Appendix VI-4-A

Striped Bass Population Modeling

Impacts of power plant mortality on Hudson River striped bass

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Abstract

The impacts of power plants on Hudson River striped bass has been the subject of both litigation and scientific research. In 1974 a monitoring program was initiated to measure the abundance of different life history stages. In the mid 1980s major reductions in fishing pressure led to a 15 fold rise in the spawning stock in the Hudson River. Age-structured model fits to the data now available suggest that there is very strong compensatory mortality in the recruitment, and this density dependence occurs between the post-yolk-sac larval stage and the young-of-the-year. A Bayesian risk analysis indicates that a complete elimination of power plant mortality would result in less than a 1% increase in the abundance and catch of Hudson River striped bass. We found this conclusion is quite robust to assumptions about possible environmental change in the Hudson River.

Introduction

The impact of power plants on fish stocks of the Hudson River has been the subject of both litigation and scientific research (Barnthouse et al. 1988a). At issue has been the mortality of eggs, larvae and juveniles due to entrainment through the once-through cooling systems of the Bowline Point, Indian Point, and Roseton power plants (Barnthouse et al. 1988b). In the 1970s, certain environmental advocacy groups advocated the installation of closed-cycle cooling (cooling towers) at each power plant on the theory that cooling towers would reduce the volumes of river water needed by about 97% with like reductions in the entrainment mortality of striped bass. The total cost of construction and operation of cooling towers at these four power plants was estimated to be $1.8 billion .

The owners of the power plants requested an adjudicatory hearing to demonstrate that entrainment mortality due to once-through cooling would not adversely impact the Hudson River stock of striped bass and that closed-cycle cooling was unnecessary. Impact was examined with stock-recruitment models that used a compensatory function (Savidge et al. 1988, Lawler 1988). The degree of biological compensation (stabilizing density dependent mortality that enables populations to withstand added stress) used in these models was a source of substantial contention (Christensen and Goodyear 1988). A major concern was the use of limited biological data to justify the selection and parameterization of a Ricker model to characterize the compensatory reserve. An additional concern was the limited amount of data on abiotic processes governing the production and persistence of the Hudson River stock of striped bass . Information on both biotic and abiotic processes are needed to discriminate between anthropogenic impacts and natural environmental variability.

Barnthouse et al. (1988b) summarize the history of the controversy and litigation. The key highlights are intense litigation associated with 1977-1980 EPA hearings and a negotiated settlement reached in 1980. The key features of the negotiated settlement were that (1) utilities were not required to install cooling towers, (2) utilities agreed to schedule plant shutdowns and maintenance to try to minimize impacts on striped bass eggs and larvae, (3) utilities agreed to fund a number of data collection programs and research to provide better information on the entrainment and impingement mortality and the effects of this mortality on the striped bass population, (4) utilities agreed to fund hatchery production of striped bass and (5) utilities agreed to fund an independent foundation to support additional research.

Entrainment of striped bass has been reduced at the Bowline, Indian Point, and Roseton power plants by decreasing or eliminating the use of cooling water from the Hudson River during the spring and summer. The volumes of cooling water used by the power plants are typically reduced below the maximum during the spring to improve the thermodynamics of plant operation. Greater reductions have occurred at the power plants during outages in the spring and summer. Outages can be as effective as cooling towers in reducing entrainment when they are long enough to cover, and coincide with, the

entrainment season. However, both the length and timing of normally scheduled outages cannot be forecast with certainty, particularly at nuclear plants, and the length of outages needed for normal maintenance and refueling is generally shorter than the entrainment season. If outages had to occur annually exclusively to reduce entrainment, they could cost tens of millions of dollars.

The single most important biological question in evaluating population impacts of entrainment is the extent of natural density dependent mortality. Simply stated, the resilience of the population to wide fluctuations in egg production is critical. The impact larval and juvenile mortality caused by power plant cooling systems has on subsequent recruitment to the adult population is the focus of this study. Numerous papers in the AFS symposium (Savidge et al. 1988, Lawler 1988, Christensen and Goodyear 1988, Fletcher and Deriso 1988, and Goodyear 1988) all deal with this question. Analyses of this problem follow two main approaches: the use of mechanistic models based on biological assumptions, Savidge et al 1988, Lawler 1988; and empirical analysis of spawner-recruit relationships from the data available at that time (Christensen and Goodyear 1988). It was recognized that both approaches had limitations and that there was considerable uncertainty about the intensity of compensatory mortality, and thus uncertainty about the impacts of power plant mortality.

To characterize the spawner-recruit relationship, there must be data over a broad range of spawning stock sizes with enough observations near the extremes to provide contrast (Hilborn and Walters 1992). The abundance of adult striped bass in the Hudson River increased greatly due to a series of changes in commercial and recreational fishing regulations that began in November, 1983, when the size limit was raised from 18" TL to 24" TL. In May, 1986, a moratorium on recreational fishing was imposed for one year. Between May, 1987, and September, 1990, bag limits and progressively larger size limits were imposed on the recreational fishery in order to protect the 1982 year class that was moving through the adult population. A moratorium on commercial ocean fishing also began in May, 1986, but it continued until September, 1990. After September, 1990, slot size limits and harvest caps were imposed on the commercial fishery. The reductions in the commercial and recreational harvest of striped bass increased the abundance of striped bass larvae (the most reliable measure of reproductive effort within the Hudson River estuary), 11 fold between 1985 and 1989 and almost 20-fold between 1985 and 1991.The purpose of this paper is to estimate the long term impacts of entrainment mortality on the Hudson River striped bass stock using a population model. The estimates were derived assuming alternative levels of fishing mortality in the future.

Materials and Methods

In this section we describe the data that are now available, describe the model that is fit to the data, and describe how we evaluate the consequences of future power plant entrainment.

Data Available

The types of data available for the assessment fall into several classes

(a) indices of abundance at different life history stages

(b) age structure of fish captured in the river

(c) age specific maturity, fecundity, length and weight

(d) estimates of ocean and in-river catch and exploitation rates and size limits

(e) estimates of extra mortality induced by release of under-sized fish in the ocean fishery

(f) estimates of survival of juveniles and adults from mark-recapture

(g) qualitative observations on abundance trends since 1930

(h) entrainment and impingment rates

Indices of Abundance

Since 1972 a number of data collection systems have been in place to monitor trends in abundance of different life history stages of Hudson River striped bass. Draft Environmental Impact Assessment (DEIS) Data Evaluation Workgroup (DEW) evaluated all of the available indices of abundance and selected the following:

Life history stage	Observation or survey descriptor
Annual egg production	yolk-sac-larvae (YSL) and post-yolk-sac-larvae (PYSL)
young of the year	Utilities beach seine survey (BSS), Juvenile Striped Bass (JSB), and Western Long Island age 0 (WLI-0)
age 1+	Mark recapture study (SBMR) and Western Long Island age 1 (WLI-1)
adults	Incidental bycatch of striped-bass in the shad fishery (CFM)

The DEW assigned relative reliability to the data series as follows—those rated to have high reliability were YSL, PYSL, and SBMR; the JSB index was rated slightly *above* average; BSS and CFM were rated average; while the index WLI0 was assigned a low reliability score. The values used are given in Table 1.

Age Structure

Several sampling programs have collected data on the age structure of striped bass. The following are available to us:

1. data from haul seine and gill nets from 1976-1978 published in Table 11 of Hoff (1988; shown here in Table 2),
2. age distribution of the incidental catch of striped-bass in the shad fishery from 1980-1995 (K. Hattala NYSDEC; shown in Table 3), and
3. age distribution of fish caught by NYSDEC in-river sampling 1985-1995 (K. Hattala NYSDEC; shown in Table 4).

Maturity, fecundity, length, and mass-at-age

The maturity-at-age and fecundity-at-age schedules we use are as given in Hoff et al. (1988). From this study, estimates indicate that striped bass in the Hudson River are about 50% mature at between 5 and 6 years of age (Table 5). By age 8 over 95% of striped bass have reached maturity. Growth rates average over two inches per year with an average size of 3 year olds at about 16.5 inches (Table 5).

Ocean and in-river harvest and survival

The fishery on striped bass operates in two major areas, in-river and ocean. Crecco (1993) estimated the historical pattern of fishing mortality in the ocean fishery from 1954 to 1994 for all striped bass. These data are shown in Table 6. The in-river commercial catch of striped bass in the Hudson River occurs primarily as by-catch in the shad fishery, and the data from 1930 to 1993 are shown in Table 7. The total ocean catch of striped bass for the states of New Jersey, New York, Rhode Island, Connecticut and Massachusetts are shown in Table 7. From 1989 to 1994 NYSDEC has conducted tagging studies of striped bass in the Hudson River. The estimated survival rate of these fish is 0.56 per year for fish greater than 34" and 0.61 per year for fish greater than 28" in length.

Qualitative Observations of Abundance Trends

Goodyear (1988) reviewed the known history of Hudson River striped bass, relying on Koo (1970) for much of his information. The evidence indicates that in 1930 the stocks were considerably depleted, and during the 1930's the stocks were rebuilding due to a reduction in fishing pressure. For instance, purse seines were banned in Maryland in 1932, and size limits were imposed in New York and New Jersey in 1939, in Massachusetts in 1947 and in Connecticut in 1949. "He *(Koo)* also concluded that the stock was recovering from its depleted state in the early 1930s and was in a comparatively healthy state by the mid-1960s" (Goodyear 1988). These trends refer primarily to coast-wide striped bass stock, which was dominated by Chesapeake Bay production. It is unclear how relevant this description is to the Hudson River stock. In particular, it is widely accepted that the Hudson River stock in the early 1980s was seriously depleted. The dramatic recovery in the late 1980s and 1990s is the primary evidence. In-river monitoring of eggs and larvae showed no decline. Thus it is hard to

believe that the stock was generally healthy in 1965 and yet seriously depleted by 1972 when the egg and larval survey date begin.

Figure 1 shows the trend in by-catch in the shad fishery, both in total catch and in catch-per-unit-effort (CPUE). The total catch data certainly show a peak in the late 1950's with a continuous decline to the 1980's. The CPUE data show more or less constant values from the mid-1950s to the mid 1970s. Both show a dramatic decline in the late 1970s which is not shown in the egg and larval sampling and is most likely a result of regulations prohibiting the retention of bass in the shad fishery.

Entrainment and impingement rates

The working group provided estimates of entrainment and impingement by age class. These are provided in Table 8. In this paper we simply accept these numbers as given, and make no attempt to comment on their validity.

The Model

An age structured population dynamics model, with a stock recruitment curve relating total egg production to expected 0-year-old abundance has been used. There are four sources of loss: natural mortality, fishing mortality, impingement and entrainment. The sequence of assumed events is given below

Date or time of year	Event
April 1	Spawning (discrete)
April 1	Entrainment and Impingement mortality (discrete)
April 1	In-river fishing mortality (discrete)
April 2-March 31	Natural mortality and ocean fishery (continuous)

The key characteristics of this sequence of events is the assumption that entrainment and impingement mortality, and in-river fishing mortality are discrete processes, while natural mortality and the ocean fishing mortality are simultaneous and take place over the entire year.

Survival

The notation for all equations is given in the appendix.

The dynamics of animals of age 1 and older are governed by the equation:

$$N_{y+1,a} = \begin{cases} N_{y,0} & a = 1 \\ N_{y,a-1} Y^{riv}_{y,a-1} Y^{nat}_{a-1} Y^{ocn}_{y,a-1} Y^{imp}_{y,a-1} & 2 \le a < m \\ [N_{y,m-1} + N_{y,m}] Y^{riv}_{y,m-1} Y^{nat}_{m-1} Y^{ocn}_{y,m-1} Y^{imp}_{y,m-1} & a = m \end{cases} \quad (1)$$

where $N_{y,a}$ is the numbers in year y age a, and the Y terms represent survival from the following factors

$$\begin{aligned} Y^{riv}_{y,a} &= 1 - (F^{riv}_y S^{riv}_a) && \text{in - river fishing} \\ Y^{nat}_{y,a} &= \exp[-M_a] && \text{natural mortality} \\ Y^{ocn}_{y,a} &= \exp\left\{-\left(F^{other}_y + F^{ocn}_y\right) S^{ocn}_a \left[d\left([1 - S^{\text{ocn legal}}_{a,y}]\right) + S^{\text{ocn legal}}_{a,y}\right]\right\} && \text{ocean fishing} \\ Y^{imp}_{y,a} &= (1 - U_{y,a}) && \text{impingement} \end{aligned} \quad (2)$$

In these equations F^{riv}_y is the fishing mortality rate on fully selected fish due to in-river fishing in year y, S^{riv}_a is the selectivity of the in-river fishing gear to age a fish, M_a is the instantaneous rate of natural mortality for age a, F^{ocn}_y is the fishing mortality rate on fully selected fish due to ocean fishing in year y, F^{other}_y is the fishing mortality rate on fully selected fish due to other fishing in year, S^{ocn}_a is the selectivity of the ocean hook and line gear to age a fish, $S^{\text{ocn legal}}_{a,y}$ is the proportion of age a fish in year y that are landed and above the legal size limit for the ocean fishery, d is the proportion of fish that are released which die and $U_{y,a}$ is the fraction of age a individuals which dies because of impingement during year y.

Equation 1 is true by our definition of age classes and survival factors. This is the standard age-structured model that allows for no sources of recruitment to the population after age 0, and no sources of loss other than those defined. This assumes that the values of all Y's are the same for age m-1 and age m.

Equation 2 makes specific assertions about the different sources of mortality. We have assumed that the in-river fishery acts instantaneously, and thus written the equation as a discrete process rather than a continuous one. Given the in-river catches, we compute the mortality rate by dividing the catch by the biomass of fish vulnerable to the in-river fishery:

$$\begin{aligned} F^{riv}_y &= \left[\frac{C^{riv}_y}{B^{riv}_y}\right] \\ B^{riv}_y &= \sum_a N_{y,a} S^{riv}_a w_a \end{aligned} \quad (3)$$

where S_a^{riv} is the survival from in-river fishing, C_y^{riv} is the biomass of in-river catch, B_y^{riv} is the biomass of fish vulnerable to in-river fishing, and w_a is the average weight of an individual.

We have allowed for additional fishing mortality in three blocks of years, 1932 to 1953 (F_y^{pre54}), from 1954 to 1985 (F_y^{5485}), and from 1988 to 1995 (F_y^{post88}). In 1986 and 1987 the additional fishing mortality was considered insignificant. These can be thought of as representing ocean mortality prior to 1954, and either in-river recreational fishing or underestimated ocean fishing in the 1954-1985 and 1988-1995 periods. We have, however, assumed the ocean fishing selectivity for all forms of "other" mortality because in-general the size limit of the in-river recreational fishery was more similar to the ocean fishing selectivity than to the in-river shad by-catch selectivity. An added term to account for incidental mortality of sub-legal sized bass was included (parameter d). A value of d=0.08 was used for this assessment based on estimates of survival in released fish (NYSDEC).

We assumed natural mortality is $0.15yr^{-1}$ for fish 3 years and older, consistent with guidelines issued by the Stock Assessment Review Committee of ASMFC in 1998.For ages 1 and 2 we used a value for M of $1.12\ yr^{-1}$, based on results of utilities mark-recapture studies and discussions with NYSDEC staff. Yearly estimates of impingement are shown in Table 8. The maximum age (m) is taken to be 15. The ocean fishing mortality rate has three components, F_y^{ocn} the fishing mortality rate on fully recruited age classes which was taken from Crecco (1993) for 1954 to 1993 and a two-parameter selectivity function. The selectivity of the hook and line gear S_a^{ocn} was determined from length frequency of fish hooked by anglers and was assumed to be independent of year and is shown in Table 5. In addition there is an age specific probability of being greater than the legal size limit given that the fish was hooked and landed ($S_{a,y}^{ocn\ legal}$) which changes with the size limit.

For each year we have the size limit for ocean fisheries (l_y^*) shown in Table 6. Let S_l^{ocn} be the selectivity of the hook and line gear by length, $D(x|y,z)$ be the normal density function for value x given mean y and variance z normalized to sum to one over all integer values of x, and L_l a function that is 1 if l is above the size limit and 0 if it is below the size limit. The value of $S_{a,y}^{ocn\ legal}$ was computed as:

$$S_{a,y}^{ocn\ legal} = \sum_l S_a^{ocn} D(l|l_a, \sigma_{l_a}^2) L_l$$
$$\sigma_{l_a}^2 = l_a cv_l \qquad (4)$$

Initial Conditions

In order to determine the initial age structure at the start of the projection period (1932), we assumed the age-structure was in equilibrium with respect to the fishing mortality in that year and the number of age 1 fish was $N_{1932,1}$ which is a free parameter to be estimated.

$$N_{1932,a} = \begin{cases} N_{1932,1} & a = 2 \\ N_{1932,a-1} Y_{a-1}^{nat} Y_{y,a-1}^{ocn} & 3 \le a < m \\ N_{1932,m-1} \dfrac{Y_{m-1}^{nat} Y_{y,m-1}^{ocn}}{1 - Y_{m-1}^{nat} Y_{y,m-1}^{ocn}} & a = m \end{cases} \tag{5}$$

Recruitment

We assume that the spawner recruit relationship follows the Beverton-Holt form. It was suggested by R. Deriso in a review of an earlier analysis of these data, that there may have been a gradual environmental change between 1971 and 1992. We have modified the Beverton-Holt curve to allow for this as follows:

$$\begin{aligned} N_{y,0} &= [\frac{(1-U_{y,0})(1-E_y)B_y}{(\alpha + \beta B_y)}] J_y e^{\varepsilon_y} \\ J_y &= 1 && \text{if } y \le 1971 \\ J_y &= 1 - p(y - 1972) && \text{if } 1971 < y < 1992 \\ J_y &= J_{1991} && \text{if } y > 1991 \end{aligned} \tag{6}$$

where B_y is the total egg production during year y (spawning is assumed to occur at the beginning of each year):

$$B_y = \sum_{a=1}^{m} \phi_a f_a N_{y,a} \tag{7}$$

ε_y	is the "recruitment anomaly" for year y,
ϕ_a	is the fraction of females of age a which are mature,
f_a	is the number of eggs per mature female of age a,
E_y	is the fraction of eggs/larvae which dies due to entrainment,
α, β	are stock-recruitment parameters for the Beverton-Holt,
J_y	is a YOY multiplier due to environmental conditions
p	the rate at which survival from egg to YOY declines per year after 1972

The annual entrainment rate estimates are shown in Table 8.

Values for the stock-recruitment function parameters α and β for the Beverton-Holt curve are calculated from the values of R_0 (the number of 0-year-olds in the absence of exploitation and recruitment variability) and the "steepness" of the stock-recruit relationship (h). The "steepness" is the fraction of R_0 to be expected (in the absence of recruitment variability) when the mature biomass is reduced to 20% of its virgin level (Hilborn and Walters 1992), so that:

$$\alpha = \tilde{B}_0 \frac{1-h}{4h}$$

$$\beta = \frac{5h-1}{4hR_0}$$

$$\tilde{B}_0 = \sum_{a=1}^{m} \left(\phi_a f_a \exp(-\sum_{j=1}^{a-1} m_m) \right) \tag{8}$$

where $\tilde{B}_0$ is the deterministic eggs per recruit allowing only for natural mortality.

The model allows for the possibility that recruitment is not equal to the value predicted by the stock-recruitment relationship because of the effects of random variation in the environment or changes in environmental conditions. The recruitment anomalies ε_y were estimated for years where we had year observations (1972 to 1995). In other years we set ε_y equal to $\sigma_r / 2$ so that the expectation of recruitment in years with no stochasticity is the same as the expectation in the years when we estimate recruitments. This is because the multiplicative assumption of the recruitment errors in equation 6. The expectation of $\exp(\varepsilon_y)$ is $\exp(\sigma_r / 2)$ (See Hilborn and Mangel 1997).

There are two parameters of the Beverton-Holt stock recruitment relationship. These are the virgin biomass (B_0) and the steepness (h). The most important parameter for the purposes of this analysis is steepness, which is defined as the ratio of the recruitment at 20% of virgin egg production, to recruitment at virgin egg production. If steepness is 0.20 then recruitment is proportional to total egg production and there is no density-dependent response. If steepness is close to 1, then recruitment is constant over most of the range of possible spawning stock sizes and there is very strong density-dependent response.

Likelihood for parameter estimation

The fit of any particular combination of model parameters to the available data is judged by the method of maximum likelihood. The model makes specific predictions about the numbers at age, egg production, and catch-at-age for all years from 1932 to 1993. These predictions can be compared to the observed indices, age structure, survival rates etc. The specific likelihoods we calculate and their source of data are:

a) $L_{indices}$ - relative indices of abundance, PYSL, YSL, BSS, JSB, WLI0, SBMR, and CFM (Table 1)

b) L_{age} -age composition data, Tables 2, 3, and 4

c) $L_{89\text{-}93}$ - estimated survival rate of 34" and larger fish from the NYSDEC tagging

d) L_{ocn} - estimated percentage composition of Hudson river fish in the ocean catch

e) L_{ratio} - ratio of the 1935 to 1950 population and the 1950 to 1980 population

f) L_{ε} - recruitment anomalies

a. Indices

Table 9 shows each element of the likelihood, the model quantity related to the observed quantity, and the standard deviation or coefficient of variation assigned to this element.

It is traditional to assume that the indices of abundance are linearly proportional to the abundance of the indexed age classes. However as the spawning biomass has increased there has been no concomitant increase in measures of year-class strength. It is possible, however, that the actual year-class abundance has been increasing, but that the distribution of the young has expanded so that the indices have not captured the increase in YOY. We use five measures of year-class strength, CFM BSS, JSB, SBMR, and WLI0. The first three of these are based on in-river fixed site sampling procedures which may be biased because of changing spatial distributions of the YOY and age 1 bass. To allow for this possibility we explored several alternative models that do not imply proportional changes in the indices as true YOY abundance fluctuates. All of the relative abundance indices considered in this analysis are assumed to be log-normally distributed about their estimated values. For two measures which may not be proportional to YOY strength (BSS and JSB) the three options considered we modeled as:

$$I_{i,y} = q_i (O_{i,y})^b e^{\nu_y} \tag{9}$$

For the WLI0 and SBMR indices we assume they are proportional to YOY abundance:

$$I_{i,y} = q_i O_{i,y} e^{\nu_y} \tag{10}$$

where

$I_{i,y}$ is the index of abundance for year y,

$O_{i,y}$ is the model-quantity which corresponds to $I_{i,y}$ (for example the model-quantity which corresponds to the post-yolk-sac-larvae index is the total egg production),

q_i is the constant of proportionality between the index and the model-quantity, assumed to differ for each index of abundance,

b a power parameter to allow for non-linearity in the index and assumed to be the same for BSS and JSB and

v_y is a normally distributed random variable for year y with mean 0 and variance σ_i^2.

The contribution of a relative abundance index to the likelihood function is given by:

$$L_{indices} = \prod_{i,y}\left(\frac{1}{\left(\sigma_i\sqrt{2\pi}\right)^n}\exp\left[-\frac{1}{2\sigma_i^2}\sum\ln\left(I_{i,y}/qO_{i,y}{}^b\right)^2\right]\right) \tag{11}$$

The b term was ignored for indices other than BSS, JSB and SBMR. The variable n is equal to the number of points in the data series. A value for the parameter q is obtained by partially differentiating Equation 11 with respect to q, setting the resulting equation to zero, and then solving for q which produces a general equation of the following form

$$\hat{q}_i = \exp\left[\frac{1}{n_i}\sum_y \ln\left(I_{i,y}/O_{i,y}^b\right)\right] \tag{12}$$

The values of σ_i were determined as follows. For each indicator, the DEW group specified a level of reliability, which we converted to relative value r_i. We assumed that the values of 1.0, 1.5, 2.0 and 3.0 correspond to indices assigned high, medium-high, medium, and low reliability. The σ_i for each index was then set equal to an estimated parameter σ^* times the relative scalar (r_i)for that index (See table 9).

$$\sigma_i = r_i\sigma^* \tag{13}$$

b. Proportion-at-age

The three age composition data sets were incorporated as follows. The age distribution for each year and type of data were entered as the proportion at age in the observed sample. The predicted age distribution was multiplied by a selectivity curve for each type of data, to calculate an expected proportion at age. The selectivity model was:

$$\begin{aligned} S_{a,j} &= \exp(-\left([a - a_j^{full}]^2 / 2z_j^2\right) && \text{if } a < a_j^{full} \\ S_{a,j} &= 1 && \text{if } a \geq a_j^{full} \end{aligned} \tag{14}$$

The expected proportion at age for data set j is

$$P_{a,y,j} = \frac{N_{a,y}S_{a,j}}{\sum_a N_{a,y}S_{a,j}} \tag{15}$$

The likelihood for any observed proportion-at-age data ($\rho_{a,y,j}$) and the total likelihood of the age data are:

$$L(P_{ayj}|\rho_{ayj}) = \frac{\sqrt{\rho_{ayj}}}{\sigma_{age}\sqrt{2\pi}}\exp\left(-\frac{\rho_{ayj}}{2\sigma_{age}^2}\ln\left(P_{ayj}/\rho_{ayj}\right)^2\right)$$
$$L_{age} = \prod_a\prod_y\prod_j L(P_{ayj}|\rho_{ayj}) \tag{16}$$

Thus for each of the three types of age-structure data, we have a value of a_j^{full} and of z_j^2 which we estimate as free parameters.

c. Survival

The estimated survival rate in the period 1989 to 1993 for fish tagged at 34" or greater was 0.56 per year. This was compared to the predicted survivals from the model and used in a likelihood equation as

$$L_{89-93} = \frac{1}{(cv_{89-93}\sqrt{2\pi})}\exp\left[\frac{-1}{2cv_{89-93}^2}\ln\left(\frac{\Delta 9^+}{0.56}\right)^2\right]$$
$$\Delta 9^+ = 0.2\sum_{y=1989}^{1993}\frac{\sum_{a=9}^{m}N_{y-1,a-1}}{\sum_{a=9}^{m}N_{y,a}} \tag{17}$$

The term $\Delta 9^+$ is the average total survival of age 9 and older fish from 1989 to 1993 based on the NYSDEC tagging program.

d. Ocean proportion

The model predicts the catch of Hudson River fish to the ocean fishery by the following equations:

$$C_{y,pre}^{ocn} = \sum_a \frac{F_y^{ocn}S_a^{ocn}}{\left(F_y^{ocn}+F_y^{other}\right)S_a^{ocn}+M_a}\left(1-\exp\left[-\left(F_y^{ocn}+F_y^{other}\right)S_a^{ocn}-M_a\right]\right) \tag{18}$$

This does assume that the other sources of fishing mortality were in-river, and therefore is not correct for the period prior to 1954 when we used other fishing mortality to explicitly represent ocean fishing.

