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Stock Characteristics of Hudson River Striped Bass

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Abstract.—Striped bass, because of their tremendous popularity both commercially and recreationally, were a principal focus of the Hudson River power plant case. Between 1976 and 1979, over 23,000 age-II and older striped bass were studied as one facet of an extensive research program on the spring population in the Hudson River. Samples were collected from the overwintering as well as the spawning portion of the striped bass population, and included immature as well as mature fish. At least 12 age-groups contributed to spawning each year (some fish live to 18 years of age). Of these 12, age-groups III, IV, and V usually were most abundant, but the percentage of the population represented by any single age-group varied as the result of fluctuations in year-class strength. The 1973 year class was the strongest in recent years. Males first became sexually mature at age II and females at age IV. Fast-growing individuals within a year class tended to mature earlier. Fecundity increased with the size of fish, reaching an observed maximum of about 3 million eggs per female. The Schumacher–Eschmeyer population estimate for the 1979 population (slightly over 250,000 fish) was the largest during the interval 1976–1979. Although significant annual variations in maturity and growth were detected for Hudson River striped bass, there was no evidence of a consistent change in either variable that might be associated with increasing power plant operations (over 3,700 MW of electrical generating capacity came on-line during 1974–1976) and a reduction in striped bass abundance. Age at maturity and age structure are the two life history components that differ the most between the Hudson River population and other striped bass populations.

Striped bass, because of their commercial and recreational importance, were a principal focus of the Hudson River power plant case. The Hudson River produces 5–30% of the striped bass that enter the Atlantic coastal fishery (Van Winkle et al. 1988, this volume); only the Chesapeake Bay system contributes more. Commercial catches of striped bass reached 6,700 tonnes in 1973, of which 790 tonnes were taken in New York State, though harvests declined nearly 90% through 1983 (MAFMC 1984). Since the Marine Recreational Fishery Statistics Survey began in 1979 (NMFS 1984), Atlantic coast marine anglers have caught a further average of 263 tonnes through 1985 (MAFMC 1988).

Since the 1930s, when Merriman (1941) began his landmark study, the coastal stocks of striped bass have shown large-amplitude cycles of abundance due to irregular recruitment of strong year classes, excessive mortality within other year classes, or both. The last strong year class in the Atlantic fishery was produced in 1970. Reasons for the subsequent decline of the stocks are not fully understood, but because striped bass are anadromous and rely on the upper reaches of estuaries, including the Hudson estuary, for their reproduction, human perturbations of the environment have been cited frequently as contributing factors. Conservationists were particularly alarmed by the planned development of nuclear and conventional power plants along the Hudson River because of perceived threats to young striped bass and other species that might be entrained and killed in the large volumes of cooling water the plants would withdraw from the river. It was their concern, reflected by federal regulatory agencies, that stimulated extensive research on Hudson River fish during the 1970s.

Others have presented direct estimates of entrainment and other mortality imposed on larval and young juvenile striped bass (Muessig et al. 1988; Boreman and Goodyear 1988, both this volume). Here, we focus on the population of age-II and older striped bass in the Hudson River prior to and during the spawning period. Because of its role in producing subsequent generations, the adult population of fish can offer indirect evidence of the long-term effects of power plants

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and other environmental stresses on the species' well-being.

Most of what is now known about adult Hudson River striped bass (MMES 1987) was learned during the power plant studies that began in the late 1960s. Some of this information has been published, including the relative contribution of the Hudson stock to the coastal fisheries (Berggren and Lieberman 1978), the biology of juvenile striped bass (Klauda et al. 1980), movements of adults (McLaren et al. 1981), diet (Gardinier and Hoff 1982), reproductive effort (Young and Hoff 1988), the commercial fishery within the Hudson River (McLaren et al. 1988), and some stock characteristics from a limited sampling of the commercial fishery (Dew 1981). In this chapter, we address the age structure, size, maturity, and spawning potential of adult striped bass in the Hudson River.

