Influence of Age-Selective Surveys on the Reliability of Stock Synthesis Assessments

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We used Monte Carlo simulations to examine the reliability of assessments following a method of separable catch-at-age analysis (Methot's stock synthesis approach). Our simulations were based on the widow rockfish (*Sebastes entomelas*) fishery off the west coast of the continental United States. We designed the study to examine how the performance of the method depended upon the age-specific selectivity pattern of a survey of relative abundance. When survey selectivity increased asymptotically with age, stock synthesis estimates of final year biomass (and most other parameters) tended to be closest to the correct value. When the survey concentrated on young fish the estimates were least reliable. When the survey selectivity was "dome-shaped," concentrating on intermediate-aged fish, estimates were somewhat less precise (and less accurate) than for the asymptotic pattern but much more precise than for the survey concentrating on young fish. Predictably, estimates of recruitment and biomass were better at a higher fishing mortality rate and when the magnitude of survey error was lower. Generally, mean errors in estimated biomass and recruitment were positive, while median errors were close to zero. This pattern is due to transformation bias associated with a lognormal error structure.

Nous avons utilisé des simulations de Monte-Carlo afin de déterminer la fiabilité d'évaluations réalisées par analyse à composantes séparables des prises selon l'âge (synthèse des stocks de Methot). Nos simulations étaient fondées sur la pêche de la veuve (*Sebastes entomelas*) réalisée au large de la côte ouest des États-Unis. Nous avons conçu l'étude de façon à déterminer dans quelle mesure le rendement de la méthode dépendait de l'allure de la sélectivité spécifique quant à l'âge d'un relevé de l'abondance relative. Lorsque la sélectivité du relevé augmentait de façon asymptotique avec l'âge, l'estimation par synthèse du stock de la biomasse de dernière année (et de la plupart des autres paramètres) tendait à se rapprocher le plus de la valeur réelle. L'estimation la moins fiable était obtenue lorsque le relevé portait surtout sur les poissons les plus jeunes. Lorsque la sélectivité du relevé correspondait à la forme "en dôme" et portait donc sur les poissons d'âges intermédiaires, l'estimation était quelque peu moins précise (et moins exacte) que celle du relevé d'allure asymptotique, mais demeurait plus précise que celle du relevé portant surtout sur les jeunes poissons. Comme on peut s'y attendre, l'estimation du recrutement et de la biomasse était meilleure lorsque le taux de mortalité par pêche était plus élevé et que l'erreur du relevé était plus faible. De façon générale, l'erreur moyenne de la biomasse et du recrutement estimé était positive tandis que l'erreur médiane se rapprochait de zéro. Ce phénomène s'explique par des erreurs de transformation liées à un biais de structure lognormale.

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Separable age-structured population models are widely used to analyze fishery catch-at-age data in order to estimate recruitment, fishing mortality rates, and stock abundance. These models assume that the fishing mortality rate can be separated into a product of year and age effects (Doubleday 1976). In most instances, a wide range of solutions to a separable model can fit a set of fishery age-composition data about equally well (Doubleday 1976; Deriso et al. 1985; Shepherd and Nicholson 1986). Thus, for reasonably accurate estimates of abundance, separable models require auxiliary data such as information about abundance from trawl surveys or measures of fishing effort (Doubleday 1976; Deriso et al. 1985; Kimura 1990; Methot 1990).

In this paper, we examine the performance of a separable model when survey data on the relative abundance of a stock are available. Our objective is to compare the merits of surveys with different types of age-specific selectivity patterns. Surveys that cover the habitat occupied by adult fish sometimes have selectivity increasing to an asymptote (Rollefsen 1953). Other surveys that use selective gear (e.g., gill net or hook-and-line) or concentrate in a subhabitat occupied predominantly by certain ages may have either a dome-shaped selectivity with peak

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selectivity at an intermediate age (e.g., Hamley 1975; Methot and Hightower 1990; Ralston 1990) or peak selectivity on recruits (young fish) (Methot and Hightower 1990; Wyllie Echeverria et al. 1990). The separable model we use belongs to Methot's (1990) family of stock synthesis models, which are widely used in assessing fish stocks off the west coast of North America (PFMC 1990). We fit the model to simulated data based on the biology of widow rockfish (*Sebastes entomelas*), which supports a significant trawl fishery off the west coast of the continental United States. This species, like other *Sebastes*, is relatively long-lived, with a maximum reported age of 50 yr in California and an estimated natural mortality rate of 0.15. Although we used the biology of widow rockfish as a basis for our modeling, our goal was to determine general results regarding the performance of the stock synthesis model, not to mimic the widow rockfish fishery exactly.

Simulation Design and Methodology

The basic stock synthesis approach is to invoke a dynamic model both of the fishery and of the process by which data are generated and then fit this model to the available data (Methot 1990). The synthesis model estimates a suite of parameters and uses these along with prespecified constants to calculate fitted data values. These fitted or "synthetic data" are then compared with the observed data in likelihood equations, and a search is done for the set of parameter estimates that maximizes the likelihood.

We examined the performance of the stock synthesis model by Monte Carlo simulation. We did 200 simulations for each of the 18 combinations of age-specific selectivity patterns for the survey, average fishing mortality rates during the simulations, and levels of survey error.

We considered surveys with (1) increasing asymptotic selectivity, (2) dome-shaped selectivity, and (3) maximum selectivity for young fish (recruits) (Fig. 1). For each survey selectivity pattern, we used two average levels of fishing mortality (low: mean fishing mortality rate at age 10 (F) = 0.075 (half the natural mortality rate, i.e., $M/2$ and high F = 0.30 ($2M$)) and three levels of survey error: low (CV = 10%), medium (CV = 25%), and high (CV = 50%). Note that all cases started in an unfished condition, which is a reasonable portrayal of the widow rockfish fishery prior to 1980. The range of error in surveys is in accord with typical estimates of survey precision (e.g., Rivard 1981; Pope 1983; Pope and Gray 1983; Weinberg et al. 1984).

We first describe the synthesis model used in our simulations, then describe how we generated simulated data sets, and lastly turn to details on how the "best fit" of the synthesis model to the simulated data sets was achieved for each run. With only minor exceptions discussed below, the model fitted in the simulated assessments (i.e., the synthesis model) was the same as the model we used to produce the simulated data sets. That is, our evaluation of the stock assessment methodology did not include appreciable process error.

Stock Synthesis Model

Following after Lenarz and Hightower's (1988) assessment of the widow rockfish fishery, nine age groups of fish were included in the synthesis model (age 5 through 13+), and we followed the population for a 15-yr time period. The numbers of fish of each age group, starting with age 6, present at the beginning of the first year ($N_{a,1}$, $a = 6, ..., 13$) and the number of age 5 fish recruiting at the beginning of each year ($N_{5,y}$, $y = 1, ..., 15$) were estimated as formal parameters as described below. Given estimates of initial numbers and recruitment, the numbers of age a fish at the beginning of each year y after the first ($N_{a,y}$, $a = 6, ..., 12$; $y = 2, ..., 15$) were simply the survivors from the previous year:

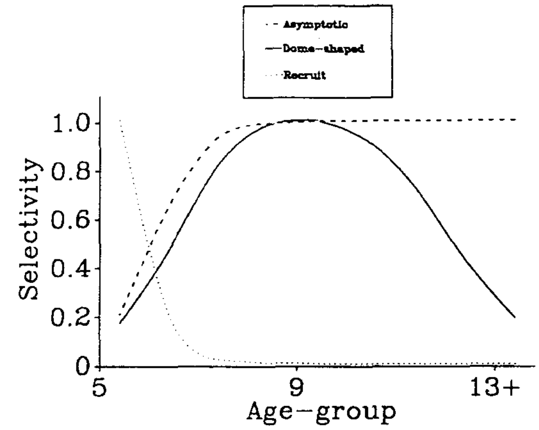

FIG. 1. Selectivity functions for the survey. Note that the dome-shaped function was also the fishery selectivity pattern. Parameters used to generate these functions are given in Table 1. Selectivity has been renormalized, for this presentation only, so that the maximum value is 1; this allows the selectivity patterns for the different surveys to be presented on the same scale.

