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PERFORMANCE INDICES THAT FACILITATE INFORMED, VALUE-DRIVEN DECISION MAKING IN FISHERIES MANAGEMENT

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ABSTRACT

This paper develops and explores the use of five indices representing resiliency, yield productivity, yield constancy, capacity constancy, and ecosystem productivity to evaluate natural-resource management alternatives. Too frequently, managers and their scientific advisors have miscommunications because managers want simple answers to complicated questions and scientists are uncomfortable providing information that might seem value-laden. Indices can give managers a framework within which to ask for scientific advice and scientists a mechanism for presenting likely consequences of management decisions without favoring particular values. Five quantitative indices representing common fishery management objectives are developed, and their use is illustrated through tests of various control rules in simple simulated-population models. The results provide an example of how to meld societal values with scientific analyses in the policy arena. They also give insight into the effectiveness of various control rules and highlight better alternatives to current practices. The benefits of such an approach extend well beyond fisheries management. Many natural-resource policy processes share the characteristics that make the use of multiple performance indices valuable, including unpredictability, complexity, and diversity of opinion.

Natural resource managers rarely explicitly address the many trade-offs resulting from the biological, physical, and socioeconomic limitations of the systems that produce, extract, and manage renewable natural resources. Conflicts among different values are usually addressed opaquely through political pressure rather than informed reason (Ludwig et al., 1993; Pauly et al., 2002). Scientists contribute to this failing by not providing managers with adequate information for fear of advocating values instead of supplying objective science. Managers contribute by not asking scientists for such information explicitly.

Managers are familiar with trade-offs, particularly between current yield and potential adverse effects on future yields, but their decisions are often biased because the immediate effects on fishing communities are almost always more certain than future benefits or costs. Some have argued that this short-term perspective has led to decades or even centuries of degradation of entire marine ecosystems (Jackson et al., 2001; Pauly et al., 2002); others have asserted that the burden of proof must be shifted to place more weight on potentially negative long-term effects of fishing (Dayton, 1998; Charles, 2001).

Trade-offs less well known among policy makers, despite long histories of scientific exploration, include those between yield productivity (high average catches) and yield constancy (high probability that next year's catches will be similar to this year's) (see, e.g., Ricker, 1958; Gatto and Rinaldi, 1976; Quinn et al., 1990) and between yield and ecosystem productivity, measured in terms of the abundance of a stock in the ecosystem (high yield constancy can be correlated with maintenance of greater stock abundance; Walters, 1975). Stock abundance can have important implications, because fishing down one species or group can artificially boost (see, e.g., McClanahan and Shafir, 1990; Tegner and Dayton, 2000) or cut (May et al., 1979) abundance of others through ecological interactions. Additional studies (e.g., Butterworth and Punt, 1999) have identified a three-way trade-off among yield productivity, yield constancy, and resiliency (the ability of a management system to perform well despite uncertainties), in which gains in any one necessitate losses in one or both of the others. Trade-offs are even known among the potential yields from cooccurring species caught in the same fishery (Ricker, 1958; Hilborn, 1976; Larkin, 1977).

Here, I develop indices that score the performance of management alternatives, illustrate their use by comparing a range of fishery-management policy options, and, I hope, provide insight into the policy options themselves. Indices are invaluable for guiding interactions between scientists and managers and for informing the general public about potential outcomes of management decisions (Hilborn et al., 1993; Restrepo et al., 1998), yet scientists have rarely examined the relative success of various policy alternatives at achieving management objectives (for a list of examples where they did, see Butterworth and Punt, 1999). I propose and illustrate the value of quantitative indices relevant to a five-way trade-off by comparing various fishery control rules—specified formulas for setting and modifying annual quotas, in this case based on current abundance—which included both common conventional techniques and some on the cutting edge. All control rules were tested over a range of intensities, varying from achieving maximum sustainable yield levels to a small fraction of that level. Quinn and Deriso (1999) provided a good summary of some strengths and weaknesses of common control rules.

Natural-resource managers should calculate performance indices as a standard practice. Many authors have identified the difficulty of bringing scientific advice to bear in a value-laden policy process (Mangel et al., 1996; Smith, 1998; Butterworth and Punt, 1999). If presented to managers and the public whenever a natural-resource management system is being developed or reexamined, the set of indices analyzed here would result in better and more transparent decision making. These indices do not cover all potentially relevant values; readers should refer to Charles (2001) for additional possibilities or consider developing their own. Generally, though, performance indices facilitate clear and direct comparison of alternatives.

Previous work has substantially influenced this paper (e.g., Plan Development Team, 1990; National Research Council, 1998). Even my approach is not unique (Smith, 1998; Butterworth and Punt, 1999; Charles, 2001), but the present effort adds an essential index, resiliency; presents the results in a form accessible to nonscientists; and will, I hope, therefore improve the use of science in management.

Methods

First, I developed quantitative indices to measure the likely success of management alternatives at achieving five management objectives—resiliency, yield productivity, yield constancy, capacity constancy, and ecosystem productivity—that measure the performance of various control rules. Each index was designed to range from 0 (bad) to 1 (good). Next, I illustrated the use of these indices by applying them to several control rules through a simple simulated-population model. The rules governed allowable catch levels on the basis of estimates of productivity, abundance, and catches but faced stochastic variability in environmental productivity (a surrogate for nondirectional errors) and sustained directional management errors.