Methods

Field collection.—Striped bass were collected annually by gill nets and haul seines as soon as the Hudson River became free of ice (approximately mid-March), and collecting continued until catches became greatly reduced (late June). Gill nets were tended around the clock for 4–6 d/week. The location of gill nets changed weekly to maximize the catch and to follow the bulk of the population as it moved. Sampling was concentrated in the vicinity of the Tappan Zee Bridge and Haverstraw Bay in the spawning season (March and April), upriver into and above the Indian Point area as the season progressed (May), and downriver (June) at the end of the spawning season. Overall, gill-net sampling was restricted to the 57-km reach from approximately the Tappan Zee Bridge to the Newburgh–Beacon bridge (see Figure 1). The spawning migration of striped bass generally begins in the Hudson River estuary around the third week in April (McLaren et al. 1981). Peak spawning usually occurs in mid-May when water temperatures are approximately 14°C (Klauda et al. 1980). Spawning activity ranges from Croton Point to Coxsackie but appears to be concentrated just upriver of West Point (Kahnle and Brandt 1985). Following spawning, most adults leave the estuary (McLaren et al. 1981) and some apparently join the coastal migratory stock. —Anchored 91-m gill nets were set in two clusters, each containing at least four nets of different standard stretched-mesh sizes (10.2, 11.4, 12.7, and 15.2 cm in 1976; 10.2, 12.7, 15.2, and 17.8 cm in 1977–1979). Two to four additional nets were usually fished per cluster. A net cluster usually spanned 2–10 km of the river, and mesh sizes were placed randomly within the clusters.

To alleviate and characterize the biases in the information collected by gill-net sampling and to gain a greater understanding of the characteristics of the striped bass, a haul seine also was used. Haul (beach) seines are less size-selective in the fish they catch than gill nets. (This gear is important in the work of several current striped bass researchers [Kahnle and Brandt 1985; Young 1986] and the cornerstone of the coastwide adult stock monitoring program begun by the Atlantic States Marine Fishery Commission in 1987 [B. H. Young, New York Department of Environmental Conservation, personal communication].) A 274-m haul seine was used to sample beaches primarily within Haverstraw Bay; on occasion, a 61-m haul seine was used to sample areas inaccessible to the larger net.

The catch of commercial fishermen, contracted to fish 2 d/week with their own fishing gear and techniques, was used to supplement each year's data on body length and weight, maturity, and fecundity. Each fisherman was accompanied by study personnel when he tended nets. The commercial gear consisted of 23–439-m-long staked, anchored, or drift gill nets of 11.4–35.6-cm stretched mesh. Four fishermen with relatively constant fishing locations were employed per year (McLaren et al. 1988).

All striped bass were measured to the nearest millimeter total length and scale samples were removed for age analysis. Annuli on the scales, which are the basis for aging the fish, are laid down in late spring or early summer (MMES 1987); however, fish were conventionally promoted to the next age-group on 1 January. Size-stratified subsamples of fish were further analyzed for determination of weight, sex, maturation state, and fecundity. The remaining fish that were active and in good physical condition were marked with nylon internal anchor tags (Floy D-67c) and released at least 100 m from the capture location.

Age composition.—The migratory nature of striped bass and the size selectivity of sampling gear, particularly gill nets, presented a challenge for accurate estimation of the stock's age composition. Our analytical approach was to assess the age structure of the population during the 6 weeks from approximately mid-April through late May, a period just prior to and including the time of spawning (Boreman and Klauda 1988, this volume). We relied on both the haul-seine and non-commercial gill-net data obtained from a region where both types of gear were fished concurrently, the Tappan Zee and Croton and Haverstraw bays. To minimize the bias introduced by the size selectivity of gill nets (Hamley 1975), only the catch from the 274-m haul seines was used to describe size composition. Gill-net data, however, provided information on the age and sex of fish of specified sizes once the catch was partitioned into 20-mm total length (TL) intervals. With this approach we assumed that the bias in age or sex that might be related to size selectivity within each 20-mm interval would be low. —Age and sex proportions for striped bass larger than 200 mm TL were calculated by:

$$P_{jk} = \frac{\sum_{i=1}^{m} C_i \left(\frac{N_{ijk}}{T_i}\right)}{\sum_{i=1}^{m} C_i};$$

P_{jk} = proportion of population for fish age j (j = 1, 2, . . ., l) and sex k;

C_i = total number collected in length interval i (i = 1, 2, . . ., m);

N_{ijk} = number of fish of length i, age j, and sex k in the combined haul-seine–gill-net catch;

T_i = total number of fish subsampled for age and sex in length interval i.

