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Designing Marine Reserves for Fishery Management

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Recent reports have raised serious concerns about the rapid declines of historically productive marine fishery resources and the degradation of essential fish habitats. This global crisis has spurred development of innovative management strategies to rebuild depleted fisheries and marine ecosystems. One highly touted strategy involves the design and creation of marine reserves (areas off limits to extractive uses) to rebuild fisheries and conserve marine biodiversity. In this paper, we propose an integrated sequence of methodologies that provides an objective, quantitative framework for the design of marine reserves in spatially heterogeneous coastal ocean environments.

The marine reserve designs proposed here satisfy the multiple, often-conflicting criteria of disparate resource user groups. This research is the first attempt to explicitly explore the trade-off between the conservation goals of fishery management and coral reef protection and the consumptive interests of commercial and recreational fishing fleets. The spatial distribution and size abundance of reef fish stocks throughout the Florida Keys coral reef ecosystem were estimated from a database consisting of more than 18,000 visual samples taken from 1979 to 2002. These distributions of multispecies abundance and biomass, in conjunction with a geographic database of coral reef habitats, are used to demonstrate an integer goal programming methodology for the design of networks of marine reserves, called plans. Once multiple plans are proposed, a simulation model is used to assess the effects of reserve size and shape on select Florida Keys reef fish populations under dynamic spatial and temporal conditions.

Key words: integer goal programming; simulation; fisheries management; marine reserves; Florida Keys
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1. Introduction

The goals of the policymakers for the world's fisheries traditionally have been concerned with food production and employment. Concomitantly, widespread declines and, in some cases, collapses of major fish stocks have pressed the United Nations Food and Agriculture Organization (FAO) to declare that the world's commercially exploited fish populations have declined to the point of becoming humanity's most severe global resource problem. While aspects of traditional policy objectives in these areas continue to be valid, policymakers increasingly need to give attention to demands for nonconsumptive and recreational uses of marine fishery resources and to the imperative demand from global civil society that the marine ecosystem as a whole be conserved and maintained (Food and Agriculture Organization of the United Nations 2002).

The depletion of the oceans' fisheries has been occurring for decades. Of the approximately 932 fish stocks commercially fished in U.S. waters, the status of only one-third has been assessed, and of these, more than 30% of the fish populations are overexploited (2001 U.S. Department of Commerce Annual Report to Congress). Even this figure is optimistic, because the legal definition of overfishing does not account for the needs of other species or overall ecosystem health (Pew Oceans Commission 2003).

In the face of this evidence, it is apparent that to this point human efforts to manage utilization of fishery resources have often failed. Ludwig et al. (1993) identified how, in the implementation phase of regulation, the economically rational pressures against reduced efforts by fishermen and processors typically win out over the uncertain projections of impending collapse by fishery scientists. This dire situation has been expanded upon by many others (e.g., Botsford et al. 1997, Jackson et al. 2001, Myers and Worm 2003). Such situations have been complicated by a number of factors. Probably most important among these are the facts that marine ecosystems are poorly understood and that the fundamental linkages between fishing and stock depletion are uncertain, as are those between fishery productivity and environment. In addition, social systems can be very complex, with intense competition for limited resources that may have long-term biological, social, and economic consequences on the sustainability and productivity of fishery ecosystems.

1.1. Support for Marine Reserves as an Emerging Management Tool

The Pew Oceans Commission (2003) formulated a body of recommendations designed to reverse the declining health of our ocean and coastal ecosystems. A primary recommendation from these was that Congress should enact legislation mandating the establishment of a national system of marine reserves to protect marine ecosystems, preserve our national ocean treasures, and create a legacy for our children. Around the world, marine reserves have demonstrated the ability to increase fish biomass inside their borders (National Academy of Sciences 2001, Roberts et al. 2001, Lubchenco et al. 2003, *Ecological Applications* 2003).

Although the process of designing reserve systems to protect terrestrial habitats has been in use for some time (see, e.g., Cocks and Baird 1989, *Environmental Modeling and Assessment* 2002), the application of quantitative tools to the process of selecting and siting marine reserves has only recently begun to receive the attention it deserves. Pressey et al. (1996) consider the application in the assessment of heuristic reserve selection algorithms. Ward et al. (1999) discussed the selection of marine reserves for biological diversity in Jervis Bay, Australia. Airame et al. (2003) applied ecological criteria to marine reserve design in the Channel Islands off California, as did Sala et al. (2002) in the Gulf of California, Mexico. In the Florida Keys, the study site of this research, Leslie et al. (2003) used various siting heuristics in the determination of marine reserves protecting specific proportions of habitat diversity.