Quantitative Indices.—The first index, resiliency (I_R), represented the capacity of the management system to maintain productive fish populations and fisheries despite sustained directional management errors, that is, consistent over- or underestimation of the productive capacity or abundance of the population. It was based on the level of error in the fishing rate that drives a population to undesirable abundance levels and was defined as

$$I_R = \frac{\varepsilon_{0.2}}{\varepsilon_{0.2} + 4}$$

Eq. 1

where $\varepsilon_{0.2}$ is the error value in the estimate of productivity or actual catch that drives the average population abundance down to $N = 0.2$, i.e., 20% of carrying capacity (a level commonly used as an undesirable abundance level in similar studies; Butterworth and Punt, 1999). The level of error in the fishing rate ($\varepsilon_{h/p}$) must be normalized to allow for comparison across a range of conditions. To constrain the index between 0 and 1, I divided it by the sum of itself and a constant of 4 (representing 400% error and here defining the level of error that would receive an index score of 0.5), chosen on the basis of my experience with poorly studied species. An equivalent index, I_{Rn}, developed from the same formula was based on errors in the estimation of actual abundance. Similar results were obtained in analyses that used a constant value of 1 (100% error) but where this value applied to the error terms for both productivity/catch and abundance (J. Sladek Nowlis, unpubl. data).

The second and third indices were more standard. Yield productivity (I_{PY}) characterized the expected size of catches, and yield constancy (I_{CY}) the lack of variability in catches from year to year. The equation for the yield-productivity index was

$$I_{PY} = \frac{\bar{h}}{p}$$

Eq. 2

where $\bar{h}$ is the average yield from the fishery and p is the maximum sustainable yield, the natural normalizer for this quantity because it is the maximum value that can be sustained from a fishery with perfect information and a stable environment.

The yield-constancy index (I_{CY}) was based on a measure of variability in yield over time (standard deviation, σ_h). It was expressed as

$$I_{CY} = \begin{cases} 1-\left(\dfrac{\sigma_h/\bar{h}}{\sigma_p/p}\right) & \dfrac{\sigma_h}{\bar{h}} < \dfrac{\sigma_p}{p} \\ & \text{if} \\ 0 & \dfrac{\sigma_h}{\bar{h}} < \dfrac{\sigma_p}{p} \end{cases}$$

Eq. 3

To normalize the variability of a given model, I divided it by the mean yield ($\bar{h}$). This ratio was further normalized by the productivity parameter (p). This second normalization addressed the link between environmental variability and catch variability. A highly variable environment is more likely to produce long-term variability in catches than a stable environment. Dividing the normalized catch variability (σ_h/h) by the normalized environmental variability (σ_p/p , where σ_p is the standard deviation of the productivity parameter, and p its average value) produced a measure of the extent to which the control rule dampened or passed through environmental variability to catches. In the unlikely event that a control rule produced catches with a normalized standard deviation higher than the environmental conditions, it scored 0 for performing poorly at yield constancy. This result would mean that the control rule amplified natural variability so that variations in catches exceeded variations in productivity.

The fourth and fifth indices were less conventional. Capacity constancy (I_{CC}) illustrated the management system's ability to avoid build-up of excess capacity early in a fishery and/or during good years, when allowable catches greatly exceed long-term average catches under certain management policies. It is the maximum amount of fishing allowed in a control rule relative to the average yield and was calculated as

$$I_{CC} = \frac{\bar{h}}{h_K} \qquad \text{Eq. 4}$$

where h_K is maximum permissible catch (likely to be highest when the population is at carrying capacity, K) and $\bar{h}$ is long-term average catch. This index is superior for measuring the incentive to develop excess capacity (lowest when h_K and $\bar{h}$ are most similar), whereas Charles' (2001) sustainable fleet capacity index is a better choice for identifying the current status of capacity.

The fifth index, ecosystem productivity (I_{PE}), was simply fish abundance, the most direct measure of the ability of fish populations to contribute to ecosystems. It was equal to the average abundance of the population ($\bar{N}$), already normalized in the model used here:

$$I_{PE} = \bar{N} \qquad \text{Eq. 5}$$

The possibility, for some populations, that high abundance might actually reduce ecosystem productivity (e.g., for sea urchins, McClanahan and Shafir, 1990; Tegner and Dayton, 2000) could be addressed by a related but distinct index (e.g., a diversity index, Charles, 2001, or a trophic level index, Pauly et al., 1998). I_{PE} is quite similar to Branch's (1998) final biomass.

All indices except resiliency were calculated without directional management error but with nondirectional error resulting from the stochastic population growth capacity. Therefore, even if a management alternative scored well on other indices, a low resiliency score would indicate that those benefits might never be realized. Note that index values were sensitive to the level of environmental variability. For the present paper, I examined a highly variable environment. A less variable one would probably have produced similar but less dramatic results (see, e.g., Sladek Nowlis and Bollermann, 2002).

CONTROL RULES.—The control rules I used, summarized graphically in Figure 1, were

- constant catch, here also referred to as constant *h*, under which a set number (or weight in an age- or size-based model) of fish were removed each year;
- constant fishing mortality rate, here also referred to as constant *F*, under which a set proportion of the current abundance was removed each year;
- the technical-guidance approach, a complex abundance-based rule recommended by the National Marine Fisheries Service (Restrepo et al., 1998), under which fishing mortality rate was held constant above a threshold abundance and scaled down proportionally below the threshold; and
- capped responsive systems, under which annual catches remained constant above target abundance levels but were reduced sharply if abundance dropped below the target. This technique is not a common one but has been proposed by several authors for a range of circumstances (e.g., by Clark, 1990, as a realistic way to maximize yields; by Smith, 1993, for management of deep-sea orange-roughy fisheries; and by the Pacific Fishery Management Council, 1998, as a tool for managing sardines and other coastal pelagic species on the U.S. West Coast).

