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Striped Bass Populations in Chesapeake and San Francisco Bays: Two Environmentally Impacted Estuaries

EILEEN M. SETZLER-HAMILTON*, JEANNETTE A. WHIPPLE† and R. BRUCE MACFARLANE†
*The University of Maryland, Center for Environmental and Estuarine Studies, Chesapeake Biological Laboratory, Solomons, MD 20688-0038;
†US Department of Commerce, National Marine Fisheries Service, Southwest Fisheries Center, Tiburon Laboratory, Tiburon, CA 94920, USA

Striped bass populations have declined precipitously in both Chesapeake Bay and the San Francisco Bay Delta system.

Parallel declines in both systems indicate possible common climatic patterns or trends affecting both populations. Climatic instability on both coasts with accompanying changes in average rainfall, outflow and temperature may be interacting with deteriorating water quality and pollution resulting in declining populations of striped bass in both areas. Declines in east coast striped bass stocks have been attributed to: overfishing; nutrient enrichment of the habitat and the resultant, temperature-oxygen squeeze on subadults; deterioration of the near-shore habitat for juvenile striped bass resulting from the loss of submerged aquatic vegetation; decreased survival of larval striped bass due to environmental pollution; poor nutritional state of larvae; and fluctuations in the physical environment and predation.

In the San Francisco Bay Delta area the decline has been attributed to the interactive effects of reduced freshwater outflow and increased freshwater diversion, and decreased bay flushing and increased pollutant burdens which have adversely affected both egg production and egg and larval survival.

The striped bass, *Morone saxatilis*, is an anadromous species distributed along the Atlantic coast from northern Florida to the St. Lawrence Estuary, Canada, and along the Gulf of Mexico from western Florida to eastern Louisiana. The San Francisco Bay Delta population of striped bass originated in New Jersey. Juvenile striped bass from the Navesink River were introduced into the lower Sacramento River in 1879; additional yearlings from the Shrewsbury River were planted in San Francisco Bay in 1881 (Setzler *et al.*, 1980).

Striped bass spawn in late spring. In the Chesapeake Bay area spawning occurs from early to mid-April through to the end of May, primarily in tidal freshwater areas just above the salt wedge. Chesapeake Bay and its tributaries (Fig. 1a) provide the principal spawning and nursery areas along the Atlantic coast. The Chesapeake stock may comprise as much as 90% of the Atlantic coastal migratory stock of striped bass during periods of peak abundance (Berggren & Lieberman, 1978).

In the San Francisco Bay Delta area spawning occurs above the salt-wedge (or null zone) from mid-April through mid-June primarily in the Sacramento River and the central delta of the San Joaquin River, the major tributaries of San Francisco Bay (Fig. 1b).

Striped bass populations have declined for the past decade over much of their East Coast range, especially in Chesapeake Bay. Both commercial and recreational fisheries depend upon the occurrence of periodic dominant year classes to sustain population levels (Florence, 1980). The last dominant year class in 1970 resulted in peak commercial landings in 1973 (Boreman & Austin, 1985). Maryland landings declined from 2268 t in 1973 to 202.3 t in 1983 (Maryland Department of Natural Resources, 1986). Current stock levels are so low that the State of Maryland issued a total moratorium on the catch, sale or possession of striped bass in Maryland effective 1 January 1985.

As on the east coast, the San Francisco Bay striped bass have declined over the last 20 years, particularly since the drought of 1976–1977. The decline has been surprisingly similar to that in Chesapeake Bay as reflected in similar downward trends in young-of-the-year (YOY) survival in the two areas (Fig. 2a & b).

Stevens *et al.* (1985) have hypothesized four possible reasons for the decline of the San Francisco Bay fishery:

