Abstract.—Modern methods for fish stock assessment are often based on age-structured models that separate each coefficient of fishing mortality at age into a time-specific factor (the rate of fishing mortality on the fully exploited age-classes) and an age-specific factor (a selectivity coefficient that measures the relative vulnerability of the particular age-class). The assumption that the selectivity coefficients are constant through time greatly simplifies the assessment process because it allows for a reduction in the number of unknown parameters. However, if the assumption is incorrect, it can lead to incorrect estimates of stock status.

The most recent stock assessment for Pacific widow rockfish (*Sebastes entomelas*) was based on the untested assumption that the selectivity coefficients have not changed over the years. This assessment was derived from an analysis of catch-at-age data by using an assessment method known as the Stock Synthesis program. The work described here examined the sensitivity of the assessment results to the assumption of constant selectivity. Simulation experiments with the Stock Synthesis program showed that the stock size estimates for widow rockfish can be highly sensitive to modest changes in selectivity. Experiments with two other assessment techniques, which also assume constant selectivity (the CAGEAN program of Deriso, Quinn, and Neal and the multiplicative catch-at-age model of Shepherd and Nicholson), showed that these methods are similarly sensitive to changes in selectivity.

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The assumption of constant selectivity and the stock assessment for widow rockfish, *Sebastes entomelas*

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In general, individual fish in a stock are not equally likely to be caught and different age-classes of fish do not experience identical rates of fishing mortality. In the fisheries literature this phenomenon is usually described as "selectivity" or "availability" or "partial recruitment" (Megrey, 1989). In some instances selectivity results from the physical properties of the fishing gear. For example, younger and smaller fish may pass unharmed through the meshes of a trawl, whereas older and larger individuals may sense and avoid an approaching net. Alternatively, selectivity can result when different age-classes of fish occupy geographic regions that are not fished with the same intensity. If younger fish are offshore and older ones are inshore, for example, then the age distribution of fish in the catch will depend not just on the stock's age distribution but also on the fishing locations. Selectivity coefficients, which measure the relative influence of fishing on the age structure of the stock, are fundamental parameters in the analysis of catch-at-age data.

Many stock assessment procedures attempt to reconcile observations of catch-at-age with an underlying age-structured population model and thereby reconstruct the demographic history of the stock (Megrey, 1989). If different age-classes experience the same relative susceptibility to fishing each year, then one can model each annual age-specific rate of fishing mortality as the simple product ($S_a \cdot F_y$) of an age effect (the selectivity coefficient, S_a) and a year effect (the fishing mortality coefficient, F_y). Because there are an infinite number of (S_a, F_y) pairs that correspond to a given age-specific rate of fishing mortality, the selectivity coefficient for at least one age class must be assumed constant. If the largest S_a is set equal to one, then the F_y values correspond to the rate of fishing mortality on the fully exploited age classes.

Formulating the fishing mortality coefficient as the product of a year-effect and an age-effect greatly simplifies an analysis of catch-at-age data because it reduces the number of essential parameters. For example, if the catch-at-age matrix contains data for A ages and Y years, and if the selectivity coefficients are constant for all years, then there are only $(A+Y)$ unknown parameters. However, if the selectivity coefficients change every year, then there are $(A \cdot Y)$ unknown parameters.

Constant selectivity, and the consequent separability of fishing mortality into age and year effects, is a fundamental assumption for numerous stock assessment procedures, including separable Virtual Population Analysis (Pope and Shepherd, 1982), the CAGEAN program (Deriso et al., 1985, 1989), the multiplicative model of Shepherd and Nicholson (1986, 1991), and the Stock Synthesis program (Methot 1989, 1990). Fish stocks that have recently been assessed by using one or more of these procedures include Pacific halibut (*Hippoglossus stenolepis*) in the northeast Pacific (IPHC, 1991), walleye pollock (*Theragra chalcogramma*) in the Gulf of Alaska (Megrey, 1991), Dover sole (*Microstomus pacificus*) along the U.S. west coast (Turnock and Methot, 1991), and scad (*Trachurus trachurus*) from Atlantic waters off Spain and Portugal (Borges, 1990).

Despite the widespread application of assessment methods that are based on the notion that selectivity is time-invariant, I know of no published studies that examine the sensitivity of these assessment procedures to violations of the constant selectivity assumption. It appears that often these assessment methods are applied without first verifying that selectivity was constant for the stock being assessed. Gudmundsson (1986) recommended extensive analysis to avoid mis-specifying the catch-at-age model (for example, incorrectly assuming that selectivity was constant), and he developed a least-squares technique for testing the separability assumption. However, his methodology does not seem to be used widely.

Several published papers document variations in selectivity through time. Houghton and Flatman (1981) examined selectivity coefficients for cod (*Gadus morhua*) in the west-central North Sea and found significant changes in the "exploitation pattern," which they attributed to shifts in the fishing pressure exerted by different segments of the fleet. Gudmundsson (1986) speculated that changes in fish size-at-age coupled with variations in the composition of the fishing gear caused changes in selectivity for the Icelandic stock of cod (*Gadus morhua*). Gordoa and Hightower (1991) analyzed data from the fishery for Cape hake (*Merluccius capensis*) off southwestern Africa and ascribed significant shifts in selectivity to the fishermen's targeting on strong year classes.

The work described here has a different focus. In this paper I do not examine how selectivity in a fishery has varied. Instead, I investigate whether the stock assessment program used to evaluate a particular stock's status is robust to changes in selectivity. For this exercise I analyzed the stock assessment for widow rockfish (*Sebastes entomelas*), an economically important component of the complex of Sebastes species found along the Pacific coast of North America. Gunderson (1984) described the history and characteristics of the U.S. fishery for widow rockfish off the coasts of Washington, Oregon, and California.

In this paper, I demonstrate that the stock size estimates for widow rockfish, which are based on the untested assumption that selectivity has been constant from year to year, can be seriously biased if the assumption is violated. Furthermore, I test two other assessment methods that also use the constant selectivity assumption and show that they produce similarly biased results. Finally, I establish that comparable problems with bias can arise in the assessment results for other fish stocks, whose biological characteristics differ significantly from widow rockfish.

Methods

One technique for testing the reliability of an estimation procedure is to produce artificial data sets with known characteristics and then to estimate the parameter values from which the data were derived. I used this approach to determine whether certain stock assessment methods were sensitive to violations of the constant selectivity assumption. First, I simulated catch-at-age data for a fish stock in which the selectivity coefficients were changing slowly from year to year. Next, I used the assessment programs to analyze the catch-at-age data and to estimate stock biomass and abundance-at-age. Finally, I measured the bias of the estimates by calculating the relative errors of the estimates. The relative error of an estimate is the difference between the estimate and its true value; all divided by the true value.

Sensitivity of the Stock Synthesis program when applied to data for widow rockfish

To investigate the sensitivity of the stock assessment results for widow rockfish to the assumption of constant selectivity, I developed a spreadsheet model to generate artificial catch-at-age data, which I then analyzed using the Stock Synthesis program. The Stock Synthesis program has been used by the Pacific Fisheries Management Council (PFMC) since 1990 to appraise the status of many of the Pacific groundfish stocks (PFMC, 1990). Methot (1989, 1990) documented the principles and equations underlying the Stock Synthesis program.