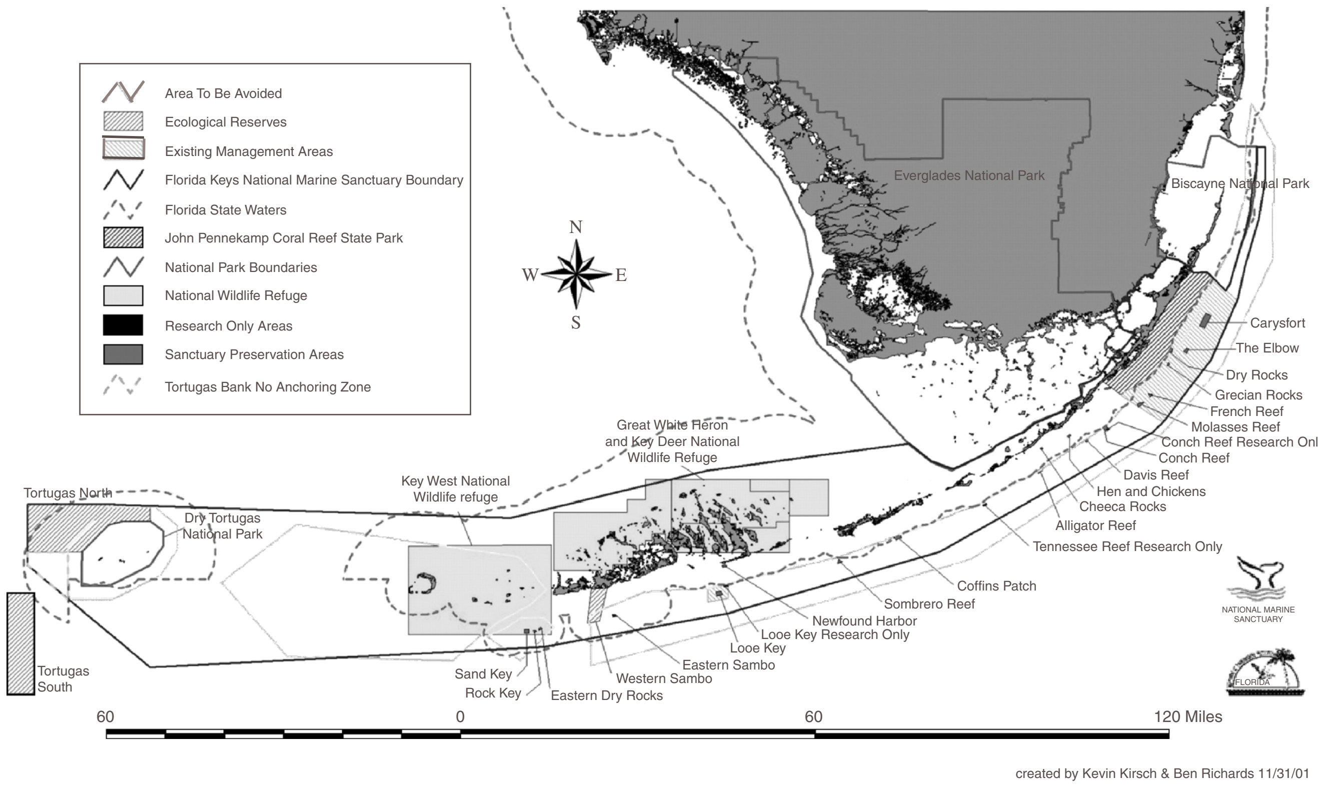
In this paper, we propose an objective, quantitative framework for the design of effective marine reserve plans. The proposed methodology involves two phases: design and evaluation. In the design phase, a clustering algorithm is used to create a large set of possible reserves that may be incorporated within the desired reserve plan. An integer goal program is then used to select a specified number of reserve plans that balance the conservation goals of fishery management and coral reef protection with the consumptive interests of the multiple user groups. In the evaluation phase, a simulation model is employed that allows each of the proposed marine reserve plans to be critically evaluated under various assumptions about fish population dynamics and movements and spatial intensity of fishing effort. Using data obtained from the Florida Keys National Marine Sanctuary (FKNMS), Biscayne National Park, and Dry Tortugas National Park (Figure 1), the experimental results of this methodology are used to provide insight into the process of marine reserve design to ensure the sustainability of multispecies coral reef fish stocks in the region.

The remainder of this paper is presented as follows. In §2, the FKNMS is described. This discussion also includes a description of the data available from this study site necessary for designing marine reserves. In §3, the criteria for effective marine reserve design are discussed. The integer goal programming model incorporating these criteria is presented in §4. Some computational issues are discussed and an application of the goal programming model is presented in §5. In §6, the simulation model is discussed. The simulation methodology is then applied to a set of marine reserve plans generated by the goal programming model. This investigation uses simulation to explore the efficacy of implementing varying numbers and sizes of marine reserves within a proposed experimental design. Finally, §7 provides a summary discussion and suggests potential future applications of these and other operations research methods.

2. The Florida Keys National Marine Sanctuary

The Florida Keys are world renowned as diverse and spectacular fishing grounds and a principal reason why the state legislature has declared Florida "Fishing Capital of the World" (www.fwc.state.fl.us). Stretching 380 km southwest from Key Biscayne to the Dry Tortugas, the Florida Keys comprise a rich tropical marine ecosystem supporting a productive multispecies coral reef fishery and a multibillion-dollar industry for fishing and tourism (Bohnsack et al. 1994; Ault et al. 1998, 2001, 2002; Johns et al. 2001). The timeless appeal of the Florida Keys has led to an ever-increasing number of residents and a simultaneous increase in pressure on the fragile resources

Figure 1 Florida Keys Coastal Marine Ecosystem

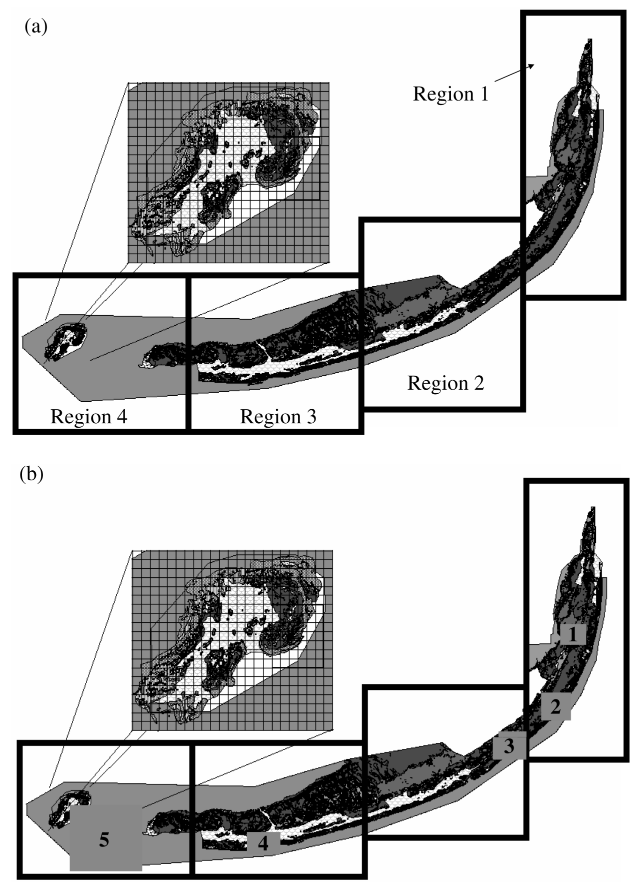


Note. The coral reef tract runs offshore from Key Biscayne 380 km southwest to the Dry Tortugas. The Florida Keys National Marine Sanctuary boundary and Biscayne National Park and Dry Tortugas National Park are shown.

that draw these residents. The Florida Keys are now an ecosystem at risk as one of the nation's most significant, yet most stressed, marine resources under management of the National Oceanic and Atmospheric Administration (NOAA), the National Park Service (NPS), and the state of Florida (National Park Service 2000, Culhane 2002, National Marine Fisheries Service 1999).