(1) $N_{a,y} = N_{a-1,y-1} \exp(-\{M + F_{a-1,y-1}\})$

where M is the natural mortality rate and $F_{a,y}$ is the fishing mortality rate for age a fish in year y. For the 13+ category, numbers in each year after the first ($N_{13,y}$) were given by

(2) $N_{13,y} = N_{12,y-1} \exp(-\{M + F_{12,y-1}\}) + N_{13,y-1} \exp(-\{M + F_{13,y-1}\})$

which were simply the survivors of the 13+ category plus the surviving 12-yr-olds from the previous year. Thus, numbers-at-age, excluding the initial age composition and recruitment each year, were not estimated as parameters, but instead were calculated from the initial age composition ($N_{a,1}$, $a = 6, ..., 13$), recruitments ($N_{5,y}$, $y = 1, ..., 15$), age- and year-specific fishing mortality rates ($F_{a,y}$, $a = 5, ..., 13$; $y = 1, ..., 15$), and the natural mortality rate (M).

$F_{a,y}$ was modeled as being separable:

(3) $F_{a,y} = F_y s_{f,a}$

where $s_{f,a}$ was the fishery (f) selectivity on age a fish and F_y scaled overall fishing mortality in year y. In the model, $s_{f,10}$ was set equal to 1, so that F_y equals $F_{10,y}$, the fishing mortality rate on age 10 fish in year y. A restriction of this type is necessary to parameterize uniquely the age and year effects (Doubleday 1976). We chose to normalize to selectivity at a constant age, rather than to the age of estimated maximum selectivity, as is often done, so that F_y would have a constant definition. Thus, selectivity for some ages could exceed unity.

Age-group-specific fishery selectivity was assumed to follow a double-logistic function (Table 1; Fig. 1). The double-logistic

TABLE 1. Parameters and values used by the stock synthesis model (SSM) and by the simulation model. Some of these values were estimated by the SSM as formal parameters (E), others were assumed known (K), and others were determined by assumed constraints (C) (see text). Note that "known" values used for the SSM were the same as the values used in the simulations.

Parameter	Description	Treatment by SSM	Values used by simulation
F_y	Fishing mortality multiplier for year	C	From lognormal distribution with CV = 30% and mean of 0.075 or $0.30 \cdot yr^{-1}$
$N_{5,y}$	Recruitment at age 5 in year y	E	From lognormal distribution; mean = 17.8M, variance = 110.3M
$N_{a,1}$	Initial numbers-at-age	E	Based on distribution for recruitment parameters
$\alpha_{f,i}$, $\beta_{f,i}$, $\alpha_{f,d}$, $\beta_{f,d}$	Fishery selectivity parameters	E	−9, 1.46, 13.28, −1.14
$\alpha_{s,i}$, $\beta_{s,i}$, $\alpha_{s,d}$, $\beta_{s,d}$	Survey selectivity parameters	E	
	Recruit		−1, 0.1, 14, −2.655
	Dome-shaped		−9, 1.46, 13.28, −1.14
	Asymptotic		−11.39, 2, 13.28, −0.001
q	Survey proportionality constant	C	1
M	Natural mortality rate	K	$0.15 \cdot yr^{-1}$
σ_s	SD of log survey catch	K	Produces CV = 10, 25, or 50%
σ_c	SD of log fishery catch	K	Produces CV = 1%

function is flexible and can be used to model a wide variety of selectivity patterns, including nearly knife-edged, dome-shaped, and asymptotic (Methot 1990). This function is composed of two logistic functions, one increasing and the other decreasing. The product of the two logistic functions, after rescaling, was selectivity:

$$(4) \quad s_{f,a} = \frac{[1/\{1+\exp(-(\beta_{fi}\, a + \alpha_{fi})\}]\,[1/\{1+\exp(-(\beta_{fd}\, a + \alpha_{fd})\}]}{\lambda_{10}}$$

where α_{fi}, α_{fd}, β_{fi}, and β_{fd} are the parameters of the increasing (i) and decreasing (d) logistic functions and λ_{10} is equal to the value of the numerator of the equation for a (age) = 10. α_{fi}, α_{fd}, β_{fi}, and β_{fd} were estimated as formal parameters, while the overall scalers of fishing mortality, F_y, $y = 1, ..., 15$, were determined by constraints as described below. (Note that the selectivity of the 13+ group was assumed equal to the value predicted by equation 4 for $a = 13$.)

The last determinant of population dynamics was the natural mortality rate (M), which was fixed at a value of 0.15 based on prior information (Hightower and Lenarz 1986).

We now turn to how the synthesis model calculated its synthetic data to compare with observed data. We assumed that the observed data for each 15-yr period consisted of fishery age-composition data, total biomass of fishery catch during each year, annual survey age composition data from subsamples of the survey catch, and catch per unit effort (CPUE), a relative annual index of biomass available to the survey gear.

The numbers of each age caught by the fishery during each year were assumed by the synthesis model to follow the Baranov catch equations:

$$(5) \quad \eta_{f,a,y} = N_{a,y}\, F_{a,y}\, [1\text{-}\exp\{-M + F_{a,y})\}]/[M + F_{a,y}].$$

The synthesis model treated the fishery catch data as consisting of two independent pieces of information: (1) the proportion of the total numbers caught each year that fell into each age-group (i.e., the age-composition data), which were directly calculated from the $\eta_{f,a,y}$'s, and (2) the total biomass caught ($C_{f,y}$). Catch biomass was calculated simply as the sum over ages of the product of numbers caught at each age (from equation 5) and the weight at each age. The weight-at-age relationship was assumed to be known a priori, and equations developed by Lenarz (1987) and Phillips (1964) for widow rockfish were used to define this relationship.

Like the fishery catch data, the survey data were treated as containing two independent types of information for each year: (1) the proportions caught by the survey at each age (the age-composition data) and (2) a CPUE value representing an index of biomass available to the survey gear. The survey was assumed to have an insignificant effect on the stock size and to have occurred after recruitment for a given year, but before fishing or natural mortality. The synthesis model calculated the proportions-at-age caught by the survey in year y, the $P_{s,a,y}$'s, as proportional to the product of the model's current values for abundance of each age and the selectivity of the survey for the corresponding age ($s_{s,a}$):

$$(6) \quad P_{s,a,y} = s_{s,a} N_{a,y} / \Sigma_i\, s_{s,i} N_{i,y}\,.$$

In our application of the synthesis model, the survey selectivity pattern was defined by a double logistic function of age, just as the selectivity of the fishery was. The four parameters defining the function were estimated as formal parameters (Table 1). The CPUE index was fit by the synthesis model by assuming it to be proportional to the weighted (by selectivity) sum over ages of population weights-at-age. Population weight-at-age was simply the product of abundance-at-age $N_{a,y}$ and expected weight-at-age of an individual (w_a, assumed known as described above). Thus, the survey CPUE index in year y was

$$(7) \quad C_{s,y} = q \Sigma_a\, w_a\, s_{s,a}\, N_{a,y}\,.$$

The proportionality constant q was determined by a constraint as described below.

Generation of Simulated Data

For each run, a new simulated data set was generated. All parameters defining the simulation model are given in Table 1, along with their values or the distribution from which they were generated.

