

**Abstract.**—Relative abundance of sablefish, *Anoplopoma fimbria*, in the waters off Alaska has been measured annually since 1979 with longline surveys. These extensive surveys provide precise measures of relative abundance. An age-structured model was fitted to the longline survey data to estimate absolute abundance. Estimates of recent exploitation rates for fully selected ages averaged 10%. Monte Carlo simulations of the age-structured model indicated that absolute abundance of Alaskan sablefish can be estimated reliably if age selectivity is asymptotic and not dome-shaped. Abundance estimates were reliable even when only length data and no age data were available. Dome-shaped selectivity gave biased and less precise estimates, probably owing to a parameter interaction between catchability and the shape of the selectivity function.

## Estimation of sablefish, *Anoplopoma fimbria*, abundance off Alaska with an age-structured population model

Michael F. Sigler

Auke Bay Laboratory, Alaska Fisheries Science Center  
11305 Glacier Hwy., Juneau, Alaska 99801-8626  
E-mail address: Mike.Sigler@noaa.gov

Sablefish, *Anoplopoma fimbria*, is a long-lived species that inhabits the northeast Pacific Ocean and Bering Sea. This species supports a fishery in Alaskan waters, with catches ranging from about 10,000 to 35,000 metric tons (t) during the last two decades (Fig. 1). The fishery mostly uses longline gear and primarily occurs on the upper continental slope, which is inhabited by adult sablefish (Fig. 2). Previously the fishery became compressed year-round during the mid-1980s to 10 days in some areas, until 1995, when management switched to individual fishing quotas and an eight-month season. The delay of the start of the season from 1 January to 1 April and later 15 May accompanied the compressed fishery season.

In Alaska, relative abundance of sablefish has been best measured by annual longline surveys since 1979. Longline surveys are preferred over trawl surveys for assessing sablefish because the longline surveys generally cover the areas that adult sablefish inhabit, namely the upper continental slope. The longline surveys have occurred between early May and late September. The survey and fishery generally take place in the same area, the upper continental slope but the fishery generally takes place over a narrower depth range. Trawl surveys have also been conducted in Alaska, but compared with the longline surveys, they have not sampled as deeply and have covered fewer years. In stock assessments for Alaskan

sablefish prior to 1996 (Fujioka, 1995; Lowe, 1995), the limited trawl data were used to convert relative abundance from the longline survey to absolute abundance by calibration to the trawl (Rose, 1986), and the population was modeled by using a delay-difference analysis (Kimura, 1985). The formulation of the delay-difference analysis applied to Alaskan sablefish was modified to provide annual recruitment estimates, with the assumption that trawl surveys measure absolute abundance (Fujioka, 1995; Lowe, 1995). The Alaskan sablefish stock assessment was like other Alaskan groundfish stock assessments, which historically have assumed that trawl surveys measure absolute abundance (Alverson and Pereyra, 1969). This assumption probably is wrong because fish can escape under the net (Engås and Godø, 1989a) and be herded by the bridles (Engås and Godø, 1989b). The motivation for the current study was to assess Alaskan sablefish without this assumption, relying only on longline survey estimates of relative abundance.

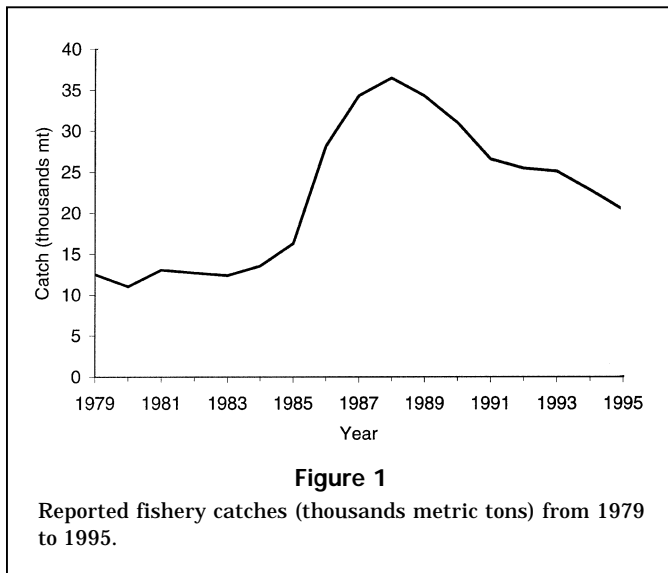
In the current study, I estimated absolute abundance for Alaskan sablefish with an age-structured population model, evaluated the estimation approach with Monte Carlo simulations, and investigated interactions of model parameters. Delay-difference analyses use annual abundance estimates and catches, whereas age-structured analyses additionally use annual

age or length data. The additional information allows explicit tracking of cohorts, but many more parameters must be estimated.

Fitting population models to survey and fishery data has long been used to estimate absolute abundance (Pope and Shepherd, 1985; Deriso et al., 1985) and is one method of estimating absolute abundance along with direct surveys, mark-recapture experiments and depletion experiments. Abundance estimation with a population model works by tracking population additions and losses and inferring absolute abundance from the manner in which catch af-

fects the survey index and age and length compositions. In simple terms and aside from other losses, if harvesting 500 individuals decreases a cohort's index 10%, then the cohort's initial abundance was 5000 individuals. Estimation depends on having an abundance index precise enough to detect cohort reductions by the fishery.

The population model presented here takes into account the following unusual attributes of the available data. Length compositions are available from the longline surveys for all years analyzed, compared with infrequently available age compositions (Table 1). Not many Alaska-wide sablefish fishery data are available, consisting only of total catches and five years of fishery lengths, but no ages (Table 1).



## Methods

### Model structure and estimation method

The analysis generally follows the approach described by Kimura (1990) for a separable age-structured population model. Let  $y$ ,  $a$ , and  $l$  be the year, age, and length indices, respectively.

$c_y$  = observed fishery catch in numbers;

$I_y$  = observed survey abundance index in numbers;

$p_{ya}$  = observed survey proportion at age;

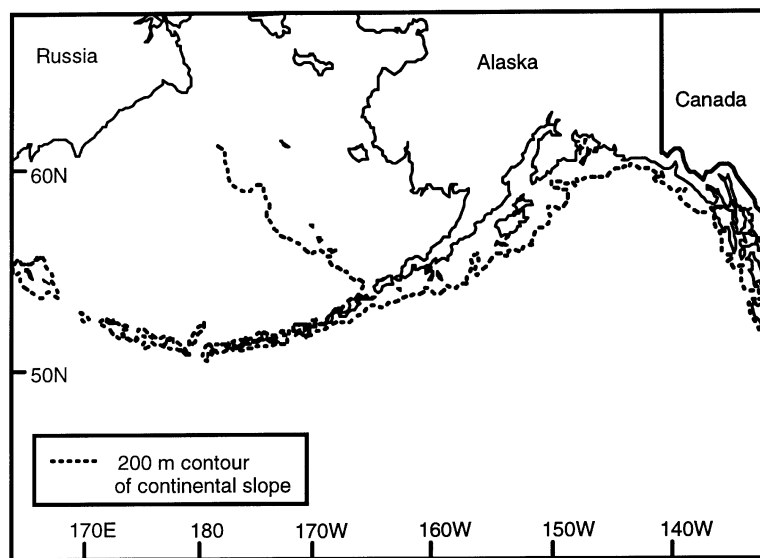
$p_{yl}$  = observed survey proportion at length;

$\mu_{ya} = \mu_y s_a$  = the exploitation fraction of age- $a$  fish during year  $y$  which is separable into  $s_a$ , the selectivity for age- $a$  fish, and  $\mu_y$ , the exploitation fraction for fully vulnerable ages;

$N_{ya}$  = the total number at age;

$N_{ya}^f = s_a N_{ya}$  = the exploitable (fishable) number at age; and

$\sum_a N_{ya}^f = N_y^f$  = the exploitable number.



