoliths and corresponding lengths and weights were collected during 1988–1992 ($n = 738$, recently re-aged), and additional lengths and otoliths

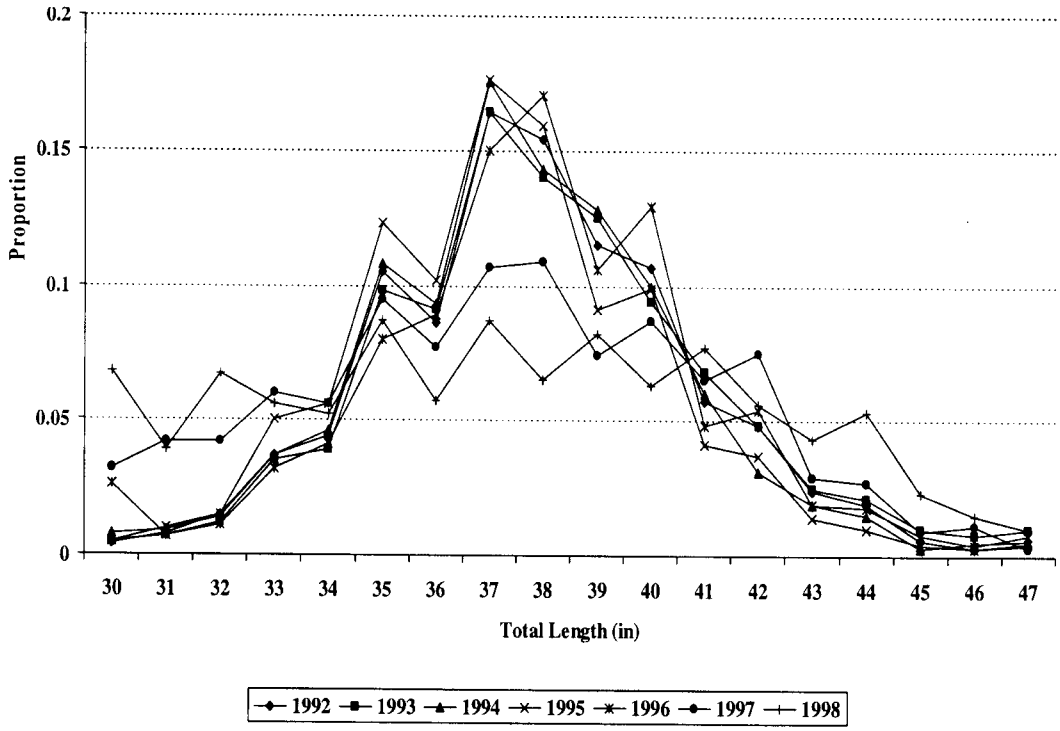


FIGURE 2. Comparison of wreckfish annual length-frequency distributions, 1992–1998.

TABLE 3. Wreckfish mean lengths and weights from biological sampling of commercial landings by fishing year for 1988–1998 and season for 1992–1998 [Early: Apr–Jun, Middle: Jul–Sep, and Late: Oct–Jan]. Weight is calculated from fish length using equation 4.

			Total length (inch)		Whole weight (pound)	
Fishing year	Season	Sample size	TL	SD	W	SD
1988		498	38.9	4.0	34.1	11.6
1989		308	38.3	3.1	32.1	8.1
1990		1,267	38.7	3.0	33.3	7.9
1991		10,381	38.8	3.1	33.4	8.1
1992		6,394	38.3	2.9	32.2	7.4
1993		7,231	38.6	3.1	32.9	8.2
1994		4,100	38.2	2.9	31.8	7.4
1995		4,579	37.9	2.9	31.1	7.2
1996		2,605	38.3	3.3	32.4	8.0
1997		1,197	37.7	4.0	31.1	9.4
1998		2,089	37.8	4.6	31.8	11.3
1992	E	744	38.3	3.0	32.1	7.7
	M	2,156	38.4	2.9	32.5	7.5
	L	3,494	38.3	2.9	32.1	7.3
1993	E	2,839	38.3	2.9	32.1	7.3
	M	2,048	38.4	2.8	32.4	7.3
	L	2,344	39.0	3.5	34.2	9.6
1994	E	1,564	38.3	2.9	32.3	7.5
	M	859	38.5	2.9	32.5	7.1
	L	1,677	37.9	2.9	31.1	7.3
1995	E	2,353	37.8	2.9	31.0	7.2
	M	1,055	37.6	2.7	30.4	6.8
	L	1,171	38.2	3.0	31.8	7.4
1996	E	1,053	38.2	3.3	32.1	8.0
	M	542	38.7	3.7	33.4	9.5
	L	1,010	38.3	3.0	32.2	7.4
1997	E	417	37.7	4.2	31.2	10.2
	M	240	37.7	3.8	31.0	8.7
	L	540	37.8	3.6	31.2	8.8
1998	E	553	37.4	5.0	31.1	12.0
	M	756	38.1	4.6	32.5	11.5
	L	780	37.8	4.5	31.6	10.8

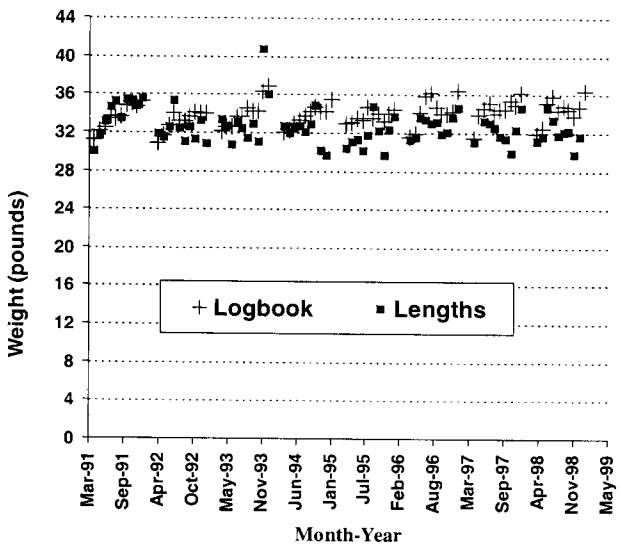


FIGURE 3. Monthly mean weight (pound) of wreckfish from logbooks and catch sampling, 1991–1998.