The simulation model made essentially the same assumptions as were incorporated into the stock synthesis model described above. Given the initial age composition, recruitments, fishing mortality rates, and other (fixed) parameters (Table 1), we used equations 1–5 to simulate population dynamics and fishery catch over time. M was fixed at 0.15, and the same set of fishery selectivity parameters (Table 1) was used in all cases, leading to a dome-shaped selectivity function (Fig. 1).

Each simulation run used randomly generated recruitments ($N_{5,y}$, $y = 1, ..., 15$), initial numbers at age ($N_{a,1}$, $a = 6, ..., 13$), and fishing mortalities (F_y, $y = 1, ..., 15$) in each year. Recruitment was generated from a lognormal distribution with specified mean and variance (Table 1, estimated from Hightower and Lenarz 1989). Initial numbers-at-age were calculated from randomly generated recruitment values, reduced for the cumulative natural mortality up to the age in question. As indicated above, this assumes insignificant fishing prior to the first year of the simulation. For age 13+, initial numbers were generated and summed for the youngest 50 year-classes in this age-group (numbers at older ages were negligible). Fishing mortality rate on age 10 fish (F_y), with the mean appropriate for the given set of runs, was generated from a lognormal distribution. The CV for F_y was 30%, roughly approximating the variability in estimated fishing mortality seen in a number of different assessments of rockfish stocks (PFMC 1990). Note that the expected fishing mortality rate was constant over years and was not changed in response to the current estimate of the status of the stock.

In this model the expected level of recruitment was not a function of the biomass of the stock when the year-class was generated, and this implies that substantial compensation was taking place. The assumption was useful because direct effects of fishing on adult stock composition were not confounded with indirect effects on recruitment that would cause the average magnitude of recruitment to differ between low and high fishing mortality rates.

Both the fishery and survey age-composition data for each year were generated as multinomial samples with effective sizes of 400. The expected proportions-at-age were calculated directly from catch-at-age (equation 5) or by equation 6 (the survey). Some estimates of the variance of catch-at-age numbers for west coast groundfish suggest that our admittedly somewhat arbitrary choice of effective sample size (after Fournier and Archibald 1982) may not be unrealistic (Sen 1986; Methot 1990; Parker and MacCall, unpublished manuscript[2]). The total biomass caught by the fishery was assumed to be measured precisely, so observed catches were generated from a lognormal distribution with a CV of 1% about the true value, matching the error assumed by the assessment methodology in likelihood calculations (see below). The survey index of biomass was generated from a lognormal distribution with CV's of either 10, 25 or 50%, depending upon the particular run, and an expected value specific to the given year of the run. The expected index value was the sum of the products of expected survey catch-at-age and weight-at-age. The expected survey catch-at-age is given by numerator of equation 6, multiplied by q (which was fixed at 1.0 for simplicity). We use the same weight-at-age relationship here as was assumed above in the synthesis model.

Fitting the Synthesis Model to the Simulated Data Sets

For each run the numbers in age categories 6–13+ in the initial year ($N_{6,1}$–$N_{13,1}$), recruitment ($N_{5,1}$–$N_{5,15}$) in each year, four selectivity parameters for the fishery and four for the survey, F_y in each year, and q (the proportionality constant for the survey) were estimated. Of the above, the F_y's and q were determined by constraints, and the others are estimated as formal parameters. Other values used in generating synthetic data and calculating likelihoods either were constants assumed known a priori or were calculated from the formally estimated parameters, parameters determined by constraints, and the assumed constants.

As mentioned above, our estimates of F_1–F_{15} and q were obtained by requiring them to satisfy constraints. The F_y's were continually updated along with the formal parameters so that the estimated catch biomass in each year exactly matched the observed catch, if this were possible (Methot 1990). A likelihood component for the catch biomass was included in the fitting so that solutions that did not allow the catch biomass to be matched (e.g., if an F is fixed so that the population cannot support the observed catch) were penalized for this lack of fit through smaller likelihoods. Because the survey is a relative one, the survey proportionality constant, q, is chosen so that the sum of the model's estimated survey catches over years equals the observed sum based on the data (Methot 1990).

The set of formal parameter estimates and constrained values that maximized the log-likelihood function was chosen as the best fit (Fournier and Archibald 1982; Kimura 1990; Methot 1990). The log-likelihood (L) was

$$(8)\quad L = L_1 + L_2 + L_3 + L_4$$

where L_1 was the log-likelihood associated with the fit to the fishery age composition, L_2 was the log-likelihood associated with the fit to the survey age-composition data, L_3 was the log-likelihood associated with the biomass of fishery catch, and L_4 was the log-likelihood associated with the survey index of biomass. These individual components (ignoring constant terms) were

$$L_1 = \Sigma_y\, 400\,(\Sigma_a \tilde{P}_{f,a,y} \log \hat{P}_{f,a,y})$$

$$L_2 = \Sigma_y\, 400\,(\Sigma_a \tilde{P}_{s,a,y} \log \hat{P}_{s,a,y})$$

$$(9)\quad L_3 = \Sigma_y - 0.5 \left\{ \frac{\log\left(\frac{\hat{C}_{f,y}}{\tilde{C}_{f,y}}\right)}{\sigma_f} \right\}^2$$

$$L_4 = \Sigma_y - 0.5 \left\{ \frac{\log\left(\frac{\hat{C}_{s,y}}{\tilde{C}_{s,y}}\right)}{\sigma_s} \right\}^2$$

where a tilde indicates observed data and a circumflex indicates values estimated by the stock synthesis model. $P_{f,a,y}$ represents

[2]K.R. Parker and A.D. MacCall. 1990. An interactive port sampling model for California groundfish. Administrative Report T-90-03, Tiburon Laboratory, 3150 Paradise Drive, Tiburon, CA.

the proportion of the sample type t (either fishery (f) or survey (s) in year y that is age a, and σ_t indicates the (assumed known) standard deviation on a log-scale of $\hat{C}^t_y$.

L_1 and L_2, the log-likelihood components for the fishery and survey age compositions, reflect the assumption that the observed proportions-at-age for each year were produced as though the sampled fishery catch or sampled survey catch were multinomial samples of size 400. This "effective sample size" of 400 is internal to the likelihood component and acts to weight the magnitude of the component based upon the assumed precision associated with the sampling program. The value of 400 used here matched the actual sample size used to generate the age-composition data (see above). In practice, an analyst could estimate the effective sample size for each year based on independent information on the precision of the catch sampling program (Methot 1990). Our approach assumed that the effective sample size was constant, and more importantly, that it had been estimated correctly.

The likelihood components for the fishery catch biomass and the survey index were of lognormal form. Thus, the likelihood increased as the squared errors between the log-transformed observed and synthetic values decreased. The values of σ_f and σ_s were assumed known and act to weight the two components in the total log-likelihood. They were determined by the assumed level of error associated with each type of data. σ_f was set at a value corresponding to a CV of 1% on the untransformed scale, which matches the level of error used to produce the observed (simulated) data. σ_s was set at values corresponding to CV's of 10, 25, or 50% on the untransformed scale, with the level of error chosen to match the level of error used to produce the observed (simulated) data for the given run.

For interested readers, the next two subsections provide technical detail on the process of searching for the maximum likelihood solution.

Numerical Details of the Fitting Procedure

The maximum likelihood solution was found using a Broyden–Fletcher–Goldfarv–Shanno update procedure combined with a cutback line search, a standard quasi-Newton method (Gill et al. 1981). Convergence was assumed when both the maximum change in any formal parameter value was less than 0.1% and the total log-likelihood changed less than 0.001%. Initial tests indicated that more stringent convergence criteria did not lead to improved estimates.

