Dusky Rockfish Age-Structured Model

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Overview

For dusky rockfish (*Sebastes ciliatus*), we explored the use of a generic rockfish model developed in a modeling workshop held at the Auke Bay Laboratory in February 2001[1]. The model was constructed with AD Model Builder software (Otter Research Ltd 2000). The model is a separable age-structured model with allowance for size composition data that is adaptable to several rockfish species. In 2002, we presented a working base model which incorporated all of the available dusky rockfish data and provided reasonable fits to the data. For 2003, we have made substantial refinements to the base model and have updated available data through 2003.

Model Structure

The dusky rockfish model is based on a rockfish model developed in 2001 and is a modification of the northern rockfish model used in 1999 (Courtney et al. 1999). The current configuration is nearly identical to that of the Pacific ocean perch model (Hanselman et al. 2003). The parameters, population dynamics and equations of the model are described in Box 1. The model's starting point is 1977 and contains all available data. The data sets used in the dusky rockfish model include total fishery catch for the years 1977-2003, size compositions from the fishery for 1991-2003, survey age compositions for 1984, 1987, 1990, 1993, 1996, 1999 and 2001, survey size compositions for 1984, 1987, 1990, 1993, 1996, 1999, and 2001, fishery age composition for 2001, and survey biomass estimates for 1984, 1987, 1990, 1993, 1996, 1999, 2001, and 2003.

Life-history parameters including natural mortality (*M*), proportion mature at age, and weight at age, were taken from the 2001 Pelagic Shelf Rockfish SAFE Document (Clausen and Heifetz, 2001). Clausen and Heifetz (1999) presented revised estimates of the von Bertalanffy growth parameters for combined sexes of dusky rockfish. These were based on age samples from 1,245 fish in the 1984, 1987, 1990, and 1993 triennial surveys. The revised parameters are: L_{inf} = 45.9 cm; K = 0.24; and t_o = 1.18. A recent manuscript has also been prepared that presents these results in more detail (Malecha and Heifetz 2000). These parameters were used in constructing the length-at-age matrix.

The best length-weight information for light dusky rockfish comes from the 1996 triennial survey, in which motion-compensated electronic scales were used to weigh a relatively large sample of individual fish for this species. For combined sexes, using the formula $W = aL^b$, where W is weight in grams and L is fork length in mm, $a = 3.28 \times 10^{-5}$ and b = 2.90 (Martin 1997).

[1]Rockfish Modeling Workshop, NMFS Auke Bay Laboratory, 11305 Glacier Hwy., Juneau, AK. February, 2001.

Size at 50% maturity for a relatively small sample (n=64) of female light dusky rockfish in the Kodiak area has been estimated to be 42.8 cm fork length (Clausen and Heifetz 1997). Age data for these fish were analyzed using a logistic function, which provided an estimated age at 50% maturity of 11.3 years[2].

Aging error matrices were constructed by assuming that the break-and-burn ages were unbiased but had a given amount of normal error around each age. The size-age transition matrix came from a lognormal fit to the Von Bertalanffy growth curve to length and age data collected from triennial trawl surveys with parameter estimates from Malecha and Heifetz (2000). The age error transition matrix was constructed by assuming the same age determination error found for northern rockfish (Courtney et al. 1999).

BOX 1. AD Model Builder Model Description

Parameter definitions	
y	Year
a	Age classes
l	Length classes
w_a	Vector of estimated weight at age, $a_0 \rightarrow a_+$
m_a	Vector of estimated maturity at age, $a_0 \rightarrow a_+$
a_0	Age at first recruitment
a_+	Age when age classes are pooled
μ_r	Average annual recruitment, log-scale estimation
μ_f	Average fishing mortality
σ_r	Annual recruitment deviation
ϕ_y	Annual fishing mortality deviation
fs_a	Vector of selectivities at age for fishery, $a_0 \rightarrow a_+$
ss_a	Vector of selectivities at age for survey, $a_0 \rightarrow a_+$
M	Natural mortality, fixed
$F_{y,a}$	Fishing mortality for year y and age class a ($fs_a \mu_f e^{\varepsilon}$)
$Z_{y,a}$	Total mortality for year y and age class a ($=F_{y,a}+M$)
$\varepsilon_{y,a}$	Residuals from year to year mortality fluctuations
$T_{a,a'}$	Aging error matrix
$T_{a,l}$	Age to length transition matrix
q	Survey catchability coefficient
SB_y	Spawning biomass in year y, ($=m_a w_a N_{y,a}$)
q_{prior}	Prior mean for catchability coefficient
$\sigma_{r(prior)}$	Prior mean for recruitment deviations
σ_q^2	Prior CV for catchability coefficient
$\sigma_{\sigma_r}^2$	Prior CV for recruitment deviations

[2] C. Lunsford, National Marine Fisheries Service, Alaska Fisheries Science Center, Auke Bay Laboratory, 11305 Glacier., Juneau, AK 99801. Pers. commun. August 1999.

BOX 1 (Continued)

Equations describing the observed data

$$\hat{C}_y = \sum_a \frac{N_{y,a} * F_{y,a} * \left(1 - e^{-Z_{y,a}}\right)}{Z_{y,a}} * w_a$$

Catch equation

$$\hat{I}_y = q * \sum_a N_{y,a} * \frac{s_a}{\max(s_a)} * w_a$$

Survey biomass index (mt)

$$\hat{P}_{y,a'} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,a'}$$

Survey age distribution
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,l}$$

Survey length distribution
Proportion at length

$$\hat{P}_{y,a'} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,a'}$$

Fishery age composition
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,l}$$

Fishery length composition
Proportion at length

Equations describing population dynamics

Start year

$$N_a = \begin{cases} e^{\left(\mu_r + \tau_{styr - a_o - a - 1}\right)}, & a = a_0 \\ e^{\left(\mu_r + \tau_{styr - a_o - a - 1}\right)} e^{-(a - a_0)M}, & a_0 < a < a_+ \\ \dfrac{e^{(\mu_r)} e^{-(a - a_0)M}}{\left(1 - e^{-M}\right)}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Subsequent years

$$N_{y,a} = \begin{cases} e^{\left(\mu_r + \tau_y\right)}, & a = a_0 \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}}, & a_0 < a < a_+ \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}} + N_{y-1,a} * e^{-Z_{y-1,a}}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Formulae for likelihood components **BOX 1 (Continued)**