ILLUSTRATIVE MODELS.—I relied on extremely simple population models characterized by Pella-Tomlinson population growth, a stochastic population growth parameter, and levels of management error that were fixed within a run but variable between runs. These models were based on the equations (adapted from Quinn and Deriso, 1999)

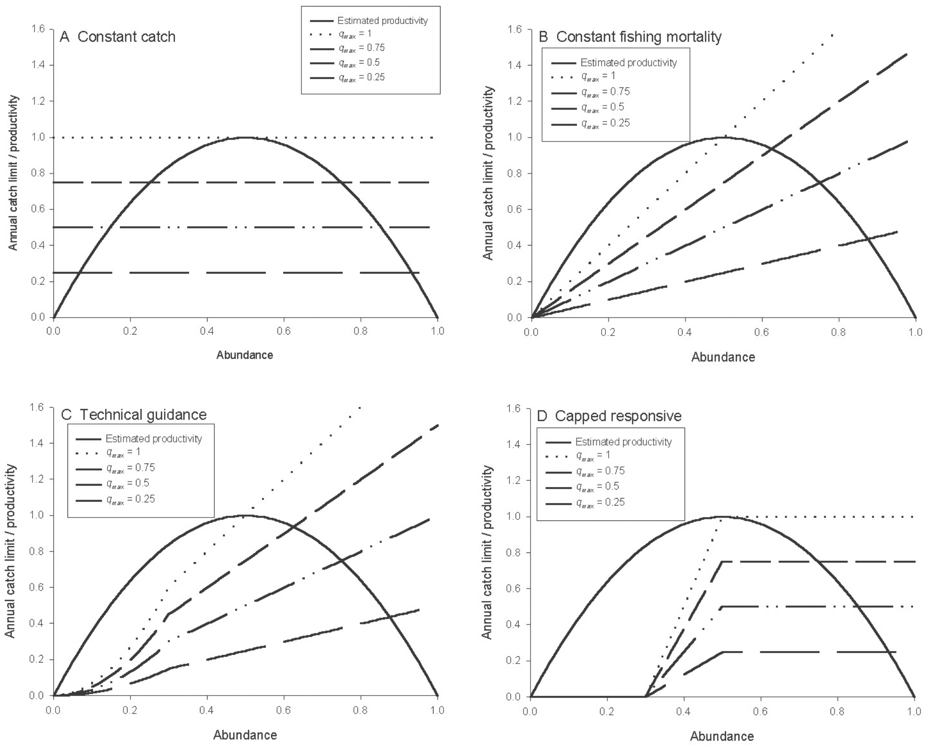

Figure 1. Control rules. Lines represent estimated productivity and quotas as a function of abundance levels. All control rules illustrated for the Graham-Schaefer growth curve (Eq. 6A, $n = 2$). (A) Constant-catch quota set at MSY or a fraction, $q_{\max}$, thereof. (B) Constant-fishing-mortality-rate quota tuned to produce a catch of MSY or a fraction, $q_{\max}$, thereof, when abundance is at MSY levels. (C) Technical-guidance control rule tuned to produce a catch of MSY or a fraction, $q_{\max}$, thereof, when abundance is at MSY levels. (D) Capped responsive control rule tuned to produce MSY or a fraction, $q_{\max}$, thereof, with $N_{\min} = 0.3$.

$$\frac{dN}{dt} = g(N) - h\left(N, \varepsilon_{h/p}, \varepsilon_N\right)$$

$$g(N) = \gamma P\left(p, \sigma_p^2\right)\left(N - N^n\right), \text{ or} \qquad \text{Eq. 6A}$$

$$g(N) = -eP\left(p, \sigma_p^2\right) N \ln N \text{ when } n = 1 \qquad \text{Eq. 6B}$$

where N represented population abundance with $N = 1$ as the carrying capacity, P was a stochastic population-productivity parameter with mean p representing the maximum sustainable yield (MSY) and variance σ_p^2, and $h(N,\varepsilon_{h/p},\varepsilon_N)$ represented catch rates as a function of abundance and of directional, constant errors in the estimation of productivity or actual catch ($\varepsilon_{h/p}$) and in actual abundance (ε_N) (the derivation of these error terms is described more fully in Sladek Nowlis and Bollermann, 2002). Equation 6A is the general form of the Pella-Tomlinson growth curve, with $\gamma = n^{n/(n-1)}/(n-1)$. n is a parameter that changes the shape of the growth curve and modifies the abundance at which MSY occurs (N_{MSY}). Values above 2 skew the curve to the right, whereas those below 2 skew it to the left. In general, $N_{MSY} = n^{1/(1-n)}$ and the fishing rate that achieves MSY, $F_{MSY} = \gamma p(n-1)/n$. As n approaches 1, these equations converge to the Gompertz-Fox form, represented in Eq. 6B, and with $N_{MSY} = 1/\mathrm{e}$ and $F_{MSY} = \mathrm{e}p$.

Four types of control rules were tuned to achieve either MSY or a fraction, $q_{\max}$, thereof, when the abundance was at MSY levels (N_{MSY}). Equation 7 represented the constant-catch, Eq. 8 the constant-fishing-mortality, Eq. 9 the technical-guidance, and Eq. 10 the capped-responsive approach; N_{MSY} and F_{MSY} were as defined above. In the Gompertz-Fox case, one can use either the specific values of these parameters listed above or the general growth and control-rule equations with a shaping parameter value that approximates 1 (e.g., $n = 1 + 10^{-14}$).

$$h\left(N,\varepsilon_{h/p},\varepsilon_n\right)=\left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}N_{MSY}=\left(1+\varepsilon_{h/p}\right)q_{\max}p \tag{Eq. 7}$$

$$h\left(N,\varepsilon_{h/p},\varepsilon_n\right)=\left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}\left(1+\varepsilon_n\right)N \tag{Eq. 8}$$

$$h\left(N,\varepsilon_{h/p},\varepsilon_n\right)=\begin{cases}\dfrac{\left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}\left(1+\varepsilon_N\right)N}{\left(1-M\right)N_{MSY}}\left(1+\varepsilon_N\right)N & \text{if } \left(1+\varepsilon_N\right)N<\left(1-M\right)N_{MSY}\\[2ex] \left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}\left(1+\varepsilon_N\right)N & \text{if } \left(1+\varepsilon_N\right)N\geq\left(1-M\right)N_{MSY}\end{cases} \tag{Eq. 9}$$

