NOAA Technical Report NMFS 149

April 2000

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A Technical Report of the *Fishery Bulletin*

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ABSTRACT

The status of the Gulf menhaden, *Brevoortia patronus*, fishery was assessed with purse-seine landings data from 1946 to 1997 and port sampling data from 1964 to 1997. These data were analyzed to determine growth rates, biological reference points for fishing mortality from yield per recruit and maximum spawning potential analyses, spawner-recruit relationships, and maximum sustainable yield (MSY). The separable virtual population approach was used for the period 1976–97 (augmented by earlier analyses for 1964–75) to obtain point estimates of stock size, recruits to age 1, spawning stock size, and fishing mortality rates. Exploitation rates for age-1 fish ranged between 11% and 45%, for age-2 fish between 32% and 72%, and for age-3 fish between 32% and 76%. Biological reference points from yield per recruit ($F_{0.1}$: 1.5–2.5/yr) and spawning potential ratio (F_{20}: 1.3–1.9/yr and F_{30}: 0.8–1.2/yr) were obtained for comparison with recent estimates of F (0.6–0.8/yr). Recent spawning stock estimates (as biomass or eggs) are above the long-term average, while recent recruits to age 1 are comparable to the long-term average. Parameters from Ricker-type spawner-recruit relations were estimated, although considerable unexplained variability remained. Recent survival to age-1 recruitment has generally been below that expected based on the Ricker spawner-recruit relation. Estimates of long-term MSY from PRODFIT and ASPIC estimation of production model ranged between 717,000 t and 753,000 t, respectively. Declines in landings between 1988 and 1992 raised concerns about the status of the Gulf menhaden stock. Landings have fluctuated without trend since 1992, averaging about 571,000 t. However, Gulf menhaden are short lived and highly fecund. Thus, variation in recruitment to age 1, largely mediated by environmental conditions, influences fishing success over the next two years (as age-1 and age-2 fish). Comparisons of recent estimates of fishing mortality to biological reference points do not suggest overfishing.

Introduction

Gulf menhaden, *Brevoortia patronus*, is a euryhaline species found in coastal and inland tidal waters from the Yucatan Peninsula in Mexico to Tampa Bay, Florida (Nelson and Ahrenholz, 1986; Christmas et al., 1988). Adult menhaden are filter feeders (feeding primarily on phytoplankton) and, in turn, support predatory food fishes. Gulf menhaden form large surface schools, appearing in nearshore Gulf waters from about April to November. Although no extensive coastwide migrations are known to occur, there is evidence that older fish move toward the Mississippi River delta (Ahrenholz, 1981). Spawning peaks during December and January in offshore waters (Lewis and Roithmayr, 1981). Eggs hatch at sea and ocean currents carry the larvae to estuaries where they develop into juveniles (Christmas et al., 1988). Juveniles migrate offshore during winter and move back to coastal waters the following spring as age-1 adults.

Gulf menhaden are subject to an extensive purse-seine fishery in the northern Gulf of Mexico from mid-April through 1 November as regulated by interstate compact (Leard et al., 1995). Since 1964, NOAA's National Marine Fisheries Service has maintained a sampling program for Gulf menhaden. Participation in the Gulf menhaden fishery, in terms of numbers of fishing companies, plants, and purse-seine vessels, has fallen dramatically since the 1970s. During the study period the number of active reduction plants where menhaden are processed for meal and oil has varied between 5 and 14, with 5 plants active in 1997 (Table 1). The number of purse-seine vessels has varied between 51 and 92, with 52 vessels active during the 1997 fishing season. The declines were primarily due to corporate consolida-

Table 1

Number of Gulf menhaden (*Brevoortia patronus*) reduction plants by port and total, number of purse-seine vessels, and number of fish sampled for age and size for fishing years, 1964–97.

Fishing year	Ports[1] A	MP	E	D	MC	IC	C	SP	No. reduction plants	No. reduction vessels	No. fish sampled
1964	0	3	2	2	1	0	2	1	11	78	12,457
1965	0	3	2	3	1	1	2	1	13	87	15,819
1966	1	3	2	2	1	1	3	1	13	92	13,016
1967	0	3	2	2	1	1	3	1	13	85	14,519
1968	1	3	2	2	1	1	3	1	14	78	16,499
1969	1	3	2	1	1	1	3	1	13	75	15,281
1970	0	3	2	2	1	1	3	1	13	76	10,560
1971	0	3	2	2	1	1	3	1	13	85	7,859
1972	0	3	2	1	1	1	3	0	11	75	10,030
1973	0	2	2	1	1	1	3	0	10	66	8,958
1974	0	2	2	1	1	1	3	0	10	71	10,120
1975	0	3	2	1	1	1	3	0	11	78	9,529
1976	0	3	2	1	1	1	3	0	11	82	13,586
1977	0	3	2	1	1	1	3	0	11	80	14,918
1978	0	3	2	1	1	1	3	0	11	80	12,985
1979	0	3	2	1	1	1	3	0	11	78	11,620
1980	0	3	2	1	1	1	3	0	11	79	9,961
1981	0	3	2	1	1	1	3	0	11	80	10,408
1982	0	3	2	1	1	1	3	0	11	82	10,709
1983	0	3	2	1	1	1	3	0	11	81	14,840
1984	0	3	2	1	1	1	3	0	11	81	16,001
1985	0	2	1	1	0	1	2	0	7	73	13,240
1986	0	2	2	1	0	1	2	0	8	72	16,530
1987	0	2	2	1	0	1	2	0	8	75	16,530
1988	0	2	2	1	0	1	2	0	8	73	12,410
1989	0	2	2	1	1	1	2	0	9	77	13,970
1990	0	2	2	1	1	1	2	0	9	75	11,670
1991	0	1	2	1	1	1	1	0	7	58	11,690
1992	0	1	1	1	1	1	1	0	6	51	15,590
1993	0	1	1	1	1	1	1	0	6	52	15,730
1994	0	1	1	1	1	1	1	0	6	55	16,820
1995	0	1	1	1	1	1	1	0	6	52	14,520
1996	0	1	1	0	1	1	1	0	5	51	13,550
1997	0	1	1	0	1	1	1	0	5	52	10,950

[1] A = Appalachicola, FL: Fish Meal Co. (1966, 1968–69); MP = Moss Point, MS: Seacoast Products Co. (1964–72, 1975–84), AMPRO Fisheries, Inc. (formerly Standard Products (1964–90), Zapata Haynie, Inc. (1964–92); E = Empire, LA: Empire Menhaden Co. (1964–91), Daybrook Fisheries (formerly Petrou Fisheries, Inc. (1964–92); D = Dulac, LA: Dulac Menhaden Fisheries (1964–68, 1970–71), Fish Meal and Oil Co. (1964–65), Zapata Haynie, Inc. (1965–92); MC = Morgan City, LA: Seacoast Products Co. (1965–84), Gulf Protein (1989–92); IC = Intracoastal City, LA: Seacoast Products Co. (1965–84), Zapata Haynie, Inc. (1985–92); C = Cameron, LA: Louisiana Menhaden Co. (1964–90), Seacoast Products Co. (1964–84), Zapata Haynie, Inc. (1967–92); SP =Sabine Pass, TX: Texas Menhaden Co. (1964–71).

tion. Major acquisitions of competitor fish companies occurred in 1984, 1992, and late 1997. Ports of landing such as Cameron, Empire, and Moss Point, which historically supported multiple plants owned by several companies, eventually harbored only a single plant per port. By early 1998, a single company dominated the fishery and owned four of five plants in the northern Gulf of Mexico. Counter to the demise of menhaden plants in recent years, has been the relative stability of fleet. Despite the fall in absolute numbers of plants, surviving plants have tended to increase processing capacity, and thus maintain a relatively stable fleet of about 50 vessels since 1992. Annual landings and nominal fishing effort data in vessel-ton-weeks (vtw), available

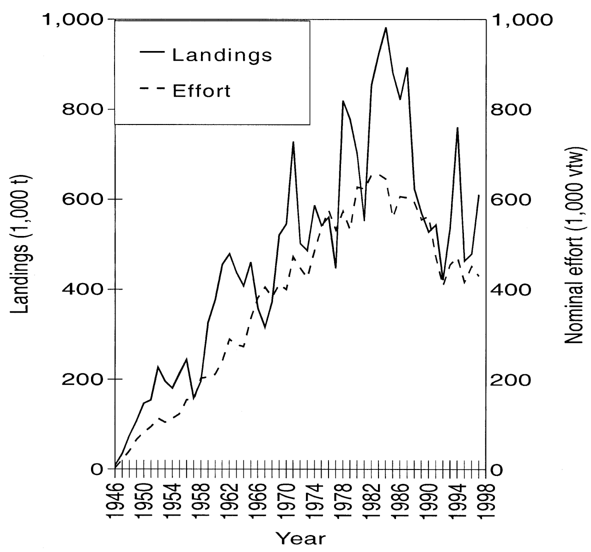

Figure 1
Landings and nominal fishing effort by the Gulf menhaden (*Brevoortia patronus*) reduction fishery, 1946–97.

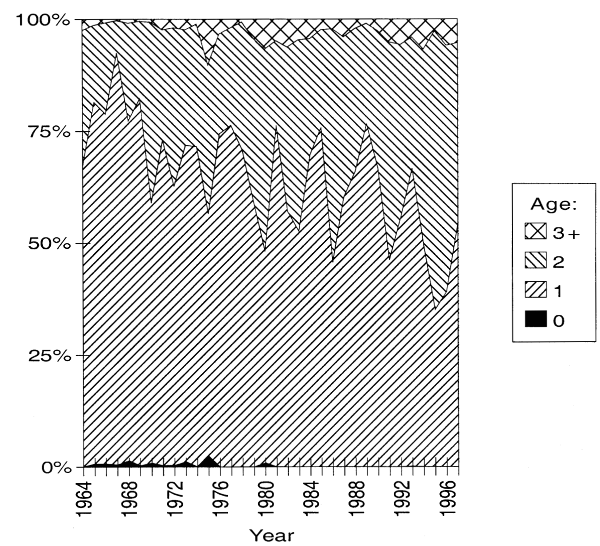

Figure 2
Percent of numbers for ages 1–3+ [figure shows 3+] estimated from landings by the Gulf menhaden (*Brevoortia patronus*) reduction fishery, 1964–97.

since 1946, show an upward trend in landings from 1946 through 1984 when landings peaked at 982,800 t (Fig. 1). Nominal effort peaked the previous year (1983) at 655,800 vessel-ton-weeks. Landings and nominal effort then declined to 421,400 t and 408,000 vessel-ton-weeks in 1992, respectively. Between 1984 and 1992, the number of reduction plants declined from 11 to 6 and the number of purse-seine vessels from 81 to 51. Since 1992, landings have varied between 463,900 and 761,600 t, while effort has varied between 417,000 and 472,000 vessel-ton-weeks without apparent trend.