We can use this predicted catch to make sure that the model predicts the total Hudson river abundance to be an appropriate order of magnitude. We considered ocean catches from New Jersey northwards, and most Hudson River fish are caught in this area.

Various estimates of the stock composition have been made and we scaled the model to aim for 15% Hudson River contribution from the period 1969 to 1975. This helps to scale the model to reasonable absolute abundance levels. The catch is incorporated into the likelihood model as follows:

$$L_{ocn} = \exp\left[- \frac{\ln\left(0.15 \cdot \sum_{y=1969}^{1975} C_y^{ocn} \Big/ \sum_{y=1969}^{1975} C_{y,pre}^{ocn} \right)^2}{2cv_{ocn}^2} \right] \tag{19}$$

e. Long term abundance trends

To assure that the model follows a time trajectory that is consistent with our understanding of the history of the population, we compare the predicted model abundance in 1935, 1950 and 1980 to specific desired ratios. As an index of population abundance we used the total egg production B_y in the years 1935, 1950 and 1980. We define the ratios as

$$\begin{aligned} R_{35-50}^{pre} &= \frac{B_{1935}}{B_{1950}} \\ R_{50-80}^{pre} &= \frac{B_{1950}}{B_{1980}} \end{aligned} \tag{20}$$

We used as target ratios 0.3 for the desired ratio between 1935 and 1950($R_{35-50}^{\text{target}}$), and 2.5 as the desired ratio between 1950 and 1980 ($R_{35-50}^{\text{target}}$). These values were chosen based on the historical evidence discussed above. The likelihood is thus:

$$L_{ratios} = \frac{\ln\left(\frac{R_{35-50}^{\text{target}}}{R_{35-50}^{\text{pre}}} \right)^2 + \ln\left(\frac{R_{50-80}^{\text{target}}}{R_{50-80}^{\text{pre}}} \right)^2}{2cv_{ratio}} \tag{21}$$

f. Recruitment anomalies

The contribution of the recruitment anomalies to the likelihood function is:

$$L_\varepsilon = \frac{1}{(\sigma_r \sqrt{2\pi})^n} \exp\left(- \frac{1}{2\,\sigma_r^2} \sum \varepsilon_y^2 \right) \tag{22}$$

where

n is the number of years for which recruitment anomalies are estimated (19 in this case),

ε_y is the recruitment anomaly for year y–the difference between the "expected" recruitment (the prediction from the stock-recruitment relationship) and the actual recruitment (see Equation 6), and

σ_r is the assumed standard deviation of the recruitment anomalies; in this analysis, σ_r is taken to be 0.6 - the basis for this selection is that it is the median of the estimates of this parameter tabulated by Beddington and Cooke (1983) for a number of species.

The total likelihood is simply the product of all the individual likelihood components:

$$L_{Total} = L_{indices} \times L_{age} \times L_{89-93} \times L_{ocn} \times L_{ratios} \times L_{\varepsilon}$$

Model fitting and evaluation of uncertainty

We began our analysis by finding the best fit to parameters using standard maximum likelihood, that is finding the values of the parameters of the model that maximize the product of all the individual likelihoods. Table 10 lists the parameters that were estimated. As is normal practice the computations were done with negative log likelihoods, which were minimized. To evaluate uncertainty and impacts of future entrainment we adopt a Bayesian framework (Berger 1985, Gelman et al. 1995). A general discussion of maximum likelihood and Bayesian methods in ecological models can be found in Hilborn and Mangel (1997).

For the numerical solution of the Bayesian analyses we used the MCMC (Monte Carlo Markov Chain) algorithm (Gelman et al. 1995) which has seen growing applications to fisheries. The MCMC method is a numerical way of integrating over all uncertain parameters and is highly efficient for developing Bayesian decision analyses. Prior distributions are assumed for several estimated parameters and (their negative-log values) are added to the negative log-likelihood functions already described. We assumed all priors were uniformly distributed over the ranges shown in Table 10.

Risk Evaluation

We made projections of the stock dynamics in the future to the year 2020 for levels of entrainment ranging from 0 to 0.8 in steps of 0.1, and different levels of ocean fishing mortality ranging from 0 to 0.8 in steps of 0.1 . The SIR algorithm was again used (10,000 draws from the posterior were used) and the following assumptions were made:

The ocean fishing size limit was 28", the in-river fishery was ignored, and environmental change stopped in 1995 and remained constant thereafter. We assumed that recruitment was stochastic with σ_r equal to 0.6.

Results

Model Fits

The basic model

Table 11 model 1 shows the maximum likelihood estimates of all the estimated parameters and in the first two rows the estimated state of the stock in 1970 and 1997 relative to the unfished equilibrium. In model 1 we are fitting the spawner recruit steepness, the selectivity parameters, the additional fishing mortality rates, and a single parameter for the overall variance of the individual indices of abundance. Figure 2 shows the fit of the individual indices to the data. The first row in Table 11 is the ratio of eggs in 1997 to eggs in the unfished condition. We estimate that in 1997 the stock was at 19% of the unexploited state. The second item in Table 11 is the ratio of eggs in 1970 to eggs in the unexploited state. We estimate that in 1970 the stock was at 3% of unexploited state. Steepness is estimated to be 1.0.

This model fits the data quite well, and provides a straightforward explanation to the available data. The stock was heavily exploited during the 1970s and early 1980s but with the dramatic reduction in catch and increase in size limit, fishing mortality was reduced, and survival to maturity increased, and the spawning stock increased about 15 fold. This explanation suggests that the spawner recruit curve is quite flat over the range of spawning stock sizes seen from 1972 onwards, and that the average year class strength has been unrelated to spawning stock size during this period.

There have been large changes in year class strength, and we can see that the two weak year classes of 1985 and 1986 show up clearly in all indices of abundance. This is valuable in that it indicates the general reliability of the individual indicators. Figure 3 shows the observed and fit age distributions for the CFM data. Again note that the 1985 and 1986 age classes show up as quite weak: 5 year olds typically constituting about 40% of the age distribution prior to 1990, and then dropping below 20% as the 1985 and 1986 year classes became 5 years olds in 1990 and 1991. This supports the belief that the changes in YOY indices are true measures of abundance rather than changes in availability to the YOY sampling gears. Figure 4 shows the fit to the NYDEC age distribution data, which also show the weak 1985 and 1986 year classes, particularly in 1992 and 1993.

The JSB is a measure of juvenile abundance in the Hudson River based on fixed sampling sites within the lower river. The SBMR is a measure of year class strength for the Hudson River population based on the recapture of age 1 fish one year after tagging. Prior to 1991 there was close agreement between the JSB and SBMR estimates. However, since 1991 the agreement between these two indices has declined. Thus, we ran the model both with and without JSB data after 1991. This is shown in Figure 5. It makes no significant difference to the model results or conclusions; both the JSB and the

SBMR show no sign of a major increase in year class strength as a result of the higher spawning stocks.

The focus of scientific attention in the legal process of the 1970s was the extent of density dependence. The change in fishing pressure in the 1980s provides a test of the density dependent hypothesis by increasing the spawning stock and egg production dramatically. We explored the extent to which this provides information on the spawner recruit relationship by calculating the likelihood profile on steepness. Likelihood profiling is a technique used to determine the relative support that the data offer for alternative levels of model parameters (Hilborn and Mangel 1997) and can also be used to compute confidence intervals for parameters in non-linear models.

Figure 6 shows the likelihood profile and Bayes posterior for steepness; note that there is no support for steepness below 0.8, and thus we can conclude that the beliefs of the 1970s that striped bass show strong density dependence was supported by the unplanned experiment of the 1980s, and that the data now available indicate very strong compensatory mortality.

Recruits per spawner and environmental change hypothesis

There is growing recognition that the environmental effects on recruitment are not necessarily random white noise, but may systematically change over time. This argument has been considered in fisheries as long as mankind has written about fish , and the debate between W.F. Thompson and Burkenroad (Skud 1975, Hilborn and Walters 1992, Smith 1994) has been an oft discussed focus in the last half century for this question. Walters (1986) popularized the term "non-stationarity" to describe temporal changes in model parameters. An alternative interpretation of the striped bass history is possible from the perspective of non-stationarity of environmental change. Figure 7 shows the BSS/PYSL plotted against time. There has been a dramatic long term decline in this ratio that the simple model, described above interprets as a density dependent spawner recruit relationship. Increasing egg production and thus PYSL has not resulted in increasing YOY because of a wide range of possible density dependent mechanisms including, cannibalism, competition for food, competition for space etc.

The alternative interpretation is that there has been a systematic decline in the environmental conditions for the life history stages between PYSL and YOY, so that the observed decline is due to changing environment rather than density dependence. Under this hypothesis, if the environment had remained constant then the YOY would have increased. In equation 6 we formulated this hypothesis in a mathematical model. The estimated value of this slope parameter in Model 1 is -0.009 which says that the environment has actually been getting better rather than worse.

We can see the extent to which the data available provide information about the rate of environmental change, which is parameterized with the term p. If p is .01 then the basic survival of YOY after density dependence declines linearly by 1% each year. If p

is .03 then survival declines by 3% each year. It is also possible that the environment has been getting better so that p has negative values. Figure 8 shows the Bayes posterior distribution for p. There is little information about this parameter from the data and p could be either range from -.03 to .05. However, if the environment has been getting worse, then there is less evidence for density dependence at the population levels of the 1970s, and therefore the impact of power plant mortality on population size is greater.

Table 11 also shows the best fit when we do not allow for environmental change (Model 2) and cases where the spawner recruit steepness is fixed at values of 0.75, 0.85 and 0.95. The most important result of these analysis is that lower steepnesses suggest the stock was more overexploited in 1970, and is currently farther below the unfished state.

Table 12 shows the individual likelihood components for models 1-5. Note here that the only major change is in the recruitment residuals, when we force the steepness to be lower, the fitting procedure compensates by adding large recruitment residuals to maintain the fit to the observed age and index data.

The environmental model in equation 6 is quite limiting, the starting and ending dates of environmental change are fixed, and the change has a strict linear form. We explored a number of variations on this form where the beginning and ending dates of environmental change were varied. To a great extent this was done because of the known changes in water quality that began and ended in the 1980s. We could not find any parameter combinations of environmental change that were consistent with steepness values that were low enough to make entrainment mortality have an impact on recruitment. This is not to say that some environmental change model could not be found which is consistent with low steepness, only that linear changes that more or less mirror the change in the YOY/egg ratio did not do so. Allowing for environmental change certainly increases the uncertainty about the spawner recruit curve, but it does not appear to increase the uncertainty about the impacts of entrainment.

Are indices proportional?

Yet another interpretation of the data is that the indices of YOY abundance are not proportional to abundance, and that as the spawning stock has increased, so has the YOY but the range of the YOY has expanded and density in the survey sites for BSS and SBMR has not increased. We have explored this quite extensively by examining the parameter b, and found that in all cases the best fits are obtained when b=1, i.e., when the indices of YOY abundance are assumed to be proportional to abundance.. If the larger spawning stocks of the late 1980s had given rise to larger year classes, then we would have expected to see this in the proportion of age data. We have seen no sign of growing year class strength in these data..

Risk analysis

Under the model considered in this paper the future condition of the striped bass population is determined dominantly by fishing. The rapid increase in spawning stock when fishing pressure was removed attests to this. We used the model to explore the consequences of both fishing mortality rate, fishing size limit, and power plant entrainment. The Atlantic States Marine Fish Commission proposes to reduce the size limit in the ocean fishery to 28 inches and increase the fishing mortality rate on fish above this size limit to F=0.4. However, the New York State Department of Environmental Conservation uses an F=0.33 as its management goal. Tables 13, 14 and 15 show the expected consequences, using full Bayesian integration described earlier, of alternative instantaneous fishing mortality rates and annual conditional mortality rates due to entrainment up to the year 2020.

The obvious conclusion here is that with a 28 inch size limit the fishing mortality largely determines the spawning stock size (Table 14), but that recruitment is largely independent of spawning stock (Table 15). This is because the integrated average effect of environmental change is more or less no change; we saw earlier that the data were consistent with both environmental improvement and environmental deterioration. So the net effect is to say that there is strong density dependence, and thus little impact of differing spawning stock sizes. We can see that at a high fishing mortality rate (F=0.6) the average spawning stock size is roughly 1/5 of the spawning stock size in the unfished state when the conditional mortality rate due to entrainment equals 0 (Table 14), but that average recruitment is only changed by a few percent (Table 15).

The impact of entrainment rates between 0 and 50% when fishing mortality rate is between 0.3 and 0.4 is negligible; the average catch would not decline if entrainment mortality increased from 0 to 10% (Table 13) and would decline from 85 thousand to 84 thousand if entrainment was increased from 0 to 20% (i.e., slightly above the maximum that the Bowline, Indian Point, and Roseton power plants could impose based on estimated through mortality rates). The impact of annual patterns of entrainment mortality that alternated between 0 and 40%, rather than a constant rate of 20% is also very small. This is not surprising since a 20% entrainment mortality rate annually would result in about a 1% reduction in recruitment assuming an instantaneous fishing mortality rate of 0.4.

Discussion

Stock history

The data available to understand the population dynamics of striped bass since 1970 are particularly informative. We have available multiple fishery-independent indices of abundance which are internally consistent for the three most important life history stages; egg/larval production, young of year, and adult population size. In addition we have a

dramatic contrast in spawning stock size induced by the reduction in fishing pressure. Few other stocks provide such a wealth of both data and contrast.

The data suggest that the stock is now at roughly 19% of its unfished state, and that in the early 1970's was severely depleted –at 3% of its virgin abundance. The implied intensity of density dependence is very high, the recruitment appears to have been, on average, the same at 3% of the virgin stock size as it is at 19%.

The future

There is considerably more uncertainty about the future than the past. A major problem with the environmental change hypothesis is it makes no prediction about the future, it is simply a possibility about what happened in the past. Thus, for purposes of evaluating harvesting and entrainment, we assumed that whatever environmental change took place in the past has now stopped changing and the future environmental conditions will be the same as those in 1991. With respect to how various changes will affect the impact of entrainment we can be somewhat more specific. The data presented here show overwhelming evidence for strong compensatory mechanisms between the PYSL and age 1. These compensatory mechanisms cause entrainment mortality to have little impact on year class strength. Changes in environmental conditions that either change carrying capacity or change survival at any life history stage other than between PYSL and age-1 would be most unlikely to impact the compensatory mechanism.

Impact of entrainment

We made no attempt in this analysis to evaluate the economic or social tradeoffs associated with alternative levels of entrainment and fishing mortality; we simply provided what we consider the best biological evaluation of the consequences. A few thousand fish would be added to the harvest by eliminating entrainment compared to an entrainment mortality rate of 50%, recruitment would be almost totally unaffected and spawning population size would be increased by a few percent. None of these differences would be of any biological significance, and we doubt that they could be measured. Entrainment at a level up to 50% offers no biological threat to the population.

It is clear from the historical data that fishing rather than entrainment is the dominant factor affecting striped bass abundance.

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Figures

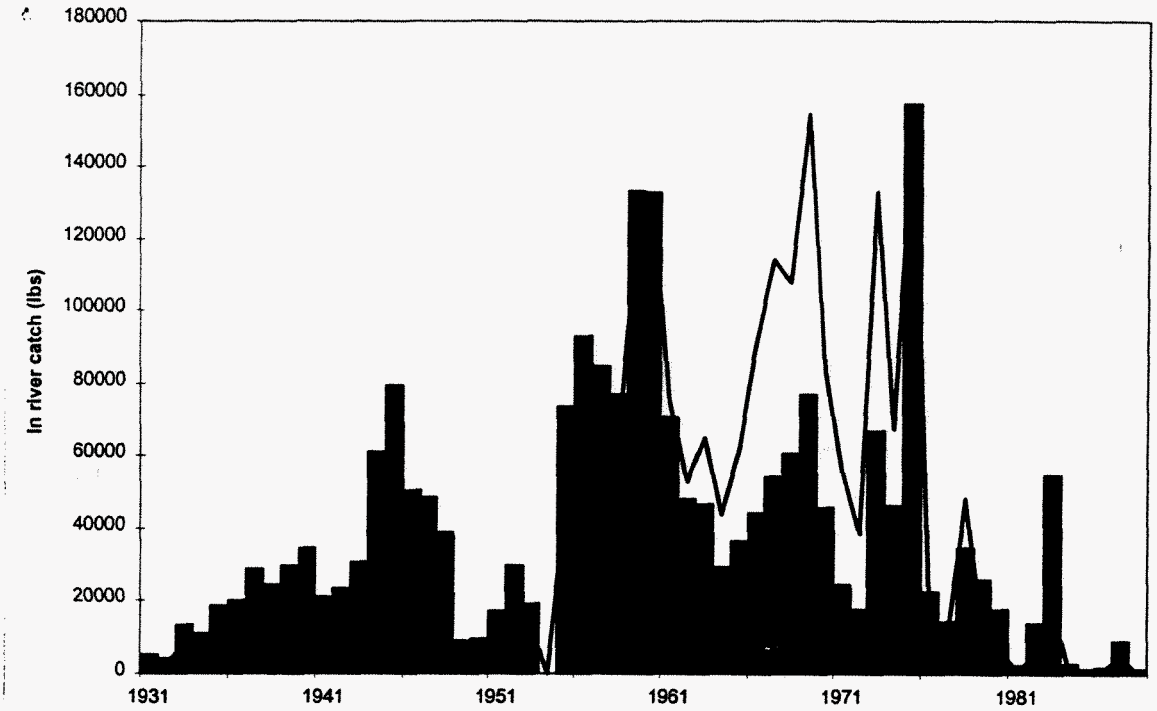

Figure 1. Incidental catch (vertical bars) and CPUE (solid line) of striped bass in the Hudson River shad fishery.

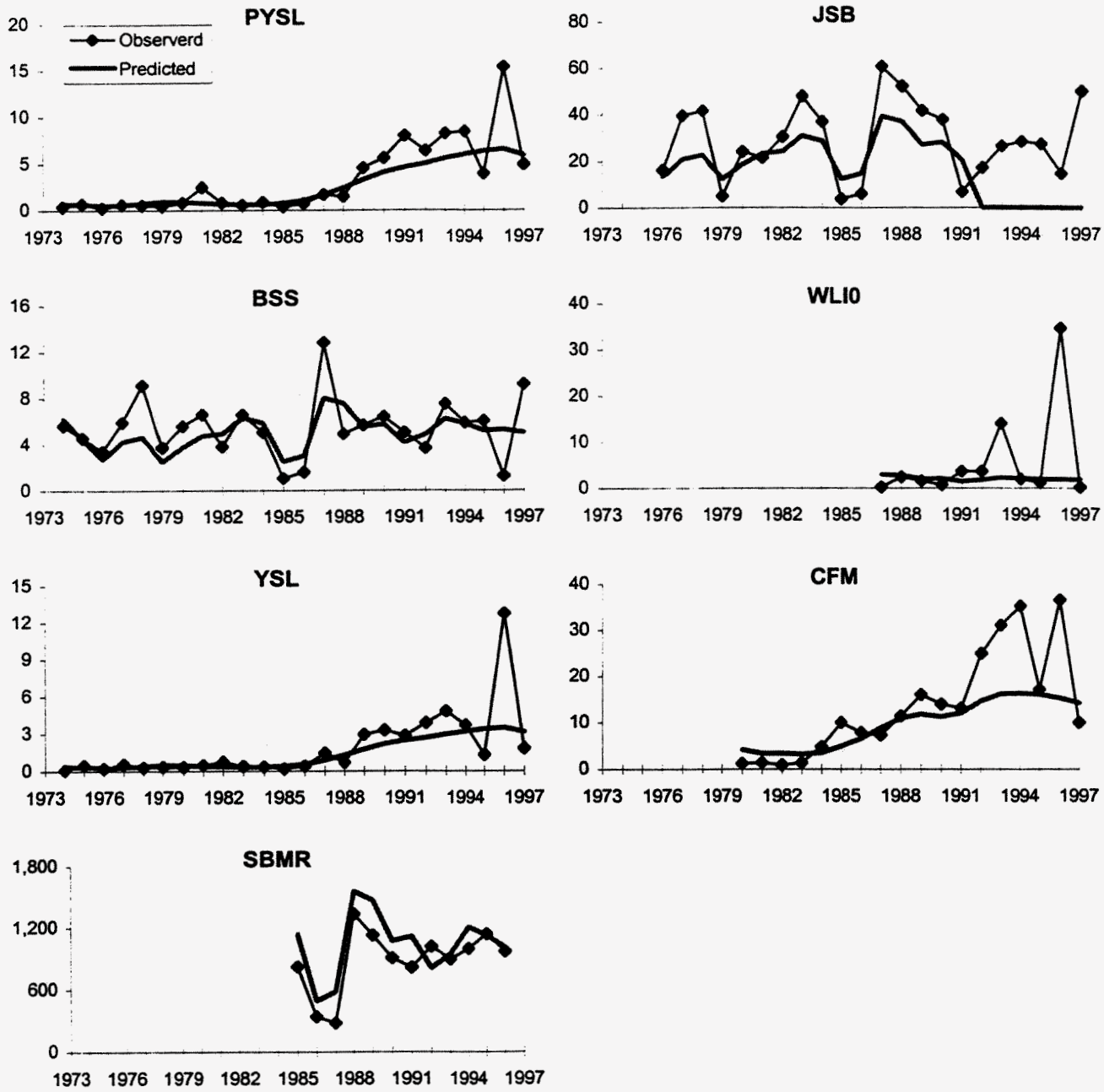

Figure 2. Model 1 fits for key indices.

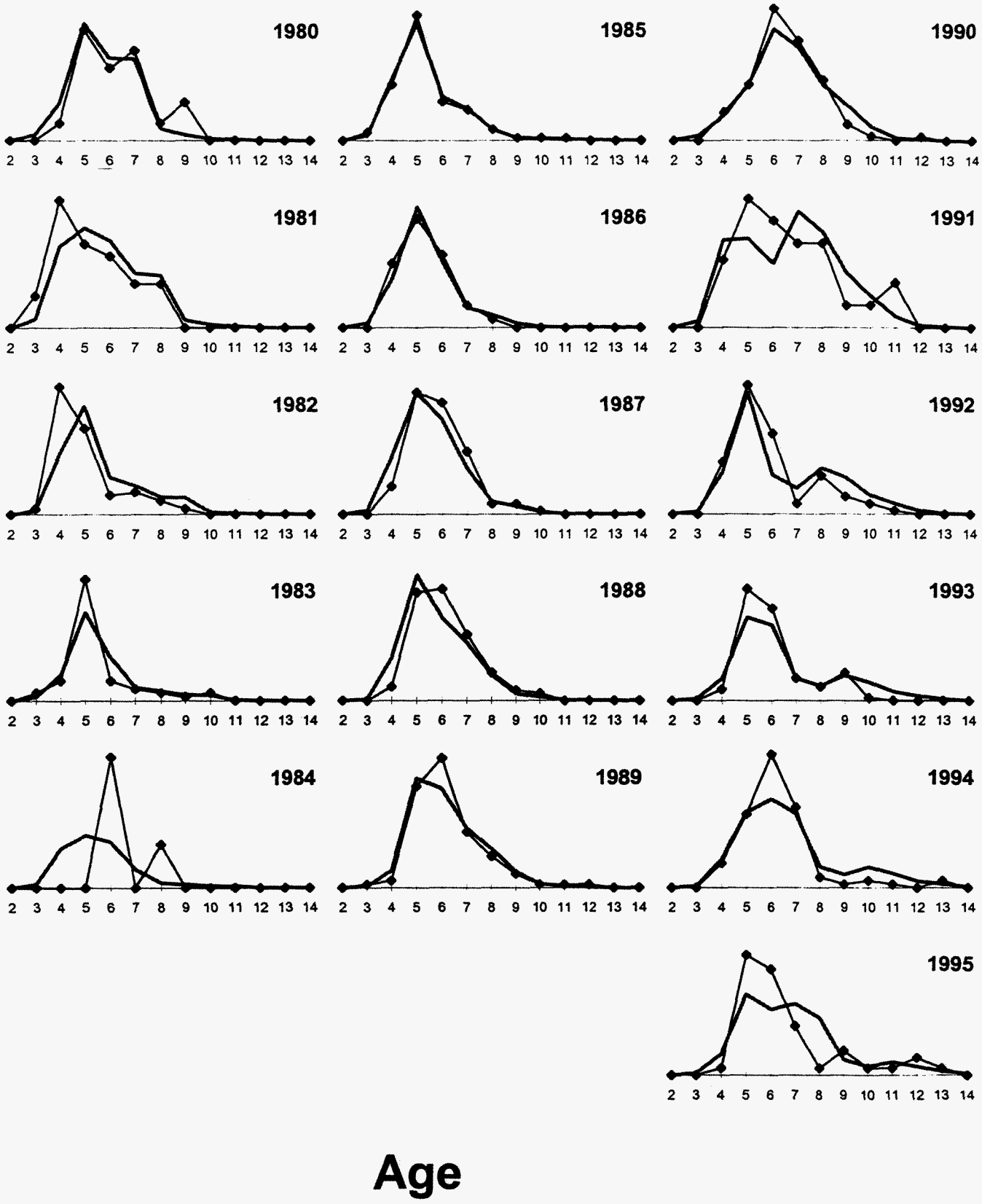

Figure 3. Age composition fits to CFM age data for Model 1.

