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Application of a Surplus Production Model to a Swordfish-Like Simulated Stock with Time-Changing Gear Selectivity

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Abstract.—Should a surplus production model be applied to a stock that exhibits pronounced age structure? Should it be applied to a stock that has experienced changing fishing mortality rates on fish of different sizes over time (i.e., changing selectivity)? These questions are of general interest to those engaged in stock assessment and of particular interest in the assessment of North Atlantic swordfish *Xiphias gladius*. In an attempt to answer them, we simulated an age-structured population, with fishery, similar to that of swordfish in the North Atlantic. The 30-year simulation included biological characteristics from the literature on swordfish and simulated fishing with increasing mortality of young fish over time; simulated catches approximated the actual catches of swordfish from 1962 through 1991. We fit a lumped-biomass, dynamic surplus production model to summary non-age-structured data from the simulated fishery. The resulting parameter estimates were compared to management benchmarks, including maximum sustainable yield (MSY), computed by age-structured methods from the growth and recruitment characteristics of the underlying simulation. The changing selectivity resulted in a small (<10%) decrease in MSY from the beginning of the series to its end; estimates from the production model were close to these underlying MSY values. Nine additional population trajectories were simulated with the same biological characteristics but other fishing histories; in most cases, the production model provided qualitatively correct estimates of stock status. Two new reliability statistics appear to be of value in judging the quality of production model fits. We conclude that for stocks similar to swordfish, the presence of strong age structure and moderate changes in selectivity should not proscribe the application of simple production models.

Surplus production models are useful tools for assessments in which the age composition of the catch is uncertain or unknown. Even when age composition is known precisely, surplus production models can provide a useful—and at times more accurate and precise—view of stock status (Ludwig and Walters 1985; Punt 1992). Nonetheless, a recurring concern is how well surplus production models perform in the presence of factors not directly accounted for by the model. One such factor is change in the size selectivity of the fishing gear over time. The maximum sustainable yield (MSY) that theoretically can be taken from a fish population depends on its patterns of growth, fecundity, and recruitment; its natural mortality rate; and the pattern of fishing mortality rate F at size (i.e., the selectivity vector) of the fishery. Simulation studies demonstrate that large changes in the fishing gear's age-specific selectivity pattern can cause large changes in the MSY attainable, and that smaller, more realistic changes should have smaller effects (Goodyear 1996). However, the likely effects of specific gear changes on a specific stock must be evaluated on a case-by-case basis.

A broader issue is the usefulness of production models when applied to stocks with many age-classes; such stocks are identified here as "strongly age-structured." Most production models assume that a population's response to harvesting is instantaneous, but strongly age-structured stocks might require several years to begin recovery from depletion of the spawning stock. Both of these issues have been of concern in connection with the use of production models in the assessment of swordfish *Xiphias gladius* in the North Atlantic Ocean (e.g., ICCAT 1993).

This paper describes simulation experiments that examined the above two issues. We fit a dynamic ("nonequilibrium") production model to data from a simulated stock based on the swordfish stock and fishery in the North Atlantic. Although the simulated population was age-structured, only total biomass data, aggregated for the entire population, were used to fit the model, thus simulating the procedure used to fit most surplus production models in actual assessments. To evaluate the results from fitting the production model, several management benchmarks (quantities, such as MSY, often used as management guidelines) were estimated from the model results on the simulated data and compared with the known "true" values derived from age-structured computations. (Throughout, we use the word "true" in quotation marks to denote known characteristics of a simulated population.)

The fisheries literature includes previous studies evaluating the performance of production models on age-structured simulated populations (e.g., Hilborn 1979; Ludwig et al. 1988; Punt 1988; Punt and Butterworth 1991), usually in conjunction with a management model. This study extends present knowledge in four ways. First, it examines the specific question of how an estimate of MSY from a production model compares with the theoretical value derived from the stock–recruitment curve, growth curve, and other biological factors listed above. Second, it examines how a realistic change in gear size-selectivity affects both the theoretical and the estimated values of MSY. Third, it uses simulations designed to mimic the stock of swordfish in the northern Atlantic Ocean, so that the results are pertinent to assessment of that stock. Fourth, it introduces two new statistics that may prove useful in the application of production models to data.

Methods

Generation of Simulated Population—Base Trajectory

A base population trajectory of 30 years was generated with the "length-oriented population simulation model" (LSIM) of Goodyear (1989) and possessed the following characteristics, closely based on those of swordfish in the North Atlantic Ocean:

Natural mortality.—The simulations used a constant rate of natural mortality of 0.2/year from recruitment at age 1 onward. This is the value used for assessment purposes by the International Commission for the Conservation of Atlantic Tunas (ICCAT 1992).

Growth.—The simulations incorporated sexually dimorphic growth, which is well documented for North Atlantic swordfish, with the sex-specific von Bertalanffy growth equations of Ehrhardt (1992). The coefficient of variation (CV = 100 × SD/mean) of length at age was set to 10% for each sex at each age; however, because the length structure of simulated cohorts was modified by length-specific fishing, the realized CVs varied.

