**Abstract.**—We developed a relatively simple and parsimonious (SMPAR) biomass dynamics model for estimating abundance of northern anchovy, *Engraulis mordax*, off southern California and Baja California, Mexico, during the 1963 to 1991 fishing seasons. The SMPAR model was a compromise between simple surplus production and complex age-structured models. It was designed to give more precise biomass estimates for management of northern anchovy for which there are no age-composition data and only noisy abundance index data. We evaluated consistent bias in biomass and recruitment estimates, bias in recruitment estimates due to log transformation, and retrospective bias. Simple corrections based on bootstrap procedures were used to remove consistent bias and log transformation bias. Retrospective bias was not a significant problem. Results indicate that the SMPAR model estimates stock biomass more reliably than recruitment because abundance indices for northern anchovy contain little information about interannual recruitment variability. Asymptotic variance estimates calculated by inverting the Hessian matrix averaged 20% smaller than variances calculated by bootstrapping. Outliers in abundance data were the biggest source of uncertainty in biomass estimates. Simulation results indicate that our approach could be useful in a variety of situations.

# A biomass-based assessment model for northern anchovy, *Engraulis mordax*

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Northern anchovy, *Engraulis mordax*, is a small (<18 cm TL), short lived (<8 years) pelagic schooling fish (Baxter, 1967). The central stock of northern anchovy extends from Mexico to central California (lat. 30°–35°N); most of the stock inhabits the Southern California Bight. Spawning occurs all year with a peak between February and April (MacCall and Prager, 1988).

The central stock of northern anchovy is among the world's most thoroughly studied fish stocks. Reliable estimates of northern anchovy biomass were not available, however, until the daily egg production method was used to estimate spawning biomass from 1980 to 1985 (Lasker, 1985). Estimates of long-term trends in biomass were not available until the stock synthesis model for northern anchovy was developed (Methot, 1989). The stock synthesis model was used to manage northern anchovy until 1992 after availability of age-composition data declined.[1]

As data became limited, variance and bias of biomass estimates[2] from the stock synthesis model increased. Bias problems included a positive "retrospective" bias in recent estimates and a smaller but consistent positive bias in estimates for earlier seasons (Lo et al., 1992).

Retrospective bias is a newly recognized but common problem in fish stock assessment work (Sinclair et al., 1991) that makes recent biomass estimates too large. Consistent bias (usually positive) is a problem of variable severity in biomass estimates from most assessment models including the stock synthesis model (Lo et al., 1992; Bence et al., 1993), derivatives[3] of CAGEAN (Deriso et al., 1985), and virtual population analysis or VPA (e.g. Lapointe et al., 1989). Consistent bias, unlike retrospective bias, affects all or most of the biomass estimates from a model.

We hypothesized that problems in the stock synthesis model for north-

ern anchovy were exacerbated by use of a complicated model with insufficient data. The model we developed for northern anchovy was, therefore, simpler and more parsimonious (SMPAR).

The SMPAR model is a biomass dynamic model designed to give more precise biomass estimates for management of northern anchovy. SMPAR is a hybrid between simple surplus production and complex age-structured models. It resembles a surplus production model because age-composition data are not used and fishing mortality rates are equal for all age groups. The model is age structured, however, and some rudimentary relationships between age-specific abundance and abundance indices are assumed.

As described above, the SMPAR model for northern anchovy did not use any age-composition data, although data were available for most fishing seasons prior to 1991. We chose to exclude age-composi-

tion data from our model because the data are difficult to interpret, require complex modeling approaches, and were not available for recent seasons.

In this paper, we describe the SMPAR model and data for northern anchovy. Bias and variance in biomass and recruitment estimates are assessed by using bootstrap techniques. Sensitivity analyses show how model assumptions and contradictory trends in the data affect biomass estimates from SMPAR. We use simulation analysis to show how SMPAR would perform under a wide range of fishing mortality and recruitment conditions.
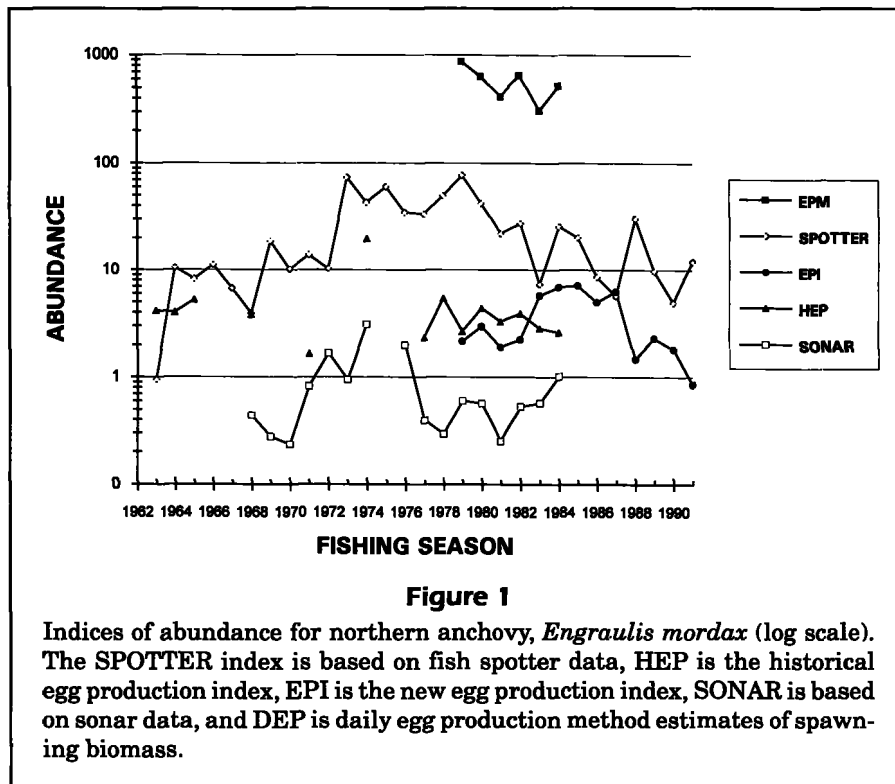
## Data and methods

Fishing seasons were used to aggregate most of our data including landings data and indices of abundance (Table 1; Fig. 1). Fishing seasons for northern

### Table 1

Data for northern anchovy, *Engraulis mordax*, by fishing season (1 July to 30 June): fish spotter data (SPOTTER), historical egg production data (HEP), new egg production index (EPI), sonar data (SONAR), and daily egg production method data (DEP). CV denotes coefficient of variation. Temperatures are average sea surface temperatures at Scripps Pier, San Diego, California during January and February.