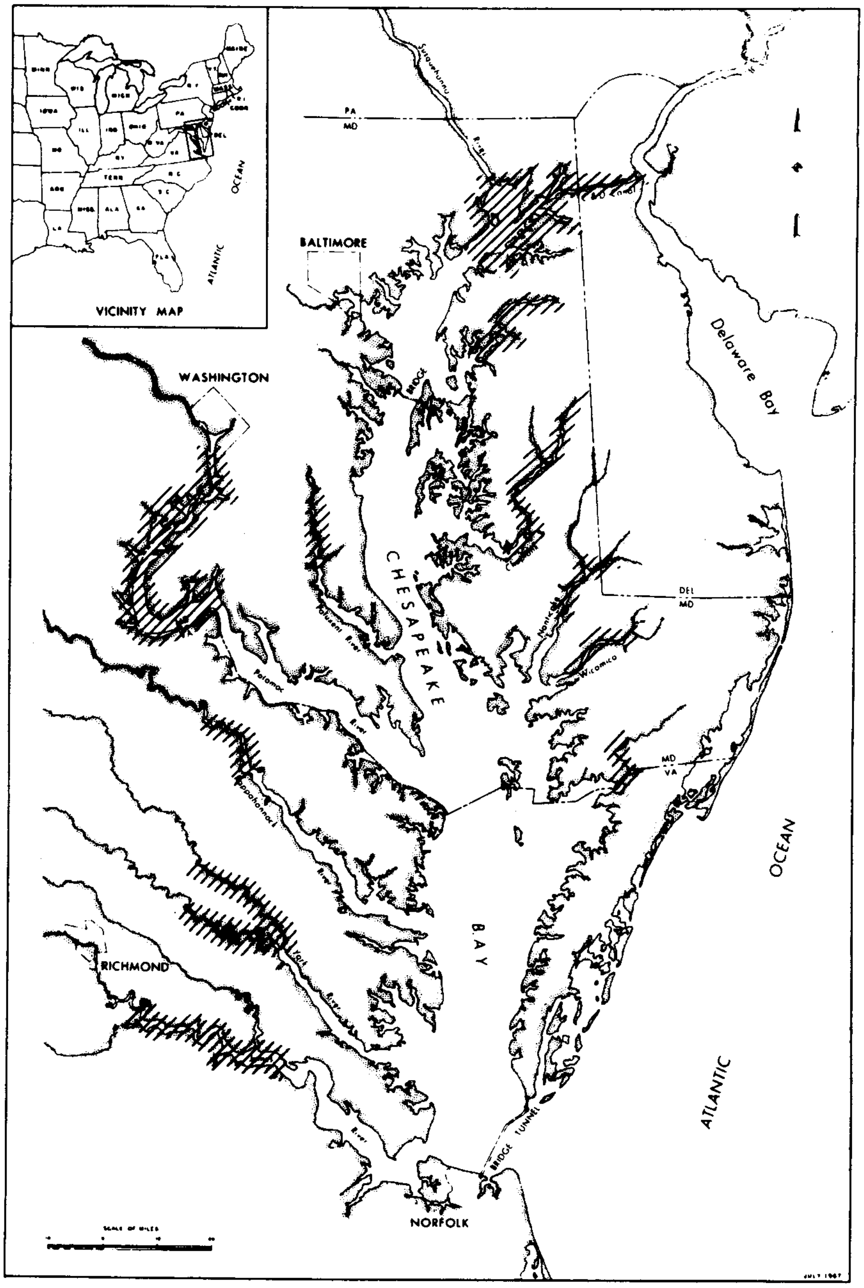

Fig. 1A Spawning areas of striped bass in Chesapeake Bay and its tributaries.

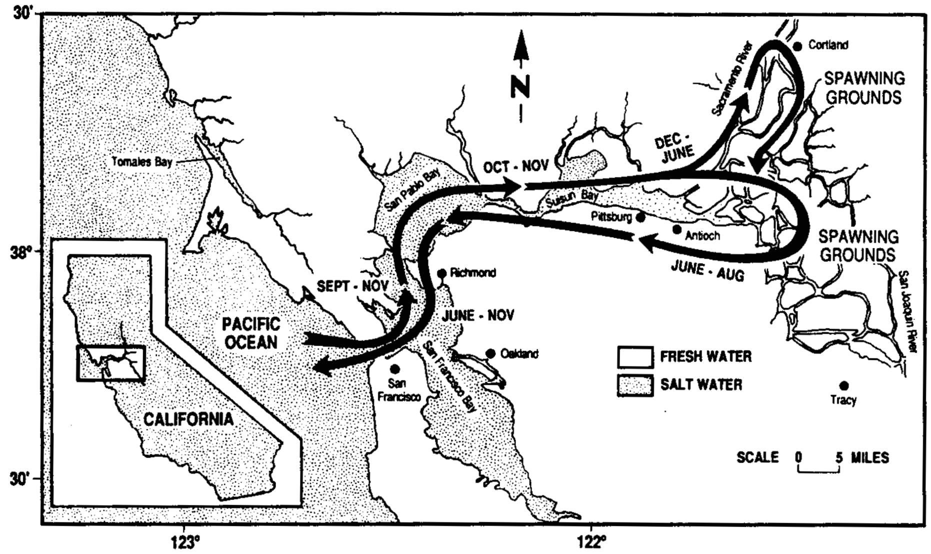

Fig. 1B Spawning areas and spawning migration of striped bass in the San Francisco Bay Delta estuary.

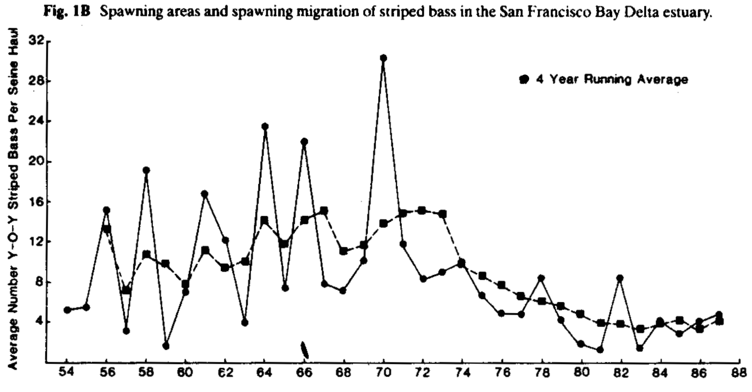

Fig. 2A Average number of YOY striped bass per seine haul from Maryland waters of Chesapeake Bay. This number is commonly referred to as the "Maryland Juvenile Index".

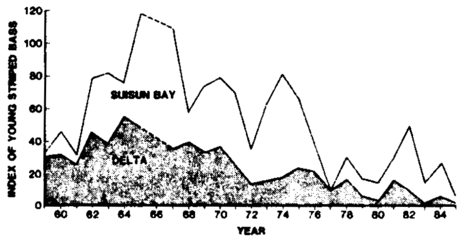

Fig. 2B Annual index of YOY striped bass by area in the Sacramento–San Joaquin Estuary. The young-of-year index is based on the catch per net tow when the average fork length of YOY striped bass reaches 38 mm. (Stevens *et al.*, 1985).

1. increased adult mortality resulting in low egg production, *2.* reductions in the planktonic prey of young striped bass in the western Sacramento-San Joaquin Delta and Suisun Bay during the spring, *3.* substantial losses of young fish by entrainment in water diversions, and *4.* physiological stress to the population by toxic substances such as petroleum hydrocarbons and pesticides.

Recent analysis by the California Department of Fish and Game (CDF&G, 1987) suggests the decline is probably due to a combination of increased adult mortality, lowered total fecundity affecting the total survival of YOY and decreased survival of eggs and very early larval stages (prior to 6 mm). Food abundance for older larvae may be less important than previously thought since it appears that mortality of eggs and larvae less than 6 mm has a greater effect on YOY recruitment than mortality of later stages (Low, 1986; CDF&G, 1987).

Unlike Chesapeake Bay, excessive water temperatures, low oxygen concentrations, and low pH do not appear to be major problems for San Francisco Bay

Delta populations of striped bass, although some larvae are lost to power plant entrainment (Chadwick, 1977). Overfishing is probably not a major factor contributing to the decline of striped bass in the San Francisco Bay Delta area (Stevens *et al.*, 1985).

There are levels of toxic pollutants in both Chesapeake and San Francisco Bay Delta areas and their tributaries, which are potentially harmful, including several petroleum and chlorinated hydrocarbons and trace metals (Jung *et al.*, 1984; Gunther *et al.*, 1987; Phillips, 1987). Research in San Francisco Bay (Whipple *et al.*, 1987; Jung *et al.*, 1984) has shown relatively high concentrations of many pollutants in tissues of striped bass. There are significant correlations among pollutants and reductions in reproduction and effective fecundity in striped bass, as well as evidence of effects on the adults.