Detailed information on daily vessel landings and fish sampled for length, weight, and age (from scales) is available from 1964 to the present. This information is used to estimate the number of fish landed at age, 1964–97 (Table 2). A new computer program for estimating catch at age was developed during 1996–97 and re-estimation of catch in numbers at age based on this program was done for 1985–97. The fishery depends primarily on age-1 (comprising 35–92% of the landings) and age-2 fish (7–62%) (Fig. 2). The remaining ages (age-0, -3, and -4+) generally contribute insignificantly to the landings (<1% to 13%), although age-3 contributed 10% in 1975. Age-2 menhaden comprised over 50% of the landings in 1986, 1995, and 1996.

Vaughan et al. (1996) last analyzed coast-wide Gulf menhaden data for the 1964–92 fishing years. At that time, landings had been declining for almost a decade since the record high in 1984. The purpose of this paper is to reevaluate the status of the Gulf menhaden stock using five additional fishing years (through 1997 fishing year). The analyses that follow parallel to some extent those presented in Nelson and Ahrenholz (1986), Vaughan (1987), and Vaughan et al. (1996) with modifications as described. Estimates of population numbers and fishing mortality rates by age are obtained from virtual population analysis (VPA), specifically by separable VPA for the period 1976–97. The Murphy VPA results for 1964–75 from Vaughan et al. (1996) are used in population models. For each fishing year, length at age is estimated by fitting the von Bertalanffy growth curve to obtain parameter estimates; weight at age is obtained by relating weight to length. Biological reference levels of fishing mortality are obtained from yield per recruit and spawning stock biomass per recruit approaches. Spawning stock biomass is compared with subsequent recruitment to age 1, from which Ricker spawner-recruit model parameters are estimated. Effective fishing effort is obtained by adjusting nominal effort for estimated variability in the catchability coefficient, from which parameters and biological reference values from surplus production models are estimated (with annual landings data using PRODFIT [Fox, 1975] and ASPIC [Prager, 1995]). Recruitment estimates are compared to juvenile abundance data recently made available from Louisiana and Texas, and to several environmental factors. The results from these models are used to evaluate the Gulf menhaden stock status.

Table 2

Estimated landings of Gulf menhaden (*Brevoortia patronus*) in numbers at age (0–4+), total numbers landed (ages 0–4+), total landings by weight, and nominal fishing effort (vessel-ton weeks) for the fishing years, 1964–97. New method of estimation of catch at age used for 1985–97.

Fishing year	Landings in nos. at age (10^9) landings 0	1	2	3	4+	Total	Total landings (1000 t)	Nominal fishing effort[1]
1964	0.0	3.33	1.50	0.12	0.0	4.95	409.4	272.9
1965	0.04	5.03	1.08	0.08	0.0	6.23	463.1	335.6
1966	0.03	3.31	0.87	0.03	0.0	4.24	359.1	381.3
1967	0.02	4.27	0.34	0.01	0.0	4.64	317.3	404.7
1968	0.07	3.48	1.00	0.04	0.0	4.58	373.5	382.3
1969	0.02	6.08	1.29	0.03	0.0	7.41	523.7	411.0
1970	0.05	3.28	2.28	0.04	0.0	5.65	548.1	400.0
1971	0.02	5.76	1.96	0.18	0.0	7.92	728.2	472.9
1972	0.02	3.05	1.73	0.09	0.0	4.89	501.7	447.5
1973	0.05	3.03	1.11	0.10	0.0	4.29	486.1	426.2
1974	0.0	3.85	1.47	0.06	0.0	5.38	587.4	485.5
1975	0.11	2.44	1.50	0.46	0.0	4.51	542.6	538.0
1976	0.0	4.59	1.37	0.20	0.0	6.17	561.2	575.8
1977	0.0	4.66	1.33	0.11	0.01	6.11	447.1	532.7
1978	0.0	6.79	2.74	0.05	0.01	9.59	820.0	574.3
1979	0.0	4.70	2.88	0.34	0.01	7.92	777.9	533.9
1980	0.07	3.41	3.26	0.44	0.05	7.22	701.3	627.6
1981	0.0	5.75	1.42	0.33	0.03	7.54	552.6	623.0
1982	0.0	5.15	3.30	0.50	0.06	9.01	853.9	653.8
1983	0.0	4.69	3.81	0.38	0.03	8.90	923.5	655.8
1984	0.0	7.75	2.88	0.44	0.05	11.12	982.8	645.9
1985	0.0	8.68	2.50	0.23	0.04	11.45	881.1	560.6
1986	0.0	4.28	4.89	0.17	0.03	9.37	822.1	606.5
1987	0.0	6.70	3.98	0.43	0.01	11.12	894.2	604.2
1988	0.0	5.34	2.58	0.15	0.02	8.09	623.7	594.1
1989	0.0	5.55	1.62	0.07	0.00	7.24	569.6	555.3
1990	0.0	3.89	1.79	0.14	0.01	5.83	528.3	563.1
1991	0.0	2.22	2.34	0.22	0.03	4.80	544.3	472.3
1992	0.0	2.19	1.51	0.20	0.03	3.92	421.4	408.0
1993	0.0	3.49	1.53	0.19	0.02	5.24	539.2	455.2
1994	0.0	3.63	3.20	0.44	0.05	7.32	761.6	472.0
1995	0.0	1.37	2.42	0.10	0.00	3.90	463.9	417.0
1996	0.0	1.78	2.51	0.25	0.02	4.57	479.4	451.7
1997	0.0	3.24	2.40	0.28	0.04	5.95	611.2	430.2

[1] Units are 1,000 vessel-ton weeks.

Virtual Population Analyses

The results from two methods of virtual population analysis (VPA) are used in this assessment. The first method, that of Murphy (1965), is described in Vaughan (1987) and is used for 1964–75. The second method, that of Doubleday (1976), is referred to as "separable" VPA and is applied to more recent years, 1976–97; it assumes that age- and year-specific estimates of *F* can be partitioned into the product of an age component (partial recruitment) and a year component. We used the computer program (SVPA.EXE) as modified by Clay (1990) from Pope and Shepherd (1982). This method was applied to the catch-in-numbers-at-age matrix (or catch matrix) based on annual ages (not quarterly ages as in the Murphy VPA).

Because Vaughan et al. (1996) demonstrated that the two VPA approaches (Murphy VPA and separable VPA) gave similar results for the period 1976–92, the latter approach was used for updating the period 1993–97. Additional separable VPA runs were made to explore the

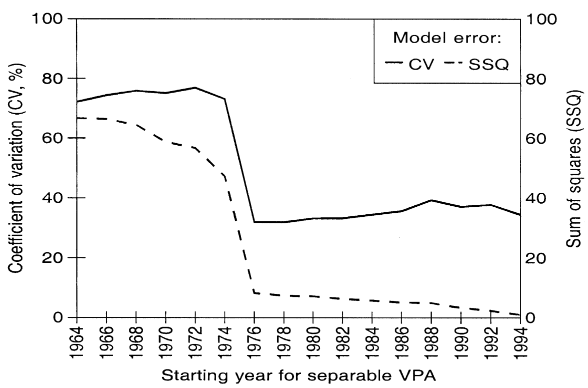

Figure 3
Coefficient of variation (CV) of catch data and sum of squared (SSQ) deviations of log catch ratios plotted against increasing starting year of the Gulf menhaden (*Brevoortia patronus*) catch matrix used in the separable VPA approach. Starting year varies between 1964 and 1994 and final year in the catch matrix for all computations is 1997.

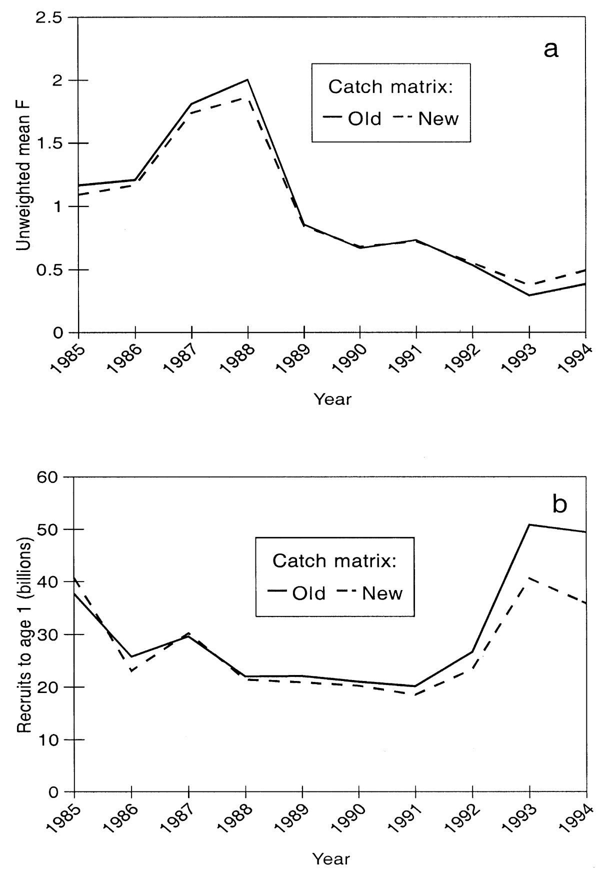

Figure 4
Comparison of (a) unweighted mean *F*, and (b) recruits to age 1 estimated using separable virtual population analysis on old and new methods for estimating catch at age of Gulf menhaden (*Brevoortia patronus*) applied to overlapping years, 1985–94.

plausibility of the separable assumption for the period 1976–97. Inspection of the approximate coefficient of variation (CV) and sum of squared deviations (SSQ) (output produced by SVPA.EXE program), when plotted against initial year of data appearing in the catch matrix (Fig. 3), suggested that the separable assumption continued to be reasonable when extending the catch matrix (1976–92) to 1997. See Vaughan et al. (1996) for discussion of possible causes for this discontinuity in CV and SSQ.

A new method for estimating catch-in-numbers at age was developed which uses a more statistically-rigorous approach to filling missing port/week combinations for which sampling was unavailable. A general linear model (GLM) approach was used to estimate catch-in-numbers at age for each port and week combination throughout the fishing year based on season (quarterly) and NMFS area (east and west of Mississippi River) using length, weight, and age structure information, rather than ad hoc approaches previously used. Sensitivity of VPA output to the change in catch-at-age estimation procedure (which overlaps for 1985–94) was explored. Only small differences are noted in estimates of weighted mean F (ages 1–4 with M=1.1/yr) and recruitment to age 1 (except 1993 and 1994) (Fig. 4a, b).

An estimate for natural mortality (M) of 1.1/yr was used in previous assessments (Nelson and Ahrenholz, 1986; Vaughan, 1987; Vaughan et al., 1996). As noted in Vaughan et al. (1996), estimates of M based on tagging studies range from 0.7 to 1.6/yr. Life history approaches provide estimates of M that range from 0.9 to 1.1/yr based on Pauly (1979) using mean temperature and von Bertalanffy growth parameters, and 0.7 to 1.1/yr based on Hoenig (1983) using maximum age. As noted in Vaughan et al. (1996), life history approaches for estimating M do not reflect additional mortality due to other sources (e.g., losses to a small bait fishery or as bycatch in other fisheries). Hence, most analyses that follow assume M = 1.1/yr, although sensitivity runs are made with M = 0.8, 0.9, and 1.0/yr.