The spreadsheet model simulates the characteristics of an age-structured population and employs the same equations as the Stock Synthesis program for describing the temporal progressions in abundance-at-age, biomass, catch-at-age, and total catch. The model uses parameters for mortality and growth that are similar to those observed in the U.S. stock of widow rockfish (Table 1). I generated values for abundance-at-age and catch-at-age for 10 years and 20 age classes, ages 4 through 22, as well as age 23 and older (Table 2). In 1989, almost 95% of the U.S. coast-wide landings of widow rockfish were fish between the ages of 5–10 years; about 3% of the landings were fish older than 15 years (Hightower and Lenarz, 1990).

Table 1
Parameters for simulating a stock of widow rockfish: annual recruitment was 10^6 fish per year; natural mortality[1] was 0.15 per year. Selectivity parameters[2] (Curve B (Fig. 1), 100% selection at age 8): lower inflection age was 6.0 years; lower slope was 2.5 per year; upper inflection age was 12.0 years; and the upper slope was 0.3 per year.

Age (years)	Selectivity coefficients (%)	Weight[3] (kg)
4	0.8	0.549
5	8.9	0.662
6	56.2	0.780
7	99.0	0.936
8	100.0	1.025
9	93.1	1.150
10	84.6	1.255
11	75.2	1.400
12	65.5	1.427
13	55.7	1.596
14	46.4	1.798
15	37.9	1.899
16	30.3	1.965
17	23.9	1.965
18	18.6	2.008
19	14.3	2.099
20	10.9	2.031
21	8.2	2.704
22	6.2	2.299
23+	4.7	2.388

[1]From Hightower and Lenarz (1990).
[2]The equation for the double-logistic selection curve and the meaning of these parameters are described in Methot (1990).
[3]From Barss and Echeverria (1987).

In the first set of experiments, I examined combinations of three factors to determine how they affect bias in the estimates from the Stock Synthesis program. They were 1) the age of full selection was either gradually increasing or decreasing from year to year, or it varied randomly; 2) the annual fishing mortality coefficients were either increasing, decreasing, or constant; and 3) the program was either given the true values of annual recruitment or it was required to estimate these values. For simplicity, I limited my experiments to these three factors, although undoubtedly there are others that can also have significant effects. Examples are trends in annual recruitment, the level of natural mortality, or the shape of the selectivity curve.

True values for the selectivity coefficients were generated from a double logistic function (Methot, 1990) and were similar to those reported for widow rockfish in Hightower and Lenarz (1990). The strongly domed shape of the selectivity curve (Fig. 1), which may be due to the movement of older individuals into deeper, less heavily fished waters, seems to be a common feature for many of the groundfish stocks in the U.S. Pacific Northwest.

To simulate temporal changes in selectivity, I shifted the selectivity coefficients forward or backward by one age class (Fig. 1). When selectivity increased, 100% selection occurred at age 7 for the first three years (Curve A), at age 8 for the next four years (Curve B), and at age 9 for the last three years (Curve C). When selectivity decreased, full selection occurred at age 9 for the first three years, at age 8 for the next four years, and at age 7 for the last three years. To measure the effects of "random" changes in selectivity, I generated data sets for 10 trials. Selectivity in the first year of each trial always followed selection curve B, but the sequence of curves that applied in the subsequent years came from a random shuffling of the sequence AAABBBCCC (Fig. 2). Curve A applied in three randomly chosen years, curve B applied in three other randomly selected years, and curve C applied in the remaining three years. I did not examine other forms of change in selectivity, such as variation in the basic shape of the curve.

When simulating an increasing trend in fishing mortality, the fishing mortality coefficients changed linearly from 0.10 to 0.28 per year, at increments of 0.02 per year. When the trend was decreasing, the fishing mortality coefficients varied from 0.28 to 0.10 per year, at increments of –0.02 per year. When there was no trend in fishing mortality, the fishing mortality was 0.20 per year, which is approximately the rate of fishing that reduces the reproductive output from this simulated stock to 35% of its unexploited level when full selection is at age 8 years (Fig. 1, Curve B).

All methods for analyzing catch-at-age data require additional information with which to tune the analysis and thereby resolve a basic indeterminacy in the model for catch[1] (Shepherd and Nicholson, 1986). In the most recent assessment for widow rockfish, Hightower and Lenarz (1990) tuned the Stock Synthesis analysis to a single fishing mortality coefficient, but in many contemporary assessments of other Pacific groundfish stocks the Stock Synthesis runs have been tuned to estimates of abundance-at-age or biomass from research vessel surveys. In the sensitivity analysis, I gave the Stock Synthesis program auxiliary data for tuning either in the form of the true annual fishing mortality coefficients or the true proportions-at-age.

Sensitivity of other stock assessment programs that assume constant selectivity

To confirm that the assumption of constant selectivity, rather than some unique feature of the Stock Synthesis program, was responsible for any bias in the results, I experimented with two other

[1]Catch-at-age is approximately equal to the product of stock abundance-at-age and fishing mortality-at-age. If only catch data are available, one cannot distinguish between a case of large abundance and low fishing mortality versus one of small abundance and high fishing mortality.

Table 2

Simulated widow rockfish abundance and catch data. (**A**) Selectivity increasing, fishing mortality constant (0.20 year). (**B**) Selectivity decreasing, fishing mortality constant (0.20/year). Selection curves are indicted in parentheses.