Our experience in fitting age-structured models to fishery data has indicated that results can be sensitive to initial parameter values, so we attempted to mimic the approach an analyst might use to specify initial values. Initial numbers at age and recruitment in each year were set by doing a cohort analysis (Pope 1972), following the approach used in Deriso et al.'s (1985) catch-at-age software (CAGEAN). Initial values for parameters determining fishery selectivity were set as follows. First, the $F_{a,y}$'s estimated by the cohort analysis were divided by $F_{y,10}$. These were then averaged over years to obtain an estimate of $s_{f,a}$ for each age, and the double-logistic function was fit to these estimates by least squares. The shape of the survey selectivity function was assumed to be essentially unknown, and a single set of initial values that produced a mildly dome-shaped selectivity function was used in all runs.

Local versus Global Maxima on the Likelihood Surface

When maximizing a parameter-rich function, there is a real danger that a solution may only maximize the likelihood function locally. This is of special concern in simulation studies because it is generally not practical to simulate the critical review of a stock assessment scientist for each individual run. We found that the model occasionally converged to solutions that did not have the global maximum likelihood. We discovered this by first noting that in some cases the estimated fishery selectivity function was asymptotic, or more rarely flat or decreasing, instead of the correct dome-shape. In a separate set of runs, we examined whether these solutions were true maximum likelihood solutions by fixing the fishery selectivity parameters at the correct values and reestimated the remaining parameters. Cases that originally estimated either a flat or declining fishery selectivity curve showed a substantial increase in the likelihood function, while likelihoods were similar to original values for cases where the original estimated fishery selectivity was either dome-shaped or asymptotic. In some test cases, we did not have success reaching the true maximum likelihood solution by restarting the fitting process from the incorrect solution.

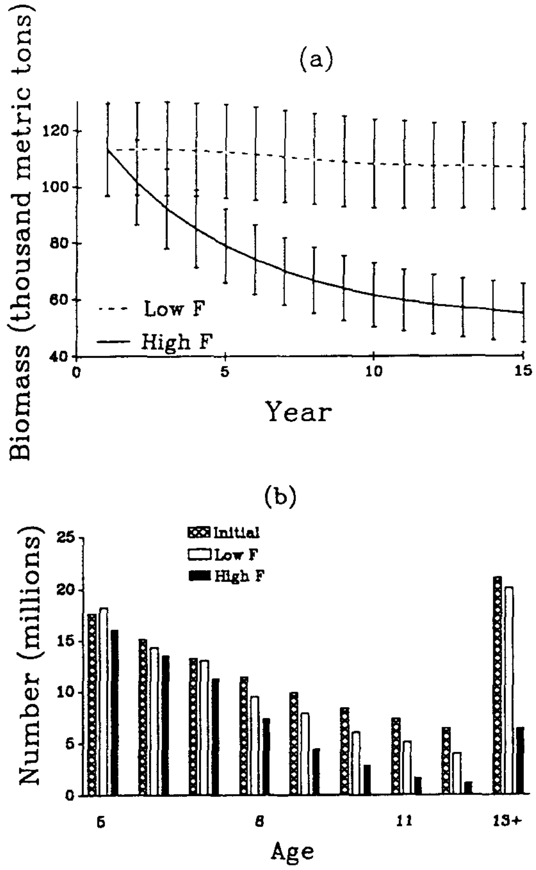

FIG. 2. True population dynamics of simulated populations. (a) Average biomass (± SD) plotted against time for high and low fishing mortality rates and (b) average initial and final numbers-at-age for low and high fishing mortality rates.

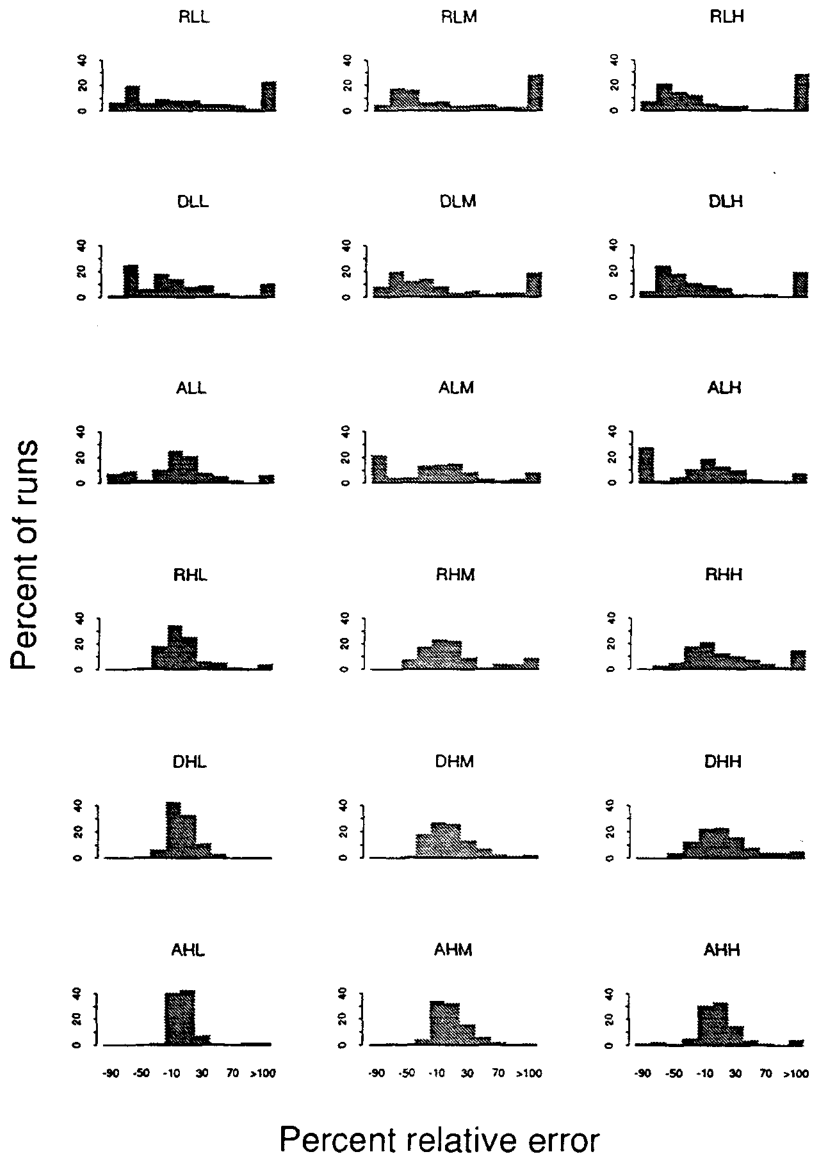

FIG. 3. Distributions of relative errors in estimated year 15 biomass for each case. Headings of the form "XYZ" denote the survey selectivity (X = R, D, or A for recruit, dome-shaped, or asymptotic, respectively), the fishing mortality rate (Y = L for low ($0.075 \cdot yr^{-1}$) or Y = H for high ($0.3 \cdot yr^{-1}$), and the survey coefficient of variation (Z = L, M, or H for low (10%), medium (25%), or high (50%), respectively) for each case.