The proportions (P_{jk}) were considered the most reliable representations of the sex and age composition of the population falling within each 20-mm interval, because they included fish caught both in the shore zone (less than 3-m depths) by haul seines and in the shoals (3–6-m depths) by gill nets. Each of these proportions was weighted by the fraction of the 274-m haul-seine catch (C_i) that represented the least size-selective estimate of relative abundance of that 20-mm length grouping in the river.

Maturity.—Maturity was determined from striped bass collected in haul seines and gill nets (including commercial gear) over the entire sampling region during mid-March through June of each year. Catches were sampled on a stratified basis, biweekly sampling period, length, and sex being the strata.

All fish were classified by inspection into four groups: obviously mature (eggs developed in females, milt running in males); obviously immature (gonads undeveloped); indeterminable maturity; and spent (most of eggs or milt gone). Obviously mature and immature fish were then used to calculate a total-body-weight:gonad-weight ratio that could be used as a criterion for separating mature from immature fish; spent fish were not used in this calculation. Fish in the indeterminable category and those visually classified as mature and immature then were reclassified on the basis of their individual total-body-weight:gonad-weight ratios. All spent fish were added to fish classified as mature by the weight-ratio method, and the overall percentage of mature fish in each age-group was calculated.

Fecundity.—Fecundity was estimated for ripe females by counting the number of eggs in a sample aliquot of ovaries. The aliquot was removed from the center of one ovary as a triangular section 1–2 mm thick and constituting approximately one-eighth of the cross section of the ovary. A single aliquot per fish was chosen because Lewis and Bonner (1966) found no significant differences in the number of mature ova found in the anterior, mid, or posterior sections of striped bass ovaries or between right and left ovaries. The ratio of the total weight of both ovaries to the weight of the aliquot was multiplied by the number of eggs in the aliquot to determine the total number of eggs per female. Fecundity analyses were performed on several ripe females incidentally collected during the 1973–1975 spawning season as well as during the large-scale directed efforts from 1976 through 1979.

Length and weight.—Mean total lengths at time of capture were calculated to the nearest millimeter for striped bass caught by all gill nets and haul seines during 1976–1979. The annual growth of individual year classes was followed as incremental growth between two consecutive years of sampling.

Mean fresh weights were calculated from random subsamples within body-length strata of 0–400, 401–549, 550–699, 700–899, 900–1,099, and over 1,100 mm TL in 1976 and 200–299, 300–399, 400–499, 500–649, 650–799, 800–1,000, and over 1,000 mm TL in 1977–1979. Fish less than 400 mm TL were weighed to the nearest gram and larger fish were weighed to the nearest 50 g.

Population size.—The population size of striped bass of approximately age V and older within the Hudson River was estimated annually by mark–recapture methods. The estimates were derived for fish equal to or greater than 500 mm TL from gill-net and haul-seine collections thoroughly examined for tagged individuals. A Schumacher–

TABLE 11.—Age and sex composition of striped bass collected in gill nets and haul seines in the Hudson River estuary below km 62 during 19 April–30 May 1976, 10 April–21 May 1977, and 16 April–27 May 1978.[a] Dashes indicate less than 0.05%.