$$h\left(N,\varepsilon_{h/p},\varepsilon_n\right)=\begin{cases}0 & \left(1+\varepsilon_N\right)N<N_{\min}\\ \left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}N_{MSY}\dfrac{\left(\left(1+\varepsilon_N\right)N-N_{\min}\right)}{\left(N_{MSY}-N_{\min}\right)} & \text{if } N_{\min}\leq\left(1+\varepsilon_N\right)N<N_{MSY}\\ \left(1+\varepsilon_{h/p}\right)q_{\max}F_{MSY}N_{MSY} & \left(1+\varepsilon_N\right)N\geq N_{MSY}\end{cases} \tag{Eq. 10}$$

where $N_{\min}$ was set at 0.3 to yield a fairly high degree of responsiveness (see Sladek Nowlis and Bollermann, 2002, for a discussion of the implications of other values of $N_{\min}$). Although the natural mortality rate (M) can have a substantial effect on a population's growth characteristics and ability to withstand fishing, here it only influenced the shape of the technical-guidance control rule. The biological characteristics associated with M were instead represented by the population-growth parameter, P. Age structure, which was not included in this model, could have also affected these results.

The parameter $q_{\max}$ allowed each control rule to be tuned to yield various management targets. Setting this parameter at its maximum value, 1, caused the control rule to strive to achieve the estimated MSY. Setting $q_{\max}$ at lower values scaled back catches accordingly for a given abundance level but had less effect on long-term average catches for some control rules because fishing at lower levels maintained a higher abundance.

All model runs started at abundance levels capable of sustaining maximum sustainable yields (N_{MSY}) and ran for 500 yrs/generations. I simulated high environmental variability under two different conditions: a high-productivity species (Gompertz-Fox model, Eq. 6B, or $n \sim 1$ in the general model, Eq. 6A; chi-square distributed P with $p = 0.1$; $\sigma_r = 0.15$; and natural mortality $M = 0.4$, or approximately three-halves of F_{MSY}) and a low-productivity species (Graham-Schaefer model with $n = 2$ in the general model, Eq. 6A; chi-square distributed P with $p = 0.025$; $\sigma_r = 0.038$; and $\mathrm{M} = 0.0625$, or five-fourths of F_{MSY}). I used the same stochastic production history (scaled to the appropriate p level) for all runs to facilitate comparison, on the assumption that a 500-yr simulated history already provided a high degree of replication.

RESULTS

Results from the simulations highlighted the trade-offs inherent in fisheries management decisions. In most cases, tuning the control rule so that it achieved lower yields (i.e., lower $q_{\max}$) reduced the yield productivity but increased the other index values for both high- and low-productivity stocks (Tables 1 and 2). Two exceptions were evident. The constant-catch rule crashed both stocks, and the constant-fishing-mortality rule showed reduced yields for the high-productivity stocks when tuned to achieve MSY ($q_{\max} = 1$), even without any directional management error. All other cases yielded a fundamental trade-off between high yields and high resiliency, yield constancy, capacity constancy, and ecosystem productivity.

Some control rules had starker trade-offs than others. These differences were evident when I compared the performances of the control rules when they were tuned to yield a specific management objective, for example maximizing yields (Figs. 2A,3A), producing 75% of MSY (Figs. 2B,3B), achieving a resiliency-index score of 0.5 (Figs. 4A,5B), or achieving a resiliency-index score of 0.75 (Figs. 4B,5B).

Table 1. Quantitative performance indices for various management control rules and a high-productivity stock. These indices all vary between 0 and 1; 1 represents desirable and 0 undesirable performance. Indices were calculated on the basis of simulations of a high-productivity stock with Gompertz-Fox population growth, chi-square-distributed productivity parameter with average P = 0.1 and standard deviation $\sigma_p = 0.15$, and a high natural mortality of M = 0.4 used to shape the technical-guidance control rule. I_{Rn} = resiliency against errors in estimating abundance, I_{Rp} = resiliency against errors in estimating productivity or catches, I_{PY} = yield productivity, I_{CY} = yield constancy, I_{CC} = capacity constancy, and I_{PE} = ecosystem productivity.

Constant catch						
$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0	0	0.137	0	0.137	0.073
0.75	0	0	0.203	0	0.271	0.172
0.5	1	0.078	0.5	1	1	0.770
0.25	1	0.295	0.25	1	1	0.893
Constant fishing mortality						
$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.076	0.076	0.847	0.587	0.312	0.312
0.75	0.161	0.161	0.874	0.689	0.429	0.429
0.5	0.292	0.292	0.786	0.786	0.578	0.578
0.25	0.518	0.518	0.52	0.886	0.765	0.765
Technical guidance						
$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.111	0.153	0.881	0.589	0.324	0.335
0.75	0.185	0.244	0.877	0.686	0.43	0.433
0.5	0.304	0.379	0.786	0.786	0.578	0.578
0.25	0.520	0.595	0.520	0.886	0.765	0.765
Capped responsive						
$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.468	0.454	0.815	0.72	0.815	0.534
0.75	0.87	0.542	0.7	0.845	0.934	0.63
0.5	1	0.651	0.5	0.994	1	0.77
0.25	1	0.797	0.25	1	1	0.893

Table 2. Quantitative performance indices for various management control rules and a low-productivity stock. These indices all vary between 0 and 1; 1 represents desirable and 0 undesirable performance. Indices were calculated on the basis of simulations of a low-productivity stock with Graham-Schaefer population growth, chi-square-distributed productivity parameter with average P = 0.025 and standard deviation $\sigma_p = 0.038$, and a low natural mortality of M = 0.0625. I_{Rn} = resiliency against errors in estimating abundance, I_{Rp} = resiliency against errors in estimating productivity or catches, I_{PY} = yield productivity, I_{CY} = yield constancy, I_{CC} = capacity constancy, and I_{PE} = ecosystem productivity.

