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TITLE XII
Collaborative Research Support Program

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FINMAN: Simulated Decision Analysis With Multiple Objectives

by

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FINMAN: Simulated Decision Analysis with Multiple Objectives

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Abstract.—Management of large-scale, multiuser fisheries requires simultaneous consideration of several competing objectives. Simulation analysis was used to select the most "effective" strategy to attain optimum sustainable benefits. A fishery management institution and resource structure were simulated with the microcomputer-based model FINMAN, which simulates decision-making responses at three levels within the institution: fishery management rules, the fishery agency's general budget allocations, and research budget allocations. The program also allows for a variety of fishery types, rule development structures, and levels of authority over the fishery. Effectiveness was defined as a complex function of the attributes cost, rate of profit, degree of enforcement, population capacity, and time to achieve goals. A decision analytic model was developed for evaluating management policy strategies. Attributes can account for effects over time, and probability density and utility functions were assessed over the five attributes. Unique aspects of this study were an assessment of a multiattribute utility function and use of that function to help make an important fishery policy decision.

Fisheries require rigorous management policy due to multifarious competing uses for finite available resources. With escalating resource usage, decision makers (DMs) are pressured to make spontaneous decisions on the regulation of marine resources that may have important biological, economic, and social effects. Conflicts over the quantity of fish present, who will catch which fish, what gear may be used, and how much will be caught provoke great and long debate and are commonplace in all forms of the journalistic media, state and federal legislatures, and national and international fishery management councils. Fishery institution management decisions are based on complex systems of many state variables. Management success depends upon decisions made by the institution's component members: fishery managers, agency administrators, and research supervisors. The recognized key to smoothly functioning fishery institutions is the clear understanding of each component's needs and of the bases for the actions of each component. Thus, fishery DMs need to understand these complex relationships and to anticipate future situations. These precepts may seem trivially obvious, but it is important to note that the ideal interactions within the institution are never fully realized. However, the ideals can be approached if individuals receive extensive experience in each of the three major components of the fishery management institution. The historical paradigm for individual professional development within the institution was to enter in the research component and, with seniority, experience, and success, sequentially graduate to the research program's management component. Relatively recently, there has been a greater overall tendency for fishery DMs to enter the institutional framework laterally rather than sequentially and to bring with them valuable expertise in resource use and program management skills. Although this approach has certain advantages, it exacerbates the communication problem within the institutional framework. Neither pathway necessarily provides direct experience in the two management components for research scientists, nor in the fishery management component for research program managers. A didactic tool has been needed for providing simulated "hands-on" experience to assist students, professionals, and fishery management appointees in making fishery management decisions and fishery research program decisions. Traditionally, as they solved problems in such disciplines as fishery development and management, DMs have considered a single objective within their frameworks for analysis, i.e., the proximal MSY (maximum sustainable yield) criterion. Over the last decade, however, there has been an increased awareness of the need to identify and consider simultaneously several objectives, particularly those derived from the study of large-scale, multiuser fishery systems.

The FINMAN Simulator

The FINMAN (Fisheries Institution Management-training simulation model) microcomputer

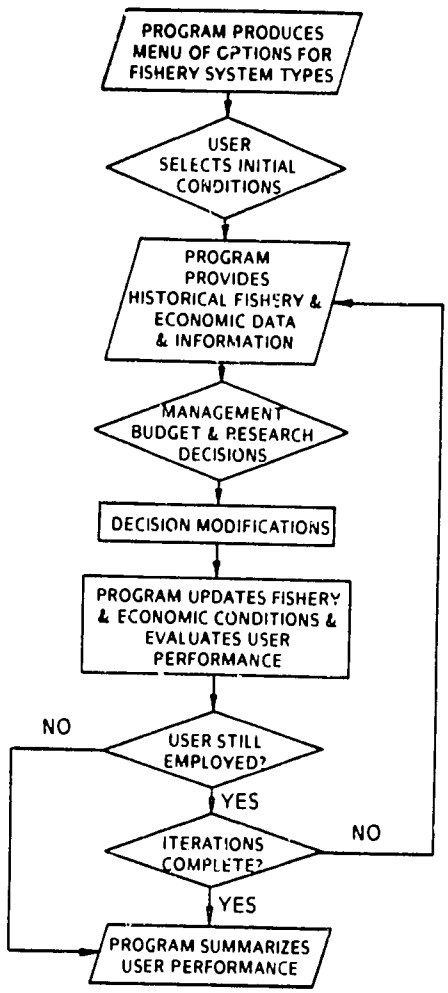

FIGURE 1.—Flow diagram of the FINMAN simulation model.

simulator was developed to meet the need for a multiobjective decision model (Ault and Fox 1986a, 1986b, 1987). A flowchart of the age-structured discrete-time FINMAN simulation model is shown in Figure 1. To this end, FINMAN was designed as both a didactic tool and a systems analysis tool. The essence of simulation is to provide a realistic and detailed representation of the problem under study, which allows the DM to test various alternative approaches to the problem (Bradley et al. 1977). Simulation is useful in resolving questions posed by the analyst. Simulation models evaluate each alternative by calculating a corresponding measure of performance. Simulation models do not generate optimum solutions, but simply permit evaluation of alternative solutions supplied externally by the DM.

The FINMAN model allows the user to select among several options. The program then generates the initial data and information set, including the situation the user is confronted with in terms of his or her continued employment, and queries the user about a series of budget and management decisions. To establish the constraints placed on management authority and abilities, a series of options is shown so that an information base of initial conditions, used to make basic decisions regarding management measures and institutional budget allocations, can be generated. These decisions include management measures to be implemented; overall budget allocations among research, enforcement, and development; and research budget allocations among data collection and analysis projects. The basic biological and fishery-specific model is a modified extension of Fox's (1973) generalized exploited population simulator. The precision and accuracy of the overall view of the fishery state may be controlled in part by the budget allocations and particular management decisions. Most processes have a stochastic element, so the program uses chance variables in formulating each "annual" update. When the user's employment is terminated due to poor performance, or when a selected number of iterations has been performed, FINMAN provides a summary of the user's performance. The user's goal is to maximize a multiattributed utility objective function that embodies comparisons, by preferential ordering, of different manager's orientations and varying human attitudes towards management objectives. Survival of the user through all the iterations is based on probabilities influenced by the performance of the fishery and by constituency contentment.

