CALIBRATION OF NORTHERN ANCHOVY SPAWNING BIOMASS ESTIMATES DERIVED BY EGG PRODUCTION AND LARVAL CENSUS METHODS

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ABSTRACT

A mathematical procedure is developed for converting estimates of northern anchovy spawning biomass derived by egg production methods to values equivalent to those derived by larval census methods. This calibration is based on the results of concurrent spawning biomass surveys conducted for both methods in 1980 and 1981. Two egg production surveys were made in 1981. The coefficient of proportionality for the two biomass estimators is not a simple constant but a function of egg survival, daily population fecundity, and larval mortality rate—all of which may vary from year to year. The common link between these two biomass estimators is the daily production of larvae at the time of hatching. The coefficient of proportionality between the hatching rates derived from the two estimators is relatively constant for the three test cases. The proposed equation for converting egg production estimates of spawning biomass to equivalent larval census estimates may result in a bias of 3.1% in the equivalent larval census estimate.

RESUMEN

Se desarrolla un procedimiento matemático para convertir estimaciones de la biomasa de la puesta de *Engraulis mordax* (anchoa), derivado de los métodos equivalentes para la producción de huevos y del censo larval. Esta calibración está basada en los resultados obtenidos sobre la biomasa de la puesta utilizando ambos métodos, durante exploraciones en 1980 y 1981. En 1981 se efectuaron dos exploraciones para determinar la producción de huevos. El coeficiente de proporcionalidad para los dos valores en la estimación de la biomasa, no es una constante simple, sino una función de la supervivencia de huevos, fecundidad diaria de la población y valor de la mortalidad larval, factores que varían de un año para otro. El eslabón común entre estas dos estimaciones de la biomasa es la eclosión diaria de larvas. El coeficiente de proporcionalidad entre los valores de eclosión derivados de los dos valores estimados resultó relativamente constante para las tres pruebas efectuadas. La ecua-

ción que se propone para convertir la estimación de la producción de huevos en la estimación de la biomasa de la puesta y la estimación equivalente del censo de larvas, puede resultar con una desviación del 3.1% en la estimación equivalente del censo de larvas.

INTRODUCTION

The Fishery Management Plan (FMP) for northern anchovy specifies the seasonal catch quota for the U.S. fishery off California based on an annual estimate of anchovy spawning biomass. The quota formula options presented in the original FMP were evaluated using an anchovy population model developed from the 1951-75 time series of larval census estimates (Smith 1972; Huppert et al. 1980). The La Jolla laboratory of the Southwest Fisheries Center (SWFC), National Marine Fisheries Service, is responsible for making these annual estimates. Parker (1980) described and demonstrated the feasibility of a new method of estimating anchovy spawning biomass referred to as the egg production method. In 1980 the SWFC conducted concurrent surveys to estimate spawning biomass by both methods (Stauffer and Picquelle 1981; and MS[2]). The results indicated that the value of the egg production estimate may be 50% to 60% of the corresponding larval census estimate. Because of the advantages of the egg production method[2]—particularly fewer vessel days at sea—the SWFC decided to convert the annual surveys to the egg production method by 1982 and to conduct concurrent surveys by the two methods in 1981.

The Pacific Council instructed the anchovy plan development team to modify the FMP and to fit the anchovy population model to a time series of spawning biomass estimates equivalent to the egg production method. The council also requested that the SWFC convert the egg production estimates to equivalent larval census estimates in the intervening years until the new plan is implemented. The purpose of this report is to document the procedure for converting egg production estimates to equivalent larval census estimates beginning in 1982, based on the concurrent surveys of 1980 and 1981.