This article examined the role of environmental degradation and pollution in the decline of Chesapeake Bay and San Francisco Bay striped bass stocks.

Overview of Chesapeake Bay Studies

Chesapeake Bay is a highly eutrophic, partially mixed, stratified estuary (see e.g. Kemp *et al.*, 1983; Officer *et al.*, 1984; Price *et al.*, 1985; Tuttle *et al.*, 1987). A major loss of submerged vegetation involving both native and exotic species has continued in Chesapeake Bay since the mid 1960s. Kemp *et al.* (1983) demonstrated that recent losses in Bay vegetation were linked to increased eutrophication and ultimately to light stress. Reduction in seagrass beds result in habitat loss for both finfish and epibenthic invertebrate populations (Orth & Heck, 1980; Heck & Orth, 1980). Shorezone fishes (such as juvenile striped bass) generally prefer naturally vegetated bottoms over bare bottoms (Briggs & O'Connor, 1971); such areas provide abundant food supply and protection from predators (Orth, 1977).

Coutant (1985) has hypothesized that adult striped bass are 'squeezed' from Chesapeake Bay during summer months because of their thermal and dissolved oxygen preferences or requirements. The thermal niche of striped bass decreases as the fish ages. Maximum growth rate of 1 yr-old juveniles occurs at 24–26°C (Cox & Coutant. 1981); whereas striped bass >5 kg (age 3+) prefer 20–22°C and avoid water temperatures >25°C and dissolved oxygen concentrations <2–3 mg l^{-1} (Coutant, 1985, 1987).

The deep, mesohaline waters of Chesapeake Bay have experienced annual summer anoxia or hypoxia since at least 1936 (Tuttle *et al.*, 1987). Based on a 30 yr old O_2 record for Chesapeake Bay. Officer *et al.* (1984) concluded that the summer volume of water having oxygen concentrations <0.5 mg O_2 l^{-1} increased approximately 15-fold between 1950 and 1980. If low dissolved oxygen (DO) concentrations have reduced striped bass habitat sufficiently to influence reproductive success than one would expect that upper Bay (Maryland rivers) striped bass would be more significantly impacted than lower Bay stocks (Virginia rivers). However, both upper and lower Bay stocks have suffered severe declines. Since a large portion of adult striped bass (primarily females) are migratory, the impact of the dissolved oxygen squeeze on reproductive success is questionable. Female striped bass do not mature sexually until ages 5, 6, and 7 yr; however, immature female striped bass begin migrating at 2 yr; approximately 50% of immature female striped bass leave the bay at 3 yr and join the coastal migratory stock (Kolenstein, 1981). These coastal migrants do not return to the Bay until they are sexually mature and participate in the spring spawning migrations. Gill net surveys indicate that more 2 yr old immature females leave the Bay than previously thought (Harley Speir, Maryland Department of Natural Resources, personal communication). Whether this is related to the temperature-oxygen squeeze as Coutant (1985) hypothesized, or to the reduction in fishing mortality of 2 yr old males after the imposition of the striped bass moratorium is open to question. Prior to the moratorium, sexually mature 2 and 3 yr old males experienced high fishing mortality during the spring spawning migration; immature females did not participate in spawning migrations to any great extent and thus were subjected to a smaller fishing mortality. Higher fishing mortality among 2 yr old males together with some migration of immature 2 yr old females could result in the approximately even sex ratios of 2 yr old striped bass seen in gill net surveys conducted prior to the total ban on fishing imposed by the moratorium.

Upper Chesapeake Bay stocks of all anadromous fish species are currently experiencing severe declines (Bonzek & Jones, 1984; Stagg, 1985). However Chesapeake Bay populations of marine spawners; i.e. bluefish and the various sciaenids; Atlantic croaker, spot and weakfish (sea trout) have not undergone similar declines. This implies that environmental impacts are likely to be operating primarily in the tributary rivers and the tidal freshwater portion of the upper Bay, the spawning areas of the anadromous species.

There is increasing evidence that water quality in the traditional striped bass spawning areas of Chesapeake Bay may adversely affect spawning and survival of striped bass early life history stages. A mixture of organic and inorganic contaminants at realistic environmental concentrations (EC) was created from analyses of Choptank, Elk and Nanticoke River water in 1980 (CNFRL, 1983). This mixture significantly reduced survival of striped bass yolk-sac larvae (prolarvae) reared in soft water (Hall *et al.*, 1984).

Mehrle *et al.*, (1987) reported significant mortality of striped bass larvae reared in hard well water at 2 and 4X EC within 30 days. Larvae reared in low salinity waters were more tolerant of the contaminants. Striped bass larvae reared in 2 ppt salinity incurred significant mortality in the 4 EC treatment after 30 days of exposure; whereas significant mortality occurred in the 2 and 4 EC in 5 ppt after 90 days exposure.

Tests on metals and organics carried out separately (Palawski *et al.*, 1985) indicated that the acute toxicity of the mixture was largely due to metals, particularly zinc, cadmium and copper. Cadmium and copper were implicated in an *in situ* toxicity bioassay carried out during the spring of 1986 in the spawning reaches of the Potomac River (Hall *et al.*, 1987b). Poorly buffered eastern shore tributaries such as the Choptank and Nanticoke are particularly susceptible to episodic drops in pH, especially during wet years. It is likely that low pH with or without the potentiating influence of aluminium (Buckler *et al.*, 1987) may create toxic conditions in these rivers during the time of spring run-off which is also the beginning of striped bass spawning season.

The pH of rainfall in the Chesapeake Bay area averages 4.0 with individual events recorded as low as 3.0 (pH of 'normal' rainfall is 5.0–5.4 due to naturally occurring organic acids and CO_2 in the atmosphere (Maryland Department of Natural Resources, 1985)). Even during relatively dry springs pH values on the spawning grounds in Eastern Shore tributaries may be marginal. Average pH values for stations sampled in the peak spawning areas of the Nanticoke and Choptank Rivers during 1986 a dry spring, ranged 6.00–6.60 and 6.23–6.86, respectively (Setzler-Hamilton, 1987).