Age	1976 % Male	1976 % Female	1976 Total	1977 % Male	1977 % Female	1977 Total	1978 % Male	1978 % Female	1978 Total	3-Year mean % Male	3-Year mean % Female	3-Year mean Total
II	1.0	0.5	1.5	3.6	2.2	5.8	0.2	–	0.2	1.6	0.9	2.5
III	12.7	15.0	27.7	12.0	8.9	20.9	8.2	4.5	12.7	11.0	9.5	20.3
IV	10.1	11.0	21.1	28.5	23.2	51.7	8.0	8.3	16.3	15.6	14.2	29.8
V	6.4	11.3	17.7	4.9	3.9	8.8	18.0	21.6	39.6	9.8	12.3	22.0
VI	3.3	7.3	10.6	2.5	2.3	4.8	2.7	4.9	7.6	2.9	4.8	7.7
VII	1.3	7.5	8.8	1.4	1.5	2.9	3.1	4.5	7.6	1.9	4.5	6.4
VIII	0.5	1.8	2.3	0.4	1.4	1.8	1.9	4.2	6.1	0.9	2.5	3.4
IX	0.4	0.2	0.7	0.3	0.2	0.5	1.2	2.1	3.3	0.6	0.8	1.5
X	–	2.9	1.9	–	0.4	0.4	0.4	0.6	1.0	0.1	1.3	1.5
XI	0.5	2.5	3.0	0.1	0.5	0.6	0.2	1.2	1.4	0.3	1.4	1.7
XII	–	2.4	2.4	–	0.5	0.5	–	1.4	1.4	–	1.4	1.4
XIII	–	1.1	1.1	0.1	0.4	0.5	0.2	0.6	0.8	0.1	0.7	0.8
XIV	–	0.2	0.2	0.3	0.2	0.5	0.7	0.6	1.3	0.3	0.3	0.7
XV	–	–	–	–	–	–	0.2	0.4	0.6	0.1	0.1	0.2
XVIII	–	0.2	0.2	–	–	–	–	–	–	–	0.1	0.1
Total	36.2	63.9	100.1	54.1	45.6	99.7	45.0	54.9	99.9	45.2	54.8	100.0

[a] Fish in combined gill-net and haul-seine catches were aged and sexed, then calibrated to the size distribution of fish in the seine catch only. Total and seine samples were, respectively, 591 and 268 in 1976, 1,169 and 538 in 1977, and 2,271 and 436 in 1978. The seine catch was too small in 1979 (111 fish) to establish a size distribution for that year.

Eschmeyer multiple census estimate (Ricker 1975) was calculated as

$$\hat{N} = \frac{\Sigma(C_b M_b^2)}{\Sigma(R_b M_b)};$$

$\hat{N}$ = estimated population size;
C_b = total catch during biweekly interval b;
M_b = total number of marked fish available for recapture at midpoint of biweekly interval b;
R_b = number of recaptured fish in C_b.

A 90% confidence interval (CI) for $\hat{N}$ was determined from

$$\mathrm{CI} = \frac{\Sigma(C_b M_b^2)}{\Sigma R_b M_b \pm t_{s-2(0.05)}\,(S^2 \Sigma C_b M_b^2)^{1/2}};$$

$t_{s-2(0.05)}$ = t-value for s sampling intervals ($P_\alpha = 0.10$);

$$S^2 = \frac{\sum\left(\frac{R_b^2}{C_b}\right) - \frac{(\Sigma R_b M_b)^2}{\Sigma(C_b M_b^2)}}{s-2}.$$

Only tagged fish at large at least 2 d prior to recapture were used, which allowed for dispersal of marked fish into the unmarked population. All sampling gears were employed for both marking and recapture, without spatial segregation of marking and recapture effort. Tag loss and tagging-induced mortality were considered to be low because the population estimate encompassed only 3 months, and the cumulative effects of these sources was not expected to be great during this term; therefore, no adjustments to these data were made for these two factors in this analysis. Emigration and immigration were also assumed to be slight during this short time (McLaren et al. 1981).

Results

Age Composition

The population of striped bass larger than 200 mm TL during the 1976–1978 spawning runs contained fish of ages II–XVIII (Table 11). Age-groups III–V were the most abundant. A conspicuous feature of the age distributions was the strong 1973 year class (Klauda et al. 1980), which was age III in 1976.

Maturity

Male striped bass from the Hudson River matured earlier than females. Males began to mature at age II, and three-quarters of them were mature by age IV (Table 12). Females began to mature 2 years later than males. Ninety percent of the females were mature by age VII and all were mature by age XI. The ratios of total-body-weight:gonad-weight that best separated obviously mature and immature fish were 235:1 for males and 70:1 for females. Fish appar-

TABLE 12.—Percentage maturity (N) by age of male[a] and female[b] Hudson River striped bass, March–June 1976–1979.