were collected during 1995–1998 ($n = 117$). We continued to use the following relationships estimated using the earlier data set (1988–1992): (1) total length (TL) versus fork length (FL), (2) total or whole weight (TW) versus gutted weight (GW), and (3) whole weight versus total length. These equations were estimated as follows:

$$\text{TL(mm)} = 4.607 + 1.041\ \text{FL(mm)},\ n = 226,\ r^2 = 0.99, \quad (1)$$

$$\text{TW(kg)} = -0.367 + 1.141\ \text{GW(kg)},\ n = 223,\ r^2 = 0.98, \quad (2)$$

$$\text{TW(kg)} = 0.000000035\ \text{TL(mm)}^{2.956},\ n = 284,\ r^2 = 0.87, \quad (3)$$

$$\text{TW(lbs)} = 0.001094\ \text{TL(in)}^{2.956},\ n = 284,\ r^2 = 0.87, \quad (4)$$

where equations 3 and 4 have been adjusted for bias (Beauchamp and Olson 1973).

Sagittal otoliths collected from wreckfish landed during 1988–1992 and 1995–1998 were sectioned and aged. Mean lengths at age from these analyses differed considerably from those previously reported (Vaughan et al. 1992, 1993, 1994, 1995, 1996, 1997). We thought that the assigned ages for 1995–1998 otoliths were more correctly determined than those assigned previously for several reasons. First, our aging facility has more state-of-the-art equipment. Second, the ages assigned most recently, done without reference to the initial age assigned to 1988–1992 otoliths, were agreed upon by two readers rather than one as occurred for the first set. Finally, recent aging was done after consultation with a researcher from New Zealand (M. Francis, National Institute of Water and Atmospheric Research, Wellington, New Zealand, personal communication) who has worked with a congeneric species for many years and who felt that our earlier samples may have been underaged.

Using the newer aged data set from 1995 to 1998, estimates of the parameters were obtained for the von Bertalanffy growth equation:

$$L_t = L_\infty(1 - \exp(-K(t - t_0)), \quad (5)$$

where L_t is total length in inches, t is age in years, and L_∞, K, and t_0 are parameters to be estimated. For each fish, only observed length at age adjusted for time of year collected was used (Vaughan and Burton 1994). Parameter estimates and standard errors are given as ($n = 117$ fish):

Parameter	Estimate	Standard error
L_∞	64.5 in	4.8 in
K	0.032 yr^{-1}	0.006 yr^{-1}
t_0	−12.48 yr	1.76 yr

Both the estimate for L_∞ and K are smaller than that given in our previous assessment ($L_\infty = 70.7$ in TL and K = 0.044 $years^{-1}$ in Vaughan et al. [1997]). With the re-aging of the early data set (1988–1992), estimates of all three parameters for the von Bertalanffy growth equation failed to converge. Hence, the estimate of L_∞ was fixed at 64.5 in TL, and the remaining parameters (K and t_0) were estimated for the period 1988–1992 ($n = 738$):

K	0.028 yr^{-1}	0.001 yr^{-1}
t_0	−16.56 yr	0.59 yr

Growth curves based on initial and recently assigned ages for 1988–1992 otoliths diverged considerably (Figure 4a). However, very little divergence was noted when comparing the growth in total length between the re-aging of the 1988–1992 data and aging of the 1995–1998 data (Figure 4b).

As in previous assessments for SAFMC (Vaughan et al. 1992, 1993, 1994, 1995, 1996, 1997, 1999), limited data were available for a wreckfish maturity schedule with one female wreckfish immature at 24 in TL (age 4). All other female wreckfish that were checked for maturity were at least 33 in TL (age 8 and older) and found to be mature. Hence, a linear relation was used to generate an approximate maturity curve with 0% of female mature at age 4, 25% at age 5, 50% at age 6, 75% at age 7, and 100% at age 8 and older.

Data on wreckfish fecundity from South Carolina Department of Natural Resources (SCDNR) were fitted to a linear relationship between fecundity or number of ova (E) and female biomass or weight (W) to produce the following relationship (Vaughan et al. 1997):

$$E = -200109 + 53012\ W\ (\text{lbs}), \quad (6)$$

where $n = 25$, and $r^2 = 0.80$.

Catch-at-age matrix

Annual and seasonal age-length keys were developed for estimating catch in numbers at age from commercial landings and length-frequency data. There were no recreational landings. With the new aging studies, we used an age-plus group defined as 26 and older (26+), and 47 in as a size plus group. Annual keys were developed from age-length data pooled across seasons to represent 1988–1990 ($n = 411$), 1991–1993 ($n = 327$), and 1994–1998 ($n = 117$); seasonal keys were developed from age-length data pooled across years for