Fecundity.—Individual batch fecundity ϕ was computed for each simulated female fish as a function of lower-jaw fork length L by the relationship $\phi = P \times B$, where the probability of maturity P for a given length (Arocha et al. 1994) was

$$P = \frac{1}{1 + \exp[-0.06778(L - 189)]}, \quad (1)$$

and the maximum batch fecundity B for a given length (Arocha and Lee 1995) was

$$B = 70{,}016 \exp(0.18L). \quad (2)$$

The number of batches per year was assumed constant. Because the scaling parameter α of the recruitment function was adjusted to obtain the correct simulated yields, as explained below, the actual number of batches per year was inconsequential. It was set to 1, making the total population fecundity Φ the sum of the individual fecundities for all female fish.

Fishing mortality rate and yield.—The trajectory of simulated overall fishing mortality rate F was chosen so that simulated yields (Figure 1) would approximate closely the actual reported yields of North Atlantic swordfish from 1962 through 1991, as given in ICCAT (1993:217). This was achieved by our generating a slowly increasing trend in F for 20 years, then a more rapidly increasing F. We started with $F_1 = 0.1$ (subscripts represent year); $F_{20} = 0.2$; $F_{30} = 0.8$; and used linearly interpolated values for the intervening years. We then adjusted the F series slightly until yields were within 5% of the reported yields from ICCAT (1993). As will be described, recruitment was also adjusted to make the desired yields obtainable.

Recruitment.—Each year's recruitment R (at age 1) to the simulated population was determined by the population fecundity Φ through a deterministic Ricker (1975) recruitment model, $R = \alpha\Phi \exp(-\beta\Phi)$. The parameter β was set to the value that produced the presimulation recruitment from the equilibrium presimulation population fecundity, and the parameter α was then made large enough to allow the simulations to closely approximate the reported yields (ICCAT 1993).

Initial conditions.—Presimulation recruitment was assumed to be the ratio of mean yield to mean yield per recruit for the first 9 years of the simulation. The initial age distribution was set to the steady-state age distribution resulting from the presimulation recruitment level and the vector of F by length in the first year.

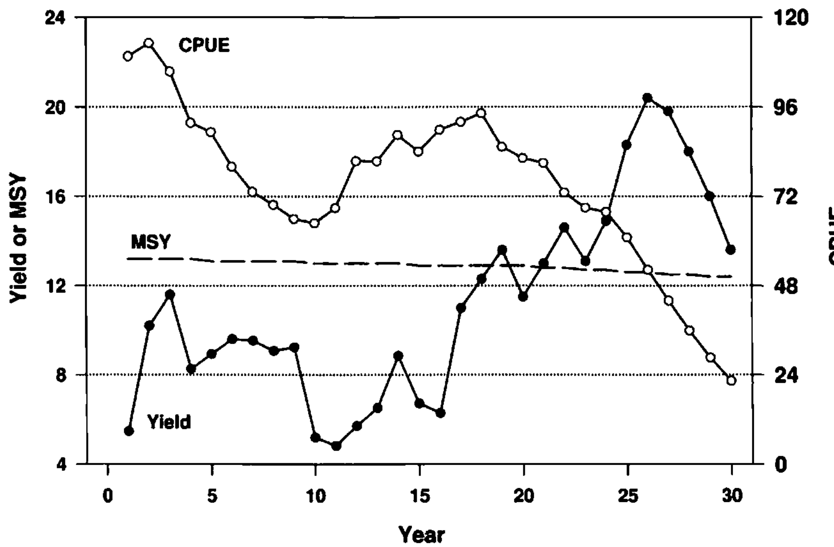

FIGURE 1.—Yield (10^3 metric tons), CPUE (10^6 units), and MSY (10^3 metric tons/year) from simulation of an age-structured swordfish-like stock subject to a base trajectory of fishing mortality (see text for details). The MSY was computed from recruitment and growth curves; it varied over time because of simulated gear changes in the fishery but had the same pattern in the base trajectory and in nine additional trajectories.

Selectivity.—For fish of age L in any year, the effective fishing mortality rate in the simulation was the product of the overall fishing mortality rate F in that year and the selectivity of the gear for fish of that length $S(L)$ in that year, where $0 \leq S(L) \leq 1$. The simulated selectivity curve was made to vary through time in two stanzas, mimicking the observed North Atlantic swordfish fishery. Years 1 through 20 simulated the change from a fishery using mainly harpoons to one using mainly longlines; years 21 through 30 simulated, through a more rapid change, the expansion of the longline fishery to geographic areas where smaller fish were increasingly vulnerable to the gear.

The selectivity pattern in simulation year 30 was given by the logistic function estimated by Kimura and Scott (1994) for the North Atlantic swordfish stock,

$$S(L) = 1/[1 + \exp(8.75 - 0.062L)], \quad (3)$$

which implies $S = 0.5$ at $L = 141$ cm. Selectivity in year 1 was given by a similar curve with $S = 0.5$ at 175 cm. The year-20 selectivity was set midway between these two, and other years' selectivities were interpolated linearly between those of years 1 and 20 or years 20 and 30 (Figure 2).

Resulting age structure.—The simulation model included 20 age-classes. Because of the rates of natural and fishing mortality applied, fewer than 1% of the simulated fish were of age 20 in any year.

Additional Population Trajectories

To provide a more general examination of the production model's performance, nine additional population trajectories were simulated and fit by the same procedure. The additional trajectories used the same biological and selectivity characteristics as the base trajectory but differed widely in initial population size and in the strength and pattern of fishing through time. Thus they were, one might say, simulations of the same swordfish stock as it might have evolved under different histories of fishing.