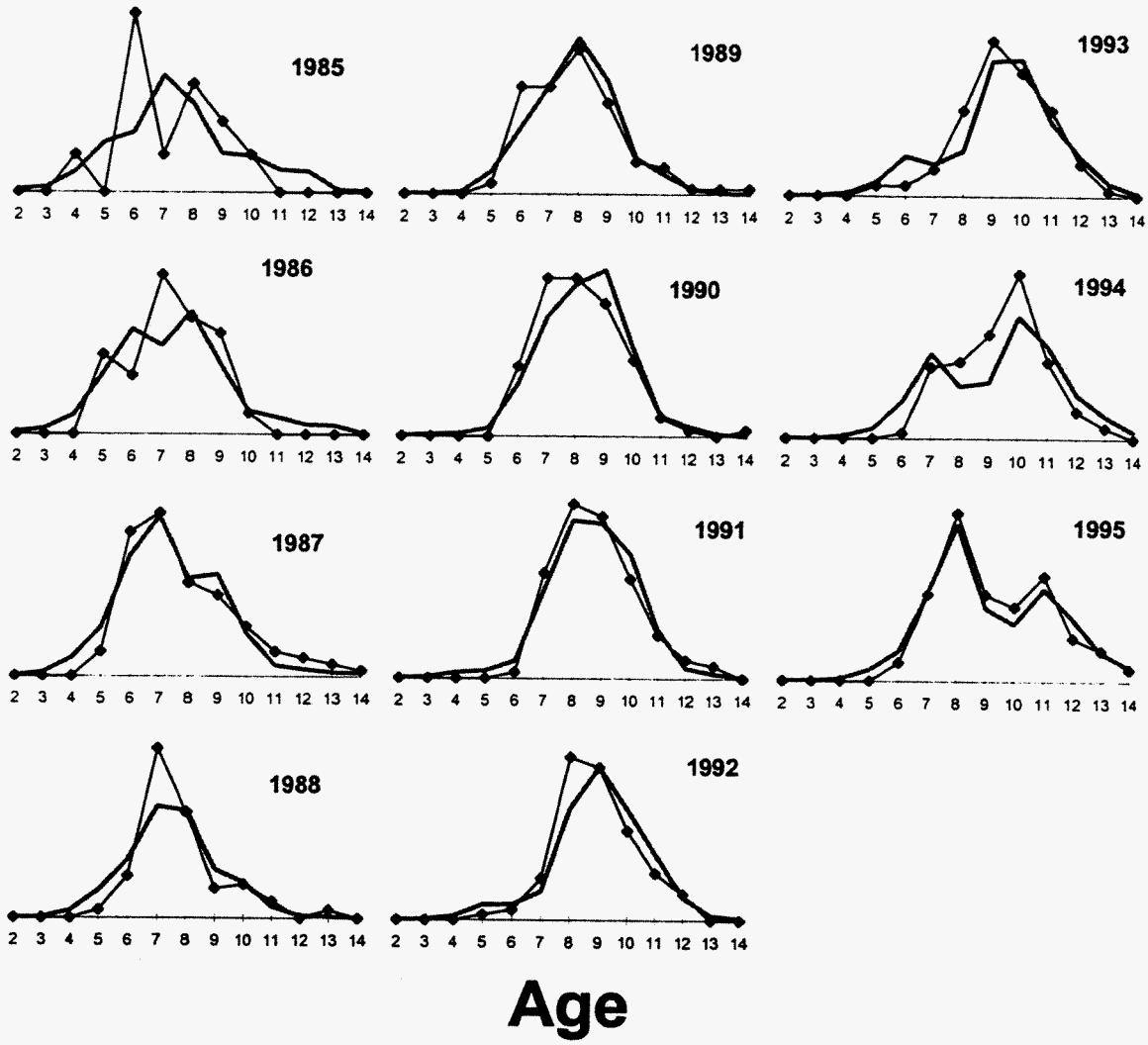

Figure 4. Age composition fits to NYDEC age data for model 1.

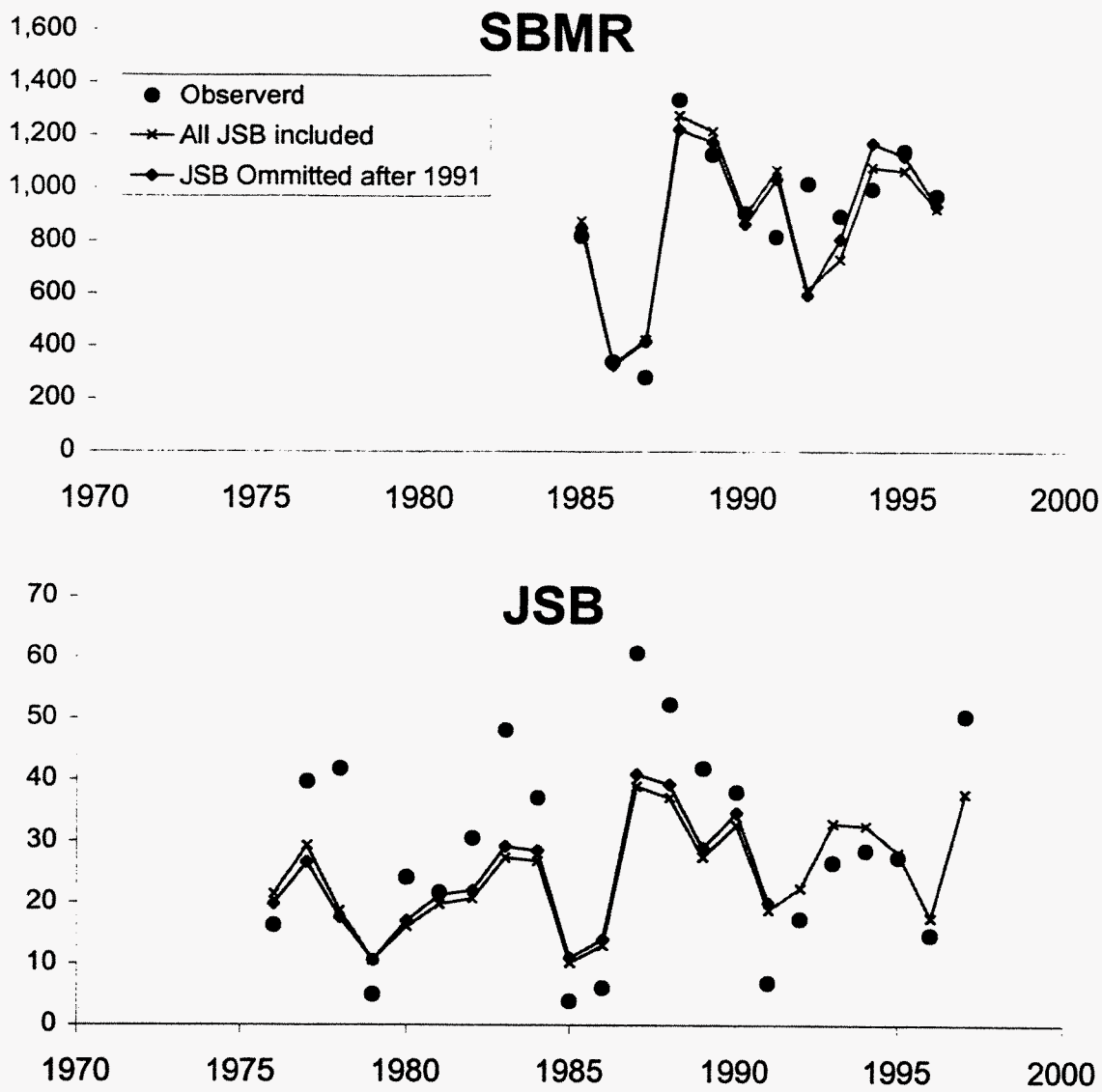

Figure 5. Sensitivity of model fit to JSB and SBMR indices to JSB data after 1991.

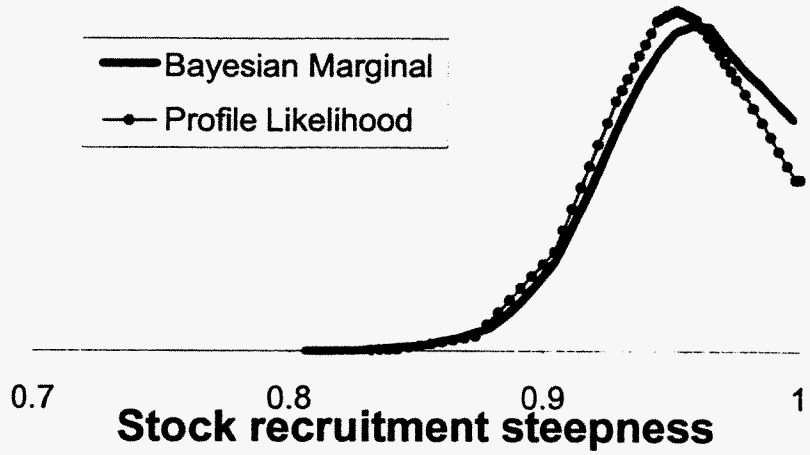

Figure 6. Relative probability based on the profile likelihood (spotted line) and Bayes MCMC posterior (solid line) of for stock-recruitment steepness.

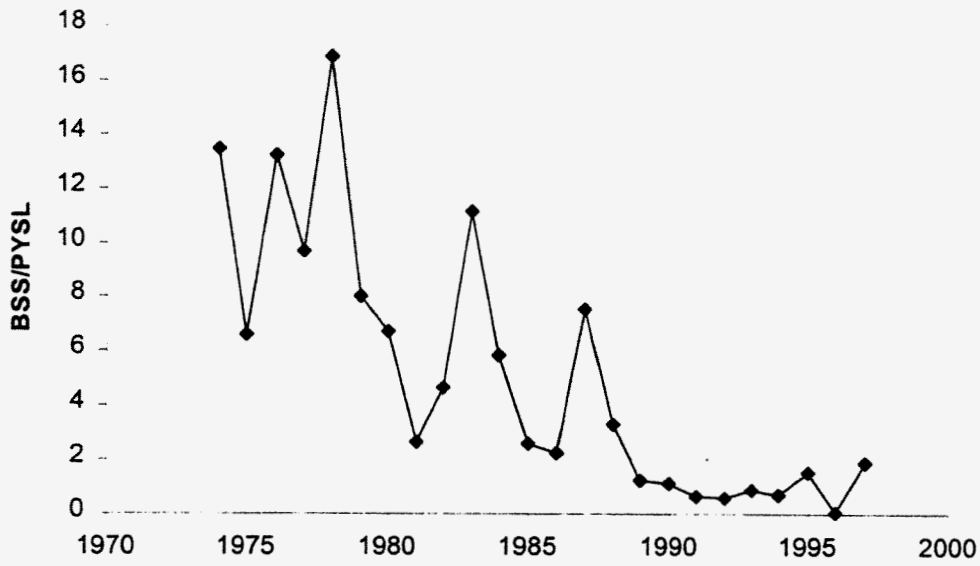

Figure 7. The temporal trend since 1972 in young of year per larvae (BSS/PYSL)

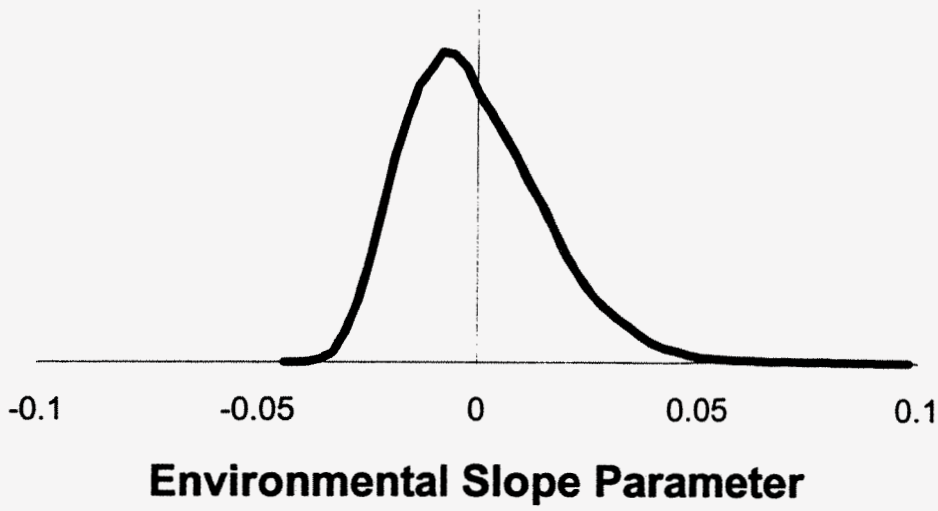

Figure 8. Bayes marginal posterior distribution on the rate of environmental change.

Table 1. Indices used in the model. All data supplied by DEW group.

	Eggs			YOY		1+	Adults
year	PYSL	YSL	BSS	JSB	WLI0	SBMR	CFM
1974	0.42	0.08	5.65				
1975	0.69	0.49	4.56				
1976	0.26	0.25	3.44	16.30			
1977	0.61	0.57	5.92	39.70			
1978	0.54	0.31	9.11	41.80			
1979	0.47	0.36	3.76	5.00			
1980	0.83	0.32	5.60	24.10			1.25
1981	2.50	0.49	6.61	21.60			1.45
1982	0.82	0.74	3.83	30.50			0.93
1983	0.59	0.39	6.58	48.10			1.38
1984	0.87	0.36	5.06	37.10			4.78
1985	0.41	0.20	1.07	3.90	0	821	9.97
1986	0.72	0.42	1.62	6.10	0	342	7.82
1987	1.70	1.45	12.82	60.70	0.26	282	7.28
1988	1.48	0.71	4.91	52.30	2.46	1,336	11.39
1989	4.54	2.94	5.66	41.90	1.58	1,128	15.99
1990	5.64	3.27	6.41	38.00	0.76	908	13.95
1991	8.01	2.85	5.03	6.90	3.7	817	13.06
1992	6.38	3.88	3.68	17.30	3.7	1,017	24.93
1993	8.25	4.81	7.50	26.50	14.07	895	31.05
1994	8.45	3.68	5.88	28.50	1.98	996	35.29
1995	3.94	1.31	6.04	27.40	1.23	1140	17.09
1996	15.40	12,74	1.25	14.70	34.76	971	36.53
1997	4.89	1.80	9.18	50.3	0.26		10.01

Table 2. Age composition data from Hoff et al. 1988 Table 11. Shown are proportion-at-age.

	Age										
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1976	0.01	0.24	0.17	0.18	0.11	0.12	0.03	0.00	0.05	0.04	0.04
1977	0.05	0.20	0.51	0.09	0.05	0.03	0.03	0.00	0.01	0.01	0.01
1978	0.00	0.08	0.15	0.39	0.09	0.08	0.08	0.04	0.01	0.02	0.03

Table 3. Age composition from bycatch of striped bass in commercial shad fishery. Shown are proportion-at-age. Data from New York Department of Environmental Conservation (NYDEC).

	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1980	0.00	0.04	0.07	0.33	0.27	0.20	0.06	0.03	0.00
1981	0.00	0.06	0.33	0.18	0.16	0.12	0.14	0.00	0.00
1982	0.00	0.03	0.42	0.28	0.06	0.12	0.05	0.02	0.00
1983	0.00	0.02	0.19	0.52	0.15	0.04	0.04	0.02	0.01
1984	0.00	0.01	0.19	0.32	0.37	0.09	0.00	0.02	0.00
1985	0.00	0.03	0.20	0.45	0.14	0.11	0.04	0.01	0.01
1986	0.00	0.00	0.23	0.39	0.26	0.08	0.03	0.00	0.00
1987	0.00	0.00	0.08	0.35	0.32	0.18	0.03	0.03	0.01
1988	0.00	0.00	0.04	0.31	0.32	0.19	0.08	0.03	0.02
1989	0.00	0.01	0.02	0.29	0.37	0.16	0.09	0.04	0.01
1990	0.00	0.00	0.07	0.14	0.33	0.25	0.15	0.04	0.01
1991	0.00	0.00	0.12	0.23	0.19	0.15	0.15	0.04	0.04
1992	0.00	0.00	0.15	0.37	0.23	0.03	0.11	0.05	0.03
1993	0.00	0.00	0.04	0.40	0.33	0.08	0.05	0.10	0.01
1994	0.00	0.00	0.07	0.21	0.38	0.23	0.03	0.01	0.02
1995	0.00	0.00	0.02	0.34	0.30	0.14	0.02	0.07	0.02

Table 4. Age composition of fish in NYSDEC marking program. Shown are proportion-at-age. Source NYDEC.

	4	5	6	7	8	9	10	11	12
1985	0.08	0.00	0.38	0.08	0.23	0.15	0.08	0.00	0.00
1986	0.00	0.15	0.11	0.30	0.22	0.19	0.04	0.00	0.00
1987	0.00	0.04	0.23	0.26	0.15	0.13	0.08	0.04	0.03
1988	0.00	0.02	0.10	0.40	0.25	0.07	0.08	0.04	0.00
1989	0.00	0.02	0.20	0.20	0.27	0.17	0.06	0.05	0.01
1990	0.00	0.00	0.11	0.25	0.25	0.21	0.12	0.03	0.01
1991	0.00	0.00	0.01	0.17	0.28	0.26	0.16	0.07	0.03
1992	0.00	0.01	0.02	0.08	0.29	0.29	0.17	0.10	0.05
1993	0.00	0.02	0.02	0.05	0.16	0.29	0.23	0.16	0.06
1994	0.00	0.00	0.01	0.13	0.14	0.19	0.30	0.14	0.05
1995	0.00	0.00	0.03	0.14	0.27	0.14	0.12	0.17	0.07

Table 5. Maturity and fecundity schedules for Hudson River striped bass. The age specific maturity and fecundity schedules are from Hoff et al. (1988) tables 12 and 14. The length and weight at age were given in Hoff et al.'s (1988) table 13. Weights and lengths of age 11 and older supplied by NYDEC.

Age	Percent Mature ϕ_a	Fecundity (000' eggs per mature female) - f_a	Length (inches)	Weight (lbs.)	Vulnerability to hook and line gear
0	0	0			0.00
1	0	0			0.02
2	0	0			0.14
3	0	0	16.44	0.77	0.43
4	3	373	18.45	2.50	0.65
5	19	585	21.24	2.60	0.84
6	62	664	23.89	3.10	0.93
7	90	830	27.30	4.50	0.97
8	95	1141	29.41	5.40	0.98
9	97	1496	33.38	7.00	0.99
10	97	1728	35.94	9.00	1.00
11	100	2022	37.56	11.00	1.00
12	100	2301	40.00	15.00	1.00
13	100	2285	42.00	18.00	1.00
14	100	2342	44.00	20.00	1.00
15+	100	2591	46.00	22.00	1.00

Table 6. Estimated instantaneous fishing mortality rate and the legal size limit in the ocean fishery. F's from Crecco (1993).

Year	F	Size Limit	Year	F	Size Limit
1954	0.35	17	1975	0.45	17
1955	0.35	17	1976	0.45	17
1956	0.35	17	1977	0.45	17
1957	0.35	17	1978	0.45	17
1958	0.35	17	1979	0.45	17
1959	0.35	17	1980	0.45	17
1960	0.35	17	1981	0.45	17
1961	0.35	17	1982	0.45	17
1962	0.35	17	1983	0.45	24
1963	0.35	17	1984	0.45	24
1964	0.35	17	1985	0.40	24
1965	0.40	17	1986	0.40	29
1966	0.40	17	1987	0.35	31
1967	0.40	17	1988	0.35	33
1968	0.40	17	1989	0.30	36
1969	0.40	17	1990	0.25	36
1970	0.45	17	1991	0.25	36
1971	0.45	17	1992	0.25	36
1972	0.45	17	1993	0.25	34
1973	0.45	17	1994	0.25	34
1974	0.45	17	1995	0.25	34

Table 7. Annual commercial catch of striped bass in the Hudson River (pounds) and in ocean the ocean (thousands of pounds). Source: NYDEC.

Year	River Catch	Ocean Catch	Year	River Catch	Ocean Catch
			1966	44300	2156
1932	4508	81	1967	54600	2766
1933	13616	75	1968	60800	3021
1934	10905	63	1969	77200	2939
1935	18667	51	1970	45900	2943
1936	20120	423	1971	24700	2329
1937	28854	795	1972	17900	2673
1938	24579	562	1973	67000	4449
1939	29937	682	1974	46179	3672
1940	34634	487	1975	157271	6144
1941	21336	518	1976	22381	2542
1942	23565	548	1977	14211	2228
1943	30889	644	1978	34570	2107
1944	60918	1030	1979	25885	1378
1945	79350	948	1980	17938	1540
1946	50622	828	1981	2405	1782
1947	48453	374	1982	13950	1386
1948	38830	509	1983	54980	703
1949	9133	800	1984	2970	768
1950	9539	782	1985	1450	662
1951	17338	1015	1986	2150	119
1952	29847	1179	1987	9080	85
1953	19352	1091	1988	1265	86
1954	0	674	1989	0	172
1955	73400	574	1990	0	244
1956	92824	450	1991	0	367
1957	84500	681	1992	0	505
1958	77100	475	1993	0	414
1959	133100	731	1994	0	414
1960	132900	923	1995	0	414
1961	70700	1512	1996	0	414
1962	48100	1785	1997	0	414
1963	46700	1960			
1964	29500	2594			
1965	36700	1987			

Table 8. Historical entrainment and impingement rates from 1974 through 1997 (see DEIS Section VI).

Year	Entrainment of eggs and larvae	Impingement of ~~eggs and larvae~~juveniles	Impingement of one year olds	Impingement of two year olds	Impingement of three year olds
1974	0.1143	0.0040	0.0270	0.0020	0.0020
1975	0.1464	0.0010	0.0260	0.0030	0.0030
1976	0.1268	0.0040	0.0100	0.0040	0.0040
1977	0.1967	0.0050	0.0190	0.0030	0.0030
1978	0.1400	0.0130	0.0130	0.0030	0.0030
1979	0.1736	0.0020	0.0320	0.0040	0.0040
1980	0.1988	0.0020	0.0150	0.0170	0.0170
1981	0.1107	0.0116	0.0116	0.0020	0.0020
1982	0.1702	0.0067	0.0067	0.0020	0.0020
1983	0.1672	0.0088	0.0088	0.0020	0.0020
1984	0.2471	0.0116	0.0116	0.0020	0.0020
1985	0.1053	0.0067	0.0067	0.0020	0.0020
1986	0.2661	0.0088	0.0088	0.0010	0.0010
1987	0.1569	0.0088	0.0088	0.0020	0.0020
1988	0.2094	0.0024	0.0024	0.0020	0.0020
1989	0.1382	0.0018	0.0018	0.0010	0.0010
1990	0.1688	0.0082	0.0082	0.0010	0.0010
1991	0.2016	0.0030	0.0030	0.0010	0.0010
1992	0.1560	0.0027	0.0027	0.0010	0.0010
1993	0.1112	0.0024	0.0024	0.0010	0.0010
1994	0.1297	0.0038	0.0038	0.0010	0.0010
1995	0.1182	0.0038	0.0038	0.0010	0.0010
1996	0.1716	0.0038	0.0038	0.0010	0.0010
1997	0.1131	0.0038	0.0038	0.0010	0.0010

Table 9. List of elements of the total likelihood. Note that measure of variability is scaled based on reliability measures.

Name of Element	Related Model Quantity	Measure of variability
Yolk-sac-larvae YSL	B_y	$1\times\sigma^*$
Post-yolk-sac-larvae PYSL	B_y	$1\times\sigma^*$
Utilities age 1+ mark recapture index SBMR	$N^b_{y,1}$	$1\times\sigma^*$
Utilities Beach Seine Survey BSS	$N^b_{y,0}$	$2\times\sigma^*$
NYSDEC Juvenile striped bass Beach seine survey JSB	$N^b_{y,0}$	$1.5\times\sigma^*$
NYSDEC shad by-catch monitoring CFM	B^{riv}_y	$2\times\sigma^*$
NYSDEC Long Island beach seine survey of age 0 WLI0	$N_{y,0}$	$3\times\sigma^*$
Hoff (1988) age distribution data	$P_{a,y,1}$	σ_{age}
Shad by-catch age distribution	$P_{a,y,2}$	σ_{age}
Age distribution in NYSDEC tagging program	$P_{a,y,3}$	σ_{age}
Survival 1989-1993	$\Delta 9^+$	cv_{89-93}
Hudson contribution to ocean catch	$C^{ocn}_{y,pre}$	cv_{ocean}
Abundance ratios between 1935, 1950 and 1980	$R^{pre}_{35-50}, R^{pre}_{50-80}$	cv_{ratio}
Recruitment anomalies	ε_y	σ_r

Table 10. List of parameters being estimated and those assumed fixed.