A	Year									
Age	1981 (A)	1982 (A)	1983 (A)	1984 (B)	1985 (B)	1986 (B)	1987 (B)	1988 (C)	1989 (C)	1990 (C)
Initial population size (1000's of fish)										
4	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
5	845.6	845.6	845.6	845.6	859.3	859.3	859.3	859.3	860.6	860.6
6	650.4	650.4	650.4	650.4	715.0	726.6	726.6	726.6	738.4	739.5
7	459.3	459.3	459.3	459.3	500.3	550.0	558.9	558.9	614.5	624.4
8	323.7	323.7	323.7	323.7	324.3	353.3	388.4	394.7	429.9	472.6
9	231.3	231.3	231.3	231.3	228.1	228.5	249.0	273.7	278.7	303.6
10	168.1	168.1	168.1	168.1	165.2	163.0	163.3	177.9	192.9	196.4
11	124.4	124.4	124.4	124.4	122.1	120.1	118.4	118.7	127.1	137.8
12	94.0	94.0	94.0	94.0	92.1	90.4	88.9	87.7	86.3	92.4
13	72.3	72.3	72.3	72.3	70.9	69.6	68.3	67.1	64.9	63.9
14	56.7	56.7	56.7	56.7	55.7	54.6	53.6	52.6	50.7	49.0
15	45.3	45.3	45.3	45.3	44.5	43.7	42.8	42.0	40.5	39.0
16	36.7	36.7	36.7	36.7	36.1	35.5	34.9	34.2	33.0	31.8
17	30.1	30.1	30.1	30.1	29.7	29.3	28.8	28.2	27.3	26.3
18	25.0	25.0	25.0	25.0	24.7	24.4	24.0	23.6	22.9	22.1
19	20.9	20.9	20.9	20.9	20.7	20.5	20.2	19.9	19.4	18.8
20	17.6	17.6	17.6	17.6	17.5	17.3	17.1	16.9	16.5	16.1
21	14.9	14.9	14.9	14.9	14.8	14.7	14.6	14.4	14.1	13.8
22	12.7	12.7	12.7	12.7	12.6	12.5	12.5	12.3	12.1	11.9
23+	74.3	74.3	74.3	74.3	74.1	73.9	73.7	73.4	72.8	72.2
Catch (1000's of fish)										
4	16.30	16.30	16.30	1.49	1.49	1.49	1.49	0.13	0.13	0.13
5	83.61	83.61	83.61	13.78	14.01	14.01	14.01	1.28	1.28	1.28
6	108.74	108.74	108.74	64.31	70.70	71.85	71.85	11.85	12.04	12.06
7	77.51	77.51	77.51	76.78	83.64	91.95	93.44	55.26	60.75	61.74
8	51.17	51.17	51.17	54.62	54.73	59.62	65.54	65.98	71.88	79.02
9	33.49	33.49	33.49	36.56	36.06	36.13	39.36	46.18	47.03	51.23
10	21.85	21.85	21.85	24.34	23.93	23.60	23.65	28.12	30.49	31.05
11	14.21	14.21	14.21	16.18	15.88	15.61	15.40	17.19	18.41	19.96
12	9.22	9.22	9.22	10.73	10.52	10.33	10.15	11.40	11.21	12.01
13	5.96	5.96	5.96	7.10	6.96	6.83	6.70	7.67	7.42	7.29
14	3.85	3.85	3.85	4.68	4.59	4.50	4.41	5.16	4.97	4.81
15	2.48	2.48	2.48	3.07	3.02	2.96	2.90	3.46	3.34	3.22
16	1.59	1.59	1.59	2.01	1.98	1.94	1.91	2.32	2.23	2.15
17	1.02	1.02	1.02	1.31	1.29	1.27	1.25	1.54	1.49	1.44
18	0.65	0.65	0.65	0.85	0.84	0.83	0.81	1.02	0.99	0.96
19	0.42	0.42	0.42	0.55	0.54	0.54	0.53	0.67	0.66	0.64
20	0.27	0.27	0.27	0.35	0.35	0.35	0.34	0.44	0.43	0.42
21	0.17	0.17	0.17	0.23	0.23	0.22	0.22	0.29	0.28	0.28
22	0.11	0.11	0.11	0.15	0.14	0.14	0.14	0.19	0.18	0.18
23+	0.48	0.48	0.48	0.64	0.64	0.64	0.63	0.84	0.84	0.83

Table 2 (Continued)

B	Year									
Age	1981 (C)	1982 (C)	1983 (C)	1984 (B)	1985 (B)	1986 (B)	1987 (B)	1988 (A)	1989 (A)	1990 (A)
Initial population size (1000's of fish)										
4	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
5	860.6	860.6	860.6	860.6	859.3	859.3	859.3	859.3	845.6	845.6
6	739.5	739.5	739.5	739.5	727.7	726.6	726.6	726.6	661.0	650.4
7	625.3	625.3	625.3	625.3	568.8	559.8	558.9	558.9	513.1	466.7
8	481.0	481.0	481.0	481.0	441.6	401.7	395.3	394.7	393.9	361.6
9	339.7	339.7	339.7	339.7	339.0	311.2	283.1	278.5	282.0	281.4
10	239.4	239.4	239.4	239.4	242.7	242.2	222.3	202.2	202.4	205.0
11	171.0	171.0	171.0	171.0	174.0	176.4	176.0	161.6	149.8	149.9
12	124.3	124.3	124.3	124.3	126.6	128.8	130.6	130.3	122.0	113.1
13	92.0	92.0	92.0	92.0	93.8	95.6	97.3	98.6	100.3	93.9
14	69.5	69.5	69.5	69.5	70.9	72.3	73.6	74.9	77.3	78.7
15	53.5	53.5	53.5	53.5	54.5	55.6	56.7	57.7	59.7	61.7
16	42.0	42.0	42.0	42.0	42.7	43.5	44.3	45.2	46.8	48.4
17	33.5	33.5	33.5	33.5	34.0	34.6	35.2	35.9	37.1	38.4
18	27.1	27.1	27.1	27.1	27.5	27.9	28.4	28.9	29.8	30.8
19	22.3	22.3	22.3	22.3	22.5	22.8	23.1	23.5	24.2	24.9
20	18.5	18.5	18.5	18.5	18.6	18.8	19.1	19.3	19.8	20.4
21	15.4	15.4	15.4	15.4	15.5	15.7	15.8	16.1	16.4	16.8
22	13.0	13.0	13.0	13.0	13.1	13.2	13.3	13.4	13.6	13.9
23+	73.4	73.4	73.4	73.4	73.7	73.9	74.2	74.6	75.2	75.9
Catch (1000's of fish)										
4	0.13	0.13	0.13	1.49	1.49	1.49	1.49	16.30	16.30	16.30
5	1.28	1.28	1.28	14.03	14.01	14.01	14.01	84.97	83.61	83.61
6	12.06	12.06	12.06	73.12	71.95	71.85	71.85	121.48	110.50	108.74
7	61.83	61.83	61.83	104.55	95.10	93.58	93.44	94.32	86.59	78.76
8	80.42	80.42	80.42	81.17	74.52	67.78	66.70	62.40	62.27	57.17
9	57.32	57.32	57.32	53.70	53.59	49.20	44.75	40.34	40.84	40.75
10	37.84	37.84	37.84	34.66	35.14	35.07	32.20	26.29	26.31	26.64
11	24.77	24.77	24.77	22.23	22.61	22.93	22.88	18.45	17.10	17.12
12	16.16	16.16	16.16	14.19	14.46	14.71	14.91	12.79	11.97	11.09
13	10.51	10.51	10.51	9.03	9.21	9.38	9.54	8.13	8.27	7.74
14	6.82	6.82	6.82	5.73	5.84	5.96	6.07	5.08	5.24	5.34
15	4.41	4.41	4.41	3.63	3.69	3.77	3.84	3.16	3.27	3.37
16	2.84	2.84	2.84	2.29	2.33	2.38	2.43	1.96	2.03	2.10
17	1.83	1.83	1.83	1.45	1.47	1.50	1.53	1.22	1.26	1.30
18	1.18	1.18	1.18	0.92	0.93	0.95	0.96	0.76	0.78	0.81
19	0.75	0.75	0.75	0.58	0.59	0.60	0.61	0.47	0.48	0.50
20	0.48	0.48	0.48	0.37	0.37	0.38	0.38	0.29	0.30	0.31
21	0.31	0.31	0.31	0.23	0.24	0.24	0.24	0.18	0.19	0.19
22	0.20	0.20	0.20	0.15	0.15	0.15	0.15	0.12	0.12	0.12
23+	0.84	0.84	0.84	0.63	0.63	0.64	0.64	0.48	0.48	0.49

assessment methods that also use the assumption of constant selectivity. I analyzed the simulated catch-at-age data with the CAGEAN program (CAGEAN-PC, version 4, release 2) of Deriso et al. (1985, 1989) and with the multiplicative catch-at-age model of Shepherd and Nicholson (1986, 1991).

The Stock Synthesis program and the CAGEAN program use similar approaches for modeling catch-at-age, but they differ in their assumptions about variability in the observed data. Stock Synthesis assumes a multinomial error structure for the catch-at-age data. If $\hat{p}_a$ is the predicted proportion of age class (a) captured, then the variance associated with a random observation of p_a is proportional to $\hat{p}_a \cdot (1-\hat{p}_a)$. CAGEAN, however, assumes a lognormal error structure. If $\hat{c}_a$ is the predicted number of fish caught of age class (a), then $\log_e(c_a/\hat{c}_a)$ is normally distributed with a zero mean and a constant variance.

