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Assessment of the Wreckfish Fishery on the Blake Plateau

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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: Pounds	U.S. landings: Numbers	Number sampled	Percent sampled	FAO landings[a] (pounds)
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.

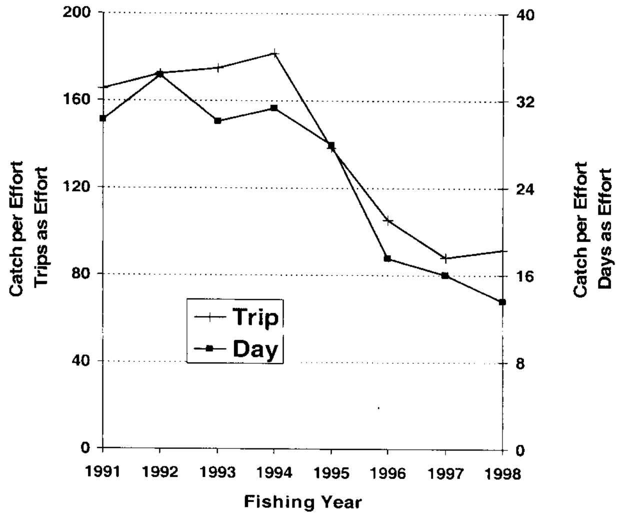

FIGURE 1. Wreckfish catch-per-unit effort based on catch in numbers per trip and per day estimated from ANOVA models applied to logbooks from "High 5" (continuously active) vessels.

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

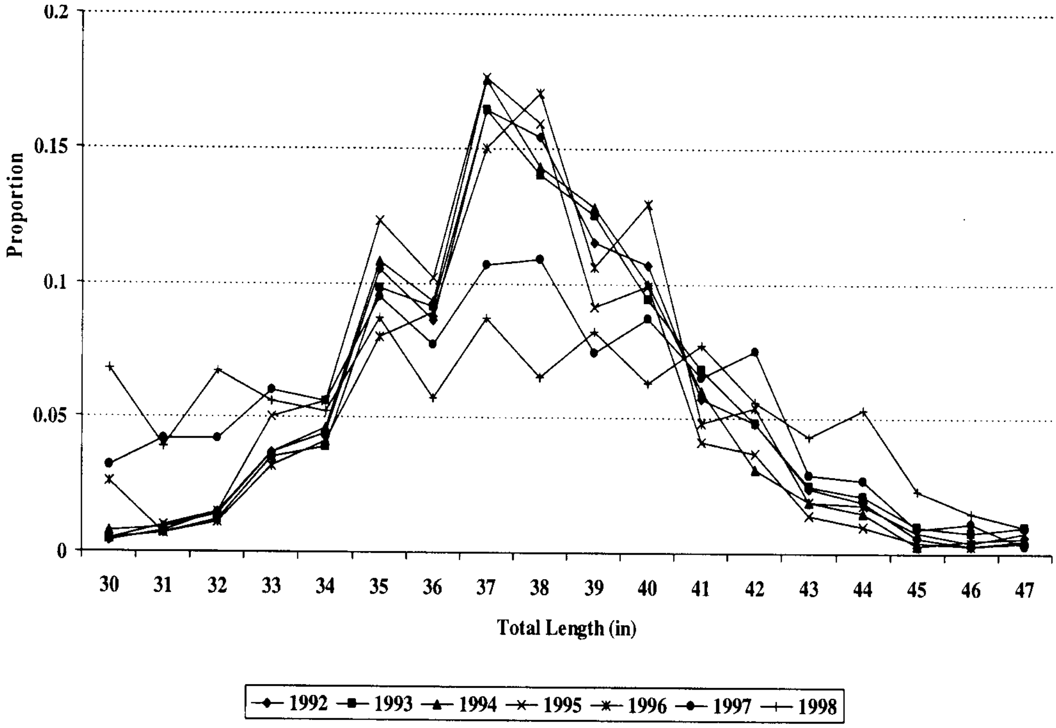

FIGURE 2. Comparison of wreckfish annual length-frequency distributions, 1992–1998.