$L_1 = \lambda_1 \sum_y \left(\ln\left[\frac{C_y + 0.01}{\hat{C}_y + 0.01} \right] \right)^2$	Catch likelihood
$L_2 = \lambda_2 \sum_y \frac{\left(I_y - \hat{I}_y\right)^2}{2 * \hat{\sigma}^2\left(I_y\right)}$	Survey biomass index likelihood
$L_3 = \lambda_3 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001\right) * \ln\left(\hat{P}_{y,a} + 0.001\right)$	Fishery age composition likelihood ($n^*{}_y$ =square root of sample size, with the largest set to one hundred)
$L_4 = \lambda_4 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001\right) * \ln\left(\hat{P}_{y,l} + 0.001\right)$	Fishery length composition likelihood
$L_5 = \lambda_5 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001\right) * \ln\left(\hat{P}_{y,a} + 0.001\right)$	Survey age composition likelihood
$L_6 = \lambda_6 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001\right) * \ln\left(\hat{P}_{y,l} + 0.001\right)$	Survey size composition likelihood
$L_7 = \frac{1}{2\sigma_q^2}\left({q}/{q_{prior}} \right)^2$	Penalty on deviation from prior distribution of catchability coefficient
$L_8 = \frac{1}{2\sigma_{\sigma_r}^2}\left({\sigma_r}/{\sigma_{r(prior)}} \right)^2$	Penalty on deviation from prior distribution of recruitment deviations
$L_9 = \lambda_9 \left[\frac{1}{2 * \sigma_r^2} \sum_y \tau_y^2 + n_y * \ln\left(\sigma_r\right) \right]$	Penalty on recruitment deviations
$L_{10} = \lambda_{10} \sum_y \phi_y^2$	Fishing mortality regularity penalty
$L_{11} = \lambda_{11} \bar{s}^2$	Average selectivity penalty (attempts to keep average selectivity near 1)
$L_{12} = \lambda_{12} \sum_{a_0}^{a_+} \left(s_i - s_{i+1}\right)^2$	Selectivity dome-shapedness penalty – only penalizes when the next age's selectivity is lower than the previous (penalizes a downward selectivity curve at older ages)
$L_{13} = \lambda_{13} \sum_{a_0}^{a_+} \left(FD(FD(s_i - s_{i+1})\right)^2$	Selectivity regularity penalty (penalizes large deviations from adjacent selectivities by adding the square of second differences
$L_{total} = \sum_{i=1}^{13} L_i$	Total objective function value

2003 Model Changes

Several substantial changes were made to the 2002 base model in 2003. To improve size and age fits we increased recruitment age from 3 to 4 years of age, reduced the number of age bins from 29 to 18, and reduced the number of length bins from 32 to 27. The tails of the observed age and length composition distributions contained insufficient data to attempt to estimate them. In 2002, we restricted the prior on the coefficient of variation (CV) of catchability (q) which constrained the model to estimate a q close to 1. For the 2003 model, we relaxed the CV of the prior on q to allow the model more flexibility in estimating its value. In the 2002 model there were larger objective function penalties on selectivity and fishing mortality regularity. These were reduced in the new model. And selectivity was estimated separately for the survey and the fishery.

For 2003, the alternative model was evaluated using Markov Chain Monte Carlo (MCMC) simulations to estimate posterior distributions of key parameters (Gelman et al. 1995). Here we only use the MCMC method to estimate 95% confidence intervals for spawning biomass and recruitment. We expect to use MCMC more as a model evaluation tool as the dusky model is refined.

Model Results

Base Model

Our model introduced in 2002 was run with the updated data, but identical likelihood weights and penalties. For this model the fit to survey biomass was questionable for the more recent surveys. Model fits to survey age compositions attempted to track a fairly strong year class from 1984-1990 that weakened in the observed ages in the 1993 survey. Fishery size and survey ages had a substantial effect on the objective function indicating some contradiction with other parts of the model. Considering the relatively small amount of data in the model, the results show an unlikely amount of certainty (e.g. a CV of 10% for predicted biomass, Table 10A-1). This is a result of the penalties and tight constraints placed on the model.

Alternative Model

For 2003 we focused on relaxing the weights on the penalty functions and allowing the model to estimate some of the key parameters without constraints. Table 1 summarizes results from the two models. The 2003 model successfully converged while estimating survey catchability and provided a reasonable estimate of q = 0.68. We attempted to estimate natural mortality, but the model failed to converge, therefore for the alternative model, natural mortality remained fixed at M = 0.09. One parameter that had to be restricted was the prior mean for recruitment deviations parameter (σ_r). The model drove the prior to well below one which seems unreasonable for rockfish species. This also occurred when running the northern rockfish data through the 2003 Pacific ocean perch model (D. Hanselman, Oct. 2003). The mean of the recruitment deviations prior distribution was set to be 1.7 with a CV of 0.02, which essentially was required to keep that portion of the objective function positive. Restricting this prior may be a consequence of the highly variable recruitment often associated with rockfish populations, or a lack of data to estimate recruitment.

The predicted survey biomass from the 2003 model is generally less than the observed survey biomass (Figure 10A-1). This is likely due to the model's emphasis on the 1984, 90, and 2001 survey estimates. These surveys have had much tighter confidence intervals and the model places greater emphasis on estimates with less variability. The model predicted spawning biomass trend is generally flat to slightly decreasing indicating a stable but slightly decreasing population (Figure 10A-2).

The 2003 model fits to the data are an improvement over the 2002 model fits (Table 10A-1). The better fits for size and age are likely a consequence of redefining the number of length and age bins (Figures 10A-3, Figure 10A-4). Fits to the size data over time may be confounded by the separation of dark dusky rockfish from light dusky rockfish in later years. Beginning in 1996, dark dusky and light dusky rockfish were treated as separate species in the survey data collection procedures. Low numbers of dark dusky rockfish are generally caught in the survey but there are likely larger numbers of dark duskys represented in the fishery length data. However, the survey size compositions are similar to the fishery and the model accurately fits the fishery lengths.

