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Abstract.—The effect of research programs designed to increase precision in estimates of stock assessment parameters were evaluated for Gulf of Mexico king mackerel *Scomberomorus cavalla.* Monte Carlo simulations of the entire assessment analysis were used, consisting of separable virtual population analysis (VPA), calibrated VPA, estimation of target fishing mortality rate, and projection of catch at that rate. The distribution of estimates of allowable biological catch (ABC) from the simulations indicated that realistic improvements in research could substantially reduce the uncertainty in ABC estimates from a 40% to a 20% coefficient of variation. Expected yield for risk-averse strategies increased with enhanced research programs. Opportunity losses of forgone yield and lost surplus were diminished as well. Benefits of research combined with risk-averse management strategies to the fishery and to the economy appear to substantially exceed the costs of the research.

The idea that scientific research programs enhance effective management of fishery resources is often espoused, but the benefits of such programs are seldom evaluated. Logically, it is expected that research information will improve the assessment of the status of a fish stock (increase the precision in the estimate of that status) and that this will be translated into the opportunity for improved management (Gulland 1984). However, gains are not expected to be linear over research investments, and relative benefits of research on specific population parameters are not readily apparent. Additionally, the benefit of alternative research programs is dependent upon the management strategy that is chosen. As a result, quantitative evaluation of stock assessment research benefits has not been regularly conducted.

This article addresses issues of stock assessment research and ensuing management for a specific example, king mackerel *Scomberomorus cavalla* in the Gulf of Mexico. Monte Carlo simulation methods (Restrepo et al. 1991) were used in a decision-analytic framework (Raiffa 1968) to evaluate effects of candidate research programs for this stock and to explore the interaction between benefits of research and strategies chosen for managing the stock.

Gulf of Mexico King Mackerel: Status and Assessment

King mackerel in the U.S. Gulf of Mexico were heavily impacted by fisheries in the late 1970s and early 1980s, but with the implementation of regulatory measures in the mid-1980s, the stock appears to be recovering (Powers 1991). Long-term potential production by the present directed fisheries on this stock has been estimated to be 8,200 tonnes annually (Powers 1985). Allowable biological catch (ABC) under the current fisheries management regime for fishing year 1991–1992 is about 2,200 tonnes. This marks significant improvement over 1985–1986, at which time the ABC was approximately 650 tonnes. At that time stringent management procedures including commercial quotas, recreational bag limits and closures, and associated state regulations were implemented under the mandate of the Coastal Pelagics Fishery Management Plan of the Gulf of Mexico Fishery Management Council (GMFMC 1985), leading to reductions in fishing mortality rate and subsequent increases in ABC.

The fishery management plan developed an operational protocol that included an annual assessment of the stock and a review of that assessment

TABLE 1.—Data elements used in the estimation of allowable biological catch (ABC), and the distribution and precision information used in the Monte Carlo simulations with the initial (status quo) research program. Coefficient of variation (CV) = 100 × SE/mean; CV measures uncertainty and is inversely related to precision. A plus sign with an age denotes that age or older (e.g., age 11+ denotes age ≥11). CPUE = catch per unit effort.

Element	Description
Catch (C)[a]	Total catch, in numbers of fish, for fishing years 1979–1980 to 1989–1990; lognormally distributed; mean as estimated and CV of 21.25% (CV combined from the CV of recreational catch estimated from sample survey data [30%] and an assumed CV of 5% for commercial "census" data)
Proportion of catch at age (CAA)[a]	Proportions by year and age (age 1–11+); proportions (p) multinomial and CV $\propto \sqrt{(1-p)/(np)}$, where n is assumed to be 1/500th of total catch (equivalent to the average sampling fraction of approximately 0.2% during the assessment period)
Bycatch (BY)[b]	All catch of age-0 fish; lognormally distributed; mean and CV (=30%) approximated from general linear model estimate (Nichols et al. 1990)
Indices of abundance (IA)[b]	Six indices, lognormally distributed; means and CVs from general linear model analyses (Powers et al. 1991): (1) Florida commercial CPUE, ages 4–6, 1984–1985 to 1989–1990, CV = 22.27%; (2) northwest Florida charterboat CPUE, ages 1–3, 1982–1983 to 1989–1990, CV = 30.69%; (3) Florida headboat CPUE, ages 3–5, 1979–1980 to 1989–1990, CV = 18.15%; (4) Gulf larval index, ages 5+, 1984–1985 to 1986–1987, CV = 100%; (5) Gulf private recreational CPUE, ages 3–6, 1980–1981 to 1989–1990, CV = 86.89%; and (6) northern Gulf groundfish survey index, age 0, 1979–1980 to 1989 (excluding 1983–1984, 1986–1987, and 1987–1988), CV = 30.69%
Natural mortality rate (M)[c]	Uniformly distributed between 0.1 and 0.2
Projected recruitment (age 0) for 1990–1991 and 1991–1992 (R)[d]	Lognormally distributed; mean and CV as observed from the estimates for the time series of 1979–1980 to 1988–1989 from individual VPA minimizations in a Monte Carlo simulation (with all of the above random inputs)

[a] Point estimate and recreational CV were from data analyses; distribution type and CV of commercial catch were assumed.
[b] Point estimate, distribution type, and CV were all from data analyses.
[c] Point estimate, distribution type, and range were all assumed.
[d] Point estimate and CV were from virtual population analyses (VPA); distribution type was assumed.

by an assessment panel; these were most recently conducted in April 1991 (Powers 1991). At that time the status of the stock was evaluated through the 1989–1990 fishing year (through June 30, 1990), and estimates of stock size at age were given for that date. Then ABC for the 1991–1992 fishing year (July 1, 1991 through June 30, 1992) was obtained by projecting stock size at age through the 1990–1991 season by using preliminary 1990–1991 catch estimates, and subsequently projecting stock size at age for 1991–1992 by using the target (criterion) fishing mortality rate of management. The criterion presently used is the fishing mortality rate at which equilibrium spawning potential per recruit is 30% of what it would be with no fishing. The catch projection that resulted from the application of this rate to the stock in 1991–1992 was the estimated ABC for that year.