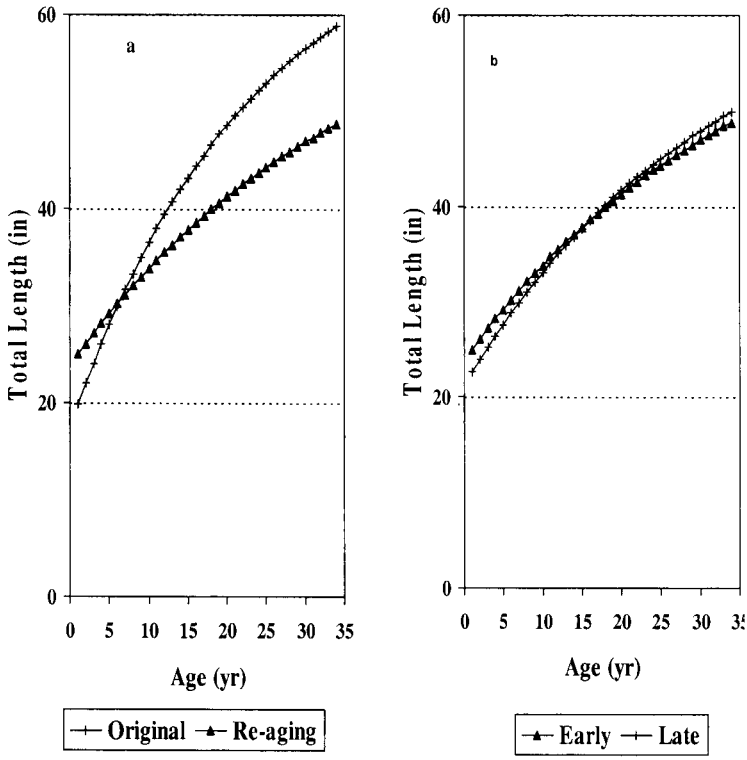


FIGURE 4. Wreckfish total length at age compared between a) original aging and re-aging of otoliths collected during 1988–1992, and b) re-aging of 1988–1992 otoliths with aging of otoliths collected from 1995 to 1998.

April–June (n = 444), July–September (n = 175), and October-end of fishing year (n = 236). These keys were used with corresponding commercial landings (in numbers) and length-frequency distributions to estimate annual catch in numbers at age by year. The catch matrix estimated from age-length keys for the different time periods and pooled across seasons is referred to as the annual catch matrix (Table 4). Similarly, the catch matrix estimated from age-length keys for the different seasons and pooled across years is referred to as the seasonal catch matrix (Table 5). Strong bimodality in these catch matrices may reflect strong year classes recruiting to the population; for example, catch peaks at age 10 and again at about age 14–17 in both catch matrices. In some years the higher peak is at age 10, notably 1990–1993 and 1998 in the annual catch matrix and 1997–1998 in the seasonal catch matrix.

Natural mortality

Natural mortality (M) is estimated from life history characteristics as suggested in Pauly (1979) and Hoenig (1983). The approach of Pauly (1979) uses estimates of L_∞ (cm) and K (yr^{-1}) from the von Bertalanffy growth curve (equation 5) and mean temperature (T°C):

$$\log_{10}M = 0.0066 - 0.279\log_{10}L_\infty + 0.6543\log_{10}K + 0.4634\log_{10}T. \quad (7)$$

Values for L_∞ and K (1988–1992: 163.7 cm and 0.028 $years^{-1}$; and 1995–1998: 163.7 cm and 0.032 $years^{-1}$) and mean estimated temperature for the Blake Plateau (provided earlier by G. Ulrich, SCDNR, unpublished data) for different months were used to obtain the following estimates of M:

Month	Temperature (C°)	M (yr^{-1})	
		1988–1992	1995–1998
August	13.2	0.08	0.09
September	15.2	0.08	0.09
October	8.4	0.06	0.07

Hoenig (1983) suggested the following relationship based on maximum age expected in the unfished stock (t_{max}):

$$ln\ Z = 1.46 - 1.01\ ln\ t_{max}, \quad (8)$$

TABLE 4. Catch in numbers at age matrices based on annual age-length keys for wreckfish caught during 1988–1998.

	Fishing year										
Age	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
5-	107	144	132	107	57	63	164	55	173	134	240
6	61	239	53	43	23	25	73	33	52	57	86
7	186	807	180	196	125	108	173	91	95	111	152
8	469	3,155	785	906	701	551	671	431	201	306	305
9	276	2,258	3,066	2,950	2,300	1,938	619	401	170	288	277
10	459	3,648	8,217	7,681	5,891	4,994	2,335	1,484	648	622	513
11	362	2,998	5,022	4,596	3,547	3,048	3,102	1,862	912	572	410
12	1,591	13,172	2,273	2,109	1,534	1,294	2,659	1,627	764	502	358
13	1,126	9,533	4,440	4,050	2,895	2,465	3,401	1,911	1,033	540	371
14	1,343	11,391	3,285	3,038	2,139	1,803	4,341	2,427	1,379	665	441
15	1,822	15,145	4,685	4,593	3,004	2,567	3,300	1,811	1,064	483	314
16	2,014	16,153	5,578	5,297	3,415	3,069	2,895	1,551	956	416	280
17	2,019	14,895	4,465	4,566	2,807	2,471	2,741	1,371	917	439	317
18	1,574	10,612	3,388	3,766	2,163	1,891	1,985	950	664	298	232
19	1,050	6,983	3,605	3,644	2,191	1,998	1,865	840	641	355	285
20	815	4,605	3,733	3,833	2,198	2,059	1,322	587	461	302	276
21	552	2,984	1,077	1,192	622	590	811	365	295	257	231
22	553	2,922	1,321	1,291	707	721	1,760	791	621	441	383
23	394	2,059	662	707	322	356	745	326	276	249	271
24	339	1,841	923	1,015	535	507	225	89	84	78	116
25	209	1,049	1,399	1,356	756	774	234	101	101	99	155
26+	769	2,939	861	770	274	511	349	153	150	85	157
Sum	18,090	129,532	59,150	57,706	38,206	33,803	35,770	19,257	11,657	7,299	6,170

where the total mortality rate Z = M for an unfished stock. The maximum age was 39 years in the early data set (1988–1992) and 30 years in the later data set (1995–1998), suggesting an estimate of M of about 0.11–0.14 years^{-1}. Older maximum ages (t_{max}) give lower estimates of M; for example, 0.12 years^{-1} at 35 years and 0.10 years^{-1} at 40 years. This assessment used values of 0.05, 0.10, and 0.15 years^{-1},

TABLE 5. Catch in numbers at age matrices based on seasonal age-length keys for wreckfish caught during 1988–1998.