The integer goal program and the spatial simulation model of reef fish population dynamics used in this study were calibrated from extensive datasets that characterize the spatial and temporal distributions of coral reef fishery resources and benthic (i.e., sea floor) habitats encompassed by the boundaries of the FKNMS. The reef fish and benthic habitat resources of the FKNMS coral reef ecosystem have been extensively studied for several decades, creating reliable long-term, systemwide databases for model parameterization. A 1 km $\times$ 1 km grid system was overlaid onto bathymetric and benthic databases (Meester 2000) for the FKNMS provided by the NOAA and the state of Florida (National Oceanographic and Atmospheric Administration 1998) (Figure 2a). For our model, the resulting database was comprised of 11,200 geographic units, each containing specific benthic habitats and environmental parameters, including the coral reef area from Miami to the Dry Tortugas (Meester 2000, Franklin et al. 2003). Long-term data (1979–2002) from intensive underwater visual surveys of reef fishes (Ault et al. 1998, Bohnsack et al. 1999) and statistical sampling models that related fish population density and length distributions to essential habitats (Smith and Ault 1993; Bohnsack et al. 1999; Meester 2000; Ault et al. 2001, 2002) were used to estimate spatial population density and size structures. Reserve design experiments were performed on three key species of exploited reef fish chosen from the FKNMS reef fish visual census dataset: red grouper (Epinephelus morio), yellowtail snapper (Lutjanus chrysurus), and white grunt (Haemulon plumieri). These species are representative of the range of life histories that typify the exploited snapper-grouper-grunt reef fish complex of the FKNMS and are targets of important fisheries (Bohnsack et al. 1994, Ault et al. 1998). Additionally, it is anticipated that these species will respond best to marine reserve implementation given the current serial overfishing of these stocks (Bohnsack and Ault 1996; Bohnsack 1998; Ault et al. 1998, 2001, 2002). This unique spatial dataset linked more than 250 species of coral reef fishes with benthic habitats over the 11,200 km^2 Florida Keys coral reef ecosystem. The reef fish database was collected over a 23-year period from 1979 to the present and consists of more than 18,000 visual census samples taken

Figure 2 **Florida Keys National Marine Sanctuary**



Notes. (a) Inset of the 11,200 units and the four regions
(b) Marine reserves resulting from the goal program experiment

throughout the range of the FKNMS (Bohnsack et al. 1999; Ault et al. 2001, 2002). Population dynamic and life history parameters used in this study are from Ault et al. (1998).

3. Design Criteria for Marine Reserves

A reserve plan is a configuration of distinct spatial areas designated as open or closed to fishing and other extractive activities. The closed areas are called reserves. In this section, we explore various criteria for the design and implementation of a network of marine reserves.

3.1. Shape and Compactness

The shape of a marine reserve is a critical factor in its effective delineation and enforcement. Because visible landmarks on the open ocean are generally not available, reserve boundaries must be determined by line of sight between fixed marker buoys. The most desirable reserve shapes are squares or rectangles, because they can be delineated by lines of latitude and longitude and thus are more easily identified and accepted by user groups. Shape preferences of this type were consistent with the opinions expressed in numerous consultations with the marine researchers and fishery managers responsible for delineating marine reserves in the Florida Keys.

To produce desirably shaped reserves from the FKNMS dataset, a graph theoretic modeling approach similar to that used by Mehrotra et al. (1998) for political districting was employed. Each of the 11,200 1-km square geographic units in the spatial domain of the study site was associated with a node on a graph. Let $G(U, E)$, represent this graph, where U is the set of nodes and E is the set of edges in the graph. An edge is said to exist between two nodes in the graph if the corresponding geographic units share a common boundary. A reserve (J) is defined to be a connected subgraph of G. In this discussion, we will use J to denote the set of nodes in the reserve as well.

Within the collection of all possible rectangular reserves, more compact reserves are preferred. Buechner (1987) reports that reserves with greater perimeters will likely lose more fish across their borders due to exploitation effects; therefore, reserves with smaller perimeter-to-area ratios are more desirable. For example, a 16 km^2 reserve can be designed as a 4 km square or as a 64×0.25 km rectangle. The latter choice has eight times the perimeter and is harder to implement, utilize, and enforce. It is also convenient in the comparison of various reserve plans to eliminate the bias that may arise due to shape differences in individual reserves. Consequently, ideal shapes were defined as $m \times n$ rectangles where either $m = n$ (squares) or $m = n + 1$ (compact rectangles).

A review of the literature indicates that there is no universally acceptable mathematical formula to estimate the compactness of a geographic area. Typically three characteristics have been used to estimate unit compactness: area and perimeter (Young 1988) and some notion of distance (Chowdhury 1989, Klein and Aronson 1991, Krumke et al. 1997) between points in the area. While it is difficult for any compactness measure to satisfy all desirable geometric requirements (Young 1988), the index proposed here defines ideal shapes through a single number that easily identifies variation from an ideal shape. We use the concept of shortest paths in graphs in our proposed index.

We define the length of a path from u to v, where $u, v \in J$, as the number of edges in a path from u to v, and the shortest path from u to v as the path with the shortest length. The shortest path from u to v defines the distance from u to v. The area of J is equal to K, the number of nodes within J. We define the degree(u) as the number of nodes adjacent to node u, where the maximum degree of any node is 4, because G is a grid graph. The perimeter of reserve J is defined as $\sum_{u=1}^{K}(4 - \text{degree}(u))$. The status of node u in J is the sum of the shortest path distances from u to every other node in J. The center of J is determined by finding the node, c, that has the minimum status of the smallest superimposed grid graph (n by $n+k$); that is,

$$c = \arg\min_{j\in J} \sum_{u=1}^{K} D_{uj}, \quad (1)$$

where D_{uj} is the shortest path from u to j. The status of reserve J is defined as the status $\mathrm{St}(c)$ of its center node c. We deviate from the classic definition of a center of a graph to enable getting an $\mathrm{St}(c)$ that is consistent with our goals.

Initially, we formed an index of $(\mathrm{St}(c) * \text{perimeter})/\text{area}^2$ that turned out to be at most 2.0 for an ideal reserve. It was discovered, however, that some nonideal shapes also had a value of less than 2.0 for this measure. To penalize nonideal shapes, a modified perimeter (ModP) was employed as follows. Superimpose an extended grid graph A^* over and around J such that every node in J has a degree of 4. Let T be the set of nodes ($T \subseteq A^* \setminus J$) that are adjacent to some node in J. The ModP of J is defined as the sum of the perimeter of J and the number of nodes in T adjacent to two or more nodes in J, defined as T_J. By using the ModP instead of the perimeter in the compactness index, a final index Q is formed as

$$Q = \frac{\text{ModP} * \mathrm{St}(c)}{\text{area}^2}. \quad (2)$$

It can be shown that for any m by n rectangular reserve, where $m = n + k$, the index $Q \le 2.0$ if $k \le 1$ or if $k = 2$ and n is odd. Otherwise, it was found that $Q > 2.0$.