The model has six preprogrammed fish-stock life history modules, each parameterized with the economic, sociological, and biological settings that typify fishery institution management frameworks for the respective fisheries. The available species modules for management strategy simulation are grouper (Serranidae), tuna (Scombridae), anchovy (Engraulidae), shrimp (Penaeidae), corvina (Sciaenidae), and snapper (Lutjanidae). One can use FINMAN to visualize the approximate system response of a particular exploited stock even when the fine details of the fishery system are not known, a situation prevalent in developing countries and developing fisheries. For such situations, the user may approximate the unknown variables by "best guesses," transferring information from other similar but better understood fish stocks. In this way, the investigator may study system responses to various parameter scalings to gain insight concerning system sensitivity.

to determine the envelope in which system responses in the deterministic model are guaranteed to occur, and thereby to disregard infeasible regions of system space. Intuition may be gained with respect to developing or implementing prudent management alternatives for successful system evolution. The model is useful in demonstrating large-scale and often counter-intuitive interactions. One can use FINMAN to plan, to evaluate alternatives, and to identify sensitive areas of the system.

Goals for Fishery Resource Management

Shifting of societal values and norms has prompted the enactment of laws regulating the use and management of natural resources toward multiple objectives. The most obvious concurrent fishery management objectives are the biological objectives of maintaining environmental quality by conservation of resources while maximizing the physical yields from the stock(s); the economic objectives of providing short-term and long-term capital needs, maximization of profits, and minimization of production costs; and the sociopolitical objectives of creating employment opportunities, promoting development, and achieving equitable distribution of resources. Fish and fish sales play a powerful role in the international political arena, and fish have important domestic recreational potential. It is not possible to satisfy all objectives simultaneously at their respective optima, and trade-offs between competing objectives must be made. Thus it is necessary to decide the overall goal of management. In an uncertain world, the responsible DM balances judgments about uncertainties with his or her preferences for possible consequences or outcomes (Keeney and Raiffa 1976). It often is necessary to reconcile several partly or wholly conflicting objectives. However, fishery management plans rarely specify explicitly what these trade-offs should be. To establish an overall goal for the management of specific resources entails a definitive statement of how much the various objectives are of concern to the DM in some common measure. The objective function would be constrained to avoid the worst conditions of any one objective.

Techniques to formulate this problem involve decision analysis, a concept and procedure for systematically analyzing problems in a rational manner. Hertz and Thomas (1983) identified two roles of decision and risk analyses: the analyses offer a broad perspective for structuring the process of decision making, and they provide a set of techniques for evaluating the worth of alternative decision options. Both analytic approaches involve decomposing and structuring the problem, assessing the uncertainties and values of the possible outcomes, and determining the preferred strategy in terms of some specific choice criterion. Under these approaches, it is assumed that the DM's preferred course of action will depend on the probabilities that this course of action will result in the various possible consequences, and the DM's preferences for those consequences (Keeney 1971). Thus, more than one attribute or measure of "effectiveness" is needed to describe the possible effects of the outcomes on each of the important groups concerned with the problem. The following five measures were selected for evaluating effectiveness:

X_1 ≡ years in position for the manager (performance ethic); as X_1 increases, the newness decreases;
X_2 ≡ the practical capacity of the population in terms of population abundance (conservation ethic);
X_3 ≡ rate of growth of the within-year investment (commercial ethic);
X_4 ≡ relative amount of money to development (development ethic);
X_5 ≡ number of potential regulation schemes enacted (civil rights ethic).

The DM must fulfill the responsibilities of each generation as trustee of the environment for succeeding generations so that environmental quality may be preserved. Furthermore, the value attached to money is not the same for all decision makers. Both the DM's wealth and her or his attitude toward risk affect the DM's utility function.

Most complex problems involve multiple objectives. One of the most important problems in decision analysis concerns quantification of the DM's preferences for the various objectives. To quantify the DM's preferences, we must obtain a utility function over all possible consequences. In utility theory, it is assumed that an individual can choose among the available alternatives in such a manner that the satisfaction derived from the choice is as large as possible. Finally, the desire is to obtain an objective function involving multiple measures of effectiveness to indicate the degrees to which the various objectives are met.

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Multiattribute Utility Function Development and Parameterization

From the aforementioned measures a multiattribute utility function (MUF) was developed. It is called an MUF because the argument of the utility function is a vector indicating levels of the various attributes. A utility function is simply a mapping of the values in the range of an attribute (i.e., an objective) into a cardinal (counting) worth scale, as determined by the individual. In effect, an individual's utility function is a formal, mathematical representation of his or her preference structure. Utility theory is being applied with increasing credibility to consumer demand and economics, public decision making, and corporate management (e.g., Keeney 1973; Powers and Lackey 1976; Goicoechea et al. 1982; Hertz and Thomas 1983). If a DM conforms to several axioms relating to choices among certain and uncertain outcomes, a utility function can be constructed. Normally, a utility function is defined over a set of attributes (i.e., the domain) and takes values in the set of real numbers (i.e., the range). The domain may contain one or several attributes. In the case of several attributes, the function is called an MUF. For multiobjective problems, utility functions, in principle, can order completely the set of nondominated solutions. A utility or worth can be associated with each nondominated solution, and the solution with the highest utility is referred to as the best-compromise solution.

Given the five attributes that contribute to our "quality of fishery management" criterion, we desired to construct a utility function reflecting all of these measures. In general, we were interested in assessing the utility function over X ($X = X_1 \times X_2 \times \ldots \times X_n$), denoted by $u(X_1, X_2, \ldots, X_n)$ or $u(\mathbf{X})$, and the function is assumed to be continuous, each X_i having a definite effect on preferences. Rendering decision analysis operational for multiobjective problems may entail assessing the DM's utility function model. A multiobjective programming problem is characterized by a p-dimensional vector of objective functions and a feasible region $\mathbf{X}$ as given by

$$u(\mathbf{x}) = f[u_1(x_1), u_2(x_2), \ldots, u_p(x_p)]; \qquad (1)$$

$u_i(x_i) \equiv$ the ith objective function evaluated over attribute x_i.

Each X_i may be either a scalar attribute or a vector of scalar attributes. It is assumed that preferences over X are bounded, and X_i^* designates the most desirable and X_i^0 the least desirable consequence. This function has two properties that make it useful in addressing the issue of trade-offs between the objective functions. First, $u(x') > u(x'')$ if and only if, x' is preferred to x''. Second, in situations with uncertainty, the expected value of u is the appropriate guide for making decisions, that is, the alternative with the highest expected value is most preferred. This second property follows directly from the axioms of utility theory postulated first by Von Newmann and Morgenstern (1947).

Let

$x_i^* \equiv$ most preferred outcome of x_i;
$x_i^0 \equiv$ least preferred outcome of x_i.