The multiplicative catch-at-age model is essentially an approximation to the catch model that underlies

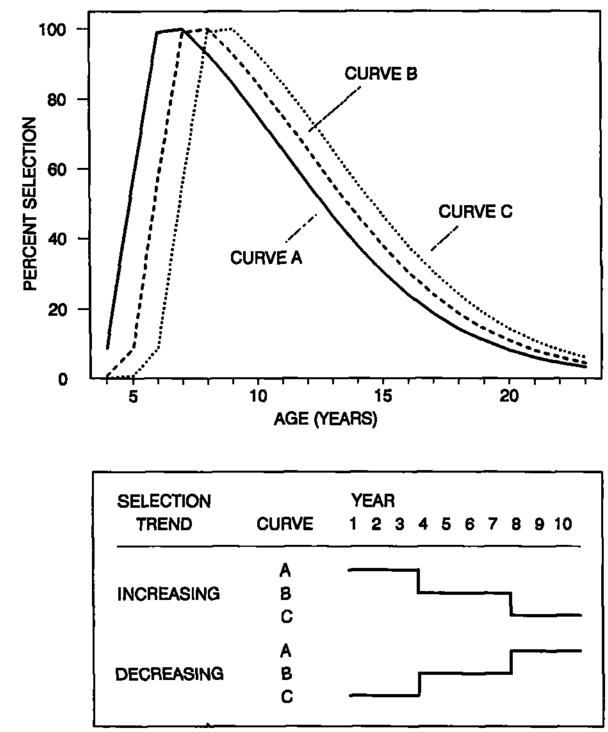

Figure 1
Selectivity curves used in the simulations. To simulate the effects of changing selectivity, the selectivity curve was either shifted towards older fish through time (increasing selectivity) or towards younger fish (decreasing selectivity).

both the Stock Synthesis and CAGEAN programs. Unlike the other two assessment procedures, the multiplicative model estimates relative, rather than absolute, abundance. To conduct the multiplicative catch-at-age analyses, I used the GLIM statistical program (Baker and Nelder, 1985) and assumed a lognormal error structure.

In the experiments with CAGEAN and the multiplicative catch-at-age model, I used a subset of the data from the earlier experiments with the Stock Synthesis program. Two sets of catch-at-age data were analyzed, one from a population with selectivity shifting to older ages (selectivity increasing) and fishing mortality constant (Table 2A), the other from a population with selectivity shifting to younger ages (selectivity decreasing) and fishing mortality constant (Table 2B). I tuned the CAGEAN program to the true fishing mortality coefficients, and constrained the multiplicative catch-at-age analysis to have a trend of zero in the annual fishing mortality coefficients. The experiments here correspond to the cases examined earlier in which the Stock Synthesis program was tuned to fishing mortality and recruitment was estimated.

Sensitivity of the Stock Synthesis program when applied to data from a heavily exploited stock

To determine whether the results from the experiments with a simulated stock of widow rockfish would apply to fish stocks with different biological characteristics, I generated two additional data sets, one from a population with selectivity shifting to older ages (selectivity increasing), the other from a population with selectivity shifting to younger ages (selectivity decreasing). Both simulated populations, which suffered an instantaneous natural mortality rate of 0.30 per year and an instantaneous fishing mortality rate of 0.60 per year, had significantly fewer old animals compared to the populations in the previous simulations. I analyzed the two data sets with the Stock Synthesis program, with tuning to the true fishing mortality coefficients, and with recruitment estimated.

Results

The assessment programs that I investigated all produce a wide variety of estimates, including selectivity coefficients and matrices of abundance and catch by age and year. Rather than evaluating bias for all estimates, my analysis focussed on estimates of annual stock biomass, numerical abundance, and recruitment. Of special importance to a stock assessment scientist or fishery manager is the bias in the estimate of average biomass for the final year of a data series. This estimate is approximately the biomass estimate on which the catch quota for the next year is based[2]. If the estimate of average biomass in the final year is, say, 20% too high, then the quota will be roughly 20% too high; if the estimate is 10% too low, the quota will also be about 10% too low.

Selectivity of the Stock Synthesis program when applied to data for widow rockfish

The results of the experiments with the Stock Synthesis program and the data for the simulated stock of widow rockfish suggest that some of the assessment results can be highly sensitive to slight trends in selectivity. For example, when selectivity shifted towards younger ages, the biomass estimate for the final year of the series was 74% too high (Table 3A; selectivity decreasing, tuned to fishing mortality, fishing mortal-

[2]The annual catch quota is derived from an estimate of the biomass at the end of the previous year, plus an appropriate amount for the new recruitment. In practice this differs little from the estimate of average biomass in the final year.

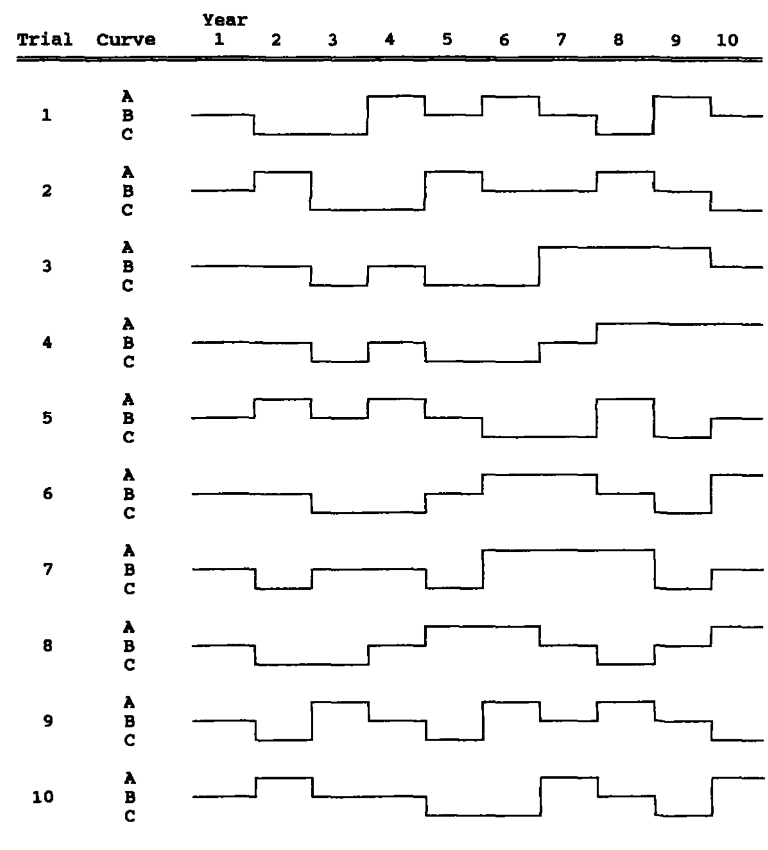

Figure 2

Simulations with random variation in selectivity. The effects of random variation in selectivity were simulated by shuffling the sequence of selectivity curves (AAABBBCCC, Fig. 1) that applied in each of the nine years after the first. The ten sequences shown here were used.

ity constant, and recruitment estimated), and the estimated age distribution in the final year was grossly incorrect (Fig. 3A). The estimated numbers of five-year-old to seven-year-old fish were much too high and the numbers of fish 15 years and older were all slightly too high. When selectivity shifted towards older ages, the biomass estimate for the final year was as much as 59% too low (Table 3A; selectivity increasing, tuned to fishing mortality, fishing mortality increasing, and recruitment estimated) and the program underestimated the numbers of very young and very old fish (Fig. 3B).