3.2. User-Group Design Criteria

In addition to the shape and compactness of the reserves, there are multiple user-group criteria that influence the design and constituency acceptance of a reserve plan. These criteria originate from the conflicting interests of commercial and recreational fishing fleets, divers, tourists, fishery managers, and other user groups. The fishing industry wants to minimize the number of fishing vessels displaced by a reserve plan. Many constituents want to minimize the total area of reserves in a plan. Many fishing vessels also operate within a fairly localized area because of the time and expense associated with running to the fishing grounds. Thus, it is also desirable to be able to spread reserves across the study area to minimize the impact on any one region and thereby minimize opposition from both the fishing fleets and other local user groups. The following eight criteria are addressed in our model for designing marine reserves:

(C1) Marine reserves in the plan should not be overlapping or adjacent.

(C2) The model should allow for prespecifying the number of reserves.

(C3) Each reserve must protect a certain proportion of population abundance or biomass for each exploited species of the reef fish stock under consideration (here, red grouper, yellowtail snapper, and white grunt).

(C4) The model should allow for specifying a target of no more than a certain number of fishing vessels displaced upon implementation.

(C5) The total area of coral reef habitat protected by the reserves in a reserve plan must meet a desired target level.

(C6) The total area covered by the reserves in a reserve plan must meet a desired target area.

(C7) The methodology must be able to distribute reserves throughout various regions of the study area.

(C8) Each reserve should be contiguous, compact, and desirably shaped.

4. An Integer Goal Programming Formulation

Only a few studies in the literature have used a mathematical programming approach in the formulation and solution of reserve siting problems. Cocks and Baird (1989) used a goal programming model to choose among candidate reserve components on the Eyre Peninsula of South Australia. Additionally, the recent paper of Leslie et al. (2003) provided a mathematical model of the reserve selection problem in an investigation of various algorithms for that purpose.

In this paper, we develop an integer goal programming (GP) model for choosing the network of reserves comprising a reserve plan that fulfill the criteria given in §3.2. Let M be the set of all possible feasible and contiguous reserves. Let x_m be a binary variable that equals 1 if reserve m is included in the reserve plan and equals zero otherwise, where $m \in M$. Let U be the set of all possible units, and δ_{im} be equal to 1 if unit i ($i \in U$) is included in reserve m, and equal to zero otherwise. Let S be the set of all species of fish to be protected within the reserve plan, p_{ms} be the population proportion of species s ($s \in S$) in reserve m; p_s^+, p_s^- the number of fish that exceed or fall short of the target population p_s in the plan for species s; and, μ_s^+, μ_s^- be the penalties for going over or under p_s, respectively. Let f_m be the nominal fishing effort in number of vessels for reserve m; f^+ and f^- the number of vessels that exceed and fall short of the desired number of vessels f in the overall reserve plan; and, μ_f^+, μ_f^- be the unit penalties for going over and under f, respectively. Let R be the set of all regions (a set of nonoverlapping partitions within the study area where the total area of the regions equals the area of the study area); a_{mr} be the area of reserve m in region r, where $r \in R$; a_r be the desired reserve area within region r; a_r^+, a_r^- be the area that exceeds or falls short of a_r; and μ_{ar}^+, μ_{ar}^- be the penalties for going over and under a_r, respectively. Let a_m be the area (in km^2) of reserve m, where $a_m = \sum_r a_{mr}$. The total area desired in the plan is defined as a, a^+ and a^- are the area over or under a, and the penalties associated with a^+ and a^- are μ_a^+, μ_a^-, respectively. Let c_m be the area of coral reef in reserve m, c^+ and c^- the area of coral reef that exceeds and falls short of the desired area c in the overall reserve plan, and μ_c^+, μ_c^- be the unit penalties for going over and under c, respectively. Define n as the desired number of reserves in the final plan. We used the Q score (developed in §3.1) as a proxy for compactness, shape, and contiguity of a reserve; let q_m be the Q score for reserve m. Based on our construction, the desirable reserves will have a Q score of at most 2, while all others will have a $Q > 2.0$. So let $q^+ = \sum_{m\in M} q_m x_m - 2n$ and $q^- = 2n - \sum_{m\in M} q_m x_m$, and let μ_q^- and μ_q^+ be the penalties for falling short and exceeding $2n$.

The integer GP may then be stated as (to the left of each constraint is the criterion to which it corresponds):

$$\begin{aligned}\text{Minimize}\quad & \mu_q^+ q^+ + \sum_{s\in S}(\mu_s^+ p_s^+ + \mu_s^- p_s^-) \\ & + (\mu_f^+ f^+ + \mu_f^- f^-) + (\mu_c^+ c^+ + \mu_c^- c^-) \\ & + (\mu_a^+ a^+ + \mu_a^- a^-) + \sum_{r\in R}(\mu_{ar}^+ a_r^+ + \mu_{ar}^- a_r^-) \qquad (3)\end{aligned}$$

s.t.

$$\text{(C1)}\quad \sum_{m\in M} \delta_{im} x_m \le 1, \quad i \in U, \qquad (4)$$

$$\text{(C2)}\quad \sum_{m\in M} x_m = n, \qquad (5)$$

$$\text{(C3)}\quad \sum_{m\in M} p_{ms} x_m - p_s^+ + p_s^- = p_s \quad \text{for each } s \in S, \qquad (6)$$

$$\text{(C4)}\quad \sum_{m\in M} f_m x_m - f^+ + f^- = f, \qquad (7)$$

$$\text{(C5)}\quad \sum_{m\in M} c_m x_m - c^+ + c^- = c, \qquad (8)$$

$$\text{(C6)}\quad \sum_{m\in M} a_m x_m - a^+ + a^- = a, \qquad (9)$$

$$\text{(C7)}\quad \sum_{m\in M} a_{mr} x_m - a_r^+ + a_r^- = a_r \quad \text{for each } r \in R, \qquad (10)$$

$$\text{(C8)}\quad \sum_{m\in M} q_m x_m - q^+ + q^- = 2n, \qquad (11)$$

$$x_m \in \{0, 1\}, \quad m \in M. \qquad (12)$$

The GP model is used to determine an appropriate set of reserves. Note that in the formulation, criterion (C1) is expressed mathematically by constraint (4) and prevents the overlap of reserves. These constraints will be useful in developing an implicit solution of the problem as explained in the next section. By suitably restricting our choice of feasible reserves, we will address the adjacency portion of criterion (C1) as explained in the next section.