Management Benchmarks

For each simulation, we computed the "true" values of three management benchmarks that were later compared with the corresponding estimates from the surplus production model. These benchmarks are typically used to guide management when a production model is fit. The first benchmark was MSY in units of metric tons per year. The second was the fishing mortality rate in the final year relative to the fishing mortality rate that can produce MSY. This unitless quantity, F_{30}/F_{MSY}, forms an indication of the desirable increase or decrease in fishing. The third benchmark

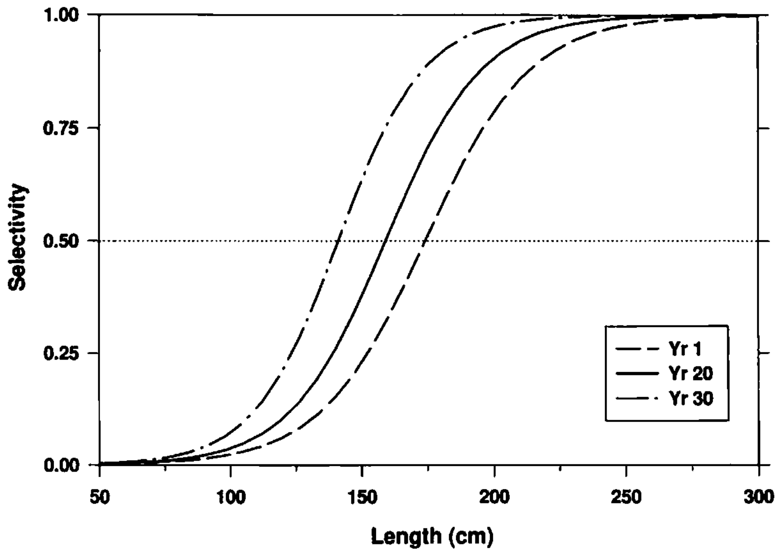

FIGURE 2.—Selectivity (relative F-at-length) curves for years 1, 20, and 30 of a simulated swordfish-like stock. Selectivity in other years was linearly interpolated.

was the biomass in the final year relative to the biomass at which MSY can be attained. This quantity, B_{30}/B_{MSY}, is also unitless and gives an indication of the relative stock status.

Estimation—Production Model

For fitting the production model, we used the yield (total simulated catch in biomass) and a simulated abundance index (Figure 1) from each simulation. We computed the abundance index by dividing the yield by the corresponding fishing mortality rate. This index was thus based on catch per unit effort (CPUE), as are most such indices derived from fishery data. For simplicity, no error was introduced into this index.

The production model used was the dynamic logistic surplus production model described by Prager (1994). This is an extension of the Schaefer (1954, 1957) model and uses a fitting procedure similar to that developed by Pella (1967). The basic model is derived by postulating that the time rate of surplus biomass production (the excess of growth and recruitment over natural mortality) can be represented by the differential equation

$$\frac{dB_t}{dt} = (r - F_t)B_t - \frac{r}{K}B_t^2, \tag{4}$$

where B_t is the population biomass at time t, F_t is the corresponding rate of fishing mortality, r is a constant model parameter often considered the population's intrinsic rate of increase, and K is a constant model parameter often considered the carrying capacity of the environment (maximum population size). For conversion of fishing effort rate f to fishing mortality rate, the common assumption $F_t = qf_t$, with constant catchability q, was used. By integrating equation (4) with respect to time, one can obtain model equations for projection of the biomass over time as well as the corresponding catch equations relating the yield in a time period to the starting biomass and the applied fishing effort. For a more detailed development, see Prager (1994).

Given the annual yields from the fishery and an annual index of abundance (or, equivalently, data on the annual fishing effort rate), and after assuming a statistical error model, one can fit the model and obtain estimates of the model parameters K and r, the catchability q, and the stock biomass throughout the time period. The management benchmarks are derived from these quantities; in particular MSY = $rK/4$.

For fitting, we used the ASPIC computer program (Prager 1995). That program fits the model under the assumption of no process error, but lognormal observation error in the annual abundance index. Thus, the program implements an "observation-error estimator" in the sense of Polacheck et al. (1993), who found such estimators superior to others for this application. Besides the usual point estimates, median bias-corrected estimates and 80% confidence intervals were computed on all benchmarks (as in Prager 1994) through bootstrapping with 401 realizations.

One other statistical detail must be mentioned. The method used for fitting introduces a nuisance parameter, the biomass in the first year of the data series. Estimates of this parameter often possess large standard errors and furthermore may take on unreasonable values. To avoid such values, the parameter can be constrained to a reasonable range or to a single value based on external information. Estimates of management benchmarks are, in some cases, sensitive to the value chosen, which complicates interpretation. To reveal any such sensitivity, two sets of estimates were made for each trajectory: one with all parameters estimated freely, the second with a penalty term (Prager 1994) added to the objective function (sum of squared residuals) to discourage solutions in which the estimated initial biomass was substantially greater than the estimate of K (the carrying capacity).

Reliability Statistics

In examining parameter estimates from any fitted assessment model, an analyst must always question the validity of the results. Goodness of fit is often used as a criterion; however, goodness of fit is of limited value in assessing a model's utility. There is no a priori guideline as to what constitutes "good" fit, and an arbitrarily complex model can always attain near perfect goodness of fit. Standard errors of parameter estimates are generally more useful in this regard.