In these experiments, bias in a particular estimate was not a simple linear function of the factors examined, but instead involved complicated interactions between factors. Nevertheless, some general effects seemed to apply. When the Stock Synthesis program was tuned to fishing mortality and used to estimate recruitment, shifts in selectivity towards older ages (selectivity increasing) always induced negative bias in the estimates of average biomass, and shifts in selectivity towards younger ages (selectivity decreasing) always induced positive bias (Table 3, A and B). When the recruitment values were known or tuning to the proportion-at-age data was used, however, trends in selectivity had no consistent effect on the direction of bias. Estimation of recruitment values, often, but not always, increased the magnitude of the bias in the estimates of biomass (Table 3, A and B) and abundance (Table 3C). Tuning to proportion-at-age data, instead of to annual fishing mortality coefficients, often decreased the amount of bias in the estimates of biomass, abundance, and recruitment. Bias in these estimates usually was smallest when the trend in fishing mortality was increasing and largest when the trend in fishing mortality was decreasing.

When the Stock Synthesis program estimated recruitment, improvements in the fit were observed relative to those obtained when recruitment values were known (Table 3D). To the assessment scientist interpreting these results, the improved fit would suggest that the program had provided better estimates, when, in fact, the estimates were more biased and less reliable. When selectivity shifted toward older fish, there was a systematic change from year to year in the catch-at-age data, which the program attempted to match by imposing a decreasing trend in recruitment (Fig. 4). When selectivity shifted towards younger fish, the program imposed an increasing trend in recruitment. Similar distortions occurred when the program was tuned to the true proportion-at-age data. This last result suggests that using age-frequency data from research vessel surveys will not eliminate the bias induced by changes in selectivity, even though survey data may not be subject to the changes in selectivity that the fishery might experience.

When selectivity varied randomly (Table 4), the magnitude of the bias in the estimate of the final year's average biomass was usually less than what occurred when selectivity had a trend (Table 3A), but the general patterns seen in the earlier experiments remained.

Table 3

Sensitivity analysis of the Stock Synthesis program. (**A**) Bias[1] in the estimated average biomass in the final year. (**B**) Average and standard deviation[2] of the bias in the estimates of annual average biomass. (**C**) Average and standard deviation of the bias in the estimates of annual numerical abundance. (**D**) Average and standard deviation of the bias in the estimates of annual recruitment[3] and the improvement in fit[4] when recruitment was estimated.

A	Increasing selectivity		Decreasing selectivity	
	Known recruitment %	Estimated recruitment %	Known recruitment %	Estimated recruitment %
Tuned to fishing mortality				
F increasing	−1.0	−58.8	−1.2	49.8
F decreasing	16.9	−54.4	13.6	72.0
F constant	12.1	−54.0	10.4	74.3
Tuned to proportion-at-age				
F increasing	3.4	−26.1	−2.9	1.0
F decreasing	23.3	−24.6	11.7	5.7
F constant	17.3	−14.0	7.4	5.2

B	Increasing selectivity				Decreasing selectivity			
	Known recruitment		Estimated recruitment		Known recruitment		Estimated recruitment	
	Mean (%)	SD (%)	Mean (%)	SD (%)	Mean (%)	SD (%)	Mean (%)	SD (%)
Tuned to fishing mortality								
F increasing	3.9	2.1	−32.5	12.7	−4.5	1.3	24.6	16.2
F decreasing	46.0	21.6	−20.8	18.2	21.4	8.0	63.3	18.8
F constant	29.5	11.5	−20.5	17.0	11.8	4.0	53.2	18.2
Tuned to proportion-at-age								
F increasing	4.5	0.5	−12.1	8.4	−3.8	0.4	−6.3	6.9
F decreasing	51.7	20.2	7.6	20.5	24.9	9.6	9.1	11.0
F constant	32.0	10.0	10.8	15.2	13.7	4.9	4.3	7.9

C	Increasing selectivity				Decreasing selectivity			
	Known recruitment		Estimated recruitment		Known recruitment		Estimated recruitment	
	Mean (%)	SD (%)	Mean (%)	SD (%)	Mean (%)	SD (%)	Mean (%)	SD (%)
Tuned to fishing mortality								
F increasing	2.9	3.0	−27.3	20.4	−2.1	3.4	23.6	27.7
F decreasing	23.1	14.0	−24.1	24.2	8.4	3.5	40.9	27.7
F constant	15.8	8.9	−21.5	24.3	4.7	2.3	38.5	29.9
Tuned to proportion-at-age								
F increasing	3.5	1.6	−10.8	14.8	−2.5	1.6	−3.8	14.0
F decreasing	26.8	13.3	−4.4	22.8	10.2	4.5	−1.3	13.6
F constant	17.7	7.9	1.6	19.7	5.6	2.1	−1.2	13.2

Table 3 (Continued)

D	Increasing selectivity			Decreasing selectivity		
	Mean (%)	SD (%)	Improvement in fit (%)	Mean (%)	SD (%)	Improvement in fit (%)
Tuned to fishing mortality						
F increasing	–30.0	45.3	45.7	24.3	89.8	29.5
F decreasing	–38.0	42.1	56.7	29.8	95.7	32.2
F constant	–32.8	45.2	51.9	30.7	96.0	31.6
Tuned to proportion-at-age						
F increasing	–13.5	40.0	25.6	0.5	60.0	18.5
F decreasing	–21.9	39.2	37.7	–4.6	61.7	23.8
F constant	–13.3	41.1	30.9	–2.5	59.6	21.4

[1]Bias is measured here as the relative error of the estimated value, (estimate – true) / true.
[2]The Stock Synthesis program estimates average biomass for each year of the input data series. The values here are the averages and standard deviations of the ten annual estimates.
[3]The Stock Synthesis program can estimate recruitment for each year of the input data series. The values here are the averages and standard deviations of the ten annual estimates.
[4]The "improvement in fit" is measured here by the relative increase in the value of the log-likelihood when the Stock Synthesis program estimates the annual recruitment rather than being given the true values. This is defined as

$$(L' - L)/L$$

where L is the value of the log-likelihood when the program was given the true annual recruitment values, and L' is the value of the log-likelihood when the program estimated the annual recruitment values. The log-likelihood is given by

$$\Sigma_y J_y \cdot \Sigma_a p_{y,a} \log_e(\hat{p}_{y,a});$$

where J_y is the number of fish in the (y)th catch-at-age sample, $p_{y,a}$ is the observed proportion of fish in the (y)th sample that are from the (a)th age class, and $\hat{p}_{y,a}$ is the predicted proportion of fish in the (y)th sample from the (a)th age class (Methot, 1990).