Uncertainty in ABC estimates has been characterized in numerous ways. For example, the uncertainty has been expressed as a range of the ABC values resulting from sensitivity tests, and it has been represented by a lognormal distribution derived from ad hoc estimates of variance around the deterministic ABC value that was established by the assessment and which is treated as the mode (Powers 1985, 1991). In the most recent assessment, Monte Carlo methods were also used and found to produce results similar to the ad hoc lognormal approach (Powers 1991). The GMFMC evaluates the ABC estimate and its variance, takes into consideration what it perceives to be relevant social and economic factors and risks, and then sets a total allowable catch (TAC), which may be greater or smaller than ABC.

Assessment Methods and Monte Carlo Simulations

The assessment methodology presently being used for Gulf of Mexico king mackerel is virtual population analysis (VPA) calibrated with auxiliary information on indices of abundance (see Appendix). The data inputs are in Powers et al. (1991) and consist of a catch-at-age matrix, annual relative-abundance values for each of six indices, and a series of constraints (e.g., natural mortality rate is assumed to be 0.15/year; other constraints are given in the Appendix). The fishing mortality rates (F) at age for 1989–1990 were computed from the parameter solutions and used to determine the target fishing mortality rate (F at 30% spawning potential per recruit). Subsequently, a 2-year projection of the 1989–1990 stock was carried out under the assumption that recruitment for 1990 and 1991 was constant and equal to the geometric mean of the VPA estimates for the entire time series. The projected catch in the 1991–1992 season at the target F is the estimate of ABC.

TABLE 2.—Existing (Θ_k: $k = 0$) and alternative research programs (Θ_k: $k = 1, 2, \ldots, 5$), defined as percent reductions in the coefficients of variation (CV = 100 × SE/mean) for each data element in the stock assessment. See Table 1 for definitions of data elements. Also, approximate relative research costs are estimated for each research activity.

Data element	Research program Θ_k $k=0$	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$
	Percent reduction in CV of data element					
C	0.0	25.0	50.0	50.0	50.0	50.0
IA	0.0	25.0	50.0	50.0	50.0	50.0
CAA	0.0	25.0	50.0	50.0	50.0	50.0
BY	0.0	25.0	0.0	25.0	25.0	50.0
M[a]	0.0	12.5	0.0	12.5	25.0	50.0
R	0.0	12.5	0.0	12.5	25.0	50.0
	Relative research costs (US$)					
C	1.00	1.33	2.00	2.00	2.00	2.00
IA	1.00	1.33	2.00	2.00	2.00	2.00
CAA	1.50	2.00	3.00	3.00	3.00	3.00
BY	0.50	0.67	0.50	0.67	1.00	1.00
M	0.10	0.50	0.10	0.50	0.58	0.88
R	0.10	0.50	0.10	0.50	0.58	0.88
Total cost	4.20	6.33	7.70	8.67	9.17	9.75
Total normalized cost[b]	1.00	1.51	1.83	2.06	2.18	2.32

[a] For *M*, alternative research programs ($k = 1, 2, \ldots, 5$) used a triangular distribution with a mode of 0.15 and end points defined by the appropriate reduction in CV from that at uniformity.
[b] Normalized to $k = 0$.

Monte Carlo methods (Restrepo et al. 1991) were used to characterize the uncertainty in the estimation of 1991–1992 ABC. The distributions and coefficients of variation (which measure uncertainty) of six basic data elements were defined from input distributions (Table 1). These distributions were either derived from the original analyses by which these data elements were estimated, or were subjectively specified after discussions by the assessment panel (Powers 1991). Thus, in the case of abundance indices obtained from general linear model analyses after logarithmic transformations, the estimates were taken to be lognormally distributed and their standard errors were available from the analyses. The choice of lognormal distributions for the catch estimates was largely out of analytical convenience, because negative catches cannot occur with a lognormal distribution (as they could, for instance, with a normal distribution). The choice of a uniform distribution for natural mortality (*M*) is heuristic and reflects the fact that the scientists involved perceived, from life history characteristics, that *M* could take on any value in the interval 0.1–0.2 with equal probability.

A single simulation experiment consisted of 1,000 Monte Carlo iterations of the sequence of a separable VPA (SVPA), the Marquardt minimization of the calibrated VPA, determination of the target fishing mortality rate vector, and the 2-year projection. The resulting set of ABC estimates was sorted and classified for further analysis.

Alternative Research Programs

Five enhanced research programs ($k = 1, 2, \ldots, 5$) were hypothesized and tested with the Monte Carlo simulation methods (Table 2). Each program was defined by percent reductions in coefficients of variation (CV) in each of the six basic data elements for the April 1991 assessment (Table 1; $k = 0$: the status quo research program). Therefore, relative to $k = 0$, an enhanced research program produced an increased precision in three or more of the six data elements. Each enhanced program consisted of CV reductions for the entire time series for which data were included. The research programs were arbitrarily selected, but represent a realistic integration of activities. No attempt was made to directly define the mechanism by which a CV reduction was obtained, as in other studies (e.g., Silvert and Powles 1983). For example, reduction in the CV of catch might be obtained by increasing dockside survey samples by a specified amount. For any specific data element, there could be numerous ways in which a CV reduction could be achieved.