Parameters estimated	**Prior Assumption**
Initial population size $N_{1932,1}$	Uniform[100,10000]
Stock recruitment steepness h	Uniform[0.2, 1.0]
Recruitment at unfished equilibrium R_0	Uniform[100,10000]
Environmental change slope p^{env}	Uniform[-0.05, 0.05]
Age of full selectivity in Hoff (1988) data a_1^{full}	Uniform[1, 15]
Standard deviation of selectivity in Hoff (1988) data $\sigma_{1,age}$	Uniform[0, 100]
Age of full selectivity in shad by-catch data a_2^{full}	Uniform[1, 15]
Standard deviation of selectivity in shad by-catch age composition data $\sigma_{2,age}$	Uniform[0, 100]
Age of full selectivity in NYSDEC tagging data a_3^{full}	Uniform[1, 15]
Standard deviation of selectivity in NYSDEC tagging age composition data $\sigma_{3,age}$	Uniform[0, 100]
Ocean fishing mortality prior to 1954 F_y^{pre54}	Uniform[0,5]
Additional fishing mortality between 1954 and 1984 F_y^{5484}	Uniform[0,5]
Additional fishing mortality after 1988 F_y^{post88}	Uniform[0,5]
Standard deviation of proportion of fish at age σ_{age}	Uniform[0,5]
Recruitment residuals for 1972 to 1995 ε_y	Normal[0, σ_r]
Parameters assumed known	
Ocean fishing mortality rates from 1954 to 1993 F_y^{ocn}	Fixed values
Natural mortality rate by age M_a	Fixed values
Relative reliability of indices of abundance r_i	Fixed values
Standard deviation of length at age $\sigma_{l_a}^2$	Fixed value
Standard deviation of proportion of fish at age σ_{age}	Fixed value
Standard deviation of recruitment residuals σ_r	Fixed value
Coefficient of variation of proportion of ocean catch from Hudson River cv_{ocean}	Fixed value
Coefficient of variation of the ratio of biomass between 1935, 1950 and 1980 cv_{ratio}	Fixed value
Coefficient of variation of estimated survival from 1989-1993 cv_{89-93}	Fixed value
Mortality rate due to releases of undersized fish d	Fixed value

Table 11. Estimated parameters for different models. Model 1 is the full model. Model 2 is the same model with no environmental change. Models 3, 4, and 5 have steepness set to 0.75, 0.85, and 0.95 respectively. Model 6 is the same as Model 1 but with JSB index ignored after 1991.

	Model 1 full Model	Model 2 no environmental change	Model 3 h=0.75	Model 4 h=0.85	Model 5 h=0.95	Model 6 No JSB after 1991
$B_{1997} / \widetilde{B}_0$	0.19	0.23	0.10	0.17	0.19	0.19
$B_{1970} / \widetilde{B}_0$	0.03	0.03	0.02	0.03	0.02	0.02
H	0.951	0.956	0.750	0.850	0.950	0.9498
R_0	1,422	1,197	3,031	1,730	1,435	1,433
p_2^{env}	-0.00920	0.00000	0.03480	0.01470	-0.00929	-0.00919
a_1^{full}	14.00	14.00	5.76	12.46	14.00	14.00
$\sigma_{1,age}$	3.50	3.54	1.51	3.39	3.50	3.51
a_2^{full}	11.14	11.08	10.69	10.78	11.15	11.17
$\sigma_{2,age}$	2.19	2.18	2.13	2.13	2.19	2.20
a_3^{full}	5.26	5.24	5.22	5.22	5.26	5.26
$\sigma_{3,age}$	0.81	0.80	0.79	0.78	0.81	0.81
F_y^{pre54}	0.33	0.29	0.16	0.24	0.33	0.33
F_y^{5484}	0.18	0.14	0.00	0.05	0.18	0.17
F_y^{post88}	0.34	0.33	0.24	0.25	0.34	0.34
σ_{age}	0.21	0.21	0.21	0.21	0.21	0.21
σ^*	0.41	0.41	0.44	0.42	0.41	0.42

Table 12. Likelihood components (and totals) for the different models. The values represent negative log-likelihood values (hence smaller values indicate a better fit to the data). Model 1 is the reference case, Model 2 drops the effect of environmental change, Models 3-5 use different fixed values for stock-recruitment steepness, and Model 6 ignores JSB data after 1991.

Element	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
Total	79.01	79.17	92.74	83.83	79.01	80.95
Indices	-1.23	-1.28	6.69	1.41	-1.21	1.09
Age compositions	95.81	95.63	95.38	95.45	95.80	95.63
Long-term	4.92	5.38	2.84	4.28	4.90	4.87
Recruitment (ε)	-20.49	-20.56	-12.16	-17.31	-20.48	-20.64
Individual indices						
PYSL	-6.09	-6.34	-3.71	-5.49	-6.08	-6.10
BSS	-1.21	-1.08	1.30	-0.04	-1.21	-0.29
YSL	3.43	3.25	5.02	4.17	3.44	3.05
JSB	-2.32	-2.15	-0.08	-1.16	-2.31	0.04
SBMR	-7.90	-7.71	-8.18	-8.45	-7.91	-7.74
CFM	1.93	1.84	2.14	1.80	1.93	2.07
WLI 0	10.93	10.92	10.21	10.59	10.93	10.06

Table 13. Total harvest from the Hudson River population of striped bass based on stochastic simulations using the joint Bayesian posterior distribution projected to the year 2020 at annual conditional mortality rates due to entrainment (CMR) ranging from 0 to 0.5 and instantaneous fishing mortality rates ranging from 0 to 0.9, assuming a 28-inch size limit.

	Total Harvest in thousands									
	Instantaneous fishing mortality rate									
CMR	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0	49	72	82	85	84	81	76	71	66
0.1	0	49	72	82	85	83	80	75	70	65
0.2	0	48	72	82	84	83	79	75	69	64
0.3	0	48	71	81	84	82	79	74	68	63
0.4	0	48	71	81	83	81	78	73	67	61
0.5	0	48	70	80	82	80	76	71	65	59

Table 14. Total number of spawners from the Hudson River population of striped bass based on stochastic simulations using the joint Bayesian posterior distribution projected to the year 2020 at annual conditional mortality rates due to entrainment (CMR) ranging from 0 to 0.5 and instantaneous fishing mortality rates ranging from 0 to 0.9, assuming a 28-inch size limit.

	Total number of spawners in thousands									
	Instantaneous fishing mortality rate									
CMR	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1,631	1,161	857	652	509	405	327	267	221	184
0.1	1,629	1,159	855	650	506	403	325	265	219	182
0.2	1,625	1,156	852	647	504	400	322	263	216	179
0.3	1,621	1,152	848	644	500	397	319	260	213	176
0.4	1,616	1,147	843	639	496	392	315	255	209	172
0.5	1,607	1,139	836	632	489	386	308	249	203	166

Table 15. Total number of recruits from the Hudson River population of striped bass based on stochastic simulations using the joint Bayesian posterior distribution projected to the year 2020 at annual conditional mortality rates due to entrainment (CMR) ranging from 0 to 0.5 and instantaneous fishing mortality rates ranging from 0 to 0.9, assuming a 28-inch size limit.

	Total number of recruits in thousands									
	Instantaneous fishing mortality rate									
CMR	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	1,783	1,776	1,767	1,757	1,744	1,730	1,713	1,694	1,673	1,649
0.1	1,781	1,773	1,763	1,751	1,738	1,722	1,703	1,682	1,659	1,632
0.2	1,779	1,770	1,759	1,745	1,730	1,712	1,691	1,668	1,641	1,611
0.3	1,775	1,765	1,752	1,737	1,719	1,699	1,675	1,648	1,618	1,584
0.4	1,771	1,759	1,744	1,726	1,705	1,681	1,654	1,622	1,587	1,547
0.5	1,765	1,750	1,732	1,711	1,686	1,657	1,624	1,586	1,544	1,497

Appendix I. List of symbols and acronyms

YSL	yolk-sac-larvae
PYSL	post-yolk-sac-larvae
SBMR	Utilities age 1+ mark recapture survey
BSS	beach seine survey
JSB	Juvenile Striped Bass Survey
CFM	striped bass by-catch in in-river shad fishery
WLI0	Western Long Island 0 year old index
NYDEC	New York Department of Environmental Conservation

a	a parameter representing the maximum value of the index of abundance
a_j^{full}	the age at which fish in age-composition data set j are fully selected
b	a power parameter to allow for non-linearity between specific indices of abundance (BSS, JSB, SBMR) and the corresponding model quantity
B_y	is the total egg production during year y (spawning is assumed to occur at the beginning of each year):
B_y^{riv}	the biomass of fish vulnerable to in-river fishing in year y
$\tilde{B}_0$	is the total egg production in the absence of exploitation (and recruitment variability) expressed as a fraction of R_0.
C_y^{riv}	the biomass of fish caught by the in-river fishery in year y
$C_{y,pre}^{ocn}$	the predicted ocean catch of Hudson River fish in year y
$C_{y,total}^{ocn}$	the total ocean catch from New Jersey north in year y
cv_l	the coefficient of variation of the length of fish at any age
cv_{89-93}	the coefficient of variation of the estimated survival of age 9 and older fish from 1989 to 1993
cv_{ocean}	the coefficient of variation of the Hudson river contribution to ocean catch
cv_{ratio}	the coefficient of variation of the ratio in biomass between 1935 and 1950 and between 1950 and 1980
E_y	is the fraction of eggs/larvae which dies due to entrainment in year y,
d	the proportion of fish that die after being hooked and released
f_a	is the number of eggs per mature female of age a,
F_y^{riv}	the fishing mortality rate on fully selected fish due to in-river fishing in year y

F_y^{ocn} the fishing mortality rate on fully selected fish due to ocean fishing in year y

F_y^{other} the fishing mortality rate on fully selected fish due to other fishing in year y

F_y^{pre54} the fishing mortality rate on fully selected fish due to other fishing from 1932 to 1953

F_y^{5484} the fishing mortality rate on fully selected fish due to other fishing from 1954 to 1984

F_y^{post88} the fishing mortality rate on fully selected fish due to other fishing 1988 to 1993

h the steepness of the stock recruitment curve defined as the fraction of R_0 recruits expected when the egg production is reduced to 20% of its virgin level.

I_y the predicted value of an index of abundance in year y

J_y is a YOY multiplier due to environmental conditions

l_y^* the size limit for the ocean fishery in year y

l_a the length of age a fish

L_{ocean} the negative log likelihood related to ocean catch composition

L_{ratios} the negative log likelihood related to the ratio of 1950 to 1935 and 1980 abundance

m is the maximum age (taken to be fish age m and above).

M_a is the instantaneous rate of natural mortality for age a fish- assumed to be independent of year,

$N_{1932,1}$ is the number of animals of age 1 fish in 1932, used as an initial condition

$N_{y,a}$ is the number of animals of age a at the start of year y, a>1

$N_{y,0}$ is the number of recruits from spawning in year y

O_y the model quantity which corresponds to an index of abundance

p the rate at which survival from egg to YOY declines per year after 1972

$P_{a,y,j}$ the expected proportion at age a, year y, in age composition data set j

q the constant of proportionality between an index of abundance and the corresponding model quantity

r_i a relative measure of reliability of index of abundance i

R_0 is the number of 0-year-olds in the absence of exploitation and recruitment variability

R_{35-50}^{target} the target ratio between 1935 and 1950 biomass

R_{50-80}^{target} the target ratio between 1950 and 1980 biomass

R_{35-50}^{pre} the model-predicted ratio between 1935 and 1950 biomass

R_{50-80}^{pre} the model-predicted ratio between 1950 and 1980 biomass

S_a^{riv} the selectivity of the in-river fishing gear to age a fish (maximum=1)

$S_{a,y}^{ocn}$ the selectivity of the ocean hook and line gear to age a fish in year y (maximum=1)

$S_{a,y}^{ocn\ legal}$ the proportion of age a fish in year y that are above the legal size limit for the ocean fishery

$U_{y,a}$ is the fraction of age a individuals which dies because of impingement during year y,

w_a the mass of age a fish

Y_a^{nat} the survival from natural mortality of age a fish

$Y_{y,a}^{riv}$ the survival from in-river fishing of age a fish in year y

$Y_{y,a}^{ocn}$ the survival from ocean fishing of age a fish in year y

$Y_{y,a}^{imp}$ the survival from impingement of age a fish in year y

$\sigma_{l_a}^2$ the variance of the length of fish of age a

σ^* the standard deviation of indices of abundance which were assigned relative reliability of 1

σ_i the standard deviation of index of abundance i

$\sigma_{j,age}$ the standard deviation of selectivity at age for age distribution data set j

σ_{age} the standard deviation of age composition data, which determines the weight assigned to age composition data

σ_r the standard deviation of the recruitment anomalies

ε_y is the "recruitment anomaly" for year y,

ϕ_a is the fraction of females of age a which are mature,

α, β are stock-recruitment parameters for the Beverton-Holt,

$\rho_{a,y,j}$ the observed proportion of age a fish, year y, age composition data set j

$\Delta 9^+$ the average survival of age 9 and older fish from 1989 to 1993

Appendix VI-4-B

Atlantic Tomcod Population Modeling

An equilibrium analysis of power plant entrainment mortality on Hudson River Atlantic tomcod

Ray Hilborn
Lorraine Read

Introduction

Entrainment of Atlantic tomcod through the cooling water systems of the Bowline Point, Indian Point 2, Indian Point 3, and Roseton power plants is an issue associated with renewal of the State Pollutant Discharge Elimination System (SPDES) permits for these facilities. Population level assessments of entrainment mortality are both feasible and desirable (Van Winkle 1977). The purpose of our analysis is to examine the effects of entrainment mortality at the four power plants on the population of Atlantic tomcod in the Hudson River.

Materials and Methods

We used a simple model to calculate the long-term equilibrium population size as a function of entrainment mortality and basic population parameters. This simple approach was chosen because the most useful data series for Atlantic tomcod is relatively short, 1991-1997 (See DEIS Section V) and our confidence in a population projection model fitted to a short time series would be low. Methods that calculate the equilibrium impact of fishing mortality form the basis of many NMFS guidelines on fishing as stated Federal Register 1997-600.310(a)(3).

The basic elements of our population dynamics model are recruitment, natural mortality, maturity, fecundity, and power plant entrainment mortality. Impingement mortality was not considered because the total for all plants on the Hudson River is projected to be less than 1% (See DEIS Section VI) and thus, not consequential. As part of the recruitment modeling process we must determine which stock-recruitment relationship properly accounts for any density dependence exhibited by the stock and when that density-dependence occurs.

Data

The age specific data used in the analysis are shown in Table 1 and the year class specific data are shown in Table 2 (See DEIS Appendix to Section V). The instantaneous natural mortality rate was calculated using data from the years 1991 through 1996 by summing the number at each age across years, dividing the total number of age 2 fish by the total

number of age 1 fish, and calculating the natural log of the survival.. We assumed that all individuals die before age 3 since few 3 year olds have been observed.

Table 1. Age specific data for Atlantic tomcod from 1991 through 1997.

Age (years)	% mature	Fecundity (eggs/female)	Natural mortality
1	100	18,386	1.1
2	100	50,543	

Table 2. Year class specific data for Atlantic tomcod.

Year class	Egg deposition (billions)	Cohort combined index of PYSL/Juv	Estimated Number at age 1 (millions)	Estimated number at age 2 (millions)
1991	52	0.19	0.3	0.4
1992	7	0.06	2.2	0.2
1993	30	0.21	0.5	0.3
1994	7	0.11	2.1	0.03
1995	32	0.15	0.06	0.9
1996	2	0.09	2.4	0.6
1997	47	0.05	0.7	

+ PYSL refers to post- yolk sac larvae; see section---- for explanation of the index

Selection of the stock-recruitment relationship

Data from 1991 through 1997 were used to select the stock-recruitment relationship (See DEIS Section V).

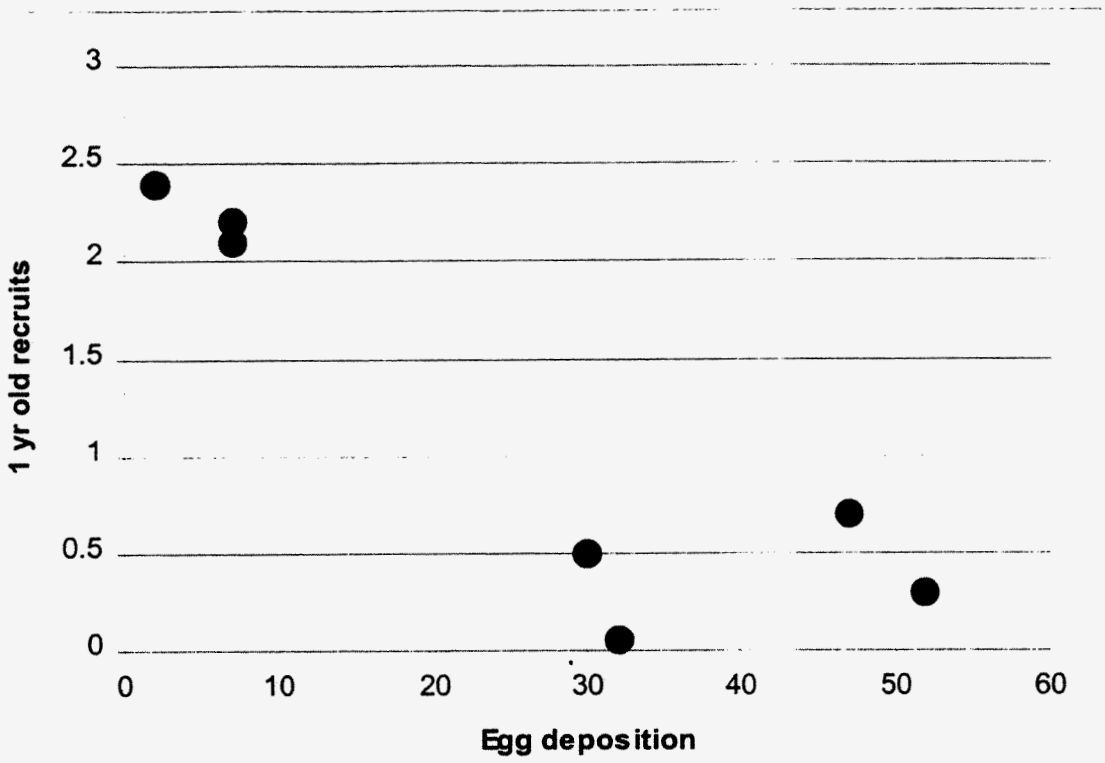

Figure 1. Spawner (egg deposition in billions) and recruit (1 year olds in millions) data for Atlantic tomcod in Hudson River.

Egg deposition (a measure of stock size) and subsequent Age 1 spawners (recruits) since 1991 strongly indicate that the Ricker curve is the appropriate form for the stock-recruit curve (Figure 2). Figure 2 also shows the best-fit Ricker curve (Hilborn and Walters 1992 chapter 7).

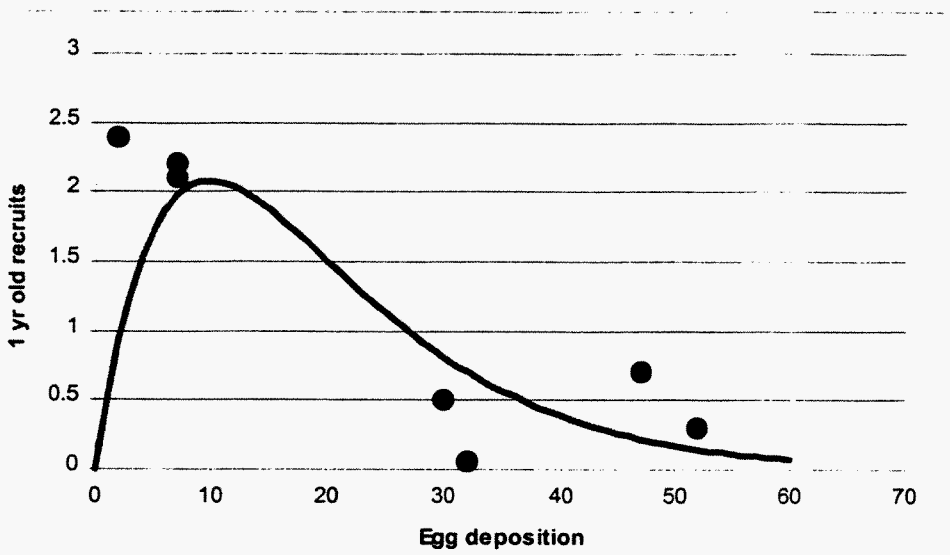

Figure 2. Egg production and age 1 recruits for 1991 to 1997 brood years with the best- fit Ricker stock-recruit curve.

Consistent with the data, we constructed our equilibrium model using the Ricker stock-recruitment relationship.

Equilibrium equations

If external influences on a fish stock could be held constant for an indefinite period of time, the stock would reach a theoretical equilibrium where recruitment is constant. Although the notion of equilibrium is theoretical, its properties are still useful for describing stock behavior in response to a change in a single variable. In particular, the equilibrium values for the stock can be expressed as a function of power plant mortality thereby providing an evaluation of the power plant impacts in an otherwise (theoretically) stable environment. The equilibrium equations for an age-structured population were derived in Lawson and Hilborn (1985), which are modified here to include entrainment. The model of tomcod life history follows the cycle described below:

- 1. Spawning – eggs are released
- 2. A period of density independent natural mortality and power plant entrainment mortality
- 3 A period of density dependent natural mortality, and impingement mortality
- 4. Recruitment measured at First birthday (Age 1)
- 5. Spawning at Age 1

- 6, Density independent natural mortality
- 7. Spawning at Age 2
- 8. Certain death after spawning at Age 2

The first step in modeling the tomcod life cycle is to derive the equation describing how many eggs are produced during spawning at equilibrium. Since the population is composed of two age classes (1 and 2), the eggs produced at equilibrium, in the absence of power plant mortality is:

$$E_\infty = m_1 f_1 R_\infty + m_2 f_2 R_\infty e^{-Z}$$
$$= R_\infty \left[m_1 f_1 + m_2 f_2 e^{-Z} \right] \qquad (1)$$

where

R_∞ is the number of age 1 recruits at equilibrium

m_a is the fraction of the population of age a which are mature females (assumed to be 50% for both age 1 and age 2 fish),

f_a is the number of eggs per mature female of age a

Z is the total mortality rate for adult fish due to natural and fishing mortality.

The life cycle is completed by an equation describing the number of age 1 recruits produced by the eggs at equilibrium. The Ricker stock-recruitment equation is:

$$R_\infty = E_\infty \exp(a - bE_\infty) \qquad (2)$$

where

R_∞ is the equilibrium recruitment,
E_∞ is the equilibrium egg production,
a is the parameter of the Ricker spawner recruit curve describing the initial slope,
b is the parameter of the Ricker spawner recruit curve describing the number of eggs that produce the maximum number of recruits.

Substituting (2) into (1) for R_∞ gives:

$$E_\infty = \frac{\ln\left[m_1 f_1 + m_2 f_2 e^{-Z} \right] + a}{b} \qquad (3)$$

Under an additional constant source of mortality from power plants acting only on pre-recruits, the population would eventually establish new equilibrium levels of egg

production (E^*_∞) and recruitment (R^*_∞). Thus (1), (2) and (3) can be rewritten to describe the new equilibrium conditions:

$$E^*_\infty = R^*_\infty \left[m_1 f_1 + m_2 f_2 e^{-Z} \right] \tag{4}$$

$$R^*_\infty = (1 - P^{post})(1 - P^{pre}) E^*_\infty \exp\left(a - b(1 - P^{pre}) E^*_\infty\right) \tag{5}$$

$$E^*_\infty = \frac{\ln\left[m_1 f_1 + m_2 f_2 e^{-Z}\right] + a + \ln(1 - P^{post}) + \ln(1 - P^{pre})}{b(1 - P^{pre})} \tag{6}$$

where

P^{pre} is the plant mortality rate that occurs prior to density dependent mechanisms
P^{post} is the plant mortality rate that occurs after density dependent mechanisms

The ratio of the two equilibrium egg productions can be used as an index of the effects of the power plant mortality on the population:

$$\frac{E^*_\infty}{E_\infty} = \frac{\ln\left[m_1 f_1 + m_2 f_2 e^{-Z}\right] + a + \ln(1 - P^{post}) + \ln(1 - P^{pre})}{(\ln\left[m_1 f_1 + m_2 f_2 e^{-Z}\right] + a)(1 - P^{pre})} \tag{7}$$

To facilitate data analysis, *a* and *b* are expressed in terms of quantities that are biologically more meaningful:

$$b = \frac{\ln(5z)}{0.8 E_\infty} \tag{8}$$

$$a = \ln\left(\frac{R_\infty}{E_\infty}\right) + bE_0 = \ln\left(\frac{R_\infty}{E_\infty}\right) + \frac{\ln(5z)}{0.8} \tag{9}$$

where

$$\left(\frac{R_\infty}{E_\infty}\right) = \left[m_1 f_1 + m_2 f_2 e^{-Z}\right]^{-1}$$

i.e., recruits per egg at equilibrium,

z = a term called steepness that is the ratio of the recruitment at 0.2 E_∞ compared to the recruitment at E_∞.

This formulation of the spawner recruit parameters has been used extensively with the Beverton-Holt relationship (Mace and Doonan 1988, Hilborn and Walters 1992), and can be easily adapted for the Ricker form. Because the Beverton-Holt curve is asymptotic the maximum value for steepness is 1.0 (that is recruits cannot be higher at 0.2 E_∞ than they

are at E_∞ but for the Ricker shape this does not hold and steepness can be greater than 1.0.

The absolute population size is determined by R_∞, but for purposes of this analysis we consider all changes in population relative, and the value of R_∞ is immaterial. Values of steepness (z) were not estimated but the sensitivity of the population to steepness was examined by assuming various values.

Timing of the density dependence

Timing of the density-dependent phenomena that determine the stock-recruitment curve is critical to assessing the effects of power plant mortality. If power plant mortality occurs prior to the density-dependent phenomena, then the effects of power plant mortality may be ameliorated by the density dependence. We can gain insight into the timing of density-dependence relative to power plant mortality by examining correlations between different life history stages. The PYSL/juvenile index measures young-of-year abundance in late May and early June, primarily but not entirely after entrainment mortality has occurred (See DEIS Section V). There is a good correlation between egg deposition and the PYSL/juvenile index, indicating little if any density dependence between these two measures (Figure 3.)