Model fits to age survey age composition are fairly good (Figure 10A-5). Several strong year classes are present throughout the survey age compositions. In the 1993 survey the age compositions are dominated by the 1986 year class. This year class is present throughout the subsequent surveys and is predicted by the model. In 1999, the 1992 year class appears as 7 year olds and is also predicted by the model. The fits to these year classes vary slightly from the observed values. Slight inconsistencies from these fits regarding exact ages may be due to assuming the same age determination error found for northern rockfish. Fishery ages are only available for 2001, and observed ages indicate relatively strong 1986 and 1992 year classes (Figure 10A-6). Model fits are similar to observed ages for the 1986 year class but are not as evident for the 1992 year class. These strong year classes also appear in the estimated recruitments over time predicted by the model (Figure 10A-7).

MCMC confidence intervals around the model's spawning biomass estimates reflect much uncertainty (Figure 10A-2). Uncertainty around estimated recruitment is also high, especially in recent years when recruitments are low (Figure 10A-7). This is likely a more realistic portrayal of uncertainty than that given by the base model. The model estimates for spawning stock biomass and estimated recruitment fall near the middle of the 95% confidence intervals indicating that the likelihood and MCMC approach are reasonably consistent. Figure 10A-2 also suggests that our estimates may be conservative since the model estimate is lower than the mid-point of the confidence intervals.

Overall, the objective function for the 2003 model is considerably lower than the 2002 model (Table 10A-1). Much of this is due to better fits to survey biomass, survey age, and fishery size. The management performance path indicates the stock is in the 'optimum' quadrant where B_{now}/B_{40} exceeds one and F_{now}/F_{40} is below one (Figure 10A-8). The estimated 2004 female spawning biomass, B_{2004} is 16,157 mt. Since B_{2004} is greater than the estimated $B_{40\%}$ value of 14,280, the computation in tier 3a [i.e., $F_{ABC} = F_{40\%}$] is used to determine the maximum value of F_{ABC}. The ABC based on an $F_{40\%}$ harvest rate (0.123) is 4,001 mt.

This particular model was chosen over a mosaic of alternative model runs because the fits to the data are good, the objective function is minimized, and the ABC is similar to what our previous management strategy has been recommending. Alternative model runs provide varying estimates of biomass and ABC with insignificant increases in the overall objective function. Choosing the "correct" model under these circumstances is difficult. Light dusky rockfish have the least amount of available data of the rockfish species in the GOA that use an age-structured assessment. This results in a relatively smooth likelihood surface with different model configurations providing similar fits. Increasing the number of survey and fishery ages would greatly improve the model's ability to converge to a more certain outcome.

For 2004, we have been requested to include estimates for a harvest rate based on $F_{50\%}$, a more conservative harvest strategy. For this strategy the model estimated $F_{50\%}$ at 0.082 which corresponds to an $ABC_{F50\%}$ of 2,666 mt (Table 10A-1). We do not recommend harvesting at $F_{50\%}$ unless new information regarding rockfish populations in Alaska suggests this is preferable.

Apportionment

The geographic apportionment of this ABC was calculated using the same procedure as in previous years, in which prior survey biomass is weighted based on the relative proportion of variability attributed to survey error. This method results in weights of 4:6:9 for the 1999, 2001, and 2003 surveys or 8.3%, 67.3%, and 24.4% of total ABC. The apportionments for 2004 are: Western area, 332 mt, Central area, 2693 mt, and Eastern area, 976 mt. The Eastern area is further apportioned into West Yakutat (56% of Eastern area) and East Yakutat/Southeast Outside (44% of Eastern area) which results in 547 mt for West Yakutat and 429 mt for East Yakutat/Southeast Outside.

Model Projections

A standard set of projections is required for each stock managed under Tiers 1, 2, or 3. This set of projections that encompasses seven harvest scenarios is designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2003 numbers at age estimated in the assessment. This vector is then projected forward to the beginning of 2004 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2003. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2004, are as follow ("max F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendment 56):

Scenario 1: In all future years, F is set equal to max F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)

Scenario 2: In all future years, F is set equal to a constant fraction of max F_{ABC}, where this fraction is equal to the ratio of the F_{ABC} value for 2004 recommended in the assessment to the max F_{ABC} for 2004. (Rationale: When F_{ABC} is set at a value below max F_{ABC}, it is often set at the value recommended in the stock assessment.). The authors do not suggest a proportion of F_{ABC} and do not present this scenario in Table 10A-2.

Scenario 3: In all future years, F is set equal to 50% of max FABC. (Rationale: This scenario provides a likely lower bound on FABC that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.)

Scenario 4: In all future years, F is set equal to the 1999-2003 average F. (Rationale: For some stocks, TAC can be well below ABC, and recent average F may provide a better indicator of FTAC than FABC.)

Scenario 5: In all future years, F is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follow (for Tier 3 stocks, the MSY level is defined as B35%):

Scenario 6: In all future years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be 1) above its MSY level in 2004 or 2) above ½ of its MSY level in 2004 and above its MSY level in 2014 under this scenario, then the stock is not overfished.)

Scenario 7: In 2003 and 2004, F is set equal to max FABC, and in all subsequent years, F is set equal to FOFL. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is expected to be above its MSY level in 2016 under this scenario, then the stock is not approaching an overfished condition.)

Projections and Status Determination

Harvest scenarios #6 and #7 are intended to permit determination of the status of a stock with respect to its minimum stock size threshold (MSST). Any stock that is below its MSST is defined to be overfished. Any stock that is expected to fall below its MSST in the next two years is defined to be approaching an overfished condition. Harvest scenarios #6 and #7 are used in these determinations as follows:

Is the stock overfished? This depends on the stock's estimated spawning biomass in 2003:

a) If spawning biomass for 2004 is estimated to be below ½ B35%, the stock is below its MSST.
b) If spawning biomass for 2004 is estimated to be above B35%, the stock is above its MSST.
c) If spawning biomass for 2004 is estimated to be above ½ B35% but below B35%, the stock's status relative to MSST is determined by referring to harvest scenario #6 (Table 10A-2). If the mean spawning biomass for 2014 is below B35%, the stock is below its MSST. Otherwise, the stock is above its MSST.