Constant catch

$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0	0	0.374	0.148	0.374	0.199
0.75	1	0.078	0.75	1	1	0.734
0.5	1	0.2	0.5	1	1	0.844
0.25	1	0.429	0.25	1	1	0.923

Constant fishing mortality

$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.115	0.115	0.959	0.856	0.480	0.480
0.75	0.205	0.205	0.917	0.9	0.611	0.611
0.5	0.338	0.338	0.74	0.932	0.74	0.74
0.25	0.559	0.559	0.433	0.954	0.866	0.866

Technical guidance

$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.195	0.388	0.97	0.842	0.485	0.503
0.75	0.255	0.482	0.917	0.899	0.611	0.612
0.5	0.359	0.603	0.74	0.932	0.74	0.74
0.25	0.56	0.767	0.433	0.954	0.866	0.866

Capped responsive

$q_{\max}$	I_{Rn}	I_{Rp}	I_{PY}	I_{CY}	I_{CC}	I_{PE}
1	0.915	0.843	0.933	0.906	0.933	0.580
0.75	1	0.879	0.749	0.994	0.999	0.734
0.5	1	0.916	0.5	0.999	1	0.844
0.25	1	0.957	0.25	1	1	0.923

The constant-catch control rule typically scored highest for yield constancy, capacity constancy, and ecosystem productivity. When set at high catch levels (Figs. 2–5), though, this control rule had extremely low resiliency to errors in estimation of productivity and/or catch rates. In fact, it crashed without any error of either type whenever tuned to a $q_{\max} \geq 0.667$ for the high-productivity species (Table 1) or $q_{\max} \geq 0.999$ for the low-productivity species (Table 2). At lower tunings, resiliency remained unimpressive for errors in estimating productivity or actual catches but was extremely high for errors in the estimation of abundance. Nonetheless, this control rule had to be tuned to produce very low yields to achieve moderate to high resiliency (Figs. 4,5) and thus have the potential to satisfy other management objectives.

The capped responsive control rule, on the other hand, had a relatively mild trade-off between yield productivity and resiliency. It could therefore be tuned to score relatively well on both indices. As a result, it had the highest resiliencies for any given catch level (Figs. 2B,3B) and the highest yield productivities for any given level of resiliency (Figs. 4,5). It was even more resilient to errors in abundance estimates (Tables 1,2). (In contrast, the constant-fishing-mortality-rate control rule was equally resilient to the two types of error, whereas the technical-guidance control rule was less resilient to errors in estimating abundance than to those in estimating productivity and/or actual catch levels; Tables 1,2).

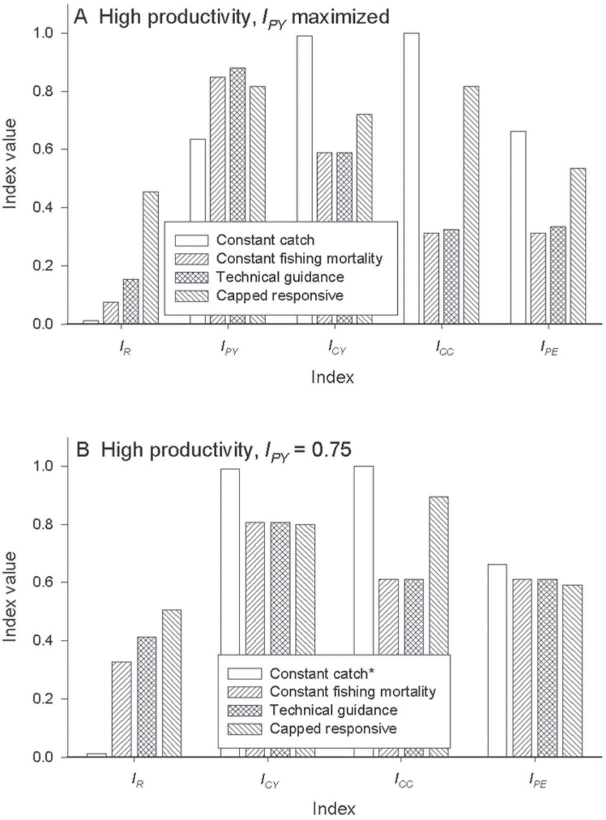

Figure 2. Values of indices with the tuning parameter ($q_{\max}$) set to achieve high yields from a high-productivity stock ($n \sim 1$, $p = 0.1$, $M = 0.4$). (A) Note the low resiliency (I_R) of all control rules except the capped responsive when maximum yields are the goal, which makes them risky for any but the best-understood fisheries. Note also that the capped responsive system sacrifices a small amount of yield (81.5% as opposed to 88% of MSY from the technical-guidance approach) to achieve this resiliency as well as relatively high performance in yield constancy (I_{CY}), capacity constancy (I_{CC}), and ecosystem productivity (I_{PE}). (B) When control rules tuned to achieve 75% of MSY were compared, the constant-catch policy produced the best results for all indices except resiliency, but its low resiliency cautions against its use. The capped responsive system had the highest resiliency and also scored well on other performance indices, particularly capacity constancy. *The closest the constant-catch policy could achieve to $I_{PY} = 0.75$ was $I_{PY} = 0.636$.

The only very mild limitation of the capped responsive system was its ability to maximize catches. The technical-guidance and constant-fishing-mortality control rules were able to achieve higher average yields when tuned to maximize them, but the gains in yields were modest (from 81.5–88% of MSY, Fig. 2A; from 93.3–97% of MSY, Fig. 3A) and were associated with substantially lower resiliency-index scores.

Trade-offs among performance indices were generally more pronounced for the high-productivity stock. In almost every case, scores on all five indices were higher for the low-productivity stock. Changing the tuning parameter ($q_{\max}$) within a control rule generally produced bigger performance differences than changing the control rule while keeping the tuning parameter constant.