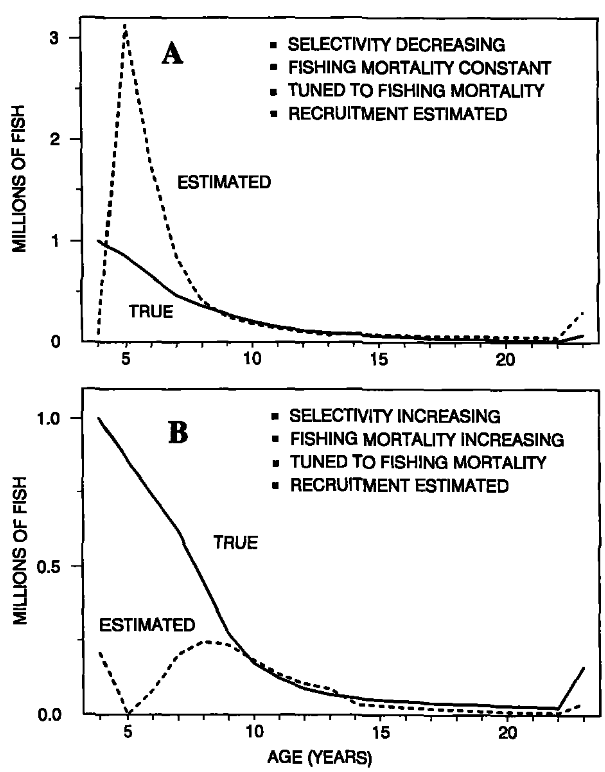

Figure 3

True versus estimated age distributions. For the age distribution shown in the upper panel (**A**) the Stock Synthesis program produced an estimate of average biomass in the final year that was 74% too large. For the distribution in the lower panel (**B**) the program produced an estimate that was 59% too small.

Sensitivity of other stock assessment programs that assume constant selectivity

The results of the experiments with CAGEAN and the multiplicative catch-at-age model indicate that these assessment methods, like the Stock Synthesis program, are also sensitive to violations of the constant selectivity assumption. When selectivity increased, both the Stock Synthesis and CAGEAN programs incorrectly produced a large decrease in the biomass of the simulated population during the last few years, and large declines in recruitment (Fig. 5). The multiplicative catch-at-age model does not provide estimates of biomass, but its estimates of relative recruitment were almost identical to those from the CAGEAN program. When selectivity decreased, the Stock Synthesis program and the CAGEAN program both overestimated the biomass in the last few years, but the estimates from the CAGEAN program were grossly incorrect (Fig. 6). Both the CAGEAN program and the multiplicative catch-at-age model estimated very large increases in recruitment.

Sensitivity of the Stock Synthesis program when applied to data from a heavily exploited stock

When the Stock Synthesis program was applied to data for a simulated population suffering heavy exploitation, the program produced estimates of biomass and recruitment that were even more biased than in the

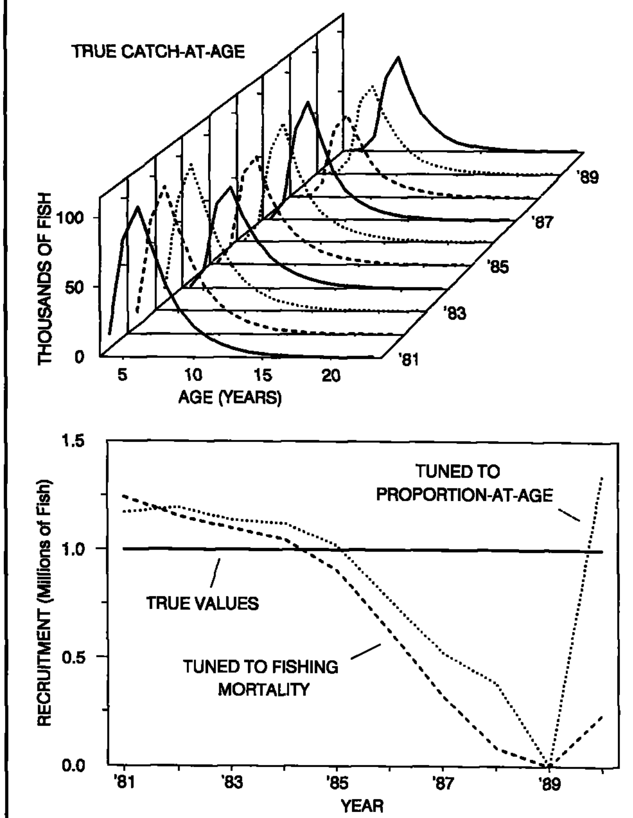

Figure 4

Trends in selectivity induce trends in recruitment. True catches-at-age (upper panel) shift through time towards older fish because of the changes in selectivity. Fishing mortality was constant for the entire period. The Stock Synthesis program attempted to mimic the changes in catch-at-age by generating estimates of recruitment that had a decreasing trend (lower panel).

earlier experiments with the simulated stock of widow rockfish. With increasing selectivity, the bias in the estimated average biomass in the final year was –86% (Fig. 7) as opposed to the bias of –54% found earlier (Table 3A; selectivity increasing, tuned to fishing mortality, fishing mortality constant, and recruitment estimated). With decreasing selectivity, the estimated average biomass in the final year was 213% too high (Fig. 8); in the earlier experiment the corresponding estimate was only 74% too high (Table 3A; selectivity decreasing, tuned to fishing mortality, fishing mortality constant, and recruitment estimated).

Discussion

In the experiments described in this paper, the assessment programs were unable to fit exactly the simulated catch-at-age data because the catch model was mis-specified. Selectivity was falsely assumed constant, and the biomass and abundance estimates were biased as a consequence. In any real application, not only would the assessment program be ignorant of the true model structure, but the program would also have to contend with "noise" in the data due to measure-

Table 4

Sensitivity analysis of the Stock Synthesis program. Bias in the estimated average biomass in the final year when selectivity varied randomly.

	Known recruitment		Estimated recruitment	
	Mean (%)	SD (%)	Mean (%)	SD (%)
Tuned to fishing mortality				
F increasing	–1.4	0.8	–19.7	21.9
F decreasing	11.3	4.4	–17.0	24.0
F constant	7.8	3.5	–18.6	23.2
Tuned to proportion-at-age				
F increasing	–0.1	0.8	–4.2	3.5
F decreasing	13.3	4.6	–8.5	5.7
F constant	8.9	3.8	–6.0	4.9

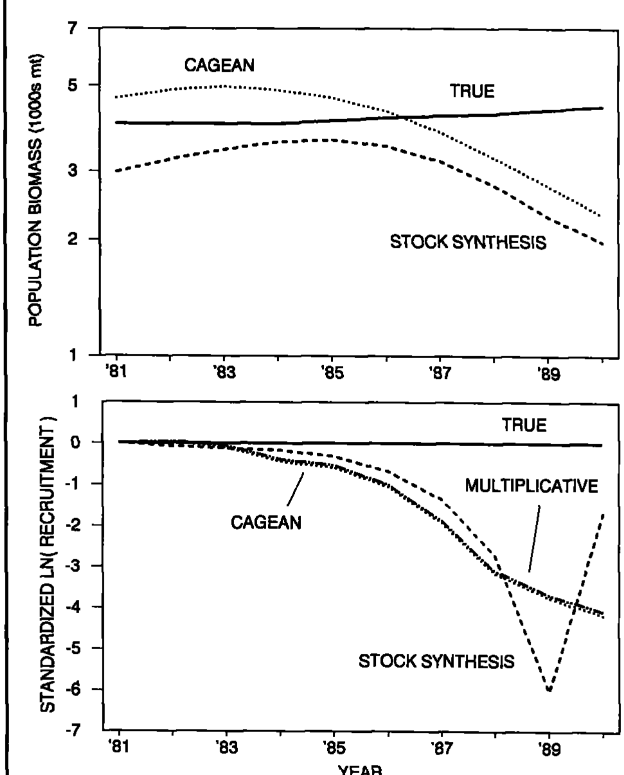

Figure 5

Estimated biomass and recruitment from different assessment programs with selectivity increasing. Three assessment programs, all of which assume constant selectivity, were applied to the simulated widow rockfish data in which selectivity shifted to older ages and fishing mortality was constant (Table 2A). All three programs were sensitive to the shifts in selectivity.