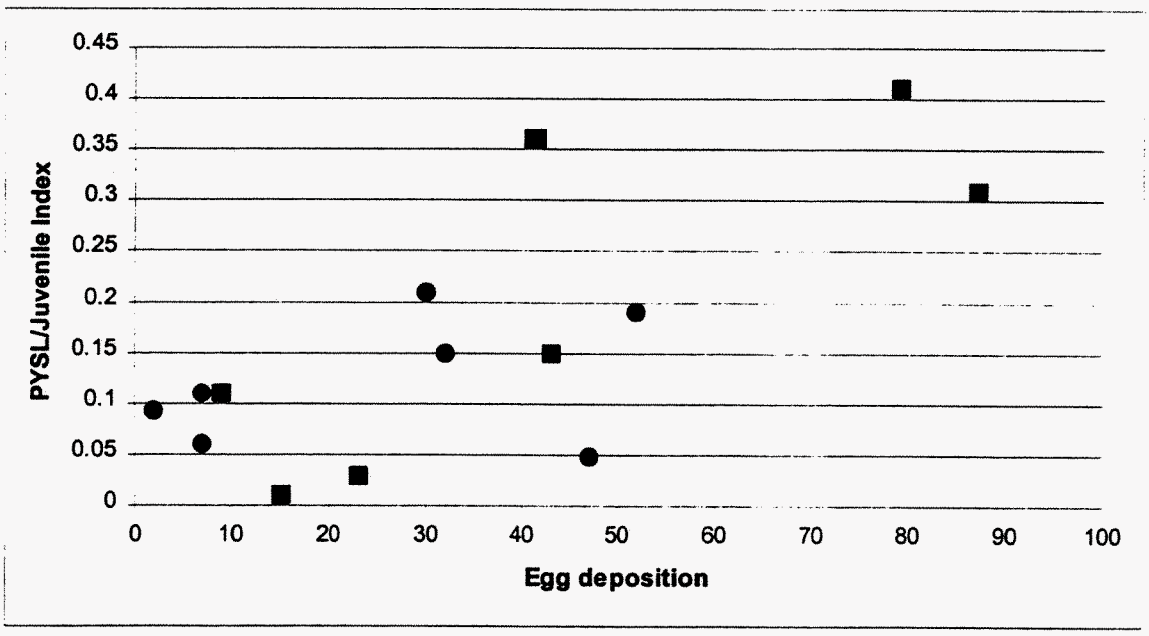

Figure 3. Relationship between egg deposition and PYSL/juvenile index. Circles indicate data from 1991-1997, squares represent data before 1991.

We find the opposite pattern when we look at the relationship between the juvenile index and the age 1 estimates as seen in Figure 4. Here we see almost no correlation, indicating strong density dependence.

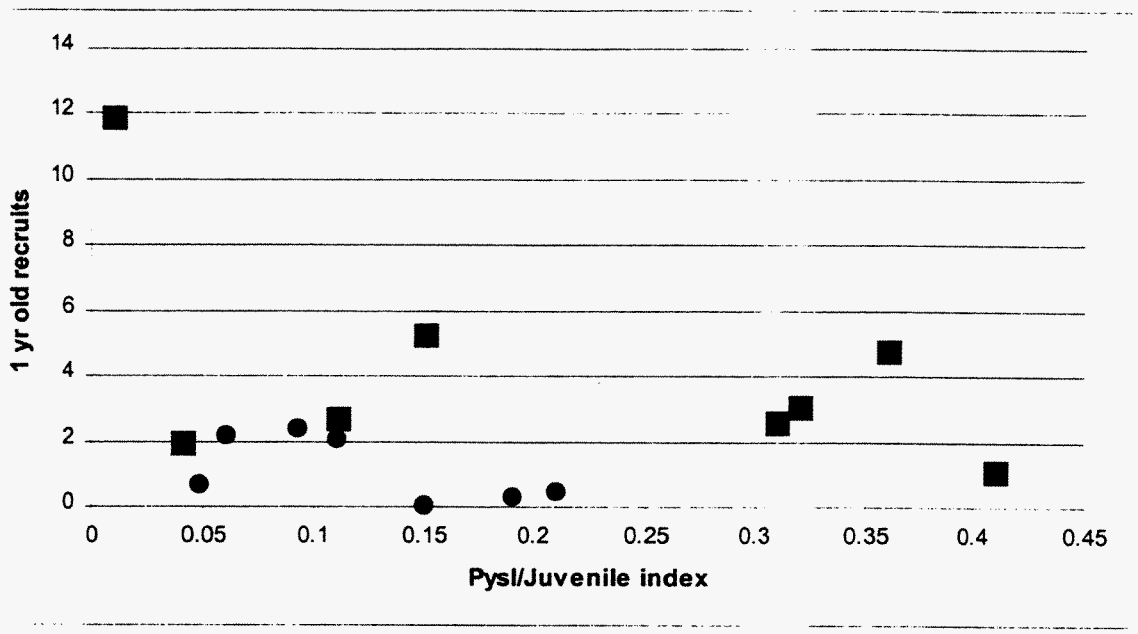

Figure 4. Relationship between the PYSL/juvenile index and age 1 abundance. Squares are data prior to 1991, circles are data from 1991 to 1997.

The highest mortality during the juvenile stage occurs during the summer months, which would be expected for a boreal species at the southern limit of its breeding range (Dew and Hecht 1994). The density dependent mortality probably occurs during July and August when the water temperature reaches it seasonal maximum (See DEIS Section V). Thus, most entrainment mortality occurs prior to the density dependent mortality.

Results

The estimated steepness from the Ricker fit in Figure 2 is approximately 1.7, indicating that the productivity of this stock is much greater at lower levels of spawning biomass with the maximum recruitment rate occurring at spawning biomass levels around 0.4 of E_0.

For these data and the Ricker stock-recruit curve, we explored steepness values ranging from 0.5 to 2.0 and entrainment mortality rates ranging from 0 to 0.5. These ranges bracket the range of reasonable values. Figure 5 and Table 3 show the relationship between pre-density dependent plant mortality, spawner recruit steepness and equilibrium egg production assuming the Ricker spawner recruit curve.

The average annual entrainment mortality rate from 1974 through 1997 for the Bowline Point, Indian Point, and Roseton power plants was 22% based on estimated through-plant

survival and 29% assuming 100% through-plant mortality (See DESI Section V). For an entrainment mortality rate of 22%, egg production after entrainment is expected to be greater than or equal to100% of virgin stock size for steepness ranging from 0.5 to 2.0. For an entrainment mortality rate of 29%, egg production after entrainment is expected to be greater than or equal to100% of virgin stock size for steepness ranging from 0.7 to 2.0 and 99% of virgin stock size for steepness of 0.5.

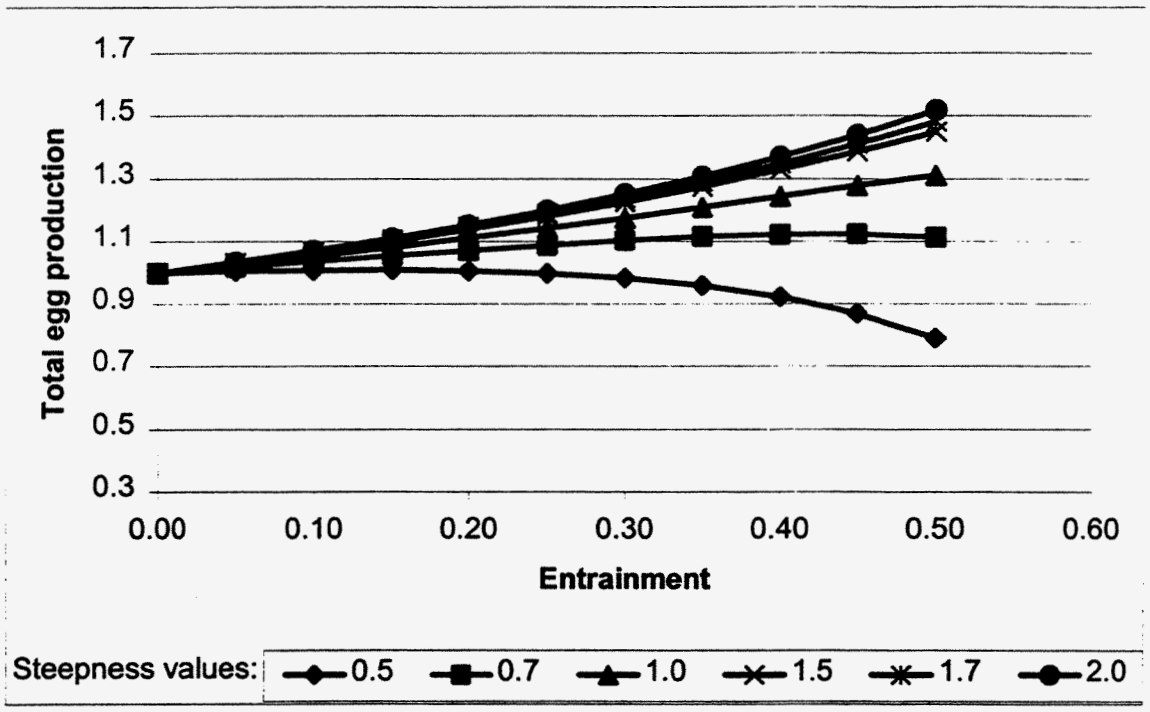

Figure 5. Ricker total egg production (expressed relative to E_0, egg production in the absence of plant impacts) vs. plant entrainment mortality for six steepness values, with all plant impacts occurring prior to density dependence.

Table 3. Ricker equilibrium egg production expressed relative to E_0 for six steepness values and 11 pre-compensation entrainment mortality levels.

Pre-Compensation Entrainment Mortality	Steepness					
	0.5	0.7	1.0	1.5	1.7	2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000
0.05	1.005	1.018	1.026	1.031	1.032	1.034
0.10	1.009	1.036	1.053	1.065	1.067	1.070
0.15	1.010	1.054	1.081	1.101	1.105	1.110
0.20	1.006	1.072	1.111	1.139	1.146	1.153
0.25	0.998	1.088	1.143	1.181	1.190	1.200
0.30	0.984	1.103	1.175	1.226	1.238	1.252
0.35	0.960	1.115	1.209	1.275	1.291	1.308
0.40	0.923	1.123	1.243	1.329	1.348	1.371
0.45	0.869	1.124	1.278	1.387	1.412	1.441
0.50	0.790	1.115	1.311	1.450	1.482	1.518

Discussion

Based on the empirical pattern of egg deposition, PYSL and juvenile abundance, and recruitment observed in the Hudson River since 1991, the Atlantic tomcod population would appear to be robust to the effects of power plant entrainment. Only if the steepness parameter of the stock-recruitment relationship were as low as 0.5 and entrainment mortality above 20%, would the equilibrium egg production decline. At the level of steepness estimated from the data (1.7), or at any steepness higher than 0.7, entrainment mortality would actually raise the equilibrium egg production by decreasing the competition at the early life stages and lower the density-dependent mortality. Thus, if the processes regulating the tomcod population since 1991 continue in the future, entrainment mortality would appear to pose no threat to the Hudson River tomcod population.

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Appendix VI-4-C

American Shad Population Modeling

Hudson River Shad Assessment and Equilibrium Calculations: Revision of the 1995 Report to include data through 1997

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May 1999

Summary

This report summarizes stock assessment and equilibrium calculations on American shad of the Hudson River based on the method described in Deriso *et al* (1995). Research reported here is directed towards addressing two subjects: (1) a statistical estimation of abundance, fishing mortality, and certain critical life-history parameters of shad during the last roughly twenty years, (2) Equilibrium calculations of commercial yield of the shad fishery and of abundance of one-year-olds based on results from the estimation phase of the research and from results of application of the long-term model of Walters (1994).

Results show that the total fishing mortality on older shad have averaged around 0.25 (sd = 0.11) between 1974-1997. Median abundance of one-year-olds is estimated at 1.3 (sd = 0.61) million fish during that time period. The sum of natural mortality rate plus unreported fishing mortality rate for adult females (males) is estimated at 0.54 (0.81) annually. A cycle of low-high-low-medium abundance of adults is estimated for the period 1974-1997. While less precise than earlier years, the mid-1990s indicate an increase in abundance from the low point around 1990. Our result reported in 1995 that the 1989 and 1990 year-classes appear to be somewhat above average has proven to be the case. Those year-classes were followed by even strong year-classes in 1992-1994. Preliminary indications from the juvenile indices are that the 1995-1997 year-classes could be below average and warrant some concern for the near-term future of the stock.

Equilibrium calculations were made for each of three hypotheses regarding (S-R) spawner-recruit relationships. Those three hypotheses are based on assumptions of low, moderate, and high density-dependent mortality in the S-R relationship, as measured by a parameter *b* described in the paper. High density-dependence is indicated by fitting a Beverton-Holt S-R model to recent (1974-1994) estimates. Moderate to low density-dependence is indicated by the long-term model of Walters (1994). Equilibrium calculations show that the shad stock is fully-exploited to over-exploited unless one assumes high density-dependence.

Estimation Methods

Maximum likelihood estimates of abundance were obtained by fitting an age-specific and sex-specific population model to several types of data. The model treats separately four groups of shad: immature females, mature females, immature males, and mature males. Age-specific time-dependent dynamics are modeled for each of the four groups along with transition rates to describe the shift from one state (immature) to another (mature). The transition is assumed to be permanent so that once an individual becomes sexually mature then that fish would continue to spawn each year until death. The time sequence of events during any given year is assumed to be the following:

1. Annual rate of transition from immature state to mature state occurs.
2. Coastal harvesting occurs.
3. In-river commercial fishing occurs on mature fish.
4. Haul seine survey samples are taken from the escapement, which are the spawning fish.
5. Natural mortality is applied for the calendar year.

Equations to describe the dynamics are similar for males and females. Let y represent the abundance of immature females, then annual mortality and loss of immatures to the mature state are accounted for in the dynamics by the following equation,

$$y(a+1,t+1) = [1 - p(a)]y(a,t)e^{-M-Focean(a,t)}$$

for which *Focean(a,t)* is the age-specific fishing mortality rate in the coastal ocean fishery, which is assumed to be 0 for ages younger than three years of age and a constant for those fish age three and older. The quantity *p(a)* is the proportion of age *a* immature fish that become mature in year *t*. The *p(a)* estimates for the model are obtained by including in the model estimation of a generalized logistic maturity function, given by

$$p(a) = [1 + e^{-arate(a-amid)}]^{-apower}$$

in which sex-specific sets of the parameters *arate, amid, apower* are fitted as part of the likelihood. Two additional assumptions are made about the maturity ogive: female shad age 9 and older are assumed to be 100% mature; secondly, male shad age 8 and older are assumed to be 100% mature.

Abundance of mature fish, denoted by symbol x, are described by a model that contains recruitment from the immature state and losses due to gill-net and coastal ocean fishing. The abundance equations for mature fish, evaluated prior to a current year coastal ocean fishing, are given by

$$x(a,t,afirst) = p(a)y(a,t,afirst) \quad \text{for newly mature}$$

$$x(a+1,t+1,afirst) = x(a,t,afirst)e^{-M-Fgill(a,t)-Focean(a,t)}$$

for those who were mature previously at age *afirst*. The equations above generate a matrix of abundance by sex for each given age and given age of first maturity.

The gill-net fishery modeled above operates within the Hudson River. Size-specific gill-net fishing mortality is modeled as a separable function of the sex-specific median length of fish and year, as follows:

$$Fgill(a,t) = \exp\{-.5[(l(a) - lbar)/ls]^2\}Fg(t)$$

where *lbar* and *ls* are selectivity shape parameters estimated, where *l(a)* are the median sex-specific lengths by age given in Table 3, and where *Fg(t)* is the fully vulnerable gill-net fishing mortality for year *t*, which is a parameter estimated by the model.

Predicted catch by the Hudson River fishery is obtained by summing abundance of the mature fish weighted by their body weight and by gill-net fishing exploitation:

$$Cgill(t) = \sum_{sex,a,aft} w(a,t)x(a,t,af)e^{-Focean(a,t)}[1 - e^{-Fgill(a,t)}]$$

Likewise, coastal landings are predicted by

$$Cocean(t) = \sum_{sex,a,afirst} w(a,t)[y(a,t) + x(a,t,afirst)][1 - e^{-Focean(a,t)}$$

where care is taken not to double-count the newly mature fish.

Repeat spawning data collected from the Hudson River fishery and from NYDEC haul seines provide estimates of age composition. The Hudson River fishery samples represent fish that escaped that year's coastal fishery. The predicted proportion, *pgill,* of a given sex of fish of given age *a* with first spawning age *afirst* is written as

$$pgill(a,t,sex,afirst) = cgill(a,t,sex,afirst) / cgill(\cdot,t,\cdot,\cdot)]$$

where *cgill ( )* denotes predicted number of fish caught with attributes listed in the parentheses. A similar calculation can be made for samples collected by the haul seines. Age-specific fishing within the Hudson differs by age so that in-river mortality must be included in the equation to describe the predicted proportion, *phaul*, of, say females in the haul seines, as follows:

$$phaul(a,t,afirst) = x(a,t,afirst)e^{-Fgill(a,t)} / [\sum x(j,t,jfirst)e^{-Fgill(j,t)}]$$

where the denominator is simply total escapement of mature fish from the gill-net fishery.

We found it unnecessary to formally model the length distributions by age and sex of catches. This improvement over the 1995 model was made possible by improvements in the amount of age composition data now available for shad.

Equilibrium Calculation Methods

Recruitment is assumed to be given by a S-R function in order to calculate equilibrium. The Beverton-Holt S-R function with the parameterization given in Walters 1994 was used. In this parameterization, recruitment, defined here as abundance of one-year-olds (given by the immatures) is given by

$$y(1,t+1)=E_t\,(1-e_t)R_0(1+b)/[bE_0+E_t(1-pe_t)]$$

where e is the entrainment-impingement loss rate, p is the proportion of entrainment-impingement occurring before compensation (assumed $p=0.5$), R_0 is the unfished recruitment rate (millions of age 1 fish), E_0 is the unfished egg production, and b is the compensation parameter. The compensation parameter b is mathematically the fraction of virgin egg production needed to produce one-half the maximum, asymptotic recruitment. As a measure of density-dependence, low values of b correspond to high density-dependent mortality (that is recruitment would stay high even with a large reduction in egg production).

Based on the parameters listed in Table 3, life-time egg production of a single recruit can be calculated for any given schedule of fishing mortality. In particular, we can calculate a schedule of fishing mortality by multiplying both the age/sex specific rates of gill-net and coastal ocean fishing mortality listed in Table 3 by a multiplier f. A value f=1 corresponds to the average fishing mortality rates estimated for the 1974-1997 time period. Denote the life-time egg production of a single recruit by the notation rv, which stands for reproductive value of a recruit; note that rv is as a function of f. At equilibrium we equate egg production with the product of recruitment and reproductive value to get

$$E=rv\,E\,(1-e)R_0(1+b)/[bE_0+E(1-pe)]$$

and solve for E to find

$$E=[rv\,(1-e)R_0(1+b)-bE_0]/(1-pe).$$

Equilibrium egg production is projected through the S-R function to project equilibrium recruits, which are in turn projected through the abundance dynamic equations and catch prediction equations listed in the previous section. The projected catches and abundance are all equilibrium calculations as a function of the fishing mortality multiplier f and assumed entrainment-impingement rate e.

Materials

Data listed in Tables 1 and 2 were used in the estimation. Table 1 lists sample age composition data collected from the Hudson River commercial fishery and from the NYDEC haul seine samples. That information is stratified by year, sex of fish, current age, and age of first spawning. Commercial aged fishery samples were available from 1980 to 1995. Haul seine aged samples were available from 1983 to 1997 excluding 1996.

Indices of abundance are listed in Table 2. They include PYSL index of post-sac larvae sampling from 1974 – 1996. The juvenile JASG index is available from 1980 through 1997. The catch-per-unit-effort indices were calculated by year as the cumulative of weekly estimates for fixed gill net fishing in the Hudson River. Landings data are also fitted by the model and the coastal component of the catch was revised upward from ASFMC estimates to provide NYDEC "best" estimates. We use the "best" estimates in our fitting of the population model.

Likelihood Function

The model was fitted to the data by maximum likelihood. The likelihood for the assessment model has several components:

1. log-normal PYSL assumption ,
2. log-normal juvenile JASG assumption,
3. log-normal landings assumption,
4. log-normal gill-net CPUE indices for sex-specific catches of fish, and
5. multinomial repeat spawning samples for each sex of fish for each of the two gear types.

Components (1)-(4) have log-normal error assumptions, similar to those assumed in our 1995 paper. The multinomial assumption in (5) gives a way to assign relative weighting of the various repeat spawning data. However, one weakness of the multinomial assumption is that it can over-weight the influence of the age or length data if sampling of the Hudson River stock does not occur strictly on a random sampling basis. We have chosen to assign a weighting factor to each component so that they can be adjusted to adjust the influence of each component on the likelihood estimates.

The log-likelihood for this problem can be written as

$$\ln L = C + \lambda_0 \sum c_{a,t,b} \ln(p_{a,t,b}) - \sum_i \lambda_i SSQ_i$$

up to a constant C and a constant proportionality factor. The weighting coefficients theoretically represent a ratio of variances for the log-normal data. Let component (1) be the standard then λ_j is the ratio, Var(index 1)/ Var(index j). The multinomial component has the λ_0 equal to 2Var(index 1). The notation SSQ indicates residual sum of squares.

The first group of "*c*" data are the observed repeat sample data and the first group of *p* quantities are the corresponding predicted proportions of fish with attributes of age *a* and first spawning age *b*. Initial fitting of the model indicates indices have variances of roughly 0.5 or larger. Thus a straight multinomial weighting would assign λo to be above 1.0. The base case weighting was chosen to have all λ 's for the indices set to 1.0 and λ for the landings set to 10.0 (to insure the model fits closely observed landings), and λ_0 set to 0.5 to insure the age and length data is not over-weighted.

The base runs of the estimation routine fit 1105 data points with 95 parameters. The parameters fitted are the following: year-class strengths from 1971-1995 [we assume that year-class strength in 1996 and 1997 equal 1995 due to a lack of data], the parameters governing gill-net selectivity and sex-specific maturity, full-recruitment fishing mortality rates for ocean and gill-net fishing for 1970-1997, initial conditions for abundance in 1970, and natural mortality rate of mature females and males. The computer program internally computes scaling factors for the pysl and juv JASG indices. Initial conditions for the modeled abundance's was determined by adding a parameter for total initial annual mortality and assuming stationarity of the initial age composition with respect to that mortality and the initial 1970 year-class strength parameter. Natural mortality rate was assumed to be 0.3 annually for the sexually immature fish, in accordance with our previous paper.

Assessments were made with the full model, which includes everything listed in the likelihood equation above.

Estimation Results

Estimated abundance by sex and year are shown in Tables 4 and 5. Fishing mortality rates given in Table 5 are lower than in our 1995 paper due to the larger estimate of natural mortality found for older shad. Results indicate M=.53 (sd=.06) for mature female shad and M=0.80 (sd=.04) for mature males. Those natural mortality rates are likely biased high because of unreported catches, which would be attributed in the model to natural mortality. Abundance estimates of mature shad in the Hudson River are shown in Figure 6. Those estimates compare favorably with estimates obtained from tagging studies (Hattala et al 1998), although the tagging results indicate a considerable range in the abundance estimates.

This report supports the overall conclusion in our 1995 report and in Walters (1994) that by 1990 the stock was substantially lower in abundance than present in 1930. With more data we now conclude that in recent years a partial recovery of the stock has taken place .

Equilibrium Results

Equilibrium calculations of fishery yield and abundance of one-year-olds were made for several combinations of fishing mortality, entrainment rates, and levels of density-

dependence of recruitment survival. Different levels of overall fishing mortality were calculated by scaling the age and sex-specific rates listed in Table 3 by multiplying them by a fixed scalar, defined to be the Fishing Mortality Multiplier. A Multiplier value of 1.0 corresponds to the average level of fishing mortality for 1974-1997, as calculated from the full assessment model. For reference, the total fishing mortality of females at age of full-vulnerability is 0.25 in the Table 5. Levels of density dependence correspond to those discussed in our 1995 paper for which b=0.01, 0.20, and 0.50 correspond to high, moderate, and low levels of density dependence.

Figures 4 and 5 show equilibrium yield and abundance of one-year-olds, respectively, for varying levels of fishing mortality in each panel. Several panels are given in each Figure to show the consequences of changes in overall entrainment-impingement mortality rates. As seen in Figure 5, equilibrium yield is maximized at from 50% to 100% of average fishing mortality levels under the hypotheses that density-dependence is low-to-moderate and entrainment-impingement is above 0.16 annually. With high density-dependence one would conclude that further increases in yield are possible, however as seen in Figure 4, the level of high density-dependence assumed with *b=0.01* implies that recruitment would barely decline under even a tripling of the average fishing mortality. Maximum yield levels are adversely impacted by entrainment-impingement mortality in all cases with the decline in maximum yield most severe under the low density-dependence hypothesis. For example maximum sustainable yield would increase from about 500,000 pounds to over 1,000,000 pounds if entrainment-impingement were decreased from a mortality level of 0.33 to 0.0, under the moderate density-dependence hypothesis.