Relative costs of research were assigned to each element by scaling approximate costs to that which is spent on catch and abundance index research in the status quo research program ($k = 0$). These two were assigned a cost of 1.0 and other elements within the status quo program were then scaled proportionally (Table 2). Costs of the expanded research efforts ($k > 0$) were generally assumed proportional to CV (i.e., linearly related to the square root of sample size). The exceptions to this rule were the costs of initial reductions in CVs for recruitment and natural mortality estimates (12.5% reductions in their CVs) would require some start-up costs at the level of five times the status quo. Total costs for a research program were then normalized to the status quo program ($k = 0$: Table 2) and, thus, yield per cost was measured in tonnes of yield per status quo research cost. The cost matrix is approximate; for example, it does not address economies resulting from integrated sampling for multiple species. However, the relative values are reasonably accurate and useful for the purposes of the analyses in this example.

Our hypothetical research programs address the effect on ABC uncertainty if the data elements had been collected with increased precision in the past. Therefore, this evaluation is a retrospective analysis of the potential effects of implementation of these research programs on the 1991–1992 TAC decision, had the management decisions and their implementation in prior years not changed. One thousand Monte Carlo simulations were performed for each of the five alternative research programs ($k = 1, 2, \ldots, 5$), exactly as they were conducted for the status quo program ($k = 0$).

Decision Analysis

Allowable catch of Gulf of Mexico king mackerel was evaluated within a decision analysis framework (Raiffa 1968) in which the fisheries managers are presented estimates of the state of nature (ABC), which they use to decide on TAC; the effect of research on that decision is also examined. The analysis assumes that there is a "true" state of nature (i.e., the ABC in 1991–1992). However, any calculated ABC value is an estimate of a parameter; hence, uncertainty remains in the assessment. Implicit in our evaluation is the notion that the collection of assessment analyses (estimation of catch at age, general linear models, SVPAs, tuned VPAs, and projections) lead to unbiased estimates of ABC—in other words, that we are using the right data and that our assessment efforts (model constraints, etc.) are a realistic representation of the state of nature.

The simulations were used to generate probability distributions of ABC estimates. The 1,000 ABC_{ik} estimates ($i = 1, 2, \ldots, 1{,}000$) from each of the six simulation experiments ($k = 0, 1, 2, \ldots, 5$) were sorted to provide the relative frequency distribution. The results were also grouped into five classifications ($j = 1, 2, \ldots, 5$) for each 20th-percentile group of ABC estimates ($j = 1$ refers to the smallest 200 of the 1,000 ABC estimates, and $j = 5$ refers to the largest 200 estimates among the 1,000 simulations). These five groups represent degrees of risk: for each of these five groups, there is a 20% chance that the "true" ABC could fall within that group (Figure 1). Fisheries managers partially base their selection of TAC on the degree of risk they wish to take that the TAC will be greater or less than the true ABC. Hence, the five groupings based on percentiles are termed *TAC risk strategies.*

The analysis makes reference to the following symbols:

- $\boldsymbol{\Theta}$ = a vector of research experiments (Θ_k: $k = 0, 1, \ldots, 5$), where Θ_0 is the initial status quo research program;
- **ABC** = the matrix of estimates of the state of nature (i.e., the distribution of ABC estimates; $\mathrm{ABC}_{ik}: i = 1, 2, \ldots, 1{,}000$; $k = 0, 1, \ldots, 5$);
- **TAC** = a vector of decisions (i.e., the TAC risk strategy alternatives ($\mathrm{TAC}_j: j = 1, 2, \ldots, 5$);
- **\$** = relative cost vector of research ($\$_k: k = 0, 1, \ldots, 5$), where $\$_0$ is the cost of the status quo research program, assigned a relative cost of 1; costs are assumed to be specified without error;
- **Y** = Yield matrix (Y_{jk}, tonnes) for TAC strategy alternatives ($j = 1, 2, \ldots, 5$) and research experiments ($k = 0, 1, \ldots, 5$);
- **Y/\$** = yield per cost matrix, $(Y/\$)_{jk}$, for TAC strategy alternatives ($j = 1, 2, \ldots, 5$) and research experiments ($k = 0, 1, \ldots, 5$);
- P_{ijk} = conditional probability of ABC_{ik} given decision TAC_j and research Θ_k; if ABC_{ik} falls within the jth-percentile group, then this probability is equal to the reciprocal of the number of all ABC estimates that fall within that percentile group (1/200); if ABC_{ik} does not fall within the jth-percentile group, then this probability is 0.

Several expected values were calculated, including expected allowable biological catch given research program k,

