Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Ecological Economics 48 (2004) 303–315
ECOLOGICAL ECONOMICS
www.elsevier.com/locate/ecolecon

ANALYSIS

Evaluating ecological tradeoffs in fisheries management: a study case for the yellowfin tuna fishery in the Eastern Pacific Ocean

Roberto Ramón Enríquez-Andrade[a,*], Juan Guillermo Vaca-Rodríguez[a,b]

[a] *Universidad Autónoma de Baja California, Km 103, Carretera Tijuana-Ensenada, Ensenada, Baja California, Mexico*
[b] *Programa Nacional de Aprovechamiento del Atún y de Protección de Delfines. Km 107, Carretera Tijuana-Ensenada, campus CICESE, Ensenada, Baja California, Mexico*

Received 19 September 2002; received in revised form 20 August 2003; accepted 5 September 2003

Abstract

Multiobjective decision analysis (MDA) is a useful assessment method when fishery managers need a systematic investigation of the tradeoffs involved in the selection of alternative policy options. An important class of techniques within MDA is vector optimization, consisting of mathematical programming models with vector valued objective functions. From the management perspective, vector optimization models are particularly suited for situations when the decision rule requires each objective to be kept as high (or low) as possible. Solving vector optimization problems usually entails finding a set of Pareto-optimal solutions. These solutions are relevant to the decision-making process specially if decision-makers have monotonic preferences. In this paper, a vector optimization model of the Eastern Pacific yellowfin tuna fishery is used to generate Pareto-optimal solutions and to evaluate the tradeoffs (shadow prices) involved in the selection of alternative policy options. Three conflicting biological objectives are considered: (a) minimizing dolphin incidental mortality, (b) minimizing by-catch of all non-dolphin species and (c) maximizing total yellowfin tuna catch. Results are presented and discussed by means of non-linear tradeoff curves.

Keywords: Multiobjective decision analysis; By-catch in fisheries; Tuna-dolphin controversy

1. Introduction

Historically the yellowfin tuna (*Thunnus albacares*) fishery in the Eastern Pacific Ocean (east of 150°W, between 40°N and 30°S) has been one of the most important in the world, it accounted for approximately 270,000 metric tons in 2000, roughly 25% of the yellowfin tuna global production in the same year (http://www.iattc.org/). The purse-seine is the main fishing gear used in this fishery, which is a gear designed to fish at the surface on large schools. It is especially useful in the tropical Eastern Pacific, where the thermocline is shallow and the thermally sensitive species of tuna are forced into surface waters. The main target species are yellowfin tuna and to a lesser extent skipjack (*Katsuwonus pelamis*) and bigeye tuna (*Thunnus obesus*) (Anonymous, 1999). These species, respectively, accounted for 68%, 24% and 7% of the 577,076 metric tons of tuna caught in the Eastern

---

* Corresponding author. PMB 302, 416 W San Ysidro Blvd, Ste L, San Ysidro, CA 92173-2443 USA. Tel.: +1-52-646-174-4570x130; fax: +1-52-646-174-4103.
E-mail address: enriquez@uabc.mx (R.R. Enríquez-Andrade).

0921-8009/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2003.09.009

Pacific in 2001 (http://www.iattc.org/). Tunas in the Eastern Pacific are also caught by means of longlines; this gear accounts for 10–15% of the total catch (Anonymous, 1998).

Since the end of World War II, the nations involved in the fishery have been making joint efforts to preserve and efficiently exploit the stocks of tuna in the region. With this purpose, in 1949, a Convention for the establishment of the Inter-American Tropical Tuna Commission (IATTC) was signed. These efforts however have not been harmonious. The main sources of conflict have been the issues of allocation, jurisdiction, incidental mortality of dolphins and more recently mounting levels of by-catch of many species including juvenile yellowfin tuna, billfishes, sea turtles and sharks. Almost all by-catch is discarded, therefore representing a wasteful utilization of the marine resources. Additionally, the increasing by-catch of immature yellowfin tuna may have serious implications for the sustainability of the stock. Another concern is the by-catch of sea turtles given their "in-danger of extinction" status.