Hall *et al.* (1986) evaluated organic contaminants, toxic metals, and water quality parameters in 10 East Coast striped bass spawning habitats: Roanoke River; James, Pamunkey, Rappahannock, Potomac, Patuxent, Choptank, and Nanticoke Rivers—all tributaries of Chesapeake Bay; the C & D Canal; and the Hudson River. Most water quality conditions appeared adequate for prolarval survival. However, low buffering capacity of 24–28 mg l^{-1} $CaCO_3$ was found in the Roanoke, Pamunkey and Rappahannock Rivers. Burton (1982) reported 78.0% mortality for striped bass yolk-sac larvae after 4 days of exposure to soft water <34.6 mg l^{-1} $CaCO_3$ in the laboratory.

Potentially toxic concentrations of monomeric aluminium and copper were also found in various spawning habitats (Hall *et al.*, 1986). Monomeric aluminium concentrations ranging from 103–104 μg l^{-1} were reported from the Roanoke, James and Patuxent Rivers in the Chesapeake system as well as the Hudson River. A combination of 100 μg l^{-1} aluminium and a pH <7.3 is toxic to 31-day striped bass (Mehrle *et al.*, 1984). Copper concentrations of 11, 12, and 15 μg l^{-1} in the Potomac, Patuxent, and Rappanhannock Rivers respectively, also may have been toxic to striped bass yolk-sac larvae. These copper concentrations exceeded the 96 h LC_{50} of 7.2 μg l^{-1} reported by CNFRL (1983) and were of the same order of magnitude as the 96 h LC_{50} found by Wright (1988) (24.0 μg l^{-1} for 16 day old larvae at a pH of 8.3 reared in ideal conditions). Both monomeric aluminium and copper occurred at potentially harmful concentrations in the Patuxent (Hall *et al.*, 1986). It is interesting to note that during two years of intensive sampling of the Patuxent spawning grounds we caught only 12 striped bass larvae and 3 juveniles in 1978 (Setzler *et al.*, 1979) and no striped bass beyond the yolk-sac stage in 1979 (only 34 yolk-sac larvae 3–5 mm TL were caught) (Mihursky *et al.*, 1980).

Hall *et al.* (1987a) found significant *in situ* mortality rates of both yolk-sac and yearling striped bass in the Potomac. Survival of yolk-sac larvae ranged from 4.5–22.5% during three 96 h experiments; control survival was $\geq 81\%$. Yearling survival ranged from 0–77% during two 7 d experiments; highest mortality occurred at the upriver station and was probably due to a point source discharge. High concentrations of monomeric aluminium, cadmium and copper, acting singly or synergistically, were implicated together with sudden decreases in water temperature to <11°C. The peak concentration of monomeric aluminium, 90 μg l^{-1} found during these *in situ* experiments is potentially toxic (Mehrle *et al.*, 1984). Peak concentrations of cadmium, 7 μg l^{-1}, and copper, 72 μg l^{-1}, from the Potomac exceeded 96 h LC_{50}s of both cadmium, and copper (CNFRL 1983; Wright, 1988).

Wright (1988) exposed larval striped bass to copper and cadmium concentrations which were acutely toxic over a 96 h period (24 and 19 μg g^{-1} respectively) and to sublethal concentrations of these metals over a 3 week period. The distribution of copper concentrations in laboratory-exposed larvae (1–30 μg g^{-1} dry wt) was completely within the range of wild larvae (0.1–60 μg g^{-1} dry wt) from the Potomac and Choptank Rivers throughout the 1985 and 1986 spawning seasons. There was considerable overlap in cadmium frequency distributions from laboratory (range 0.5–27 μg g^{-1}) and field larvae (range 0.01–12 μg g^{-1} dry wt).

Body burdens of seven metals were measured in striped bass and white perch (*Morone americana*) larvae collected from weekly sampling of the Potomac, Choptank and Nanticoke spawning grounds (Wright, 1987, Table 1). Concentrations of aluminium increased in striped bass larvae from the Potomac and Nanticoke Rivers and concentrations of copper increased in striped bass larvae from the Choptank River during the 6 week sampling period; whereas concentrations of copper and manganese in the Potomac larvae, and manganese in the Nanticoke and Choptank larvae remained approximately the same (Wright, 1987).

The DDT metabolites, DDE and DDD were present in white perch larvae collected from the Potomac River in 1985; DDE was present in white perch larvae from the Potomac, Nanticoke and Choptank Rivers in 1986. Two striped bass samples were analysed in 1985; however, no DDT derivatives were found in either. Wright (1987) also found a number of organic contaminants in white perch larvae. The herbicide Atrazine (used extensively in no-till farming in Maryland) was found in concentrations of approximately 100 ng g^{-1} wet wt in white perch from three rivers; Potomac, Choptank, and Nanticoke during the third week of May in 1985. Simazine residues were also present (data from the Maryland Department of Agriculture documented use of 1.6 million pounds of Atrazine and 0.45 million pounds of Simazine in Maryland in 1985). Residues of the insecticide, Malathion; 71.0 ng g^{-1} were found in striped bass larvae ($n=26$ larvae in a pooled sample) and in two pooled samples of white perch larvae (145 and 123 ng g^{-1} respectively) collected from the Potomac River during May, 1985 (Wright *et al.*, 1986). However the toxicity of these compounds to larval striped bass are unknown at present.

TABLE 1

Concentrations of heavy metals in striped bass from the Chesapeake Bay and San Francisco Bay Delta estuaries. Tissue concentrations are in μg g^{-1} dry wt except for CNFRL data and Mehrle *et al.* data where tissue concentrations are in μg g^{-1} wet wt.