Age	1976 Male	1976 Female	1977 Male	1977 Female	1978 Male	1978 Female	1979 Male	1979 Female	4-Year mean Male	4-Year mean Female
II	17(6)	0(1)	12(25)	0(24)	0(2)	0(2)	35(20)	0(20)	21(53)	0(47)
III	48(48)	4(25)	35(34)	0(27)	41(37)	0(43)	26(19)	0(14)	40(138)	1(109)
IV	67(33)	7(28)	62(81)	5(76)	88(82)	2(59)	76(71)	0(51)	74(267)	3(214)
V	87(53)	21(56)	70(23)	21(19)	88(114)	16(115)	83(66)	24(50)	85(256)	19(240)
VI	78(45)	47(45)	89(35)	62(48)	84(19)	60(30)	97(63)	69(91)	88(162)	62(214)
VII	100(12)	87(55)	100(18)	90(42)	93(30)	95(58)	78(9)	83(24)	94(69)	90(179)
VIII	100(13)	90(20)	90(10)	92(13)	87(15)	97(36)	100(7)	100(19)	96(45)	95(88)
IX	100(7)	100(4)	100(1)	100(5)	100(3)	100(13)	100(5)	89(9)	100(16)	97(31)
X	100(7)	100(23)	100(2)	100(5)	100(3)	100(6)	100(1)	80(5)	100(13)	97(39)
XI	100(11)	100(18)	100(2)	100(6)		100(3)			100(13)	100(27)
XII	100(3)	100(10)	100(4)	100(8)	100(1)	100(5)	100(3)		100(11)	100(23)
XIII		100(5)	100(1)	100(4)		100(3)		0(1)	100(1)	100(13)
XIV		100(1)	100(1)	100(3)	100(4)	100(2)			100(5)	100(6)
XV		100(1)		100(1)	100(1)	100(1)			100(1)	100(3)
XVI						100(1)			100(1)	100(2)
XVII		100(1)				100(1)				100(2)

[a] Males with a total body-weight:gonad-weight ratio less than 235 were considered mature.
[b] Females with a total body-weight:gonad-weight ratio less than 70 were considered mature.

ently ready to spawn (classified as "ripe and running") usually first appeared in Hudson River collections during the second week of May. Spent fish were collected during the third or fourth week of May, signifying that spawning had begun. Eggs and larvae were first collected at this time (Dey 1981; Boreman and Klauda 1988, this volume).

Fast-growing individuals within a year class tended to mature earlier. For example, the mean lengths and weights of mature striped bass were consistently greater than those of immature fish within the same age-group (Table 13). Fish size alone did not govern maturation; the largest immature fish collected—a 693-mm male and a 791-mm female—were much larger than the median sizes at maturity, which were 450-mm for males and 600-mm for females.

Changes in the number of mature individuals in each age-group (II–VIII), across years (1976–1979), and for each sex were tested by a multidimensional contingency analysis (Fienberg 1970). For female striped bass, age was the only factor significantly affecting maturity (χ^2 = 719.70; P < 0.01). The percentage of females reaching maturity increased the most between the ages of IV

TABLE 13.—Comparisons of length and weight at age between immature and mature Hudson River striped bass. Data are means + SEs (N). In all paired comparisons, mature fish were significantly larger than immature fish (t-test; P < 0.05).

Age	Maturity	Males: Total length (mm)	Males: Weight (g)	Females: Total length (mm)	Females: Weight (g)
III	Immature	351 ± 8 (50)	472 ± 32 (41)	417 ± 6 (97)	774 ± 37 (78)
	Mature	400 ± 9 (40)	690 ± 66 (26)	483 (1)	(0)
IV	Immature	404 ± 11 (24)	684 ± 55 (19)	466 ± 5 (174)	1,065 ± 52 (109)
	Mature	466 ± 6 (138)	1,082 ± 57 (90)	550 ± 47 (3)	2,500 (1)
V	Immature	458 ± 13 (32)	1,109 ± 127 (27)	528 ± 4 (355)	1,569 ± 54 (189)
	Mature	558 ± 4 (373)	1,854 ± 75 (147)	589 ± 15 (20)	2,594 ± 256 (17)
VI	Immature	515 ± 20 (5)	1,460 ± 182 (5)	546 ± 10 (48)	1,908 ± 168 (27)
	Mature	558 ± 10 (62)	2,307 ± 260 (23)	644 ± 14 (20)	3,150 ± 254 (17)
VII	Immature	528 ± 27 (3)	1,575 ± 375 (2)	561 ± 14 (11)	1,850 ± 161 (3)
	Mature	638 ± 10 (80)	3,393 ± 238 (34)	708 ± 12 (58)	4,492 ± 272 (46)
VIII	Immature	648 ± 23 (3)	3,225 ± 375 (2)	653 ± 118 (2)	4,950 (1)
	Mature	696 ± 18 (31)	4,567 ± 503 (12)	752 ± 14 (41)	5,370 ± 338 (33)