Initially, purse-seine fishermen in the Eastern Pacific Ocean mostly caught tunas by setting their nets around free swimming schools, a mode of fishing known as *school fishing*, or by fishing near floating objects such as tree trunks under which tunas often congregate, a mode known as *log fishing*. With the advent of modern purse-seine vessels, fisherman developed a technique that took advantage of the association of dolphins with schools of large yellowfin tuna. In this technique, known as *dolphin fishing* or *fishing on dolphins*, the net is set around the tunas and the dolphins. In the early years, the rate of dolphins incidentally killed was very high. More than 500,000 dolphins were estimated dead in the 1960 season (Joseph, 1994).

The 1972 Marine Mammal Protection Act required U.S. tuna fishermen to reduce dolphin mortality associated with purse seine fishing for tuna and established similar standards for foreign fishermen wishing to export their tuna to the United States. Tuna imports from countries that did not have dolphin conservation programs comparable to that of the United States were banned from import into the United States.

Since the early years of the 1980s, the member governments of the IATTC agreed to address the problem of dolphin mortality in the fishery, with the following objectives (Joseph, 1994): "(1) to maintain a high level of tuna production and also to (2) to maintain dolphin stocks at or above levels that assure their survival in perpetuity, (3) with every reasonable effort made to avoid needles or senseless killing of dolphins".

In 1990, the U.S. Congress passed legislation defining a "dolphin-safe" tuna label. Any tuna caught by a vessel that set, at least once during a fishing trip, its net on dolphins could not be labeled "dolphin-safe", even when no dolphins were killed. In 1992, the U.S. Congress went further by enacting the International Dolphin Conservation Act, which established a global moratorium from March 1, 1994 on tuna fishing that kills dolphins; imposed strict, non-discretionary embargoes and sanctions against countries failing to abide by the global moratorium; prohibits sale, purchase, transport of tuna and tuna products that are not "dolphin-safe". Mexico protested the embargo to a panel of the international General Agreement of Tariffs and Trade, which concurred that the embargo went against standards of free trade. However, the matter was not pursued further by the Mexican Government.

In 1995, representatives of the United States and eight Latin American nations that have tuna fisheries agreed to place caps on dolphin mortality and other non-target species in the Eastern Pacific, with the long-term goal of reducing mortality to levels approaching zero, in a document called de Panama Declaration. The Panama Declaration did set an annual limit of 5000 dolphins killed by tuna fishing in the Eastern Pacific and required that an observer be on-board every tuna-fishing boat. The Center for Marine Conservation, World Wildlife Fund, Environmental Defense Fund and Greenpeace International, led by its offices in Mexico, Chile, Brazil, Guatemala and Argentina, also helped draft the pact. The signatory nations envisioned that, as a result of their actions in reducing dolphin mortality, the United States would amend its laws so their participation in the International Dolphin Conservation Program would satisfy comparability requirements of the Marine Mammal Protection Act and result in the lifting of embargoes on yellowfin tuna and yellowfin tuna products.

In 1997, the U.S. Congress was able to pass a compromise measure for domestic legislation implementing the Panama Declaration known as the International Dolphin Conservation Program Act. The compromise measure required that embargoes be lifted on "dolphin-safe" tuna for all countries participating in the international dolphin conservation program (as outlined the Panama Declaration), and that the definition of "dolphin-safe" be altered to include tuna caught by encircling dolphins, so long as observers documented that no dolphins were killed or seriously injured, if a 3-year study found no long-term harm to dolphin populations from encirclement. In 1999, the International Dolphin Conservation Program became effective after Commerce Secretary Richard Daley ruled that there was insufficient evidence of any significant adverse impact to dolphins form purse-seining.