Source	Al	As	Cd	Cr	Cu	Mn	Ni	Pb	Se	Zn	Hg	Reference
Eggs												
Chesapeake Bay Tributaries												
Elk n=1*		0.16	0.003		2.0			0.012	0.13			CNFRL, 1983
Potomac n=1		0.3	0.014		4.4			0.017	1.8			
Choptank n=1		0.14	0.005		3.2			0.011	2.2			
Sacramento River		0.25	0.36		5.9			0.01	2.4			
Larvae												
Potomac 6 May 86 n=6	139±50.5		0.12±0.16	2.6±0.96	12.3±5.3	20.1±6.4		14.9±7.5		3200±4163		Wright, 1987
	34.9–196		0.03–0.48	1.4–4.45	5.1–19	14.1–29.9		2.8–24		160–12 300		
30 May 86 n=8	132±96		0.10±0.04	0.53±0.35	13.3±5.4	20.8±4.5		5.6±6.9		300±183		
	11–332		0.05–0.18	0.34–0.89	8.1–25.2	15.7–27.8		1.6–23.7		113–642		
Nanticoke 7 May 86 n=2	56–79		0.27–0.35	0.8–1.97	2.7–53.9	30.0		7.4–29.6		180–5500		
31 May 86 n=12	112±134		0.10±0.07	6.9±11.6	8.0±6.1	43±18		4.8±2.1		1800±4650		
	2.5–441		0.09–0.27	0.43–38.7	3.3–25.1	17–74		1.14–7.8		150–17 200		
13 June 86 n=8	183±65		0.14±0.09	0.71±0.19	8.4±2.7	27.7±6.7		1.1±0.6		126±19		
	81–225		0.04–0.34	0.45–1.02	5.3–13.4	19.6–38.6		0.1–1.9		90–154		
Choptank 8 May 86 n=3	1074±167		0.63±0.11	12.7±2.4	2.38±2.02	52.3±29.5		65.2±45.1		14 100		
	722–1445		0.29–1.1	5.8–21.6	0.94–3.8	22.9–81.8		24–128				
1 June 86	375±166		0.06±0.03	0.70±0.19	3.66±0.3	47.3±8.4		2.3±0.4		262±173		
	171–578		0.02–0.08	0.43–0.96	3.3–3.9	37.1–57.7		1.7–2.7		130–510		
Young-of-year												
Elk n=1	<0.4	0.16	0.02	0.36	0.88	7.2		0.08	1.3			CNFRL, 1983
Potomac n=2		0.16	0.009	0.3	1.09	6.1		0.06	0.72			
Choptank n=1	<0.6	0.15	0.013	0.34	0.94	7.6		0.04	0.37			
James n=1	<0.4	0.51	0.017	0.27	0.86	9.8		0.03	0.3			
Nanticoke n=1	<0.4	0.1	0.004	0.36	0.48	7.1		0.008	0.44			
Nanticoke n=5		0.13±0.01	0.05±0.01					0.73±0.01	0.19±0.01	39.20±4.02		Mehrle *et al.*, 1982
n=5		0.08±0.02	0.05±0.01					1.00±0.60	0.25±0.06	35.30±4.78		
n=5		0.40±0.03	0.05±0.01					0.67±0.15	0.64±0.03	32.66±4.29		
Potomac n=5		0.16±0.01	0.05±0.01					1.20±0.01	0.22±0.01	35.90±0.01		
n=5		0.20±0.19	0.05±0.01					1.34±0.73	0.66±0.14	55.48±2.05		
n=5		0.10±0.04	0.05±0.01					1.15±0.50	0.84±0.19	57.40±7.50		
Adults												
Elk n=1		0.84	0.15	0.85	1.34	3.00	0.14	0.12	0.69		0.07	CNFRL, 1983
Potomac n=1		0.55	0.40	0.90	1.47	3.33	0.23	0.16	0.60		0.09	
Choptank n=1		0.94	0.20	0.78	1.67	1.76	0.25	0.16	0.34		0.09	
Sacramento		0.38	0.15	0.84	1.46	2.09	0.26	0.19	0.48		0.27	

*Averages of duplicate pooled samples. All other YOY values represent results of a single pooled sample.

Table 2 summarizes concentrations of organic contaminants found in striped bass eggs, young-of-the-year (YOY) and adults from both Chesapeake Bay and San Francisco Bay. Concentrations of DDT derivatives and PCB's were higher in striped bass eggs than in either YOY or adults. (These organic contaminants are soluble in lipids; lipid storage in striped bass eggs is in a large oil globule.) Westin *et al.*, (1985) have demonstrated that hexachlorobenzene, chlordanes, DDTs and PCBs are passed from parent to the offspring via yolk and oil of the egg.

Reported 96 h LC_{50} concentrations of three organic insecticides to 56 day old striped bass are summarized below:

	Softwater Conc. $\mu g\ l-1$	1 ppt salinity $\mu g\ l^{-1}$
Toxaphene	5.4	7.6
Malathion	24.5	65
Carbaryl	760	2300

(From Palawski *et al.*, 1985).

The extreme toxicity of toxaphene to striped bass was not altered by water hardness whereas the toxicity of both malathion and carbaryl was reduced in water of 1 ppt salinity as compared to soft water.

The histopathology of larval striped bass has been examined in an attempt to identify causal relationships between specific water quality contaminants or stressors and the pathology or death of larval fish. Examination of striped bass larvae, 5–7 mm TL, collected from the Choptank River during 1984 revealed severe liver and muscle damage at the cellular level; necrosis of liver cells and calcium deposition in adjacent muscle cells, indicative of pending mortality (Hall *et al.*, 1985). These results correlate with results of trawl studies in the Choptank; no larvae >7 mm were collected during the first 80% of the 1984 spawning season (Maryland Department of Natural Resources, 1985).

Hall *et al.*, (1987b) found lesions in the pseudobranch, dilated glomerular capillaries and vacuolization and eosinophilic inclusions in the proximal tubules of the kidneys (indicative of osmotic imbalance) of yearling striped bass exposed to Potomac River water. They also found reduced glycogen reserves in the livers of yearling striped bass from the C&D Canal (Hall *et al.*, 1987b).

Overview of San Francisco Bay Delta Studies

The severe decline of San Francisco Bay Delta populations of striped bass in the last 20 years probably results from interacting factors. The adult population of striped bass appeared to be relatively stable from about 1969 to 1976. Subsequently, adult abundance declined to about one quarter of that 20 years ago (Stevens *et al.*, 1985). Previously water diversion was implicated in reductions of the planktonic food supply and subsequent reduction in survival of young striped bass. Recent analyses (Low 1986; CDF&G 1987) have shown that survival to very young larval stages (from egg to 6 mm) is most important in determining the year-class strength. Accumulation of toxics in the ovaries of adult prespawning striped bass may result in increased mortality of eggs and delayed mortality of larvae prior to or at the time of first-feeding.