For comparison with and as a continuation of Vaughan et al. (1996), exploitation rates u [proportion removed annually]:

$$u = F(1-e^{-Z})/Z, \tag{1}$$

where Z is the total instantaneous mortality rate (M+F) for ages 1, 2, and 3, and ages 1–4 combined are plotted against year based on the Murphy VPA (from Vaughan et al., 1996) for 1964–75 and separable VPA for 1976–97 (Fig. 5). Exploitation rates for each age and ages 1–4 combined generally have declined since 1964. Exploitation rates for age-1 fish ranged between 11% in 1995 and 45% in 1966; ranges for age-2 fish were between 32% in 1995 and 72% in 1966; and for age-3 fish were between 32% in 1995 and 76% in 1975. Overall exploitation rates (ages 1–4) ranged between 16% in 1995 and 52% in 1966.

To investigate sensitivity of fishing mortality estimates (F) to assumed values of natural mortality, additional estimates of fishing mortality were made using the separable VPA with lower estimates of M (0.8, 0.9, and 1.0/yr). Estimates of annual weighted mean F are compared between estimates of M for 0.8, 0.9, 1.0, and 1.1/yr from SVPA on the catch matrix (Fig. 6a). As M is decreased, consistently higher estimates of annual weighted mean F are obtained. Although differences are small, they are significant, especially if the present value of M is a gross overestimate (<<0.8 compared to 1.1/yr). During the period 1976–97, weighted (by catch in numbers) mean fishing mortality (ages 1–4) from the separable VPA (with M = 1.1/yr) ranged between 0.16/yr in 1995 and 0.42/yr in 1988.

Recruitment to age 1 was generally high and variable between 1976 and 1988, but has been lower and less variable since then (Fig. 7a). Because age-1 menhaden form a large component of the population size, the total population (ages 1–4) shows a similar pattern. On average, recruitment to age 1 was highest during the 1980s, with 41.1 billion recruits to age 1 in 1985.

Retrospective analyses also were conducted to determine uncertainty in recent VPA output estimates, although the analyses were not as detailed as those presented for Atlantic menhaden in Cadrin and Vaughan (1997). Retrospective analyses were run with separable VPA by parallel runs deleting the most recent year (initial year was always 1976). Terminal F value was obtained from a catch curve analysis on the cohort that was age 4 in the final year. Although the retrospective error in F (Fig. 6b) and recruits to age 1 (Fig. 7b) were occasionally large, the error is generally without bias as was found for Atlantic menhaden. Typical of retrospective error with large total mortality, this error tends to disappear after a few years. Hence, retrospective error is largest for the most recent 2–3 years of the analyses.

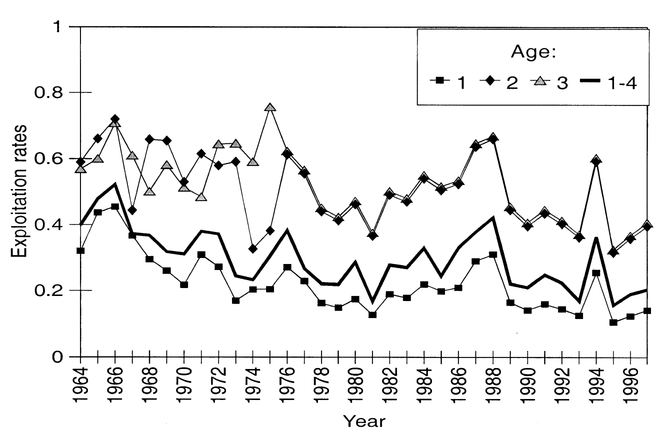

Figure 5

Gulf menhaden (*Brevoortia patronus*) exploitation rates (u) for ages 1, 2, 3, and ages 1–4 combined obtained from separable VPA approach (M = 1.1/yr), 1964–97.

Size at Age and Growth Analyses

Interpolated lengths and weights of Gulf menhaden at age are needed for estimating optimum fishing yield and spawning stock biomass. Estimates of annual mean weight-at-age for Gulf menhaden in the purse-seine catches were calculated to determine any trends in yield-per-recruit that could be expected in the fishery. No specific upward or downward trends in mean weight-at-age are noted (Fig. 8).

Weight (W, in g) is estimated from the weight-length relationship expressed in the linear form of the power function,

$$\ln W = \ln a + b \ln L, \qquad (2)$$

where L is fork length (mm), and ln a and b are parameters estimated by linear regression for each fishing year (Table 3). A correction factor ($\sigma^2/2$), where σ^2 is the variance, based on the mean squared error (MSE) was used when retransforming from ln W to W based on properties of the lognormal distribution (Beauchamp and Olson, 1973).

Fork length (L, in mm) can be estimated from age (t, in yr) on the basis of the von Bertalanffy (1938) growth equation,

$$L_t = L_\infty\left(1 - \exp\left(-K(t - t_0)\right)\right), \qquad (3)$$

where L_∞, K, and t_0 are parameters that in this case were estimated by nonlinear regression (PROC NLIN, MARQUARDT OPTION, SAS Institute Inc., 1987). The maximum length (L_∞) is approached asymptotically, at a rate described by parameter K, with t_0 shifting the curve to the left or right. Annual estimates are based on all individual fish weighted by the inverse of numbers of fish in sample at age. This is done to improve convergence and correct for parameter bias and poor precision resulting from too few older fish compared to large numbers of young fish, as noted in Vaughan and Kan-

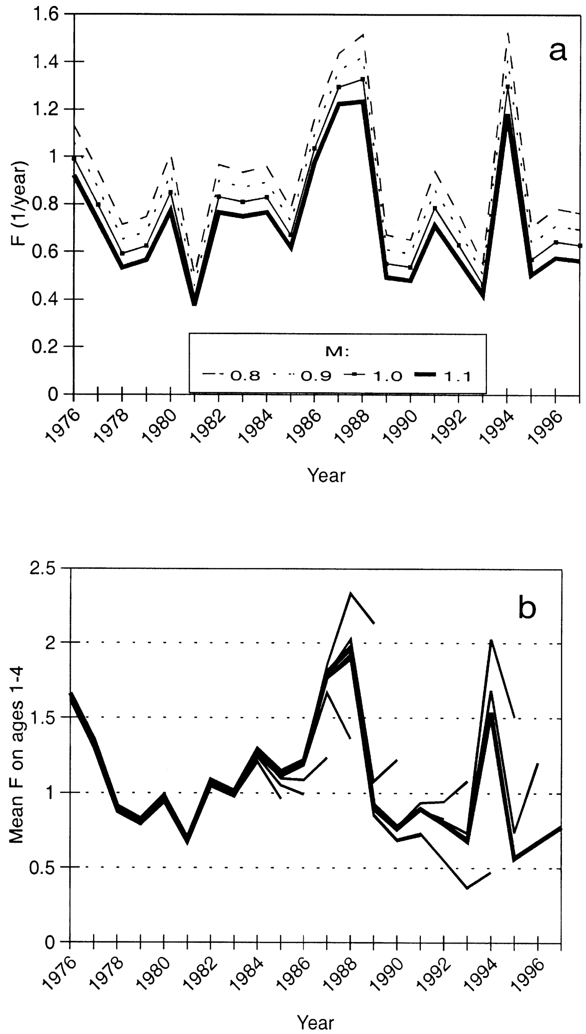

Figure 6

Mean fishing mortality (F) over ages 1–4 for Gulf menhaden (*Brevoortia patronus*) from separable VPA compared by (a) natural mortality (0.8, 0.9, 1.0, and 1.1/yr), 1976–97, and (b) retrospective comparison with decreasing maximum year in catch matrix (M=1.1/yr).

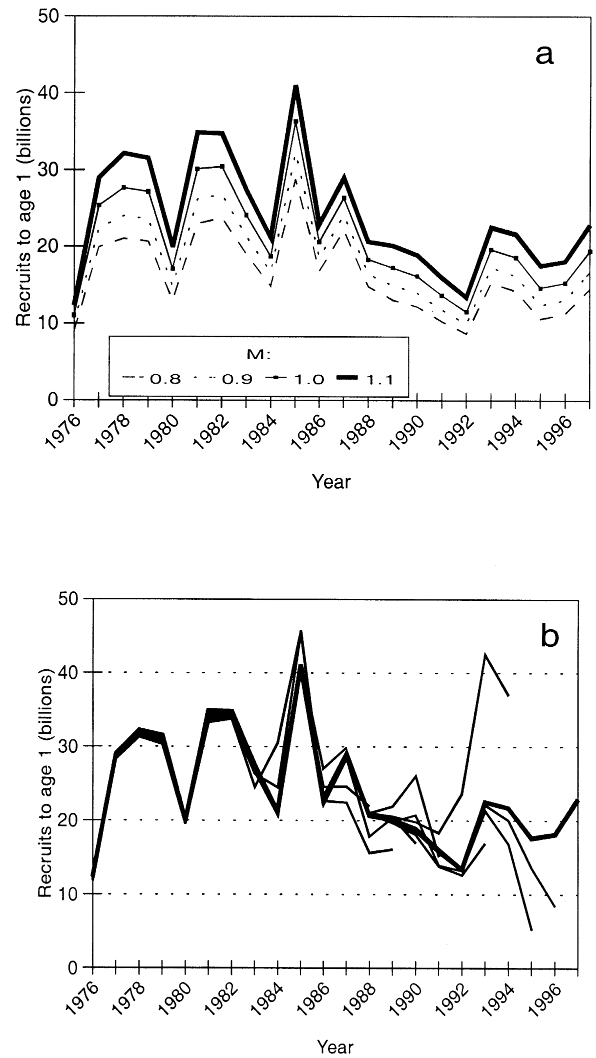

Figure 7

Recruits to age-1 Gulf menhaden (*Brevoortia patronus)* compared by (a) natural mortality (0.8, 0.9, 1.0, and 1.1/yr), 1976–97, and (b) retrospective comparison with decreasing maximum year in catch matrix.

ciruk (1982) (Table 4). Converged estimates of L_∞ ranged from 216 mm to 745 mm in fork length, with a median value of 241 mm and an interquartile range (middle 50%) between 232 and 278 mm. Converged estimates of K ranged from 0.06 to 0.84/yr, with a median value of 0.41 and interquartile range between 0.29 and 0.51/yr. One should note that because of the typically high correlations among the parameters, ranges in estimates of L_∞ and K can give an exaggerated impression of their variability. Biologically extreme values of parameters are still useful for interpolating size at age within the range of ages available for the statistical fit. It is not appropriate to extrapolate sizes at ages beyond those used in the fitting process.

Biological Reference Points for Fishing Mortality

Two modeling approaches are used in estimating biological reference points based on fishing mortality rates, to assess whether recent estimated rates are too high. Reference points from the first modeling approach (yield-per-recruit analysis) have been used for several decades,

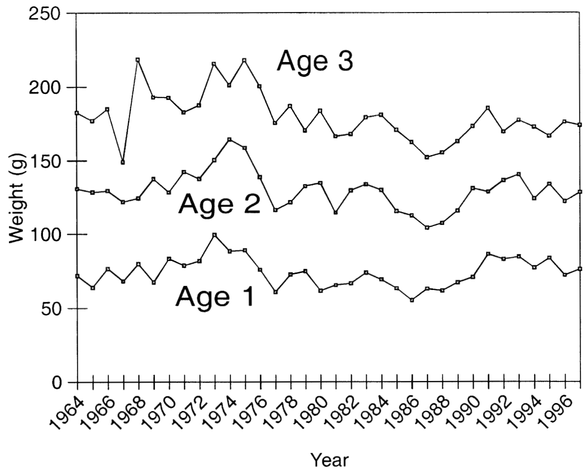

Figure 8
Gulf menhaden (*Brevoortia patronus*) mean weight at age, 1964–97.