| Fishing season | SPOTTER (short tons· block$^{-1}$) | CV (%) | HEP (eggs 0.05 m$^2$· day$^{-1}$) | CV (%) | EPI (eggs 0.05 m$^2$· day$^{-1}$) | CV (%) | SONAR | DEP (10$^3$ t) | CV (%) | Mexican landings (10$^3$ t) | US landings (10$^3$ t) | Total landings (10$^3$ t) | Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1963 | 0.9 | 28 | 4.1 | 65 | | | | | | 0.000 | 1.795 | 1.795 | 15.0 |
| 1964 | 10.5 | 31 | 4.0 | 29 | | | | | | 0.000 | 2.324 | 2.324 | 13.3 |
| 1965 | 8.2 | 32 | 5.3 | 34 | | | | | | 0.000 | 18.958 | 18.958 | 13.8 |
| 1966 | 11.2 | 30 | | | | | | | | 0.000 | 42.725 | 42.725 | 14.0 |
| 1967 | 6.7 | 31 | | | | | | | | 0.000 | 13.470 | 13.470 | 14.5 |
| 1968 | 3.9 | 35 | 3.8 | 28 | | | 0.44 | | | 0.000 | 33.224 | 33.224 | 14.3 |
| 1969 | 18.6 | 30 | | | | | 0.28 | | | 0.000 | 83.391 | 83.391 | 13.6 |
| 1970 | 10.2 | 32 | | | | | 0.23 | | | 0.000 | 81.854 | 81.854 | 13.1 |
| 1971 | 13.8 | 30 | 1.7 | 48 | | | 0.82 | | | 0.000 | 55.624 | 55.624 | 12.8 |
| 1972 | 10.3 | 33 | | | | | 1.67 | | | 0.000 | 76.059 | 76.059 | 15.0 |
| 1973 | 73.6 | 29 | | | | | 0.95 | | | 0.000 | 116.666 | 116.666 | 13.1 |
| 1974 | 42.9 | 29 | 19.7 | 53 | | | 3.09 | | | 28.088 | 113.782 | 141.870 | 13.2 |
| 1975 | 60.2 | 28 | | | | | | | | 35.287 | 135.573 | 170.860 | 13.9 |
| 1976 | 34.7 | 31 | | | | | 1.98 | | | 108.962 | 104.095 | 213.057 | 16.0 |
| 1977 | 33.4 | 29 | 2.3 | 192 | | | 0.39 | | | 127.229 | 76.236 | 203.465 | 15.7 |
| 1978 | 49.5 | 34 | 5.4 | 48 | | | 0.29 | | | 195.675 | 55.966 | 251.641 | 13.9 |
| 1979 | 77.2 | 34 | 2.7 | 47 | 2.2 | 27 | 0.60 | 870 | 26 | 157.543 | 40.091 | 197.634 | 15.0 |
| 1980 | 42.0 | 38 | 4.4 | 48 | 3.0 | 14 | 0.57 | 635 | 22 | 287.547 | 65.906 | 353.453 | 14.6 |
| 1981 | 22.0 | 38 | 3.3 | 41 | 1.9 | 17 | 0.25 | 415 | 26 | 255.086 | 53.212 | 308.298 | 14.1 |
| 1982 | 27.3 | 39 | 3.9 | 30 | 2.2 | 34 | 0.53 | 652 | 21 | 156.725 | 11.003 | 167.728 | 15.9 |
| 1983 | 7.3 | 49 | 2.9 | 37 | 5.8 | 11 | 0.57 | 309 | 17 | 66.260 | 7.507 | 73.767 | 15.0 |
| 1984 | 25.7 | 45 | 2.6 | 26 | 6.9 | 48 | 1.02 | 521 | 19 | 123.359 | 4.762 | 128.121 | 13.8 |
| 1985 | 20.2 | 42 | | | 7.1 | 32 | | | | 85.801 | 6.321 | 92.122 | 15.2 |
| 1986 | 8.6 | 43 | | | 5.0 | 16 | | | | 116.334 | 4.783 | 121.117 | 15.0 |
| 1987 | 5.7 | 46 | | | 6.3 | 33 | | | | 98.498 | 5.794 | 104.292 | 14.0 |
| 1988 | 30.5 | 40 | | | 1.5 | 29 | | | | 86.361 | 5.795 | 92.156 | 13.0 |
| 1989 | 9.7 | 45 | | | 2.3 | 35 | | | | 55.647 | 8.228 | 63.875 | 14.4 |
| 1990 | 5.0 | 55 | | | 1.8 | 23 | | | | 0.796 | 10.328 | 11.124 | 14.9 |
| 1991 | 12.1 | 54 | | | 0.9 | 32 | | | | 0.134 | 4.546 | 4.680 | 15.3 |

**Figure 1**

Indices of abundance for northern anchovy, *Engraulis mordax* (log scale).
The SPOTTER index is based on fish spotter data, HEP is the historical
egg production index, EPI is the new egg production index, SONAR is based
on sonar data, and DEP is daily egg production method estimates of spawn-
ing biomass.

anchovy begin on 1 July, end on 30 June, and are
identified by the calendar year on 1 July. We assumed
that indices for northern anchovy measured abun-
dance during the peak spawning period which is
about 15 February.

Indices of abundance used to estimate northern
anchovy biomass included 1) spawning biomass es-
timated by the daily egg production method (DEP,
Gunderson, 1993; formerly called the egg production
method or EPM, Lasker, 1985), 2) a historical egg
production index (HEP, Lo, 1985), 3) our new egg
production index (EPI), 4) relative biomass of
schooled fish estimated from fish spotter data (SPOT-
TER, Lo et al., 1992), and 5) relative biomass of
schooled fish estimated from California Department
of Fish and Game sonar data (SONAR, Mais, 1974;
Methot, 1989). Indices that measured relative abun-
dance of northern anchovy (Fig. 1) were not all posi-
tively correlated and none of the correlations were
statistically significant. Lack of significant correla-
tion may have been due to relatively few years of
data used to compute some correlations, to impre-
cise indices, and to differences among indices in area
surveyed. Of particular concern is the lack of signifi-
cant positive correlation between the EPI and SPOT-
TER indices which are the only relative abundance
data available for recent fishing seasons.

Daily egg production method (DEP) estimates of
spawning biomass during the 1979 to 1984 seasons

(Table 1, Fig. 1) measured spawning biomass in met-
ric tons (t), rather than in relative units, and are
relatively precise (coefficients of variation (CV) less
than 27%). Only six DEP observations were available,
but the DEP data were important because they helped
scale indices of relative abundance for northern anchovy
to units of absolute biomass (Bence et al., 1993).

SONAR data did not include variances that were
required in our model. We used the standard devia-
tion ($\varepsilon$=0.439) of log-scale residuals for SONAR val-
ues from a previous study[2] and the relationship

$$CV = \sqrt{e^{\varepsilon^2} - 1}$$ (1)

to obtain a crude estimate (46%) of the arithmetic
scale coefficient of variation.

The SPOTTER index used in this study (Table 1,
Fig. 1) was similar to the one developed by Lo et al.
(1992) except that April to March, rather than Janu-
ary to December, annual periods were used to aggre-
gate data. The SPOTTER index value for the 1963
fishing season was anomalously low (Fig. 1). Follow-
ing Lo et al. (1992), we excluded the 1963 value be-
cause the data collection program was new in 1963
and the information may not have been reliable.

## New egg production index (EPI)

Our new egg production index (EPI) measures egg
production by northern anchovy during the 1979 to

1991 fishing seasons in the reduced CalCOFI (California Cooperative Oceanic Fishery Investigation) sampling area surveyed since 1985 (Hewitt, 1988). The HEP index, in contrast, is based on a relatively large grid of CalCOFI sampling stations occupied prior to the 1985 season. As explained below, the EPI makes use of all egg and larva data and is more precise than the modified historical egg production (MHEP) index used for recent seasons by Lo and Methot (1989). Both the HEP and EPI indices of egg production for northern anchovy during the 1979 to 1984 fishing seasons were used so that the model could calibrate the HEP and EPI against each other and against DEP spawning biomass estimates.