We propose here two new ad hoc statistics, neither based on goodness of fit, for a quick appraisal of the probable utility of a production model fit. The first of these statistics, the *coverage index*, measures how widely the stock biomass has varied between $B = 0$ and $B = K$. The logic behind this measure is that the major cause of failure in production modeling is lack of contrast in the data (Hilborn 1979; Hilborn and Walters 1992). The second measure, the *nearness index*, measures how closely the modeled stock has approached B_{MSY}, the biomass level from which MSY can be taken as an equilibrium yield. The rationale for this index is that stocks that have been observed passing through B_{MSY} should support better estimates of MSY (and related benchmarks) than those that have not. Although the ideas behind these statistics have been expressed before, this is their first incorporation into quantitative form.

Each index would ideally be known for the underlying stock; however, because the true characteristics of the stock are unknown (except in simulation studies like this one), estimated values are used instead. The estimated coverage index has a range from 0 (least reliable) to 2 (most reliable). It is defined as

$$\hat{C} = \frac{\hat{B}^{+} - \hat{B}^{-}}{\hat{B}_{MSY}}, \tag{5}$$

where $\hat{B}^{+}$ is the smaller of either K or the largest value of estimated stock biomass in the time series, and $\hat{B}^{-}$ is the smallest value of estimated stock biomass in the time series.

The estimated nearness index $\hat{N}$ has a range from 0 (least reliable) to 1 (most reliable). It is defined as

$$\hat{N} = 1 - \frac{|\hat{B}_{MSY} - \hat{B}^{*}|}{\hat{B}_{MSY}}, \tag{6}$$

where $\hat{B}^{*}$ is the smaller of either K or the estimated stock biomass closest to $\hat{B}_{MSY}$. However, if the biomass trajectory is estimated to have crossed B_{MSY}, the index is defined to equal 1. We computed these indices for each trajectory to examine their potential usefulness.

Results

The selectivity changes applied to the simulated stock caused only minor changes in the "true" management benchmarks. Maximum sustainable yield decreased from 13,210 metric tons/year in simulation year 1 to 12,360 metric tons/year in year 30, a decrease of about 6%. Over the same period, B_{MSY}, the stock biomass at which MSY can be taken, decreased by 7%, from 69,460 metric tons to 64,480 metric tons; and F_{MSY}, the fishing mortality rate that obtains MSY from B_{MSY}, increased very slightly from 0.190/year to 0.192/year (measured as proportion of the available biomass, rather than number of fish).

In analyzing all 10 trajectories, point estimates and bias-corrected (BC) estimates of MSY, relative biomass, and relative fishing mortality rate were computed. When they were compared, the point and BC estimates were most often within a few percent of one another, with the BC estimates usually being closer to the "true" values. Both sets of estimates for the base trajectory are reported (Table 1), but for simplicity, only the BC estimates are reported for trajectories 2 through 10 (Table 2).

Base Trajectory

Estimates of MSY from the base trajectory were quite close to the "true" values (Table 1). Use of

TABLE 1.—Estimates of three management benchmarks from fitting a simple production model to 30 years of CPUE and catch data from an age-structured simulated population. The population had biological parameters and catch trajectory similar to those of North Atlantic swordfish, 1962–1991. The "true" MSY of the simulated population, computed by age-structured methods, declined from 1.32×10^4 metric tons/year under the first year's gear selectivity pattern to 1.24×10^4 metric tons/year under the final year's pattern.

Type of estimate	Estimates with all parameters freely estimated	Estimates with parameter B_1 constrained to $\leq K$
Estimates of MSY (metric tons/year)		
Point estimate	1.232×10^4	1.179×10^4
Bias-corrected estimate	1.240×10^4	1.237×10^4
80% confidence interval	9.86×10^3–1.46×10^4	1.01×10^4–1.48×10^4
Estimates of B_{30}/B_{MSY} (unitless)[a]		
True value	0.348	0.348
Bias-corrected estimate	0.445	0.444
80% confidence interval	0.373–0.508	0.373–0.495
Estimates of F_{30}/F_{MSY} (unitless)		
True value	3.2	3.2
Bias-corrected estimate	2.5	2.5
80% confidence interval	1.9–3.3	1.9–3.3

[a] Biomass ratios are estimated midyear values.

TABLE 2.—Estimated and "true" management benchmarks and estimates of proposed reliability statistics from analyzing 10 simulated, age-structured, 30-year population trajectories with a simple production model. When using a penalty term to constrain the initial biomass gave different estimates, results are designated "P" (e.g., trajectory 1P). Comparisons of MSY are with the "true" year-30 value of 1.236×10^4 metric tons/year. By this criterion, an estimate corresponding to the "true" year-1 MSY (1.321×10^4 metric tons/year) would have a positive error of 6.9%. Asterisks mark trajectories in which estimated MSY is within ±15% of the "true" value.