Table 3
Weight-length regression parameters (and standard errors) for Gulf menhaden (*Brevoortia patronus*) by fishing year, 1964–97 (ln W = ln a + b ln L). Sample size (n) and mean squared error (MSE) also given.

Fishing year	n	ln a	b	r^2	MSE
1964	12,377	–12.7 (0.04)	3.4 (0.007)	0.94	0.009
1965	15,673	–12.5 (0.03)	3.3 (0.005)	0.96	0.009
1966	12,681	–11.6 (0.03)	3.2 (0.006)	0.95	0.007
1967	14,401	–11.3 (0.03)	3.1 (0.006)	0.94	0.008
1968	15,829	–11.7 (0.03)	3.2 (0.006)	0.95	0.008
1969	15,044	–11.4 (0.03)	3.1 (0.006)	0.95	0.009
1970	10,531	–12.0 (0.04)	3.2 (0.008)	0.95	0.006
1971	7,848	–12.2 (0.04)	3.3 (0.009)	0.95	0.008
1972	9,975	–11.8 (0.04)	3.2 (0.008)	0.94	0.008
1973	8,954	–11.7 (0.05)	3.2 (0.009)	0.94	0.008
1974	10,085	–10.8 (0.04)	3.0 (0.009)	0.92	0.010
1975	9,528	–11.6 (0.03)	3.1 (0.007)	0.96	0.008
1976	13,532	–10.8 (0.03)	3.0 (0.006)	0.95	0.008
1977	14,910	–11.4 (0.02)	3.1 (0.005)	0.97	0.006
1978	12,983	–12.1 (0.03)	3.2 (0.006)	0.96	0.006
1979	11,618	–12.2 (0.03)	3.3 (0.005)	0.97	0.005
1980	9,948	–13.0 (0.05)	3.4 (0.010)	0.92	0.023
1981	10,405	–11.7 (0.03)	3.2 (0.006)	0.96	0.010
1982	10,678	–12.7 (0.04)	3.4 (0.007)	0.95	0.011
1983	14,837	–12.3 (0.03)	3.3 (0.005)	0.96	0.008
1984	15,955	–11.9 (0.03)	3.2 (0.005)	0.96	0.007
1985	13,227	–11.5 (0.03)	3.1 (0.006)	0.95	0.007
1986	16,495	–11.8 (0.02)	3.2 (0.005)	0.97	0.006
1987	16,458	–11.7 (0.03)	3.2 (0.005)	0.96	0.006
1988	12,403	–11.4 (0.04)	3.1 (0.008)	0.93	0.011
1989	13,951	–11.8 (0.03)	3.2 (0.007)	0.95	0.007
1990	11,500	–11.7 (0.04)	3.2 (0.007)	0.95	0.012
1991	11,637	–12.2 (0.04)	3.3 (0.009)	0.93	0.008
1992	15,231	–10.4 (0.03)	2.9 (0.006)	0.94	0.009
1993	15,348	–11.3 (0.04)	3.1 (0.007)	0.93	0.012
1994	16,785	–11.0 (0.03)	3.0 (0.006)	0.95	0.007
1995	14,275	–12.0 (0.04)	3.2 (0.007)	0.94	0.008
1996	12,784	–12.6 (0.05)	3.3 (0.010)	0.90	0.017
1997	10,583	–11.7 (0.03)	3.2 (0.006)	0.96	0.005

while those from the second modeling approach (spawning-stock-biomass-per-recruit) have been used recently by the fishery management councils and commissions. Mean values for growth parameters are used in these modeling approaches to reflect average conditions over a specified time period (e.g., decadal means for both weight-length relationships in Table 3 and length-age relationships in Table 4).

Yield-per-Recruit Analysis

The trade off between decreasing numbers of fish and increasing biomass per average individual fish forms the conceptual basis for yield-per-recruit analysis. The Ricker (1975; eq. 10.4) formulation was used for estimating yield per recruit [this was the basis for MAREA used in previous Gulf menhaden stock assessments (Nelson and Ahrenholz, 1986; Vaughan, 1987)]. Data required includes age-specific estimates of fishing mortality (from VPA) and weight (relationships given in Tables 3 and 4). Yield per recruit for Gulf menhaden was estimated from fishing estimates for 1976–97 (Fig. 9).

Two important biological reference points are typically obtained from this approach: F_{max} and $F_{0.1}$. F_{max} represents the level of fishing mortality which maximizes yield per recruit, while the latter represents the level of fishing mortality where the slope of the increasing yield per recruit curve is 10% of the slope at the origin (Sissenwine and Shepherd, 1987). $F_{0.1}$ was developed because it is more conservative (precautionary) than the former, so as to protect against possible recruitment overfishing. Estimates of F_{max} were not obtained for the Gulf menhaden data because yield per recruit continues to rise with increasing F (>4.0/yr). Estimate of $F_{0.1}$ ranged between 1.4 and 2.5/yr, increasing with increasing M (Table 5).

Annual (fishing year) estimates of yield per recruit (M = 1.1/yr) since 1976 ranged between 9 and 31 g with values generally lower since 1980 (Fig. 9). Yield per recruit declined from an average of 26 g in the late 1970s to 13 g during the 1980s and 1990s. A value of 13 g was estimated for the 1997 fishing year.

Table 4

Estimated von Bertalanffy growth parameters (and asymptotic standard errors) for Gulf menhaden (*Brevoortia patronus*) for fishing years, 1964–97.

Year	n	L_∞	K	t_0
1964	12,261	242.7 (0.81)	0.39 (0.005)	–0.97 (0.017)
1965	15,185	400.8 (7.18)	0.13 (0.004)	–1.81 (0.032)
1966	12,429	278.1 (1.44)	0.29 (0.004)	–1.14 (0.018)
1967	14,065	235.0 (0.80)	0.53 (0.005)	–0.50 (0.009)
1968	15,271	281.0 (1.24)	0.32 (0.004)	–0.79 (0.014)
1969	14,764	473.5 (19.6)	0.10 (0.007)	–2.15 (0.049)
1970	10,402	233.4 (0.97)	0.51 (0.008)	–0.55 (0.014)
1971	7,654	246.2 (0.88)	0.41 (0.006)	–0.85 (0.017)
1972	9,886	223.7 (0.41)	0.65 (0.006)	–0.34 (0.009)
1973	8,953	283.7 (1.93)	0.30 (0.006)	–1.19 (0.026)
1974	10,086	226.0 (0.36)	0.82 (0.006)	+0.02 (0.005)
1975	9,527	745.0 (37.9)	0.06 (0.004)	–2.28 (0.043)
1976	13,389	411.4 (19.7)	0.15 (0.013)	–1.63 (0.093)
1977	14,897	389.2 (7.28)	0.15 (0.006)	–1.52 (0.046)
1978	12,944	397.6 (12.2)	0.12 (0.007)	–2.34 (0.084)
1979	11,121	231.3 (0.48)	0.51 (0.008)	–0.61 (0.028)
1980	9,883	232.1 (0.45)	0.61 (0.006)	–0.04 (0.009)
1981	10,273	241.0 (0.67)	0.41 (0.007)	–0.67 (0.032)
1982	10,341	263.3 (0.99)	0.29 (0.005)	–1.29 (0.037)
1983	14,523	245.9 (0.75)	0.40 (0.006)	–0.85 (0.031)
1984	15,936	241.9 (0.52)	0.44 (0.005)	–0.54 (0.021)
1985	13,225	233.7 (0.65)	0.51 (0.008)	–0.37 (0.022)
1986	16,494	227.7 (0.43)	0.54 (0.006)	–0.18 (0.018)
1987	16,458	262.9 (2.23)	0.27 (0.007)	–1.47 (0.049)
1988	12,402	224.0 (0.78)	0.51 (0.010)	–0.41 (0.029)
1989	13,950	241.1 (1.17)	0.37 (0.008)	–0.94 (0.035)
1990	11,456	234.4 (0.43)	0.44 (0.006)	–0.67 (0.026)
1991	11,378	234.4 (0.73)	0.42 (0.008)	–1.06 (0.043)
1992	14,214	235.0 (0.43)	0.44 (0.006)	–0.87 (0.029)
1993	14,578	246.8 (0.53)	0.34 (0.003)	–1.36 (0.017)
1994	16,062	235.6 (0.44)	0.48 (0.006)	–0.61 (0.022)
1995	13,489	237.6 (0.64)	0.42 (0.007)	–0.94 (0.032)
1996	11,883	215.6 (0.23)	0.84 (0.012)	–0.16 (0.020)
1997	9,879	225.9 (0.40)	0.56 (0.008)	–0.43 (0.025)

Table 5

Biological reference points from yield-per-recruit (Y/R) and spawning potential ratio (static SPR) analyses based on different virtual population analyses (M = 0.8, 0.9, 1.0, and 1.1/yr) for Gulf menhaden (*Brevoortia patronus*). The mean fishing mortality rate (ages 1–4) for the 1990s and 1997 are given for comparison. Decadal (i.e., 1990s) means for growth parameters (weight-length and von Bertalanffy growth function) were used in developing the biological reference points below.

Biological reference point	Natural mortality, M			
	0.8	0.9	1.0	1.1
Mean F for 1990s	0.83	0.77	0.69	0.63
Mean F for 1997	0.77	0.70	0.63	0.57
Y/R: $F_{0.1}$	1.4	1.8	2.1	2.5
Static SPR (biomass):				
F_{20}	1.9	2.1	2.3	2.4
F_{30}	1.2	1.4	1.5	1.6
Static SPR (eggs):				
F_{20}	1.3	1.5	1.7	1.9
F_{30}	0.8	0.9	1.0	1.2

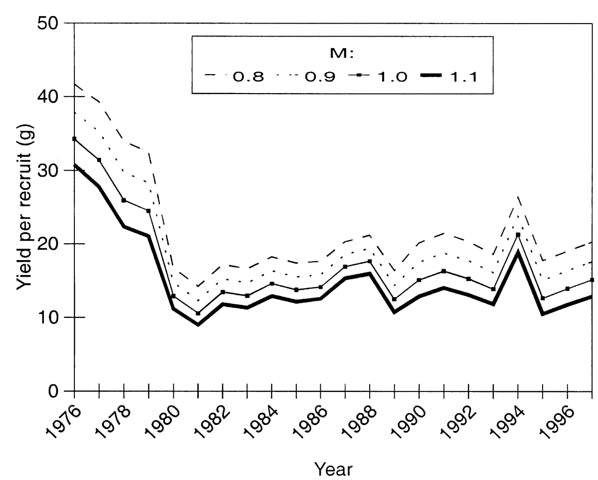

Figure 9

Yield per recruit for Gulf menhaden (*Brevoortia patronus*) compared by natural mortality (0.8, 0.9, 1.0, and 1.1/yr), 1976–97.