TABLE 3. Wreckfish mean lengths and weights from biological sampling of commercial landings by fishing year for 1988–1998 and season for 1992–1998 [**E**arly: Apr–Jun, **M**iddle: Jul–Sep, and **L**ate: 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

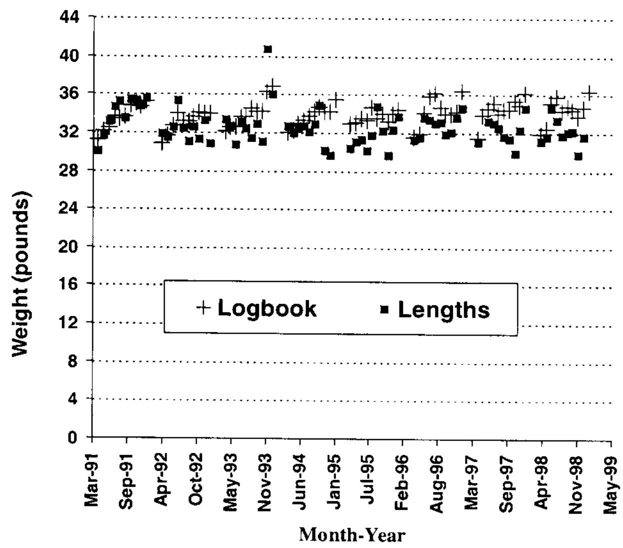

FIGURE 3. Monthly mean weight (pound) of wreckfish from logbooks and catch sampling, 1991–1998.

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:

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

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

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

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

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):

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

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

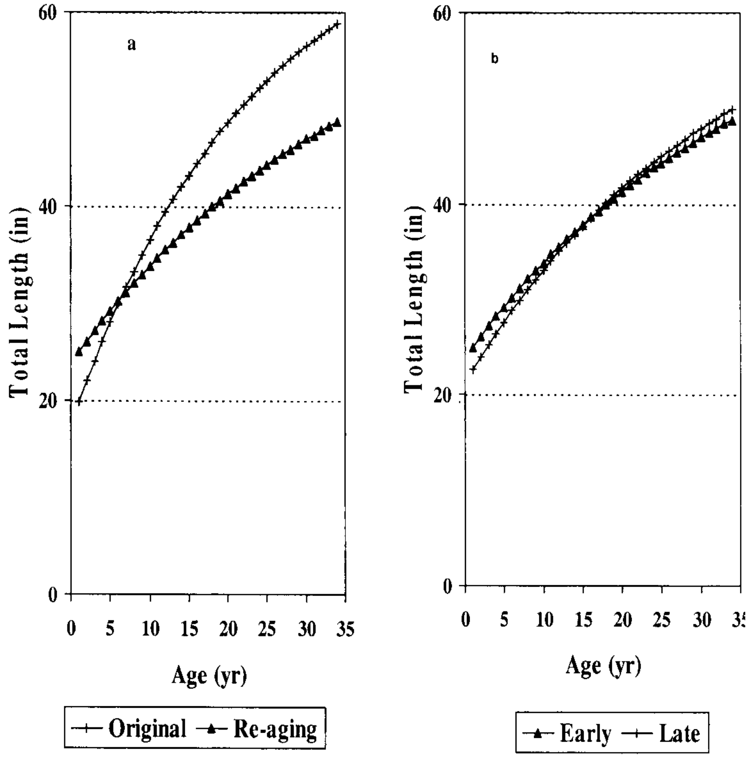

FIGURE 4. Wreckfish total length at age compared between a) original aging and re-aging of otoliths collected during 1988–1992, and b) re-aging of 1988–1992 otoliths with aging of otoliths collected from 1995 to 1998.