Map of southern Alaskan waters. Adult sablefish inhabit the upper continental slope seaward of the 200-m depth contour.

Starting with initial cohort size,  $N_{ya}$ , natural deaths and observed catch were removed to compute next year's cohort size,  $N_{y+1,a+1} = (1 - \mu_{ya}) N_{ya} e^{-M}$ . A discrete fishery was modeled,  $c_y = \mu_y N_y^f$ , because the fishery was short for recent years except 1995. The modeled discrete fishery generally matches the timing of the observed discrete fishery and occurs near the mid-point of the earlier year-round fishery.

**Table 1**  
Data sets used in the age-structured model of Alaskan sablefish. Length data are specified by sex.

Data component	Data aggregation	Years of data
Longline survey relative abundance	—	1979–95
Longline survey male lengths (cm FL)	40–41, 42–43, ..., 62–63, 64–69, 70–74, ..., 95–99	1979–95
Longline survey female lengths (cm FL)	40–41, 42–43, ..., 68–69, 70–74, 75–79, ..., 95–99	1979–95
Longline survey age	2, 3, 4, 5, 6, 7, 8, 9–10, 11–15, 16+ years	1983, 87, 89, 91, 93
Fishery total catch	—	1979–95

The modeled discrete fishery misrepresents the duration of the earlier year-round fishery, but tests with simulated data comparing a continuous fishery showed little difference in estimated abundance. The assumption of a discrete fishery simplified catch accounting and reduced model convergence time, which was important for the Monte Carlo simulations. This formulation limits the maximum exploitation rate for an age class to equal the selectivity for that age. This maximal rate would be achieved if the maximally selected age were completely harvested, with the exploitation rate equal to 1.0. This potential problem is not a real one because exploitation rates never approach such high levels for Alaskan sablefish.

Selectivity was described by the “exponential-logistic” function (Thompson, 1994),

$$s_a = \left( \frac{1}{1-\gamma} \right) \left( \frac{1-\gamma}{\gamma} \right)^\gamma \left( \frac{e^{\beta\gamma(A_{50}-a)}}{1 + e^{\beta(A_{50}-a)}} \right).$$

The “exponential-logistic” function is flexible, allowing both asymptotic selectivity when selectivity increases with age to an asymptote, and dome-shaped selectivity when selectivity increases with age to a maximum, then decreases for older fish. The exponential-logistic function automatically scales maximum selectivity to 1.0 and reduces to asymptotic selectivity as the parameter gamma ( $\gamma$ ) approaches zero. When  $\gamma = 0$ , the parameter  $A_{50}$  is the age where 50% of the population is vulnerable and  $\beta$  is the slope of the function at  $A_{50}$ . When  $\gamma > 0$ , then  $A_{50}$  and  $\beta$  lose their biological meaning, because  $A_{50}$  no longer represents the age at 50% vulnerability. Selectivity is assumed equal for the fishery and survey. Both the fishery and survey mostly use longline gear and cover the same area. Their similar length frequencies support this assumption (Fig. 3). The fishery length data were not incorporated into the model because of this similarity and because few years of fishery length data were available.

Age data were aggregated over adjacent ages (Table 1) as suggested by Deriso et al. (1989) because

sablefish are difficult to age, especially those older than eight years (Table 6 in Kimura and Lyons, 1991). Ages greater than eight years were not pooled into a single class because females continue to grow, though slowly, after eight years. This growth information was needed in the model to convert ages to lengths. Length data also were aggregated (Table 1). Another way to deal with ageing error is to include a matrix of misageing probabilities in the age-structured model (Kimura, 1990), but this approach was not used because the misageing probabilities were unknown.

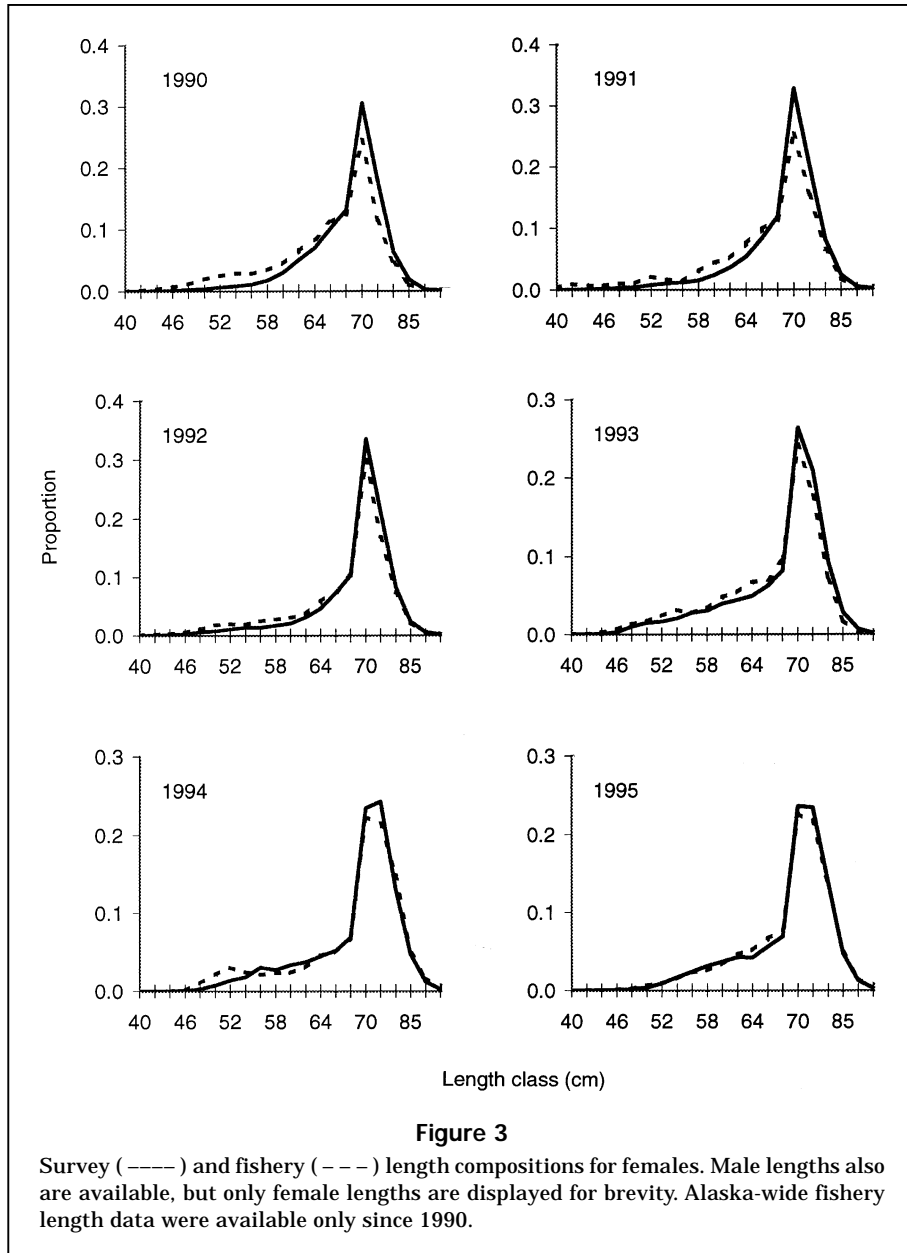
Estimated data values were computed from the parameter estimates. The estimated abundance index is  $\hat{I}_y = \hat{q}\hat{N}_y^f$ , where  $q$  is survey catchability. Quantities estimated from this model and used in the model fitting algorithm are denoted with “hats.” The estimated age compositions are