Then,

$$u_i(x_i^0) = 0$$

and (2)

$$u_i(x_i^*) = 1,$$

so

$$u(x_1^0, x_2^0, x_3^0, x_4^0, x_5^0) = 0$$

and (3)

$$u(x_1^*, x_2^*, x_3^*, x_4^*, x_5) = 1;$$

$$X_{ij-} = X_1 \times \ldots \times X_{i-1} \times X_{i+1} \times \ldots \times X_{j-1} \times X_{j+1} \times \ldots \times X_n,$$

x_{ij-} is a member of X_{ij-};

$$X_{i-} = X \times \ldots \times X_{i-1} \times X_{i+1} \times \ldots \times X_n,$$

x_{i-} is a member of X_{i-}.

The main assumptions used that allows development of equation (1) concern the concepts of preferential independence and utility independence (Keeney 1971, 1972, 1973, 1974). We say the $X_i \times X_j$ is preferentially independent of X_{ij-} if one's preference order for consequences (x_i, x_j, x_{ij-}), with x_{ij-} (read: x not ij) held fixed, does not depend on the fixed amount x_{ij-}. This implies that the indifference curves (see Keeney and Raiffa 1976) over $X_i \times X_j$ are the same, regardless of the value of X_{ij-}. In a similar fashion, we say X_i is utility independent of X_{i-} if one's preference order over lotteries on X_i, written (X_i, X_{i-}) with X_{i-} held fixed, does not depend on the fixed amount of x_{i-}. This implies that conditional utility function over X_i, given X_{i-} fixed at any value, will be a positive linear transformation of the conditional utility function over X_i, given X_{i-} fixed at any other value (Keeney 1971). In practice, if such a condition held for three or four 50:50

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lotteries covering the range of X for approximately different values of x_{i-} covering the range of X_{i-}, one would be justified to assume X_i is utility independent of X_{i-} (Keeney 1972).

Given the validity of the two assumptions, to assist the DM in articulating his preferences for the particular problem, the following multiattribute utility function (Keeney 1974) is suggested:

$$1 + Ku(\mathbf{x}) = \prod_{i=1}^{5}[1 + Kk_i u_i(x_i)]. \quad (4)$$

Expanding the product

$$1 + Ku(\mathbf{x}) = [1 + Kk_1u_1(x_1)]\,[1 + Kk_2u_2(x_2)] \times \ldots \times [1 + Kk_5u_5(x_5)] \quad (5)$$

and solving explicitly for $u(\mathbf{x})$ gives

$$u(\mathbf{x}) = \langle\{[1 + Kk_1u_1(x_1)][1 + Kk_2u_2(x_2)] \times \ldots \times [1 + Kk_5u_5(x_5)]\} - 1\rangle/K; \quad (6)$$

k_i and K are scaling constants restricted so that $0 < k_i < 1$, and $K > -1$ ($K \neq 0$). If $\Sigma k_i = 1$ and $K = 0$, the model is linear. If $\Sigma k_i \neq 1$, then $K \neq 0$ and must be evaluated.

From equation (2), we find

$$u(x_i^*, x_{i-}^0) = (x_1^0, \ldots, x_{i-1}^0, x_i, x_{i+1}^0, \ldots, x_n^0) = k_i. \quad (7)$$

The utility function of a DM is assessed by determining various points on the utility curve. The determination of the points can be accomplished in the following way. First, two functional values, x^* and x^0, are chosen so that they are sufficiently wide apart to encompass all the rewards and penalties in the decision problem. Utilities are then arbitrarily assigned to these points. Typically, $u(x^*) = 1$, x^* representing the highest functional value, and $u(x^0) = 0$, x^0 representing the lowest functional value.

Next, the DM is presented with a lottery involving x^* and x^0 and told that he or she has a probability (p) of receiving x^* and a probability ($1 - p$) of receiving x^0. The DM is then asked what amount x would be acceptable for certain in place of the above gamble. Once x has been determined, a correspondence between x and p has been established. With this known correspondence, the utility of x can now be calculated as

$$u(x) = p[u(x^*)] + (1 - p)\,[u(x^0)]. \quad (8)$$

Because $u(x^*) = 1$ and $u(x^0) = 0$, equation (8) reduces to

$$u(x) = p\cdot 1 + (1 - p)\cdot 0 = p. \quad (9)$$

By varying p and changing the gamble, any number of points on the DM's utility curve can be generated. These points can be plotted in $[x_i, u(x_i)]$ space to determine the shape of the curve. Curve-fitting procedures can be used to estimate the functional form of the utility function (Marquardt 1963; Draper and Smith 1981). The scaling factor K may be found numerically (Keeney and Raiffa 1976) by solving

$$1 + K = \prod_{i=1}^{5}(1 + Kk_i). \quad (10)$$

Equation (10) is derived from equation (1) when all attributes are offered at their most preferred amounts; i.e., $x = x^*$. If $\Sigma k_i > 1$, then $-1 < K < 0$; if $\Sigma k_i < 1$, then $K > 0$.

To use either the additive or the multiplicative form, we need to obtain exactly the same information to specify the n-attribute utility function $u(x_1, x_2, \ldots, x_n)$ completely. Then we can assess the n single-attribute utility functions $u_i(x_i)$ on scales of zero to one by application of the n scaling constants k_i (Figure 2). If $\Sigma k_i \neq 1$, the utility function is multiplicative and the additional constant K can be found numerically by solving equation (10) (Table 1).

By specifying a group of alternatives differing slightly in some feature, we can conduct a sensitivity analysis of the probabilistic inputs (Keeney and Raiffa 1976). Also, we can conduct a sensitivity analysis of the preference structure by varying such parameters as the scaling constants in the DM's MUF. Typically, not all of the inputs need to be specified as probabilistic variables because a preliminary sensitivity analysis is often used to screen and identify those input variables that need to be specified in probabilistic form. In this way, different utility functions of members of a decision-making group can be used to evaluate and rank the alternatives. This might clarify differences of opinion and suggest certain creative compromises if needed. Monte Carlo techniques can be applied to find the expected utility values for dependent probability distributions. The Monte Carlo approach would generate a sequence of x^α ($\alpha = 1, 2, \ldots, T$), and we then compute

$$\frac{1}{T}\sum_{\alpha=1}^{T} u(x^\alpha)$$

for T large.