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-

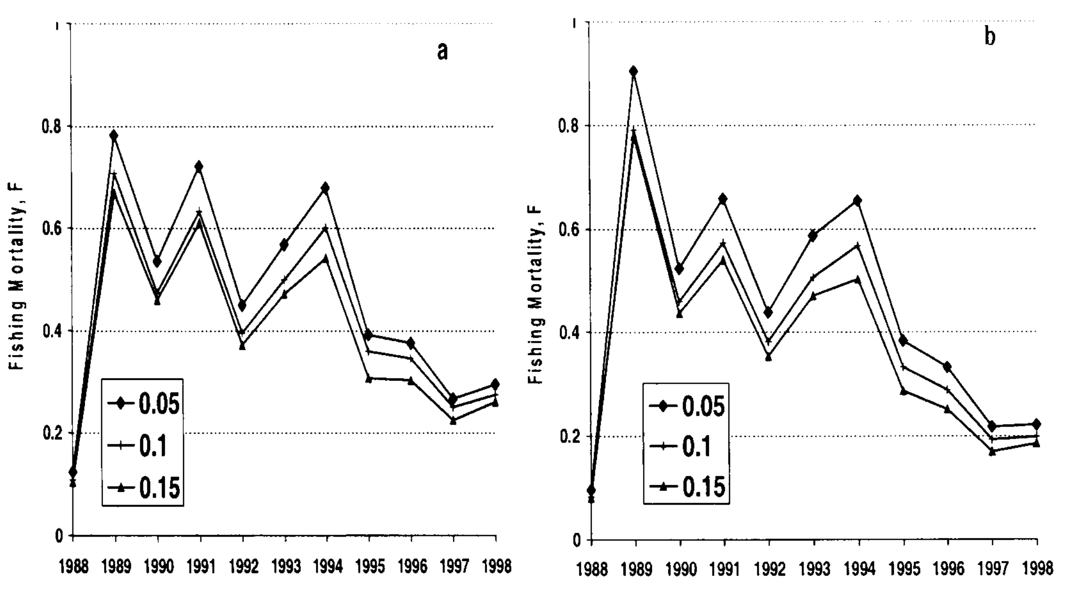

FIGURE 5. Estimates of full F (mean fishing mortality across ages 16–26+) on wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

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 Combined	M = 0.10 Catch/trip	M = 0.10 Catch/day	M = 0.15 combined
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 Combined	M = 0.10 Catch/trip	M = 0.10 Catch/day	M = 0.15 combined
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+).

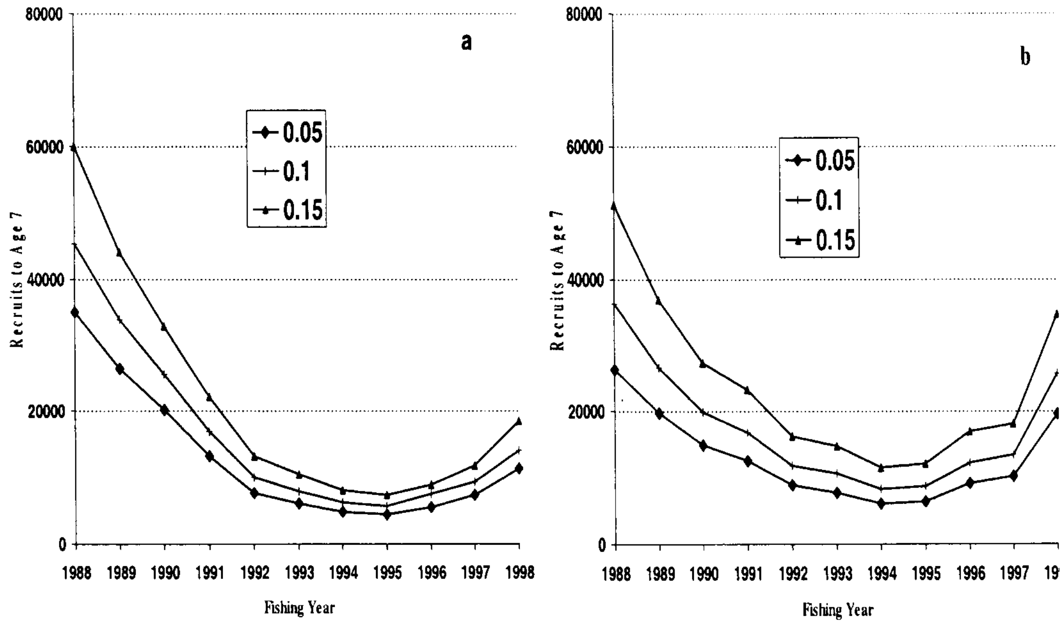

FIGURE 6. Estimates of recruits to age 7 for wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