5. Computational Issues

Given the size of the FKNMS dataset, the GP model as formulated above is too large to solve directly. In this case one can resort to solving the linear relaxation of GP implicitly using column generation. To do so, begin with a subset $\overline{M}$ of feasible reserves. Solve the linear relaxation of GP restricted to $m \in \overline{M}$, which gives a feasible solution to the linear relaxation of GP and a corresponding dual solution. Let θ_i, $i \in U$, be the dual variables corresponding to constraint (4), and let π_n, π_s $(s \in S)$, π_f, π_c, π_a, π_r $(r \in R)$, and π_q denote the dual variables corresponding to constraints (5)–(11), respectively. Now determine whether it would be useful to expand $\overline{M}$. This can be ascertained by determining whether the reduced cost of a reserve is positive. In particular, for a reserve m comprising a set of units W to be attractive,

$$\begin{aligned}\text{red cost}(m) = & \sum_{w\in W}\theta_w + \pi_n + \sum_{s\in S} p_{ms}\pi_s + f_m\pi_f + c_m\pi_c \\ & + a_m\pi_m + \sum_{r\in R} a_{mr}\pi_r + q_m\pi_q \qquad (13)\end{aligned}$$

must be positive. If such a reserve does not exist, the solution to the linear relaxation of GP over the current $\overline{M}$ also solves the linear relaxation of GP over M. Otherwise, any such reserve has the potential to improve the LP relaxation objective. In particular, reserve m, such that

$$m = \arg\max\Big\{i\colon \max_i \ \text{red cost}(i)\Big\} \qquad (14)$$

determines a reserve with the highest reduced cost. If such a reserve has nonpositive reduced cost, then an improving reserve does not exist. This process is repeated until there is no improving reserve. If the resulting solution to the linear relaxation of GP has x_m integer for all $m \in M$, then x_m corresponds to an optimal solution to GP over all reserves. When some of the x_m are not integers, though, we are faced with the problem of enforcing integrality.

To complete this algorithm, we must do two things. First, we must devise techniques that are sufficiently fast to generate reserves for pricing. Second, if the solution to the linear relaxation of GP contains fractional values, we must find a way of enforcing integrality. Standard techniques for enforcing integrality (cutting planes, fixing variables) make it difficult or impossible to generate improving reserves. We discuss these two issues next.

5.1. A Clustering Algorithm

For the proposed column-generation technique to perform well, it is necessary to have a fast algorithm for solving the problem of generating improving reserves. While it is possible to develop either a mathematical program or a combinatorial search to generate improving clusters in a clustering application (see Mehrotra et al. 2001), the size of this problem renders such methods prohibitive. In this instance, a clustering algorithm was used.

The clustering algorithm begins at a given geographic unit and attempts to add units to one side of the reserve at a time until it is rectangular in shape; then another side may be started. The method maintains contiguity and checks the population size criteria for each species as each unit is added to a reserve, and if all populations fall within the prespecified ranges, then a Q score is determined. If the Q score is below a predetermined threshold, then the reserve parameters are output to a file. This procedure is performed for all units in the study area. The method produces all feasible marine reserves (Z reserves). To facilitate the determination of adjacent reserves, the output from the clustering method can be modified easily. Each of the Z reserves is modified by adding the set of nodes T that are adjacent to any node within reserve J. This step ensures that reserves chosen by the integer program are nonoverlapping and nonadjacent, with a minimum of 1 km between reserves satisfying criterion (C1).

5.2. Integrality Requirements

A second component in implicit enumeration approaches for solving integer programs is the development of branching rules to ensure integrality. Rules that are appropriate for integer programs where the entire set of columns is explicitly available do not fit well when only a partial set of variables is used to enable implicit optimization. Consider, for example, the rule of branching on a fractional variable, where the variable is set to 1 in one subproblem and to zero in the other. The former subproblem causes no problem for GP, because setting a reserve to 1 corresponds to using that reserve. As a result, those units can be removed from consideration, and the number of reserves required and other parameters of the integer program, such as target populations, can be modified appropriately. The other subproblem is more difficult. Setting a variable to zero corresponds to prohibiting use of that reserve. Hence, this involves finding the second, third, and so on, best solutions to the problem of determining improving reserves. This is an expensive operation; i.e., finding a kth, $k \geq 2$, best solution to this problem is more difficult than finding the best solution.

This difficulty can be overcome by using Ryan-Foster branching (Ryan and Foster 1981, see also Barnhart et al. 1998, Mehrotra and Trick 1996, Vance et al. 1993). Consider a fractional solution to the linear relaxation of GP. It is easy to see that there exist two sets M_1 and M_2 and units u_1, u_2, such that $u_1 \in M_1 \cap M_2$ and $u_2 \in M_1 \backslash M_2$, and at least one of x_{m_1} or x_{m_2} is fractional. Then, create the subproblems: DIFFER(u_1, u_2) and SAME(u_1, u_2), where DIFFER(u_1, u_2) is a subproblem with u_1 and u_2 in different reserves. Adding a simple constraint in the integer programming formulation can enforce this and make sure that reserves with both u_1 and u_2 are not considered on this branch. SAME(u_1, u_2) is a subproblem where u_1 and u_2 are in the same reserve, which can be enforced by suitably combining units u_1 and u_2 into a single bigger unit. The current fractional solution is not valid for either of the two subproblems; however, any feasible integer solution is in one of them. Other branching choices are also possible.

If a full-blown branch-and-price methodology is not necessary, one can also simply solve GP heuristically by finding the best solution from among the reserves that accumulate to optimize the LP relaxation in the column-generation process. Or, instead of changing the clustering algorithm, one can also explicitly enumerate all feasible reserves and then check the reduced costs of these reserves for determining those improving reserves.