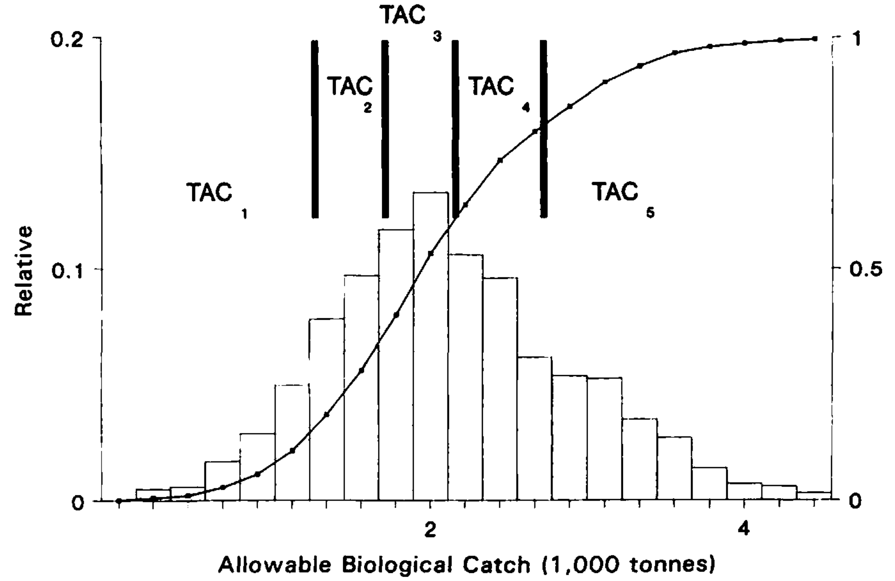

FIGURE 1.—Relative frequency and cumulative distribution of estimates of allowable biological catch (ABC) from the status quo research program (Θ_0) and different risk strategies (based on total allowable catch, or TAC_j: j = 1, 2, . . . , 5, referring to increasing 20th-percentile intervals of the probability that TAC_j exceeds the true ABC).

$$E[\text{ABC} \mid \Theta_k] = \Sigma_i\,(\text{ABC}_{ik})/1{,}000; \quad (1)$$

expected yield given research program k and decision strategy j,

$$E[Y \mid \text{TAC}_j, \Theta_k] = \Sigma_i\,(\text{ABC}_{ik}\,P_{ijk}); \quad (2)$$

expected change in yield with enhanced research (k = 1, 2, . . . , 5),

$$E[\Delta Y \mid \text{TAC}_j, \Theta_k] = E[Y \mid \text{TAC}_j, \Theta_k] - E[Y \mid \text{TAC}_j, \Theta_0]; \quad (3)$$

and expected opportunity loss (loss in yield resulting from uncertainty in ABC estimates and from a particular risk strategy),

$$\text{EOL}[Y \mid \text{TAC}_j, \Theta_k] = E[Y \mid \text{TAC}_j, \Theta_k] - E[\text{ABC} \mid \Theta_k]. \quad (4)$$

Similar expectations were calculated for yield per cost:

$$E[(Y/\$) \mid \Theta_k] = \Sigma_i\,\{(\text{ABC}_{ik}/\$_k)\}/1{,}000; \quad (5)$$

$$E[(Y/\$) \mid \text{TAC}_j, \Theta_k] = \Sigma_i\,\{(\text{ABC}_{ik}/\$_k)P_{ijk}\}; \quad (6)$$

$$E[\Delta(Y/\$) \mid \text{TAC}_j, \Theta_k] = E[(Y/\$) \mid \text{TAC}_j, \Theta_k] - E[(Y/\$) \mid \text{TAC}_j, \Theta_0]; \quad (7)$$

and

$$\text{EOL}[(Y/\$) \mid \text{TAC}_j, \Theta_k] = E[(Y/\$) \mid \text{TAC}_j, \Theta_k] - E[(Y/\$) \mid \Theta_k]. \quad (8)$$

The term *risk-averse* is used to describe TAC management decisions in which the probability of TAC exceeding the true value of ABC in 1991–1992 is small (less than 50%), whereas decisions deemed *risk-prone* have larger probabilities. A *risk-neutral* strategy is one in which the chance of TAC exceeding the true ABC would be 50%. Note that this definition of risk is limited to short-term risks of not achieving the target fishing mortality rate. The implications for long-term risks are discussed in the following section. Thus, of the TAC_j risk strategies, j = 1 and j = 2 imply risk aversion, j = 4 and j = 5 imply risk-prone strategies, and j = 3 implies approximate risk-neutral behavior (Figure 1).

Results and Discussion

Enhanced research contracted the tails of the distribution of ABC estimates (Figures 1, 2), reducing the probability of very low or high estimates of ABC. The CV of the ABC estimates was reduced from 40% for research program Θ_0 to 20% for Θ_5 (Table 3). Without an enhanced research program, there was a 20% chance that the estimate of ABC would be no greater than 1,420 tonnes (Figure 2). Research program Θ_2 reduced the risk to just 5%. Similarly, the chance that the ABC could be lower