TABLE 14.—Mean age-specific fecundity (number of eggs per mature female in thousands) for Hudson River striped bass collected April–June 1973–1979. Open cells indicate no sample.

Year	Statistic	Age IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVIII
1973	Mean			451	781	1,549	1,564	1,842		2,351		2,190		
	SE			175	139	125	155	263		356				
	N			2	9	14	9	4		2		1		
1974	Mean		779	727	1,171	1,250	1,498	1,801	1,768					
	SE		227	115	288	86	120	159	354					
	N		3	5	4	15	17	15	5					
1975	Mean	409	645	669	901	949	1,552	1,843	2,056	2,126			2,591	
	SE			39	238	227	200	140	250	263				
	N	1	1	4	2	3	9	11	9	4			1	
1976	Mean		354	765	1,005	1,056	1,798	1,644	2,000	1,918	2,126			
	SE		68	279	101	299	1,119	141	158	188	146			
	N		3	10	24	6	2	14	13	4	4			
1977	Mean			670	578	871	1,552	1,739	2,385	2,440		2,214		
	SE			138	43	118	283	237	43	561		88		
	N			8	15	6	2	2	3	4		2		
1978	Mean	337	557	609	779	958	1,474	1,968	2,182	3,089	3,859	2,753		3,019
	SE		93	145	81	101	241	1,480		477				
	N	1	8	8	30	21	5	2	1	2	1	1		1
1979	Mean		638	649	832	1,094	1,150	1,010			1,346			
	SE		111	41	179	111	168	80						
	N		5	32	7	17	5	3			1			
Years combined	Mean	373	585	664	830	1,141	1,496	1,728	2,022	2,301	2,285	2,342	2,591	3,019
	SE	36	60	50	47	54	77	85	112	180	352	142		
	N	2	20	69	91	82	49	51	31	16	6	4	1	1

and VII. Male striped bass had a significant maturity–age–year interaction ($\chi^2 = 36.54$; $P < 0.01$) generated primarily by differences between the younger age groups.

Fecundity

Mean fecundity ranged from 373,000 eggs per female at age IV to 2.3 million eggs per female at age XIV (Table 14). There were sufficient samples for ages VI–X taken during 1973–1979 for least-squares analyses of log-transformed fecundity values (Sokal and Rohlf 1969). Fecundity varied significantly ($F = 23.8$; $P < 0.01$) across ages but not across years ($F = 1.54$; $P = 0.165$). The greatest increase in fecundity occurred between ages VIII and IX. Fecundity (Fe) was significantly ($P = 0.05$) correlated with body length (TL, mm) and weight (W, g):

$$\log_{10}\text{Fe} = 3.82 \log_{10} \text{TL} - 5.04;\ r = 0.915;$$
$$\log_{10}\text{Fe} = 1.21 \log_{10} \text{W} + 1.43;\ r = 0.927.$$

Female stripped bass produced approximately 176,000 eggs/kg of body weight.

Length and Weight

The length–weight relations for Hudson River striped bass age II and older were

males:

$$\log_{10} \text{W} = -4.914 + 2.99 \log_{10} \text{TL};\ r = 0.989;$$

females:

$$\log_{10} \text{W} = -5.019 + 3.028 \log_{10} \text{TL}:\ r = 0.991.$$

The regressions included fish collected during March–June 1976, regardless of spawning condition, and were most heavily representative of fish caught in gill nets. Females were consistently larger than males after age III (Table 15).

During 1976–1979, striped bass incremental growth (ages III–XI) demonstrated a significant year–age interaction ($P < 0.01$), which appeared to be a result of generally slower growth in 1978 than in 1977 and 1976 for ages III–VI and faster growth for age VII. Changes in annual incremental growth of striped bass across ages, years, and sexes were tested in a three-way analysis of

TABLE 15.—Mean total length (mm) and sample size (in parentheses) of male and female striped bass collected in the Hudson River estuary by gill nets (10.2, 12.7, 15.2 and 17.8 cm stretched mesh) during March–June 1976–1979.