$$\hat{P}_{ya} = \frac{\hat{N}_{ya}^f}{\sum_a \hat{N}_{ya}^f}.$$

An age-length transition matrix,  $L = (L_{al})$ , also was calculated from the survey age data, where  $L_{al}$  is the probability that a sampled fish of age  $a$  will be of length  $l$ . The age-length transition matrix is assumed constant over time. Probabilities were computed by region and year, then pooled as an average weighted by sample size. Estimated age compositions were converted to estimated length compositions with the age-length transition matrix,

$$\hat{P}_{yl} = \sum_a \hat{P}_{ya} L_{al}.$$

The parameters were estimated by maximum likelihood by assuming multinomial errors for age and length data and log-normal errors for catch data (Fournier and Archibald, 1982) and by using the quasi-Newton algorithm implemented in Microsoft Excel. Assuming that the effective sample sizes are the same for age and length samples and that the



age and length samples are independent, then the log-likelihood is

$$L = \sum_{ya} p_{ya} \log \frac{\hat{p}_{ya}}{P_{ya}} + \sum_{yl} p_{yl} \log \frac{\hat{p}_{yl}}{P_{yl}} - \lambda \sum_y \left( \log(I_y) - \log(\hat{q}\hat{N}_y^f) \right)^2 + \text{constant},$$

where  $\lambda$  is the ratio of the effective multinomial sample sizes, either age or length, to the variance of the log-transformed abundance index (Deriso et al., 1985). Thus  $\lambda$  is a weighting factor that adjusts the relative influence of the abundance index and age

and length components of the likelihood. The range of  $\lambda$  from 0.02 to 10 was tested. The value  $\lambda = 1$  appeared the most reasonable and is used henceforth. This value was chosen on the basis of fit of each data type and the effect on the estimated recruitment values as  $\lambda$  was varied. As  $\lambda$  increased from 0.02 to 10, the fit of the index data improved only at the expense of the fit of the length data, but the relative sizes of the annual recruitment estimates were unaffected for  $\lambda < 2$ . Increasing  $\lambda$  substantially improved the fit of the index data until  $\lambda$  was from 1 to 2, when improvement slowed. Thus a value of  $\lambda$  between 1 and 2 seems reasonable, with  $\lambda = 1$  chosen because the fit of the age data was best at that point. In prac-

tice,  $\lambda = 1$  implies an effective sample size for the age and length samples of 100 if the CV of the survey index is 10%. This CV is reasonable according to a statistical analysis of the survey index, which found that a 10% interannual change in the survey index typically was statistically significant at the  $P=0.05$  level (Sigler and Fujioka, 1988). The reasonableness of the effective sample size is harder to determine because the age and length samples are composites of multinomial samples from survey stations with underlying geographic variation in age and length compositions, so that the effective sample size is less than the true sample size. In the above expression  $\log(\hat{p}_{ya})$  usually found in the log-likelihood for the multinomial distribution was replaced with  $\log(\hat{p}_{ya}/p_{ya})$ . This replacement removes a “nonsignificant” portion of the likelihood and makes it easier to examine the model fit and probably somewhat improves numerical performance (Kimura, 1990).

Assuming  $M$  and  $\lambda$  are known, this model contains  $Y + A + 2$  parameters: recruitment,  $N_{11}, \dots, N_{1Y}$ , the initial age composition,  $N_{12}, \dots, N_{1A}$ , and the selectivity parameters,  $A_{50}, \beta$ , and  $\gamma$  are unknown. The quantities  $\hat{\mu}_1, \dots, \hat{\mu}_Y$  are functions of the observed survey indices and observed catches and of the parameter estimates. Setting  $dL/dq$  equal to zero and solving for  $q$  gives

$$\hat{q} = \exp \left| \frac{\sum_y \log \frac{I_y}{\hat{N}_y^f}}{Y} \right|$$

The  $\hat{\mu}_1, \dots, \hat{\mu}_Y$  are computed from  $\hat{\mu}_\gamma$

$$= \frac{c_y}{\hat{N}_y^f},$$

by treating reported catches as exact. Although clearly there will always be some error in the reported catch, I concluded that this approximation generally was reasonable given the comprehensive system for tracking the Alaskan sablefish catch, which includes processor reports, fish receipts, individual fishing quota landing reports, and observer coverage. I estimated log-parameters rather than parameters on the original scale to improve reliability in the estimation process (Kimura, 1989, 1990).

An allowable biological catch ( $ABC_{96}$ ) was calculated from a 1-year future projection. The constant fishing mortality,  $F_{40\%}$ , was applied, which reduces the exploitable population to 40% of the unexploited state (Clark, 1991). A 1-year projection of recruitment was forecast as the average of recent estimated recruitments. The two most recent recruitments were

not used in the average; their estimates, based on only one or two years of data, are unreliable.

### Validation of estimation method

I used Monte Carlo simulation for model validation (Kimura, 1989; Press et al., 1989) to verify that the age-structured analysis provides reasonable results. The steps (Press et al., 1989) are as follows: 1) Fit the model using real data; 2) take the estimated parameter values as the true values for the simulation; 3) calculate the expected data based on these parameter values, then simulate a new data set by adding a particular error to the expected data based on an observed mean square error (MSE) or any hypothetical value; and 4) estimate the model parameters for the simulated data. If the resulting parameter estimates and the true parameter values are similar, then the estimation method is to some extent validated. This approach assumes that the model fits the simulated data perfectly except for random error. If the true errors were of larger magnitude or arose from a different source than that assumed in fitting the model, for example in violating the assumptions of equal fishery and survey selectivity and constant growth rates, then estimation performance with simulated data overstates the true model performance.