Is the stock approaching an overfished condition? This is determined by referring to harvest scenario #7 (Table 10A-2):

a) If the mean spawning biomass for 2006 is below ½ B35%, the stock is approaching an overfished condition.
b) If the mean spawning biomass for 2006 is above B35%, the stock is not approaching an overfished condition.
c) If the mean spawning biomass for 2006 is above ½ B35% but below B35%, the determination depends on the mean spawning biomass for 2016. If the mean spawning biomass for 2016 is

below B35%, the stock is approaching an overfished condition. Otherwise, the stock is not approaching an overfished condition.

A summary of the results of these scenarios for dusky rockfish is in Table 10A-2. For dusky rockfish the stock is not overfished and is not approaching an overfished condition.

Summary

The generic rockfish model template using AD Model Builder software has been modified for dusky rockfish. For 2003, substantial refinements were made to the base model and model fits have been improved. Model results indicate spawning biomass B_{now} is 16,157 mt which results in an ABC of 4001 mt.

Continued work will be done to improve and refine this model. We hope that we will be able to obtain larger sample sizes for age data. This will allow us to develop an age error transition matrix applicable to dusky rockfish rather than assuming the same age determination error found for northern rockfish. The current sample sizes are too small to be precise for any ages away from the center of the distribution. Improving the reliability of the data may allow the model to estimate parameters such as natural mortality and recruitment more effectively. MCMC simulations will be used to explore parameter interactions and the distributions of key parameters.

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Table 1. Likelihoods and estimates of key parameters with estimates of standard error (σ) derived from Hessian matrix.

	2002 Model			***2003 Model***		
Likelihoods	Value	Weight		Value	Weight	
Catch	0.32	100		0.02	100	
Survey Biomass	13.62	1		5.04	1	
Fishery Ages	7.96	1		1.95	1	
Survey Ages	125.5	1		58.35	1	
Fishery Sizes	106.4	1		43.73	1	
Data-Likelihood	***253.8***			**109.08**		
Penalties/Priors						
Recruitment Devs	31.59	1		14.8	1	
Fishery Selectivity	0.13	100		1.38	1	
Survey Selectivity	0	1		0.86	1	
Fish-Sel Domeshape	0	10		0	1	
Survey-Sel Domeshape	0	1		0.01	1	
Average Selectivity	0	0		0.00	1	
F Regularity	30.33	10		56.9	0.1	
σ_r prior	0.08			4.72		
Q prior	0.03			0.38		
Total	62.20			79.05		
Objective Fun. Total (unweighted)	***315.97***			**188.13**		
Parameter Estimates	Value	σ		Value	σ	
q	0.97	0.012	(1,0.00015)	0.68	0.18	(1,0.2)
M	0.09	n\a	Fixed	0.09	n\a	Fixed
σ_r	1.08	0.12	(1,0.9)	1.10	0.13	(1.7,0.02)
Log-mean-rec	0.85	0.17		1.21	0.29	
F_{40}	0.110	0.022		0.123	0.026	
Total Biomass (mt)	88336	9932		50376	21281	
B_{2004} (mt)	30419			16157		
B_0 (mt)	54447			35702		
B_{40} (mt)	21779			14280		
ABC_{F40} (mt)	7044			**4001**		
F_{50}	0.075	0.014		0.082	0.016	
ABC_{F50} (mt)	4786			2666		

Table 10A-2. Set of projections of spawning biomass (SB) and yield for dusky rockfish in the Gulf of Alaska . This set of projections encompasses six harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Protection Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). For a description of scenarios see Model Projections section. All units in mt. $B_{40\%}$ = 14,280 mt, $B_{35\%}$ = 12,496 mt, $F_{40\%}$ = 0.123, and $F_{35\%}$ = 0.153.

Year	Maximum permissible F	Half maximum F	5-year average F	No fishing	Overfished	Approaching overfished
			Spawning biomass (mt)			
2003	17,309	17,309	17,309	17,309	17,309	17,309
2004	16,157	16,310	16,247	16,465	16,084	16,157
2005	14,749	15,711	15,304	16,743	14,308	14,749
2006	13,533	15,128	14,435	16,959	12,845	13,477
2007	12,614	14,649	13,715	17,222	11,824	12,283
2008	11,924	14,219	13,088	17,451	11,089	11,425
2009	11,526	13,969	12,670	17,759	10,681	10,929
2010	11,392	13,916	12,476	18,172	10,554	10,737
2011	11,516	14,091	12,534	18,751	10,690	10,825
2012	11,818	14,446	12,790	19,474	10,999	11,097
2013	12,211	14,934	13,178	20,355	11,380	11,450
2014	12,611	15,458	13,607	21,274	11,753	11,803
2015	13,006	16,014	14,066	22,255	12,107	12,141
2016	13,359	16,555	14,510	23,244	12,410	12,433
			Fishing mortality			
2003	0.089	0.089	0.089	0.089	0.089	0.089
2004	0.123	0.062	0.087	-	0.153	0.123
2005	0.123	0.062	0.087	-	0.153	0.123
2006	0.117	0.062	0.087	-	0.137	0.144
2007	0.108	0.062	0.087	-	0.125	0.131
2008	0.102	0.060	0.087	-	0.117	0.121
2009	0.098	0.059	0.087	-	0.113	0.115
2010	0.097	0.058	0.087	-	0.111	0.113
2011	0.098	0.058	0.087	-	0.112	0.114
2012	0.100	0.058	0.087	-	0.115	0.116
2013	0.102	0.059	0.087	-	0.119	0.120
2014	0.105	0.059	0.087	-	0.122	0.123
2015	0.107	0.060	0.087	-	0.125	0.126
2016	0.109	0.060	0.087	-	0.128	0.128
			Yield (mt)			
2003	3,000	3,000	3,000	3,000	3,000	3,000
2004	4,001	2,059	2,878	-	4,898	4,001
2005	3,557	1,936	2,644	-	4,238	3,557
2006	3,131	1,888	2,526	-	3,465	3,821
2007	2,731	1,837	2,412	-	2,949	3,184
2008	2,355	1,693	2,228	-	2,498	2,654
2009	2,138	1,591	2,101	-	2,248	2,357
2010	2,018	1,523	2,005	-	2,119	2,196
2011	2,052	1,530	1,998	-	2,168	2,224
2012	2,278	1,645	2,133	-	2,441	2,482
2013	2,486	1,755	2,253	-	2,687	2,717
2014	2,663	1,852	2,357	-	2,892	2,913
2015	2,843	1,947	2,457	-	3,076	3,090
2016	2,967	2,033	2,548	-	3,224	3,234