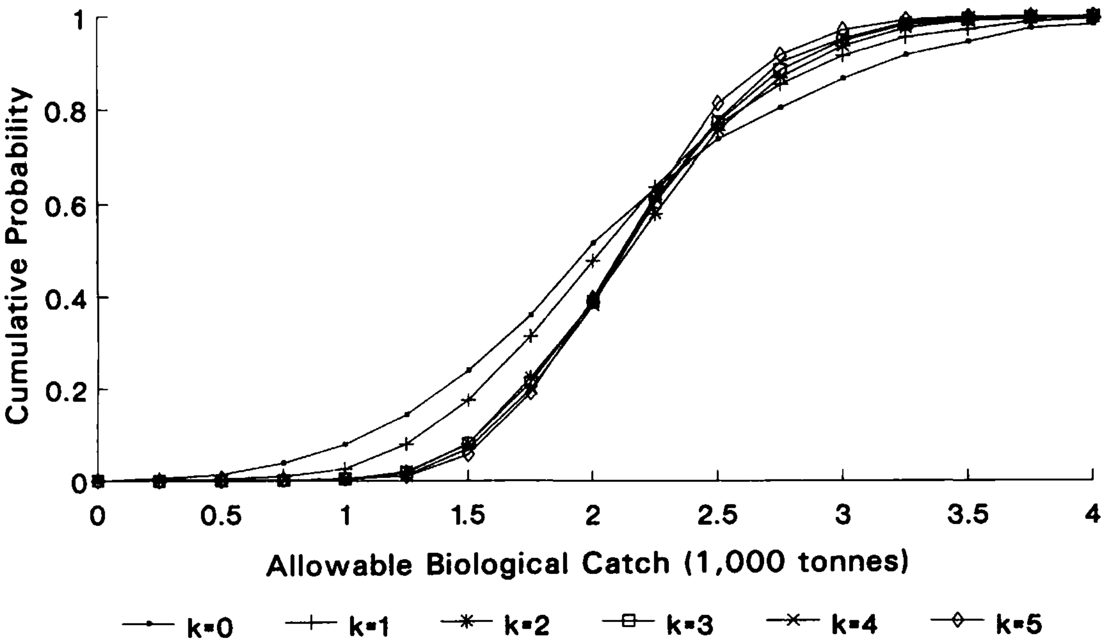

FIGURE 2.—Cumulative probability distributions of 1,000 Monte Carlo simulation estimates of allowable biological catch for each of six research options (Θ_k: status quo, $k = 0$; enhanced research programs, $k = 1, 2, \ldots, 5$).

than 1,820 tonnes was reduced from 40% (under Θ_0) to 26% (under Θ_2).

The king mackerel assessment example showed decreasing marginal returns for research investments: Θ_3, Θ_4, and Θ_5 did not produce as much improvement in precision as did Θ_1 and Θ_2 (Tables 3, 4). We did not attempt to carry out a sensitivity analysis exercise to determine which specific data elements dominated the uncertainty in the status quo program (e.g., as in Turner and Restrepo 1992). Such a study would provide valuable insight, especially if emphasis were placed on improving the precision of a single data element in the analysis. In this study, the improvement in precision was predicated on modification of a group of *existing* research programs. Large gains may still accrue from directing research toward more-expensive ecosystem and predator–prey studies. Additionally, economies of scale will be realized from research programs directed at multiple fish stocks, rather than at the Gulf of Mexico king mackerel alone. With such programs, research costs per fish stock could be considerably less.

Expected opportunity loss (EOL) is the loss that results from not knowing the true value of ABC (i.e., the loss due to the uncertainty in the estimate of ABC). For risk-averse and risk-neutral strategies ($TAC_{1,2,3}$), the loss is interpreted as forgone

TABLE 3.—Analyses of yield (Y) and yield per cost (Y/\$) by 1,000 Monte Carlo simulations for each of six research options (Θ_k: status quo, $k = 0$; enhanced research programs, $k = 1, 2, \ldots, 5$). ABC = allowable biological catch. Coefficient of variation (CV) = 100 × SE/mean.

Descriptor	Research program Θ_k					
	$k = 0$	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$
Yield (1,000 tonnes)						
Expected Y (E[ABC | Θ_k])	2.08	2.09	2.18	2.16	2.16	2.14
Median Y	1.98	2.04	2.16	2.15	2.14	2.13
CV of Y	0.40	0.31	0.24	0.23	0.22	0.20
Yield per cost (1,000 tonnes per status quo research cost [US\$])						
Expected Y/\$	2.08	1.39	1.19	1.05	0.99	0.92
Median Y/\$	1.98	1.35	1.18	1.04	0.98	0.92
CV of Y/\$	0.40	0.31	0.24	0.23	0.22	0.20

TABLE 4.—Yield (Y) analysis by 1,000 Monte Carlo simulations for each of six research options (θ_k: status quo, $k = 0$; enhanced research programs, $k = 1, 2, \ldots, 5$) and five total-allowable-catch strategies (TAC_j; $j = 1, 2, \ldots, 5$).

Strategy[a]	Research program θ_k					
	$k = 0$	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$
	Conditional expected yield (1,000 tonnes): $E[Y \mid TAC_j, \theta_k]$; equation (2)					
$j = 1$: $P(X) < 0.2$	1.03	1.26	1.51	1.52	1.54	1.56
$j = 2$: $0.2 \le P(X) < 0.4$	1.63	1.71	1.88	1.88	1.89	1.89
$j = 3$: $0.4 \le P(X) < 0.6$	1.99	2.03	2.16	2.14	2.14	2.13
$j = 4$: $0.6 \le P(X) < 0.8$	2.43	2.37	2.42	2.39	2.38	2.35
$j = 5$: $P(X) \ge 0.8$	3.32	3.06	2.94	2.88	2.85	2.77
	Conditional expected yield gain (1,000 tonnes) from research: $E[\Delta Y \mid TAC_j, \theta_k]$; equation (3)					
$j = 1$: $P(X) < 0.2$		0.23	0.48	0.49	0.51	0.53
$j = 2$: $0.2 \le P(X) < 0.4$		0.08	0.25	0.25	0.26	0.26
$j = 3$: $0.4 \le P(X) < 0.6$		0.05	0.17	0.15	0.15	0.14
$j = 4$: $0.6 \le P(X) < 0.8$		−0.06	−0.01	−0.04	−0.05	−0.08
$j = 5$: $P(X) \ge 0.8$		−0.26	−0.38	−0.44	−0.47	−0.55
	Expected opportunity loss (1,000 tonnes): $EOL[Y \mid TAC_j, \theta_k]$; equation (4)					
$j = 1$: $P(X) < 0.2$	−1.05	−0.83	−0.68	−0.64	−0.62	−0.58
$j = 2$: $0.2 \le P(X) < 0.4$	−0.45	−0.38	−0.30	−0.29	−0.27	−0.25
$j = 3$: $0.4 \le P(X) < 0.6$	−0.09	−0.08	−0.02	−0.02	−0.02	−0.02
$j = 4$: $0.6 \le P(X) < 0.8$	0.35	0.28	0.24	0.23	0.22	0.21
$j = 5$: $P(X) \ge 0.8$	1.24	0.98	0.76	0.72	0.69	0.63