Log-normal error (CV=0.10 on the original scale) was added to the expected abundance index, and multinomial error ( $n=200$ ) was added to the expected age and length data. These values were based on variability of the model residuals (difference between the observed and expected data). The log-transformed abundance indices are assumed to be independent, normally distributed random variables, and a “minor dilemma” (Kimura, 1989) arises on whether to simulate the abundance indices so that they are unbiased on the original or the logarithmic scale. I chose to simulate the abundance indices so that the survey index was unbiased on the original scale.

Age data are often limited in availability, whereas length data are nearly always available. Age data are more desirable than length data for estimating age structure because the correspondence between age and length is not one-to-one. Age data are commonly inaccurate: some individuals, especially older fish, are misassigned to ages around the true age. Thus, inaccurate age data and length data are similar in that true age does not uniquely correspond to assigned age or length. Parameters were estimated from simulated data for both accurate and inaccurate age data, the latter also being equivalent to length data. For accurate age data, 100% of fish of simulated samples were correctly assigned and cat-

egorized as {2, 3, ..., 15, 16+}. For inaccurate age or length data, 50% were correctly assigned to the true age, 20% to -1 year, 20% to +1 year, 5% to -2 years, and 5% to +2 years, then categorized as {2, 3, ..., 8, 9+}.

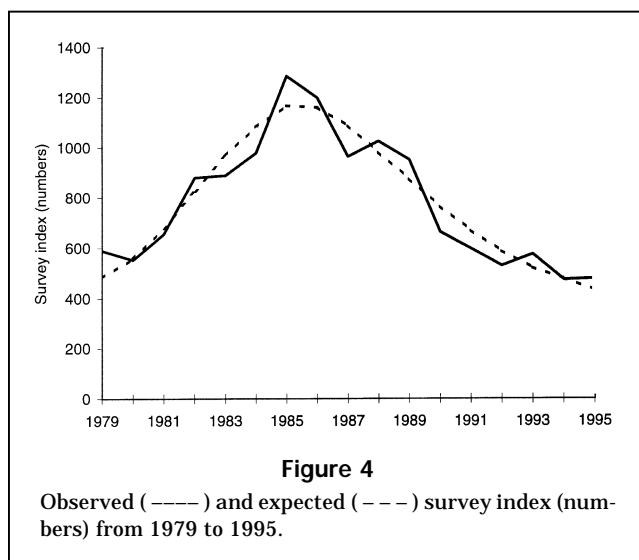
Survey selectivity may affect parameter estimation. Bence et al. (1993) found that biomass estimates were more accurate and precise for a population model with data from a survey with asymptotic selectivity than from one with dome-shaped selectivity. Therefore, both asymptotic and dome-shaped selectivity were compared. The dome-shape was chosen such that the availability of the last age group was 0.5.

A measure of the variability of biomass estimated in the simulations is the MSE computed from parameter estimates and their "true" values. Mean square error (MSE) was converted to coefficient of error (CE), defined as the "true" value divided into the square root of MSE (Kimura, 1990). Twenty-five to fifty replicate simulations were completed for each scenario.

## Results

### Model results for the original data

The model fitted all the original data well: abundance index (Fig. 4), age data (Fig. 5), and length data (Fig. 6). The estimate of survey catchability appears good; the likelihood profiled over a range of catchabilities shows a distinct, regular curvature (Fig. 7). Estimated exploitable biomass for 1995 was 181,000 t (Fig. 8), and projected  $ABC_{96}$  was 19,600 t. Estimated biomass decreased from a peak in the mid-1980s. The



peak is attributed to strong recruitment in the late 1970s; recruitment has decreased in recent years (Fig. 9). Estimates of recent exploitation rates for fully selected ages average 10% (Fig. 8), which is near the exploitation rate equivalent to  $F_{40\%}$ , the current reference point for sablefish management in Alaska. The shape of the estimated selectivity curve was asymptotic (i.e.  $\gamma=0$ ).

The estimate of natural mortality for sablefish is uncertain; therefore its effect on abundance estimation was examined. An important part of this examination was to analyze the interaction between  $M$  and other key parameters. Model parameters were estimated for several fixed values of natural mortality around  $M=0.10$  (Table 2). The log-likelihood is not maximized at  $M=0.10$ , and there is a slightly higher value for  $M=0.12$  (panel 1). Catchability was smaller and exploitable biomass was larger for larger  $M$  (panel 2); biomass was larger to account for more natural deaths. The fishable fraction of the total population

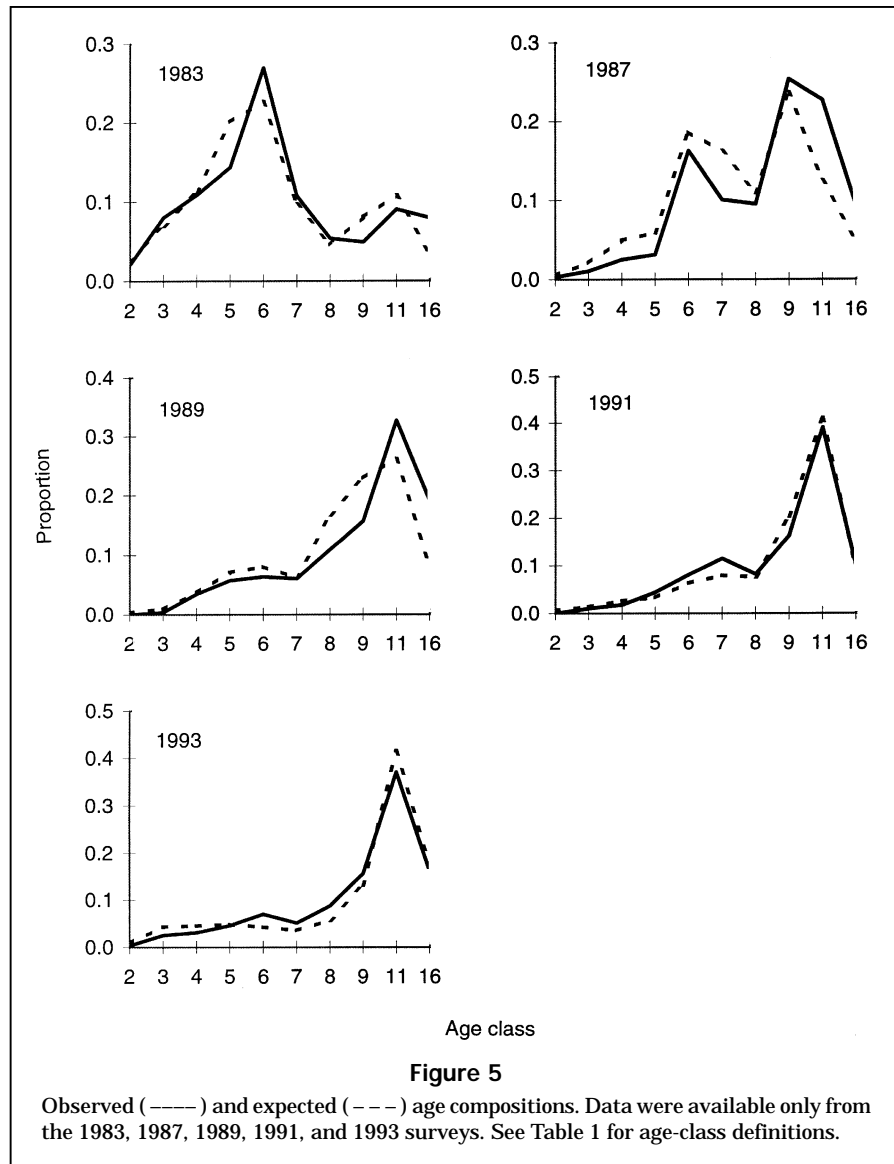
$$\left( \frac{\sum_a s_a N_{ya}}{\sum_a N_{ya}} \right)$$