Field Studies

Striped bass from the San Francisco Bay Delta area have relatively high levels of several classes of petroleum hydrocarbons, chlorinated hydrocarbons and heavy metals (Tables 1–3; Whipple *et al.*, 1983, 1987, unpublished). Concentrations of monocyclic aromatic hydrocarbons (MAH), alicyclic hepanes (AH), and unmetabolized DDT in the livers and ovaries of prespawning striped bass from the San Joaquin and Sacramento Rivers from 1978–1984 were correlated to egg resorption, abnormal egg maturation and egg death. Striped bass from San Francisco Bay had higher percentages of egg resorption, at least in certain years, than striped bass from Coos Bay, Oregon, and Hudson River, New York, populations.

Crosby *et al.* (1986) found relatively high residues of chlorinated hydrocarbons, including PCBs, DDT and metabolites, and toxaphene in tissues of San Francisco Bay Delta striped bass. Residues were significantly higher than in Coos River, Oregon striped bass (Whipple *et al.*, 1983). PCBs in SF Bay striped bass were comparable to concentrations found in striped bass from the Hudson River (Gadbois & Maney, 1983). Although the mean concentration of PCBs was lower than from Hudson River fish (0.75 vs. 1.50 mg g^{-1} wet wt), the maximum concentration (4.0 mg g^{-1}) in muscle was the highest recorded in striped bass in this comparative study. The chlorinated hydrocarbon residues in particular, PCBs, DDT, and metabolites and toxaphene, were at levels potentially impacting the adult striped bass and their eggs and larvae (Crosby *et al.*, 1986; Jung *et al.*, 1984).

A number of investigators have found lesions in livers of adult striped bass containing high concentrations of chlorinated hydrocarbon residues (Crosby *et al.*, 1986). Brown *et al.* (1987) found significant liver dysfunction in moribund striped bass collected during a die-off in Carquinez Straits in the summer of 1985.

Whipple (unpublished) has found relatively high residues of petrochemicals (mean $[MAH]=2.39\pm6.90$ mg g^{-1}, wet wt, n=9 females) in livers and gonads of moribund, postspawning adult striped bass collected from the Carquinez Strait area in 1980. These concentrations were approximately 50 times greater than concentrations found in livers of prespawning adults in 1981 (mean $[MAH]=0.044\pm0.079$ mg g^{-1} wet wt; n=19 females).

Laboratory Studies

Concentrations of benzene in tissues of wild juvenile striped bass approximated those in tissues of juvenile striped bass exposed in the laboratory to 100 n l^{-1} benzene (Whipple *et al.*, 1981). Initial laboratory studies showed that benzene was primarily taken up through the gills and accumulated at highest levels in tissues with greatest lipid content (Korn *et al.*, 1976a). Effects of benzene exposure included changes in respiration (Brocksen & Bailey, 1973; Eldridge *et al.*,

TABLE 2

Summary of mean concentrations and ranges of whole body residues of organic contaminants in striped bass from the Chesapeake and San Francisco Bay Delta estuaries. Concentrations in $\mu g\ g^{-1}$ on wet wt basis.

Source	*n*	DDT	DDD	DDE	Total PCBs	Toxa-phene	Diel-drin	Chlor-dane	PAH[a]	PASH[b]	Total PCDDs[c]	Total PCDFs[d]	Non-*o*-PCBs[e]	Reference
Eggs	1[f]													
Potomac		0.03	0.1	0.48	4.0	ND[g]	0.06	0.23						CNFRL, 1983
Elk		0.05	0.33	0.6	3.91	0.24	0.05	0.61						
Choptank		0.1	0.54	1.08	6.19	0.55	0.07	0.88	144.0	1.5	12	51	+[h]	
Nanticoke									120.7	ND	3	44	28	
Sacramento		0.53	1.11	5.17	10.74	1.44	0.1	2.1			6	34	321	
Young-of-year	1[i]													CNFRL, 1983
Potomac		0.02	ND	0.02	ND	ND	ND	ND						
Elk		0.02	ND	0.05	ND	ND	ND	ND						
Choptank		ND	ND	0.02	ND	ND	ND	ND	28.5	ND				
Nanticoke		ND	ND	0.03	ND	ND	ND	ND	21.9	ND	6	2	ND	
Young-of-year														Mehrle *et al.*, 1982
Potomac	10				0.21±0.08									
	10				0.31±0.16									
	10				0.40±0.11									
Nanticoke	10				0.06±0.04									
	10				0.08±0.04									
	10				0.09±0.04									
Adult	1[j]													CNFRL, 1983
Potomac		0.07	0.06	0.31	2.2	0.5	0.02	0.39			2	55		
Elk		0.17	0.07	0.34	1.1	ND	0.01	0.18						
Choptank		0.11	0.10	0.41	2.5±1.5 (1.2–4.5, n=4)	0.2	0.04	0.39	284.0	5.1	25	23	92	
Nanticoke					2.8±0.3 (2.5–3.3, n=4)				241.2	28.7	19	25	40	
Sacramento		0.13	0.07	0.72	2.5	0.5	0.03	0.32			ND	26	42	

[a]PAH (polycyclic aromatic hydrocarbons)—Data are sum of concentrations of the 5 prevalent compounds (phenanthrene, fluoranthene, pyrene, benzo(*a*)fluorene, benzo(*a*)anthracene. All PAH data from one pooled sample of 4 individuals or egg masses.

[b]PASH (polyaromatic sulphur heterocycles)—Data are sum of concentrations of the 3 prevalent thiophenes (dibenzothiophene, phenanthro(4,5-*bcd*)thiophene, benzo(*b*)anaphtho(2,1-*d*)thiophene). All PASH data from one pooled sample of 4 individuals or egg masses.

[c]PCDD (polychlorinated dibenzofurans)—Data are sum of concentrations of compounds containing 4 to 8 chlorine atoms. All PCDD data are from one pooled sample of 3 individuals or egg masses.

[d]PCDF (dioxins)—Data are sum of concentrations of compounds containing 4 to 8 chlorine atoms. All PCDF data from one pooled sample of 3 indiviudal or egg masses.

[e]Non-*o* PCB (non-ortho substituted polychlorinated biphenyls)—Data are sum of concentrations of compounds containing 4 to 6 chlorine atoms. All non-*o* PCB data from one pooled sample of 3 individuals or egg masses.