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Table 1a. Commercial gill net age composition samples

Repeat spawn matrix for American shad caught in the Hudson River commercial gill net fishery
1=male, 2=female

			repeat spawn marks								
year	sex	age	0	1	2	3	4	5	6	7	8
1980	1	4	9								
1980	1	5	11	15							
1980	1	6	3	15	10	1					
1980	1	7		2	18	8					
1980	1	8			2	6	2				
1981	1	4	11	1							
1981	1	5	17	5	1						
1981	1	6	3	22	19	1					
1981	1	7			37	19	1				
1981	1	8			4	14	5				
1981	1	9					1				
1982	1	3	1								
1982	1	4	11								
1982	1	5	14	10							
1982	1	6	5	12	11	1					
1982	1	7		1	15	17					
1982	1	8				13	7				
1982	1	9				1	12	4			
1982	1	10					2	1			
1983	1	4	9								
1983	1	5	21	14	2						
1983	1	6	5	8	10						
1983	1	7			11	4	1				
1983	1	8				10	9				
1983	1	9				2	5	2			
1983	1	10						4	1		
1983	1	11							2		
1984	1	4	1								
1984	1	5	14	12	2						
1984	1	6	6	7	9	2					
1984	1	7		1	2	7	1				
1984	1	8			1	7	8				
1984	1	9				1	1	4			
1984	1	10					2	1			
1984	1	11								1	
1985	1	4	4	1							
1985	1	5	13	4	3						
1985	1	6	9	7	11						
1985	1	7			5	14	2				
1985	1	8			1	1	8				
1985	1	9					3	1			
1985	1	10						2			
1986	1	4	4	3							
1986	1	5	5	16	7						

1986	1	6	6	6	12	1			
1986	1	7	1	1	6	9	1		
1986	1	8			1	3	6		
1986	1	9				1	1	2	
1986	1	10						1	
1986	1	11						1	1
1987	1	5	1	3					
1987	1	6	1	9	6				
1987	1	7	1		7	3			
1987	1	8			2	3	7		
1987	1	9					6	4	
1987	1	10						1	1
1987	1	11							3
1988	1	3	1						
1988	1	4	3						
1988	1	5	12	7					
1988	1	6	1	15	28				
1988	1	7		2	11	12			
1988	1	8				6	6		
1988	1	9					6	1	
1988	1	10						3	
1989	1	4	1						
1989	1	5	14	6	1				
1989	1	6	9	20	35				
1989	1	7			20	23			
1989	1	8				21	17		
1989	1	9				2	5	4	
1989	1	10						2	
1990	1	4	1						
1990	1	5	7	1					
1990	1	6	1	3	4				
1990	1	7		1	1	4			
1990	1	8				2	3		
1990	1	9					1		
1991	1	3	2						
1991	1	4	2						
1991	1	5		1					
1991	1	6		2	3				
1991	1	7			1	7	1		
1991	1	8				2	4		
1992	1	3	2						
1992	1	4	20						
1992	1	5	18	10					
1992	1	6	2	26	12				
1992	1	7		1	24	6			
1992	1	8				10			
1992	1	9					1		
1993	1	4	3						
1993	1	5	1	2					
1993	1	6		3	10				
1993	1	7	1	1	6	3			
1993	1	8				2			
1994	1	5	1	1					
1994	1	6		3	3				
1994	1	7			3	2			
1994	1	9				1			

1995	1	4	4						
1995	1	5	13	9					
1995	1	6	8	15	21				
1995	1	7	1	1	13	11			
1995	1	8			2	6	1		
1995	1	9					1		
1980	2	4	5	1					
1980	2	5	81	19					
1980	2	6	36	58	7				
1980	2	7	7	5	21	3			
1980	2	8			7	4			
1980	2	9					3		
1981	2	4	7						
1981	2	5	88	16					
1981	2	6	71	78	11				
1981	2	7	9	22	46	10			
1981	2	8		1	22	26	7		
1981	2	9				5	7		
1981	2	10						4	
1982	2	4	11						
1982	2	5	86	15					
1982	2	6	43	51	11				
1982	2	7	5	27	43	4			
1982	2	8		2	14	24	8		
1982	2	9				4	12	1	
1982	2	10					3	5	
1982	2	11						1	
1983	2	3	1						
1983	2	4	9						
1983	2	5	95	9					
1983	2	6	66	24	7				
1983	2	7	4	10	12	5			
1983	2	8		1	12	14	1		
1983	2	9				7	6	1	
1983	2	10				2	7	7	
1983	2	11						1	
1984	2	4	5	1					
1984	2	5	48	9					
1984	2	6	56	28	15				
1984	2	7	18	8	15	7			
1984	2	8			5	12	3		
1984	2	9			1	2	13	7	
1984	2	10					6	3	
1985	2	4	18						
1985	2	5	72	19					
1985	2	6	52	49	6				
1985	2	7	10	16	32	10			
1985	2	8			8	10	8		
1985	2	9			2	3	11	4	
1985	2	10					5	6	
1985	2	11						3	3
1985	2	12					1	1	
1986	2	4	7	1					
1986	2	5	70	15	2				
1986	2	6	34	32	24	1			
1986	2	7	7	9	24	8	1		

1986	2	8			6	13	8				
1986	2	9				4	7	5			
1986	2	10				2		4			
1986	2	11						1			
1986	2	12								2	
1987	2	4	1	1							
1987	2	5	52	11							
1987	2	6	40	53	11						
1987	2	7	5	31	27	11					
1987	2	8		1	13	23	9				
1987	2	9				20	7				
1987	2	10					10	18	2		
1987	2	11						3	9		
1987	2	12								3	
1987	2	13								1	1
1988	2	3	1								
1988	2	4	7								
1988	2	5	46	6							
1988	2	6	14	43	17						
1988	2	7		14	39	7					
1988	2	8			3	22	7				
1988	2	9					11	2			
1988	2	10					1	3			
1989	2	4	2								
1989	2	5	67	2							
1989	2	6	57	33	23						
1989	2	7	2	8	54	16	2				
1989	2	8			5	27	4				
1989	2	9				1	5	1			
1989	2	10					2	1			
1990	2	4	3								
1990	2	5	41	1							
1990	2	6	19	31	11						
1990	2	7	2	7	18	21					
1990	2	8				21	7				
1990	2	9				1	8				
1990	2	10					1	3			
1990	2	11							1		
1990	2	12									1
1991	2	4	13	4							
1991	2	5	45	12	2						
1991	2	6	30	16	11	4	1				
1991	2	7	6	7	20	11	1				
1991	2	8		1	2	2	7				
1991	2	9					7	1			
1991	2	10						1			
1991	2	11							1		
1992	2	4	11								
1992	2	5	149	10							
1992	2	6	43	78	5						
1992	2	7		19	32	5					
1992	2	8			4	12	1				
1992	2	9				2	4				
1992	2	10					1	1			
1993	2	4	5								
1993	2	5	14	2							

1993	2	6	3	13	7			
1993	2	7		2	9	1		
1993	2	8			2	4	1	
1993	2	9						1
1994	2	5	24	4				
1994	2	6	20	17	9			
1994	2	7		4	20			
1994	2	8		1	3	1		
1994	2	9					2	
1995	2	4	3					
1995	2	5	45	8				
1995	2	6	26	22	6			
1995	2	7	2	7	13	1		
1995	2	8			1	3		
1995	2	9					2	
1995	2	10						1

Table 1b. Haul Seine age composition samples.

Repeat spawn matrix - American shad caught in HR spawning stock survey

			repeat spawn marks							
year	sex	age	0	1	2	3	4	5	6	7
1983	1	3	1							
1983	1	4	4							
1983	1	5	5	3						
1983	1	6		3	2					
1983	1	7			1	4				
1983	1	8				3				
1983	1	9					2			
1983	1	10						1		
1984	1	3	3							
1984	1	4	18							
1984	1	5	14	9						
1984	1	6	2	8	12					
1984	1	7	1		4	4				
1984	1	8				6	1			
1984	1	9					1			
1984	1	10						1		
1985	1	3	13							
1985	1	4	45	9						
1985	1	5	36	14	3					
1985	1	6	5	8	10	1				
1985	1	7		2	2	8				
1985	1	8			2	2	3	1		
1985	1	9					1	1		
1985	1	10						1		
1986	1	3	9							
1986	1	4	66	11						
1986	1	5	49	17	6					
1986	1	6	11	10	16	2				
1986	1	7		3	3	8	1			
1986	1	8					6			
1986	1	9					3			
1986	1	11					1			
1987	1	3	8							
1987	1	4	55	1	1					
1987	1	5	42	18	2					
1987	1	6	3	19	13	1				
1987	1	7	1		13	8				
1987	1	8				5	4			
1987	1	9					5	2		
1987	1	10						2		
1987	1	11							2	
1988	1	3	2							
1988	1	4	42							
1988	1	5	78	18	1					
1988	1	6	6	20	16					
1988	1	7		2	13	11				
1988	1	8				3	4			
1988	1	9					3	1		
1988	1	10					1	1		
1989	1	3	2							

1989	1	4	32	1				
1989	1	5	36	10				
1989	1	6	8	18	10			
1989	1	7		2	8	13		
1989	1	8				6	11	
1989	1	9					4	1
1989	1	10						1
1990	1	4	13					
1990	1	5	22	3				
1990	1	6	2	2	4			
1990	1	7	1	1	3	1	1	
1990	1	8				1		
1991	1	3	12					
1991	1	4	44	4				
1991	1	5	25	8				
1991	1	6	9	5	2			
1991	1	7	1		2	1		
1991	1	8					1	
1992	1	3	13					
1992	1	4	165	7				
1992	1	5	186	44	2			
1992	1	6	22	29	17			
1992	1	7		4	3			
1992	1	8					1	
1992	1	9	1				1	
1993	1	3	5					
1993	1	4	86	6				
1993	1	5	108	44	4			
1993	1	6	17	19	11			
1993	1	7	1	3	8	5		
1993	1	8				2		
1994	1	3	2					
1994	1	4	30	2				
1994	1	5	22	10	4			
1994	1	6	1		6			
1994	1	7				2	1	
1995	1	3	23					
1995	1	4	88	8				
1995	1	5	50	27	5			
1995	1	6	2	13	16			
1995	1	7	1		4	4		
1997	1	3	4					
1997	1	4	24					
1997	1	5	20	10				
1997	1	6		6	3	1		
1997	1	7				1		
1997	1	10						1
1983	2	4	7					
1983	2	5	12	5				
1983	2	6	7	3	2			
1983	2	7	2		5	1		
1983	2	8			2	3		
1983	2	9				2	1	
1983	2	10					1	
1984	2	4	1					
1984	2	5	6	1				

1984	2	6	7	6	1	1				
1984	2	7	3	3	7	1				
1984	2	8				4	4			
1984	2	9					4	1		
1984	2	10					1	2		
1984	2	11						1		
1985	2	3	1							
1985	2	4	10							
1985	2	5	12	4						
1985	2	6	7	16	4					
1985	2	7	2	4	9	2				
1985	2	8			2	6	3			
1985	2	9				3	1	1		
1985	2	10					1	3		
1985	2	11						3		
1986	2	4	14	3						
1986	2	5	42	13	1					
1986	2	6	40	19	6					
1986	2	7	6	5	10	5				
1986	2	8	2	2	1	4	8			
1986	2	9				2	5	3		
1986	2	10					1	1		
1986	2	11						2	1	1
1987	2	4	15							
1987	2	5	66	5						
1987	2	6	26	22	2					
1987	2	7	2	11	11	3				
1987	2	8		1	6	14				
1987	2	9				6	9			
1987	2	10					3	5		
1987	2	11							1	
1987	2	12							1	1
1987	2	13								1
1988	2	4	16							
1988	2	5	86	4						
1988	2	6	24	64	16					
1988	2	7	1	17	28	10				
1988	2	8		1		12	1			
1988	2	9			1	4	5	1		
1988	2	10					4	2		
1988	2	11					1	2	2	
1988	2	12							2	
1989	2	4	8							
1989	2	5	53	4						
1989	2	6	36	12	4					
1989	2	7		10	26	9				
1989	2	8		1	3	14	1			
1989	2	9			1	2	2	2		
1989	2	10					3	2	1	
1989	2	11						1	2	
1990	2	4	3							
1990	2	5	23							
1990	2	6	11	4						
1990	2	7		4	10					
1990	2	8			1	5				
1990	2	9					1			

1990	2	10						1
1991	2	3	1					
1991	2	4	10					
1991	2	5	29	4				
1991	2	6	24	9	1	1		
1991	2	7	6	2	5	1		
1991	2	8			2	1		
1991	2	9					1	
1991	2	10						1
1992	2	4	21					
1992	2	5	150	19				
1992	2	6	87	65	9			
1992	2	7	10	34	21	2		
1992	2	8			5	2	1	
1992	2	9				2	3	1
1992	2	10					1	1
1993	2	4	9					
1993	2	5	49	10				
1993	2	6	31	16	6			
1993	2	7		8	10			
1993	2	8		1	2	6		
1994	2	5	36	11	2			
1994	2	6	8	7	4			
1994	2	7	2	1	2	2		
1994	2	8				1	1	
1995	2	3	3					
1995	2	4	64					
1995	2	5	156	58	1			
1995	2	6	51	49	31	1		
1995	2	7	10	6	14	4		
1995	2	8			1	2		
1997	2	4	12	1				
1997	2	5	31	1				
1997	2	6	4	7	2			
1997	2	7		2	2	2		
1997	2	8			1	3	1	
1997	2	9			1	3	2	

Table 2: Data used in fitting of the model. CPUE indices are fixed gill-net CPUE.

	LANDINGS (lbs.)			ABUNDANCE		INDICES	
Year	Hudson River	ASMFC coastal	Best" Estimate	PYSL	JUV jasg	Male CPUE	Female CPUE
1970	241400	32411	46875				
1971	173900	19408	28228				
1972	311800	31183	45123				
1973	255000	24039	34987				
1974	231900	31949	46722	0.17			
1975	233600	54648	79937	0.28			
1976	214900	67100	98032	0.16			
1977	185400	121289	177387	0.17			
1978	419400	112435	162981	0.09			
1979	498200	108009	157507	0.49			
1980	1420800	163233	240395	0.48	23.87	4.28	19.11
1981	673600	247657	371193	0.78	19.12	6.17	14.47
1982	452200	443140	671039	0.59	12.17	3.04	8.02
1983	520600	300929	434873	0.57	18.24	5.65	9.16
1984	678300	325447	507325	0.38	7.79	3.42	9.49
1985	827264	312166	465989	0.67	26.65	10.66	26.65
1986	849168	298616	456895	1.05	46.32	24.54	52.09
1987	682182	340944	538170	0.18	20.2	13	47.34
1988	786132	420129	665172	0.73	27.59	19.4	42.22
1989	483300	516972	803320	1.04	47.3	9.3	33.79
1990	449338	684391	1024042	1.17	41.24	3.53	16.61
1991	345328	664237	1018571	0.32	24.05	2.32	18.31
1992	284564	436147	677094	0.62	35.17	1.32	14.61
1993	142898	453635	688948	0.23	11.64	0.91	13.02
1994	194110	315943	454485	0.37	26.09	0.86	24.35
1995	258440	336426	496960	0.20	5.74	1.4	11.49
1996	183910	343499	514076	0.26	30.89	2.19	20.25
1997	140306	343499	514076		9.51	0.91	7.11

Table 3. Population parameters estimated for American shad of the Hudson River

age (years)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
weight male (lbs.)			2.20	2.73	3.35	3.77	4.05	4.60	4.77	5.11	6.03	6.03	6.03	6.03
weight female (lbs.)			1.96	3.93	4.30	4.88	5.57	6.21	6.84	7.26	7.68	7.40	8.43	8.43
fecundity (scaled)			96	158	220	282	344	406	468	530	592	654	716	778
maturation male	0.00	0.00	0.04	0.48	0.86	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
maturation female	0.00	0.00	0.00	0.15	0.63	0.91	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
gill-net selectivity male	0.00	0.00	0.00	0.03	0.14	0.34	0.56	0.75	0.88	0.95	0.98	1.00	1.00	1.00
gill-net selectivity female	0.00	0.00	0.04	0.22	0.53	0.83	0.98	1.00	0.93	0.79	0.63	0.47	0.34	0.24
ocean selectivity	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
median length male gill-net	303.82	350.45	388.23	418.84	443.64	463.74	480.02	493.21	503.89	512.55	519.57	525.25	529.86	533.59
median length female gill-net	358.24	393.59	424.99	452.89	477.68	499.70	519.27	536.65	552.10	565.82	578.01	588.84	598.46	607.01
Average F gill-net male	0.00	0.00	0.00	0.01	0.03	0.07	0.12	0.16	0.19	0.20	0.21	0.21	0.21	0.21
Average F gill-net female	0.00	0.00	0.01	0.05	0.11	0.18	0.21	0.21	0.20	0.17	0.13	0.10	0.07	0.05
Average F ocean rate	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 4. Abundance by Age and Year

Males								
Age/Year	3	4	5	6	7	8	9	10
1974	242425	54871	43343	26849	15406	8818	6154	5576
1975	618790	174064	32160	19655	11023	6008	3304	2245
1976	1274470	443471	101673	14309	7668	3949	2012	1058
1977	1347540	919140	260699	45579	5636	2780	1341	654
1978	1271943	969994	540396	119324	19119	2275	1090	515
1979	892259	918430	571986	247675	49970	7680	885	415
1980	1027288	644581	542083	263609	105274	20575	3088	350
1981	1193949	738677	377964	243437	104974	38961	7187	1038
1982	957473	852307	430736	171750	101590	42247	15254	2763
1983	879925	671808	488732	193412	71542	41247	16832	6001
1984	894822	624871	389847	221806	81229	29210	16490	6636
1985	760725	631853	360418	175172	91498	32303	11297	6260
1986	584738	537324	364362	161049	71080	35383	12035	4105
1987	385630	411509	308647	161801	64633	27048	12918	4274
1988	404159	267117	232707	135219	64338	24479	9865	4594
1989	472841	272485	146880	98139	50710	22490	8096	3144
1990	552787	308363	145001	60246	36155	17599	7449	2599
1991	483956	347057	157822	56639	20717	11467	5235	2123
1992	529622	301556	176330	61346	19475	6603	3442	1510
1993	546294	348356	161845	72936	22785	6812	2204	1113
1994	443846	360740	187965	68275	28447	8631	2525	805
1995	736263	303409	201457	81882	27377	11027	3261	938
1996	642523	505169	170028	87845	32699	10513	4110	1191
1997	794985	442516	284317	74882	35838	12983	4091	1578

Females								
Age/Year	3	4	5	6	7	8	9	10
1974	242425	55749	52832	42739	30548	21989	16938	15306
1975	618790	176848	39154	30778	20880	14178	10163	7940
1976	1274470	450558	123522	21767	13386	8372	5645	4144
1977	1347540	933830	316761	69346	9612	5454	3388	2338
1978	1271943	985509	658459	188443	35556	4729	2675	1679
1979	892259	933119	696811	390984	95755	17305	2294	1312
1980	1027288	654892	660809	419654	205615	48639	8767	1172
1981	1193949	750484	459521	374287	190513	87010	20460	3764
1982	957473	865941	524917	271892	191691	93824	42720	10144
1983	879925	682557	596016	309668	141837	97099	47423	21737
1984	894822	634868	475343	354528	161991	71903	49109	24163
1985	760725	641960	439217	277892	179159	78764	34856	24042
1986	584738	545917	443690	252839	135058	82943	36321	16287
1987	385630	418089	375722	252768	120368	60962	37275	16564
1988	404159	271389	283361	212003	120315	54529	27506	17044

1989	472841	276841	178607	151128	91216	48355	21789	11208
1990	552787	313294	176439	93494	65253	37110	19575	8967
1991	483956	352604	191785	86417	36148	23339	13184	7114
1992	529622	306376	214342	93888	33762	13115	8414	4855
1993	546294	353926	196931	113128	40856	13837	5348	3488
1994	443846	366511	229171	108830	54898	19185	6482	2524
1995	736263	308263	245547	130207	53760	26154	9114	3107
1996	642523	513250	207166	139004	63386	25123	12183	4291
1997	794985	449595	346694	119713	70808	31312	12382	6047

Table 5. Population estimates for various quantities. Ocean F's apply equally to all ages 3+. Gill-net F's correspond to rates for fully-vulnerable age groups (see Table 3 for gill-net age-specific selectivities).

		Female			Male			Total	F	F
Year	Eggs (10^6)	YoY abundance	Gill CPUE/Q	Hudson Abundance	YoY abundance	Gill CPUE/Q	Hudson Abundance	Hudson Abundance	Ocean	Hudson
1974	74088	3314413	0	214889	3314413	0	152695	367584	0.01	0.21
1975	42849	3128475	0	158520	3128475	0	185381	343901	0.02	0.36
1976	44546	2194604	0	216134	2194604	0	390387	606521	0.01	0.35
1977	90682	2526720	0	445482	2526720	0	792351	1237833	0.01	0.16
1978	170588	2936640	0	818177	2936640	0	1154606	1972783	0.01	0.17
1979	249650	2355004	0	1098496	2355004	0	1305302	2403799	0.01	0.13
1980	253875	2164267	2196010	1201108	2164267	2196010	1230089	2431197	0.01	0.31
1981	262768	2200908	1662808	1066430	2200908	1662808	1128986	2195416	0.02	0.15
1982	270325	1871081	921612	1049503	1871081	921612	1141294	2190797	0.04	0.10
1983	281738	1438224	1052614	1091948	1438224	1052614	1113417	2205364	0.03	0.11
1984	269282	948496	1090535	1048808	948496	1090535	1024800	2073608	0.03	0.15
1985	241714	994070	3062463	968266	994070	3062463	960175	1928441	0.03	0.20
1986	217249	1163001	5985879	885971	1163001	5985879	876427	1762397	0.03	0.22
1987	193078	1359636	5440037	771666	1359636	5440037	734436	1506102	0.05	0.20
1988	147207	1190339	4851676	620519	1190339	4851676	555854	1176373	0.08	0.30
1989	109562	1302661	3882950	441811	1302661	3882950	422310	864121	0.11	0.25
1990	77600	1343666	1908724	343128	1343666	1908724	372431	715560	0.15	0.34
1991	65798	1091685	2104078	302071	1091685	2104078	369223	671294	0.16	0.32
1992	69194	1810915	1678896	313585	1810915	1678896	382860	696445	0.10	0.25
1993	79264	1580353	1496182	329877	1580353	1496182	405901	735778	0.10	0.12
1994	89801	1955348	2798160	377560	1955348	2798160	446910	824470	0.06	0.14
1995	97178	531841	1320364	409188	531841	1320364	459763	868951	0.06	0.16
1996	106980	531841	2327012	435273	531841	2327012	535582	970856	0.06	0.11
1997	129354	531841	817040	516846	531841	817040	608570	1125416	0.05	0.07
Avg.	151432	1686084	1858210	630219	1686084	1858210	697906	1328125	0.05	0.20

Figure 1. Fits of the model to indices on young shad.

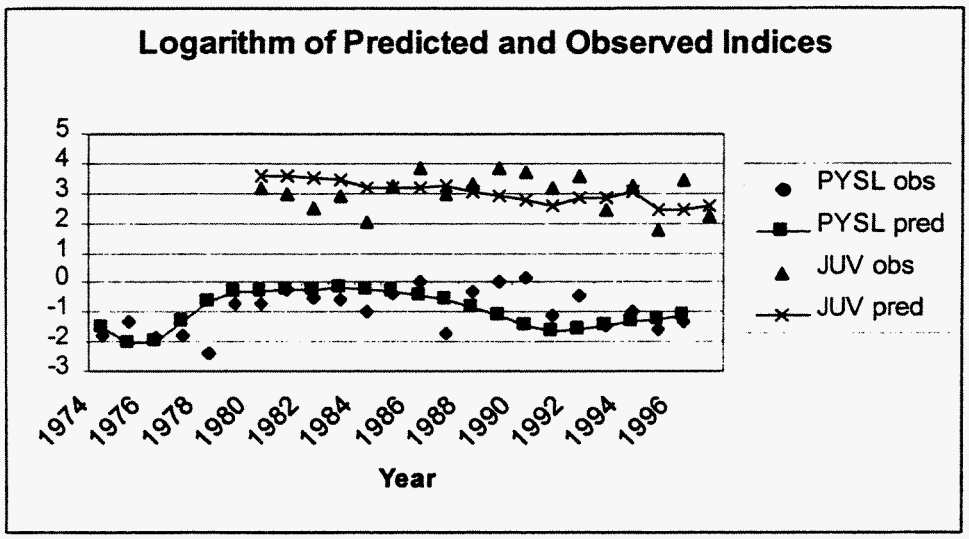


Figure 2. Fits of the model to indices on Adult shad.

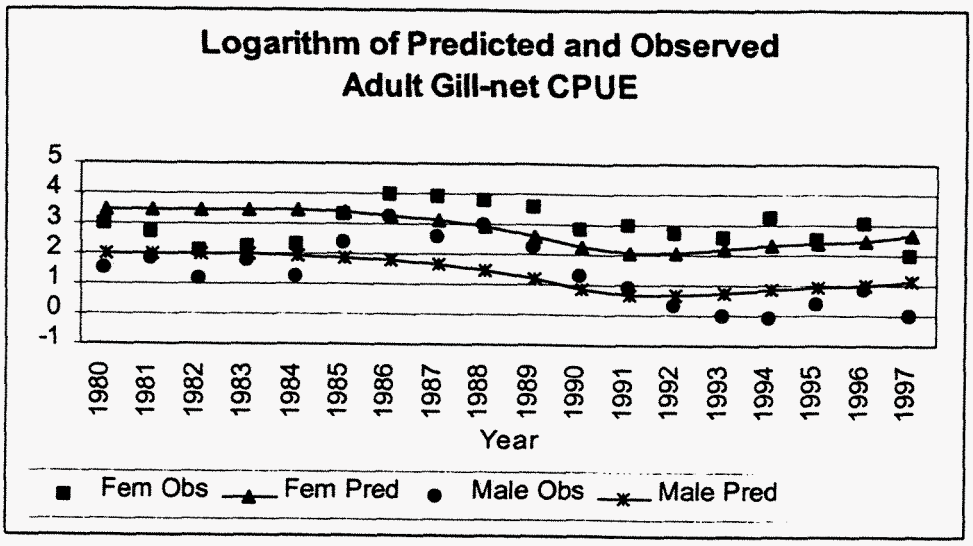

Logarithm of Predicted and Observed
Adult Gill-net CPUE
5
4
3
2
1
0
-1
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
Year
Fem Obs
Fem Pred
Male Obs
Male Pred

Figure 3 . Beverton-Holt S-R model fitted to 1974-1994 data (assuming b=.01) is shown along with (b=0.2) and (b=0.5) curves found in the long-term assessments. Results are given for in terms of female recruits (one-year-olds) and the sex-ratio is 1-1 for the age ones.