DERIVATION OF CALIBRATION

Simple Case of Proportionality

The basis for the calibration between the two spawning biomass estimators is that the larval census estimate, B_1, is proportional to the egg production estimate, B_e, for any year in which concurrent surveys have been conducted. This can be described by

$$B_1 = c \, B_e, \tag{1}$$

where c is a coefficient of proportionality. If c is constant from year to year then the larval census estimate in year j can be derived from an egg production estimate from equation (1) where c is estimated for the calibration years. This conversion equation becomes more complex if c is quite variable from year to year, violating the assumption of constant proportionality.

Complex Case of Variable Proportionality

The calibration in the case when c is not equal from year to year can be derived from the relationship of the larval census estimate, B_1, to the daily production of newly hatched larvae, L_h, and from the relationship of the egg production estimate, B_e, to daily rate of hatching eggs, P_h. A common link between these two biomass estimators is the daily production of larvae at the time of hatching. The production of larvae estimated from the plankton data collected on the larval census survey should be proportional to the daily rate of hatching eggs estimated from the plankton data collected on the egg production survey. This says that

$$L_h = b \, P_h, \tag{2}$$

where b is a constant of proportionality. The value of b would be 1.0 if the two survey methods give equivalent estimates of L_h and P_h. The conversion from one biomass estimator to the other can be specified by expressing L_h and P_h as functions of B_1 and B_e, respectively.

Daily production of larvae. Lo[3] has found that the survival of anchovy larvae increases with age such that the instantaneous rate of mortality is not constant, as previously considered (Hewitt 1982). She modeled the decay in a daily cohort of larvae, $L'(a)$ as:

$$\frac{dL'(a)}{da} = -\frac{\beta}{a} L'(a) \tag{3}$$

where a is age of larvae with time zero at fertilization, and β is the mortality coefficient. The number of larvae within a cohort at age a is the intregral of (3)

$$L'(a) = L'_h \left(\frac{a}{a_h}\right)^{-\beta} \tag{4}$$

where L'_h is the number of larvae hatched, and a_h is their age at hatching.

For the larval census estimate of spawning biomass, Smith (1972) derived B_1 proportional to the census of larvae, L, for the year, that is,

$$B_1 = 8.9 \times 10^{-8} L, \tag{5}$$

where B_1 is in units of metric tons. The computation of the larval census, L, can be modeled as the quarterly sum of the integral of the larval mortality function (5), that is,

$$L = \sum_{i=1}^{4} L_i = \sum_{i=1}^{4} \int_{a_h}^{A} L_{hi}(t) \left(\frac{a}{a_h}\right)^{-\beta_i(t)} da$$

where $L_{hi}(t)$ is the daily production of newly hatched larvae on day t, quarter i, $\beta_i(t)$ is the mortality coefficient on day t, quarter i, and A is the maximum age larvae are effectively sampled by plankton net (505-micrometer-mesh bongo).

Solving this integral, the quarterly larval census, L_i, is equivalent to

$$L_i = \frac{L_{hi} \, a_h}{\beta_i - 1} \left(1 - \left(\frac{a_h}{A}\right)^{\beta_i - 1}\right),$$

assuming $L_{hi}(t)$ and $\beta_i(t)$ are constant for quarter i. Since the sum of the larval census for the summer and fall quarters is about 6% of the sum for the winter and spring quarters (Stauffer and Parker 1980), the annual larval census can be approximated by a function of winter-spring average production of larvae, L_h, and larval mortality rate, β, that is,

$$L = 2.12 \frac{L_h a_h}{\beta - 1} \left(1 - \left(\frac{a_h}{A}\right)^{\beta - 1}\right).$$

Substituting for L into (5) and solving for L_h gives

$$L_h = \frac{B_1}{18.9 \times 10^{-8}} \left(\frac{\beta - 1}{a_h}\right) \left(1 - \left(\frac{a_h}{A}\right)^{\beta - 1}\right)^{-1} \tag{6}$$

Daily rate of hatching eggs. The egg production estimator, B_e, from Parker (1980) and Stauffer and Picquelle[4] is

$$B_e = \frac{k_1 k_2 \, PW}{R \, F \, S}, \tag{7}$$

where k_1 is the geographic area for the stock, k_2 is conversion from grams to metric tons, P is daily rate of egg production in the sea per 0.05 m^2 surface area, W is average weight of female anchovies, R is fraction

of females in the stock, F is batch fecundity per fish, and S is fraction of female fish spawning per day.