	Fishing year										
Age	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
5-	50	159	139	124	57	78	109	41	124	96	174
6	42	178	35	64	87	60	91	47	50	80	114
7	78	347	134	192	146	126	173	82	107	122	178
8	276	1,521	758	848	748	586	700	423	221	295	306
9	254	1,982	1,577	1,717	1,137	982	1,108	761	341	411	380
10	637	4,863	4,555	4,031	2,695	2,414	2,643	1,799	774	694	539
11	512	3,446	3,297	2,669	1,920	1,721	1,871	1,195	533	379	273
12	880	4,985	3,670	3,427	3,087	2,495	2,861	1,616	822	517	392
13	733	4,769	4,311	4,009	2,915	2,422	2,743	1,533	831	416	268
14	950	6,094	3,277	4,243	3,333	2,634	2,960	1,660	959	479	339
15	1,151	7,190	6,035	5,282	3,677	3,132	3,487	1,884	1,079	503	320
16	1,643	9,995	5,917	5,646	3,869	3,289	3,609	1,795	1,112	558	402
17	1,659	11,095	5,210	6,117	3,862	3,299	3,536	1,820	1,196	581	428
18	1,562	10,979	3,686	5,095	2,970	2,622	2,615	1,368	948	491	406
19	895	6,835	3,468	3,417	1,803	1,781	1,789	941	615	337	247
20	935	5,988	4,002	3,128	1,877	1,786	1,898	704	617	365	323
21	807	5,247	1,721	1,981	1,185	1,072	1,023	446	365	238	239
22	514	3,696	2,451	1,748	1,003	1,050	993	441	339	263	218
23	590	4,148	1,364	1,381	718	715	575	254	220	185	216
24	364	2,636	1,110	874	433	522	407	172	137	120	129
25	345	2,424	698	717	304	394	261	117	103	81	124
26+	1,261	8,813	1,206	993	377	623	317	159	163	89	156
Sum	16,138	107,390	58,621	57,703	38,203	33,803	35,769	19,258	11,656	7,300	6,171

which bracket the range of estimated M. The mid-range M value of 0.10 years^{-1} is recommended as the preferred estimate.

Virtual population analysis

Restrepo's (1996) FADAPT program, modified from ADAPT (Gavaris 1988; Conser and Powers 1990) allows for calibration (or tuning) by a series of indices of abundance at age. These runs were calibrated using the fishery-dependent indices of CPUE for three levels of M (0.05, 0.10, and 0.15 years^{-1}). The two indices of CPUE are based on the ANOVA models for catch in numbers per trip, and catch in numbers per day based on the wreckfish logbook data from five vessels ("High 5") participating significantly during 1991–1998. Data based on these five vessels were used to reduce the tautological effect of using CPUE from all vessels, data which were used in developing the catch matrices.

Because of limitations in the FADAPT program relative to number of ages (20), these runs were made with ages 7–26+. Selectivity or partial recruitment vectors for the final year (1998) were obtained from corresponding separable VPA (Clay 1990). All fishing mortality rates for earlier years were estimated by the FADAPT program with the assumption proposed by Murphy (1965) that F in the oldest two ages are equal in the same fishing year.

Based on the FADAPT (calibrated) VPA analyses, estimates of full F (mean F over ages 16–26+) were compared between the annual and seasonal catch matrices for three levels of M (Figure 5). Although the modal age varied among years, especially for the annual catch matrix, the modal peak (older of bimodal peaks) generally varied about age 16. Estimates of full F from these two catch matrices showed similar values and temporal pattern. Values were somewhat higher in the early years and lower in the most recent years from the FADAPT VPA using the seasonal catch matrix. The FADAPT was allowed to estimate the appropriate weighting among CPUE indices when both were used together. This weighting was typically 41–44% for catch per trip, and 56–59% for catch per day. Mean estimates of fishing mortality rate at age for the recent period 1995–1997 and estimates of fishing mortality rate at age for 1998 are compared among the FADAPT runs (Tables 6 and 7). For the period 1995–1997, mean fishing mortality rates at age are summarized for ages 7–15 separately and for the mean over ages 16 through 26+.

The pattern in recruits to age 7 was also developed from FADAPT for three levels of M (0.05, 0.10, and 0.15 years^{-1}) (Figure 6). The pattern showed declining recruitment from 1988 until about 1994, when recruitment subsequently increased. Stock bio-

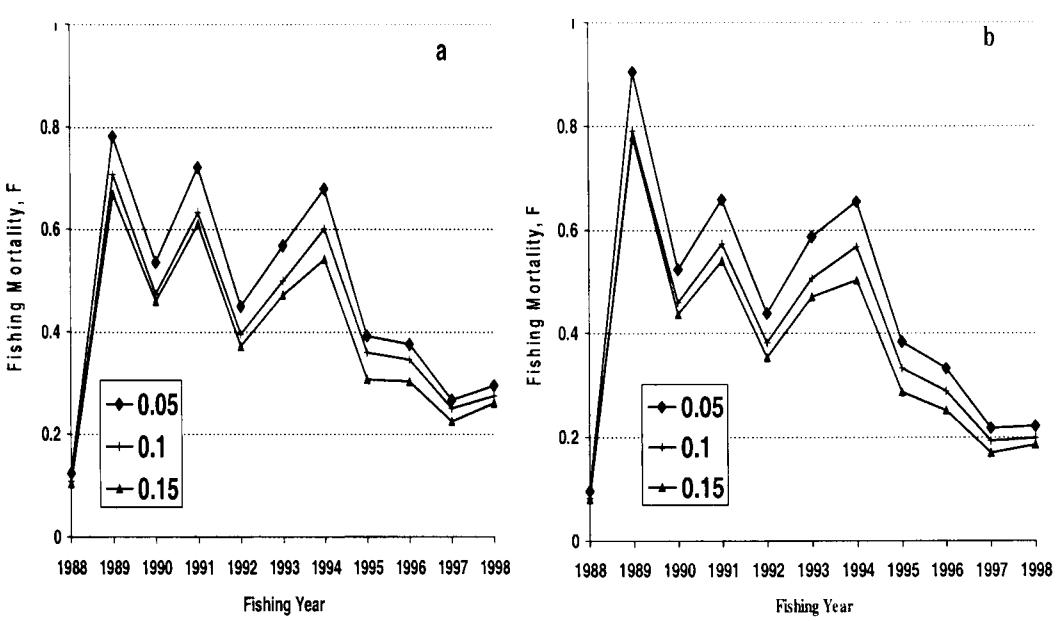


FIGURE 5. Estimates of full F (mean fishing mortality across ages 16–26+) on wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

TABLE 6. Mean fishing mortality rates at age, percent spawning potential ratio (egg production), and biological reference points for wreckfish, based on the annual catch-at-age matrix for the period 1995–1997 and fishing mortality rate estimated for the current year 1998. Combined refers to the use of both CPUE indices (catch/trip and catch/day) in the FADAPT calibration.