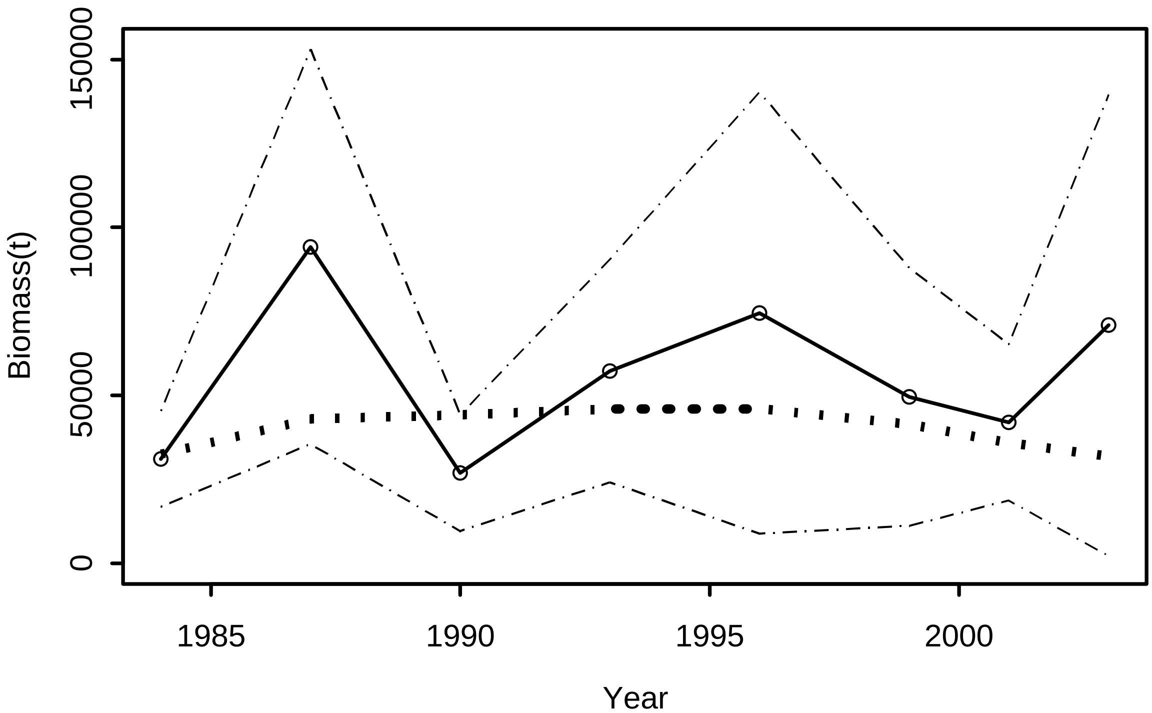

Figure 10A-1. Observed and predicted GOA Lt. Dusky survey biomass. Observed (solid line) and recommended model's survey biomass (dotted line). Outer dashed lines represent 2 s.d. sampling error of observed biomass.

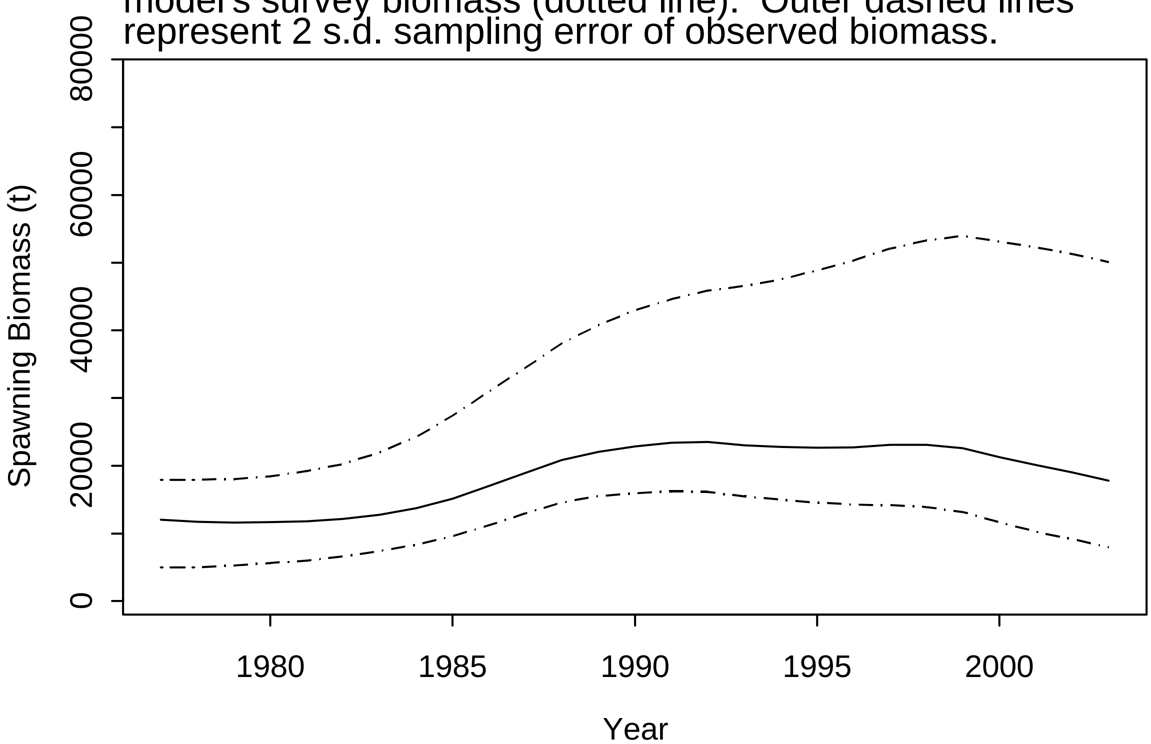

Figure 10A-2. Predicted spawning biomass for GOA Lt. Dusky. Dashed lines are 95% confidence intervals from 5,000,000 MCMC ru