By combining parameters so that the daily egg production in the sea for the anchovy stock is

$$P' = k_1 P .$$

and the daily production of eggs per ton of adult fish or daily population fecundity is

$$p = RFS/WK_2,$$

equation (7) simplifies to

$$B_e = P'/p. \qquad (8)$$

The daily rate of hatching eggs, P_h, can be estimated from the exponential egg mortality model,

$$P_h = P'e^{-Za_h} = P's$$

where Z is egg mortality rate, and s is total egg survival over the incubation period.

Substituting into (8) and solving for P_h gives

$$P_h = B_e \, p \, s. \qquad (9)$$

Calibration equation. The equation for converting from the egg production biomass estimate to the larval census estimate is obtained by substituting L_h from (6) and P_h from (9) into (2) and solving for B_1. This gives

$$B_1 = b(18.9 \times 10^{-8})$$

$$B_e \left(\frac{a_h}{\beta-1}\right)\left(-1\left(\frac{a_h}{A}\right)^{\beta-1}\right) ps . \qquad (10)$$

The coefficient of proportionality, c, from equation (1) is now

$$c = b(18.9 \times 10^{-8})$$

$$\left(\frac{a_h}{\beta-1}\right)\left(-1\left(\frac{a_h}{A}\right)^{\beta-1}\right) ps . \qquad (11)$$

The source of any variability in the coefficient c from year to year, other than sampling error, should be due to changes in larval mortality rate, egg survival rate, the production of eggs per unit weight of adult fish, or departures from the assumed egg and larval mortality functions.

In any year with an egg production survey, an equivalent larval census estimate of spawning biomass can be derived from equation (10) using a value of b estimated from the calibration years 1980 and 1981. If an estimate of larval mortality rate, β, equivalent to estimates derived from the analysis of larval data is not available, then a value of β must be assumed. In addition, simplification of equation (10) is possible by substituting P' for pB_e from equation (8), giving

$$B_1 = b(18.9 \times 10^{-8})$$

$$P's \left(\frac{a_h}{\beta-1}\right)\left(-1\left(\frac{a_h}{A}\right)^{\beta-1}\right) . \qquad (12)$$

This says that the larval census estimate can be estimated from just an ichthyoplankton survey of anchovy eggs and an assumption of larval mortality. A survey of adult fish, then, is only necessary if an egg production estimate of biomass is also desired.

ESTIMATION OF CALIBRATION COEFFICIENTS

The calibration between the two anchovy biomass estimation methods can be evaluated from the paired surveys of 1980 and 1981. The estimates of the biomass and related parameters for the larval census and egg production methods are reported by Stauffer and Picquelle (1981; also footnote 2), Stauffer and Charter (1982), and Picquelle and Hewitt (1983). These estimates are summarized in Table 1. The larval census estimates of biomass are 1,611,000 metric tons (MT) and 2,544,000 MT for 1980 and 1981, respectively. The egg production estimates of biomass are 782,000 MT in 1980, 585,000 MT for the February 1981 survey, and 343,000 MT for the second 1981 survey (April). The coefficient of proportionality, c, from equation (1) is 2.06, 4.35, and 7.42 for the three surveys, respectively. The changes in c for the two

TABLE 1
Estimates of Parameters, Spawning Biomass, and Coefficients of Proportionality for Three Calibration Surveys