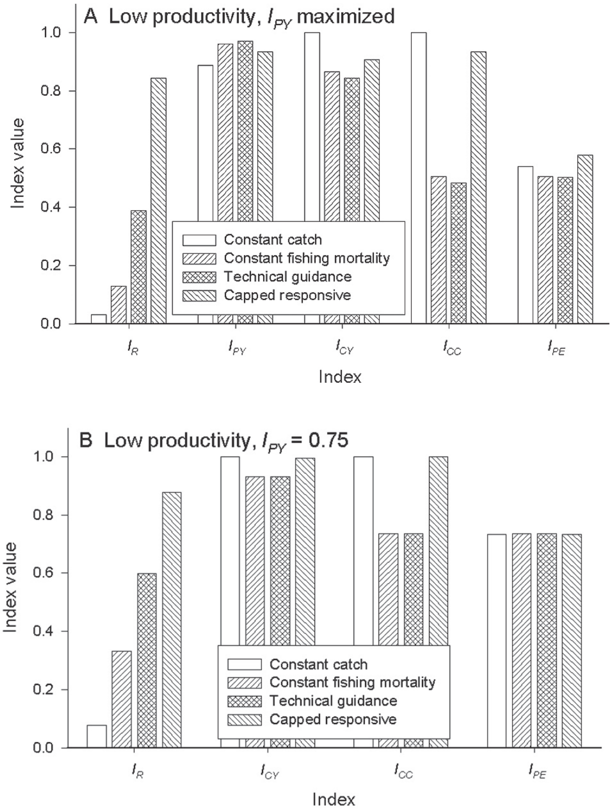

Figure 3. Values of indices with the tuning parameter ($q_{\max}$) set to achieve high yields from a low-productivity stock ($n = 2$, $p = 0.025$, $M = 0.0625$). In this model formulation, the capped responsive control rule outperformed others in virtually every attribute when either (A) maximizing yield or (B) achieving yields at 75% of MSY. Its maximum yield was slightly less than those of other control rules (93.3% as opposed to 97% of MSY from the technical-guidance approach). Instead it provided superior resiliency (I_R) and ecosystem productivity (I_{PE}) and better yield constancy (I_{CY}) and capacity constancy (I_{CC}) than any other control rule except the constant-catch policy (constant h). It fared even better when all control rules were tuned to achieve 75% of MSY, when it equaled or outperformed all other control rules in every attribute.

Discussion

Current fisheries-management systems still need substantial improvement, especially in their ability to address trade-offs in an informed manner. Performance indices offer great promise for addressing this challenge. Managers are more likely to specify quantifiable management objectives if asked which indices they want analyzed, and they could even be supplied a list of options, such as those presented here and others from Charles (2001). These indices also provide objective cover for scientists, who can offer managers useful information on the chances of achieving various value-laden management objectives without bias as to which values should be emphasized.

Such an approach has been taken in the past, but too rarely or incompletely. The Plan Development Team (1990) ranked the ability of a range of management tools to achieve various management objectives. Their approach was a good one but could have benefited

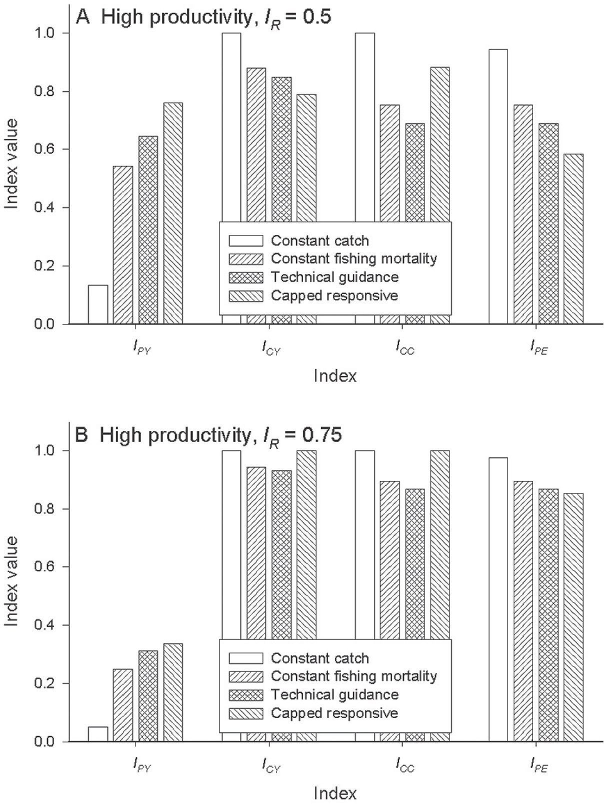

Figure 4. Values of indices with the tuning parameter ($q_{\max}$) set to achieve high resiliency from a high-productivity stock ($n \sim 1$, $p = 0.1$, $M = 0.4$). The constant catch (constant h) policy produced the best yield constancy (I_{CY}), capacity constancy (I_{CC}), and ecosystem productivity (I_{PE}) but sacrificed substantial yield productivity (I_{PY}) to achieve these results and a resiliency index score of (A) 0.5, suitable for many assessed stocks, or (B) 0.75, more suitable for data-poor stocks. Of the control rules tested, capped responsive consistently produced the highest yields and fewest incentives to develop excess capacity. Its one consistent sacrifice was in ecosystem productivity (a direct result of its higher catches).

from the use of simulated testing of the management tools to provide a greater sense of objectivity. Charles (2001) proposed the use of sustainable fisheries indices and provided a wide range of possibilities, yet did not illustrate them with detailed examples. Branch (1998) examined the performance of a number of control rules that set fishing limits. His results were encouraging in that his best-performing control system was identical to the one identified here. Yet he did not look at what I believe is the fundamentally most important performance index: resiliency.