	1976		1977		1978		1979	
Age	Male	Female	Male	Female	Male	Female	Male	Female
III	404(64)	408(61)	416(68)	427(45)	399(89)	434(60)	377(9)	397(11)
IV	428(76)	448(71)	455(411)	476(352)	459(244)	481(110)	460(284)	478(164)
V	520(121)	539(104)	479(141)	512(96)	531(632)	559(301)	498(329)	534(184)
VI	570(70)	595(87)	570(118)	642(61)	569(111)	594(93)	586(329)	611(278)
VII	662(23)	710(64)	627(46)	688(51)	620(105)	677(98)	598(51)	655(74)
VIII	741(6)	740(14)	675(9)	763(19)	683(37)	723(49)	716(38)	747(35)
IX	757(11)	874(5)	824(4)	851(9)	718(19)	776(14)	733(20)	764(23)
X	872(8)	941(14)	829(1)	914(7)	790(6)	784(4)	832(5)	811(9)
XI	875(12)	954(16)	899(7)	960(11)	883(3)	940(1)	840(3)	857(3)

variance (Sokal and Rohlf 1969). Mean lengths from gill-net collections during 1976–1979 (Table 15) were used in this analysis because they were based on similar fishing effort each year.

Fork length (FL) of Hudson River striped bass can be derived from total length by

$$FL = -13.313 + 0.969\ TL.$$

Population Size

The Schumacher–Eschmeyer population estimate of Hudson River striped bass larger than 500 mm TL increased numerically from 1976 to 1979 (90% confidence intervals in parentheses):

1976: 102,000 (56,000–548,000);
1977: 174,000 (93,000–1,394,000);
1978: 188,000 (130,000–336,000);
1979: 254,000 (146,000–976,000).

Because the confidence intervals were large, the annual estimates were not significantly different, but a trend of increasing population size would be consistent with recruitment of the 1973 year class. Some fish hatched in 1973 reached 500 mm at age IV in 1977, and recruitment to this size-group was complete by age VI in 1979.

Discussion

Although annual variations in age at maturity and growth have been detected for Hudson River striped bass, there is no evidence of a consistent change in either variable that might be associated with increasing power plant operations and a reduction in striped bass abundance. Other factors in the environment of the striped bass are likely responsible for the observed annual variations, such as variations in food availability or water temperature in the river or in coastal overwintering areas.

Males matured at an earlier age than females in the Hudson River population. Earlier maturation of males than of females is common among fishes. Bell (1980) proposed that early maturity in female fishes comes at a higher cost than early maturity in males because ovarian maturation diverts more energy from somatic growth than testicular development, and fecundity is related to fish size. Variations in the age of maturation by individual fish may well be inversely related to the amount of somatic growth accumulated.

Age at maturity and age structure are the two life history aspects of the Hudson River population that differ the most from other striped bass populations. The age at which all Hudson River females are mature is 2–4 years greater than that of other populations (Table 16). These differences in the rate of maturity are not clearly a function of latitude, as postulated for the American shad (Carscadden and Leggett 1975). Along the Pacific coast, female striped bass mature 2 years earlier in Oregon than in California. Along the Atlantic coast, females mature 1 year later in South Carolina than in Maryland and 2 years later than in North Carolina. The Oregon and Hudson populations are located at about the same latitude, yet the Hudson River female population is fully mature 3–4 years later. There is some indication of delayed maturation of females in the St. John River, New Brunswick, which has the northernmost population of striped bass, but 100% maturation there is complete 2 years prior to that of the Hudson River. Males also mature later in the Hudson River than elsewhere, the difference in ages of 100% maturity being approximately 3 years (Table 16).

Most estimates of age composition (Table 17) are derived from commercial catches, which may be size selective, or from pound nets and fyke nets, which are considered to be relatively non–size-selective gear (Grant 1974). The available data suggest that recruitment to commercial gear occurs later in the Hudson River than in the Chesapeake Bay and Sacramento–San Joaquin

TABLE 16.—Percentage maturity at age for female and male striped bass in several estuarine systems. Empty cells indicate data were not reported.