Parameter estimates	Units	March 1980	February 1981	April 1981
P	$\dfrac{\text{egg}}{\text{tow day}}$	10.09	7.961	4.936
P'	$\dfrac{10^{12} \text{ eggs}}{\text{day}}$	23.97	19.01	11.46
p	$\dfrac{10^{6} \text{ eggs}}{\text{ton day}}$	30.65	32.60	33.46
Z		0.453	0.138	0
a_h	Days	2.71	2.75	2.75
s		0.293	0.684	1.000
β^1		1.7999	1.7056	1.7085
B_e	Metric tons	782,000	585,000	343,000
B	Metric tons	1,611,000	2,544,000	2,544,000
c		2.06	4.35	7.42
b		0.4195	0.3249	0.3699

$\bar{b} = 0.3835$

[1] Parameter values for β are taken from Picquelle and Hewitt (1983).

1981 surveys with respect to the 1980 calibration amount to a 111% and a 260% increase. This variation in c is primarily due to the large differences in egg survival, since the other parameters in (11) are relatively constant (Table 1). These large differences in c suggest that the calibration between the two biomass methods using equation (1), which assumes c is constant year to year, is rather poor.

Analysis of the calibration based on equation (10) provides relatively consistent values of the constant of proportionality, b. The values of b for the three comparisons are 0.4195 for 1980, 0.3249 for February 1981, and 0.3699 for April 1981—a maximum decrease of 23% relative to the 1980 value. These values of b are much lower than 1.0. Based on equation (2) this implies that larval production estimated from the larval data is about 38% of the value derived from the egg data. The differences between L_h (production of larvae) and P_h (rate of hatching eggs) for 1980 surveys are illustrated in Figure 1. The daily rate of hatching eggs was approximately 3.7 eggs/tow (0.05 m^2 of sea-surface area). The daily production of larvae is about 42% of the value P_h. Possible explanations for this consistent empirical value of b less than 1.0 are that the estimate of L_h is averaged over winter and spring months, whereas P_h is the average of one month during the peak of the spawning season, and that the larval census estimate has not been adjusted upward for the extrusion of larvae through the meshes of the plankton net. The scalor difference between the egg production and the larval census estimators probably results from inaccuracies in the coefficient of proportionality, 8.9×10^{-8}, of the larval census estimate (5) derived by Smith (1972).

CALIBRATION FOR AN EQUIVALENT LARVAL CENSUS ESTIMATE IN FUTURE YEARS

For years in which only an egg production survey is conducted, the optimum yield for the U.S. fishing season can be based on an equivalent larval census estimate of anchovy spawning biomass using the calibration equations (10) or (12). Estimates of egg parameters s, P' or p, and B_e can be derived from the egg production survey data. A weighted average of b for the surveys is 0.3835, given weights of ½ to the 1980 survey and ¼ to the two 1981 surveys. If a sufficient number of bongo plankton samples are collected during the egg production survey, a value of β can be estimated for the survey. Another alternative is to use the average value for 1980 and 1981 of 1.753.

A comparison of equivalent values versus the actual biomass estimates derived by larval census methods suggests that equations (10) or (12) overestimate the biomass by 3.1% using 0.3835 for b and yearly esti-
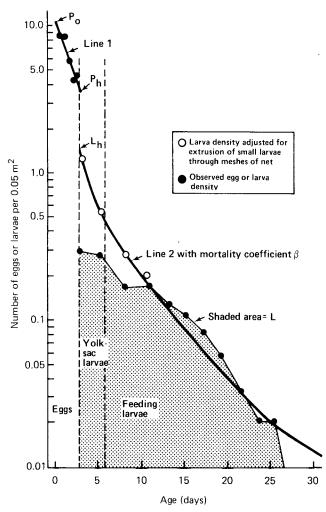

Figure 1. Conceptual basis for the calibration between the egg production and larval census estimators of anchovy spawning biomass. Lines 1 and 2 represent the mortality models for eggs and larvae, respectively.

mates of β. Procedures for estimating the precision of the predicting equations (10) or (12) have not been developed, primarily because of the unknown precision of the original biomass estimates for the larval census method.

ACKNOWLEDGMENTS

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