5.3. Determination of Penalty Weights for the Goal Program

Determination of penalty weights for the GP is illustrated through an application of the integer GP methodology to the design of a marine reserve plan for management of reef fish and protection of coral reef habitats in the Florida Keys coral reef ecosystem. The example problem was developed using known spatial distributions and abundances of reef fishes and coral reefs in the FKNMS described in §2, along with estimates of the spatial distribution of fleet fishing effort. For this problem, conservation goals were set to protect 15% of each of the spawning populations of three select reef fish species (red grouper, yellowtail snapper, and white grunt). We note that these are somewhat ambitious goals, because the design of current reserves in the FKNMS (Figure 1) protects less than 1% of these fish stocks.

Using the presidential mandate of Executive Order 13089 as a guide, we set the model constraint target to protect 20% of the coral reef habitat area in the FKNMS (criterion (C5)). Targets were also set so that the resulting reserve plan displaced only 15% of the fleet nominal fishing effort, so that the total area of the plan was less than 17.5% of the total area of the study site. To allow the reserves in the plan to be spread out over the entire area, i.e., the 11,200 subunits (or 11,200 km^2), the FKNMS was partitioned into four regions containing at least one reserve each (Figure 2a).

In these analyses, it was not necessary to have all the reserves in a plan protect the same proportion of each reef fish species, so long as the total proportion of each population protected in the overall reserve plan was 15%. The clustering algorithm was used to produce all feasible reserves that explicitly contained between 1%–5% of each fish population and that had $Q \leq 2.1$. This resulted in the identification of more than 500,000 feasible reserves. The branch-and-price approach would be appropriate for solving the resulting integer program. For the purposes of this experiment, however, a smaller subset of these reserves was produced by limiting the bounds of each species to 2.5%–3.5% of the population and further limiting the size of reserves. This strategy resulted in 2,379 candidate reserves as inputs to the GP. The corresponding GP model was then directly solved with all penalties set to 1 to determine which of the design criteria, if any, were not satisfied given equal penalties. The resulting reserve plan did not satisfy several of the criteria, so an experiment was run to objectively determine penalty settings. One criterion at a time was fixed at its target value, and then the GP was solved to determine the resulting values of all other criteria in relation to their targets. This was repeated for each of the criteria. The largest conflicts in design criteria were caused by attempting to protect 20% of the coral reef (i.e., criterion (C5)) while attempting to displace only 15% of the fleet fishing effort (criterion (C4)). These results are summarized in Table 1.

Multiple combinations of penalties for a^+, c^-, and f^+ were evaluated. Best results (minimum total absolute deviation from constraint goals) were achieved by setting μ_a^+ to 1, μ_c^- to 1,000,000, and μ_f^+ to 5,000. Further combinations of objective penalties

Table 1 Results of Experimental Design Employing Eight Model Constraints to Determine Penalties for the Integer Goal Program

	Resulting criteria (%)						
	(C3)						
Criteria fixed	Red grouper	White grunt	Yellowtail snapper	(C4)	(C5)	(C6)	(C8)
(C3)-Red grouper	N/A	15.1	15.0	16.2	**16.4**	18.6	1.98
(C3)-Yellowtail snapper	15.2	N/A	15.0	15.1	**16.7**	17.5	1.96
(C3)-White grunt	15.0	15.0	N/A	15.1	**16.8**	18.2	1.98
(C4)-Fishing vessels	15.2	14.7	15.2	N/A	**15.2**	**13.9**	1.97
(C5)-Coral reef area	**17.8**	**15.3**	**18.9**	**47.16**	N/A	**21.8**	**2.08**
(C6)-Total area	15.0	15.0	15.0	16.2	**16.5**	N/A	1.99
(C8)-Q score	15.0	15.0	15.0	16.2	**16.3**	17.5	N/A
Target	15.0	15.0	15.0	15.0	20.0	17.5	≤2.0

Note. Values represent the percentage of the fleet nominal fishing effort displaced by a given reserve plan.

Table 2 Characteristics of the Modeled Marine Reserves Dynamics

	Resulting criteria (%)						
	(C3)			(C4)	(C5)	(C6)	(C8)
Reserve	Red grouper	White grunt	Yellowtail snapper	Fishing vessels	Coral reef	Total area	Q
1	3.0	3.0	2.8	4.4	1.8	1.6	2.07
2	3.2	3.3	3.4	3.6	4.9	2.3	2.09
3	3.5	2.9	2.9	3.1	2.6	1.7	2.09
4	2.6	3.4	3.2	3.1	3.9	2.8	2.01
5	3.5	3.2	2.6	1.0	4.9	10.6	2.06
Total	15.8	15.8	14.9	15.2	18.1	19.0	10.32

were attempted, but no superior results could be attained. This resulted in a final reserve plan that consisted of five reserves (Table 2). This plan protected 15.8% of the red grouper population, 14.9% of the yellowtail snapper population, and 15.8% of the white grunt population. The plan also displaced about 15.2% of the fishing effort, while it protected 18.1% of the coral reefs in the FKNMS. The total area required in the plan to meet these goals was 2,201 km^2 spread throughout all four regions of the FKNMS (Figure 2b).

It is of interest to compare these results with those of Leslie et al. (2003) in their study of siting algorithms for marine reserve networks in the FKNMS. These authors identified the first 23 habitats listed in the dataset and employed greedy and simulated annealing heuristics (e.g., Kirkpatrick 1983) to select grid units to form reserves subject to the constraint that specified that proportions of each habitat be covered in the overall mosaic. A boundary length modifier that minimized the system area and perimeter was used to help shape the reserves. The results of Leslie et al. (2003) tended to follow the richness of the particular habitat contours and produced reserves of irregular linear shapes. The analysis did identify, however, certain "irreplaceable" grid units so rich in habitat that they tended to be included in a majority of the reserves selected.

In contrast, the network of reserves produced by the current study used rectangular reserves distributed to various regions within the FKNMS. The rectangular shapes of this study correspond most closely to the reserve shapes produced by Leslie et al. (2003) when the value of their boundary length modifier was at a maximum. Although the current study additionally focused on meeting various fishery sustainability goals (i.e., protecting stock spawning biomass and minimizing fleet displacement), the goal for protection of coral reefs was set at 20% of their total area. The reserve system network produced by our integer goal program that comprehensively protected 18.1% of the coral reefs required a total of 2,201 km^2. This result was very similar in size to the minimum area reserve of 2,300 km^2 reported by Leslie et al. (2003) for their 20% habitat conservation goal.