Spawning Potential Ratio

Gabriel et al. (1989) refer to the percent maximum spawning potential (%MSP) as the ratio of spawning stock biomass per recruit with and without fishing mortality. This is equivalent to static SPR (Gulf of Mexico SPR Management Strategy Committee, 1996). Hence, the equilibrium spawning stock for an estimated level of fishing mortality is compared to a maximum potential spawning stock for which no fishing had occurred (ignoring adjustments to population parameters through compensatory mechanisms).

Static SPR was calculated in two ways. The first method, described by Gabriel et al. (1989), accumulates mature female spawning stock biomass per recruit across all ages within a fishing year. The second method, described by Prager et al. (1987), accumulates the corresponding number of eggs produced by the mature female biomass, using the fecundity relationship for Gulf menhaden of

Lewis and Roithmayr (1981). A knife-edged maturation schedule of 0% for ages 0 and 1 and 100% for ages 2 and older was used for Gulf menhaden (Nelson and Ahrenholz, 1986).

Spawning stock biomass is calculated annually from the number of adults (ages 2 through 4 on 1 January) times the weight at age calculated from the weight-length (Table 3) and length-age (Table 4) relationships and divided by 2 (assuming a 1:1 sex ratio).

Potential egg production was also estimated as an index of spawners. Estimates of egg production as a function of fish length were obtained from the equation (Lewis and Roithmayr, 1981):

$$\ln(\text{EGGS}) = -9.872 + 3.877 \ln L, \tag{4}$$

where EGGS equals total numbers of eggs produced per female, L equals estimated fork length (mm), $n = 70$, $s_{y.x} = 0.375$ (root mean squared error), and $r^2 = 0.65$. Expected egg production per female of a given age was calculated using Eq. (4) and lengths from Table 4, with retransformation correction. Assuming a 1:1 sex ratio, spawning stock as potential eggs (PE) is calculated by

$$PE = \frac{1}{2}\sum \text{EGGS}_i N_i, \tag{5}$$

where EGGS_i is egg production per female at age i, and N_i is population numbers at age i (ages 2–4 on January 1).

Values of static SPR below 20 or 30 are typically considered evidence of recruitment overfishing for many Exclusive Economic Zone species (Mace and Sissenwine, 1993). Levels of fishing mortality (with M = 1.1/yr) that produce 20 or 30% SPR are summarized in Table 5. Estimates of fishing mortality from additional runs of the separable VPA using lower estimates of natural mortality (M = 0.8, 0.9, and 1.0/yr) were used to estimate the same biological reference points.

Annual estimates of static SPR ranged between 20 and 50% with values generally higher since the late 1970s (Fig. 10). Static SPR (female biomass) varied among an average of 49% during the late 1970s, 48% during the 1980s, and 57% during the 1990s (Fig. 10a). A value of 59% was estimated for the 1997 fishing year. A similar pattern of static SPR was obtained based on egg production, but with lower values (Fig. 10b). These estimates of static SPR varied among a mean of 37% for the late 1970s, 38% for the 1980s, and 49% for the 1990s. A value of 51% was estimated for 1997.

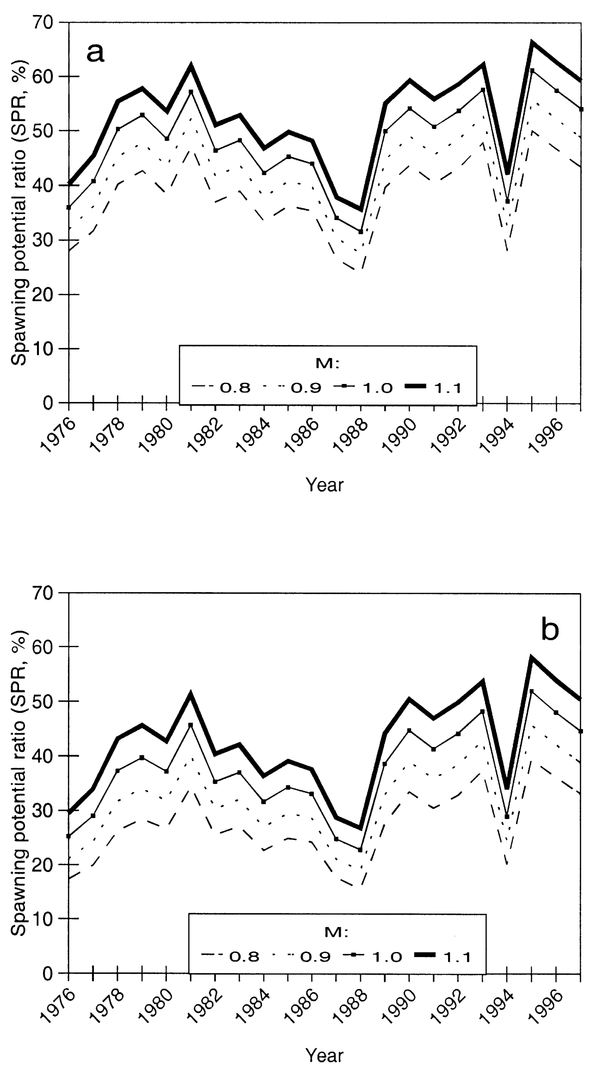

Figure 10

Spawning potential ratio (static SPR) for Gulf menhaden (*Brevoortia patronus*) compared by natural mortality (0.8, 0.9, 1.0, and 1.1/yr) based on (a) female biomass and (b) egg production, 1976–97.

Spawner-Recruit Relationships

An important question in population dynamics and in fisheries management concerns the degree of dependency between spawning stock and the number of subsequent recruits to the stock. If there is no such dependency (except in the extreme; e.g., no spawners implies no recruits), then there is little that a manager can do to control the number of recruits (and hence future stock sizes), other than to assure that there are sufficient spawners to produce subsequent recruits to the population and to preserve the quality of the habitat utilized by the pre-recruit juveniles. If there is a quantifiable relationship between spawning stock and recruits, then management can be designed to maximize the landings or some other objective based on this relationship. To investigate the relationship between spawners and recruits, the Ricker (1954) model was used [see arguments by Nelson and Ahrenholz (1986) for a dome-shaped spawner-recruit relationship].

Estimation of recruits to age 1 was described in the VPA section (Fig. 7) and spawning stock biomass indices in the SPR section. Since 1964, egg production by age-2 spawners has contributed generally greater than 80% to the total spawning egg production (Fig. 11). Note the decreasing trend in dependence on first year spawners (averaging over 90% in the 1960s to about 82% in the 1990s based on egg production).

Spawning biomass based on mature female biomass was on average highest during the 1980s when it averaged 321,900 t, and lowest during the 1960s when it averaged 98,200 t (Fig. 12). Intermediate values were obtained during the 1970s and 1990s when spawning stock biomass averaged 251,200 t and 282,200 t, respectively. A similar pattern was obtained from the index of egg production instead of mature female biomass.

Parameters of the Ricker model were estimated by nonlinear regression (SAS Institute Inc., 1987) from the equation:

$$R = \alpha S\, e^{-\beta S}, \tag{6}$$

where R equals recruits to age 1, S equals spawners (female biomass or potential egg production previous year), and α and β are parameters to be estimated.

Parameter estimates for Gulf menhaden, with spawning stock biomass estimated in 1000 t and recruits to age 1 in millions, resulted in α = 201.6 (standard error = 39.1) and β = 0.00308 (standard error = 0.00066). According to Ricker (1975), maximum recruitment occurs at $\alpha/\beta e$ (or 24.1 billion recruits to age 1) and the spawning stock biomass that will produce maximal recruitment is given by $1/\beta$ (or 324,700 t).

The fit of the Ricker model to the data is poor (Fig. 13), and considerable variability, possibly due to environmental conditions (Goodyear and Christensen, 1984) or measurement error, remains unexplained. Nonetheless, the density-dependence parameter of the Ricker function is significant (H_0: $\beta > 0$; α=0.05), suggesting that the number of future recruits depends nonlinearly on the size of the spawning stock that produced them. The simple model that recruitment is equal to its long-term mean fits the data better than the Ricker model; however, the constant-recruitment model is inconsistent with biological theory and not useful for management. The sizable unexplained variability (Fig. 13) suggests that the Ricker model is of limited use in precisely predicting future recruitment in this stock.

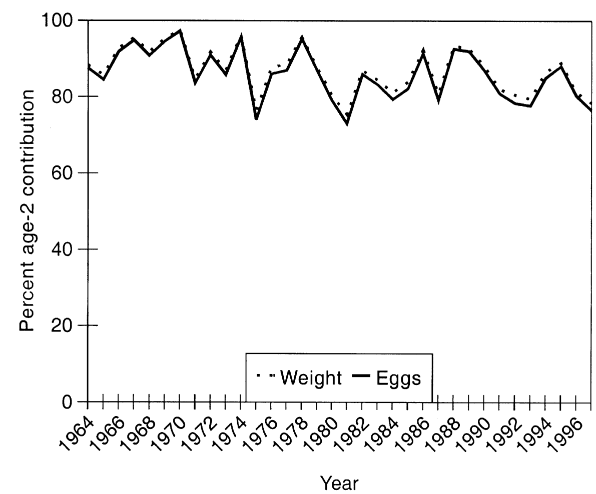

Figure 11
Percent contribution of age 2 Gulf menhaden (*Brevoortia patronus*) based on mature female biomass and egg production, 1964–97.

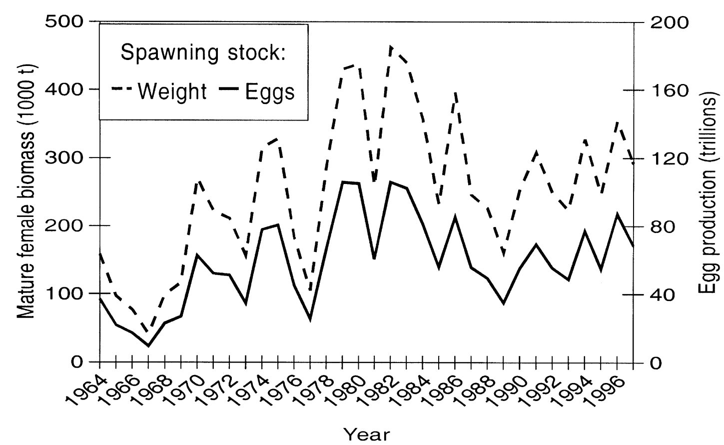

Figure 12
Indices of spawning stock biomass for Gulf menhaden (*Brevoortia patronus)* based on mature female biomass and egg production.

Survival from spawning biomass to recruitment to age 1 can be indexed for 1964–97 by:

$$S_0 = R_1/\mathrm{SSB} \tag{7}$$

where R_1 is recruits to age 1 and SSB is spawning stock biomass for the previous year. The pattern of survival generally varies between 0.05 and 0.15 with two large peaks during 1966–69 and 1976–78. (Fig. 14a). Relative survival (S_r) was calculated by dividing observed survival by predicted survival (S_e; based on Ricker spawner-recruit curve) and rescaling to 0 by subtracting 1 ($S_r = 0$ at $S_0 = S_e$); that is,

$$S_r = (S_0 / S_e) - 1 \qquad (8)$$

Estimates of relative survival suggest that better than expected survival occurred from 1966–69, 1973, 1976–78, 1980–82, 1984, and most recently in 1986 (Fig. 14b). Poorer than expected survival is particularly noted in 1964–65, 1971, 1974–75, 1990–91, and possibly 1994–95. Since recruitment success greatly affects fishing success, it is not surprising that high landings were common during the 1980s when better than expected relative survival occurred and lower during the 1990s when poorer than expected relative survival occurred.