[a] X denotes the event that the TAC yield will exceed the true allowable biological catch and that the actual fishing mortality rate will be greater than the target fishing mortality rate.

yield (negative EOL values in Table 4, equation 4). We emphasize that this yield is forgone only in 1991–1992 with respect to what could be caught while still not exceeding ABC in that fishing year; it is the short-term cost of risk-averse TACs. Thus, the term *forgone* should not be interpreted as biomass that becomes unavailable in 1991–1992 and remains unavailable in subsequent years. With the most risk-averse strategy (TAC_1; probability that TAC will exceed ABC is less than 20%) then, considerable yield could be forgone (−1,050 tonnes) in EOLs in the short term (Table 4; Figure 3).

Opportunity losses of yield from risk-prone decisions ($TAC_{4,5}$) are interpreted as lost surplus and, in the case of Gulf of Mexico king mackerel, as increased time until recovery. These losses will be carried over to future years, resulting in reduced ABCs and the need for even lower TACs in the future (i.e., the risk is likely to increase with time). Long-term characteristics are not directly evaluated in this example. In the short-term (2-year) focus of our example, EOLs from risk-prone strategies ($TAC_{4,5}$) are positive (Table 4, equation 4), indicating that reducing uncertainty will decrease the expected yield. However, the long-term interpretation is that positive EOLs are indirect measures of forgone surplus and the accumulation of spawning biomass needed for stock recovery. With risk-prone management strategies, significant accumulations of surplus would be forgone. The hypothesized research programs could reduce these losses by about 40% (Figure 3).

The expected gains in yield-per-cost ratio for risk-averse, risk-neutral, and moderately risk-prone strategies (probability that TAC will exceed ABC is less than 80%) were maximized by the intermediate-cost research program ($k = 2$; Table 5). Additional enhancements to the research program contribute only marginally to the reduction in uncertainty.

Because positive EOLs in yield for risk-prone decisions (Table 4, equation 4) indicate lost surplus and increased time until recovery for this overexploited king mackerel stock, then the more risk-averse strategies are beneficial to stock recovery. King mackerel live a relatively long time (15 years or more) and do not begin reproduction until age 4 or 5. If the long-term potential of this stock is to be realized within a reasonable time horizon, then the short-term TAC decisions should include risk-averse strategies (i.e., those in which the chances that TAC will exceed the true value of ABC are less than 50%). The benefits of such strategies coupled with research programs were evaluated by looking at the expected yield versus the

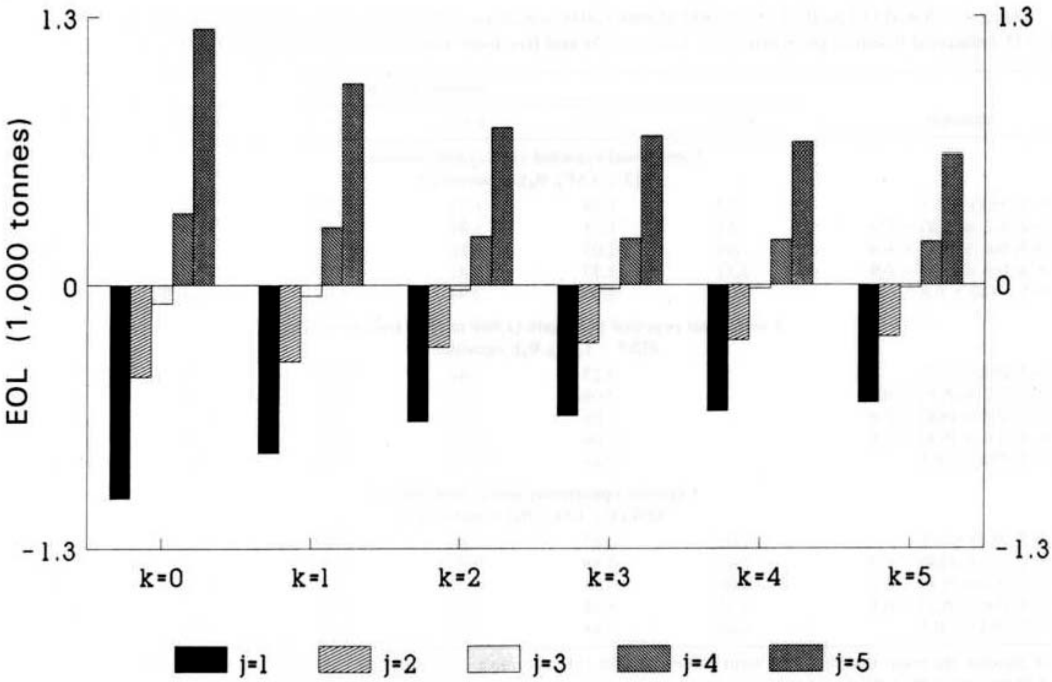

FIGURE 3.—Expected opportunity loss of yield (EOL) given different research programs (Θ_k: k = 0, 1, . . . , 5) and risk strategies (based on total allowable catch, TAC_j : j = 1, 2, . . . , 5).

cumulative probability that TAC exceeds the true value of ABC (Figure 4). The decision may be couched in terms of maximizing TAC for a given level of risk or, alternatively, minimizing the risk for a given TAC. If a TAC is selected such that the risk of exceeding the target ABC is less than 50%, then enhancing research could increase the expected yield for a given level of risk (Figure 4). If a TAC is selected to keep expected yield constant, then enhanced research would greatly reduce the risk (Figure 4).