Trajectory	Brief description of trajectory dynamics (also see Figures 3–14)	MSY		F/F_{MSY}, year 30		B/B_{MSY}, year 30		Nearness index (estimated)	Coverage index (estimated)
		Estimated	Percent error	True	Estimated	True	Estimated		
1*	Base run; similar to North Atlantic swordfish	1.240×10^4	0.3	3.18	2.45	0.35	0.45	1.00	1.50
1P*	(same)	1.237×10^4	0.1	3.18	2.48	0.35	0.44	1.00	1.51
2	F varies between low level and approximately F_{MSY}	1.635×10^4	32.3	0.63	0.35	1.11	1.52	0.53	0.53
2P	(same)	1.539×10^4	24.5	0.63	0.38	1.11	1.48	0.62	0.62
3*	F starts high and declines to below MSY level	1.262×10^4	2.1	0.63	0.66	1.13	1.08	1.00	0.71
4*	Relatively constant high F	1.413×10^4	14.3	2.14	2.56	0.24	0.19	0.54	0.36
5*	Relatively constant low F	1.057×10^4	−14.5	0.63	0.73	1.07	1.03	1.00	0.49
6[a]	Relatively constant, very high F								
7[a]	Varying F always very low								
7P	(same)	6.804×10^3	−45.0	0.21	0.28	1.36	1.67	0.46	0.46
8*	F starts low; increases to very high level in year 11; declines to low levels by year 16; remains low	1.065×10^4	−13.8	0.21	0.27	1.70	1.63	1.00	1.32
9	Varying F high for first 13 years; low for other years	1.757×10^4	42.2	0.99	1.20	1.05	0.57	0.61	0.51
10*	F oscillates near F_{MSY}	1.250×10^4	1.1	1.36	1.32	0.94	0.96	1.00	0.15

[a] No convergence; no estimates could be obtained.

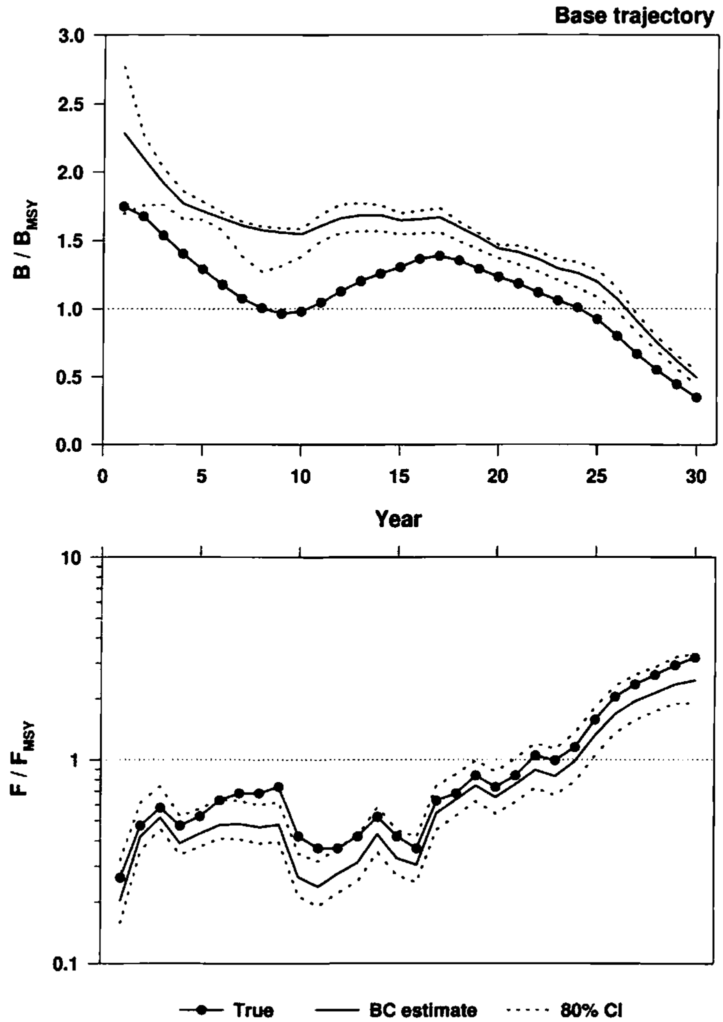

FIGURE 3.—Results of a production model assessment of a simulated swordfish-like stock (base trajectory). "True" trajectories of B/B_{MSY} and F/F_{MSY} are shown with bias-corrected estimates and corresponding 80% nonparametric confidence intervals. Ratio estimates are more precise than estimates of absolute biomass and fishing mortality rate.

the penalty term to constrain $\hat{B}_1$ produced a slightly worse estimate; however, use of the bias correction reduced that difference, and the two BC estimates were only negligibly different from the population's "true" MSY in year 30. The constrained estimate had a slightly narrower confidence interval on MSY.

The estimates of relative biomass over time were overly optimistic, particularly in the first half of the series (Figure 3). The estimated trajectory lagged the true decline below $B = B_{MSY}$ by about 2 years. Estimates of the relative fishing mortality rate were somewhat too optimistic (Figure 3), although the approximate 80% confidence intervals encompassed the true values for much of the time series.

Estimated reliability indices were high for the base trajectory, suggesting relatively reliable results. This was true of both the coverage index and the nearness index (Table 2).