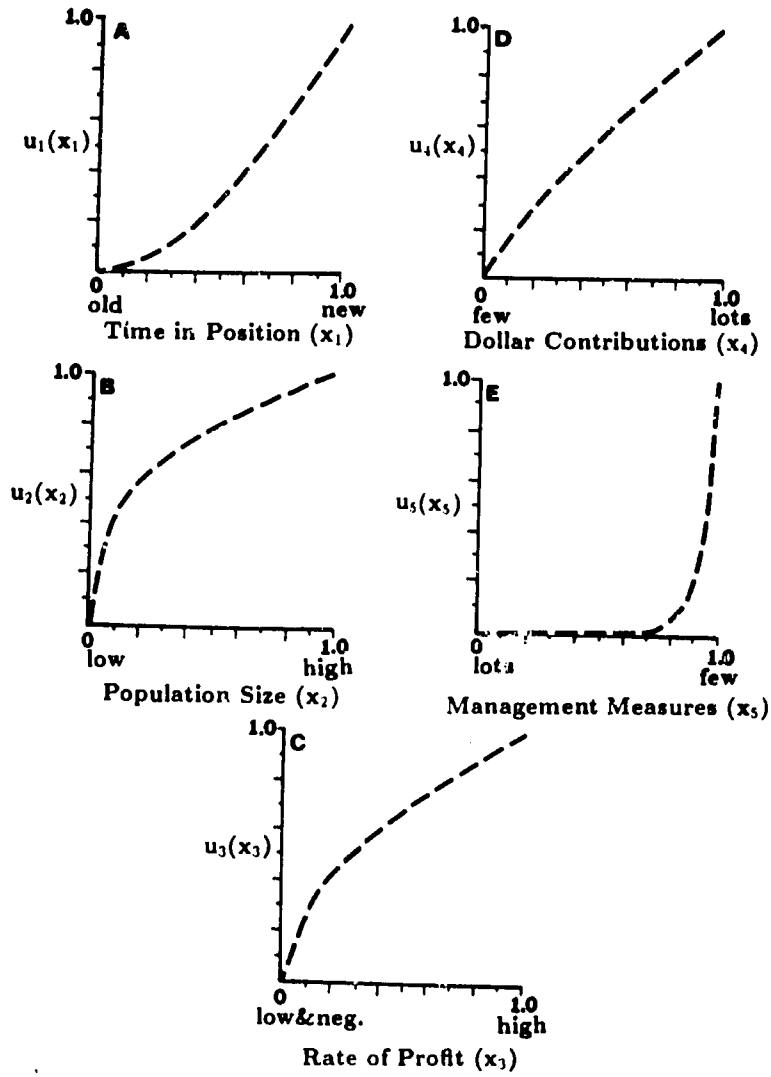

FIGURE 2.—Individual utility functions, $u_i(x_i)$, for the five attributes specified in the multiattribute utility function for the FINMAN simulation of a grouperoid fishery. Utility functions are (A) newness on the job (performance ethic), (B) conservation ethic, (C) commercial ethic, (D) budget development (development ethic), and (E) perceptions (civil rights ethic).

Example of the MUF Applied to Tropical Grouperoids

The FINMAN model was designed for examination of system responses to biological, socioeconomic, and political fishery management decisions and fishery research program management decisions in a variety of situations. Although the simulation model has been developed along generalized lines to accommodate a variety of fishery complexes, the impetus here was to examine the response to exploitation and the attendant management structure decisions for optimal policy. The grouperoids (fish with grouper-like life history strategies) are an important component of commercial and recreational catches in tropical and subtropical regions. The grouperoid treated here is an Atlantic-province grouper recognized as an apex predator. It is a reef and continental shelf slope dweller that is slightly migratory. Their populations seem to behave as unit stocks. Typically they are protogynous hermaphrodites (i.e., they mature as females and later in life transform to males). The ability to model hermaphroditic stocks has been accounted for in the FINMAN model (Table 2; Ault and Fox 1986a, 1986b). For grouperoids, the dynamic pool relation for the population of yields in weight can be viewed in any three planes as a four dimensional surface.

$$Y_w = f(F, t_{p'}, R); \qquad (11)$$

$F \equiv$ instantaneous fishing mortality;
$t_{p'} \equiv$ time or age of first capture;

TABLE 1.—Utility attributes and their ranges for individual utility functions.

Factor or outcome[a]	Utility attribute[b]				
	Performance ethic $u(x_1)$	Conservation ethic $u(x_2)$	Commercial ethic $u(x_3)$	Development ethic $u(x_4)$	Civil rights ethic $u(x_5)$
k_i	0.8	0.45	0.4	0.6	0.8
x_i^*	0	Maximum population	Maximum profit	0.33 of total budget	None
x_i^0	30	0	Zero and negative profits	0	All possible

[a]k = scaling factor for utility function i; x_i^* = most preferred outcome of x_i; x_i^0 = least preferred outcome of x_i.
[b]The multiattribute utility function (MUF) scaling factor (K) = −0.995.

R ≡ recruitment of individuals to the exploitable phase;
Y_w ≡ total catch in weight for the stock.

Two different response surfaces are visualized if one assumes either a constant recruitment function through time or a stock density-dependent recruitment function (Figure 3). The yield model for the constant-recruitment function predicts that globally highest marginal yields are obtained at low to intermediate fishing mortalities and mid-range ages of first capture. The density-dependent recruitment yield model predicts that low fishing mortalities generate the highest maximum sustained yields, and that high fishing mortalities potentially cause extinction of harvests.

Yield-per-recruit theory assumes equilibrium dynamics. However, developing fisheries are time-bound and dynamic, and effects follow a transitional course. The question is how to proceed over the yield surface in a transitional dynamic path to achieve optimal yields. Suppose, for example, that an artisanal level of fishing mortality ($F \cong 0.02$) is presently operating on the grouperoid population of interest. The decision analysis problem is one of deciding how to achieve acceptable levels of marginal yield, effort capitalization, stock biomass, spawning stock,

TABLE 2.—Parameters of the simulated grouperoid population (data from Ault and Fox 1986b).

Parameter	Symbol[a]	Value										
		General	At age (years)									
			1–4	5	6	7	8	9	10	11	12	13
Number of year classes	t_λ	13										
Natural mortality	M_{ij}	0.2										
Age at first recruitment	t_p	in $^1/_{12}$ year										
Year of first maturity	t_m	5										
Recruitment (Beverton and Holt function)	α	1.0×10^{-6}										
	β	7.0×10^{-4}										
Maturity fraction												
Female	ϕ_f		1.0	0.98	0.85	0.70	0.50	0.40	0.25	0.10	0.05	
Male	ϕ_m		0.0	0.02	0.15	0.30	0.50	0.60	0.75	0.90	0.95	
von Bertalanffy growth function												
Asymptotic length	L_∞	1,290 mm										
Asymptotic weight	W_∞	25 kg										
Growth constant	K	0.122										
Initial time	t_0	−1.127 year										
Fecundity (millions of eggs)	λ_i		0.0	0.3	0.4	0.53	1.5	3.5	5.0	6.0	7.0	
Unit cost	C_i	$1,000.00										
Value of catch	VC_i	$4.40/kg										

[a]Subscript i denotes age; subscript j denotes year.