The EPI for northern anchovy averages values obtained by using the HEP method and a single equation model (SEM) developed by Lo (1986). We refer to the HEP "method" here to distinguish between the HEP index and calculations for recent seasons based on data from the reduced CalCOFI grid.

The EPI index was computed as

$$I_{EPI,y} = W_{SEM,y} I_{SEM,y} + W_{HEP,y} I_{HEP,y}, \qquad (2)$$

where the $I_{t,y}$ are indices of egg production for northern anchovy during fishing season $y$, and the $W_{t,y}$ are weights. Weights were derived from squared inverse coefficients of variation:

$$W_{s,y} = \frac{\frac{1}{CV_{s,y}^2}}{\frac{1}{CV_{HEP,y}^2} + \frac{1}{CV_{SEM,y}^2}}, \qquad (3)$$

where $CV_{s,y}$ is the coefficient of variation for index $s$ (either SEM or HEP) in fishing season $y$. Variances for the EPI index were approximated

$$VAR(I_{EPI,y}) = W_{SEM,y}^2 \, VAR(I_{SEM,y})$$
$$+ W_{HEP,y}^2 \, VAR(I_{HEP,y}), \qquad (4)$$

where $VAR$ denotes variance.

The weighted EPI estimates of egg production for northern anchovy were similar to HEP method and SEM estimates but more precise (Table 2). The improvement in precision is overestimated, however, because covariance between measurement errors in SEM and HEP values in each year were not included in Equation 4.

## Model

Our model for northern anchovy was based on a forward simulation approach (Hilborn and Walters, 1992) like that used in the stock synthesis model (Methot, 1989; Methot, 1990) and CAGEAN (Deriso et al., 1985). The model simulated abundance of northern anchovy during the 1963 to 1991 fishing seasons given a set of parameter estimates, data for catches, and ocean temperatures. Parameters were estimated by maximum likelihood calculations that compared observed abundance indices with values predicted by the simulation model. Catch data for northern anchovy and temperature data were assumed to be measured without error; abundance indices were assumed to include measurement error.

### Table 2

Egg production indices for northern anchovy, *Engraulis mordax*, in the reduced CalCOFI area during peak spawning (15 February): historical egg production method (HEP), single equation model (SEM), and the new weighted index (EPI). SE is standard error, CV is coefficient of variation, and "weights" are weights used in computing EPI values.

| | | HEP | | | | SEM | | | | EPI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calendar year | Fishing season | Eggs (0.05 m⁻¹ day⁻¹) | SE | CV (%) | Weights | Eggs (0.05 m⁻¹ day⁻¹) | SE | CV (%) | Weights | Eggs (0.05 m⁻¹ day⁻¹) | SE | CV (%) |
| 1980 | 1979 | 1.49 | 0.49 | 33 | 0.61 | 3.19 | 1.30 | 41 | 0.39 | 2.16 | 0.59 | 27 |
| 1981 | 1980 | 2.20 | 0.37 | 17 | 0.64 | 4.33 | 0.98 | 23 | 0.36 | 2.96 | 0.42 | 14 |
| 1982 | 1981 | 1.16 | 3.42 | 296 | 0.00 | 1.90 | 0.32 | 17 | 1.00 | 1.90 | 0.32 | 17 |
| 1983 | 1982 | 3.18 | 1.72 | 54 | 0.36 | 1.71 | 0.69 | 40 | 0.64 | 2.24 | 0.76 | 34 |
| 1984 | 1983 | 6.12 | 3.57 | 58 | 0.04 | 5.74 | 0.65 | 11 | 0.96 | 5.75 | 0.64 | 11 |
| 1985 | 1984 | 8.13 | 4.43 | 55 | 0.70 | 3.92 | 3.30 | 84 | 0.30 | 6.89 | 3.27 | 48 |
| 1986 | 1985 | 8.23 | 4.48 | 54 | 0.35 | 6.53 | 2.62 | 40 | 0.65 | 7.13 | 2.32 | 32 |
| 1987 | 1986 | 8.98 | 3.18 | 35 | 0.17 | 4.13 | 0.67 | 16 | 0.83 | 4.97 | 0.78 | 16 |
| 1988 | 1987 | 6.58 | 3.41 | 52 | 0.40 | 6.05 | 2.54 | 42 | 0.60 | 6.26 | 2.04 | 33 |
| 1989 | 1988 | 0.23 | 0.11 | 46 | 0.30 | 2.01 | 0.61 | 30 | 0.70 | 1.47 | 0.43 | 29 |
| 1990 | 1989 | 2.35 | 0.85 | 36 | 0.91 | 1.89 | 2.24 | 119 | 0.09 | 2.31 | 0.80 | 35 |
| 1991 | 1990 | 2.13 | 1.07 | 50 | 0.20 | 1.74 | 0.44 | 25 | 0.80 | 1.82 | 0.41 | 23 |
| 1992 | 1991 | 0.15 | 0.04 | 29 | 0.61 | 1.98 | 0.71 | 36 | 0.39 | 0.86 | 0.28 | 32 |

## Population dynamics

Fishing seasons were used as annual time steps, and ages 0 to 4+ were included (age group 4+ includes northern anchovy age 4 and older). Fish were aged in the model at the beginning of each fishing season on 1 July when recruitment of age-0 northern anchovy was assumed to occur (Methot, 1989). In reality, some recruitment of northern anchovy occurs throughout the year (MacCall and Prager, 1988). Therefore, our estimates of recruitment should be regarded as estimates of "effective" recruitment, i.e. biomass of age-0 fish that would have been necessary on 1 July to account for the biomass of the cohort in later years.

Numbers of northern anchovy were not included in SMPAR; abundance was measured solely in units of biomass because weight at age for northern anchovy changes rapidly throughout the year, and depends on where samples are taken (Parrish et al., 1985). In addition, weight-at-age data from commercial fisheries for northern anchovy were not available for recent fishing seasons.

Biomass dynamics were modeled as

$$B_{a+1,y+1} = B_{a,y} e^{-\eta_y}, \qquad (5)$$

where $B_{a,y}$ is the biomass of northern anchovy age $a$ ($a>0$, i.e. excluding new recruits) at the beginning of fishing season $y$ and $\eta_y$ is the net instantaneous rate of change for northern anchovy in fishing season $y$. Random process errors (e.g. variation in growth and natural mortality, Hilborn and Walters, 1992) were captured in the model by recruitment estimates.

For modeling purposes, recruitment of northern anchovy in each year was assumed independent of spawning stock size:

$$B_{0,y} = \bar{B}_0 e^{\delta_y}, \qquad (6)$$

where $B_{0,y}$ is recruitment (biomass age-0 fish) in fishing season $y$, $B_0$ is mean recruitment during the study period, and $\delta_y$ is a log-normally distributed error term for fishing season $y$ with mean zero and standard deviation $\sigma$. Recruitments in each fishing season ($B_{0,y}$) were treated as parameters and estimated by the model.