Trajectories 2 through 10

Trajectory 2 represented a stock whose biomass is always above B_{MSY}; i.e., an underexploited stock. Estimated reliability indices were both lower than those for the base trajectory (Table 2), suggesting less reliable results. Estimates of stock status and MSY correctly identified the stock as un-

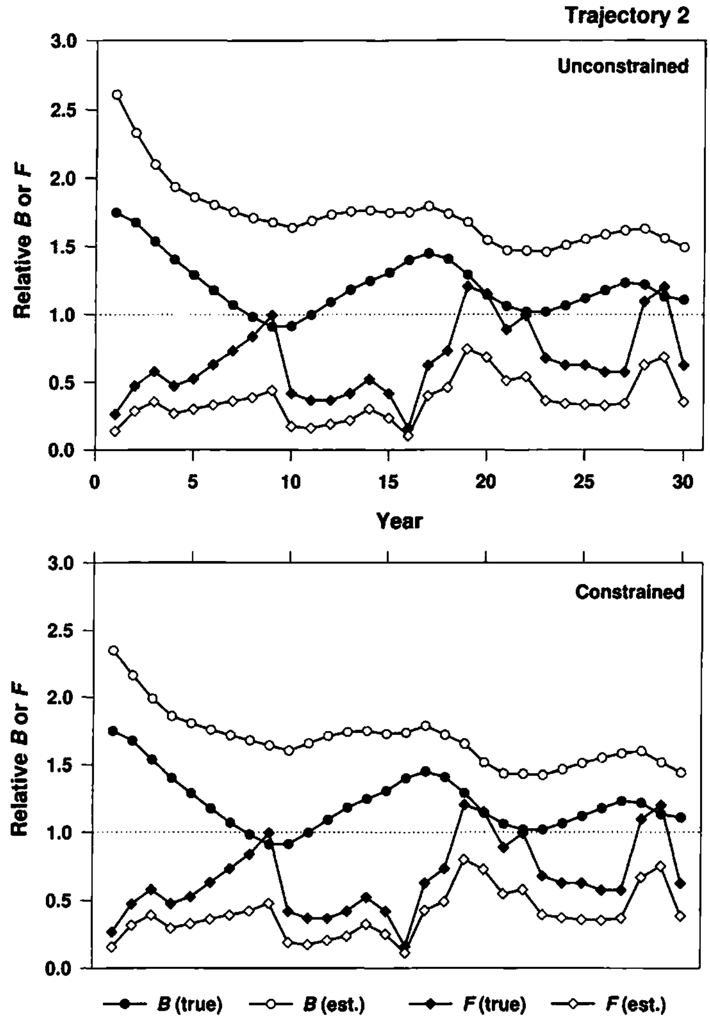

FIGURE 4.—Results of a production model assessment of a simulated swordfish-like stock (trajectory 2). Relative B is the ratio of B/B_{MSY}. Relative F is the ratio F/F_{MSY}. The constrained estimation (est.) used a penalty term used to discourage (but not prevent) estimates of $B/B_{MSY} > 2.0$. Estimates incorporate bias correction.

derexploited but exaggerated the degree of additional exploitation possible (Figure 4; Table 2). Results using the penalty term were slightly better (Figure 4; Table 2) but still too optimistic.

Trajectory 3 characterized a simulated stock with diminishing fishing pressure. As the F declined from a very high to a moderate level, the biomass increased, passing through B_{MSY}. The estimated nearness index for this trajectory was high (1.0), but the estimated coverage index was only moderate (Table 2). The MSY was estimated well, as was the stock status in the last year (Table 2; Figure 5). Because the unconstrained estimate of B_1 was well below K, the penalty term played no part in estimation.

Trajectory 4 had little contrast through time: F was high throughout, and the biomass level, low at the start, declined further over time. Both nearness and coverage indices were estimated as low to moderate. The model correctly identified the stock as overexploited and with a low and declining biomass, but it was slightly too pessimistic about stock status (Table 2; Figure 5).

Trajectory 5 pictured a slightly underexploited stock with some trend towards full exploitation in the final years. The model correctly characterized the stock as slightly underexploited (Figure 5; Table 2). The estimate of MSY was slightly too small and the estimates of F/F_{MSY} were slightly too large.