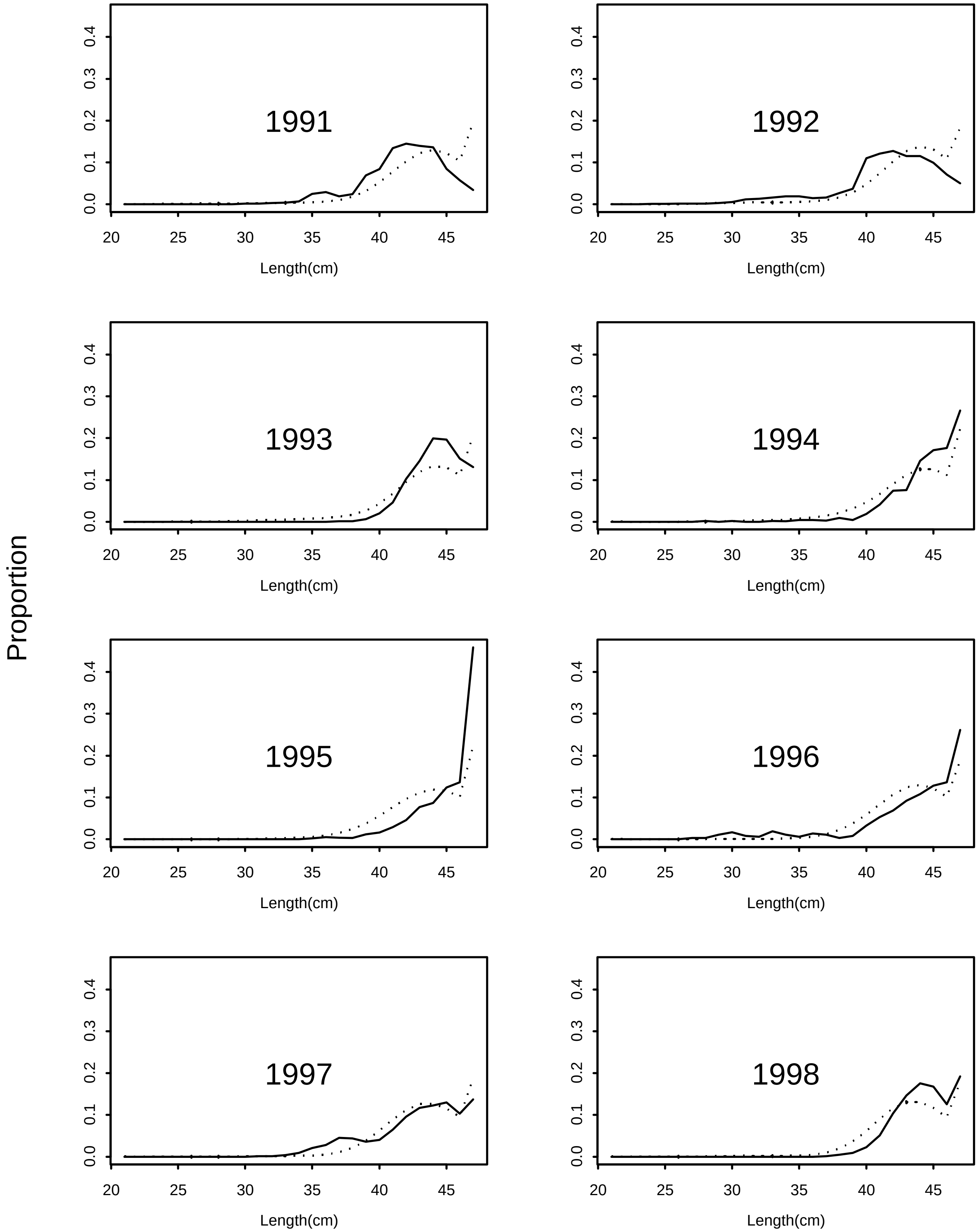

Figure 10A-3. Fishery length composition by year (solid line = observed, dotted line = predicted). GOA Lt. Dusky recommended model.