The net instantaneous rate of change for northern anchovy biomass in each fishing season ($\eta_y$ in Eqn. 5) is the sum of rates for fishing mortality, growth, and natural mortality:

$$\eta_y = F_y + M - G, \qquad (7)$$

where $F_y$ is the fishing mortality rate in fishing season $y$, $M$ is the natural mortality rate, and $G$ is the growth rate. All rates are defined as positive values. The fishing mortality rate for each fishing season ($F_y$) was assumed constant over ages but variable over time, whereas rates for natural mortality ($M$) and growth ($G$) were assumed constant over ages and time. Fishing mortality rates were calculated by using the "forward solution" algorithm in Sims (1982) and actual catch data (Table 1; Fig. 1).

The rate of natural mortality ($M$) for northern anchovy was assumed to be 0.8 yr$^{-1}$, which is reasonable for a fish that seldom exceeds seven years in age (Hoenig, 1983). Methot (1989) found that different levels of natural mortality had only modest effects on biomass estimates for northern anchovy because the estimates were anchored by DEP spawning biomass measurements.

Modeling growth as an instantaneous rate ($G$) is appropriate for northern anchovy because fish grow rapidly throughout the fishing season (Zhang and Sullivan, 1988). By treating growth as an instantaneous rate, northern anchovy are, in effect, allowed to continue growing in the model until they are caught.

The rate for growth used in the SMPAR model for northern anchovy ($G$=0.198 yr$^{-1}$, SE=0.0166) was estimated by fitting an exponential growth model to mean weight at age data from three sources (Methot, 1989). The exponential growth model was logarithmically transformed to give

$$\ln(W_{d,a}) = \ln(W_{d,0}) + aG, \qquad (8)$$

where $W_{d,a}$ is the mean weight of northern anchovy age $a$ in data set $d$, and $W_{d,0}$ is the estimated weight at age 0. The approach assumes that northern anchovy may differ in initial weight as measured by the $W_{d,0}$ parameters but experience the same rate of exponential growth ($G$). Parameter estimates for Equation 8 were obtained by linear regression and standard general linear model techniques (Weisberg, 1980). Residuals were dome-shaped because of the linear approximation to the asymptotic growth pattern but the linear regression model explained most of the variation in log-scale size at age ($R^2$=93%).

## Abundance data

Abundance data (EPI, HEP, SONAR, DEP, and SPOTTER abundance indices) were assumed to be measured with log-normally distributed random errors. Predicted values for abundance data during each fishing season were calculated in the model as:

$$\hat{I}_{t,y} = Q_t \sum_{a=0}^{4+} \rho_{t,a} B_{a,y} e^{-\eta_y}, \qquad (9)$$

where hats ($^\wedge$) denote estimates, $I_{t,y}$ is the value for abundance index $t$ in fishing season $y$, $Q_t$ scales northern anchovy biomass to the units of abundance index $t$, and $\rho_{t,a}$ is the relative contribution of a northern anchovy at age $a$ to abundance index $t$. We assumed age-specific selectivity patterns for abundance indices because estimates for most parameters were available outside of the model. This approach gave a more realistic model without increasing the number of parameters estimated. Values of $\rho_{t,a}$ were relative measures scaled to the interval $[0,1]$, and the age with maximum relative contribution for abundance index $t$ had $\rho_{t,a}=1.0$.

Estimates of the scaling parameter for DEP data ($Q_{DEP}=1$) and age-specific parameters ($\rho_{t,a}$) for DEP, HEP, and EPI data were from Methot (1989). Two-year-old northern anchovy are all sexually mature during the peak spawning period ($\rho_{DEP,2+}=1.0$), whereas the fraction of one-year-olds that are mature ($\rho_{DEP,1}$) depends on water temperatures. Maturity of age-1 northern anchovy during the peak spawning season was calculated from mean January–February sea surface temperatures at Scripps Pier, San Diego, California (Table 1), as described in Methot (1989).

Estimates of age-specific egg production for actively spawning northern anchovy (Methot, 1989) were used to estimate the age-specific parameters ($\rho_{HEP,a}$ and $\rho_{EPI,a}$) for egg production indices. No age-0 northern anchovy spawn during the peak spawning period but all are actively spawning by age 2. The fraction of actively spawning fish was also calculated from mean sea surface temperatures (Methot, 1989).

Age-specific parameters for contribution to egg production indices ($\rho_{HEP,a}$ and $\rho_{EPI,a}$) were assumed to be the product of relative egg production and fraction active. Relative egg production values were the same as those used by Methot (1989) and originally by Parrish et al. (1986).

For simplicity, relative age-specific contributions to indices of schooling biomass (SPOTTER and SONAR) for northern anchovy ages 1 and older ($\rho_{SPOTTER,1+}$ and $\rho_{SONAR,1+}$) were assumed to be 1.0. The contribution of age-0 northern anchovy to the SPOTTER and SONAR indices was estimated as

$$\rho_{SPOTTER,0} = \rho_{SONAR,0} = \frac{e^{\pi}}{1+e^{\pi}}, \qquad (10)$$

where $\pi$ was a parameter estimated by the model.

## Objective function

Parameters in SMPAR were estimated by maximizing a function proportional to the total log-likelihood ($L_{total}$):

$$L_{total} \sim -\sum_{t=1}^{5} \lambda_t \sum_{y=1}^{N_t} D_{t,y}^2 - \lambda_6 \sum_{y=1}^{N_y} R_y^2, \qquad (11)$$

where $N_t$ is the number of observations for abundance index $t$, and $N_y$ is the number of recruitment estimates. The $\lambda_t$ values are weights that determine how important different types of data are in parameter estimation; they were set to one except during sensitivity analyses. $D_{t,y}$ is the log-scale standardized residual for abundance index $t$ in fishing season $y$ and $R_y$ is the log-scale standardized residual for recruitment in fishing season $y$:

$$D_{t,y} = \frac{\ln(I_{t,y}/\hat{I}_{t,y})}{\varepsilon_{t,y}} \qquad (12)$$

$$= \frac{\ln(I_{t,y}) - \ln(\hat{I}_{t,y})}{\varepsilon_{t,y}},$$

$$R_y = \frac{\ln(B_{0,y}/\overline{B}_0)}{\sigma} \qquad (13)$$

$$= \frac{\delta_y}{\sigma},$$

where $\varepsilon_{t,y}$ is the log-scale standard error for abundance type $t$ in fishing season $y$, and $\sigma$ is the standard deviation for log-scale recruitment deviations ($\delta_y$ in Eqn. 6). Log-scale standard errors for abundance data ($\varepsilon_{t,y}$) were calculated from arithmetic scale coefficients of variation by inverting Equation 1.

The first term on the right side of Equation 11 gives the log likelihood of abundance indices given parameters in the model. The second term gives the log likelihood of recruitment estimates. Mean recruitment ($\overline{B}_0$ in Eqn. 13) is a "nuisance" parameter that was set equal at each iteration to the mean of current recruitment estimates. The log-scale standard deviation assumed for recruitments ($\sigma=0.71$) was calculated from stock synthesis model[2] recruitment estimates and was higher than the average standard deviation (0.48) for 41 other stocks of clupeoid fishes (Beddington and Cooke, 1983; Myers et al., 1990).

The likelihood term for recruitments in Equation 11 is a constraint that penalizes individual recruitment estimates that are different from the mean. Larger deviations and smaller $\sigma$ values result in larger penalties. The constraint does not penalize serial correlation so that "runs" of good or bad recruitments can be estimated by the model. This was important because northern anchovy recruitments tend to be serially correlated (see below).