The most recent estimate of spawning stock biomass is 292,100 t (in 1997); this is 32,600 t below the estimate of spawning stock biomass from the Ricker equation which gives maximum recruitment. Mean recruitment during the 1980s (27.2 billion) exceeded the maximum predicted by the Ricker curve by 3.1 billion recruits to age 1. During that time (1980s), spawning stock biomass averaged 321,900 t (or only 2,800 t less than the "optimal" spawning stock biomass). However, because of the large unexplained error remaining from fitting the Ricker curve, the predicted value of 23.9 billion recruits from 292,100 t of spawners has a very large confidence interval (approximate 95% confidence interval is between 15.9 and 34.7 billion recruits to age 1).

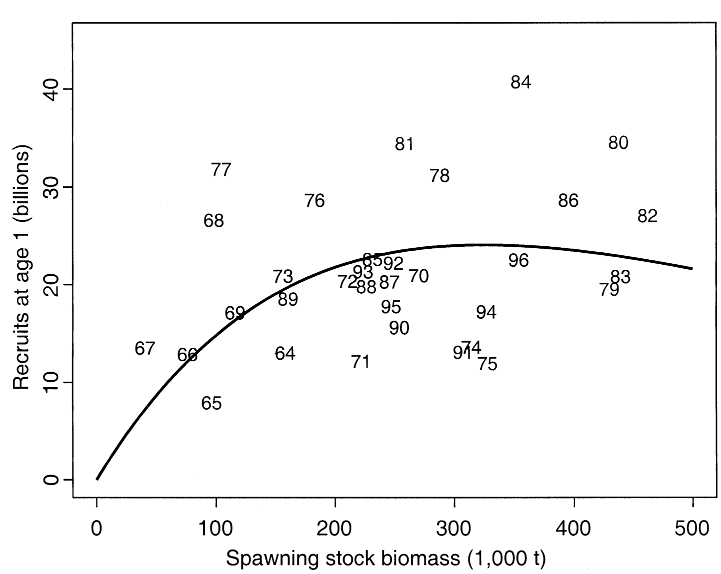

Figure 13

Spawner-recruit relation for Gulf menhaden (*Brevoortia patronus*), 1964–97. Number indicates year of spawning.

Surplus-Production Models

Surplus-production models (Schaefer, 1954, 1957; Pella, 1967; Fox, 1970; Prager, 1994) use data on removals from the stock and relative abundance through time to obtain estimates of maximum sustainable yield (MSY) and related benchmarks. In fitting production models, it is common to use the reported landings to represent removals, under the assumption that landings are a constant fraction of total removals. To index population abundance, the most commonly used measure is catch per unit effort (CPUE), under the assumption (used frequently in fisheries modeling) that CPUE is proportional to abundance.

Under the theory of production models, sustainable yield can be represented by a dome-shaped function of abundance; if stock abundance is in equilibrium, plotting observed landings against effort also gives a dome-shaped curve. Such a curve does not represent the Gulf menhaden data well; this may indicate lack of equilibrium, or the data may lie along the ascending limb of such a curve (Fig. 15).

When using CPUE as an index of abundance, fishing effort rate (E) is assumed proportional to instantaneous fishing mortality rate (F). Specifically, the catchability coefficient (q) is assumed to be constant in the following equation:

$$F = qE, \qquad (9)$$

where the unit of fishing effort, E, for Gulf menhaden is defined as vessel-ton-weeks. As noted in Nelson and Ahrenholz (1986), unadjusted fishing effort (nominal effort) is not a reliable index of fishing mortality rate for menhaden. The difficulty in directly obtaining a reliable unit of fishing effort results from the schooling nature of clupeid fishes, which at small population sizes are relatively more susceptible to fishing effort [see discussion of "dynamic aggregation process" in Clark and Mangel (1979)]. The resulting concern is that severe stock depletion could occur before being detectable from an analysis of landings and nominal CPUE data.

To determine whether the catchability coefficient, q, for Gulf menhaden is constant or dependent upon population size, it was estimated by solving Eq. (9) for $q (= F/E)$ for each fishing year since 1964 and compared with

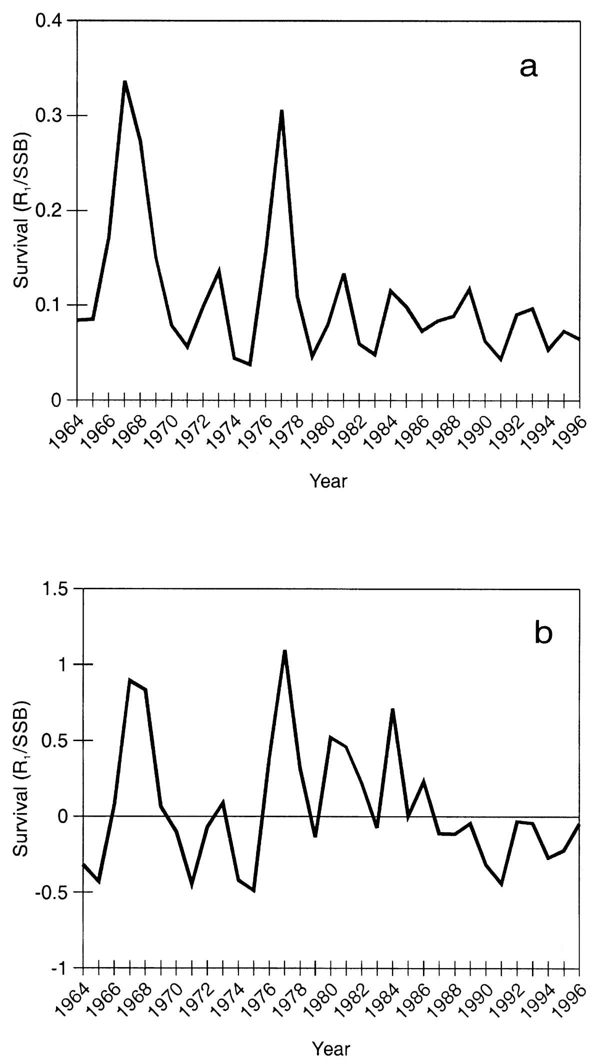

Figure 14
Indices of (a) observed and (b) relative survival for Gulf menhaden (*Brevoortia patronus*) based on recruits to age 1 divided by spawning stock biomass, 1964–96. Relative survival adjusted by expected survival from Ricker spawner-recruit relationship.

the population biomass (ages 1–4) for the same fishing year (Fig. 16; F and population biomass estimates were from VPAs for ages 1–4). As noted in Nelson and Ahrenholz (1986), there is a pronounced inverse relationship between the catchability coefficient and population biomass.

A measure of fishing effort proportional to fishing mortality rate F is referred to as "effective effort." To adjust nominal fishing effort to account for variations in q, the 1964 value of $q(q_a)$ was used to adjust nominal effort (E) so that E' is proportional to F; i.e.,

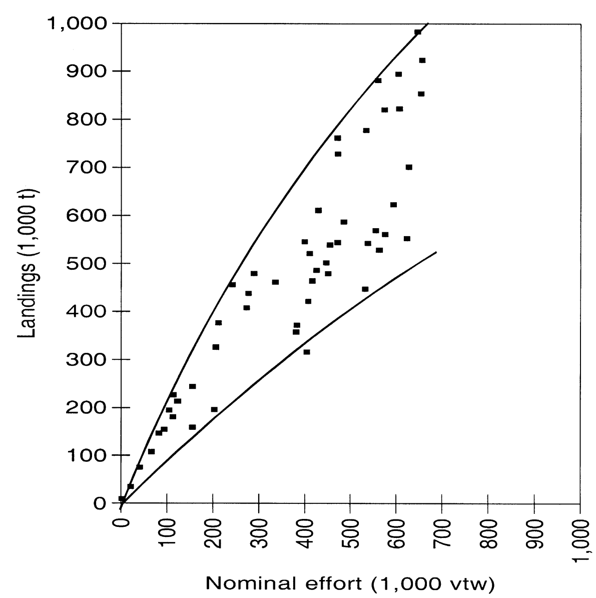

Figure 15
Gulf menhaden (*Brevoortia patronus*) landings plotted against nominal fishing effort (vessel-ton-weeks), 1946–97.

$$E' = Eq_t / q_a, \tag{10}$$

where E' is a unit of effective fishing effort and q_t is the catchability coefficient in that year, normalized to the catchability coefficient in 1964 (Fig. 17). Note that while nominal effort was increasing from 1964 through the mid-1980s, effective effort remained low. A CPUE index derived from effective effort is frequently referred to as adjusted CPUE.

Two varieties of production model were fit to data on Gulf menhaden. The computer program PRODFIT (Fox, 1975), which attempts to account for nonequilibrium conditions through a smoothing process, was used to estimate parameters (and MSY) for the Pella-Tomlinson generalized production model (Pella and Tomlinson, 1969):

$$U = (A + BE')^{1/(m-1)} \tag{11}$$

where U is catch per unit of effort, and A, B, and m are parameters to be estimated. In using PRODFIT, reported landings and effective effort, as estimated above, were used, and two ages were assumed to contribute to the landings (Fig. 2). Parameter estimates and associated square root of the variability index (Fox, 1975) were estimated using landings and effective effort for 1964–97: A = 2.14 (1.26), B = –0.0031 (0.0035), m = 1.33 (0.90), MSY = 717,200 t (32,000 t), and f_{MSY} = 171,400 vtw (20,600 vtw) (Fig. 18). Although effort in 1997 was 430,200 vtw, it was only 118,000 vtw in terms of 1964 equivalent units of effort. Estimated f_{MSY} has only been exceeded once during the 1990s (in 1994), four times during the 1980s, six times during the 1970s, and exceeded in all years from 1964–69.

The second production modeling approach was the non-equilibrium production model described by Prager (1994) and implemented in the ASPIC computer program (Prager, 1995). The models described were fit to the observed landings data and the effective CPUE data derived in Eq. (10), above.

The model used (Prager, 1994) is an extension of the logistic Schaefer (1954, 1957) model and uses a fitting procedure similar to that developed by Pella (1967) and later used by Pella and Tomlinson (1969) in their GENPROD computer program. The model makes no equilibrium assumption, but rather represents the population as a dynamic quantity of biomass subject to removals (fishing) and net biological production (the surplus of growth and recruitment over natural mortality). In fitting, an observation-error estimator is used, conditioned on yield and assuming lognormal error in the adjusted CPUE index, which is mathematically equivalent to assuming lognormal error in E'.