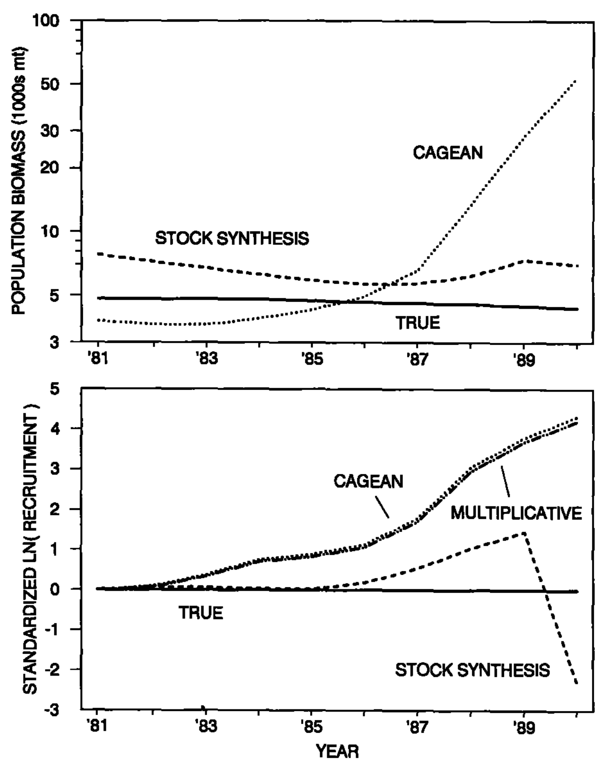

Figure 6
Estimated biomass and recruitment from different assessment programs with selectivity decreasing. The three assessment programs were also applied to the simulated widow rockfish data in which selectivity shifted to younger ages and fishing mortality was constant (Table 2B). Again, all three programs were sensitive to the shifts in selectivity.

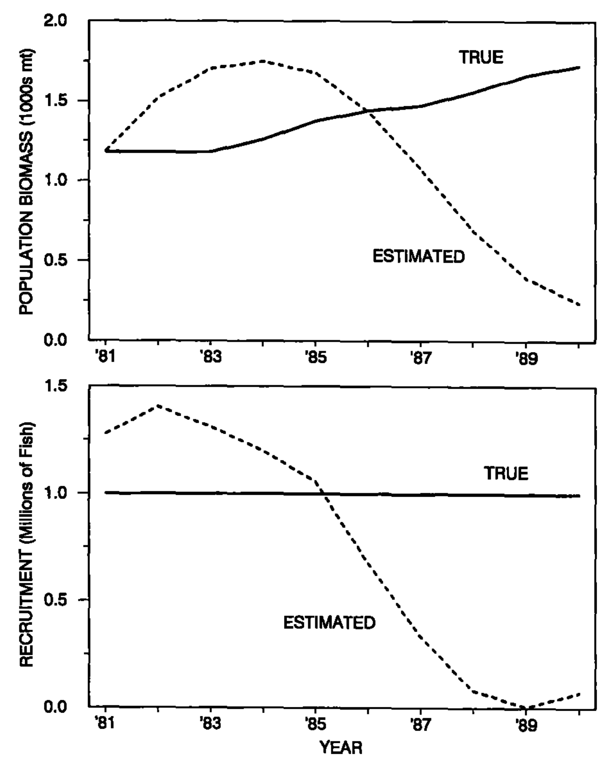

Figure 7
Stock synthesis estimates of biomass and recruitment for a heavily fished stock with selectivity increasing. The Stock Synthesis program was applied to simulated widow rockfish data in which the fishing mortality rate was constant at 0.60 per year, the natural mortality rate was 0.30 per year, and selectivity shifted to older ages. The estimates were even more biased than the ones from the corresponding earlier experiment.

ment errors and to randomness in the catch process. A complete analysis of the problem would measure how the assessment program transforms variability in the catch-at-age data into variability in the resulting estimates (e.g., Kimura, 1989).

Because the catch model with constant selectivity has fewer unknown parameters, when applied to noisy catch-at-age data, the assessment program's estimates could obtain greater precision (but not accuracy) by assuming constant selectivity, even though the assumption was incorrect[3]. However, it seems unlikely that noise in the data could ever reduce the bias resulting from a structural deficiency in the underlying catch-at-age model.

[3]John Shepherd, Ministry of Agriculture, Fisheries, and Food, Fisheries Laboratory, Lowestoft, Suffolk, NR33 0HT, U.K., pers. commun. April 1992.

In the experiments with the simulated catch-at-age data, the year-to-year changes in selectivity were not particularly drastic, but I know of no studies to support my conjecture that they are realistic for the stock of widow rockfish. The simulated changes in selectivity were comparable to those observed by Houghton and Flatman (1981) for North Sea cod and by Gordoa and Hightower (1991) for Cape hake. The fact that experiments with "random" changes in selectivity produced results similar to those from experiments with trends in selectivity confirm that the biased estimates were not just artifacts of having a simple trend in selectivity, rather than a more complex type of variation.

One surprising result of the experiments with different assessment methods was the large discrepancy between the estimates from Stock Synthesis and CAGEAN when selectivity decreased (Fig. 6). The two programs differ primarily in how they account for vari-

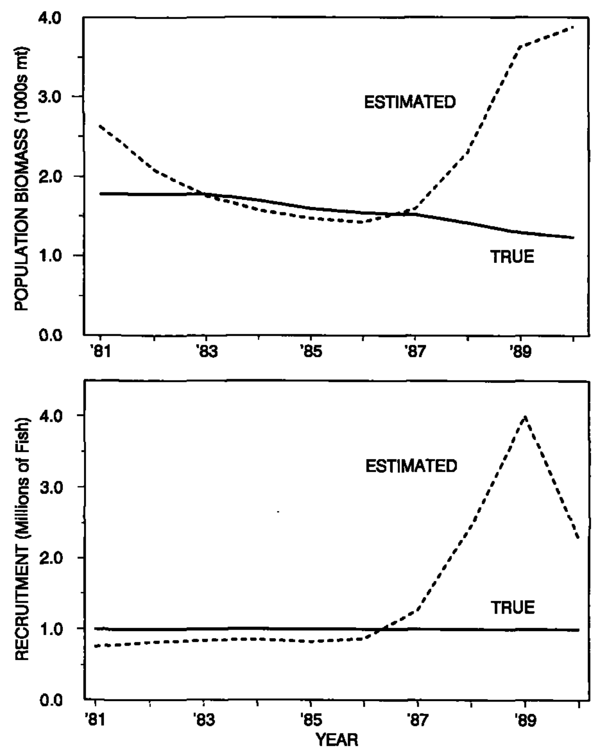

Figure 8

Stock synthesis's estimates of biomass and recruitment for a heavily fished stock with selectivity decreasing. The Stock Synthesis program was applied to simulated widow rockfish data in which the fishing mortality rate was constant at 0.60 per year, the natural mortality rate was 0.30 per year, and selectivity shifted to younger ages. Again, the estimates were more biased than the ones from the corresponding earlier experiment.

ability in catch-at-age. Stock Synthesis assumes multinomial error, but CAGEAN assumes lognormal error. Using simulation techniques, Kimura (1990) directly compared estimates derived by using these alternative assumptions and found little difference between the estimates obtained.