was smaller for larger  $M$  (panel 3) because the fish recruited later (panel 4). Asymptotic selectivity was estimated whatever the value of  $M$  (panel 5).  $ABC_{96}$  was larger for larger  $M$  (panel 6) because exploitable biomass was larger and the fishing rate,  $F_{40\%}$ , increases with  $M$ .

Natural mortality and survey catchability can affect abundance estimates; therefore their effect was examined. Model parameters were estimated for several fixed values of  $q$  and  $M$  (Table 2). For each fixed  $M$ , the approach was to fix  $q$  at values near the estimated  $q$ . The results are likelihood profiles of  $q$  for each fixed  $M$  (panel 1). Given  $M$ , exploitable biomass was smaller for larger  $q$  (panel 2). The effect of  $q$  on the fishable fraction was more complicated. Given  $M$ , the fishable fraction was smaller for the fixed  $q$  that was less than the estimated  $q$  (panel 3) because older fish were less vulnerable to the fishery (panel 5). Given  $M$ , the fishable fraction was less for the fixed  $q$  that was greater than the estimated  $q$  because fish recruited later (panel 4). Selectivity was asymptotic and could not increase above 1.0, forcing the decreased fishable fraction to occur by means of a later recruitment age.  $ABC_{96}$  was larger for smaller values of  $q$  (panel 6) because exploitable biomass was larger (panel 2).

### Model results for the simulated data

Biomass estimates were unbiased for simulations based on a survey with asymptotic selectivity, when



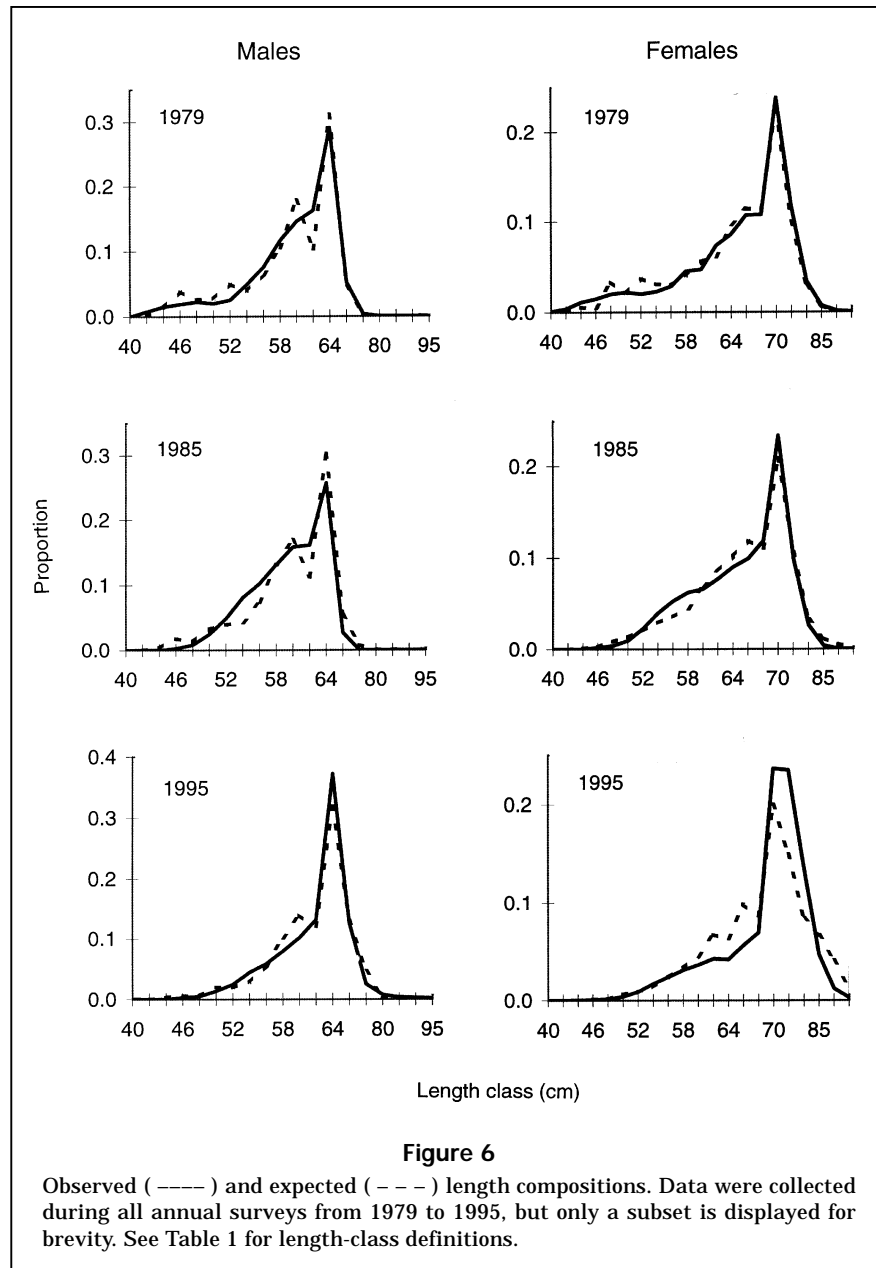
age and length data were used (Fig. 10A). Estimated error (CE [exploitable biomass]) was about 0.08, increasing for the later years to about 0.12 (Fig. 11), values similar to the assumed CV for the abundance index of 0.10. These values all imply that sablefish abundance could be estimated given the type and quality of data assumed in these simulations. These simulations match my evaluation of the actual data. Biomass estimates also were unbiased for asymptotic selectivity, no matter whether age or "length" data were used (Fig. 10, B and C); CE (exploitable biomass) ranged from 0.10 to 0.15 (Fig. 11). In contrast, biomass estimates were positively biased by 14% to 17% for dome-shaped selectivity (Fig. 10D) and CE (exploitable biomass) ranged from 0.40 to 0.50 (Fig. 11). Thus, estimating abundance from a survey with asymptotic selectivity appears reasonable; biomass

estimates derived from a survey with dome-shaped selectivity can be estimated, but may be biased and less precise.