In real assessments, we expect that declining or flat selectivity curves would be considered suspect, and additional runs would be done with different initial values for the parameters, so that a solution close to the maximum likelihood might be found. A real analyst might also run the stock synthesis model with a grid of starting values and potentially avoid the problem we encountered in the cases described above. We have therefore excluded runs that, by inspection, would be categorized as nearly flat or generally declining. (We defined as nearly flat or declining any case where the estimated fishery selectivity for age- 5 fish was greater than 70% of the maximum estimated selectivity; this is substantially above the true selectivity at age 5, which is 17% of the maximum, and nearly all values over 25% were also over 70%.) Because of the rarity of the "flat" and declining estimated curves (about 5% of the runs), excluding these runs does not influence any of our qualitative con-

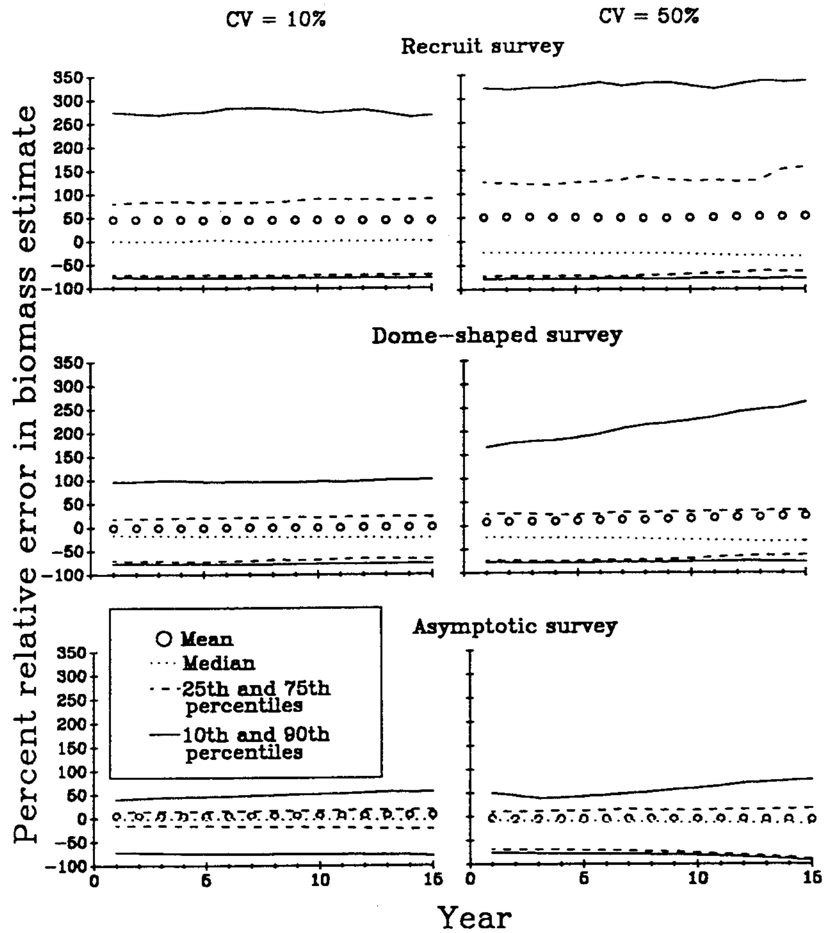

FIG. 4. Relative error in biomass estimates plotted aginst year for the low fishing mortality rate. Shown are results for survey CV's of 10 and 50%. For conciseness, results for survey CV's of 25% are not displayed; they were intermediate between the displayed cases.

TABLE 2. Percentage of runs with estimates of year 15 biomass within 20% of the correct value.

Survey type	Fishing mortality	Survey variability Low	Medium	High
Recruit	Low	16.8	11.8	8.8
	High	60.6	46.1	33.7
Dome-shaped	Low	22.6	12.0	16.2
	High	76.0	53.0	45.5
Asymptotic	Low	46.2	29.2	32.0
	High	84.2	66.5	64.0

clusions. If included, these runs would accentuate the patterns presented below because the cases with the most variable results also produced more estimated flat and declining selectivity functions, and runs with these erroneous selectivity patterns also tended to have large errors in other parameters.

Results

Population Dynamics

Under the high fishing rate scenario, average biomass fell by about half from year 1 to 15, and the contribution of the older ages, particularly the 13+ category, declined markedly (Fig. 2). On average, biomass leveled off in the final years of the simulations because the population was coming into balance with the higher mortality imposed by fishing. Under the lower fishing rate, the decline in biomass was only slight, and the shift in the age distribution was not marked.

Skewed Distribution of Errors

We examined the distributions of percent relative error (PRE) = 100 × (estimated-true)/true for each run both for biomass and recruitment estimates. For each type of survey the distribution of errors was skewed, so that the mean PRE typically exceeded the median (Fig. 3–7). Median errors were typically

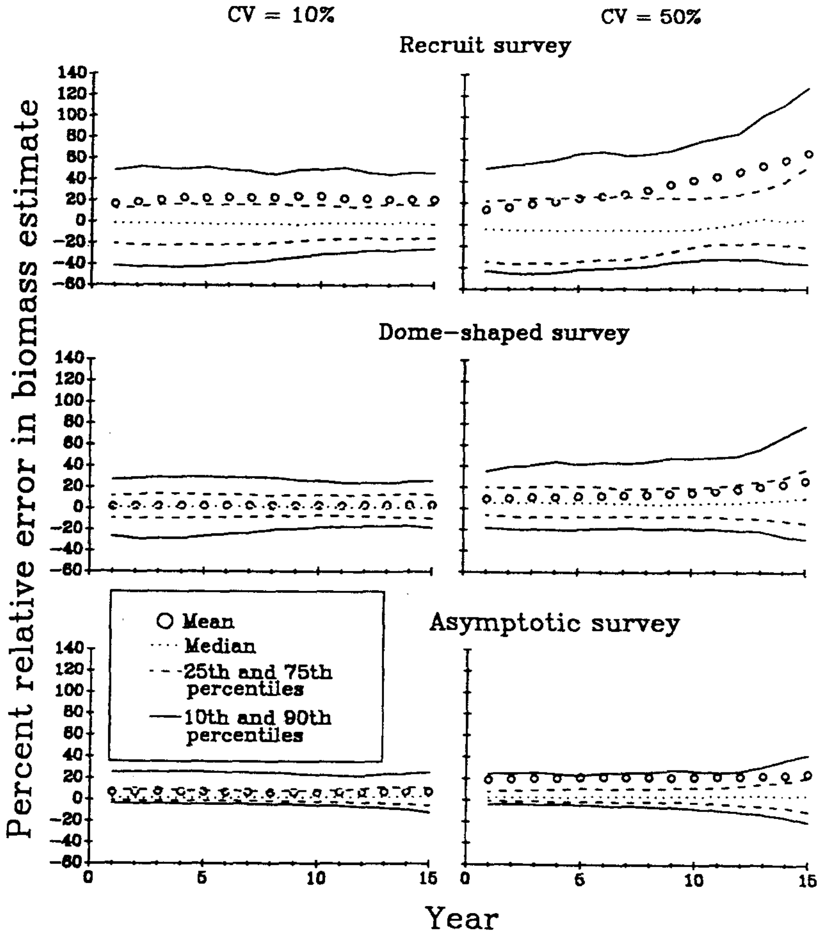

FIG. 5. Relative error in biomass estimates plotted against year for the high fishing mortality rate. Shown are results for survey CV's of 10 and 50%. For conciseness, results for survey CV's of 25% are not displayed; they were intermediate between the displayed cases.

close to zero. Given the variability in the magnitude of errors and the skew of the distributions, it was clear that the mean error alone would sometimes be an insufficient measure of the performance of the stock synthesis model.

Accuracy and Precision in Biomass and Recruitment Estimates

For management purposes, the accuracy of biomass estimates in the final year of an assessment is usually of greatest interest. Consequently, we examined the distribution of relative errors in estimated biomass in the 15th year (Fig. 3) and also tabulated the percentage of runs with year 15 biomass estimates within 20% of the correct value (Table 2). Although 20% is a somewhat arbitrary cutoff, we felt that stock assessments with errors less than 20% would be classified as successful by most workers. The overall pattern in the results is for greater accuracy and precision given a higher fishing mortality level and when survey precision was higher (Table 2; Fig. 3). Errors were most concentrated around zero for the asymptotic survey and least concentrated around zero for the recruit survey (Table 2; Fig. 3). The difference in accuracy and precision between the recruit and asymptotic surveys was comparable with differences within a survey type when its CV ranged from 10 to 50%. The difference between the asymptotic and dome-shaped surveys was accentuated at a low fishing rate (Table 2; Fig. 3). This latter result is reasonable because the asymptotic survey sampled older fish to a greater extent, and these constituted a larger proportion of the year 15 stock at a low fishing rate (Fig. 2).