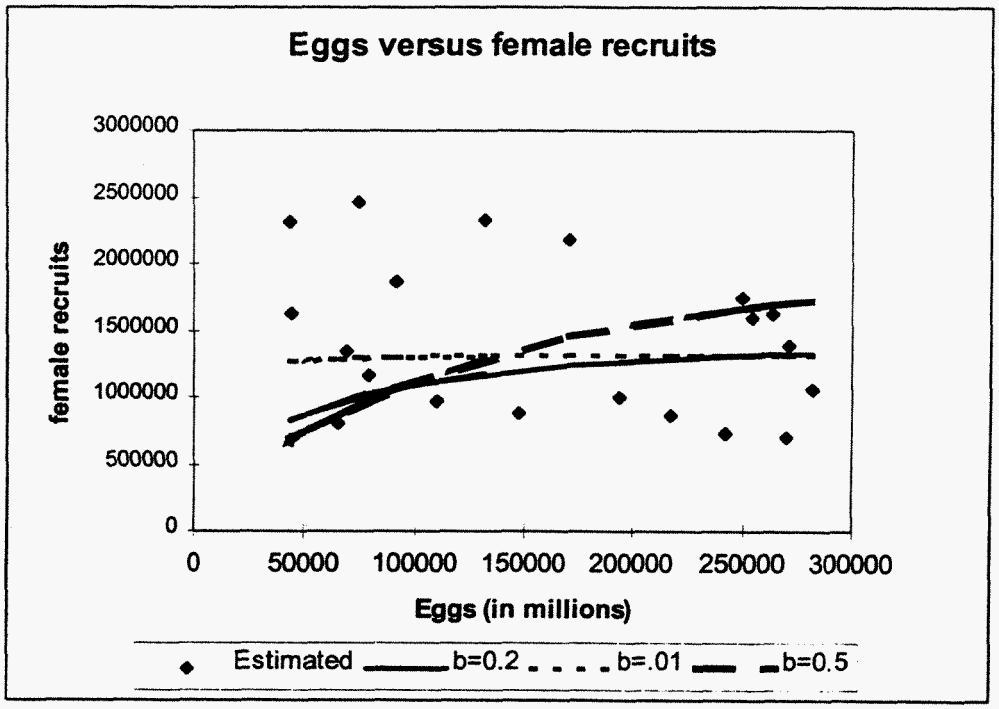


Figure 4. Several panels show the consequence of changes in entrainment-impingement loss rates to equilibrium yield. Graphs are drawn as a function of one of the three S-R hypotheses (given by *b* value) and as a function of the fractional multiple of fishing mortality to the average rates shown in Table 5.

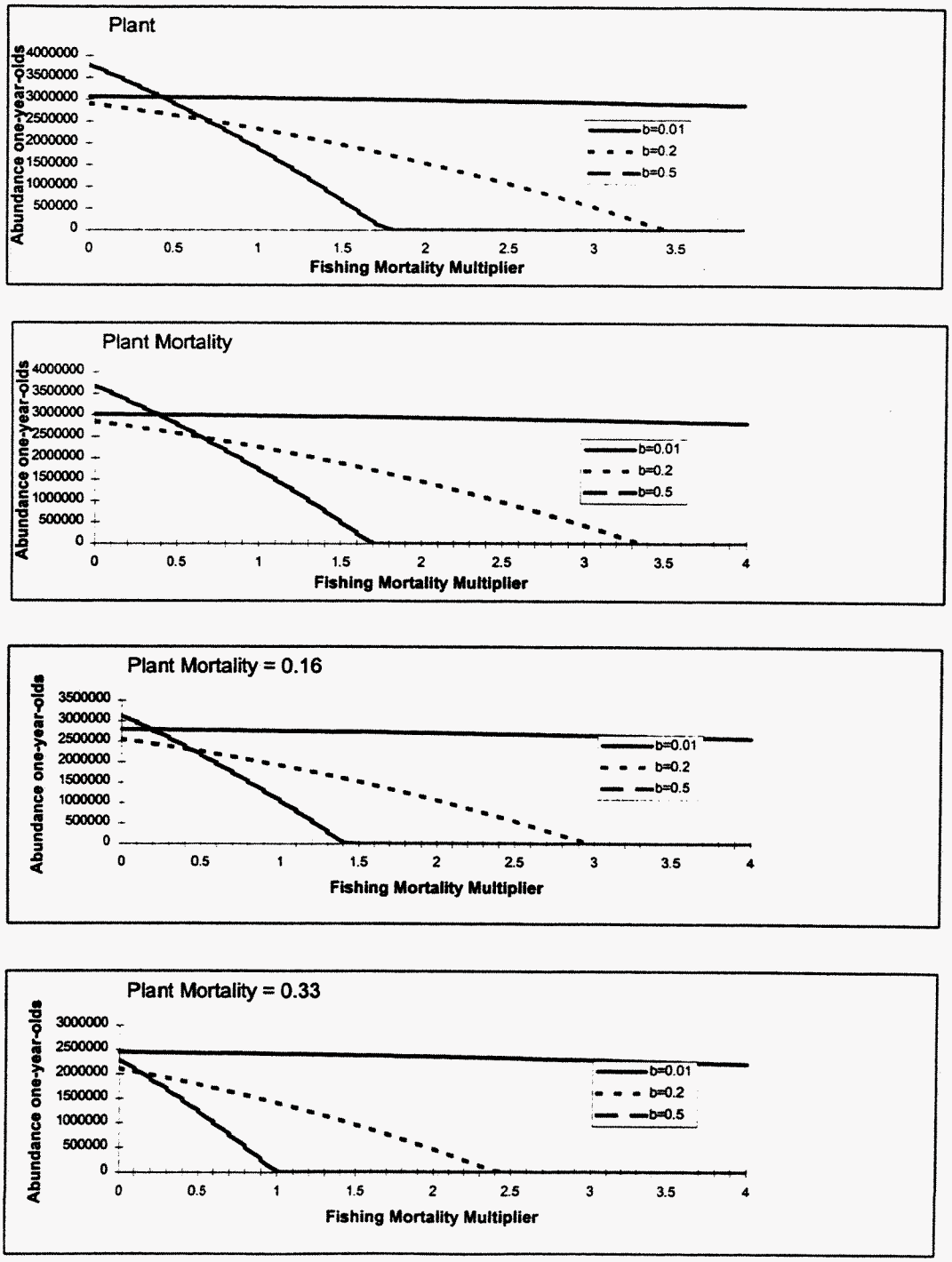


Figure 5. Several panels show the consequence of changes in entrainment-impingement loss rates to equilibrium recruitment. Graphs are drawn as a function of one of the three S-R hypotheses (given by *b* value) and as a function of the fractional multiple of fishing mortality to the average rates shown in Table 5.

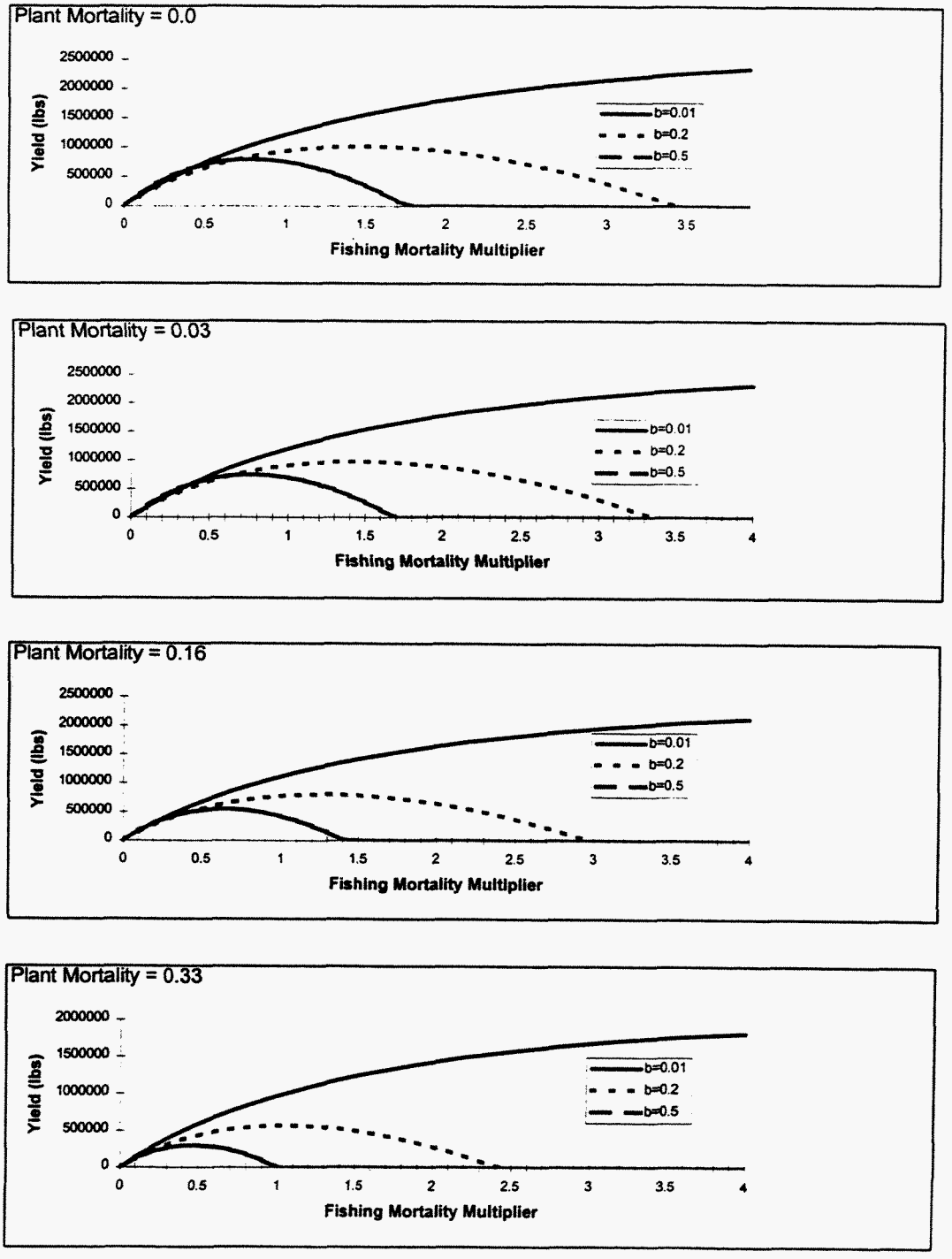
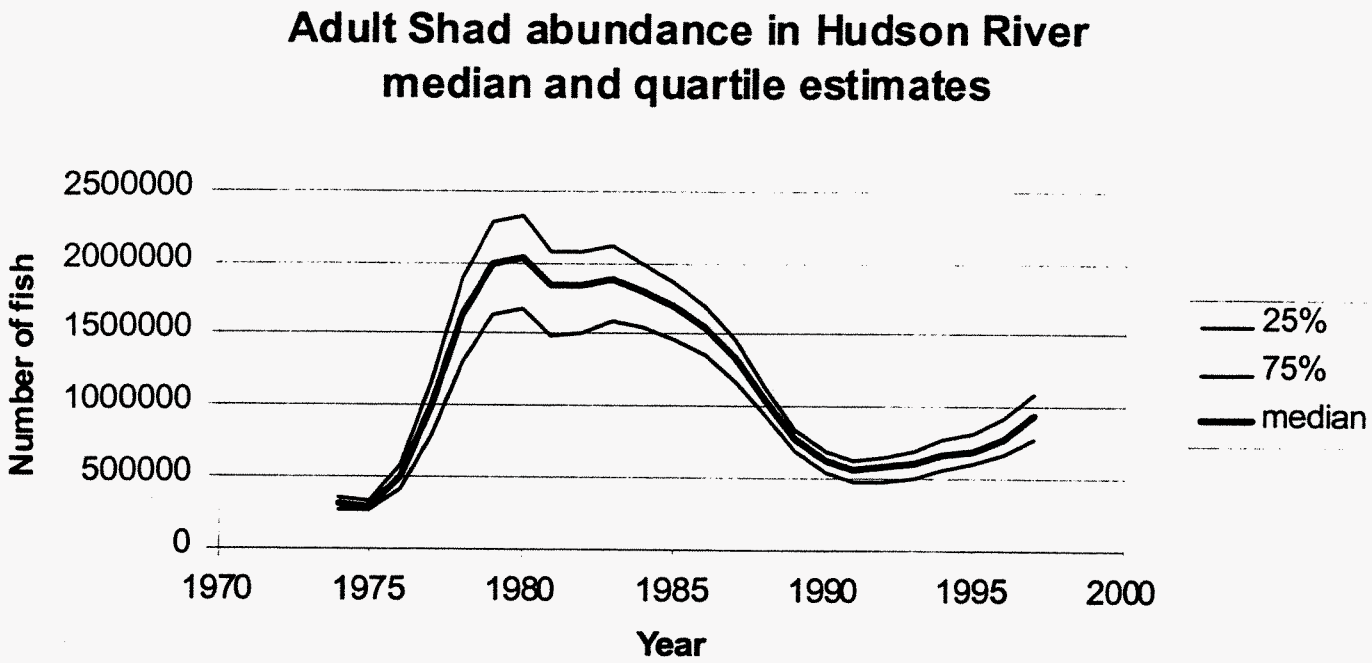


Figure 6. Abundance of American shad in the Hudson River. Median and quartile estimates are shown.



Appendix VI-4-D

Bay Anchovy Population Modeling

INTRODUCTION

Bay anchovy are a common fish in the Hudson River estuary during summer and early fall months when adults enter the estuary to spawn. Eggs, larval stages, and juveniles (young-of-year) are found in the lower part of the estuary from July through early fall when spawning ceases. Shortly afterwards, the juveniles and adults move downriver and by the end of the year have apparently emigrated from the system (Hartman ___). Once leaving the Hudson, it is believed that they mingle with bay anchovy from other coastal systems as part of a larger coastal stock.

The lack of a distinct Hudson River population makes it difficult to model the population effects of entrainment on the species since the number anchovy returning to the Hudson each spring may be the result not only of the success of past year classes in the Hudson, but also along the larger Atlantic coast. This life history pattern necessitated alternative approaches to assessing impacts on bay anchovy which concentrate not on long-term population projections for bay anchovy, but on the short-term changes in the abundance of bay anchovy within the Hudson since the species is believed to be an important food source for many estuarine piscivores. The methods selected are based on the individual-based models derived from the Electric Power Research Institute's Compensatory Mechanism project. Three analyses have been derived from this modeling effort: 1) predatory demand for bay anchovies, 2) production foregone as a result of entrainment, and 3) changes in biomass and consumption as a result of entrainment. All three analyses begin with the bay ancovy individual-based model (Rose 1996).

Predatory demand of striped bass and bluefish for bay anchovy was analyzed during the technical workshops that occurred following the submittal of the preliminary DEIS. A description of the bay anchovy IBM, the model assumptions, and estimates of predatory demand are found in " " (Rose 1996). This appendix will present the results of the production foregone and biomass change analyses.

1. PRODUCTION FOREGONE FOR HUDSON RIVER BAY ANCHOVY

Introduction

Bay anchovies have been entrained through the Bowline Point, Indian Point, and Roseton power plants. To assess the effects of that entrainment, the New York State Department of Environmental Conservation requested that production foregone be calculated for the Hudson River bay anchovy population. Production foregone is a measure of the weight that bay anchovies would have gained over their life span had they not died from entrainment (Rago 1984).

Methods

Production foregone was calculated by multiplying two numbers, production per bay anchovy during the first year of life from Rose (1996b) and the number of bay anchovies that die from entrainment. Rose used a population model to estimate the mean production of Hudson River bay anchovy in four life stages: egg, yolk-sac larva (YSL), post yolk-sac larva (PYSL), and juvenile (Table 1). Production was expressed as the increase in body weight per individual due to growth from the start of a life stage through the expected age at death, assuming death only occurred due to natural causes. Weight in Table 1 is expressed as both wet weight and dry weight, assuming that dry weight is 25% of wet weight (Hartman 1993).

We estimated the number of bay anchovy that died from entrainment in each life stage using river-wide abundance by life stage and the fraction of the river-wide abundance entrained, with the assumption that all entrained anchovy died. River-wide abundance was estimated from the river-wide average sample densities from the Longitudinal River Survey (LRS) and life-stage specific gear efficiencies. Weekly estimates of entrainment mortality were computed and summed over the period of vulnerability to entrainment. Methods for estimating the river-wide average densities and the fraction that die from entrainment are described in Appendix VI-1.

Data from experiments by Murphy and Clutter (1972) were used to develop gear efficiency estimates for bay anchovy PYSL. Murphy and Clutter (1972) sampled Hawaiian anchovy (*Stolephorus purpurpes*) with a plankton purse seine 30.5 m (100 ft) long and 6.1 m (20 ft) deep with a 0.333 mm mesh. The net surrounded about 356 m^3 of water. A 1-m plankton net equipped with a flow meter was towed in the area of the plankton purse seine after it was set. Gear efficiency was estimated by comparing night catches in the meter plankton net with catches in the purse seine, which was assumed to be 100% efficient.

We estimated gear efficiency for Hudson River PYSL (Table 2) as a weighted average of the arctangent-transformed ratios (1-m net over purse seine) of size-class specific night catch rates presented in Murphy and Clutter (1972). The weights were proportional to size-class abundance from Rose (1996a). PYSL abundance in the Hudson River based on LRS data was calculated using the gear efficiency estimated from the Murphy and Clutter (1972) data. The gear efficiency for eggs and YSL were then calculated as the values that caused the ratios of egg to YSL and YSL to PYSL abundance from the LRS data to match the ratios from the Rose model (Table 3). The very low gear efficiency for YSL may be due to extrusion through the nets. Bay anchovy eggs and PYSL are large enough to be retained by the nets.

Gear efficiency for juvenile bay anchovy was estimated as the reciprocal of the relative probability of capture (RPC) factor (2.6) used for calculating the conditional entrainment mortality rate for juvenile bay anchovy (Appendix VI-1). The approach is consistent with that used for the calibrated W-ratio incorporated in the estimates of the fraction of river-wide stock of bay anchovy entrained. The gear efficiency estimate is based on two assumptions. The first assumption is that in-plant gear efficiency is 100% because we believe that (1) juvenile bay anchovy are not extruded through the gear used

in sampling the discharge canals of Bowline, Indian Point, and Roseton and (2) juvenile bay anchovy are unable to avoid the sampling gear in the discharge canal due to water turbulence. The second assumption is that entrainable-size juvenile bay anchovy in the river do not avoid the power plant intakes. The lower gear efficiency for juveniles compared to PYSL (Table 2) is probably due to net avoidance by juveniles.

The fraction of fish entrained each week was estimated from the ETM model with calibrated W-ratios (Appendix VI-1). River-wide abundance values were calculated using 13 river regions.

Results and Discussion

Production Foregone

Average annual (1991 through 1997) production foregone for bay anchovy was estimated to be 2,216 kg dw/yr (8,864 kg ww/yr). Yearly estimates ranged from 884 kg dw/yr (3,536 mg ww.yr) in 1996 to 4,461 kg dw/yr (17,844 kg ww/yr) in 1991 (Table 4).

Comparison of Bay Anchovy Production Foregone with Predatory Demand

Rose (1996a) simulated bluefish and striped bass predation of anchovy in the Hudson River. The total predation rate in mass per year, called predatory demand, of these two predatory fish species is similar to production foregone and can be used to compare anchovy losses due to power plant operation to natural losses. Rose's simulations were based on bioenergetics models.

The basic bioenergetics model is that intake or consumption (C) equals the sum of metabolism (M), specific-dynamic action (S), egestion (E), excretion (U), and growth (G), when all quantities are expressed in terms of energy, typically calories. This model is expressed as

$$C = M + S + E + U + G .$$

The model can be adapted to describe changes in weight (W), where $G = \Delta W$.

Rose applied simulation models developed by Hartman (1993) and by Steinberg (1994) for striped bass and bluefish, respectively. Starting with an initial weight of each species, Rose modeled growth and consumption. Descriptions of model parameters are summarized in Table 5. Bioenergetics and population data were used to estimate total consumption by the predator populations. Where possible, Hudson River data were used. For example, temperatures were Hudson River water temperatures near Indian Point as estimated from Poughkeepsie Water Works temperatures from 1987 to 1991.

Striped bass were assumed to remain in the estuary and feed on anchovy until age 5. Anchovies were assumed to account for 25% of the diet of age-1 striped bass and 50% of age 2 and older striped bass. Striped bass older than age 5 were assumed to migrate

and were not taken into account in predatory demand analyses. Predatory demand of striped bass per fish increased with increasing age, and the total through age 5 was 136.4 mg dw/m^3/yr (545.6 mg ww/m^3/yr, Table 6).

In the initial bluefish simulations using Steinberg's (1994) model, the estimated consumption rate per individual exceeded the maximum consumption rate. To balance the equation, Rose adjusted the active metabolism rate down. Active metabolism (the metabolic rate of an actively moving individual) was estimated from basal metabolism (the metabolic rate of an individual at rest) using the coefficient "ACT" (for active metabolism). Rose adjusted ACT from 3 to 2 (active metabolism twice basal metabolism), a value typical of many fish species.

In determining consumption by the bluefish population, Rose found that the initial bluefish densities in his base years, 1992 and 1993, were about a fourth of densities in the 1980s. Therefore, he also ran simulations with four times the initial densities of 1992 and 1993 in order to provide information about years of higher bluefish densities. Two sets of initial densities and two values of ACT resulted in four simulations of bluefish predator demand (Table 7). Assuming that the ACT = 2 is a more realistic value than ACT = 3, bluefish predatory demand on anchovy would be 127.7 mg dw/m^3/yr (510.8 mg ww/m^3/yr) in years of low bluefish density and 510.6 mg dw/m^3/yr (2,042.4 mg ww/m^3/yr) in years of high bluefish density.

Assuming that Rose's densities of striped bass and bluefish are river-wide estimates, the predatory demand of these species in the whole Hudson River can be calculated and compared to production foregone due to power plant operation. The volume of the Hudson River from Albany to the Battery is about 2.476×10^9 m^3 (EA, No date). Multiplying the predatory demands (from Tables 6 and 7) times the river volume shows that production foregone due to power plant operation is a small fraction of predatory demand by bluefish and striped bass (Table 8). Production foregone is about 0.7% of age 1-5 striped bass predatory demand and ranges from about 0.3% of bluefish predatory demand assuming high bluefish densities and ACT = 3 to about 7% of bluefish predatory demand assuming low densities and ACT = 2.

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Table 1.—Geometric mean production per individual by life stage for Hudson River bay anchovy (based on Rose 1996b).

Life Stage	Production	
	Dry Weight (mg dw / individual)	Wet Weight (mg ww / individual)
Average Egg	0.0717	0.2868
Average YSL	0.310	1.240
Average PYSL	6.84	27.36
Average Juvenile	62.5	250

Table 2.—Gear efficiency estimates used in the Hudson River bay anchovy production foregone analysis.

Life Stage	Gear Efficiency
Egg	0.326
Yolk-Sac Larva	0.000256
Post Yolk-Sac Larva	0.877
Juvenile (1/RPC = ½.6)	0.385

Table 3.—Hudson River bay anchovy abundance and production per individual (based on Rose 1996).

Length (mm)	Abundance (Number / 1500 m^3)	Production per Individual	
		Dry Weight (mg ww / individual)	Wet Weight (mg dw / individual)
Eggs	56,734,050		
YSL	14,361,705		
First Feeding	3,082,766		
3	1,395,744	6.8	1.7
4	871,382	10.8	2.7
5	668,170	14.0	3.5
6	290,574	32.4	8.1
7	209,255	44.8	11.2
8	160,574	57.6	14.4
9	113,727	80.8	20.2
10	89,544	101.6	25.4
11	71,368	126.4	31.6
12	59,282	150.8	37.7
13	49,697	178.4	44.6
14	39,457	223.2	55.8
15	34,874	250.0	62.5
16	32,027	269.2	67.3
17	29,821	285.6	71.4
18	28,042	299.6	74.9
19	26,600	310.8	77.7
20	25,372	320.4	80.1
21	24,295	328.4	82.1
22	23,319	335.2	83.8
23	22,414	340.4	85.1
24	21,612	344.0	86.0
25	20,855	346.4	86.6
26	19,768	354.8	88.7
27	18,619	363.6	90.9
28	17,534	371.6	92.9
29	16,476	379.2	94.8
30	15,446	386.8	96.7
31	14,452	394.0	98.5
32	13,553	398.4	99.6
33	12,628	404.8	101.2
34	11,765	408.8	102.2
35	10,932	412.8	103.2
36	10,126	415.6	103.9
37	9,351	417.2	104.3
38	8,623	417.6	104.4
39	7,927	416.0	104.0

Table 4.—Bay anchovy production foregone estimates by year.

Year	Production Foregone	
	Dry Weight (kg dw/yr)	Wet Weight (kg ww/yr)
1991	4,661	18,644
1992	962	3,848
1993	1,398	5,592
1994	3,309	13,236
1995	2,227	8,908
1996	884	3,536
1997	2,073	8,292
Mean	2,216	8,864

Table 5.—Data used in bioenergetics modeling of predatory demand.

Parameter	A Function of
C	Temperature, Weight at time *t*
M	Temperature, Weight at time *t*
S	*C*
E	*C*
U	*C*
G	Initial weight, final weight, initial date, final date

Table 6.—Simulated predatory demand on Hudson River anchovy by striped bass.

Age	Consumption of Anchovy	
	Dry Weight (mg dw/m^3/yr)	Wet Weight (mg ww/m^3/yr)
1	3.7	14.8
2	17.3	69.2
3	45.6	182.4
4	37.6	150.4
5	32.2	128.8
Total	136.4	545.6

Table 7.—Simulated predatory demand on Hudson River anchovy by bluefish.

Cohort	Density (No. / 1000 m^3)	Consumption			
		Dry Weight (mg dw/m^3/yr)		Wet Weight (mg ww/m^3/yr)	
		ACT* = 3	ACT* = 2	ACT* = 3	ACT* = 2
Spring	20	87.4	96.4	349.6	385.6
Summer	10	43.7	31.3	174.8	125.2
Total		131.1	127.7	524.4	510.8
Spring	80 (4 x 20)	501.2	385.6	2004.8	1542.4
Summer	40 (4 x 10)	174.8	125.0	699.2	500.0
Total		675.9	510.6	2703.6	2042.4

* ACT = Activity coefficient relating active metabolism to basal metabolism.