6. Spatial Simulations to Evaluate Marine Reserve Plan Efficacy

The results of the previous section produced a network of marine reserves that attempted to meet a diverse set of design criteria. However, because real-world implementation of reserves often involved debate on multiple, alternative reserve plans, a method was needed to quantitatively compare these alternatives. Testing alternative marine reserve configurations under varying population dynamics and fishery exploitation scenarios required use of a spatial simulation model that included detailed aspects of fish population dynamics. In fact, Pelletier and Magal (1996) argue that the effective evaluation of marine reserves cannot be accomplished unless the temporal and spatial dynamics of fish populations are considered.

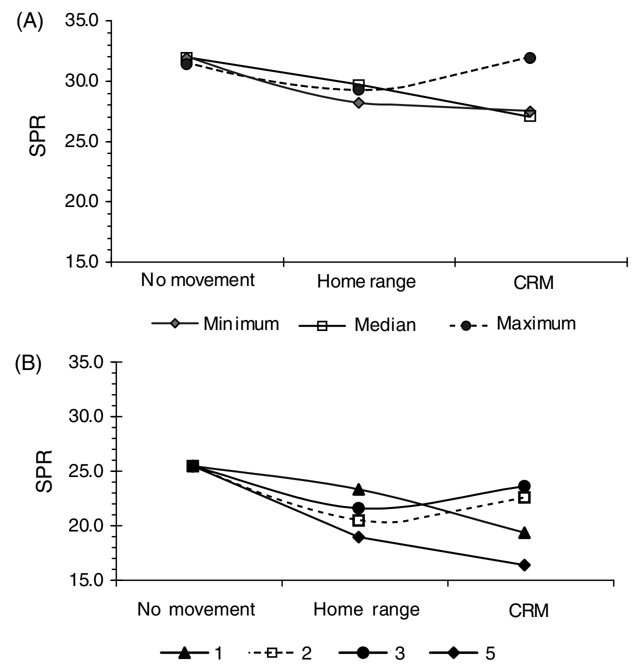
To account for the temporal and spatial dynamics of the various fish populations in a marine reserve plan, an object-oriented simulation model was developed (Ault et al. 1998, Meester 2000, Meester et al. 2001). The spatial structure of the model was based on the 11,200 subunit grid of the FKNMS dataset. The three reef fish populations were simulated using an integrated cohort (i.e., individuals born at the same time) structure where each cohort of fish was comprised of a group of genetically identical individuals. Each cohort was then linked to a geographic subunit and uniquely identified in time, space, and age and by sex. Female and male cohorts were treated separately to allow for dimorphic growth and hermaphroditic reproductive life history strategies. In these experiments, the simulation model was run for a time horizon of 20 years using daily time steps. This strategy allowed population equilibrium conditions to be achieved during the scenario time horizon.

To provide guidance in the selection of alternative reserve plans, two simulation experiments were designed to determine the relative impact of both size and number of marine reserves on the reproductive health of the reef fish stock. The first experiment explored the impact of variation in reserve size on both reef fish stocks and fish movement strategies. Three experimental categories were formed for each species. Each category consisted of a reserve plan with five nonoverlapping 3% reserves, resulting in an overall reserve proportion of 15% for the plan. The experimental categories were formed by ordering, in increasing area, all Z' reserves generated by the clustering algorithm. The three smallest possible reserves were then used as Minimum Reserves Plan, three median-sized reserves as the Median Reserves Plan, and the three largest reserves as the Maximum Reserves Plan. The second experiment explored the impact of the number of reserves in a plan. Four experimental categories were formed for each species, each consisting of a reserve plan with a 15% reserve plan proportion. The total area of each simulated reserve plan was identical. The experimental category reserve plans were: (1) 5 reserves (five 3% reserves); (2) 3 reserves (three 5% reserves); (3) 2 reserves (two 7.5% reserves); and (4) 1 reserve (one 15% reserve). The movement strategy employed by a fish stock was also used as an experimental factor because it undoubtedly impacts the effectiveness of a reserve plan. For the simulation experiments, each factor category was run for three different movement strategies: no movements, home range movements constrained within a 3-km radius, and constrained random movements occurring throughout the study area. This factor arrangement produced a total of 21 simulations for each species, resulting in a combined total of 63 simulations for each experiment.

Results for both numbers and sizes of reserves experiments were presented in terms of spawning potential ratio (SPR) for the reef fish stocks. Briefly, SPR is the ratio of current population spawning biomass, here measured in fecundity (number of eggs), relative to the spawning biomass produced by the population at equilibrium without fishing. For example, an SPR of 100% would imply the reproductive potential of an unexploited stock. An SPR of zero would imply that fishing had removed all of the population spawning biomass, leaving no potential for replacement and causing eventual extinction of the stock. Federal guidelines to prevent overfishing suggest that a typical minimum SPR is greater than 30%. Maximum sustainable yields may require slightly higher SPR values. In this manner, the SPR provides a quantitative estimate of the stock's capability to produce optimal yields on a sustainable basis. Results of the simulation studies for all three reef fish species for both experiments showed that the sizes and numbers of marine reserves in a plan are only partially responsible for the reserve plans' impact on SPR, mainly through the indirect impacts of other design factors. Results from yellowtail snapper simulations from Experiment 1 (sizes of reserves) (Figure 3a) and red grouper simulations from Experiment 2 (numbers of reserves) (Figure 3b) show that the three different types of movement strategies employed resulted in different optimal sizes and numbers of reserves in a plan.

The effectiveness of a particular reserve plan varied according to the movement strategy and its interaction with various reserve parameters, including the number of fishing vessels displaced, the number of fish living on the boundaries of the reserves, and the residence times of fish. The results also indicated that the variation in reserve performance increases as the range of movement increases. This suggests that effective reserve design is particularly critical when attempting to protect fish that move over large areas.

Figure 3 **Results from Fishery Management Simulation Experiments**



Notes. (A) Yellowtail snapper SPR dependent on the movement strategy employed for size of reserves Experiment 1

(B) Red grouper SPR dependent on movement strategy for numbers of reserves Experiment 2

7. Summary and Conclusions

This paper has presented an integrated sequence of quantitative techniques for the design and assessment of marine reserve plans. The first part of the methodology combined a clustering algorithm and a compactness index to generate a candidate list of feasible reserves. An integer GP model was then used to select a subset of these reserves based upon multiple design criteria. The utility of this procedure was shown through a marine reserve design example for the Florida Keys. The results provided quantitative evidence that given spatially heterogeneous fish populations, several small reserves provided coverage of resources equivalent to that of a single large reserve, with less total area required. Using this methodology, fishery managers may produce alternative marine reserve designs that balance fishery management and coral reef protection goals with the interests of multiple user groups.