Jacobson and Lo[2] showed that a northern anchovy model without age-composition data or a recruitment

constraint like that in Equation 11 was overparameterized because recruitments need occur only once every two to three years for the model to match observed and predicted abundance data. Age-composition data for northern anchovy indicate, however, that some recruitment occurs during every fishing season (Lo and Methot, 1989). We included the recruitment constraint and a recruitment parameter for each season to obtain a more realistic model and to constrain the recruitment estimate for the last fishing season which was otherwise difficult to estimate. The constraint on recruitment biases recruitment and biomass estimates towards the mean because recruitment estimates will be high in years with poor recruitment and low in years with high recruitment.

Parameters in the model were estimated by using the simplex algorithm (Press et al., 1990). Variances and correlations for parameter and biomass estimates were calculated by using a parametric bootstrap approach (Efron, 1982) as described in Lo et al. (1992) except that simulated abundance data were generated by assuming log-normal errors with standard deviation equal to the root-mean-squared log-scale residual for each data type (see below). Parameters for bootstrap runs were estimated as described for the original run by using the original CV's for each abundance index observation. Thus, our bootstrap runs included process error to the extent that it was reflected in the variance of residuals, and included measurement error to the extent that it was reflected in the original CV's. Two thousand bootstrap iterations were generally used. Asymptotic variance and correlation estimates for parameters were also calculated by inverting a numerical approximation to the Hessian matrix (Bard, 1974; Mittertreiner and Schnute, 1985) because we were interested in comparing the asymptotic and bootstrap approaches.

Parameters with all feasible values positive were estimated as log-transformed values. The log transformation constrains parameters to feasible values on the original scale and improves the statistical characteristics of parameter estimates. Standard errors for log-scale recruitment parameters were transformed to CV's for arithmetic recruitment estimates by using Equation 1.

## Results and discussion

Estimates from preliminary runs indicated that availability of age-0 northern anchovy to indices of schooling biomass was close to zero. For final runs, $P_{SPOTTER,0}$ and $P_{SONAR,0}$ were set to zero and not estimated even though age-0 fish were assumed to be fully recruited to the fishery.

## Outliers and residual analysis

Standardized residuals ($D_{t,y}$ in Eqn. 12) for most abundance indexes were serially correlated in preliminary runs. There were two outliers ($D_{EPI,1983}$=3.6 and $D_{SPOTTER,1979}$=3.5) identified by a $t$-test with Bonferroni $p$-values (critical value $D_{t,y}$=3.41 for $n$=77; Weisberg, 1980). Residual plots for the final run with outliers omitted still indicated some serial correlation. All but three biomass estimates for northern anchovy during the 1963 to 1991 fishing seasons increased when the two outliers were omitted. The average increase was 24%.

## CV's for abundance indices and goodness of fit

The root-mean-squared residual for each abundance index was calculated to measure how well the SMPAR model fit the data for northern anchovy. Standard deviations were not calculated because degrees of freedom were unknown. Arithmetic CV's implied by the goodness-of-fit statistics were calculated by using Equation 1. For comparison, median CV's for our data (Table 1) were also calculated.

Goodness-of-fit statistics and implied CV's (Table 3) indicate that the CV's for our abundance data underestimated the true log-scale standard errors. The order of abundance indices ranked by median CV's was, however, the same as when they were ranked by goodness of fit. Thus, CV's used in the model reflected the relative precision of different types of abundance data for northern anchovy.

## Consistent bias

Percent bias (%BIAS) in biomass and log-scale recruitment estimates for northern anchovy was estimated

### Table 3

Goodness-of-fit and CV statistics for northern anchovy, *Engraulis mordax*, abundance indices used in the SMPAR model. Median nominal CV's were calculated from arithmetic CV values in Table 1. Root-mean-squared residuals measure goodness of fit to abundance index. Implied CV's are the arithmetic CV values calculated from the goodness-of-fit measures.

| Abundance index | $n$ | Median nominal CV (%) | Root-mean-squared residual | Implied CV (%) |
|---|---|---|---|---|
| DEP | 6 | 21 | 0.19 | 19 |
| EPI | 12 | 31 | 0.48 | 51 |
| SPOTTER | 27 | 34 | 0.49 | 52 |
| HEP | 14 | 44 | 0.50 | 53 |
| SONAR | 16 | 46 | 0.53 | 57 |

$$\%BIAS = \frac{E_{boot} - E_{best}}{E_{best}}, \qquad (14)$$

where $E_{boot}$ is the average of estimates from two thousand bootstrap runs and $E_{best}$ is the best estimate from the model fit to the original data. We used the correction factor $\gamma_y = E_{boot} - E_{best}$ to remove consistent bias (Efron, 1982). The corrected estimate of log recruitment in fishing season $y$, for example, was $\beta_y - \gamma_y$, where $\beta_y$ was the original biased log-scale recruitment estimate.

Uncorrected log-scale recruitment estimates were biased by amounts ranging from $-7\%$ to $7\%$ and arithmetic scale biomass estimates by amounts ranging from $-15\%$ to $27\%$ (Fig. 2). Consistent bias was exaggerated when uncorrected recruitments were transformed to arithmetic scale ($-40\%$ to $43\%$, Fig. 3).

## Bias from log-transformed recruitment estimates

Arithmetic scale recruitments in each fishing season ($B_{0,y}$) were calculated

$$B_{0,y} = e^{\left(\beta_y - \gamma_y + \frac{VAR(\beta_y)}{2}\right)}, \qquad (15)$$

where $VAR$ is a variance estimated by bootstrapping. The term $VAR(\beta_y)/2$ adjusts for bias due to transformation of log-normally distributed random variables