Our example analysis has reiterated an important principle: a research program coupled with risk-averse management will improve the yield of the fishery without increasing the risk of overfishing (Figure 4). Research will allow an increase in catch without taking chances with the fish stock and its long-term potential economic yield. With risk-prone management, full recovery of the Gulf of Mexico king mackerel stock would be highly unlikely within any reasonable time frame. Conversely, research with risk-averse management would allow the fishery to achieve the desired long-term yield and at the same time reduce the losses in potential due to uncertainty about the status of the stock.

Is the research investment worthwhile economically? A reasonable (albeit somewhat subjective) approximation of the absolute annual research costs for Θ_1 and Θ_2 is \$0.45 million and \$0.55 million, respectively. If a risk-averse strategy is chosen in which the chance that yield will exceed the true ABC is 20% or less, then research investments could increase expected yield 25–50% (Figure 4; k = 1, 2). At the present stock level, this could amount to an additional dockside value of US\$0.836 to \$1.752 million to the fishery (based on \$3.63/kg, or \$1.65/lb, from all sectors; this is likely to be an underestimate of the true dockside value to the recreational sector [Milon 1989]). If the same relative probability distribution of ABC upon full recovery of the stock is assumed, enhanced research with risk-averse management would allow additional catches of about 900–1,800 tonnes by the fishery (Tables 3, 4: for k = 1, 8,200 tonnes × [230 tonnes gain/2,090 tonnes expected ABC]; for k = 2, 8,200 tonnes × [480 tonnes gain/2,180 tonnes expected ABC]). Annually, this could be worth \$3.3 to \$6.6 million dockside and perhaps \$16.4 to \$32.8 million to the gross national product (if a factor of five can be assumed for multiplier contributions to the national economy).

TABLE 5.—Analysis of yield per research cost ($Y/\$$) by 1,000 Monte Carlo simulations for each of six research options (Θ_k: status quo, $k = 0$; enhanced research programs, $k = 1, 2, \ldots, 5$) and five total-allowable-catch strategies (TAC_j: $j = 1, 2, \ldots, 5$). Values for yield per cost are measured in thousands of tonnes per status quo cost ($k = 0$, normalized) in U.S. dollars.

Strategy[a]	Research program Θ_k $k = 0$	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$
		Conditional expected $Y/\$$: $E[(Y/\$) \mid TAC_j, \Theta_k]$; equation (6)				
$j = 1$: $P(X) < 0.2$	1.03	0.84	0.82	0.74	0.71	0.67
$j = 2$: $0.2 \le P(X) < 0.4$	1.63	1.13	1.03	0.91	0.87	0.81
$j = 3$: $0.4 \le P(X) < 0.6$	1.99	1.35	1.18	1.04	0.98	0.92
$j = 4$: $0.6 \le P(X) < 0.8$	2.43	1.57	1.32	1.16	1.09	1.01
$j = 5$: $P(X) \ge 0.8$	3.32	2.03	1.60	1.40	1.31	1.19
		Conditional expected gain in $Y/\$$: $E[\Delta(Y/\$) \mid TAC_j, \Theta_k]$; equation (7)				
$j = 1$: $P(X) < 0.2$		0.15	0.26	0.24	0.23	0.23
$j = 2$: $0.2 \le P(X) < 0.4$		0.05	0.14	0.12	0.12	0.11
$j = 3$: $0.4 \le P(X) < 0.6$		0.03	0.09	0.07	0.07	0.06
$j = 4$: $0.6 \le P(X) < 0.8$		−0.04	−0.01	−0.02	−0.02	−0.03
$j = 5$: $P(X) \ge 0.8$		−0.17	−0.21	−0.21	−0.22	−0.24
		Expected opportunity loss in $Y/\$$: $EOL[(Y/\$) \mid TAC_j, \Theta_k]$; equation (8)				
$j = 1$: $P(X) < 0.2$	−1.05	−0.55	−0.37	−0.31	−0.28	−0.25
$j = 2$: $0.2 \le P(X) < 0.4$	−0.45	−0.25	−0.16	−0.14	−0.12	−0.11
$j = 3$: $0.4 \le P(X) < 0.6$	−0.09	−0.05	−0.01	−0.01	−0.01	−0.01
$j = 4$: $0.6 \le P(X) < 0.8$	0.35	0.19	0.13	0.11	0.10	0.09
$j = 5$: $P(X) \ge 0.8$	1.24	0.65	0.41	0.35	0.32	0.27

[a] X denotes the event that the TAC yield will exceed the true allowable biological catch and that the actual fishing mortality rate will be greater than the target fishing mortality rate.

Although this economic valuation is unlikely to be either accurate or precise, it is nevertheless clear that the gains to the fishery and to the economy exceed the research investment.