Estimates of biomass and recruitment in earlier years are also of interest because they can provide information on how the stock is changing over time. In general, the precision and accuracy of biomass (Fig. 4 and 5) and recruitment (Fig. 6 and 7) estimates over the entire time series showed the same qualitative patterns as year 15 biomass estimates. The most accurate and precise estimates came from the asymptotic survey and the least accurate and precise from the recruit survey. As might be

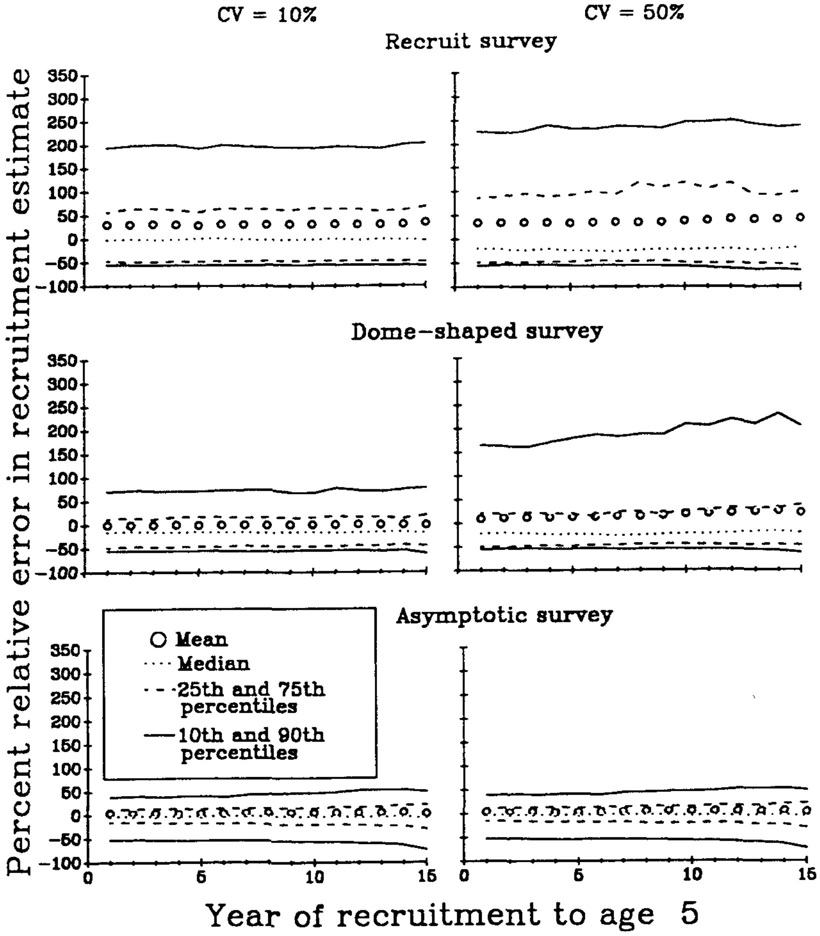

FIG. 6. Relative error in recruitment estimates plotted against year for the low fishing mortality rate. Shown are results for survey CV's of 10 and 50%. For conciseness, results for survey CV's of 25% are not displayed; they were intermediate between the displayed cases.

expected, estimates were better when the survey CV was lower or the fishing mortality rate was higher.

Errors in estimated biomass in year 15 were generally associated with an overall scaling error. These scaling errors caused the correlation between errors in biomass estimates and errors in initial number and recruitment parameter estimates to be high, although the correlations did fall off some at the beginning and end of the time series (Fig. 8). The correlation between errors in recruitment (or initial numbers-at-age) and errors in year 15 biomass estimates tended to be weakest in cases where absolute estimates of biomass were best. For example, correlations were generally lower at the higher fishing mortality rate, especially for the dome-shaped and asymptotic surveys with a CV of 10%.

To the extent that errors were due to an overall scaling problem, estimates of relative year-class strength might still be quite good even when absolute estimates were poor. We measured relative recruitment, on a log scale, as log-transformed recruitment minus the mean of log-transformed recruitment. Estimated and true values of relative recruitment were highly correlated (Fig. 9). Although lower, the correlations were still substantial even at the end of the time series. The lowest correlations were for the dome-shaped survey at the end of the time series of recruitment estimates. This is not unexpected because these year-classes were never well sampled by this survey.

Substantial errors in year 15 biomass were sometimes associated with trends in estimated recruitment, as estimated by linear regression of recruitment estimates against year. Stong trends were most evident when the fishing mortality rate was low, especially when final biomass was substantially overestimated (Fig. 10). For this case, although more trends were positive, some strong trends were negative, and in these cases, biomass in the first year was overestimated to an even greater degree than year 15 biomass. Strong trends were less common at the higher fishing mortality rate, and underestimates tended to have more declining trends and overestimates more increasing trends (Fig. 10).

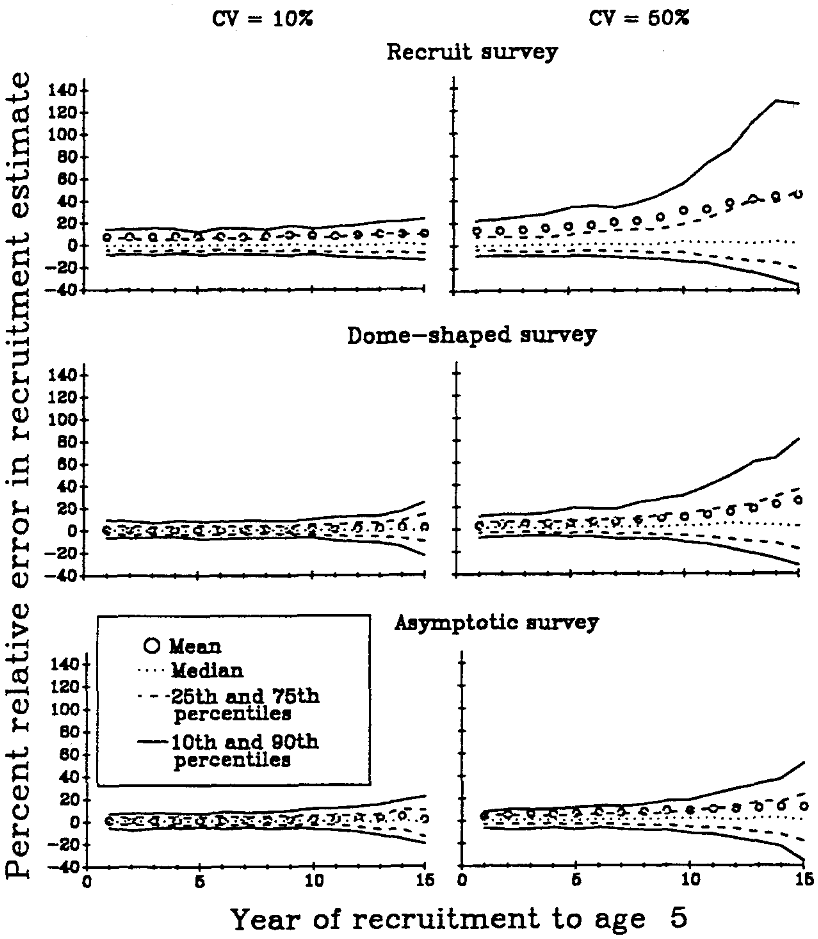

FIG. 7. Relative error in recruitment estimates plotted against year for the high fishing mortality rate. Shown are results for survey CV's of 10 and 50%. For conciseness, results for survey CV's of 25% are not displayed; they were intermediate between the displayed cases.