Variable	M = 0.05 combined	M = 0.10			M = 0.15 combined
		Combined	Catch/trip	Catch/day	
F on Age 7	0.02	0.01	0.01	0.02	0.01
F on Age 8	0.07	0.06	0.05	0.06	0.05
F on Age 9	0.07	0.06	0.06	0.07	0.05
F on Age 10	0.24	0.21	0.19	0.22	0.18
F on Age 11	0.29	0.27	0.24	0.27	0.22
F on Age 12	0.28	0.25	0.23	0.26	0.22
F on Age 13	0.35	0.32	0.31	0.33	0.29
F on Age 14	0.52	0.47	0.45	0.49	0.43
F on Age 15	0.45	0.41	0.39	0.43	0.37
F on Ages 16-26+	0.35	0.32	0.29	0.33	0.28
F on Ages 16-26+ in current year	0.29	0.28	0.25	0.30	0.26
Static SPR (biomass)	14.10	29.00	29.80	28.40	45.50
Static SPR (egg)	12.50	26.50	27.40	26.00	42.70
$F_{0.1}$	0.08	0.15	0.14	0.15	0.23
F_{max}	0.14	>1.44 [a]	>1.31 [a]	>1.49 [a]	>1.26 [a]
F_{30} (eggs)	0.10	0.25	0.24	0.24	0.80
F_{40} (eggs)	0.07	0.14	0.14	0.14	0.34

[a] Exceeds 4.5 times the full F (mean over ages 16–26+).

mass (weight of population ages 7 and older) also declined from high values in 1988–1989 until about 1997 (Figure 7). A slight increase in biomass was noted in 1998 for the FADAPT analyses based on the seasonal catch matrix, but not for analyses based on the annual catch matrix. There appeared to be a one year lag in the turnaround in recruitment to age 7 between the analyses for the two catch matrices (1994 for seasonal catch matrix versus 1995 for annual catch matrix). Because the analysis of the seasonal catch matrix suggested a slight increase in stock biomass in 1998, an analysis of the annual catch matrix with one more year of data might show a slight increase in stock biomass in 1999 as well.

TABLE 7. Mean fishing mortality rates at age, percent spawning potential ratio (egg production), and biological reference points for wreckfish, based on the seasonal catch-at-age matrix for the time period, 1995–1997 and fishing mortality rate estimated for the current year 1998. Combined refers to the use of both CPUE indices (catch/trip and catch/day) in the FADAPT calibration.

Variable	M = 0.05 combined	M = 0.10			M = 0.15 combined
		Combined	Catch/trip	Catch/day	
F on Age 7	0.08	0.01	0.01	0.01	0.01
F on Age 8	0.06	0.04	0.04	0.04	0.03
F on Age 9	0.09	0.08	0.07	0.08	0.06
F on Age 10	0.24	0.20	0.18	0.21	0.16
F on Age 11	0.16	0.13	0.12	0.14	0.11
F on Age 12	0.24	0.21	0.19	0.22	0.17
F on Age 13	0.24	0.20	0.19	0.21	0.17
F on Age 14	0.27	0.24	0.22	0.25	0.21
F on Age 15	0.30	0.26	0.25	0.27	0.23
F on Ages 16-26+	0.31	0.27	0.26	0.29	0.24
F on Ages 16-26+ in current year	0.22	0.20	0.18	0.22	0.19
Static SPR (biomass)	16.10	32.90	32.10	34.00	51.00
Static SPR (egg)	14.50	30.50	29.70	31.50	48.40
$F_{0.1}$	0.11	0.15	0.14	0.15	0.25
F_{max}	0.16	>1.22[a]	>1.17[a]	>1.31[a]	>1.08[a]
F_{30} (eggs)	0.11	0.28	0.28	0.28	0.90
F_{40} (eggs)	0.07	0.16	0.16	0.16	0.40

[a] Exceeds 4.5 times the full F (mean over ages 16–26+).

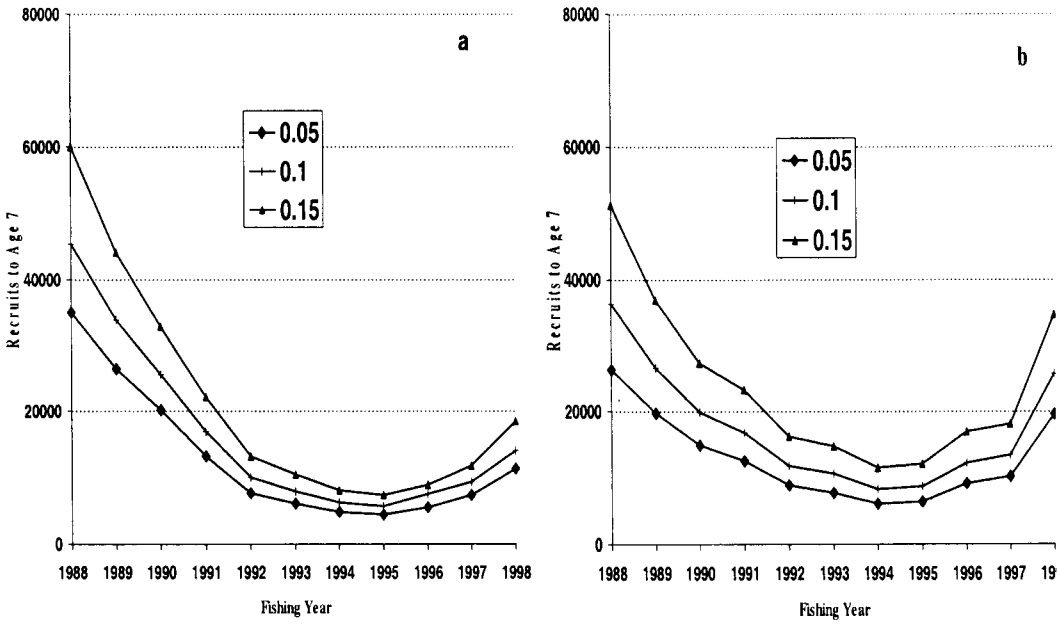


FIGURE 6. Estimates of recruits to age 7 for wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