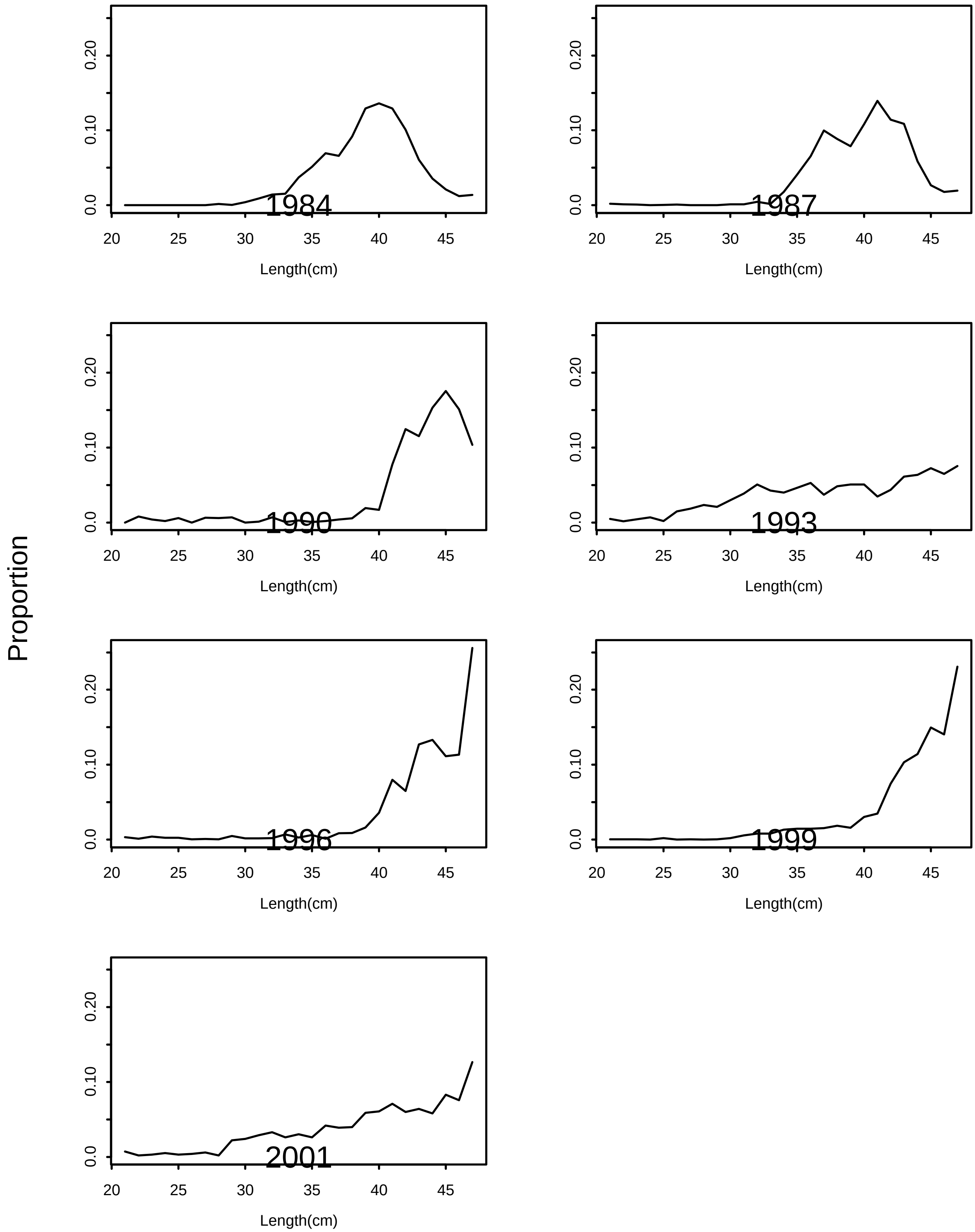

Figure 10A-4. Survey length composition for GOA Lt. Dusky by year.

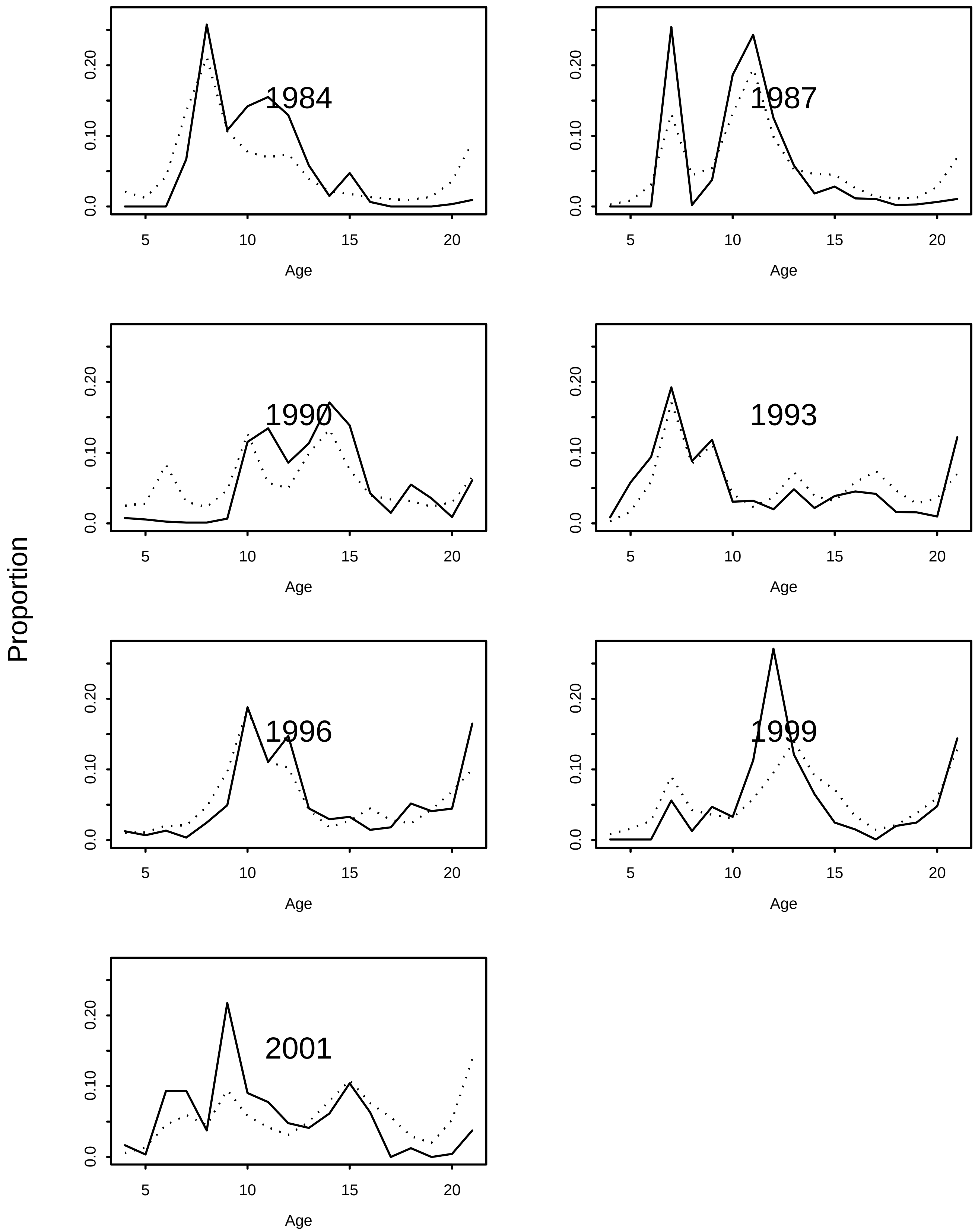

Figure 10A-5. Survey age composition by year (solid line = observed, dotted line = predicted). GOA Lt. Dusky recommended model.