System	Age								Reference
	II	III	IV	V	VI	VII	VIII	IX+	
					Females				
Sacramento–San Joaquin, California			35	87	98	100	100	100	Scofield (1931)
Coos Bay, Oregon		18	68	100	100	100	100	100	Morgan and Gerlach (1950)
Albemarle Sound–Roanoke River, North Carolina		3	78	100	100	100	100	100	Lewis (1962)
Albemarle Sound–Roanoke River, North Carolina		4	94	100	100	100	100	100	Lewis (1962)
Potomac River, Maryland, spawning area		44	79	99	100	100	100	100	Jones et al. (1977)
Potomac River, Maryland, over-wintering area		17	43	86	100	100	100	100	Jones et al. (1977)
Santee–Cooper Reservoir, South Carolina			23	65	85	100	100	100	Scruggs (1955)
St. John River, New Brunswick		0	20	21	82	100			Williamson (1974)
Hudson River, New York		1	3	19	62	90	95	99	TI data (1976–1979)[a]
					Males				
Potomac River, Maryland, spawning area	93	99	100	99	100	100	100	100	Jones et al. (1977)
Potomac River, Maryland, over-wintering area		92	96	100	100	100			Jones et al. (1977)
St. John River, New Brunswick		25		84					Williamson (1974)
Hudson River, New York	21	40	74	85	88	94	96	100	TI data (1976–1979)[a]

[a] Data collected by Texas Instruments during the Hudson River power plant studies.

systems but at approximately the same age as in the St. John and Annapolis rivers of Canada. The age structure of an exploited fish population is a reflection of both natural and fishing mortality.

The fecundity of Hudson River striped bass is similar to that for other striped bass populations (Morgan and Gerlach 1950; Jackson and Tiller 1952; Lewis and Bonner 1966). Based on reported regressions of mean fecundity on body weight, 6-kg females produce approximately 1.0 million eggs in the Roanoke River, 0.9 million eggs in Chesapeake Bay, 1.2 million eggs in Coos Bay (Oregon), and 1.1 million eggs in the Hudson River. Mean fecundities for 14-kg females in the four systems are 2.3 million, 3.2 million, 3.1 million, and 2.4 million eggs, respectively.

It appears unlikely that another large-scale environmental study of the Hudson River, such as this one associated with the power plant case, will ever occur again, but it is important that some of these data again be collected. The four years of this study occurred after a tremendous increase in electrical generating capacity along the river (over 3,700 MW of capacity came on-line during 1974–1976). Population responses to this increased generating capacity may take decades to actually occur, let alone be detected. Therefore, large-scale studies similar to this one should be performed perhaps every 5 years. Additionally, the commercial striped bass fishery in the Hudson River was closed in 1976. The closure certainly decreased the fishing mortality of the Hudson stock, but whether this decrease has forestalled a population collapse such as the Chesapeake stock experienced in the late 1970s and early 1980s (MMES 1987) is unknown.

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TABLE 17.—Percentage age composition of age-II and older striped bass, sexes combined, in several estuarine systems.

System	Age						Reference
	II	III	IV	V	VI	VIII+	
Chesapeake Bay, Maryland[a]	18	43	13	22	[b]		Tiller (1950)[b]
James River, Virginia	53	18	9	3	4	12	Grant (1974)[c]
York River, Virginia	66	19	6	3	2	5	Grant (1974)
Rappahannock River, Virginia	64	19	6	2	1	8	Grant (1974)
Sacramento–San Joaquin, California[d]		47	23	12	6	12	Collins (1978)
St. John River, New Brunswick		5	14	29	12	40	Williamson (1974)
Annapolis River, Nova Scotia		7	27	31	14	22	Williamson (1974)
Hudson River, New York[e]	2	20	30	22	8	18	This report

[a] From commercial pound-net catches of 1944 and 1945.
[b] Age-VI and older fish.
[c] From commercial pound-net and fyke-net catches of 1967–1971.
[d] From stratified mark–recapture population estimates of 1969–1976; age-II fish are not included.
[e] Mean age composition, 1976–1978: Table 11.

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