Although resiliency is often overlooked in a management context, an ideal management system should be resilient to any number of possible shocks to the system because, if a stock collapses, the other performance benefits a control rule might have otherwise provided go unrealized. Given the universally high level of uncertainty in our knowledge of marine fisheries, resilient management systems are essential if we are to avoid stock collapses. Directional error presents an especially difficult challenge, but the simulations reported here also explored the effects of less severe, nondirectional errors in the form

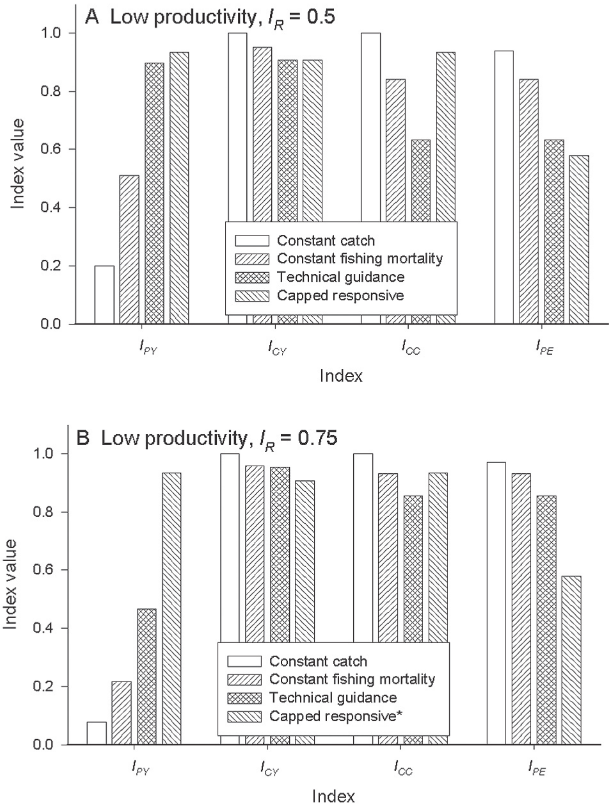

Figure 5. Values of indices with the tuning parameter ($q_{\max}$) set to achieve high resiliency from a low-productivity stock ($n = 2$, $p = 0.025$, $M = 0.0625$). The relative performances of the control rules were similar with a resiliency (I_R) of (A) 0.5, suitable for many assessed stocks, or (B) 0.75, more suitable for data-poor stocks. In both cases, the constant-catch policies (constant h) produced the best yield constancy (I_{CY}), capacity constancy (I_{CC}), and ecosystem productivity (I_{PY}) but sacrificed substantial yields (I_{PY}) to achieve the target resiliency. The capped responsive systems gave the highest yields, producing a notable decrease only in ecosystem productivity, a natural outcome of allowing more fishing. *At the highest meaningful value of $q_{\max}$ (= 1), this policy was more resilient than the intended value ($I_R = 0.843$).

of variable productive capacity. Because the variability precluded prediction of productivity in any given year, even when the averages were estimated accurately, it added a source of nondirectional error that varied from year to year. This source of error did not affect the index for resiliency directly but did affect all indices indirectly.

These analyses of resiliency-index scores resulted in a promising finding—that relatively small sacrifices of yields, if strategic, can provide for substantially higher resiliency (i.e., realized moderate yields may be better than unrealized high yield potential). Another interesting outcome was that changing the tuning parameter ($q_{\max}$) within a control rule generally produced bigger performance differences than changing the control rule while keeping the tuning parameter constant. This finding has especially important policy implications in the U.S., where fishery management targets known as optimum yields are supposed to account for relevant social, economic, and ecological factors (16 U.S.C. § 1802(28)). The results reported here would indicate that the tuning of a control rule (i.e., setting of optimum yields) can profoundly affect a number of social, economic, and ecological factors. Yet the norm in U.S. fisheries management today is to use a tuning parameter (q_{max}) of 0.75, regardless of the particular factors surrounding the management of the stock in question.

Capacity planning is less often associated with fish population biology than are the other management objectives addressed here, but it is worth including because of the important link between fish population biology and the incentive to develop excess capacity. Many control rules allow catch levels during good times that greatly exceed the levels under average conditions. Especially in emerging fisheries or under unusually productive conditions, these policies can promote the development of excessive fishing capacity (a significant problem in many fisheries; Clark and Munro, 2002; Hilborn, 2002). Consecuently, inclusion of an index of capacity constancy is important when control rules are compared.

TRADE-OFFS.—The most direct and consistent trade-offs I identified were between yield productivity and the other four indices. Most of these have been identified previously (e.g., by Ricker, 1958; Walters, 1975; Thompson, 1992; Engen et al., 1997), but this set of trade-offs is not universal. Sladek Nowlis and Bollermann (2002) showed that, by varying the zero-fishing threshold in a responsive control rule (N_{min} in the capped responsive system here), they could achieve high yields while facing a trade-off between resiliency and yield constancy. Their results were consistent with the work of Mangel et al. (2002), who showed that high yields and resiliency could be achieved simultaneously, as well as studies examining the performance of marine reserves (e.g., Lauck et al., 1998; Sladek Nowlis and Roberts, 1999).

One interesting trade-off presented above was between two ecosystem-oriented indices. Note in Figures 4 and 5 that the capped responsive systems typically had the lowest index score for ecosystem productivity. These results make sense in that this alternative allowed the highest fishing rates, and no policy can allow heavier fishing and also maintain more fish in the ocean. Because the capped responsive systems are inherently resilient, they were able to achieve higher yields, thus driving down abundance and the ecosystem productivity index. This result led to the trade-off between resiliency, a performance objective with strong implications for ecosystems, and ecosystem productivity. Note, though, that this trade-off was relatively mild; ecosystem-productivity-index scores for this control rule ranged from moderate to high. One could conclude from these results that resiliency is more important for ecosystems than estimated abundance because the alternatives analyzed here varied more substantially in it. The general applicability of this finding remains to be tested.

HIGH VS LOW PRODUCTIVITY.—In the analyses presented here, the high-productivity stock presented a more difficult management challenge than the low-productivity one, because of starker trade-offs among the performance indices, which resulted from the slow population response of the low-productivity stock. Although conventional wisdom and the rich literature on longevity, multiple reproductive events, and resiliency to population crashes (see, e.g., Charlesworth, 1980) would not predict this result (Musick et al., 2000), the low-productivity population grew relatively slowly, and removals were also slow because fishing rates were set relative to the biologically acceptable levels. Therefore, even when management error led to overfishing, the resulting declines were slow. As a result, two factors made these populations more robust. First, the populations were more likely to experience a switch in fortune, in the form of productivity, before they declined to dangerous levels, and second, managers had more time in which to respond to abundance changes before getting into a difficult situation.