## Discussion

### Comparison of age-structured and delay-difference analyses

The estimates of sablefish exploitable biomass from age-structured analysis and delay-difference analysis are similar (Fig. 12). Both analyses show exploitable biomass rising from about 170,000 t in 1979, peaking at about 420,000 t around 1986, and falling since then to about 200,000 t in 1995. The trend from the sablefish delay-difference analysis is less smooth



because the estimates are linear functions of the survey abundance index. Exploitable biomass follows every up and down in the abundance index. All measurement error is reflected in the recruitment estimate. The trend from the age-structured analysis is a complicated function of the abundance index and the age and length data and smooths annual changes in the abundance index.

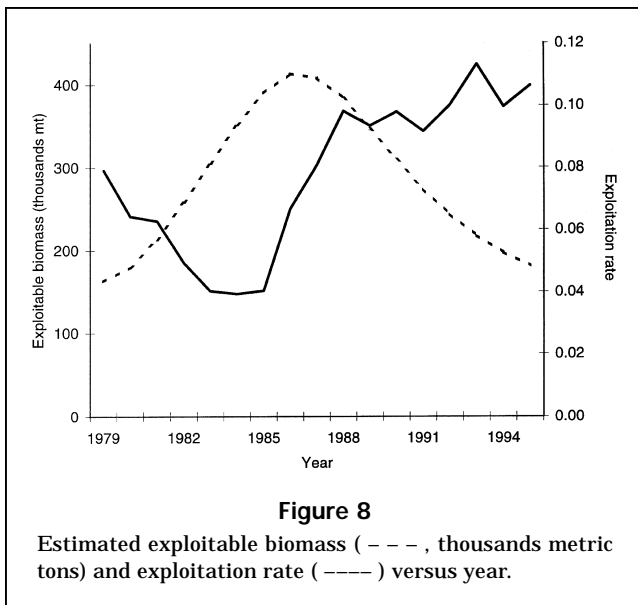
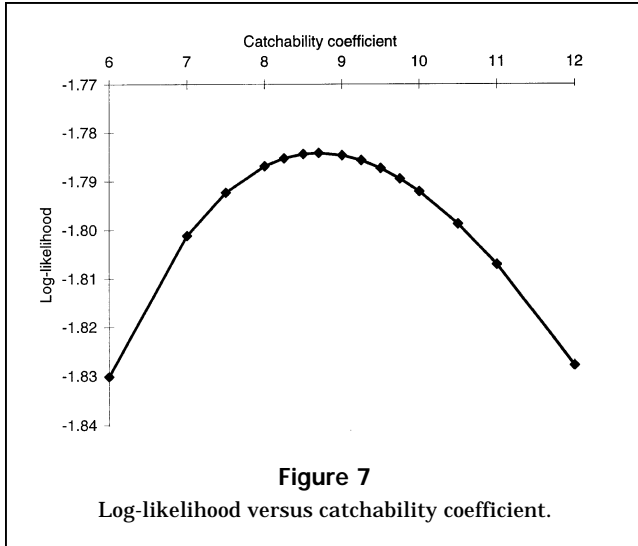
The simulations in this paper imply that the age-structured model provides reliable estimates of sablefish absolute biomass. The assumption that trawl surveys provide absolute biomass estimates required for the sablefish delay-difference analysis can be dropped. Starting with the 1997 fishing year, the age-

structured analysis has supplanted the delay-difference analysis in the stock assessment for estimating biomass (Fujioka et al., 1996).

#### Comparison to other estimates of sablefish abundance

Sablefish absolute abundance was estimated in two other studies, but the estimates were unreasonable. Sablefish longline catchability was estimated by depletion experiments (Clausen et al., 1997). The computed longline catchabilities were applied to the sablefish longline survey results for the Gulf of Alaska; the resultant biomass estimates of 50,000–





60,000 t were unreasonably low because during the same period, the longline relative abundance index was stable even though annual commercial catches were 20,000–30,000 t (Clausen et al., 1997).

Eggers et al. (1982) described a quantitative method of estimating the effective radius of a baited hook or pot by comparing catch rates between gear with different spacings between baits. They applied this method to a hook-spacing experiment for sablefish longline gear and estimated that the bottom area fished per hook was 4.8 m<sup>2</sup>. I applied this estimate to the time series of longline relative abundance indices, which implied that sablefish absolute biomass in Alaska ranged from 7 to 16 million t during 1979 to 1996, a range that seems improbably high because catches of about 50,000 t in the early 1970s subse-

**Table 2**

Log-likelihood, estimated values of exploitable biomass (thousands metric tons, age 2+) for 1995, the fishable fraction of the total population in numbers for 1995, age at 50% vulnerability, vulnerability of the last age class ( $s_{term}$ , where  $s_{term} < 1$  implies a dome-shaped selectivity function), and projected allowable biological catch for 1996 ( $ABC_{96}$ ). Values were estimated from the original data. Log-likelihood is the value of the objective function. Selectivity, recruitment, and initial age composition always were estimated. Asterisk (\*) indicates results where survey catchability was estimated and natural mortality was fixed. No \* indicates results where survey catchability and natural mortality were fixed.

Catchability coefficient <i>q</i>	Natural mortality ( <i>M</i> )				
	0.05	0.08	0.10	0.12	0.15
<b>Log-likelihood</b>					
4.17				-1.781	-1.757*
6.85			-1.795	-1.770*	-1.789
8.70		-1.817	-1.784*	-1.786	
10.61	-1.869	-1.802*	-1.801		
13.59	-1.834*	-1.837			
<b>Exploitable biomass</b>					
4.17				366	362*
6.85		229	226*	215	
8.70		184	181*	175	
10.61	152	151*	146		
13.59	121*	115			
<b>Fishable fraction</b>					
4.17				0.735	0.821*
6.85			0.770	0.826*	0.789
8.70		0.772	0.830*	0.806	
10.61	0.673	0.833*	0.809		
13.59	0.837*	0.801			
<b>Age at 50% availability</b>					
4.17				4.0	4.2*
6.85			4.0	4.1*	4.6
8.70		3.9	4.0*	4.4	
10.61	4.0	4.0*	4.3		
13.59	3.9*	4.5			
<b><math>s_{term}</math></b>					
4.17				0.70	1.00*
6.85			0.78	1.00*	1.00
8.70		0.78	1.00*	1.00	
10.61	0.52	1.00*	1.00		
13.59	1.00*	1.00			
<b><math>ABC_{96}</math></b>					
4.17				68.5	62.9*
6.85			33.4	30.2*	39.0
8.70		22.7	19.6*	24.0	
10.61	23.0	12.8*	16.2		
13.59	6.4*	10.1			

quently resulted in sharp declines in fishery catch rate (Fujioka, 1986; McDevitt, 1986).