(Beauchamp and Olson, 1973). Bias due to log transformation is in addition to consistent bias estimated by $\gamma_y = E_{boot} - E_{best}$. The correction for bias due to log transformation increased northern anchovy recruitment estimates by 1% to 22% (average 9%).
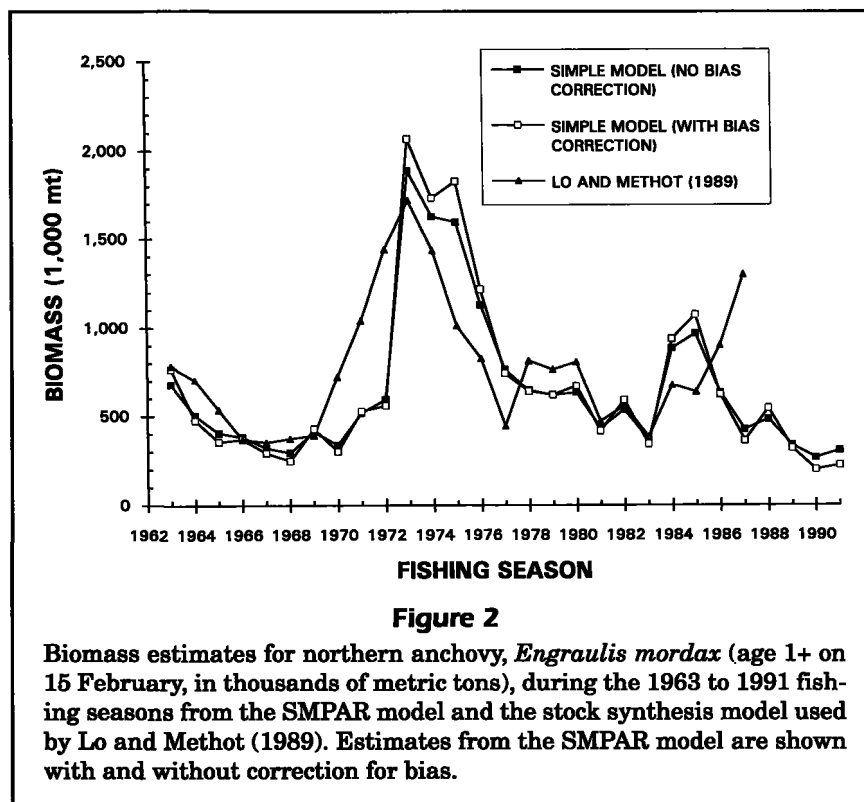
Corrections for bias due to log transformation make arithmetic recruitment estimates for northern anchovy easier to interpret because the amount of bias varies among uncorrected recruitment estimates as a function of their variance. Many stock assessment models (Deriso et al., 1985; Methot, 1990) estimate recruitments as log-scale parameters but corrections for bias in arithmetic-scale recruitment estimates are not made. We recommend that bootstrap or other variance estimates be used to correct arithmetic scale recruitment estimates for bias where appropriate.
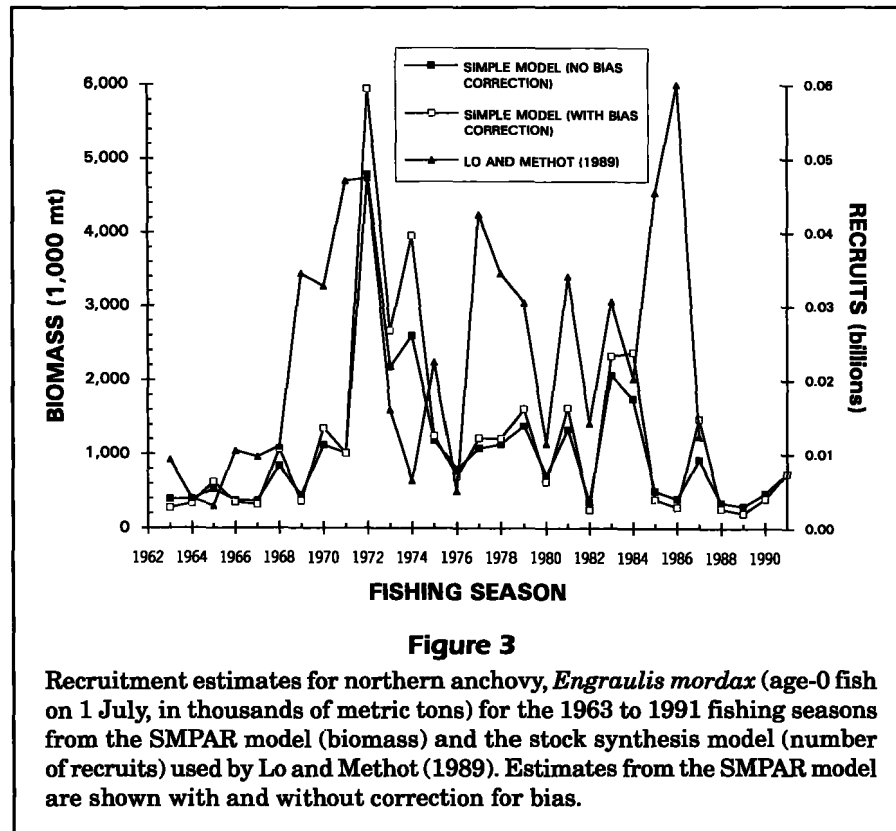
### Retrospective bias

We evaluated potential for retrospective bias in the SMPAR model by comparing our best biomass estimates to estimates from runs that omitted data for recent years. Bias corrections for retrospective analysis were based on fifty bootstrap iterations. Results indicated a negligible amount of retrospective bias.

### Estimates and comparisons

Biomass estimates for northern anchovy age 1 and older from the SMPAR (Table 4) and stock synthesis



2,500

2,000

1,500

1,000

500

0

BIOMASS (1,000 mt)

— SIMPLE MODEL (NO BIAS CORRECTION)
—□— SIMPLE MODEL (WITH BIAS CORRECTION)
—▲— LO AND METHOT (1989)

1962 1964 1966 1968 1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990

**FISHING SEASON**

**Figure 2**

Biomass estimates for northern anchovy, *Engraulis mordax* (age 1+ on 15 February, in thousands of metric tons), during the 1963 to 1991 fishing seasons from the SMPAR model and the stock synthesis model used by Lo and Methot (1989). Estimates from the SMPAR model are shown with and without correction for bias.

**Figure 3**

Recruitment estimates for northern anchovy, *Engraulis mordax* (age-0 fish
on 1 July, in thousands of metric tons) for the 1963 to 1991 fishing seasons
from the SMPAR model (biomass) and the stock synthesis model (number
of recruits) used by Lo and Methot (1989). Estimates from the SMPAR model
are shown with and without correction for bias.

models were generally similar (Fig. 2) except where
retrospective bias in previous estimates was a prob-
lem. Results from SMPAR indicate that high north-
ern anchovy biomass in the early 1970's was due to a
single large cohort spawned in the 1971 fishing sea-
son (age 1 in 1973) rather than to a series of strong
recruitments (Figs. 2 and 3). This difference is due
to omission of age-composition data and inclusion of
SPOTTER data not available to Lo and Methot
(1989). Unlike SONAR data, SPOTTER data did not
increase significantly until the 1973 fishing season
(Fig. 1).

Coefficients of variation for northern anchovy 1+
biomass estimates ranged from 14% to 38% and av-
eraged 26% (Table 4). Precision of the biomass esti-
mate for the most recent fishing season (29%) was
better than that from the original stock synthesis
model for northern anchovy (CV=40%, Lo et al.,
1992). Improvements in data contributed to higher
precision, but this result indicates a substantial im-
provement as a result of using a simpler, more par-
simonious model.

Recruitment estimates for northern anchovy from
the SMPAR model showed less year-to-year varia-
tion than those from the stock synthesis model al-
though both sets of estimates indicate that northern
anchovy recruitment was low during the 1963 to 1968

fishing seasons and high in the 1972 fishing season
(Fig. 3). CV's for arithmetic-scale recruitment esti-
mates (11% to 69%, average 41%) from the SMPAR
model were about 50% larger on average than CV's
for biomass estimates (Table 4).

The most important conclusion to be drawn in com-
paring recruitment estimates from SMPAR with
those from the stock synthesis model for northern
anchovy is that disparate recruitment estimates (Fig.
3) resulted in similar biomass estimates (Fig. 2). This
suggests that abundance index data for northern
anchovy contain relatively little information about
recruitment variability. The SMPAR model probably
underestimates recruitment variability for northern
anchovy because it uses only abundance data and
includes a recruitment constraint that biases recruit-
ment estimates towards the mean.

## Comparison of bootstrap and asymptotic variance estimates

Asymptotic standard errors for parameters obtained
by inverting the Hessian matrix were about 19%
smaller, on average, than standard deviations ob-
tained by bootstrapping. This result indicates that
asymptotic variance estimates for parameters in the
SMPAR model were too small.