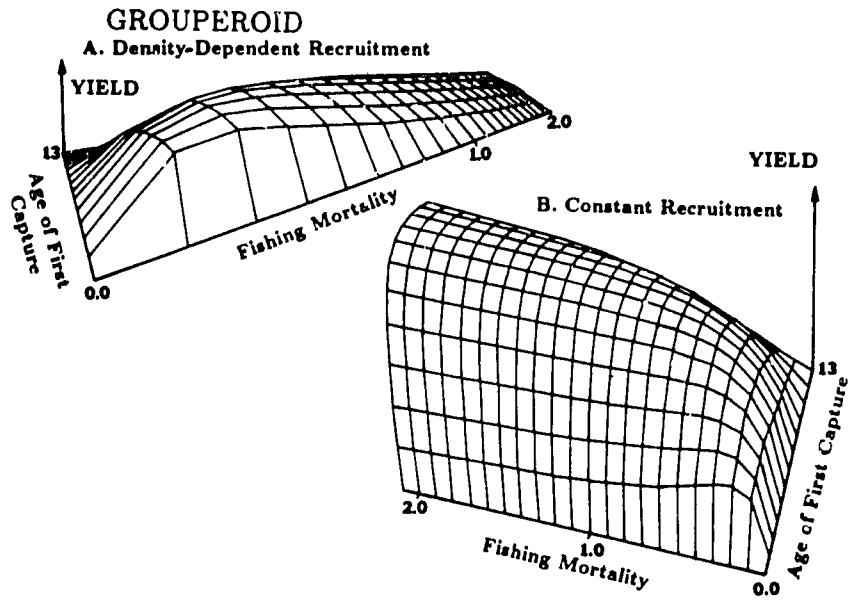

FIGURE 3.—Response surfaces showing yield in weight per equilibrium recruitment for the grouperoid fishery used in the FINMAN simulation, under hypotheses of (A) density-dependent recruitment and (B) constant recruitment.

and profit given the appropriate individual evaluation of each factor's utility. Three exploitation policies—I, medium risk; II, conservative; III, high risk—were used to test management strategies under several conditions (Table 3). Fishing mortality was applied as a time-stratified linear multiple of the form

$$F(t + 1) = F(t) + F(t)\cdot\Delta F; \qquad (12)$$

$\Delta F \equiv$ percentage change in fishing mortality for the time step t.

All exploitation policies had linear rates of increase applied against the existing fishing mortality in the present year. We also investigated optimal harvesting policies of two types: policies under which the optimal level of effort was determined for each year of a fixed planning horizon; and policies in which the optimal harvest was determined by deterministic and stochastic escapement. Monte Carlo simulations were run on the various stochastic policies.

Results

The medium-risk and high-risk exploitation policies (I and III) involved increases in fishing mortality of 25%/year. In both cases, fishing mortalities were decreased after the 18th year of the planning horizon at different rates. Under the conservative exploitation policy (II), fishing mortality increased at 12.5%/year throughout the planning horizon (Figure 4). The highest harvest, in terms of physical yield in weight, was captured under policy III through the 15th year of the planning horizon, under policy I from year 16 through year 22, and under policy II thereafter (Figure 4).

The characteristics of equilibrium yields and profits were identical under policies I and III (Figure 5). In both cases, yield curves were asymptotic and indicated an apparent MSY of about 1,300 tonnes. Marginal yields apparently were highest when F was 0.3–0.4. The equilibrium

TABLE 3.—Hypothetical policies for harvest of a simulated grouperoid population.

Policy	Annual increase in fishing mortality (F^*)[a]	t_p[b]	Starting N condition[c]
I: medium risk	0.25	7	Equilibrium: F_{i1} = 0.02
II: conservative	0.125	7	Equilibrium: F_{i1} = 0.02
III: high risk	0.25	4	Equilibrium: F_{i1} = 0.02

[a]$F_{ij} = F_{i-1,j} + F_{i-1,j}(F^*)$ for $i = 2, 3, \ldots, N$ and $j = 1, 2, \ldots, t_N$; F_{ij} is instantaneous fishing mortality for age i in year j of planning horizon N.
[b]Age of first capture.
[c]N is the population age-distribution vector.

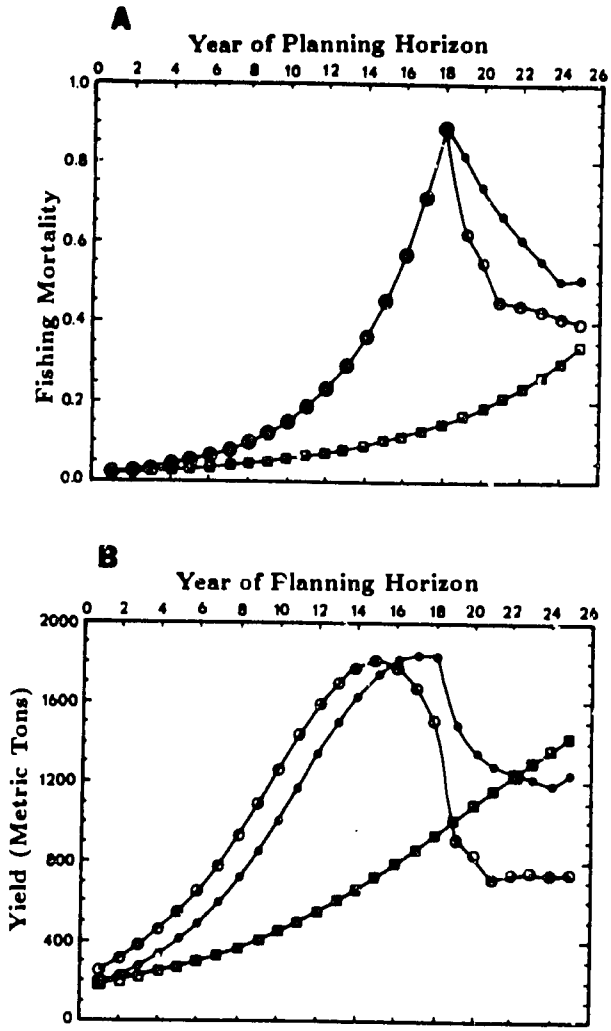

FIGURE 4.—Temporal plots of (A) average fishing mortality and (B) average yield in weight for a FINMAN-simulated grouperoid fishery operated under three management policies: I, medium risk (closed dots); II, conservative (open squares); and III, high risk (open circles). Superimposition of symbols indicates identical values.

profit surfaces were parabolic, and maximum economic yields occurred when F was 0.15–0.2.