Table 8.—Production forgone and predatory demand on Hudson River bay anchovy.

Source	Production Foregone or Predatory Demand	
	Dry Weight (kg dw/yr)	Wet Weight (kg ww/yr)
Power Plant Operation	2,216	8,846
Striped Bass Predation	337,500	1,350,000
Bluefish Predation (ACT =2)		
Low Densities	31,620	126,500
High Densities	1,264,000	5,056,000
Bluefish Predation (ACT = 3)		
Low Densities	324,500	1,298,000
High Densities	1,674,000	6,694,000

2. ENTRAINMENT EFFECTS ON DAILY BIOMASS OF BAY ANCHOVY

Introduction

The Individual-Based Model for bay anchovy developed at Oak Ridge National Laboratory (Rose 1996a) was also used to assess the seasonal pattern of anchovy biomass in the river under conditions of no entrainment losses, and at various entrainment mortality rates. This was undertaken to provide additional perspective on the perturbations potentially caused by entrainment losses of bay anchovy to the available food supply for anchovy predators, without requiring additional assumptions about predator food preferences or mortality rates. Temporal patterns of daily biomass within the model box, and the amount of biomass removed each day due to natural and entrainment mortality.

Methods

For this series of model runs, a constant immigration of 311 female spawners per year was used. The model was run for 10 years without entrainment mortality to eliminate the effects of initial conditions. Beginning with the 11th year, entrainment mortality was imposed and the daily biomass values (mg dw/m^3) were recorded. Biomass was recorded each day for eggs, yolk-sac larvae, post yolk-sac larvae, juveniles, YOY adults, age 1 adults, age 2 adults, age 3 adults, total YOY (eggs through YOY adults combined), and total for all life stages. For individuals that died, their biomass was summed to obtain a daily total biomass removed each day for each life stage category. The dying biomass was apportioned between natural and entrainment mortality according to the relative magnitude of the instantaneous daily mortality rates. Simulations were run for the following cases:

Run	Entrainment Mortality in Year 11			
	Daily Rate	Life Stages	Duration (d)	~CMR
1	0.0000	None	0	0.000
2	0.0025	Egg - PYSL	34.3	0.082
3	0.0025	Egg - Juv	68.8	0.158
4	0.0025	Egg - YOY adult	297.9	0.525
5	0.0050	Egg - PYSL	34.3	0.158
6	0.0050	Egg - Juv	68.8	0.291
7	0.0050	Egg - YOY adult	297.9	0.775
8	0.0100	Egg - PYSL	34.3	0.290
9	0.0100	Egg - Juv	68.8	0.497
10	0.0100	Egg - YOY adult	297.9	0.949

The approximate conditional mortality rate (CMR) for each run was determined as 1 - exp(-z^*d) where z^* is the daily instantaneous entrainment mortality rate and d is the duration of entrainment exposure in days. The life stage durations varied little between runs and the average values used to estimate conditional mortality rate were:

Life Stage	Size (mm)	Duration (days)	Cumulative Duration
Egg		0.84	0.84
YSL	<2.8	1.26	2.1
PYSL	2.8-25	32.2	34.3
Juvenile	25-40	34.5	68.8
YOY adult	40-50	229.1	297.9

The purpose of the analysis was to estimate the effects of entrainment mortality on daily biomass of anchovy available to their predators, the change in biomass consumed by predators, and the actual biomass diverted to alternate energy pathways due to entrainment. The following assumptions are inherent in the analysis:

1) The IBM based on primarily Chesapeake Bay data is a reasonable representation of conditions in the Hudson River estuary.

2) The risk of entrainment mortality applies equally across the vulnerable life stages in each run.

3) Since under baseline conditions mortality due to starvation was negligible (Rose 1996a), all natural mortality is assumed to be due to predation.

4) Bay anchovy predators do not switch their foraging preferences and tactics as abundance of anchovy changes, i.e. anchovy are consumed in proportion to their abundance.

Results

To illustrate the results of the simulations, runs 1, 3, 6, and 9 have been used to examine the range of potential effects of entrainment on YOY bay anchovy biomass through the end of the first growing season. The entrainment runs (3, 6, and 9) all include entrainment mortality through the juvenile life stage, a period of 68.8 days from hatching. The levels of daily entrainment mortality (0.0025, 0.005 and 0.01 per day) result in conditional entrainment mortality rates of 0.158, 0.291, and 0.497, respectively.

The biomass of YOY bay anchovy in the river was reduced as entrainment mortality increased (Figure 1). Peak YOY biomass was reached in late September under all levels of entrainment mortality, with the baseline peak at about 500 mg dw/m^3. Entrainment mortality of 0.01 per day produced a peak biomass of approximately 400 mg dw/m^3, with

the intermediate levels of entrainment producing intermediate peaks. The relative change in bay anchovy biomass from the baseline condition was greatest in early August, with maximum reductions of approximately 18%, 40%, and 44% for the three levels of entrainment mortality (Figure 2). Biomass recovered relatively quickly afterwards and by late September the changes had stabilized at approximately 8%, 10%, and 20% below baseline, reductions considerably less than the conditional entrainment mortality rates.

Estimated biomass consumed (under the assumption that all natural mortality represents predation) peaked at approximately 20 mg dw/m^3 in late July for all entrainment scenarios (Figure 3), with relatively little difference among the scenarios up to that point. After the peak was reached, daily consumption declined steadily until the end of the year and was quite variable from day to day due to the stocastic nature of the simulations. The relative change in consumption was based on 7-day moving averages in order to smooth the pattern and aid interpretation. The 0.0025 daily entrainment case (Run 3) fluctuated widely above and below the baseline (Figure 4). The relative change for the two higher entrainment runs also fluctuated both above and below the baseline, but overall were approximately 10% below the baseline on average. However, during the late summer period of peak consumption, the relative changes were generally no more than about 5%.

The actual biomass of entrained anchovy was extremely small compared to either the river biomass or the biomass consumed under all three entrainment scenarios. The peak daily biomass entrained was about 0.24 mg dw/m^3 under the 0.01 daily entrainment rate, and only 0.06 mg dw/m^3 under the 0.0025 daily entrainment rate (Figure 5). The entrained biomass was approximately 10% or less of the surviving daily river biomass and 1% of the daily consumption at the beginning of the simulations (Figure 6). However, from mid-June through late July, entrained biomass was approximately 2 orders of magnitude lower than the biomass consumed, and an even small fraction of consumed biomass after that time. From mid-May until early July, biomass consumed daily exceeded the surviving daily biomass.

Discussion

Simulation of the biomass of anchovy in the river, consumed by predators, and entrained at power plants indicated that effects on anchovy biomass are less severe than is suggested by the conditional mortality rate. In the past, conditional mortality rates have sometimes been viewed as an estimate of the reduction in food supply for predators of bay anchovy (assuming no prey switching would occur). Even if anchovy were the only available prey for certain predators, the reduction in the available anchovy biomass approaches the CMR value for only a short period of time, and for most of the time when anchovy are in the estuary, is generally much less than the ultimate CMR value. In addition, due to the timing of the actual biomass reduction, and the stocastic nature of prey encounters, changes in the amount of anchovy consumed would be difficult to detect even at CMRs approaching 0.5. The amount of anchovy biomass diverted to alternate pathways through the food web due to entrainment mortality appears to be a very small fraction (<1%) of the total bay anchovy YOY biomass.

Figure 1. Biomass of YOY bay anchovy remaining in the river under baseline (no entrainment) and under three levels of entrainment mortality.

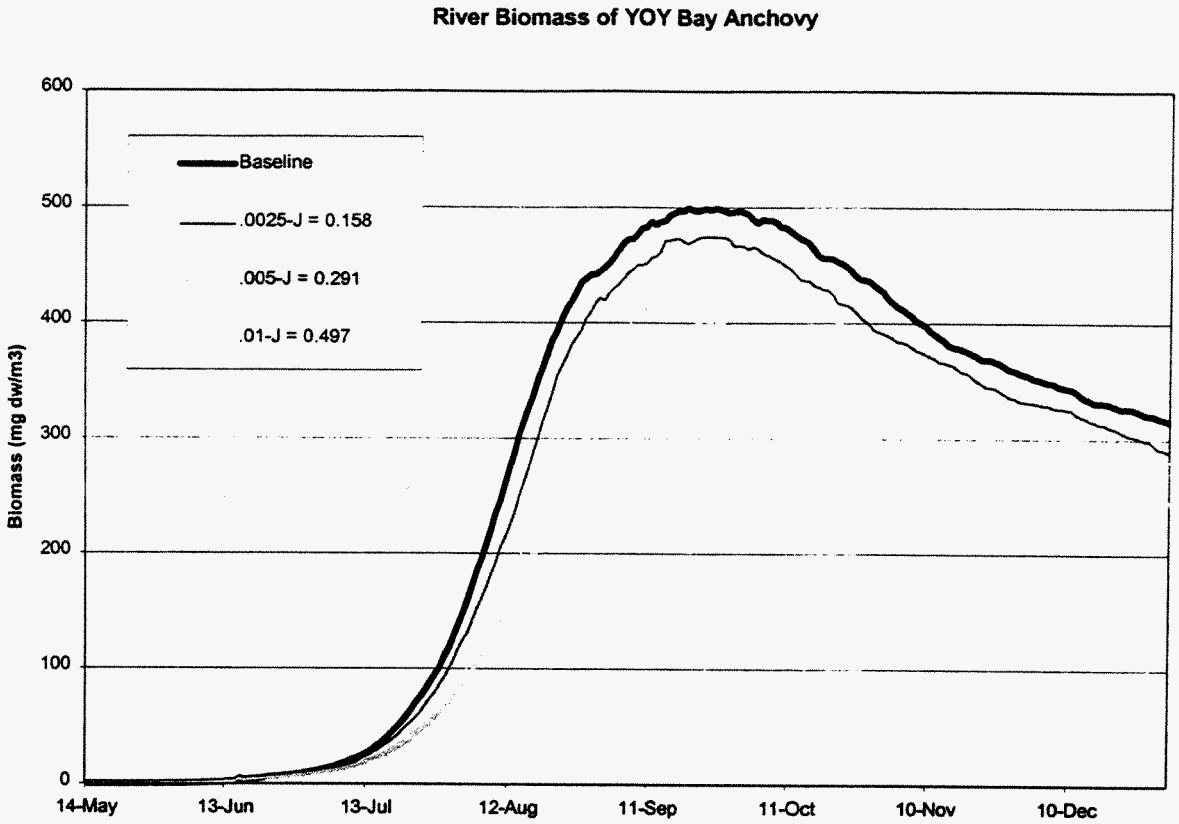

Figure 2. Relative change in biomass of YOY bay anchovy remaining in the river from baseline (no entrainment) under three levels of entrainment mortality.

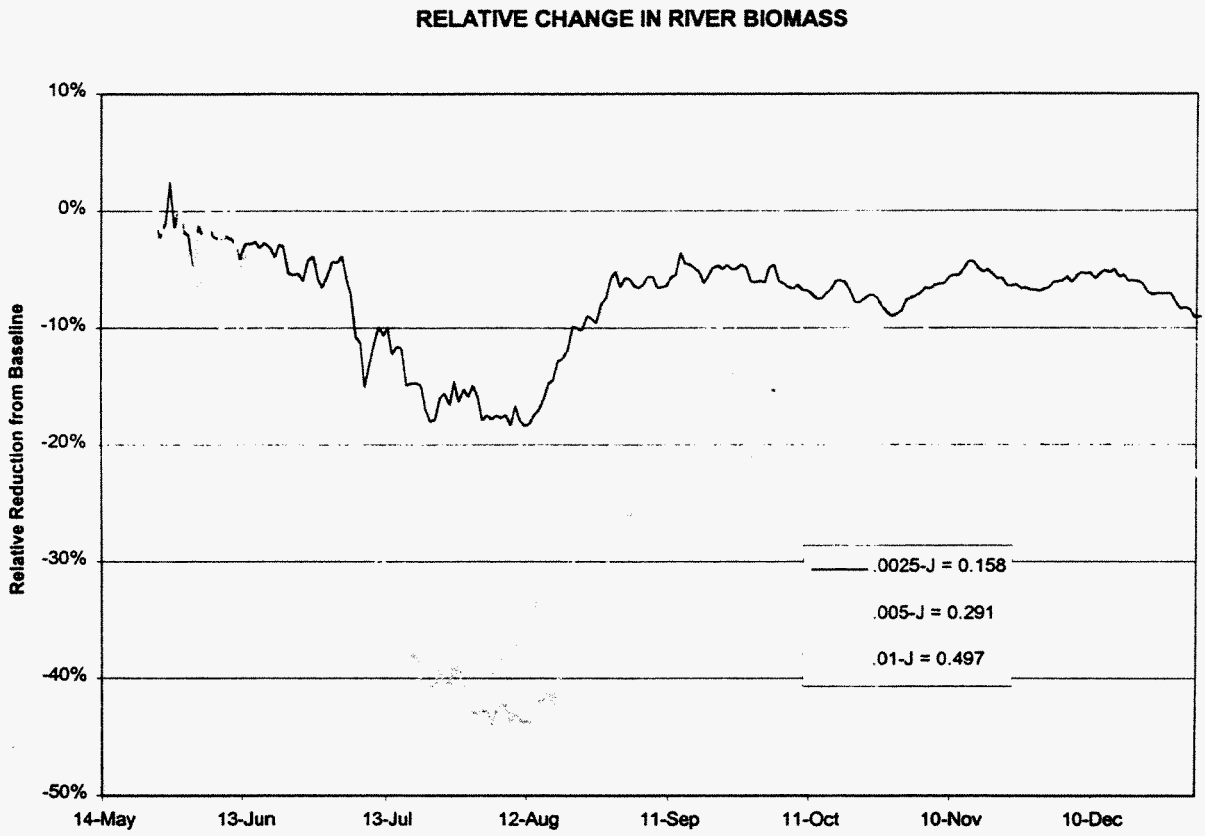

Figure 3. Biomass of YOY bay anchovy consumed under baseline (no entrainment) and under three levels of entrainment mortality.

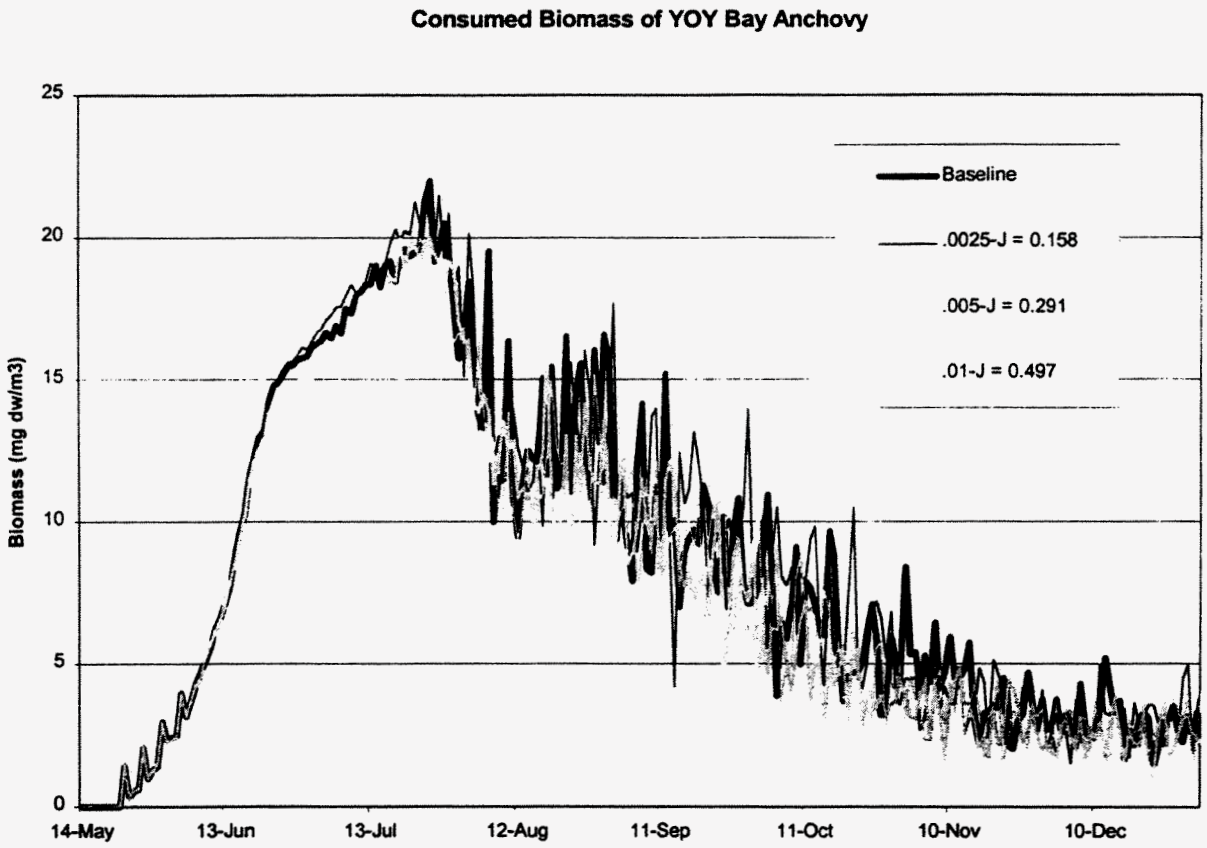

Figure 4. Relative change in biomass of YOY bay anchovy consumed from baseline (no entrainment) under three levels of entrainment mortality.

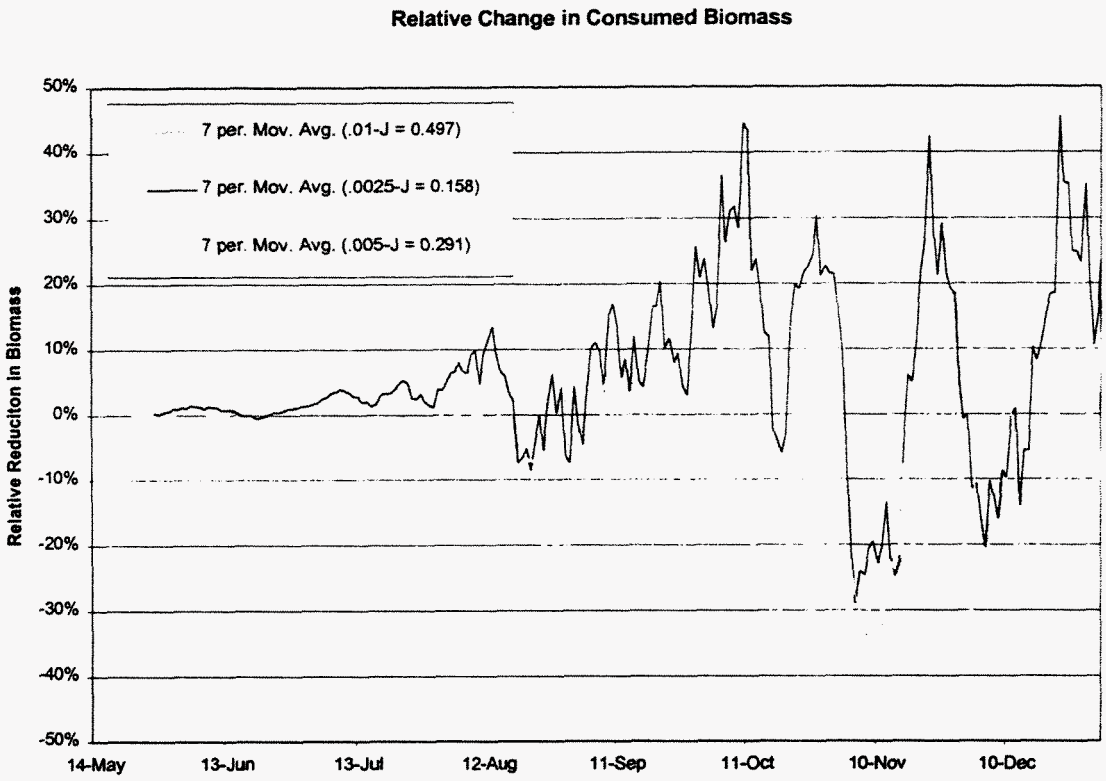

Figure 5. Biomass of YOY bay anchovy entrained under three levels of entrainment mortality.

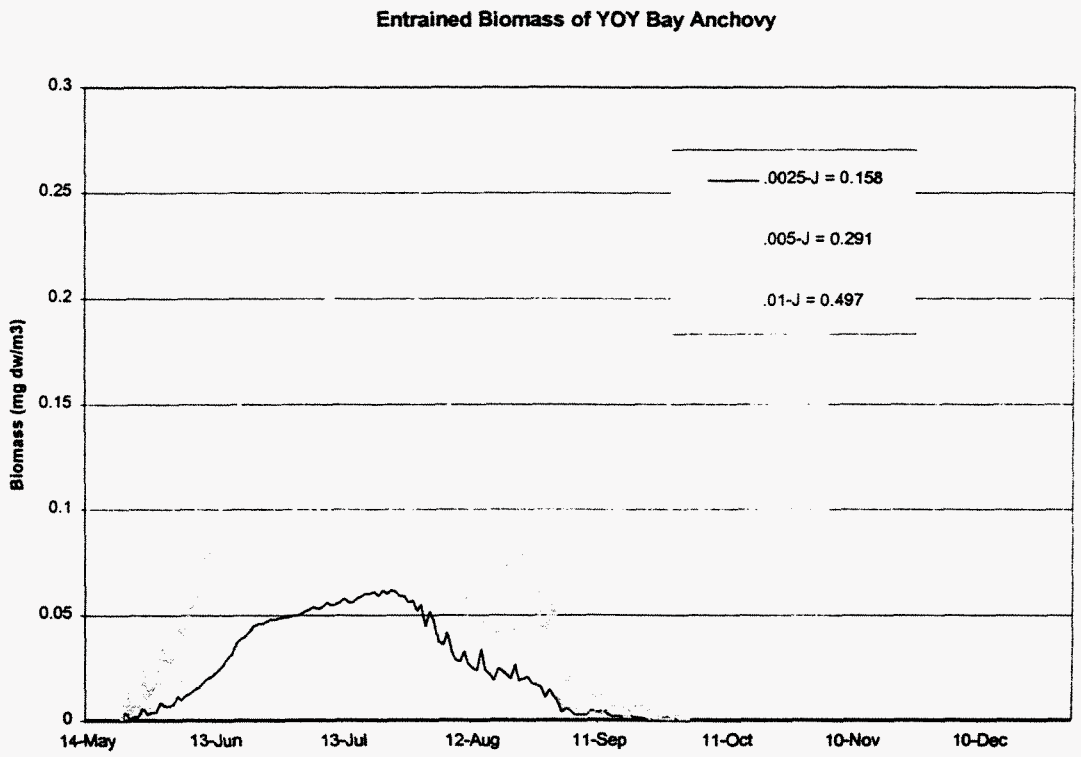
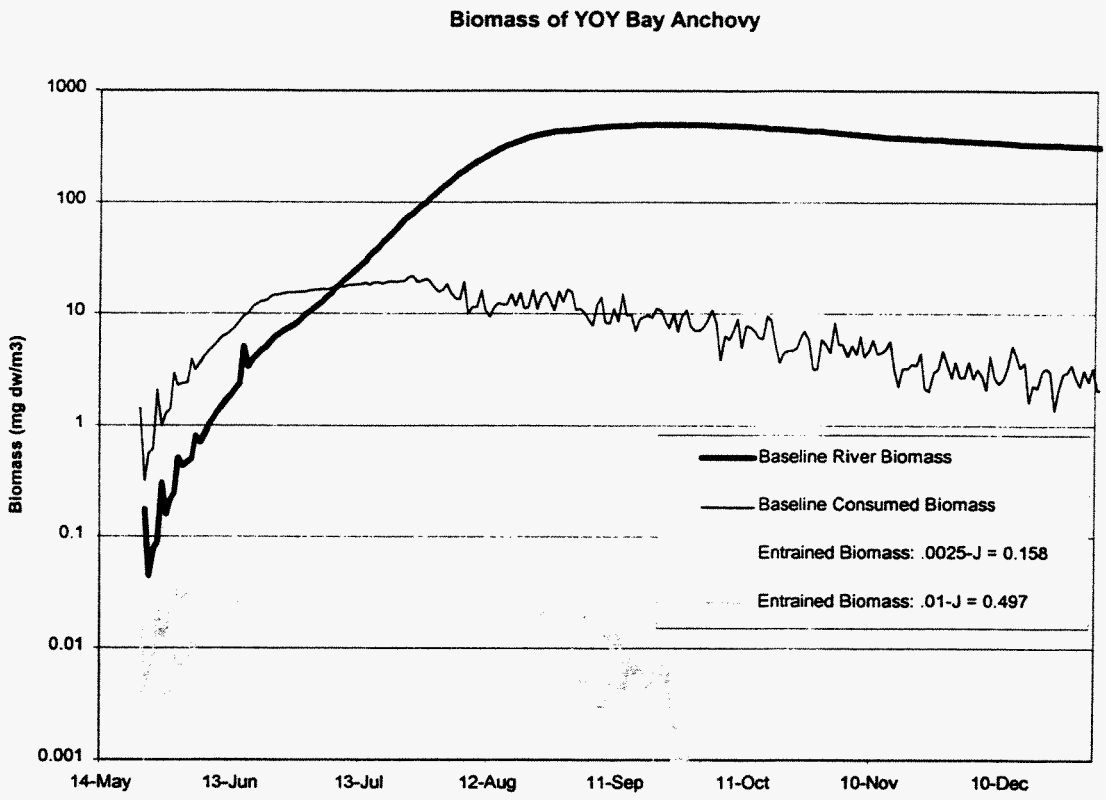
Figure 6. River biomass and consumed biomass under baseline conditions (no entrainment), and entrained biomass under two levels of entrainment.