A simulation model was then used to evaluate the temporal and spatial dynamics of the fisheries within the alternative marine reserve plans. An experimental design was developed to investigate the impact of varying the number and size of reserves versus various movement patterns of the species studied. It was shown that while holding the total area of the reserves constant, the number of reserves in a plan that produced the highest SPR was dependent upon on the movement strategy employed by the fish population. Thus, the combined steps of design and evaluation are necessary to ensure that the proposed marine reserve designs will meet the goals of the various user groups and conservation interests.

The utility of fully protected marine reserves, in concert with conventional management approaches, has been embraced by resource managers in the Florida Keys as a tool for managing ocean resources and conserving fisheries, habitats, and biological diversity (Bohnsack and Ault 1996, Florida Keys National Marine Sanctuary 1995, National Park Service 2000, Culhane 2002). The FKNMS offers a unique opportunity to test reserve design theory and to examine designs, efficacy in meeting resource management goals. A set of 23 fully protected "no-take" marine reserves was established within the FKNMS in 1997 with the objective of building sustainable fisheries and conserving marine biodiversity.

Our models were used to objectively evaluate alternative designs and to select final boundaries for implementing new marine reserves in the Dry Tortugas. The amount of protected area in the Florida Keys was increased in 2001 by 520 km^2 with the addition of the Tortugas Reserve in the westernmost part of the FKNMS (National Park Service 2000, Meester et al. 2001, Ault et al. 2002, Cowie-Haskell and Delaney 2003). The plan was developed with broad public outreach and a great deal of participation with the National Marine Fisheries Service, NPS, the state of Florida, fishing organizations, and interest groups. A key facet of the design process was the direct involvement of scientists and the acceptance of their information by the various stakeholders collaborating on the reserve's design (Cowie-Haskell and Delaney 2003). The Tortugas Reserve now represents the largest fully protected marine reserve in the United States and the third largest protected coral reef area in the world. In light of the severe overfishing problems that have been observed in the Florida Keys, the process of reserve design and implementation by FKNMS and NPS represents a precautionary and proactive marine resource management measure. Additionally, both agencies are implementing monitoring programs to track reserve performance. These areas are expected to provide tangible long-term benefits for protection of marine resources in the national park and the national marine sanctuary and for recreational and commercial fishers. It will also advance science, serving as a reference site for distinguishing between natural and human-induced changes to the Florida Keys coral reef ecosystem. To meet congressional and state legislative mandates, a comprehensive research assessment cruise will be conducted in the Tortugas region by university, federal, and state personnel in summer 2004 to monitor fishery and habitat resource changes and assess design efficacy. Research to date has indicated that FKNMS marine reserves are having compelling positive impacts on sustaining marine fisheries and conserving biodiversity in the Florida Keys coral reef ecosystem.

The methodology developed in this paper can also be used to develop alternative plans comprising varying numbers of reserves to protect fixed proportions of reef fish stocks. The results would then provide insight into the single large or several small dilemma (Soule and Simberloff 1986) in marine reserve design with respect to ensuring the sustainability of multispecies coral reef fish stocks. This is certainly one potential further research area.

While this research has focused on balancing the design of marine reserves in fisheries management with multiple user groups, marine reserves are being implemented for myriad reasons other than the protection of fish stocks. These reasons include facilitating scientific research, encouraging species diversity, and protecting sensitive marine habitats. Designing marine reserve plans to meet these added goals may be accomplished by integrating additional constraints into the GP model proposed in this paper. For example, encouraging species diversity would necessitate spatial information on all relevant species of fish or a spatial index of diversity that could be included in the model. Likewise, spatial information on multiple habitats could be used to design reserves that also protect a certain area of multiple habitat types. Given the necessary data, the methodology presented here is sufficiently flexible to include these additional design criteria.

In a broader sense, marine resource management and conservation decision problems are becoming fertile ground for operations research. Mathematical programming methods, for example, have been used to determine strategies for fishery development and longer-term fishery policy evaluation (Glen 1997), to evaluate the efficiency of harvesting methods (Getz and Haight 1989), to determine optimal harvesting strategies (Tuck and Possingham 1994), to assess environmental and economic tradeoffs facing policymakers due to harvesting and climate changes (Walters and Parma 1996), and to determine the routing and scheduling of fisheries law enforcement aircraft and vessel patrols (Armacost 1992).

In a similar vein, knowledge-based decision-support systems that integrate spatially explicit data in an analytical tool have been shown to be ideal for the assessment and monitoring of marine resources and for strategic market planning (Borch and Hartvigsen 1991, Rothschild et al. 1996, Jensen et al. 2000). Additionally, artificial neural networks have been used to forecast fisheries catches, recruitment, spatial distributions of species, impacts of habitat modification on fish populations, and the environmental variability and stochastic behavior of fishery resources (Olden and Jackson 2001, Batabyal 2002, Huse and Ottersen 2003).

The inherent uncertainty of fisheries and marine resource systems also makes simulation, game theory, and risk analysis important tools in performing risk assessments of differing management strategies (Walters 1986, Grant 1986, Linder et al. 1987, Ault and Fox 1989, Condue and Francis 1994, Frederick and Peterman 1995, Hilborn 1996, Lane and Stephenson 1998, McAllister and Kirkwood 1998, Varis and Kuikka 1999). Game theory and simulation have also been used to plan responses to oil spills, to manage highly migratory fish stocks, to assess the ecological and economic impact of changes in fleets and environmental variation, and to find optimal solutions to allocation problems in fishery conservation and management (e.g., Galt and Payton 1999, Sumaila 1999, Bjorndal et al. 2000, Armstrong and Sumaila 2001, Doyen and Bene 2003). Other problems of interest to operations researchers involve complex market dynamics and price fluctuations under adaptive learning in renewable resource markets and—because of their flexibility—may include bioeconomic optimization models and application of nonmarket valuation to marine reserve management (e.g., Hommes and Rosser 2001, Bhat 2003).

In summary, marine resource management and conservation is becoming a major consumer of operations research technology. The complex decision problems involved in the sustainability of these precious resources should motivate new and important basic research well into the foreseeable future.

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