Biological reference points

Estimates of F summarized in Tables 6 and 7 were used in estimating biological reference points based on YPR using Ricker's (1975) approach for different assumed values of M (0.05, 0.10 and 0.15 years^{-1}, respectively) and selectivity pattern for 1995–1997. Estimates of F_{max} and $F_{0.1}$ were derived from this approach, where F_{max} is defined as that level of fishing mortality rate that maximizes yield per recruit, while $F_{0.1}$ is defined as that level of fishing mortality rate that corresponds to the tangent which is 10% of the

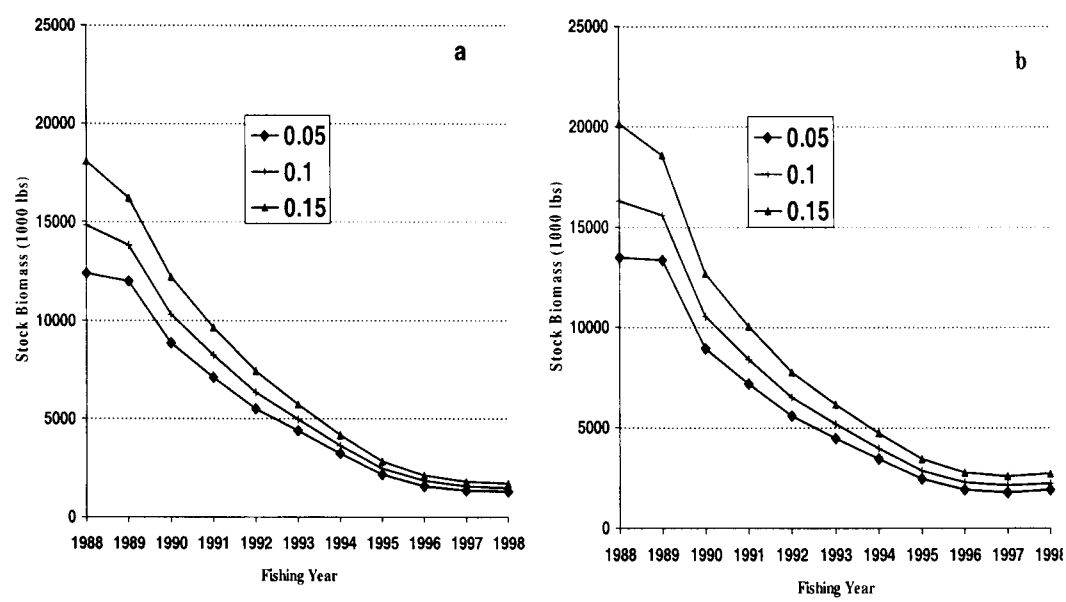


FIGURE 7. Estimates of stock biomass (ages 7+) of wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

slope at the origin for a given selectivity pattern. Estimates for F_{max} varied from 0.14 to 0.16 years^{-1} for M = 0.05 years^{-1} (with different catch matrices) to values that exceed 4.5 times full F for M = 0.10 years^{-1} and M = 0.15 years^{-1} for the period 1995–1997. Meanwhile, estimates of $F_{0.1}$ ranged from 0.08 to 0.11 years^{-1} for M = 0.05 years^{-1} to about 0.23–0.25 years^{-1} for M = 0.15 years^{-1}, with estimates of 0.14–0.15 for runs with M = 0.10 years^{-1}.

These fishing mortality estimates were combined with proportion of females (default assumption of 50%) and an age-specific maturity schedule to estimate static spawning potential ratio (static SPR) or percent maximum spawning potential (%MSP) (Gabriel et al. 1989). Static SPR, based on female biomass, was calculated using equations 4 and 5 to model length and weight from age. Estimates of static SPR based on egg production (equation 6) tended to be somewhat smaller than those based on female biomass. Static SPR was seen to increase in recent years in the FADAPT analyses (Figure 8). For the period 1995–1997, the FADAPT run with M = 0.05 years^{-1} that produced estimates of static SPR significantly below 30% (Tables 6 and 7).

Estimated values of static SPR and biological reference points related to these values (based on egg production) are summarized in Tables 6 and 7. Recent levels of static SPR were calculated to be 12–14% for M = 0.05 years^{-1}, 26–34% for M = 0.10 years^{-1}, and 43–48% for M = 0.15 years^{-1}. The South Atlantic Fishery Management Council is currently using F_{30} (30% static SPR) as its threshold for defining overfishing and F_{40} (40% static SPR) as its target level. Estimated values for F_{30} seem to be intermediate between $F_{0.1}$ and F_{max} with values of about 0.35 for M = 0.10 years^{-1}; while F_{40} is similar to or slightly below $F_{0.1}$.

Discussion

No general trend in mean weight of wreckfish was noted from 1991 through 1998, either calculated from logbook data or from biological sample data (Figure 3). This would normally suggest that the stock is maintaining its integrity with little sign of overfishing; however, if this stock is maintained by recruitment from the eastern North Atlantic, then signs of overfishing may be delayed for a considerable period based on the modal age in the fishery (14–16 years). Furthermore, the eastern North Atlantic stock may be supplied by larvae recruiting from spawning on the Charleston Bump (Sedberry et al. 1996).