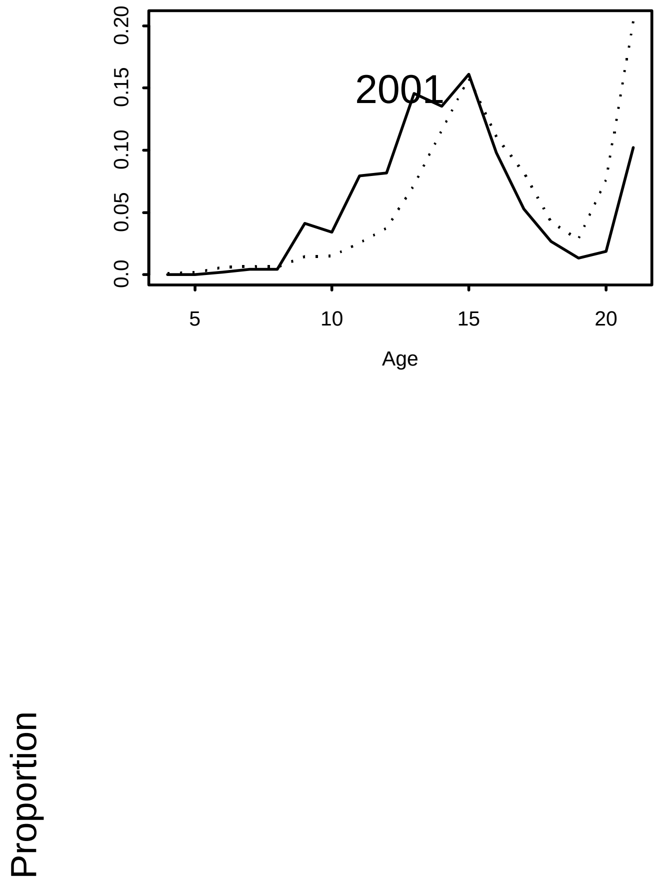

Figure 10A-6. Fishery age composition by year (solid line = observed, dotted line = predicted). GOA Lt. Dusky recommended model.

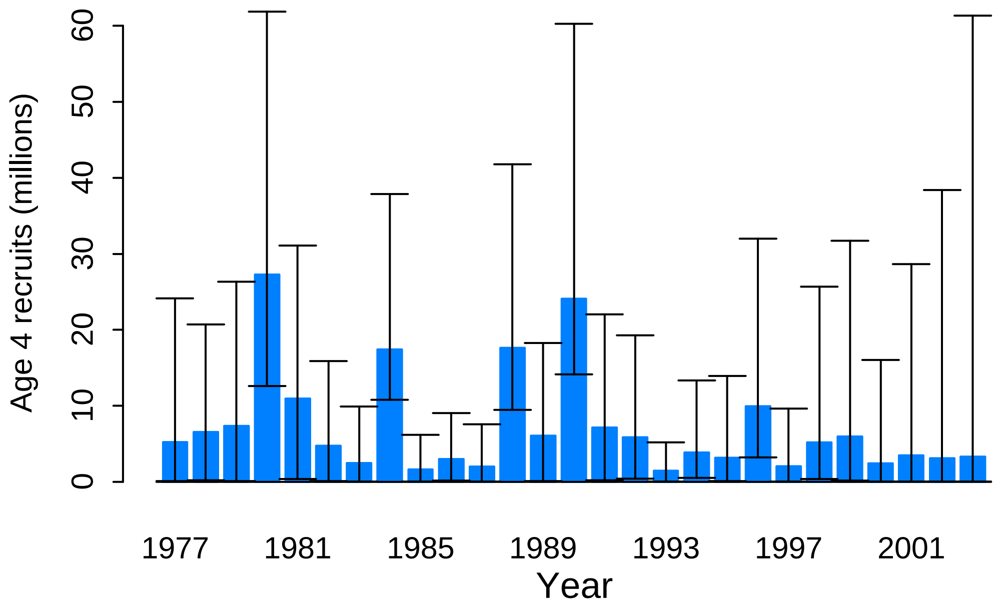

Figure 10A-7. Estimated recruitment (age 4) of GOA Lt. Dusky
Error bars represent 95% MCMC confidence intervals. Recommended mo

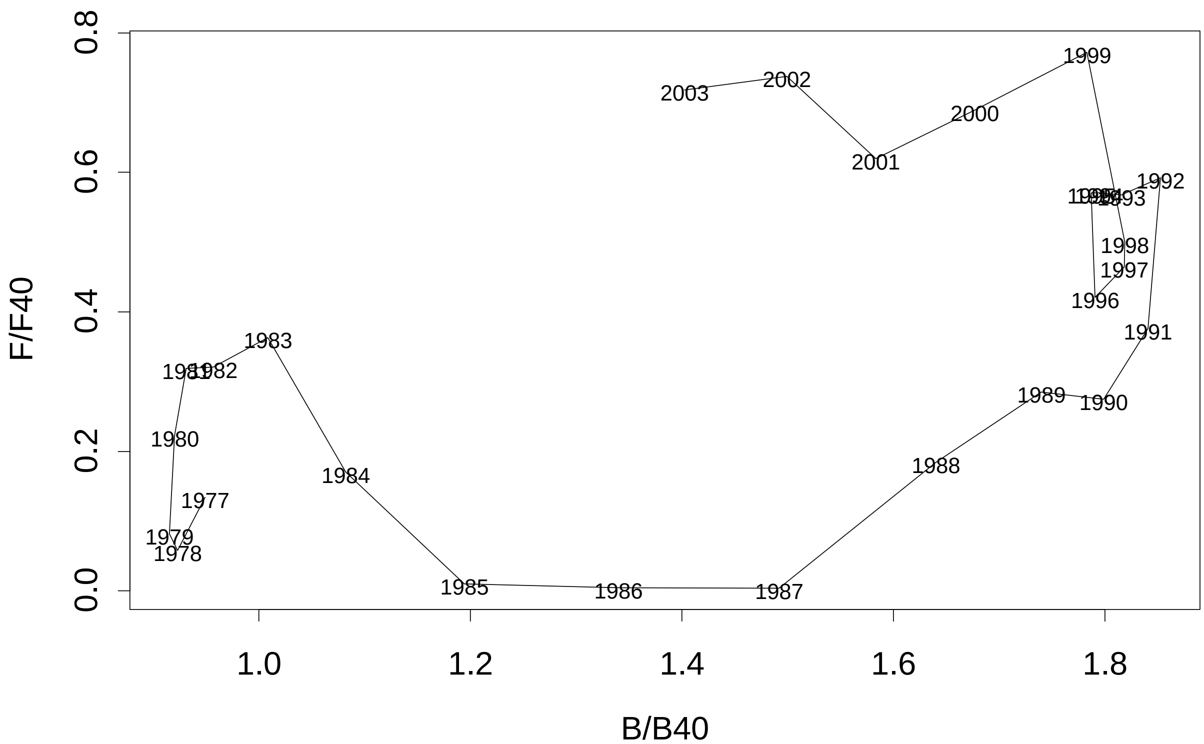

Figure 10A-8. Time series of estimated fishing mortality over F40 versus estimated spawning biomass over B40

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