Under policy I, fishing mortality was decreased after the 18th year because we detected a decline in transitional yields. The approach is referred to as a "surfing" policy (see Walters 1986). Reduction of fishing mortality caused yields to dip below the equilibrium curve (Figure 5). Equilibrium finally was achieved at about the 25th year of simulation. Profit from the fishery maximized at year 13, subsequently declined, and became negative for years 18–23, resulting in a substantial loss of profits. Although policy II had the same equilibrium structure as policy I, the lower rate at which fishing mortality was increased allowed physical yields to increase throughout the planning horizon. At the end of the planning horizon, yields slightly exceeded the apparent highest marginal increment. Profits increased through year 22, but then decreased slightly through the remainder of the planning horizon.

Policy III had a different equilibrium structure with respect to physical yields and profits. Selectivity for the grouperoids was reduced (age at first recruitment, 4 years: Table 3), and the equilibrium yield surface was more Gompertz in form (Figure 5). This suggests that high levels of fishing mortality ($F > 1.0$) could reduce the grouperoid population to harvest extinction, because fishing disrupted the stock's reproductive value and recruitment processes. The MSY was depressed under this approach, and equilibrium MSY occurred when F was 0.15–0.30. The equilibrium profit curve was parabolic, reaching a maximum when F was 0.15–0.20. The destructive high-risk fishing policy showed high gains in physical yields up to about the 15th year of the planning horizon, but then yields severely declined to levels below the equilibrium relation. Profits reached very high levels by year 12, but then collapsed radically and became decidedly negative after the 17th year of the planning horizon.

Cumulative physical yields under policy III dominated those under other policies through year 20, but then were superceded by yields under policy I for the remainder of the planning horizon (Table 4). Rankings of cumulative yields showed policy III engendered the highest average yield in weight, and policy II the lowest. Marginal yields were greatest under policy III through year 15, under policy I for years 16–20, and under policy II for the remaining planning segment. The highest average marginal yields were realized by policy III through year 15.

In period 11–15, policy III was 1.3 and 2.3 times more profitable than policy I or policy II, respectively (Table 4). After year 15, policy II yielded the best profits, and policies I and III both induced financial losses. Because of enormous early gains, policy III showed the highest average profit for the 25-year planning horizon, as evidenced by simple ranking. Policy II produced the least profit overall.

Utility Evaluation and Effective Strategies

Control of utility functions for newness, budget development, and perceptions allowed examination of system sensitivity to the various policies in terms of the forcing provided by the utility func-

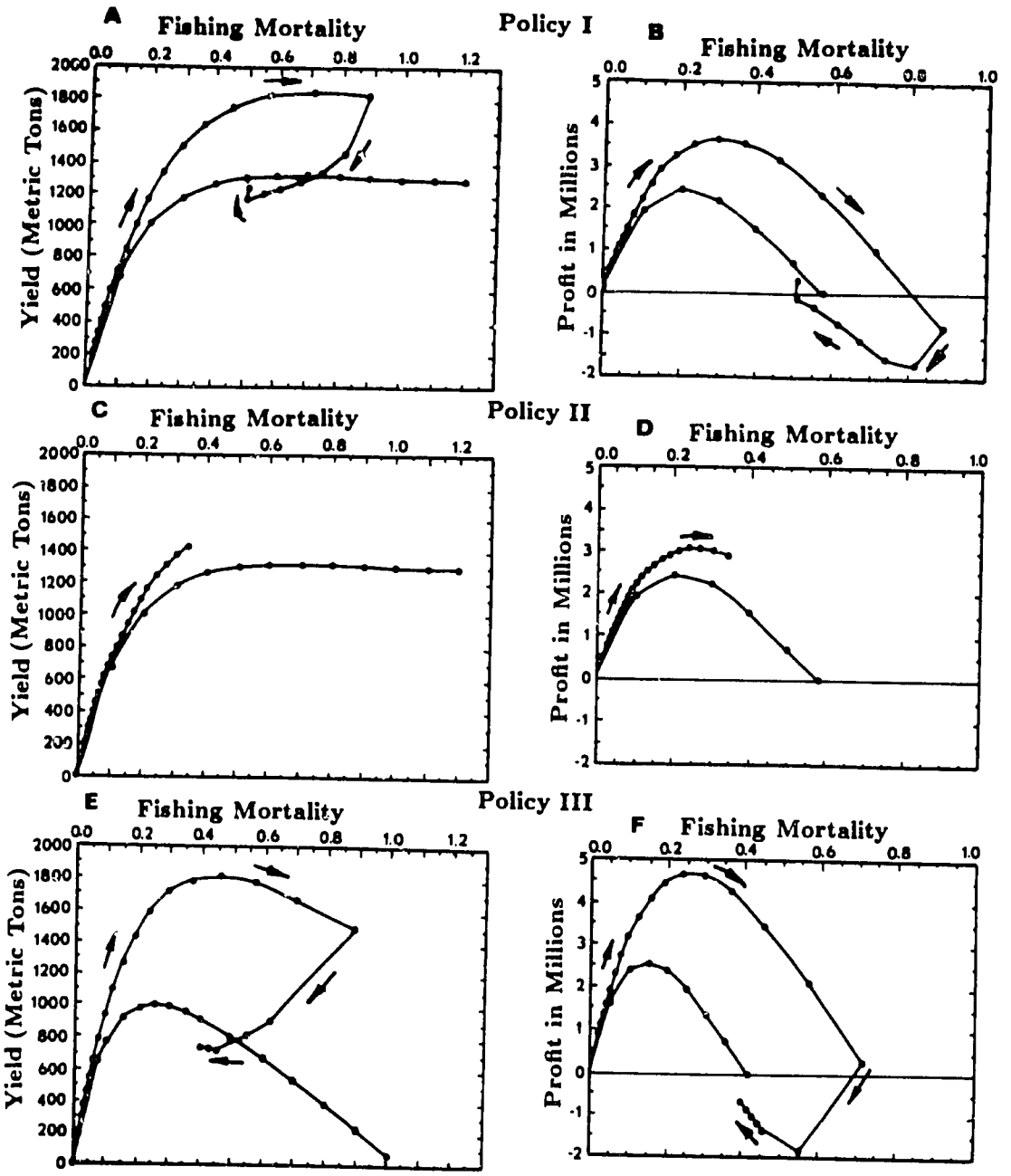

FIGURE 5.—Relationships of yield (tonnes) and profit (dollars) to fishing mortality for a FINMAN-simulated grouperoid fishery operated under three management policies: I, medium risk (panels A, B); II, conservative (panels C, D); and III, high risk (panels E, F). In each panel, the upper curve tracks transitional yield or profits and the arrows indicate the dynamic transitional time path; the lower curve tracks equilibrium values.

tions $u_2(x_2)$ (conservation), $u_3(x_3)$ (commercial), and also the combined utility function $f[u_1(x_1), u_2(x_2), u_3(x_3), u_4(x_4), u_5(x_5)]$ (Figure 6). Probability density functions were altered by changes in the maximum and minimum values for each of the attributes. These changes represent fine-tunings relative to the alternatives.