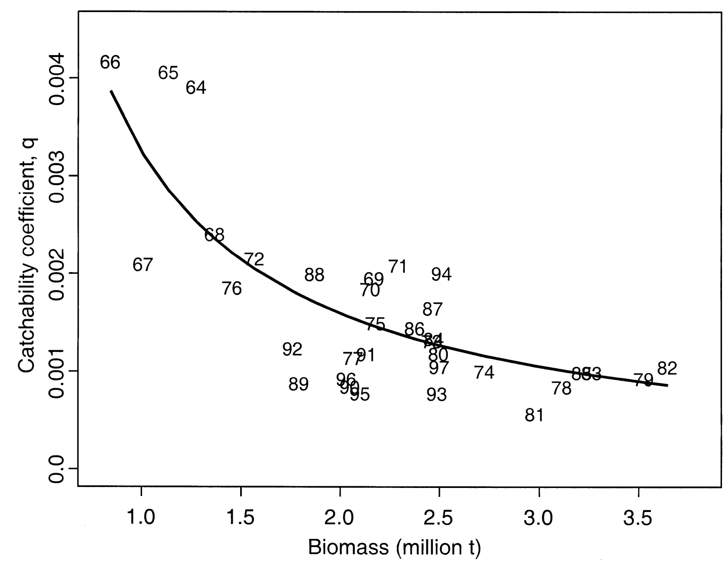

Figure 16

Catchability coefficient (q) versus estimated population abundance for Gulf menhaden (*Brevoortia patronus*), 1964–97. Number indicates year.

The ASPIC run for Gulf menhaden, which used the estimated effective effort series for 1964–97, estimated MSY = 752,700 t and f_{MSY} = 196,900 vtw (and $f_{0.1}$ = 177,200 vtw). R^2 for this model was 0.542. A plot of annual fishing mortality rate relative to that fishing mortality rate producing MSY is shown in Fig. 19a; while a plot of population biomass relative that population biomass producing MSY is shown in Fig. 19b. If relative biomass (B/B_{MSY}) is below 1, the stock is depressed (whether from natural phenomena or overfishing) and cannot provide MSY; if the relative F (F/F_{MSY}) is above 1, the rate of fishing mortality is above that which can provide MSY, and if continued through time will result in a stock size below $B_{MSY.}$ In the 1960s and late 1980s, relative F was significantly above 1, while relative biomass was significantly below 1 only in the 1960s. In recent years, relative F was significantly below 1, while relative biomass was significantly above 1.

Both methods of surplus production modeling agree as to when the stock was in good condition and the fishing rates were in acceptable ranges. Also, both estimated MSY and F_{MSY} are at about the same levels.

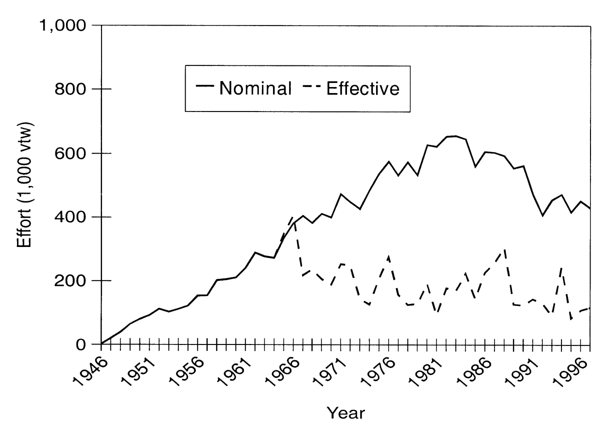

Figure 17

Gulf menhaden (*Brevoortia patronus*) nominal and effective fishing effort from reduction fleet, 1964–97. Nominal fishing effort only is shown for 1946–63.

Juvenile Abundance Indices and Environmental Factors

Attempts have been made to relate estimates of juvenile abundance to subsequent year class strength of menhaden. For example, Ahrenholz et al. (1989) were unable to relate Gulf menhaden juvenile abundance from a gulf-wide surface-trawl survey conducted by the NMFS Beaufort Laboratory to VPA estimates of recruits to age 1 during 1971–78. However, for this assessment two juvenile Gulf menhaden data sets were investigated as potential indices of year class strength (i.e, recruitment): trawl data

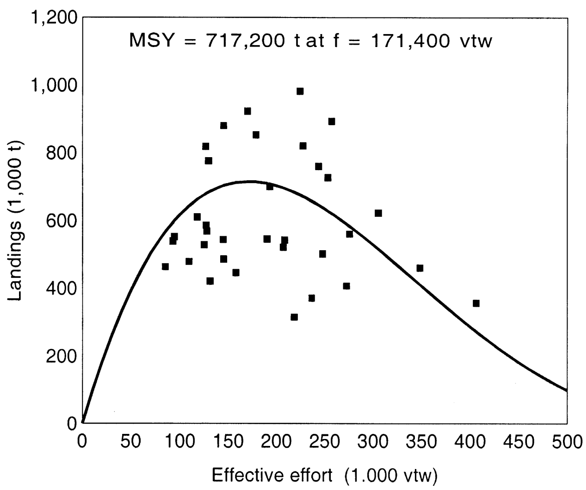

Figure 18
Generalized surplus production model (PRODFIT) for Gulf menhaden (*Brevoortia patronus*) using reduction landings and effective fishing effort, 1964–97.

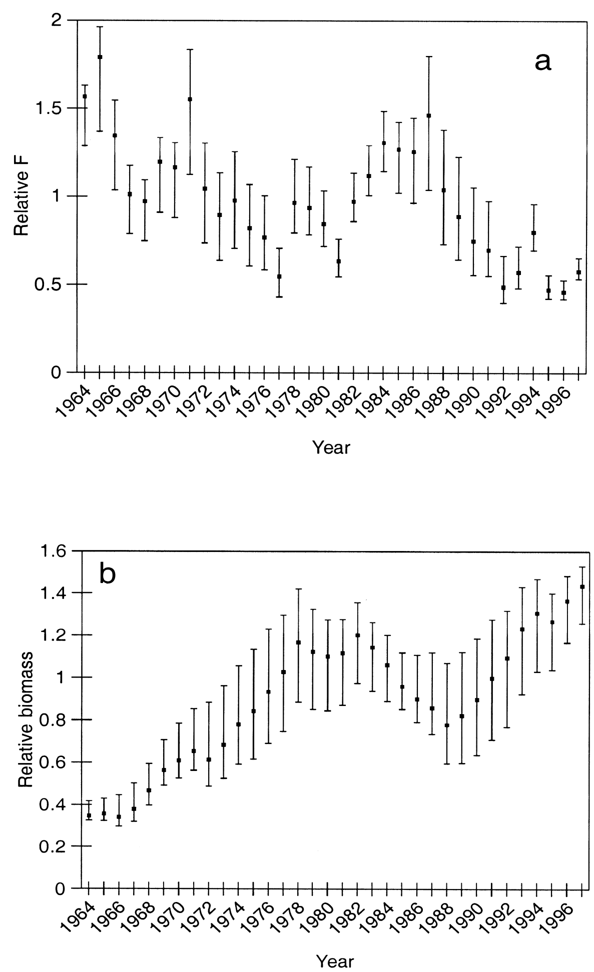

Figure 19
Plots of (a) relative fishing mortality (F/F_{MSY}) and (b) relative biomass (B/B_{MSY}) from ASPIC production model for Gulf menhaden (*Brevoortia patronus*), 1964–97.

from Louisiana and bag seine data from Texas. In addition, several environmental factors were investigated that may contribute to recruitment success; these included Mississippi River flow, indices of El Niño (e.g., NINO 3.4 Anomaly), North Atlantic sea surface temperature (SST), and North Atlantic Oscillation (NAO). These juvenile indices and environmental variables are compared to VPA estimated recruitment to age 0 (approximately 6 months of age). Recruits to age 0 for a given year are equal to recruits to age 1 for the following year times $e^{0.55}$. Estimates for recruits to age 1 are from the VPA using the catch matrix with ages 1–4 and years 1976–97 (providing estimates of age 0 recruits for 1975–96). All time series in this section are normalized by subtracting the series mean and dividing by the series standard deviation, prior to any statistical comparison.

Louisiana Trawl Juvenile Abundance Index

Juvenile abundance data for Gulf menhaden were obtained from otter trawl samples collected by Louisiana Department of Wildlife and Fisheries (LDWF) from 1966 through 1997. As described in Guillory (1993): "Samples were taken weekly or biweekly throughout the year at selected stations across the coast. The otter trawl measured 4.9 meters (m) in length with 19.1 mm bar mesh wings and 6.4 mm bar mesh tail. Samples consisted of ten-minute tows at speeds of approximately three knots."

Sampling locations, or Coastal Study Areas (CSA), from east to west are as follows: 1) Lake Borgne/Pontchartrain, 2) Breton Sound, 3) Barataria Bay, 4) Timbalier/Terrebonne Bay, 5) Caillou Lake/Lake Mechant, 6) Vermilion Bay, and 7) Calcasieu Lake. Coastal areas 1B4 (deleting CSA 3 - Barataria Bay) and 5B7 were combined into two groups, respectively. Based on availability of young menhaden, we used data from March through August.

Three types of juvenile abundance indices were computed by two area groups and coastwide for Gulf menhaden: presence/absence, catch per effort (CPE), and retransformed General Linear Model (GLM). The GLM was based on ln(count+1) as the dependent variable with year, season (nested in year), area, and station (nested in area) as class variables. This model was run outputting least squares mean (SAS Institute Inc., 1987) by year as index of juvenile abundance. Coastwide esti-

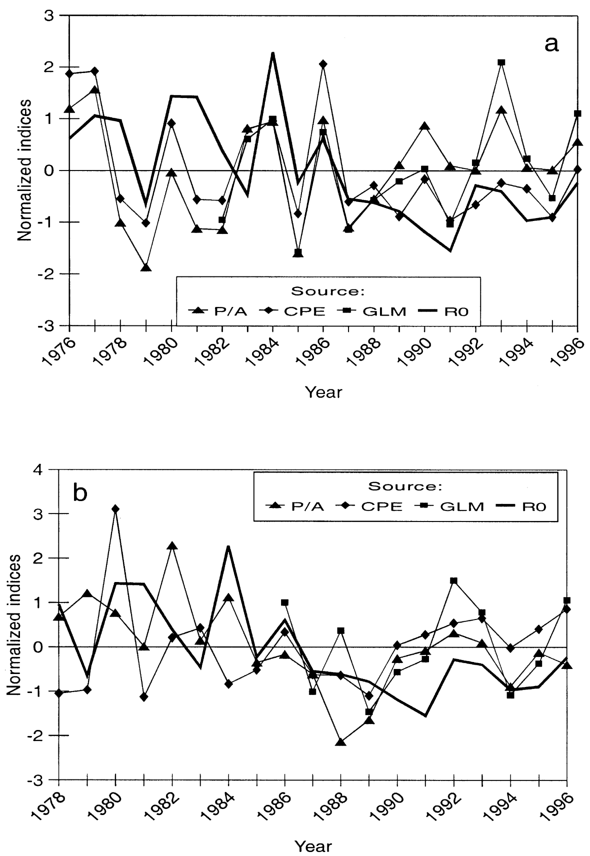

Figure 20

Comparison of normalized half-year-old Gulf menhaden (*Brevoortia patronus*) recruits (R_0) with normalized juvenile abundance indices calculated from presence-absence (P/A), catch per unit effort (CPE), and general linear model (GLM) from (a) Louisiana trawl data and (b) Texas bag seine data.

mates of the three index types are compared to the estimate of recruits to age 0 (six months of age) (Fig. 20a).