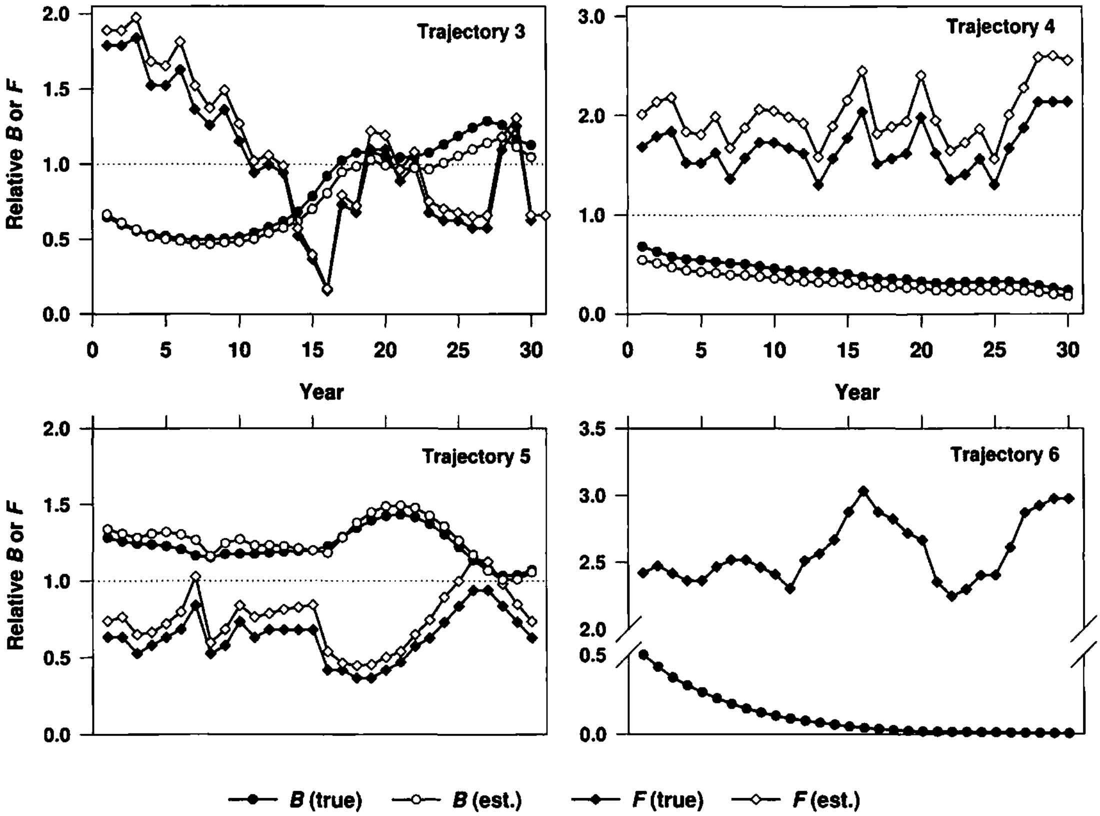

FIGURE 5.—Results of production model assessments of a simulated swordfish-like stock subjected to four different trajectories of fishing mortality. Relative B is the ratio B/B_{MSY}. Relative F is the ratio F/F_{MSY}. Estimates incorporate bias correction.

Trajectory 6 illustrated the end of what has been called a "one-way trip" (Hilborn and Walters 1992). An extremely high F was applied throughout (Figure 5), and the stock biomass, depleted in year 1, became increasingly depleted each year. We were unable to obtain estimates from the production model, because the solution algorithm did not converge. This indicates insufficient information to estimate the desired benchmarks.

Trajectory 7 represented the opposite of trajectory 6: the stock was near virgin levels and was exploited very lightly (Figure 6). Estimation without a constraint on B_1 did not converge. When the penalty term was used to constrain B_1, convergence was achieved. The model correctly identified the stock as very lightly exploited; however, the estimate of MSY was about 45% too low (Table 2), although estimated as substantially above the largest recorded catch. The 80% confidence intervals on MSY were particularly wide for this trajectory: 4,669–24,570 metric tons/year. Relative stock size and relative F in year 30 were both overestimated.

The stock in trajectory 8 was near carrying capacity in year 1 and was subjected to a strong pulse of fishing mortality that ended by year 15. The model estimated the patterns of biomass and fish mortality quite well (Figure 6; Table 2). Although MSY was underestimated by about 14%, the model correctly identified the stock as substantially over B_{MSY} and being fished at substantially below F_{MSY}.

In trajectory 9, F changed erratically, with a decreasing trend overall; the simulated stock responded with a modest recovery by the end of the trajectory (Figure 6). The model estimated the relative F trends fairly well, especially in the most recent years, although estimates of F were a bit high throughout. Estimates of relative biomass were also overly pessimistic throughout, and the model markedly underestimated the recovery in the final 10 years. The value of MSY was over-