## Sensitivity to weights

We varied weights $(\lambda_t)$ in the objective function of the SMPAR model to determine how sensitive recent biomass estimates were to different types of data and to the recruitment constraint. Biomass estimates for age 1+ northern anchovy during the 1991 fishing season and average biomass during the 1985 to 1991 fishing seasons were calculated with the weight for each data type set equal to a range of values while other weights were kept at 1.0. Sensitivity analysis for the weight applied to the recruitment constraint $(\lambda_6$ in Eqn. 11) is equivalent to a sensitivity analysis on the standard deviation for log-scale recruitments ($\sigma$ in Eqn. 13). Doubling the weight $(\lambda_6=2.0)$ is the same as reducing the assumed standard deviation by $1/\sqrt{2}=0.71$. For simplicity, biomass levels in sensitivity analyses were not corrected for bias. SMPAR did not completely converge when the weight for the recruitment constraint was set to 0.0 or 10.0.

Results indicate that current biomass estimates and management advice are affected by weights on EPI data and the recruitment constraint (Table 5). Estimates of anchovy biomass for 1991 were sensitive (changes >10%) to halving $(\lambda_t=0.5)$ or doubling $(\lambda_t=2.0)$ weights on EPI data and the recruitment constraint, but estimates of average biomass during 1985 to 1991 were not. Biomass estimates for 1991 were sensitive to removing $(\lambda_t=0.0)$ EPI data, EPM data, or the recruitment constraint from the model. Average biomass estimates were sensitive to removing EPI, EPM, or SPOTTER data.

## Simulation analyses

We used simulation analyses to determine how well SMPAR would estimate biomass under a wide range of recruitment and fishing mortality rates during the 1985 to 1991 fishing seasons. Calculations were the same as those for bootstrapping except that fishing

## Table 4

Total, spawning, and recruitment biomass estimates for northern anchovy, *Engraulis mordax*, during the 1963 to 1991 fishing seasons (corrected for bias). Recruitment estimates are for age-zero northern anchovy at the beginning of the fishing season (1 July). Total and spawning biomass estimates are for northern anchovy age 1 and older during the peak spawning period (15 February) of each fishing season.

| Fishing season | Total biomass (1,000 t) | CV (%) | Spawning biomass (1,000 t) | CV (%) | Recruitment biomass (1,000 t) | CV (%) | Fishing mortality (yr$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1963 | 764 | 38 | 734 | 38 | 275 | 43 | 0.002 |
| 1964 | 477 | 27 | 434 | 31 | 334 | 40 | 0.003 |
| 1965 | 356 | 24 | 313 | 23 | 627 | 42 | 0.023 |
| 1966 | 370 | 26 | 311 | 25 | 347 | 42 | 0.063 |
| 1967 | 293 | 26 | 281 | 26 | 319 | 39 | 0.022 |
| 1968 | 249 | 25 | 232 | 24 | 1,066 | 39 | 0.037 |
| 1969 | 429 | 26 | 260 | 23 | 364 | 43 | 0.111 |
| 1970 | 301 | 27 | 232 | 25 | 1,348 | 47 | 0.074 |
| 1971 | 527 | 33 | 195 | 25 | 1,008 | 52 | 0.045 |
| 1972 | 558 | 32 | 547 | 32 | 5,941 | 45 | 0.020 |
| 1973 | 2,066 | 34 | 638 | 25 | 2,667 | 69 | 0.034 |
| 1974 | 1,733 | 31 | 1,243 | 29 | 3,955 | 64 | 0.042 |
| 1975 | 1,827 | 30 | 1,481 | 27 | 1,242 | 54 | 0.068 |
| 1976 | 1,216 | 26 | 1,215 | 26 | 693 | 49 | 0.120 |
| 1977 | 742 | 26 | 741 | 26 | 1,211 | 48 | 0.132 |
| 1978 | 639 | 26 | 530 | 24 | 1,204 | 36 | 0.172 |
| 1979 | 619 | 20 | 607 | 20 | 1,611 | 31 | 0.121 |
| 1980 | 670 | 16 | 630 | 15 | 623 | 35 | 0.301 |
| 1981 | 415 | 19 | 381 | 17 | 1,624 | 22 | 0.224 |
| 1982 | 589 | 14 | 587 | 14 | 246 | 32 | 0.200 |
| 1983 | 341 | 14 | 339 | 14 | 2,321 | 26 | 0.039 |
| 1984 | 937 | 20 | 609 | 17 | 2,372 | 58 | 0.062 |
| 1985 | 1,072 | 32 | 1,057 | 32 | 388 | 35 | 0.065 |
| 1986 | 620 | 27 | 616 | 27 | 280 | 39 | 0.125 |
| 1987 | 360 | 24 | 343 | 24 | 1,480 | 38 | 0.095 |
| 1988 | 543 | 27 | 235 | 25 | 261 | 38 | 0.120 |
| 1989 | 317 | 30 | 309 | 30 | 201 | 37 | 0.112 |
| 1990 | 199 | 31 | 198 | 31 | 396 | 39 | 0.018 |
| 1991 | 223 | 29 | 221 | 29 | 739 | 11 | 0.005 |

mortality rates and recruitment levels for 1985 to 1991 were adjusted. For simulations, fishing mortality rates during the 1985 to 1991 fishing seasons were either low (best-fit estimates from actual data, 0.005 to 0.12 $yr^{-1}$, Table 4) or high ($F$=1.0 $yr^{-1}$). Recruitment levels were either low (one third of best-fit estimates in Table 4), equal to best-fit levels, high (three times best-fit levels), or alternating (three times best fit for 1985, one third of best fit for 1986, and so on). There were eight scenarios in total (two fishing mortality patterns combined with four recruitment patterns) and results for each scenario are averages based on fifty simulations. Each scenario used the same series of random numbers to facilitate comparisons.

Results indicate that the SMPAR model is able to track trends in biomass (Fig. 4) under a wide variety of conditions. Uncorrected estimates underestimated year to year variability but this problem would be reduced after bias corrections were applied.

### Table 5

Sensitivity of biomass estimates for northern anchovy, *Engraulis mordax*, to weights ($\lambda_i$) used in SMPAR. Differences between best-fit results and results with different weights are shown in metric tons and as a percentage of the best-fit estimates. Percentages of values are in parentheses.

| Weight ($\lambda_i$) | EPI | EPM | HEP | SONAR | SPOTTER | Recruitment constraint |
|---|---|---|---|---|---|---|
| **1991 Biomass** | | | | | | |
| 0.0 | 141 | 65 | −18 | 2 | −4 | −55 |
| | (46) | (21) | (−6) | (1) | (−1) | (−18) |
| 0.5 | 52 | −6 | −1 | 7 | 0 | −32 |
| | (17) | (−2) | (0) | (2) | (0) | (−11) |
| 2.0 | −50 | 10 | 8 | −1 | 2 | 53 |
| | (−16) | (3) | (3) | (0) | (1) | (17) |
| 10.0 | −166 | 22 | 22 | −31 | −17 | 209 |
| | (−54) | (7) | (7) | (−10) | (−6) | (69) |
| **Mean 1985–91 Biomass** | | | | | | |
| 0.0 | −51 | −137 | −28 | 12 | 53 | 35 |
| | (−10) | (−28) | (−6) | (2) | (11) | (7) |
| 0.5 | −11 | −14 | −1 | 13 | 24 | 0 |
| | (−2) | (−3) | (0) | (3) | (5) | (0) |
| 2.0 | 7 | 22 | 11 | −8 | −35 | 10 |
| | (1) | (4) | (2) | (−2) | (−7) | (2) |
| 10.0 | −76 | 53 | 34 | −59 | −145 | 53 |
| | (−16) | (11) | (7) | (−12) | (−30) | (11) |

## Age composition in the Mexican fishery

Catch curves (Ricker, 1975) for a segment of the Mexican fishery based in Ensenada, Baja California, indicate that age at full recruitment to the Mexican fishery decreased from age 2 to age 0 during 1982 to 1988.[4] Prior to 1983, most year classes reached full recruitment at age 2 but the 1985 and 1986 year classes were fully recruited at about age 1. The trend toward younger recruitment continued with the 1987 and 1988 year classes, which were fully recruited at age 0.