Temporal Patterns in Biomass and Recruitment Estimates

By analogy with cohort analysis, it is reasonable to expect convergence of estimated values of recruitment as we move back in time, with the convergence being stronger at higher fishing mortality rates (Pope 1972). To the extent that the convergence property carries over to separable models, and the convergence is toward the true value, we would expect to see tighter distributions of relative errors in estimated recruitment earlier in the time series and at higher fishing mortality rates. Our results match this expectation. At the lower level of fishing mortality, there appears to have been only slight convergence in earlier years toward the correct value of recruitment (Fig. 6). In contrast with the low fishing rate results, there was substantial convergence for estimates of recruitment at the high level of fishing mortality (Fig. 7).

In a number of cases, biomass estimates improved as we moved backward in time (Fig. 4 and 5). This, however, is not a general result. For example, at a high fishing mortality level with a low-variability dome-shaped survey, the most accurate biomass estimates are in year 10, with slightly less accurate estimates in earlier years (Fig. 5). This may have occurred because some of the cohorts contributing to biomass in the early years were observed only for a few years before moving into the 13+ category (see also Kimura 1989).

Discussion

In this paper, we used Monte Carlo simulation to evaluate the performace of the stock synthesis model. Our study was unique in its assessment of the value of a relative survey (i.e., one proportional to available stock, but with the proportionality constant unknown) to the synthesis model, and especially in the comparison of such surveys with different selectivity patterns. Although we only examined the stock synthesis model in our simulations, we suspect that many of our results apply more generally to statistically based catch-at-age methods such as

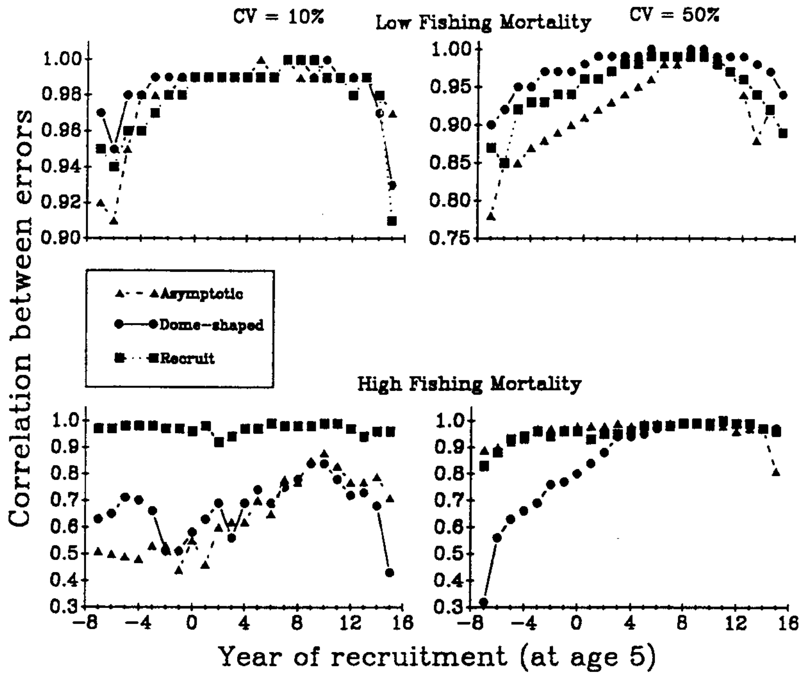

FIG. 8. Correlation between relative error in estimated biomass in year 15 and relative error in estimates of initial numbers-at-age and recruitment parameters. Correlation is plotted against the year of recruitment to age 5 associated with the parameter. Thus, the correlations with recruitment parameters ($N_{5,y}$, $y = 1, \ldots, 15$) are plotted at X values of $y = 1, \ldots, 15$, and the correlations with initial numbers-at-age ($N_{a,1}$, $a = 6, \ldots, 13$) are plotted at X values of $a - 6 = 0, -1, \ldots, -7$. For example, the correlation between the relative error in estimated year 15 biomass and initial numbers at age 8 ($N_{8,1}$) is plotted at an X value of -2 because age 8 fish in year 1 recruited at age 5 3 yr earlier. For conciseness, results for survey CV's of 25% are not displayed; they were similar to displayed results.

CAGEAN (Deriso et al. 1985) and perhaps also to tuned virtual population analysis (e.g., Pope and Shepherd 1985). Care should be taken in extrapolating from our results to short-lived species because the role of survey selectivity could be quite different when the population is composed of only a few age-classes.

Although tangential to the main thrust of this paper, we think that it is of interest that the synthesis estimates of recruitment and biomass were generally positively biased. In contrast with the mean errors, median errors were generally quite close to zero. This kind of "transformation bias" is a well-known phenomenon arising from the skew in the lognormal distribution of errors we assumed. We suspect that such a bias is built into many catch-at-age methods and is probably a real phenomenon because in practice, most distributions of errors will be skewed. However, whether a median or mean error of zero (or something else) is desired depends in part upon management goals (see also Pope and Shepherd 1985).

In our study, an asymptotic survey was best for estimating current stock size within some fixed percentage of the correct value. Accuracy fell some for the dome-shaped survey, and the recruit survey produced estimates that were considerably less accurate than those associated with the other survey types. These results suggest that, all else being equal, an asymptotic survey should be chosen. The extent, however, to which the selectivity pattern of a survey can be controlled or chosen is of pragmatic concern. For example, fish behavior, distribution, and ability to avoid capture may make it difficult to design an asymptotic survey. However, a combination of surveys that together capture a broad range of ages may provide many of the benefits we have associated with an asymptotic survey. In the end, choices among survey types will involve their relative costs, the value of forecasting future recruitment (e.g., Walters 1989), as well as the expected accuracy of the resulting estimates of current biomass. When these trade-offs are being made, it is important to keep in mind that differences in the performance of surveys with different selectivity patterns can be quite substantial, rivaling differences in performance resulting from severalfold differences in coefficients of variation in survey error.

A relative survey can be used to help determine absolute abundance primarily because it provides information on how the fished stock changes from year to year. The magnitude of these relative changes can then be related to the absolute magnitude of the fishery catch. The poor performance associated with the recruit survey can be understood by noting that most fish captured by the recruit survey have not yet experienced fishing mortality. Thus, changes in survey CPUE reflect year-to-year variations in relative recruitment, but are largely uncoupled from changes in the stock due to fishing. Furthermore, the