Relatively limited aging data (n = 841) reduced the ability to reflect both seasonal growth patterns and annual variation in growth within the estimation framework for converting catch in numbers by size to catch in numbers by age (via age-length keys). Hence the need to develop separate sets of age-length keys to examine either the consequences of annual variation (as represented by separate keys for 1988–1990, 1991–1993, and 1994–1998) or seasonal variation (as represented by separate keys for April–June, July–September, and October to the end of a fishing year). Because only a small difference in growth was noted between 1988 and 1992 and 1995–1998 (Figure 4b), analyses based on the seasonal catch matrices may be more useful than those based on the annual catch matrices.

The FADAPT allows calibration with the fishery-dependent indices of abundance estimated from the ANOVA model applied to the "High 5" vessels. The FADAPT approach is also an improvement over early assessments that were restricted to application of the separable VPA approach (Clay 1990), which required the assumption of constant selectivity or partial recruitment over the study period.

For FADAPT, the range of estimates of static SPR are between 13 and 48% for the 1995–1997 fishing years (Tables 6 and 7), and higher values for 1998 (18–60% static SPR depending on M) (Figure 8). Because SAFMC's definition of overfishing threshold (30%) is similar in value to the static SPR (ranges from 27 to 33% when calibrated to both CPUE indices obtained for the intermediate level of M), the assumption of M is critical for inferring current stock status. Values of M lower than 0.1 year^{-1} will suggest increasing concern for overfishing, while values of M greater than 0.1 year^{-1} will suggest decreasing concern for overfishing. Based on current aging techniques with a maximum age of 39 observed in the two aging studies, M is probably close to or slightly greater than 0.1 year^{-1}.

Declining stock biomass raises concern about stock depletion. Stock biomass (ages 7 and older) in 1998 has fallen to 10–14% of levels in 1988 (based on M = 0.1 year^{-1} with annual and seasonal catch matrices, respectively). Encouraging signs are noted with the increasing levels of recruits to age 7 starting about 1994–1995. It should be noted that a limited retrospective analysis was conducted on the FADAPT approach. This analysis found very small error in estimates of F

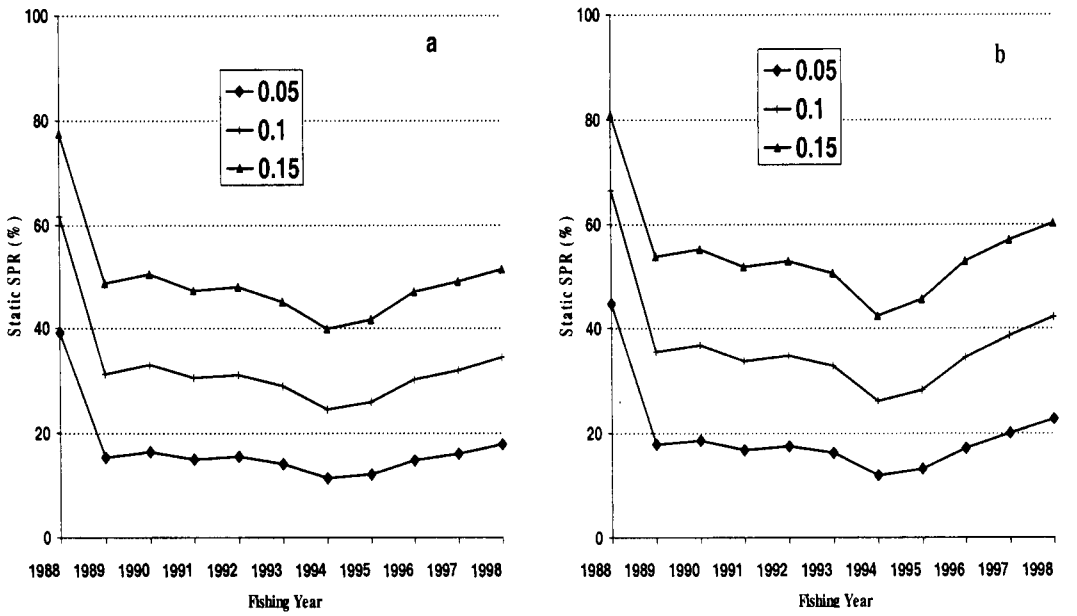


FIGURE 8. Estimates of static spawning potential ratio (SPR) of wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

and population size for the most recent years when the number of years in the analysis were reduced.

The wreckfish stock was undergoing overfishing prior to 1994 (especially in 1989), leading to depressed levels of stock biomass. Levels of fishing mortality rates since have declined to values at or about threshold levels for overfishing as defined by the SAFMC. Recruitment levels appear to be improving and will hopefully lead to rebuilding of the stock as long as fishing mortality does not significantly increase from current levels.

The recent re-authorization of the Magnuson-Stevens Act requires that two factors be assessed (Restrepo et al. 1998). The first factor concerns overfishing, or whether the rate of removal (fishing mortality rate), is too high; while the second factor concerns reduction of stock size, or whether the spawning stock biomass (or capacity for egg production) has been depleted. The biological reference points presented here address only the first factor. The second factor is considered, but not related at this time to any biological reference point, although the recent low levels may fall below such a reference point (e.g., B_{MSY} or biomass at maximum sustainable yield [MSY]).

The primary assumption for all VPA models is that the catch matrix represents all losses due to human activity. Wreckfish are fished upon in other areas (Sedberry et al. 1999). Although landings are generally available, size data are sparse, and certainly not comparable to data available from the U.S. fishery. Specific data supporting this concern are the occurrence of various small hooks (dissimilar to those used by U.S. fisheries) on wreckfish caught on the Blake Plateau. This assumption was addressed in a limited fashion in Vaughan et al. (1995, Appendix A). Those analyses, based on data through 1994, suggested that, if wreckfish landed from the total North Atlantic are treated as a single stock, then lower estimated values of static SPR would be expected. Thus, until more data are available for the entire stock (especially from the eastern North Atlantic areas defined as FAO 27, 34, and 37), the analyses presented in this paper should be viewed with some caution.