Gulf of Mexico king mackerel is an example of the benefits of research to fishery management in the USA. In terms of potential economic yield, Gulf of Mexico king mackerel are a rather small component of U.S. fisheries, even within the region. Yet for many other stocks that are presently

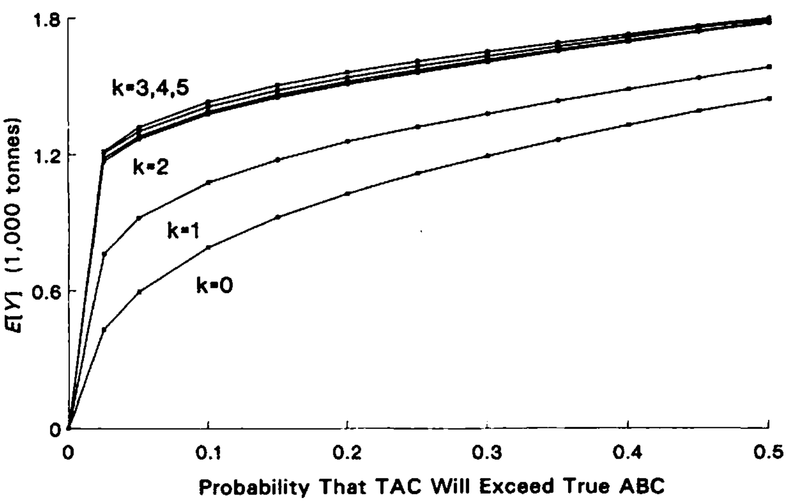

FIGURE 4.—Expected yield resulting from different risk levels (the probability that total allowable catch [TAC] will exceed the true allowable biological catch [ABC]) and different research programs (Θ_k: status quo, $k = 0$; enhanced research programs, $k = 1, 2, \ldots, 5$).

highly exploited or overfished, rather small research investments are likely to result in comparable percent additions to stock yield potential and to the economy.

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Appendix: Assessment Methodology

The methodology used to assess the status of Gulf of Mexico king mackerel is virtual population analysis (VPA) calibrated to indices of abundance. Some assumptions and constraints may change between assessment years as experience is gained. The following is a brief description of the assessment methods used in 1991. Readers interested in more details specific to Gulf of Mexico mackerel assessments should consult Powers et al. (1991); those interested in the general estimation framework should consult Parrack (1986), Gavaris (1988), Conser and Powers (1990), and Powers and Restrepo (1992).

Let

a = age (0–11+, where 11+ denotes age 11 and older);
t = fishing year (1979–1980 to 1989–1990);
i = index of abundance sequence number (1–6);
N = stock size, in numbers of fish;
I = relative abundance, in numbers or biomass of fish;
C = catch, in numbers of fish;
F = fishing mortality rate per year;
M = natural mortality rate per year; and
Z = total mortality rate ($Z = F + M$).

The change in stock size of a group of individuals from one year to the next is, if $a < 11$,

$$N_{a+1,\,t+1} = N_{at}\exp(-Z_{at}) \tag{A.1}$$

or, if $a = 11+$,

$$N_{a,\,t+1} = N_{at}\exp(-Z_{at}) + N_{a-1,\,t}\exp(-Z_{a-1,\,t}). \tag{A.2}$$

Catch is given by

$$C_{at} = F_{at}N_{at}\,[1 - \exp(-Z_{at})]/Z_{at}. \tag{A.3}$$

Abundance indices are linearly related to stock size (or biomass) for one or more ages. In our cases, where all indices reflect the average stock size of multiple age-classes (ages j–k), the relationship is

$$I_{it} = q_i \sum_{a-j}^{k} W_a N_{at}[1 - \exp(-Z_{at})]/Z_{at}, \tag{A.4}$$

where W_a is the age-specific weight if the index is in biomass, or 1.0 if the index is in numbers, and q_i is the scaling constant for the index.

The objective is to minimize the weighted residual sum of squares:

$$\text{RSS} = \min \sum_i \sum_t w_i(I_{it} - \hat{I}_{it})^2, \tag{A.5}$$

where w_i values are weights obtained with iterative reweighting (Seber and Wild 1989, Powers and Restrepo 1992), and I_{it} and $\hat{I}_{it}$ denote observed and predicted indices of abundance. The objective function is minimized with a Marquardt–Levenberg algorithm (Seber and Wild 1989) in which the number of parameters directly estimated varies depending on the number of constraints that are made. Seven parameters were estimated in the 1991 assessment: one scaling constant (q_i) for each of the six indices used, and the stock size of age-5 fish at the beginning of the 1990–1991 fishing year. The latter is equivalent to an estimation of F at age 4 for the 1989–1990 season, the last year of data (i.e., the "terminal" year). The remaining estimable parameters in the terminal year (F for ages 0–3 and 5–11+) were not directly estimated in the parameter search because the following constraints and assumptions were made. Fish were assumed to be fully recruited at age 4 (thus, $F_a = F_4$ for a = 5–11+). For fish of ages 0–3, it was assumed that their selectivities were known relative to age-4 fish; these were estimated from a separable VPA (SVPA: Pope and Shepherd 1982). No parameters were directly estimated for the last age-group in each year. Instead, it was assumed that $F_{11+,t} = F_{10,t}$ for all t.

Given the assumptions and constraints listed above, the steps involved in obtaining a solution are as follows:

(1) Run an SVPA to obtain the selectivities at ages 0–3 relative to age 4. Set the remaining selectivities equal to 1.
(2) Guess initial values of the parameters to be estimated and set w_i equal to $1/6$ for all six indices.
(3) Set new parameter values from the iterative search.
(4) Carry out a VPA to fill in the entire $a \times t$ matrix of stock sizes subject to equations (A.1)–(A.3).
(5) Compute the predicted indices of abundance from equation (A.4) and the weighted residual sum of squares from equation (A.5).
(6) Iterate steps 3–5 until equation (A.5) is at a minimum.
(7) For each index, compute new weights based on the inverse of the index-specific partial residual sums of squares (adjusted for the degrees of freedom) and renormalize them so they add up to 1. Go back to step 6 and stop if the minimum appears to be global and the weights do not change between consecutive solutions.