The stock synthesis model interpreted the Mexican age-composition data as evidence for increased recruitment and biomass of northern anchovy. In retrospect, this interpretation seems incorrect because biomass estimates for anchovy declined steadily after the 1985 fishing season (Fig. 2). Declines in biomass were not evident at the time, how-

ever, because only one index of relative abundance for northern anchovy (the modified historical egg production index or MHEP, Lo and Methot, 1989) was available, and because recent biomass estimates are relatively uncertain.
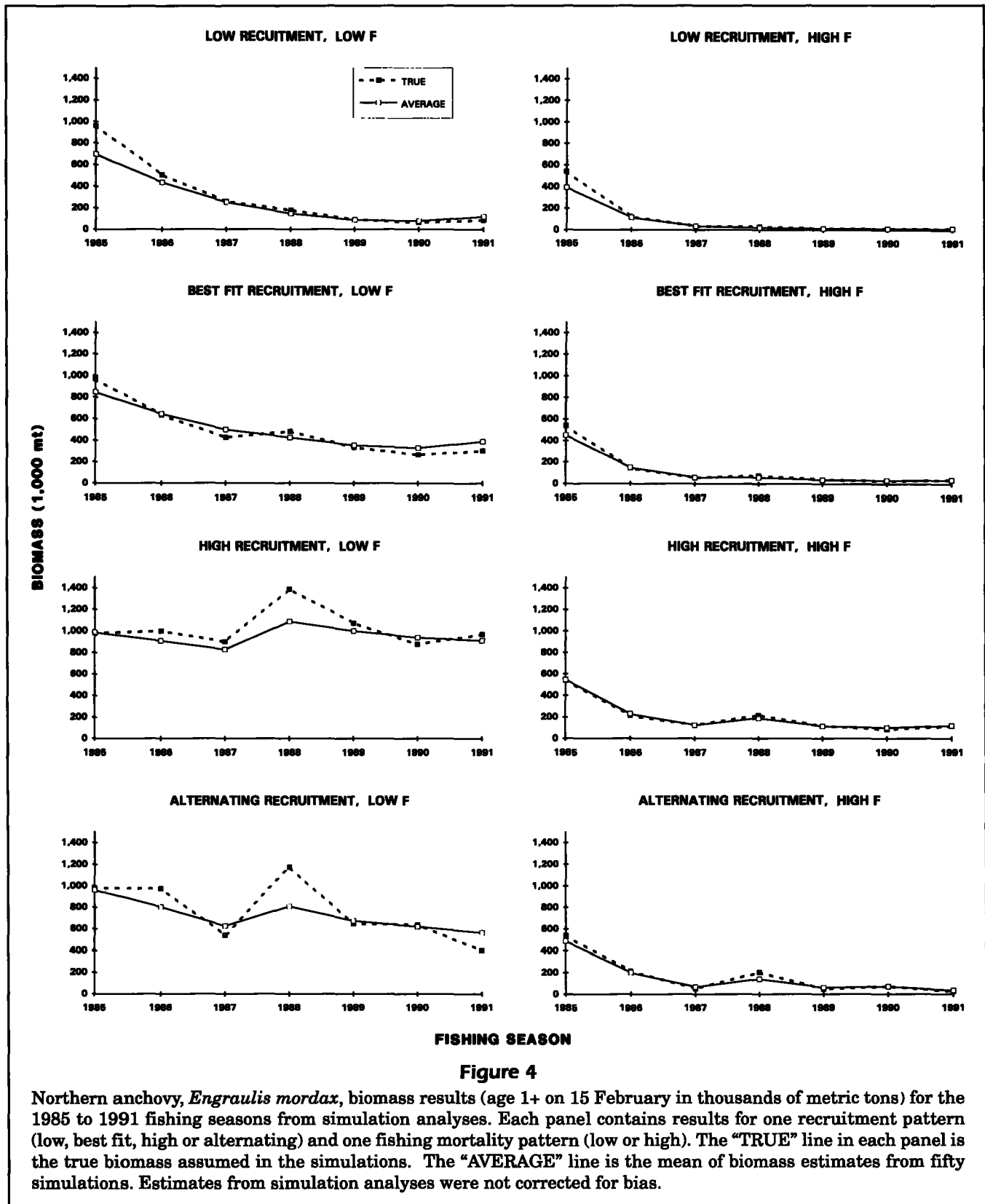
## Status of the stock

Northern anchovy biomass (Fig. 2) and recruitment (Fig. 3) declined after the 1985 fishing season to about the same levels as during the 1963 to 1971 fishing seasons. Northern anchovy have been too scarce off Baja California, Mexico, to support a fishery since the 1990 season (Table 1). Declines in biomass during recent years were due to low recruitment rather than to high fishing mortality rates because fishing mortality rates were moderate after the 1986 fishing season (<0.14 $yr^{-1}$) and low (<0.03 $yr^{-1}$) during the 1990 to 1991 fishing seasons (Table 4). The recent period of low northern anchovy biomass occurred as Pacific sardine, *Sardinops sagax*, biomass levels began to increase in the early 1980's and water temperatures began to warm (Barnes et al., 1992). We

[4] Arenas, P., T. Barnes, and L. D. Jacobson. 1994. Fishery and biological data for northern anchovy taken in Mexican waters, 1978-1989. U.S. Dep. Commer., NOAA, Nat. Mar. Fish. Serv., Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038. Admin. Rep. LJ-94-03, 24 p.

did not attempt, however to identify environmental (Prager and MacCall, 1993) or ecological factors that

may have affected northern anchovy abundance in recent fishing seasons.



**Figure 4**

Northern anchovy, *Engraulis mordax*, biomass results (age 1+ on 15 February in thousands of metric tons) for the 1985 to 1991 fishing seasons from simulation analyses. Each panel contains results for one recruitment pattern (low, best fit, high or alternating) and one fishing mortality pattern (low or high). The "TRUE" line in each panel is the true biomass assumed in the simulations. The "AVERAGE" line is the mean of biomass estimates from fifty simulations. Estimates from simulation analyses were not corrected for bias.

## Conclusion

Finding the appropriate compromise between realistic (but potentially overparameterized and imprecise) models and parsimonious (but simplistic and potentially biased) models is an important part of a stock assessment research (Ludwig and Walters, 1985, 1989; Hilborn and Walters, 1992). The best choice among models depends on the task, data availability, and complexity of the situation. Our work indicates that models intermediate in complexity between simple surplus production and complex age-structured models can perform well under a wide range of circumstances for estimating the biomass of stocks such as northern anchovy.

## Acknowledgments

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