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

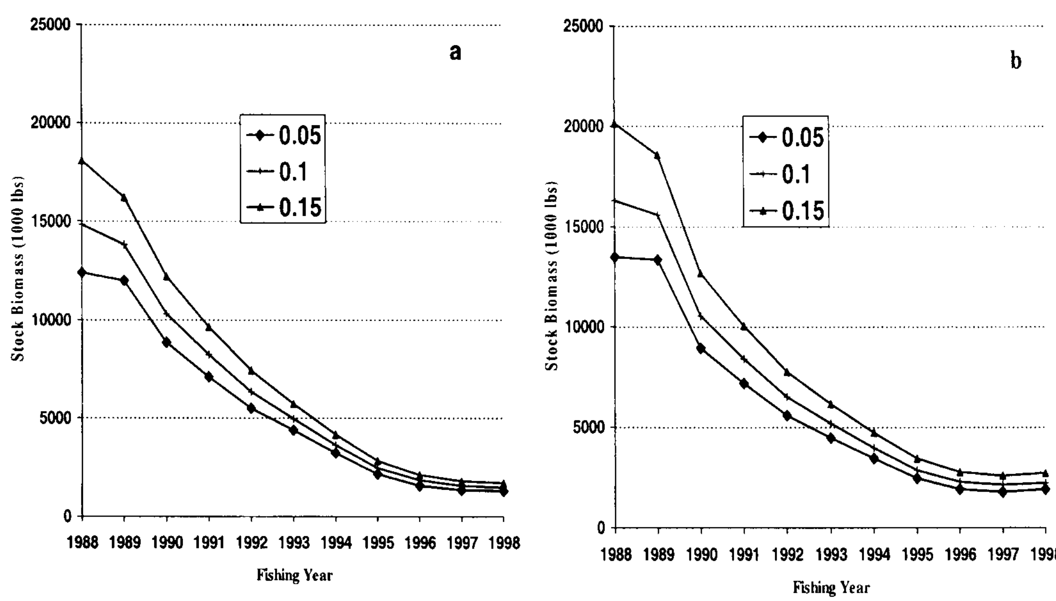

FIGURE 7. Estimates of stock biomass (ages 7+) of wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

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

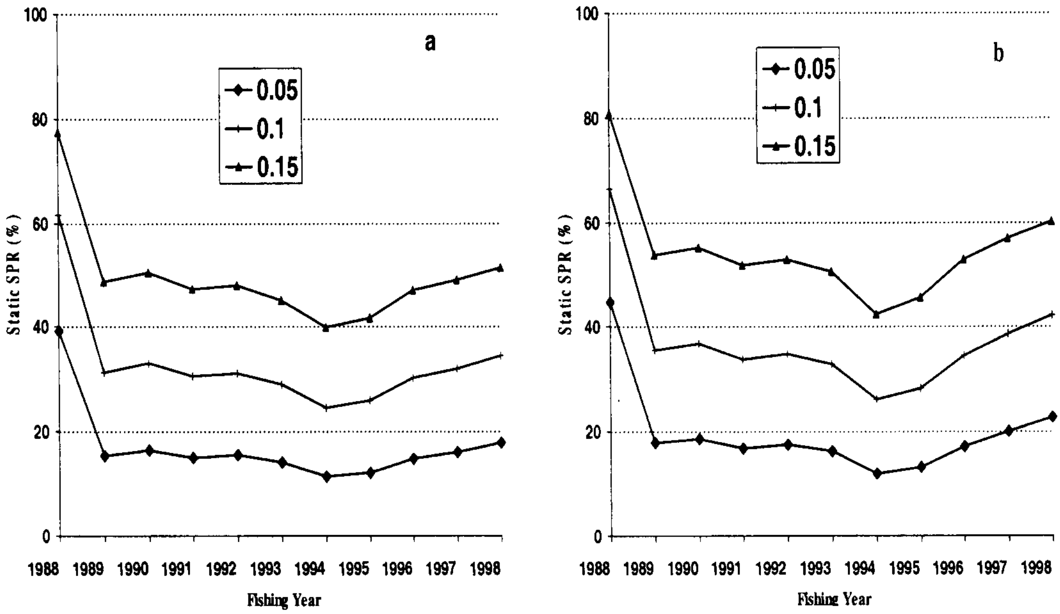

FIGURE 8. Estimates of static spawning potential ratio (SPR) of wreckfish from FADAPT with three levels of natural mortality (M) based on a) annual, and b) seasonal catch matrices for 1988–1998.

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.

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