All policies relative to $u_2(x_2)$ received about the same utility response through year 8 of the planning horizon; however, utilities associated with both policies I and III declined from that point onward. Utility $u_2(x_2)$ declined rather sharply under policy III, but remained relatively stable under policy II throughout the entire planning horizon domain (Figure 6A). The commercial utility, $u_3(x_3)$, was best under policy III through year 10, but then declined abruptly to zero by year 18 (Figure 6B). We have termed these zero utility evaluations as "dead hole" policy. Policies I and II supported similar commercial utilities through

TABLE 4.—Yield (thousands of tonnes) and profit (millions of dollars) from a simulated grouperoid population under three management policies—I, medium risk; II, conservative; III, high risk—over a 25-year planning horizon. R denotes average rank; asterisks (*) denote optimum average rank.

Policy	Cumulative yield or profit (rank) through year						Yield or profit (rank) within period					
	5	10	15	20	25	R	1–5	6–10	11–15	16–20	21–25	R
						Yield						
I	1.4 (2)	5.1 (2)	12.5 (2)	20.8 (2)	26.9 (1)	1.8	1.4 (2)	3.7 (2)	7.4 (2)	8.3 (1)	6.1 (2)	1.8
II	1.1 (3)	3.0 (3)	6.1 (3)	10.8 (3)	17.3 (3)	3	1.1 (3)	1.9 (3)	3.1 (3)	4.7 (3)	6.5 (1)	2.6
III	1.9 (1)	6.7 (1)	15.1 (1)	21.8 (1)	25.5 (2)	1.2*	1.9 (1)	4.8 (1)	8.4 (1)	6.7 (2)	3.7 (3)	1.6*
						Profit						
I	4.6 (2)	15.8 (2)	33.1 (2)	32.5 (2)	30.8 (3)	2.2	4.6 (2)	11.2 (2)	17.3 (2)	−0.6 (2)	−1.7 (2)	2.0
II	3.7 (3)	9.7 (3)	19.1 (3)	32.4 (3)	47.6 (1)	2.6	3.7 (3)	6.0 (3)	9.4 (3)	13.3 (1)	15.1 (1)	2.6
III	6.9 (1)	22.8 (1)	44.5 (1)	40.6 (1)	33.6 (2)	1.2*	6.9 (1)	15.9 (1)	21.6 (1)	−3.9 (3)	−5.1 (3)	1.8*

year 5, but policy I went "dead hole" by year 18 of the planning horizon. A reduction of harvesting effort under policy I allowed a slight stock and profitability recovery by year 24 of the planning horizon. Policy II allowed the highest average commercial utility, which was relatively stable, profitable, and apparently satisfactory to the constituency throughout, and presumably beyond, the planning horizon.

The multiattribute utility was best (slightly) under policy III through year 10 of the planning horizon, and thus was favored early in the planning horizon (Figure 6C). But when the profitability declined due to collapse of the fish stock, policy III became the least desirable of the three. Policy II gave the most stable MUF although this utility declined during the first 3 years under all policies (which was due, incidentally, to the decline of the performance utility, $u_1(x_1)$).

By the MUF analyses conducted here, policy II was the optimal one over a 25-year planning horizon (Table 5). Although policy III initially supported high levels of profitability, its long-term approach was destructive, and the high-risk profile led to collapse of the fishery in terms of physical yields and economic chaos. The more conservative posture of policy II with respect to both the biological and industrial points of view satisfied more of the management objectives over the long run.

Discussion

We have described the use of the multiattribute utility function in conjunction with a simulation–optimization procedure to evaluate alternative management strategies for a tropical marine fishery. The MUF approach provided a rational basis for including public, industrial, and political input into the decision-making process. The MUF in our example embodied several criteria, including commercial fishery benefits, conservation ethics, agency benefits, and socioeconomic viewpoints on regulation and budget. The MUF methodology appears to provide a quantitative basis for discovering the relative magnitudes and merits of tradeoffs, and the importance of introducing finite differences within each attribute.

Policy simulation offers corporate and fishery management entities a strategic tool that enables them to examine the risk consequences of various human and financial investment policies. Our simulation model, FINMAN, provides a vehicle for testing and examining sensitivities to various policies. High- and medium-risk development policies examined here both overshot system productivity in our examples; in both cases, relaxation of fishing intensity did not result in a rapid nor near term return to former levels of productivity. These policies thus are of dubious validity. On the other hand, Walters's (1986) adaptive management doctrine advocates probing the fishery system to learn about system response. Walters's