[f]Data represent one pooled sample of eggs from 6–8 females.

[g]ND—Not detected.

[h]+—Detected, but concentration too low for accurate quantitation.

[i]Data represent one pooled sample of 4–6 individuals.

[j]Data represent one pooled sample of 6–8 adult females.

TABLE 3

Concentrations of selected pollutant classes in tissues of adult female prespawning striped bass (*Morone saxatilis*) from the San Francisco Bay Delta estuary (mean age = 5.9 yr; range = 4–20 yr). Concentrations in mg g^{-1} (ppm) wet wt for hydrocarbons, mg g^{-1} dry wt for metals. Data from Vasilleros *et al.*, 1982; Gadbois and Maney, 1983; Whipple, unpublished.

		Concentrations in tissues mg g^{-1}		
Pollutant Class				
Petroleum hydrocarbons		Liver	Ovaries	Muscle
Total monocyclic aromatics*	X±s	0.28±0.70	0.23±1.21	0.39±0.18
	n; Max	191; 10.0	187; 10.0	12;† 1.50
Total alicyclie hexanes‡		0.39±1.58	0.56±6.17	ND§
		191; 5.0	187; 10.0	
Total polycyclic aromatics		Whole fish composite 10.0		
Total naphthalenes		Whole fish composite 0.01		
Total thiophenes		Whole fish composite 6.0		
Chlorinated hydrocarbons				
Total DDT and metabolites		0.50±1.04	2.61±3.72	NM¶
		52; 1.57	12; 13.6	
Chlordane		0.02±0.02	NM	NM
		39; 0.12		
Total PCBs		0.78±0.93	2.64±2.62	1.02±1.67
		51; 5.00	12; 8.10	12; 4.00
Trace metals				
Cadmium		2.58±1.86	0.23±0.22	0.39±0.15
		52; 9.40	12; 0.710	12; 1.30
Chromium		0.44±0.67	0.95±0.52	1.24±0.38
		52; 3.30	12; 2.20	12; 2.20
Copper		61.6±60.3	5.63±1.96	2.00±3.36
		52; 220	12; 35.0	12; 3.36
Lead		0.21±0.08	0.180±0.23	0.23±0.13
		12; 0.370	12; 0.89	12; 0.62
Mercury		1.99±2.04	0.183±0.20	0.22±0.,19
		52; 13.0	12; 0.96	12; 1.60
Nickel	X±s	1.26±0.42	0.98±0.48	1.40±0.41
	n; Max	12; 1.80	12; 2.10	12; 2.00
Selenium		7.28±3.70	NM	NM
		45; 21.0		
Zinc		160±52.	61.0±49.2	21.0±31.3
		52; 272	75; 310	12; 66.0

*Benzene, toluene, ethylbenzene, *o*-, *p*-, *m*-xylenes.
†Mostly toluene.
‡Cyclohexanes, methyl cyclohexane, isomers of dimethyl cyclohexanes.
§ND—not detected
¶MM—not measured

1981), alterations in growth and fat content (Korn *et al.*, 1976b), abnormal hatching and larval development (Eldridge *et al.*, 1981), decreased effective fecundity and reproduction (Whipple unpublished), abnormalities in organs and tissues (Taberski, 1982) and increased serum cortisol and secondary stress responses (MacFarlane & Benville, 1986).

Discussion

It is interesting to note that the decline in YOY striped bass follows a similar pattern in the two areas. Survival in the San Francisco Bay Delta is significantly correlated to survival in Maryland Waters of Chesapeake Bay (r=0.568; p=0.0023; Table 4). A simple method of the first difference transformation was applied to reduce the possible effects of autocorrelation on the abundance trends (Bakun & Parrish, 1980). Preliminary examination shows the trends persist after the transformation. We feel that further analysis and investigation of the possible causes of these common trends would be interesting.

At this time, the tertiary factors which may be responsible for affecting populations similarly in both areas are unknown. Both coasts have experienced unstable climatic conditions in the last 10 years when compared to the more stable preceding 20 years. In the San Francisco Bay area, for example, there has been a warming trend for the past 10 years (1975–1985; Dowgiallo *et al.*, 1986). During that period, a drought (1976–1977) and a significant El Niño event (1982–1983) have occurred. This climatic instability also relates to the variability in rainfall, riverflow and temperatures on both coasts.

The Chesapeake Bay area experienced colder than normal winters in 1977 and 1978. A major drought occurred during 1985 and 1986 and summer temperatures during 1987 reached record highs. Kerr (1985) showed data confirming observations of erratic winter weather and temperatures in the Continental United States for the eight years 1976–1984. In contrast, the preceding 20 years (1955–1975) were characterized by stability of winter temperatures. Periods of stability may be related to the good year classes of striped bass in the 1960s, and early 1970s in San Francisco Bay and 1970 in Chesapeake Bay, while recent instability may relate to recent downward trends.

There was no significant correlation between YOY

TABLE 4

Correlation analysis of young-of-the-year (YOY) survival indices for Maryland rivers vs. San Francisco Bay Delta and Suisun nursery areas (1959–1985). All data was transformed to natural logarithms. YOY indices from San Francisco Bay Delta area defined in Stevens *et al.* (1985); data from Maryland rivers are average catch per seine haul (Md. Dept. Nat. Res. 1986).

YOY Index	n	Correlations					
		YOY Delta		YOY Suisun		YOY Total, California	
		r^2	Prob.	r^2	Prob.	r^2	Prob.
Delta	27			0.1640	*	0.6873	‡
Suisun	27	0.1640	*			0.6693	‡
Total California	27	0.6873	‡	0.693	‡		
Nanticoke	27	0.3815	‡	0.2527	†	0.4035	‡
Choptank	27	0.1519	*	0.2106	*	0.2057	*
Head-of-Bay	27	0.2528	†	0.0801	n.s.	0.2391	†
Potomac	27	0.0166	n.s.	0.0013	n.s.	0.0062	n.s.
Mean Maryland River	27	0.3491	‡	0.1572	*	0.3223	†

*Significant at $p < 0.05$
†Significant at $p < 0.01$
‡Significant at $p < 0.001$
n.s. Not Significant

recruitment in the San Francisco Bay Delta and YOY recruitment in the Potomac River in contrast to YOY recruitment in the upper Bay, Choptank, Nanticoke and Maryland waters as a whole (Table 4). The correlation of YOY recruitment success in upper Chesapeake and San Francisco Bays implies a common climatic influence on recruitment success.