Correlations between the two Louisiana area groups using the three indices from each area group were mostly non-significant ($P<0.057$ for group 1 CPE vs group 2 retransformed GLM). Both groups were correlated with the coastwide indices. The CPE index from area group 2 (western CSAs) and coastwide showed strong correlation with recruits to age 0 (r = 0.65 and 0.56, respectively, both significantly different from 0).

Texas Bag Seine Juvenile Abundance Index

Juvenile abundance data for Gulf menhaden were obtained from bag seine samples collected by Texas Parks and Wildlife Department in nine coastal bays from 1978 through 1997. Bag seines are "18.3 m long, 1.8 m deep with 1.3-cm stretched nylon multifilament mesh in the 1.8 m wide central bag with remaining webbing 1.9-cm stretched mesh" (Dailey et al., 1991). Details on sampling frequency and procedures for bag seines are given in Dailey et al. (1991; p. 2). Each sample covered about 0.03 h per tow of surface area. Additional environmental information was collected prior to each bag seine sample (water temperature, surface salinity, dissolved oxygen, and turbidity).

The major sampling areas from east to west are as follows: 1) Sabine Lake, 2) Galveston Bay, 3) East Matagorda Bay, 4) Matagorda Bay, 5) San Antonio Bay, 6) Aransas Bay, 7) Corpus Christi Bay, 8) Upper Laguna Madre Bay, and 9) Lower Laguna Madre Bay. The analyses that follow emphasize the four eastern most areas for March through September, with sampling commencing in East Matagorda Bay in February 1983 and in Sabine Lake in January 1986.

As with the Louisiana trawl data, three types of juvenile abundance indices were computed by area and for the northern group for Gulf menhaden: presence/absence, CPE, and retransformed GLM. The GLM was based on ln(count+1) as the dependent variable with year, season (nested in year), area, and station (nested in area) as class variables. This model was run outputting LSMEANS by year as index of juvenile abundance. Coastwide estimates of the three index types are compared to the estimate of recruits to age 0 (six months of age) (Fig. 20b).

Using the three indices from each area group, some significant correlations among the western Louisiana area group and the eastern Texas group were found. Greatest significance was shown with the western Louisiana group ($P<0.045$ for P/A and $P<0.010$ for CPE). The P/A and retransformed GLM indices for the eastern Texas group showed strongest correlation with recruits to age 0 (r = 0.57 and 0.52, respectively, both significantly different from 0).

Environmental Relationships

Several environmental variables are briefly investigated in this section as they may relate to Gulf menhaden recruitment success or failure. Changes in weather patterns and introduction of pollutants can have significant effects on Gulf menhaden survival. Patterns in survival to recruitment have been investigated relative to spawning stock earlier in this report. Govoni (1997) has demonstrated an inverse relationship between changes in Mississippi River flow with changes in Gulf menhaden recruitment to age 0. We have updated the data used by Govoni through 1997. We continue to note a significant inverse relationship (r = –0.46, $P < 0.008$) between 1-yr change in river flow with 1-yr change in recruitment success (Fig. 21).

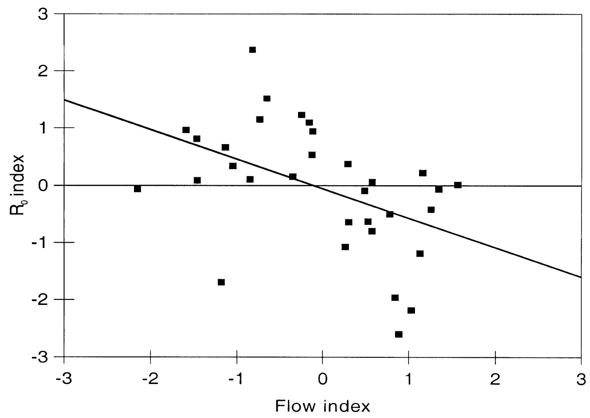

Figure 21
Normalized difference in combined average monthly discharge rates of the Mississippi and Atchafalya rivers (m^3/S) and normalized differences in the number of half year old Gulf menhaden (*Brevoortia patronus*) recruits (R_0) (r=–0.46, P<0.008) (updated for 1991–97 from Govoni, 1997).

That is, if river flow declines from one year to the next then recruits to age 0 are likely to increase (and vice versa).

Because river flow is greatly affected by weather patterns such as El Niño (i.e., NINO 3.4 anomaly), North Atlantic sea surface temperature (SST), and the North Atlantic Oscillation (NAO), intercorrelations among these variables and Gulf menhaden recruits to age 0 were investigated. El Niño refers to a warming pattern in the eastern equatorial Pacific (Cane, 1983). SST index values and anomalies (i.e., NINO 3.4 from NOAA Climate Prediction Center (NCEP))[1] were available monthly from 1950–97. An index of North Atlantic SST (5–20 N, 60–30 W) was available monthly for 1950–97 from this same web site. The NAO index, which refers to sea-level pressure changes based on the normalized pressures between Lisbon, Portugal, and Stykkisholmur, Iceland, was obtained from Hurrell[2]. Winter indices (December–March) based on the NAO have been related to long-term variations in climate (Hurrell, 1995, 1996; Hurrell and van Loon, 1997). Normalized indices were correlated among themselves and with normalized Gulf menhaden recruits to age 0.

Mississippi River flow correlated well with the North Atlantic SST and NAO (P<0.006 and P<0.020, respectively), but not with NINO 3.4 anomaly (P<0.90). NINO 3.4 anomaly correlated weakly with North Atlantic SST (P<0.09), and North Atlantic SST correlated well with NAO (P<0.005). But none of these indices showed any significant correlation with Gulf menhaden recruits to age 0. One-year differences (lagged) in these indices showed significant correlations among Mississippi River flow, North Atlantic SST and NAO, with only differences in river flow correlating with differences in recruits to age 0 as noted above (P<0.008).

Management Implications

The Gulf menhaden fishery is conducted within the territorial sea and offshore of five coastal states (Florida to Texas). All states, except Florida, enacted the cooperative management plan under the Gulf States Marine Fisheries Commission (GSMFC) in 1977 (Christmas and Etzold, 1977). The plan was revised in 1983, 1988, and 1995 (Christmas et al., 1983, 1988; Leard et al., 1995), and was revised again during 2000. Because management authority is vested in the individual states, some regulations are area-specific on a state or county basis, but other regulations, such as length of fishing season (mid-April through 1 November), are common to all states, except Florida. The extension of the fishing season through 1 November (previously mid-October) was adopted by the GSMFC at their March 1993 annual meeting. No state controls or limits the catch or fishing effort of vessels.

Landings and nominal effort were quite high during the 1980s, but have declined precipitously during the late 1980s and early 1990s. Landings peaked in 1984 with 982,800 t, while nominal fishing effort peaked in 1983 with 655,800 vessel-ton-weeks. Most recently (1997), landings were 611,200 t with 430,200 vessel-ton-weeks. Landings between 1982 and 1987 were very high, exceeding estimates of long-term MSY, but were supported by generally high recruitment to age 1. More recent landings (421,400 to 761,600 t) are comparable to, or somewhat below, recent estimates of MSY (717,000 to 753,000 t based on the PRODFIT and ASPIC estimates of surplus production). Vaughan (1987) noted an upward trend in historical estimates of MSY, which was no longer maintained in this or the previous assessment.

Relative survival index suggests that recent estimates of recruits to age 1 are below what would be expected based on the Ricker spawner-recruit relationship between spawning stock biomass and recruits to age 1. This relatively poor survival should be viewed in the context that while spawning stock biomass was generally rising from 1989 to 1997 (161,000 t to 292,100 t), recruits to age 1 have fluctuated without apparent trend (13 to 23 billion during the 1990s).

Recent estimates of fishing mortality (for M = 1.1/yr) compare favorably with the different estimates of biological reference points. Recent estimates of F (ages

[1] Web site URL: http://nic.fb4.noaa.gov/data/cddb/

[2] Hurrell, J. W. 1998. National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307. Personal commun.

1–4) are below $F_{0.1}$ for the range of natural mortality (M) considered in this assessment. For the preferred natural mortality value of 1.1/yr (based on tagging), mean of the estimates of F (ages 1–4) is 0.6/yr. This value compares favorably with $F_{0.1}$ of 2.5/yr, F_{20} between 1.9 and 2.4/yr, and F_{30} between 1.2 and 1.6/yr. When lower estimates of natural mortality (M) are assumed, then the estimated biological reference points decrease while estimates of fishing mortality increase. For M of 0.8/yr, recent estimates of F (mean of 0.8/yr for 1990–97) are below estimates of $F_{0.1}$ (1.4/yr), F_{20} (1.3–1.9/yr), and F_{30} (0.8–1.2/yr). Only the biological reference point for F_{30} based on egg production is about equal to the mean F for the 1990s. The retrospective pattern observed in current-year estimates of F indicates that it takes several years of observation for estimates of F to be known with good precision, which implies that management actions based on recruitment would be made under considerable uncertainty.

Recent estimates of relative F (F/F_{MSY}) and relative biomass (B/B_{MSY}) from the ASPIC fits to the Schaefer surplus production models suggest that recent fishing mortality is low and biomass is high relative to F_{MSY} and B_{MSY}, respectively.

Our original intent had been to use juvenile abundance indices obtained from Louisiana and Texas to calibrate the Gulf menhaden VPA. Unfortunately, unstable results were obtained from FADAPT (Restrepo, 1996), while the limited number of ages precluded use of XSA (Darby and Flatman, 1994) or ICA (Patterson and Melvin, 1995). Further exploration of calibration approaches is needed.

In summary, Gulf menhaden have higher natural mortality and are shorter lived than Atlantic menhaden, and as a result there are rapid annual changes in the Gulf menhaden fishable stock. The Gulf menhaden fishery is currently fully exploited and the population appears reasonably stable in view of the age composition, life span, and effects of environmental factors. Annual production, fishing effort, and fleet size appear reasonably balanced and risk of overfishing low with 1997–98 fleet size and recent mean recruitment. Given the variability in the data and model estimates, recent landings below long-term MSY (and well below high landings of the mid-1980s) suggest that the stock appears reasonably stable.

Acknowledgments

The authors wish to acknowledge the many past and present employees of the Southeast Fisheries Science Center, Beaufort Laboratory, who were involved in the many aspects of the menhaden data collection program, especially Ethel Hall, Eldon Levi, and Dean Ahrenholz. We also wish to thank Vince Guillory (Louisiana Dept. of Fish and Wildlife) and George Lewis and Jerry Mambretti (Texas Parks and Wildlife Dept.) for providing Gulf menhaden juvenile data from Louisiana trawl and Texas bag seine surveys, respectively. We also thank Jeff Govoni for his guidance in updating river flow data from the U.S. Corps of Engineers, and the U.S. Corps of Engineers for providing river flow data. We thank Dean Ahrenholz, James Waters, and John Merriner for reviewing the manuscript.

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