An estimate of the area occupied by adult sablefish was used to calculate the depletion and hook-

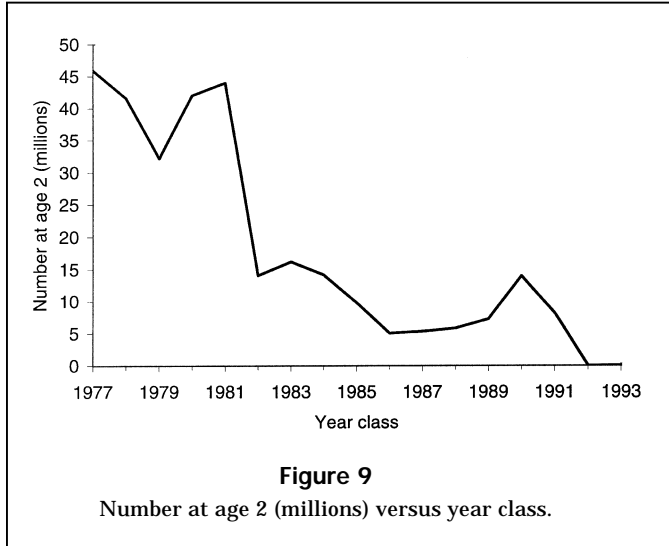
spacing estimates of absolute biomass. The estimated area is inexact and, correspondingly, so are these biomass estimates. However this area would have to be an order of magnitude higher or lower to be consistent with the observed catch effects on the abundance indices, a level of error unlikely given the extensive longline surveys for sablefish.

**Data and model requirements necessary to estimate abundance**

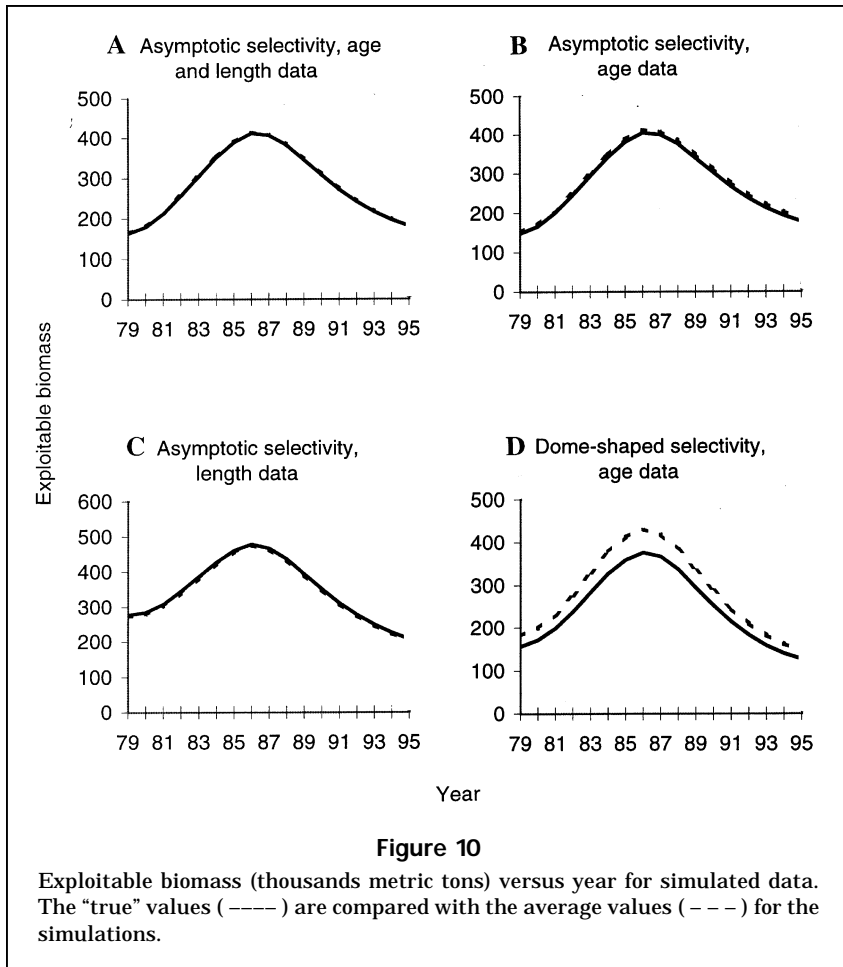
Estimates of absolute abundance for sablefish were unbiased (Fig. 10, A–C) and relatively precise (Fig. 11) when selectivity was asymptotic. Abundance estimates were relatively precise regardless of whether age data alone, length data alone, or age and length data together were used. Even though length data alone is less desirable than age data for estimating annual recruitment, the precision of the abundance estimates was similar, supporting the notion that length data is useful for abundance estimation with age-structured analyses.

Dome-shaped selectivity affects abundance estimation. Sablefish abundance estimates were positively biased (Fig. 10D) and less precise (Fig. 11) for a survey with dome-shaped selectivity. Abundance estimates for a simulated widow rockfish, *Sebastes entomelas*, fishery off the western coast of the continental United States also were less accurate and less precise for a survey with dome-shaped selectivity than one with asymptotic selectivity (Bence et al., 1993). Thus, surveys with asymptotic selectivity appear better for abundance estimation than surveys with dome-shaped selectivity.

The sablefish age-structured model was fitted with 17 years of survey length data, but only five years of survey age data and no fishery age or length data. Two assumptions probably were the keys to how it was possible to fit an age-structured model with only limited age data (Table 1). One key assumption is that selectivity is equal for the fishery and survey, so that no fishery age or length data were required to independently estimate fishery selectivity. Another key assumption is that the age-length transition matrix is constant over time, so that