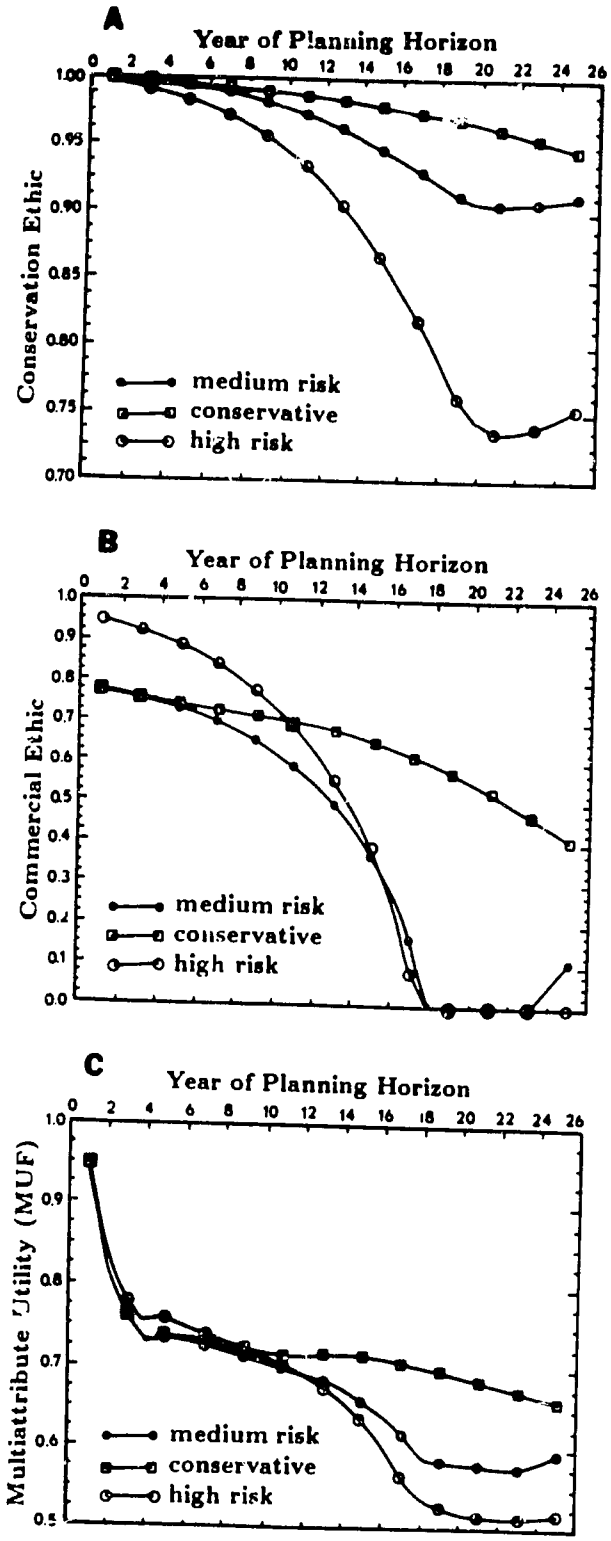

FIGURE 6.—Utility function responses for a FINMAN-simulated grouperoid fishery operated under medium-risk, conservative, and high-risk management policies: (A) conservation ethic (X_2) utility function; (B) commercial ethic (X_3) utility function; (C) multiattribute utility function.

method requires accurate monitoring systems, high stock productivity, and flexibility of management to minimize mistakes and ensure recovery from collapse. He suggested use of surfing policies that let fishing effort develop until the collapse begins, and then implement stringent management control to initiate recovery. Maximum yield over the probing cycle depends on how soon the collapse is detected and the speed of recovery.

Our medium- and high-risk policies seemed to follow this surfing policy scenario in that fishing intensity continued to develop until, in each case, 1 year of declining yields was detected. The results were the same for both deterministic and stochastic simulations. Stock productivity diminished to a point from which quick recoveries were not possible (even with substantial reductions in fishing effort); in such cases, extreme overcapitalization in gear, processing, etc., would occur which could lead to severe economic hardships (unemployment, loss of investment capital, etc). The conservative policy introduced a substantially more moderate transitional fishery and thus avoided the collapses predicted under the medium- and high-risk policies. The conservative policy stayed away from the cliff edge of the production relationship, at seemingly safe levels of transitional exploitation; as a result, it showed continued viability in terms of yield and economic input into the fishery system.

Our analysis does not preclude the possibility that other surfing-like policies might have led to greater economic productivity than policy II over the planning horizon. The point here is that although surfing is an attempt to deal with catastrophic changes, as a policy stance it requires the DM to identify domains of acceptability and reasonability. Surfing, however, can lead to wipeouts (i.e., collapse of a fishery). For this reason, and because both commercial and recreational industries require stability of employment within both the harvesting and processing sectors, and stability of average catches so that marketing and distribution channels can be established and maintained, surfing must be considered cautiously. Risk aversion is pervasive in fishing communities because these communities' livelihoods depend on the continued productivity of the stock and balance of the fishery system, under some variable amount of trade-off that can be specified within the MUF.

The FINMAN model was useful in creating integrated management structures to test various policy strategies. The model is limited to some degree by functional simplifications between management interfaces. To make the model actually

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TABLE 5.—Cumulative utilities by 5-year intervals for a simulated grouperoid population under three management policies: I, medium risk; II, conservative; III, high risk. R denotes average rank; asterisk (*) denotes optimal average rank.

Policy	Utility (rank) in planning horizon period					R
	1–5	6–10	11–15	16–20	21–25	
I	3.99 (3)	7.58 (3)	10.98 (3)	13.58 (2)	16.90 (2)	2.6
II	4.00 (2)	7.62 (2)	11.21 (1)	14.73 (1)	18.11 (1)	1.4*
III	4.10 (1)	7.76 (1)	11.14 (2)	13.91 (3)	16.49 (3)	2.0

function, we inserted several relationships or feedbacks that may not be appropriate or best for any given situation, but these can be modified as needed. The biological model might be enhanced by incorporation of a continuous-time approach that allows for protracted recruitments and probabilistic representations of growth similar to Ault's (1988) CORECS model. The FINMAN model, by integrating the biological, economic, and sociopolitical environments, has important advantages over previous classes of fishery simulation models. The simulation–optimization study described here includes only those policies conducted under conditions in which uncertainties were not of practical importance (i.e., in which the attributes of the alternatives being considered were reliably estimated and not likely to change during the relevant time interval). The uncertainty of a decision situation can be dealt with independently under particular circumstances, after the multiattribute nature of the situation has been addressed under what amounts to assumed certainty (Huber 1974). The quantification of preferences for the multiple attributes of a marine fishery management problem presented in this paper apparently represents the first attempt to obtain a complete utility function over several attributes and to use it in formulating a strategic policy decision. Our analysis, however, still will not indicate which is the best investment policy overall. That is, it does not show how the choice of a particular criterion affects the likely outcome of specific real-world variables, or what differences there are (again, in terms of real-world financial or social results) between high-risk and low-risk alternatives. Nonetheless, this analysis does demonstrate the need to consider multiple conflicting objectives when potential management policies are evaluated.

Conclusions

The fishery management entity is a complex domain of several attributes. Inclusion of multiple objectives in the planning process, as opposed to a single objective as used in past practice, will broaden the decision-making framework. These attributes should be embodied within the objective function and dealt with under the auspices of fishery management. These factors can cover a broad spectrum of overall effects. The operational method described here helped indicate effective strategies over the planning horizon and identify time differences in the policies' effects. With the aid of simulation, we were able to establish ceilings and targets in the various investment classes, and this allowed detailed descriptions of the policies used to make choices in each of them. The utility function appears robust to assumptions regarding recruitment and transitional fishing mortality. Sensitivity analysis done by simultaneously altering the ranges of the marginal probability density functions indicated that the implications of the study were not very sensitive to the probabilities. Further, if several attributes are included in the management objectives, a higher-quality fishing experience seems more likely than if only one attribute is considered, and constituency satisfaction should be enhanced accordingly. It seems likely that the fishery management institution is on the verge of becoming a major consumer of operations research technology. Concomitantly, the industry faces complex decision problems that should motivate new and important basic research.

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