I would therefore assert that management mistakes are not by themselves the principal dangers facing long-lived, slow-growing species. Instead, their relatively low productivity makes them vulnerable on three other fronts. First, it may be economically advantageous to fish these species to very low numbers rather than to sustain a productive fishery (see, e.g., Clark's 1973 study of blue whales). Second, the scale of potential fishing effort does not discriminate between low- and high-productivity species, so an unregulated fishery on the former is more likely to overfish them than one on the latter. Third, low-productivity species are more vulnerable in mixed-stock fisheries because they are likely to be fished to low levels while yields from more productive species are maximized (Ricker, 1958). On the basis of all three factors, one should conclude that low-productivity species require more resiliency than high-productivity ones, which will amplify the significance of relatively mild trade-offs identified in the analyses above.

THE BURDEN OF PROOF.—Much attention has been paid to the issue of the burden of proof in fisheries management (e.g., by Dayton, 1998; Charles, 2002), an issue that results from scientific uncertainty. Scientific uncertainty is the reason that policymakers must choose a direction to err—toward long-term health of marine ecosystems and fisheries or toward short-term profit and in some cases viability of the fishing industry. The gulf between these two extremes increases with the amount of uncertainty, amplifying the challenge to managers.

Resilient management systems have great potential to close this gap by reducing a major threat to the long-term health of marine ecosystems and fisheries: collapses due to inadvertent overfishing. Consequently, resiliency narrows the uncertainty gulf and moderates the burden-of-proof issue. By assuring the long-term viability of marine ecosystems and fishing communities, resilient management systems can refocus policy debate on balancing other values, such as yield productivity and constancy, or yield and ecosystem productivity. My findings indicate that resilient management systems are possible and require little sacrifice of long-term fishing opportunities but will require changes to the conventional approach. These changes may involve substantial rebuilding, in which case phasing in of new regulations may be socioeconomically desirable (see, e.g., Sladek Nowlis and Roberts, 1997).

REJECTION OF CONVENTIONAL ALTERNATIVES.—Although results indicated that each control rule had its own strengths and weaknesses, the most widely used—constant catch and constant fishing mortality—fared poorly in these analyses. In particular, the stark trade-off between resiliency and yield productivity makes constant catch generally undesirable. The poor real-world performance of these two control rules has motivated a call for smarter systems in fisheries management (e.g., Restrepo et al., 1998), but in the real world we are a long way away from leaving these conventional systems behind. Interestingly, constant-fishing-mortality policies have been identified in the past as a good balance between yield productivity and constancy and as an effective means for addressing environmental fluctuations (Walters and Parma, 1996). Other management systems fared better here in both respects, without loss in other performance traits.

Although the technical guidance system represented a major improvement over the most widely used approaches, it scored only moderately well in resiliency (especially against misestimation of abundance), capacity constancy, and ecosystem productivity. In addition, implementing this control rule requires the estimation of many parameters, and although it did fare very slightly better in maximum yields, it did not provide clear advantages over capped responsive systems. These concerns make it less desirable, in most cases, than capped responsive systems.

The rarely used capped responsive systems fared very well, as they did in previous comparison with other control rules (Branch, 1998). The performance benefits would have been even more pronounced had the tuning focused on resiliency against misestimation of abundance. This property is especially notable because previous studies identified noncapped, highly responsive control rules as potentially unresilient in the face of such errors (e.g., Sladek Nowlis and Bollermann, 2002). Under a capped responsive control rule, setting the cap high (e.g., $q_{\min} = 1$) provided excellent yield productivity, good yield and capacity constancy, and adequate resiliency and ecosystem productivity for relatively well-studied fishes. Setting it lower increased the resiliency, ecosystem productivity, and yield and capacity constancies, but at the cost of lower yields. As a result, tuning of this control rule provides a means of addressing the trade-offs. Managers are likely to favor lower caps if high uncertainty surrounds the fishery (motivating resiliency), income must be predictable (motivating yield and capacity constancy), or the fished species might play an important ecological role (motivating ecosystem productivity). Otherwise, managers might prefer a high-capped system, which trades off these benefits for high overall yields. In most cases, though, managers are likely to favor an intermediate cap level as a way of balancing competing objectives.

This control rule can also be manipulated by adjustment of the no-fishing threshold, $N_{\min}$; higher levels generally lead to greater resiliency but a tighter squeeze when stock abundance is down (Sladek Nowlis and Bollermann, 2002). The no-fishing threshold can be enacted in a number of ways, including size limits and closed areas (Sladek Nowlis and Bollermann, 2002). In fact, the more general analysis presented here helps to explain previous findings that closed-area management can maintain high yields while increasing resiliency (e.g., Lauck et al., 1998; Sladek Nowlis and Roberts, 1999).

The model formulations discussed here permitted examination of various management strategies for their performance under simple biological and ecological assumptions. Researchers interested in exploring fishery management systems for species or ecosystems with special traits (e.g., sex change, multispecies trophic dynamics) are encouraged to develop models with additional complexity. The model formulation is not the point of this paper, as useful models can be constructed in an infinite number of ways. The models used here, selected for their simplicity, are especially attractive for general exercises like the one presented here, as well as for cases where biological parameters are highly uncertain (Butterworth and Punt, 1999), the norm in fisheries management (Sladek Nowlis and Bollermann, 2002). Although my conclusions are by no means universal, the approach of devising and analyzing an index for each objective is recommended as a means of facilitating informed, value-driven decision making throughout natural-resources management.

These indices could be combined into a single performance measure by means of a straight average (treating each value equally) or a weighted average (varying the relative importance of each value), but doing so would detract from a central thesis of the present paper—that managers and the general public will make better-informed decisions if they have a chance to consider the performance of management alternatives across a range of management objectives, so that people can weigh them against their own unique mixes of values.

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