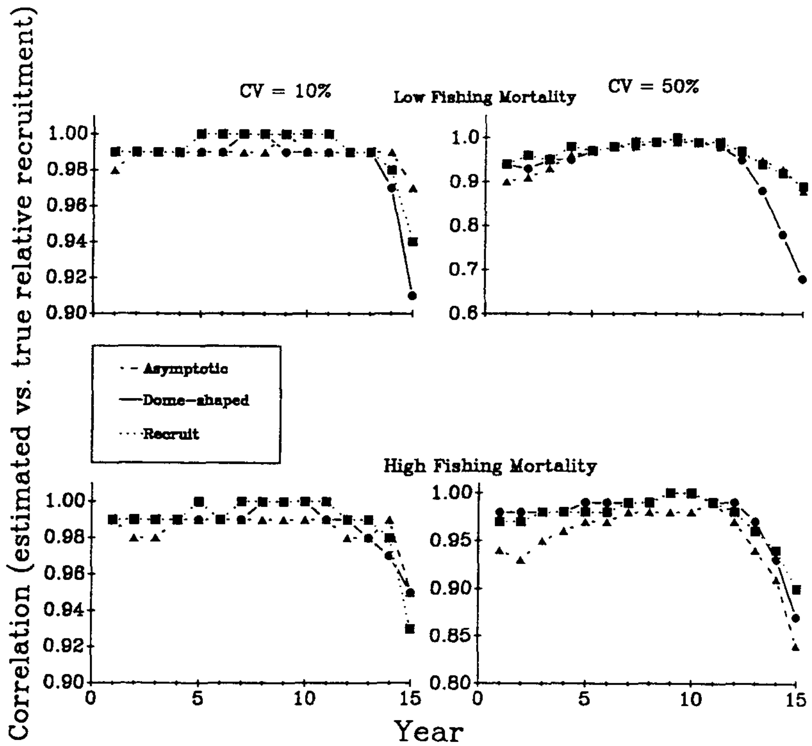

FIG. 9. Correlation between estimated relative recruitment and actual relative recruitment plotted against the year of recruitment. For conciseness, results for survey CV's of 25% are not displayed; they were similar to displayed results.

fishery age-composition data alone already contain substantial information on relative year-class strength (e.g., Ricker 1975, p. 265–272), but essentially none on absolute stock size (Doubleday 1976; Deriso et al. 1985; Shepherd and Nicholson 1986). Consequently, much of the information on relative year-class strength provided by the recruit survey is redundant and does not provide information on absolute abundance. Indeed, for the recruit survey, our stock synthesis estimates of relative recruitment were quite good, even though absolute estimates of recruitment and biomass tended to have large errors.

When fishing mortality has been low, assessments of current stock size based on fishery catch-at-age data and a survey of relative abundance will often be substantially in error. Under higher cumulative fishing mortality, it is intuitive that catch-at-age analyses give better results because such a large proportion of each cohort of fish are counted in the catches (Pope 1972). However, our results suggest that even when F is high, the relative survey must be highly precise to have a high probability that an estimate of current abundance will be within 20% of the correct value. Although large errors in estimated year 15 biomass were sometimes associated with incorrect patterns for the fishery selectivity function in our study, most of the estimated patterns were not "pathological," and we doubt that an analyst could rule them out as unreasonable without making use of information external to the assessment. With a very long time series, a relative survey might fix absolute abundance adequately, even at a low fishing mortality rate, but then the assumptions of constant natural mortality, selectivity patterns, growth, etc., are probably untenable (e.g., Walters 1986).

We believe that our simulation study presents a best-case scenario for stock assessments. In the simulations, selectivity or weight-at-age did not change over time, natural mortality was assumed known and remained constant (over years and ages) at the assumed value, and catch biomass was assumed to be known accurately. The precision of our simulated survey varied from high (CV = 10%) to modest (CV = 50%), and we assumed that there was a survey every year. In practice, the real population will deviate from the synthesis (or other) model to an unknown extent, and the quality and quantity of data will often be lower than in our simulations.

To place our simulations in context, it is worth considering the actual kinds of data usually available for use with the stock synthesis model. Assessments of several groundfish stocks on the west coast of North America make use of trawl survey data collected every third year with CV's near 50% (Bence and Rogers 1992; Rogers and Bence 1992). For many stocks, natural mortality was estimated by catch curves, maximum ages, or simply by analogy with other species (e.g., Hightower and Lenarz 1986; Bence and Rogers 1992; Rogers and Bence 1992). In our simulations, we generated data with a very low level of sampling error for catch biomass because this is the assumption under which the synthesis model is fit to the data. However, we recognize that catch biomass estimates are probably less accurate than the low level of error built into our simulations

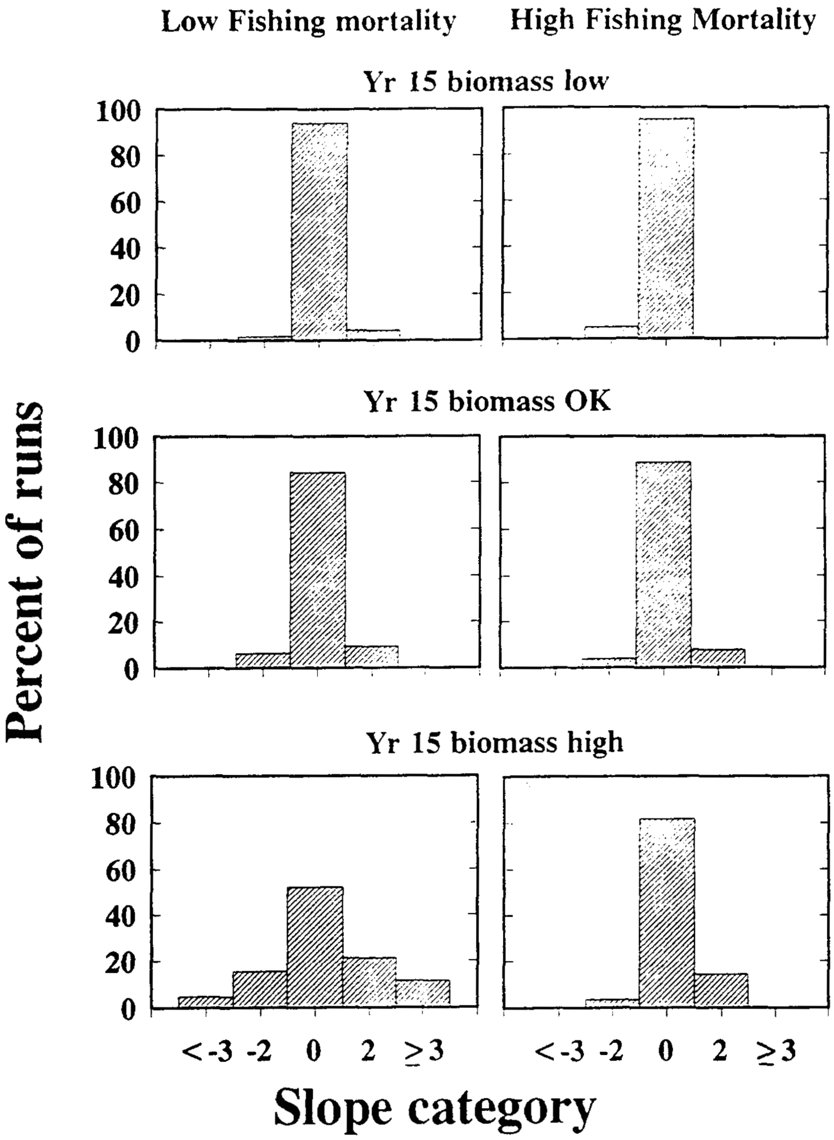

FIG. 10. Distribution of estimated slopes (by linear regression) of the trend in estimated recruitment over time. Distributions were calculated separately for replicates with low (more than 20% low), OK (within 20% of the correct value), or high (more than 20% high) estimates of year 15 biomass. Shown are results for an example low and high fishing mortality case (dome-shaped selectivity, CV = 25%); other cases showed similar patterns.

because of two general problems. First, discard levels generally are estimated roughly from an observer program of restricted spatial and temporal extent. Thus, even when landings are made in nearly pure "market categories" and reported landings are essentially a census of the landed catch, as they are for widow rockfish, the error in catch biomass could be substantial. Second, estimation of landed catch is complicated for some stocks because landings are made in mixed-species market categories that need to be sampled (Bence and Rogers 1992). This can sometimes cause the estimates of landings to have substantial sampling error. For most assessments using the synthesis model, age-composition data appear to be quite good, at least as representations of the landed catch. Estimated proportions at age in the landed catch often come from extensive sampling at the ports (stratified both spatially and by time of year) combined with the reading of thousands of otoliths.

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