Salinity regimes in the striped bass spawning region of the Potomac (≈100–170 km upriver from the mouth) are primarily controlled by freshwater input from the upper Potomac instead of freshwater input to the upper Bay. One would anticipate that global climatic events would exert a greater influence on the freshwater input to Chesapeake Bay from the Susquehanna River which drains most of Pennsylvania and central New York and supplies 90% of the freshwater to the upper Chesapeake Bay than on the freshwater input to the Potomac which has a more localized drainage area (western Maryland and the Appalachian region of northern Virginia and West Virginia).

Body burdens of some petroleum and chlorinated hydrocarbons in both populations of striped bass (Table 2) are at levels which can affect striped bass condition, growth, reproduction and survival. Highest mean concentrations of DDD and DDE were found in striped bass eggs from the Sacramento (1.1 and 5.2 $\mu g\ g^{-1}$ wet wt., respectively) and the Choptank Rivers (0.5 and 1.1 $\mu g\ g^{-1}$) which are surrounded by agricultural lands. Concentrations of total PCBs in the two systems were also highest in striped bass eggs from the Sacramento (10.7 $\mu g\ g^{-1}$) and Choptank (6.2 $\mu g\ g^{-1}$) Rivers (Table 2). Concentrations of PCBs were higher in striped bass eggs from the Hudson River, 26.4 $\mu g\ g^{-1}$, (CNFRL, 1983). Although total PCB concentrations in adult female striped bass from the Hudson were higher than in adult females from either the Chesapeake or San Francisco systems, concentrations were of the same order of magnitude (7.6 $\mu g\ g^{-1}$ in Hudson vs. 1.1–2.8 $\mu g\ g^{-1}$ in the Chesapeake and San Francisco estuaries). Concentrations of organic hydrocarbons were typically higher in striped bass from the Sacramento River than in striped bass from Chesapeake Bay tributaries (Table 2).

Survival of both starved and fed striped bass larvae in laboratory experiments was inversely related to concentrations of chlorinated hydrocarbons; HCB, DDTs, PCBs and chlordanes) in the eggs. Body burdens of chlorinated hydrocarbons increased in rough proportion to the cumulative amount of food-borne contaminant (*Artemia* nauplii containing distinctive organochlorine residues) in striped bass larvae hatched from eggs with low maternal contributions of chlorinated hydrocarbons. In larvae with high initial concentrations of contaminants however, only DDTs showed accumulation during the feeding period (Westin *et al.* 1985).

A further comparison of Chesapeake and San Francisco Bays shows other similarities and differences. High spring flows appears important to survival of striped bass in the San Francisco Bay Delta and the Potomac estuary. Stevens *et al.* (1985) found that outflow was the major factor associated with survival to YOY stage in the San Francisco Bay Delta population. In years of high flow striped bass larvae are transported down estuary to Suisun Bay where abundant populations of zooplankton prey are found. Higher than normal spring flows (April only), along with colder-than-normal winter temperatures are also correlated with successful year classes in the Potomac River (Boynton *et al.*, 1977; Mihursky *et al.*, 1981). However this relationship does not appear to hold for the upper Chesapeake Bay (Walter Boynton, CBL, pers. comm.).

Polgar *et al.* (1985) evaluated the effects of climatic factors, human population changes and dredging activity on Potomac River striped bass stocks (1929–1976). Climatic factors, specifically previous December's temperature, April temperature and April river flow most significantly affected striped bass population dynamics; pollution variables were not significant. In contrast Potomac River stocks of American shad showed strong dependence on human population levels (but not on dredging activity) compared to climatic factors (Polgar *et al.*, 1985).

Low pH and fluctuations in pH adversely affect populations of striped bass in the low conductivity, freshwater Eastern Shore tributaries of Chesapeake Bay (Hall *et al.*, 1985). In these tributaries, metals and organics input are via the pulses of freshwater resulting from precipitation. Thus for example, although the rainfall in the Choptank River watershed during the 1986 spawning season was insufficient to produce a pulse through the system, one minor storm producing ~0.5 in. of rain resulted in a two fold increase in monomeric aluminium in the spawning reaches of the river (Maryland Department of Natural Resources, 1986).

Goodyear (1985) investigated the effects of pollution-related mortality on Maryland striped bass, but found it was currently impossible to determine the relative contribution of fishing mortality and contaminant mortality. Contaminants were found in all life-history stages of striped bass in Maryland waters, however, no single contaminant was implicated in the decline. The same situation occurs with the striped bass in San Francisco Bay Delta, although fishing mortality is thought to be less important than natural mortality (Stevens *et al.*, 1985). Population modelling of Chesapeake Bay stocks of striped bass by Goodyear (1985) suggested that an immediate reduction in fishing mortality would be beneficial regardless of the causal factors in the decline.

Storm run-off may also adversely affect San Francisco Bay populations of striped bass. The Mediterranean climate in the San Francisco Bay area, with hot dry summers, followed by heavy rainstorms, tends to increase the importance of storm run-off containing high levels of pollutants such as petrochemicals.

Both Chesapeake and San Francisco Bay Delta estuaries are adjacent to agricultural development. The San Francisco Bay Delta, is the drainage system for one of the most intensive agricultural areas in the world, the Central Valley of California, with very heavy usage of pesticides and herbicides of immense diversity.

Striped bass from estuarine populations occur in an environment with highly variable conditions of flow and with urbanization and attendant pollutant and water quality problems. Larval survival and population production is also highly variable. The persistence of many estuarine populations appears dependent on dominant year classes (e.g., 1970 in the Chesapeake System and 1965–66 in the San Francisco Bay population). It is possible that the intensifying instability of climate and resultant fresh-water flow, with increasing pollution is suppressing the survival of large year classes, thereby diminishing their influence on population persistence in the estuary. The life history adaptive capacities of both Chesapeake and San Francisco Bay populations of striped bass may be increasingly unable to keep pace with their rapidly changing and deteriorating habitats.

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