Another difference between Stock Synthesis and CAGEAN is in their method for modeling selectivity. The Stock Synthesis program uses a double-logistic curve to model selectivity as a smooth function of age, but the CAGEAN-PC program estimates the selectivity coefficients independently for each age. Because the true selectivity coefficients were based on double-logistic curves, this difference between the two programs should be only a minor factor. Kimura (1990) found that the assumption of a functional form for selectivity had little effect on his analyses of simulated catch-at-age data, provided the true selectivity coefficients conformed to the general shape of the selectivity function.

The dilemma for the assessment scientist is to develop a framework for analyzing fisheries data that is simple to use and yet is adequate to describe the complex dynamics of a living and constantly changing fish stock. The assessment scientist has the difficult task of interpreting diverse and possibly conflicting information. He needs tools with which to weigh these data objectively and to draw from them reliable conclusions about the status of a stock. Stock Synthesis, CAGEAN, and the multiplicative catch-at-age analysis were designed to be such tools.

In principle, one can use the Stock Synthesis and CAGEAN programs to test for shifts in selectivity. Both programs support a limited form of variable selectivity in which abrupt changes can occur at pre-specified times with constant selectivity during the intervening periods. With either program it is a relatively simple, but tedious, matter to re-analyze the data by using different times for the selectivity changes. For example, I applied the CAGEAN program to the simulated widow rockfish data set given in Table 2A, with the data partitioned into two periods of constant selectivity, and I allowed the timing of the selectivity change to occur between all possible adjacent years. The resulting pattern in the residual sums of squares[4] (Fig. 9, upper panel) clearly indicates the true change in selectivity that occurred between the third and fourth years. I repeated the process with the data series partitioned into three periods of constant selectivity, one for the first three years, and the other periods for the remaining years. The CAGEAN program was able to fit the data exactly when selectivity changed between the seventh and eighth years (Fig. 9, lower panel).

Although the current versions of the Stock Synthesis and CAGEAN programs can be applied in the above fashion to explore systematically for changes in selection, such a brute force approach to model building is extremely repetitious and time-consuming. I hope that the next generation of stock assessment programs will automate this process in a manner similar to existing stepwise regression programs, and thereby allow the user to test rigorously for variations in selectivity.

The model used for stock assessment should not force the data to fit a particular structure unless there is evidence that the structure is real or that it does not appreciably distort the results of the assessment. The

[4]CAGEAN defines the residual sum of squares as

$$\Sigma [\log_e(c) - \log_e(\hat{c})]^2$$

where c and $\hat{c}$ are the observed and predicted catch-at-age.

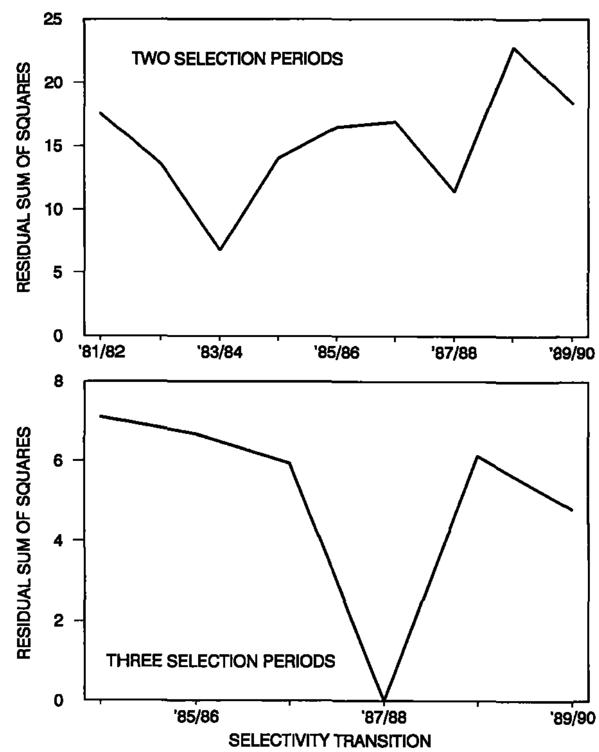

Figure 9

Residual sum of squares resulting from applications of CAGEAN with changes in selectivity. The CAGEAN program was applied to the simulated widow rockfish data in which selectivity shifted to older ages and fishing mortality was constant (Table 2A). In the upper panel the selectivity coefficients were allowed to vary abruptly between adjacent years, thereby dividing the data into two periods of constant selectivity. The minimum in the residual sum of squares corresponds to the true change in selectivity that occurred between 1983 and 1984. In the lower panel, selectivity was constant for the first three years but was allowed to vary between adjacent years in the remaining period. The zero in the residual sum of squares corresponds to the true change in selectivity that occurred between 1983 and 1984. In these analyses the age at 100% selection was fixed at age 7 for the first selectivity period, at age 8 for the second period, and at age 9 for the third.

situation is analogous to an application of two-way analysis of variance (ANOVA). In fitting a two-way ANOVA model, one should test for a significant interaction term before drawing inferences about the main effects. By the same logic, in fitting a catch-at-age model, one should test for changes in selectivity before concluding that stock size has been increasing or decreasing.

I have no real evidence of changes from year to year in the selectivity for widow rockfish off the coasts of Washington, Oregon, and California. However, the work described in this paper demonstrates that an incorrect assumption of constant selectivity can seriously distort an assessment of widow rockfish stock size. Furthermore, there is at least one reason to suspect that selectivity for widow rockfish has varied through time. During the early years of the directed fishery for widow rockfish, vessels targeted schools of fish using midwater trawls. With the rapid expansion of the fishery, the Pacific Fishery Management Council began imposing increasingly restrictive limits on the amounts of widow rockfish that could legally be landed from any single fishing trip (Gunderson, 1984). One result of these "trip limits" was a reduction in the landings by midwater trawlers relative to the landings by bottom trawlers. Midwater trawlers accounted for roughly 75% of the widow rockfish landings in Oregon during 1984 through 1988, but they accounted for only 60% in 1990, and for less than 50% in 1991. It seems quite probable that the midwater trawls have different selection characteristics than do bottom trawls, and that the shift from a midwater fishery to a bottom fishery would cause changes in selectivity.

Any stock assessment model will have to make simplifying assumptions to summarize succinctly the major features of the data. However, in my view the assumption of constant selectivity is an unnecessary and misleading oversimplification, use of which can result in catch quotas that are either needlessly conservative, resulting in immediate losses to the fishing industry, or that are excessively liberal, producing losses in recruitment and catches at a more distant time.

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