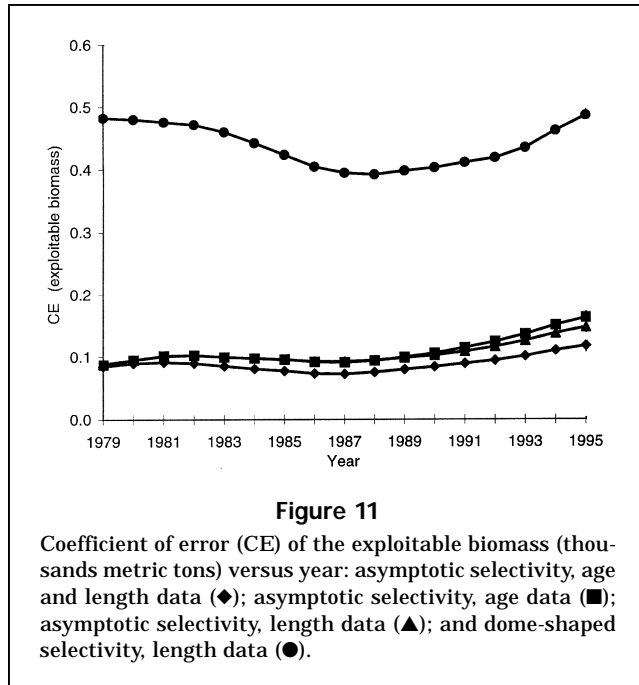


**Figure 9**  
Number at age 2 (millions) versus year class.



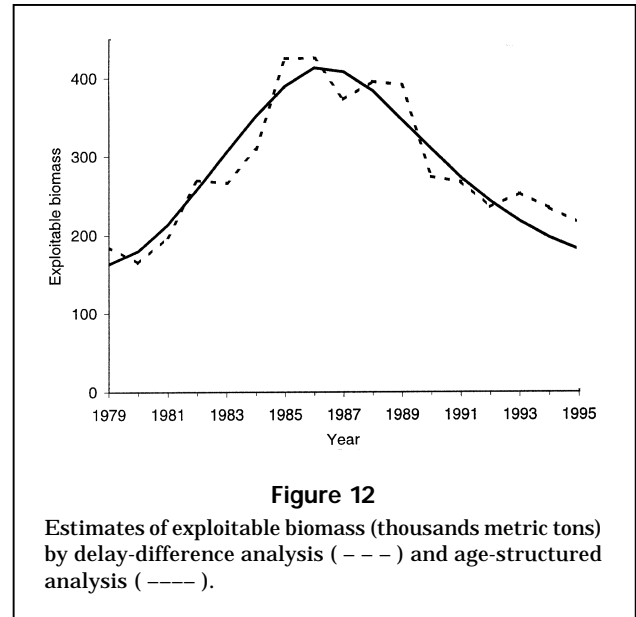
**Figure 10**

Exploitable biomass (thousands metric tons) versus year for simulated data. The "true" values (----) are compared with the average values (---) for the simulations.



age structure could be inferred from survey length data for the several years where no age data were available. This latter assumption may hold for sablefish, but would be conspicuously violated for other species such as Pacific halibut, *Hippoglossus stenolepis*, whose growth rate has changed over time. Recent improvements in Alaskan sablefish data collection eventually will lead to tests of these assumptions. Otoliths have been collected and read annually from longline surveys since 1995. Fishery lengths have been collected annually since 1990.

A measure of relative abundance, effort data, was necessary to obtain reasonable estimates of absolute abundance with an age-structured model of Pacific halibut, as shown by comparison to cohort analysis of historical data of year classes with complete catch data (Deriso et al., 1985). The frequency and number of the relative abundance estimates can affect abundance estimation. Absolute biomass was estimated successfully for Alaskan sablefish in this paper and for the simulated widow rockfish fishery (Bence et al., 1993). Annual surveys were simulated for 17 and 15 years, respectively. However, precise abundance estimates may not always be possible when survey effort is less. Three triennial surveys were insufficient to estimate absolute abundance for the eastern Bering Sea walleye pollock fishery with useful precision (Kimura, 1989). Species-specific simulations can help to determine the amount of survey effort necessary to estimate absolute abundance. For example, McAllister (1995) examined survey timing for assessments of the eastern Bering Sea



yellowfin sole fishery. A population dynamics model was fitted to two survey time series, 1975–81 and 1982–94, then the population was projected forward 15 years and annual, versus triennial, trawl surveys were compared. Net present value of the fishery was less for more frequent surveys, primarily owing to increased survey cost, but CV ( $ABC$ ) was less for more frequent surveys (28 versus 36%) when absolute abundance was estimated.

#### Parameter interactions with abundance estimates

Abundance estimates are related to estimates of several model parameters. Absolute abundance and survey catchability are inversely related because a given observation of the survey abundance index can be due to a small population that is easy to catch or to a large population that is difficult to catch. Natural mortality and catchability also are inversely related; increasing  $q$  while decreasing  $M$  tends to give similar log-likelihood values (Table 2, panel 1). Absolute abundance and natural mortality tend to be positively correlated (panel 2; Schnute and Richards, 1995). Given the observed abundance index, absolute abundance estimates must be larger for the population to sustain more natural mortality. Reducing the correlation and improving estimation of natural mortality is difficult because the number of natural deaths for marine fish species is usually unobservable; no data are available to estimate  $M$  directly. For the sablefish age-structured analysis, the overall changes in the likelihood function with respect to  $M$  were minor and not sufficient to allow estimation of  $M$  as part of the model-fitting process. I had to fix

$M$  outside the model at the “best,” most reasonable value, then estimate absolute abundance with the population model.

The likelihood surface was mapped to examine the parameter relationship between  $q$  and  $M$  (Table 2, panel 1). I found it useful to fix one parameter, then estimate the other parameter, thus ensuring that the peak of the likelihood ridge as a function of  $q$  and  $M$  was found. An alternate, seemingly useful approach is a grid over fixed values of  $q$  and  $M$ . I do not recommend this approach. It is difficult and time consuming to design a grid fine enough and large enough to map the peak of the likelihood ridge. In earlier modeling, not described in this paper, this approach led me to declare incorrectly a global minimum over  $q$  and  $M$  because the grid was too coarse and the likelihood ridge poorly mapped.

Thompson (1994) demonstrated analytically that  $M$  and the degree of curvature of dome-shape are confounded because fish may “disappear” with age, owing to natural death or decreased vulnerability. Survey catchability and selectivity also were confounded (Table 2, panel 3). Fish recruited later (panel 4) or were less vulnerable when older (panel 5), depending on the value of survey catchability. Older fish were less vulnerable when fixed  $q$  was less than estimated  $q$  (panel 5).

The lower vulnerability of older fish for lower catchability values is a clue as to why abundance estimation is less reliable when selectivity is dome-shaped. Absolute biomass is inferred in the model from how the catches affect the survey index, as described in the introduction, and this effect implies some specific estimate for absolute abundance. Older fish were less vulnerable to compensate for lower survey catchability, which helps to maintain the absolute biomass estimate implied by the catch and survey index. Estimated biomass is similar with either higher catchability or lower vulnerability of older fish, i.e. greater degree of curvature of dome-shape. This parameter interaction probably is why abundance estimation is more difficult when selectivity is dome-shaped.

In some cases, selectivity can be estimated independently to eliminate the problem of confounding parameters with selectivity. If a species is surveyed by two overlapping surveys and gear selectivity is known for one survey, then the unknown gear selectivity can be estimated by comparing the survey length compositions (Kimura, 1978). This approach helps to estimate gear selectivity, but not to estimate availability with age, where availability at age is the fraction of the population within the survey area by age. Modeling availability at age will depend on survey coverage in relation to ontogenetic changes in spatial distribution.

The age-structured model presented here is a tool for interpreting the data collected from the sablefish fishery and longline survey. Simulations and an examination of parameter relationships help one to understand how the tool performs, its reliability, and its strengths and weaknesses. The population model appears reliable for interpreting the sablefish data and has been adopted for estimating abundance and setting quotas for sablefish management. The conclusions regarding data and model requirements for estimating abundance and parameter interactions with abundance estimates should be generally applicable to other species. The sablefish age-structured model is like other north Pacific age-structured models except for the assumption of a discrete fishery. In one respect, these simulations were a more difficult test of an age-structured model to estimate abundance because one scenario examined length data alone, an imprecise measure of age structure.

## Acknowledgments

The analysis benefitted from an on-going dialogue with Jeff Fujioka. I thank Dan Kimura, Jerry Pella, and Jon Heifetz for reviewing earlier versions and two anonymous reviewers for improving the presentation of this paper.

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