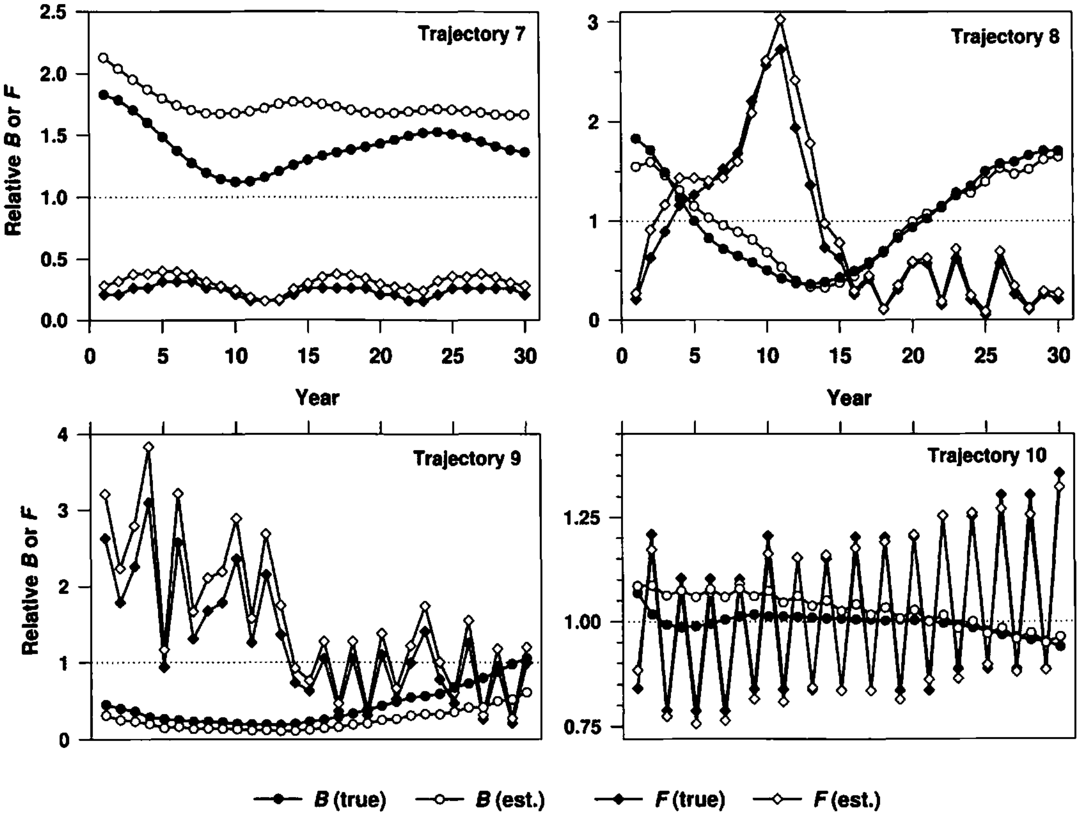

FIGURE 6.—Results of production model assessments of a simulated swordfish-like stock subjected to four different trajectories of fishing mortality. Relative B is the ratio B/B_{MSY}. Relative F is the ratio F/F_{MSY}. Estimates incorporate bias correction.

estimated by about 43%, and the estimated 80% confidence interval (16,060–19,360 metric tons/year) did not include the "true" value.

Trajectory 10 represented a stock with F oscillating about F_{MSY}, with a slight increasing trend, whereas the stock responds with a slight decline. The model estimated all three benchmarks quite well (Figure 6, Table 2).

Discussion

The results of this study provide insight into several subjects: the effects of moderate selectivity changes on MSY estimates; the applicability of production models to strongly age-structured stocks; the effects of constraints on estimates of starting biomass; and the potential usefulness of the two new statistics as indicators of reliability of production model estimates.

As noted earlier, the selectivity changes simulated in this study resulted in relatively small changes in the MSY obtainable from the stock, in the biomass that can support MSY, and in the F at which MSY can be taken. Nothing in our results suggests that selectivity changes of this magnitude should proscribe the use of a production model or cause problems in estimation for a stock similar to North Atlantic swordfish. Similarly, we found nothing to indicate that production models cannot or should not be used on strongly age-structured stocks. To the contrary, in most cases the production model produced useful assessment results, and the estimates of MSY were usually near the underlying "true" values derived from the characteristics of the simulated population, including age and size.

In this study, the major source of error in a statistical sense was specification error (i.e., the failure of the simulated population to follow the model exactly). The CPUE index was based on the exact catch and the exact fishing effort (in biomass units), and therefore did not contribute error. This was done to isolate the major questions being addressed: age structure and changing catchability. However, the fitting procedure used assumes that statistical error may occur in the CPUE index and that any such error is lognormal. In general, we expect that random error in fishery data is more likely to occur in effort or CPUE than in the catch data. On the basis of that consideration and the theory of linear and nonlinear regression, we expect that the major effect of error in the data, as found in a real analysis, would be to increase the variance of the parameter estimates. However, it is possible that such error might also introduce or increase bias (Ratkowsky 1983).

We obtained no strong impressions about the use of a penalty term to constrain the starting biomass. In two cases (trajectories 1 and 2), using the penalty term influenced the estimates slightly. In another case (trajectory 7), obtaining estimates—although very imprecise and inaccurate ones—was possible only through the use of the penalty term.

The nearness and coverage indices (N and C) proposed here appear useful as reliability indicators for production model results. In Table 2, trajectories for which the estimated MSY is within 15% of the "true" value are marked with asterisks. Most such cases have $\hat{N} = 1$ (i.e., the population is estimated to have crossed the MSY level). (Conversely, all trajectories with $\hat{N} = 1$ have errors smaller than 15% in estimating MSY.) Of the trajectories accurate within 15%, three of the four lowest percentage errors are associated with high (>1.0) values of the coverage index. Further research and experience with these indices are undoubtedly needed. Nonetheless, their use, along with such traditional measures as the CVs of the parameter estimates, may help the analyst to gauge the reliability of a production model analysis and to describe it concisely.

For several trajectories, the estimated confidence intervals in this simulation study did not encompass the "true" underlying values of MSY, B_{30}/B_{MSY}, or F_{30}/F_{MSY}. Clark (1985:209) described some of the uncertainties inherent in fisheries data, and Prager (1994) discussed several reasons why estimated confidence intervals for fisheries models are likely to be optimistic. We believe that it is probably appropriate to consider such intervals, in general, to be minimum estimates of variability. The present results are consistent with that view.

In conclusion, the results of this study suggest that production models can be useful in assessing even strongly age-structured populations with moderate changes in selectivity. In each case except for trajectory 9 (a rather artificial example), the model correctly indicated whether the population was overexploited or underexploited. The quantitative estimates of the degree of departure from the optimum state were not always accurate, but the estimates would lead to qualitatively correct management decisions about increasing or decreasing fishing effort. For simulated stocks that were near or had passed through B_{MSY}, the model was also able to make reasonably accurate estimates of MSY. For the other simulated stocks, it is reasonable to suppose that if simulated management decisions were made in accordance with the model results and if the simulation were then to continue for additional years, the realized estimates of MSY would improve as the stock approached its optimum level. Thus, our results support the use of simple surplus production models on stocks like swordfish in the North Atlantic.

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