Acknowledgments

We thank the following for providing necessary data for these analyses: Linda Hardy (NMFS Beaufort Laboratory) for logbook catch and effort data; Laura Bishop (NMFS Galveston Laboratory), and Joshua Bennett (NMFS Miami Laboratory) for commercial length data from the NMFS Southeast Fisheries Science Center TIP data file for Florida, Georgia, South Carolina, and North Carolina; Paul Phalen (North Carolina Division of Marine Fisheries, January 1991 through January 1992) for additional data from North Carolina; and David Wyanski (SCDNR, Charleston)

for data on wreckfish fecundity. We also thank John Merriner, Michael Prager, James Waters, and three anonymous reviewers for their thoughtful comments.

References

Beauchamp, J. J., and J. S. Olson. 1973. Corrections for bias in regression estimates after logarithmic transformation. Ecology 54:1403–1407.

Clay, D. 1990. TUNE: a series of fish stock assessment computer programs written in FORTRAN for microcomputers (MS DOS). International Commission for the Conservation of Atlantic Tunas, Collected Volume Scientific Papers 32:443–460.

Conser, R. J., and J. E. Powers. 1990. Extensions of the ADAPT tuning method designed to facilitate assessment work on tuna and swordfish stocks. International Commission for the Conservation of Atlantic Tunas, Collected Volume Scientific Papers 32:461–467.

FAO (Food and Agriculture Organization). 1999. FAO yearbook. Fishery statistics. Capture production. FAO Fisheries Series 52 and FAO Statistics Series 147, volume 84. Food and Agricultural Organization of the United Nations, Rome.

Gabriel, W. L., M. P. Sissenwine, and W. J. Overholtz. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. North American Journal of Fisheries Management 9:383–391.

Gavaris, S. 1988. An adaptive framework for the estimation of population size. Canadian Atlantic Fishery Scientific Advisory Commission Research Document 88/29.

Hardy, L. F. 2000. The 1999-2000 wreckfish fishery annual report. Report from National Marine Fisheries Service, Beaufort Laboratory, Beaufort, North Carolina.

Heemstra, P. C. 1986. Family no. 165: Polyprionidae. Page 509 *in* M. M. Smith and P. C. Heemstra, editors. Smith's sea fishes, 6th edition. Springer-Verlag, Berlin.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. U.S. National Marine Fisheries Service Fishery Bulletin 82:898–903.

Murphy, G. I. 1965. A solution of the catch equation. Journal of the Fisheries Research Board of Canada 22:191–201.

Pauly, D. 1979. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil International Exploration Mer 39:175–192.

Restrepo, V. R. 1996. FADAPT version 3.0. A guide. University of Miami, RSMAS, Miami, Florida. (Available from University of Miami, Rosenstiel School of Marine and Atmospheric Sciences, 4600 Rickenbacker Causeway, Miami, Florida 33149.)

Restrepo, V. R., convenor, and 10 coauthors. 1998. Technical guidance on the use of precautionary approaches to implementing national standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA (National Oceanic and Atmospheric Administration) Technical Memorandum NMFS (National Marine Fisheries Service)-F/SPO-31.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada Bulletin 191:1–382.

SAS Institute. 1985. SAS/STAT guide for personal computers, version 6 edition. SAS Institute Inc., Cary, North Carolina.

Sedberry, G. R., and eight coauthors. 1999. Wreckfish *Polyprion americanus* in the North Atlantic: fisheries, biology, and management of a widely distributed and long-lived fish. Pages 27–50 in J. A. Musick, editor. Life in the slow lane: ecology and conservation of long-lived marine animals. American Fisheries Society, Symposium 23, Bethesda, Maryland.

Sedberry, G. R., J. L. Carlin, R. W. Chapman, and B. Eleby. 1996. Population structure in the pan-oceanic wreckfish, *Polyprion americanus* (Teleostei: Polyprinidae), an indicated by mtDNA variation. Journal of Fishery Biology 49 (Supplement A):318–329.

Sedberry, G. R., G. F. Ulrich, and A. J. Applegate. 1994. Development and status of the fishery for wreckfish, *Polyprion americanus*, in the western North Atlantic. Proceedings of the Gulf and Caribbean Fisheries Institute 43:168–192.

SAFMC (South Atlantic Fishery Management Council). 1991. Final amendment 5 (wreckfish), regulatory impact review, initial regulatory flexibility determination and environmental assessment for the fishery management plan for the snapper-grouper fishery of the South Atlantic region. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina. (Available from SAFMC, One Southpark Circle, Suite 306, Charleston, South Carolina 29407-4520.)

Vaughan, D. S., and M. L. Burton. 1994. Estimation of von Bertalanffy growth parameters in the presence of size-selective mortality: a simulated example with red grouper *Epinephelus morio*. Transactions of the American Fisheries Society 123:1–8.

Vaughan, D. S., C. S. Manooch, III, and J. Potts. 1999. Assessment of southeastern U.S. Atlantic wreckfish stock for fishing years 1988-1998. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., C. S. Manooch, III, J. Potts, and J. V. Merriner. 1993. Assessment of south Atlantic wreckfish stock for fishing years 1988-1992. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., C. S. Manooch, III, J. Potts, and J. V. Merriner. 1994. Assessment of south Atlantic wreckfish stock for fishing years 1988-1993. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., J. V. Merriner, C. S. Manooch, III, and J. Potts. 1995. Assessment of south Atlantic wreckfish stock for fishing years 1988-1994. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., J. V. Merriner, C. S. Manooch, III, and J. Potts. 1996. Assessment of south Atlantic wreckfish stock for fishing years 1988-1995. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., J. V. Merriner, C. S. Manooch, III, and J. Potts. 1997. Assessment of southeastern U.S. Atlantic wreckfish stock for fishing years 1988-1996. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.

Vaughan, D. S., J. V. Merriner, and J. Potts. 1992. Summary of wreckfish analyses available for fishing years 1988-1991. Report to Snapper Grouper Assessment Group, South Atlantic Fisheries Management Council, Charleston, South Carolina.