Earth Island, Defenders of Wildlife and others brought a lawsuit contending that the Secretary's ruling ignored the legally mandated study by the agency's own marine scientists. On April 2000, a U.S. District Court Judge agreed with the conservationist and restored the meaning of the original "dolphin-safe" label, prohibiting its use for tuna landed by a vessel having intentionally encircled dolphins with its net during a particular trip.

At the end of 2002, once again, the U.S. Government through the Commerce Department made an attempt to modify the definition of the "dolphin-safe" label to include tuna caught by encircling dolphins if observers certify no dolphins were killed or seriously injured. Environmentalists sued again and, once more, the Commerce Department decision was overturned by the same District Court Judge.

Meanwhile, a successful reduction of dolphin mortality was achieved in the fishery in response to the pressure from environmental groups (Joseph, 1994; Hall, 1998). Total dolphin mortality and mortality per set decreased significantly in the early nineties (Hall, 1998), achieving lower levels than those established in international agreements (Anonymous, 1999). Present dolphin mortality levels are considered by the IATTC as not significant in terms of population effects (Hall, 1998; Anonymous, 1999).

Dolphin incidental mortality has been reduced in two different ways: first, by improvements in the nets and fishing techniques that have allowed for a declining dolphin morality per set on dolphins. Additionally, mortality can be reduced by swapping modes of fishing (i.e. from *dolphin fishing* to others). This involves a geographical redistribution of the fishing effort.

To compile with "dolphin-safe" requirements, an important segment of the fleet has changed its fishing pattern (switching to fishing on logs and free schools). Additionally, new vessels joined the fishery using Fish Aggregating Devices (FADs), a variation of fishing on logs, resulting in mounting by-catch levels of species other than dolphins (including discarded portions of yellowfin tuna catch), as well as reduced yellowfin tuna yields (Joseph, 1994; Hall, 1996, 1998). It is important to note that most U.S. tuna boats have been sold to other countries or moved to other regions to avoid the restrictions of the "dolphin-safe" law and U.S. legal jurisdiction. The main fishing nations currently fishing for tuna in the Eastern Pacific are Ecuador, Mexico and Venezuela (Anonymous, 2001).

Conflicts among the main biological policy objectives are evident in the management of the fishery: on one side reducing dolphin mortality, on the other maintaining lower by-catch levels and higher productivity of the yellowfin tuna stock. The aim of this paper is to suggest the use multiobjective decision analysis (MDA), in particular a family of solutions known as "generating techniques", to examine the nature and magnitude of these tradeoffs given current technology and fishermen behavior.

Policy decisions for the yellowfin tuna fishery affect the livelihood of people in several countries, including the United States and some Latin–American nations. Even more, at least four social groups can be identified with very different interests in the fishery. The first group comprises the tuna fishing industry and fishermen. For them policy decisions have important implications in terms of industry profits and fishermen income. Many fishermen also consider that their way of life is at stake. The second group consists of people in the animal welfare movement; they attach a high value to the protection of dolphins. This concern for dolphins may be beyond pure existence values. For some individuals, dolphin protection represents part of their livelihood (i.e. lawyers, lobbyists, staff of NGOs, etc.). The third group includes fishery managers, scientists and other conservationists concerned about the sustainability of the fishery and its impact on marine biodiversity at large in the Eastern Pacific Ocean.

2. Multiobjective decision analysis of fishery policy

Multiobjective decision analysis represents a useful generalization of more traditional, single-objective approaches to planning problems (for instance cost-benefit analysis). It is useful in situations where policy decisions must be made upon more than one objective that cannot be reduced to a single dimension (i.e. monetary) (Meier and Munasinghe, 1994). Its main purpose is the identification and display of the tradeoffs that must be made among objectives when they conflict. According to Cohon (1978), the consideration of several objectives in the planning process accomplishes three major improvements: First, it promotes more appropriate roles for the analyst in the decision-making process. Second, a wider range of alternatives is usually identified when a multiobjective methodology is employed. Third, multiobjective decision analysis provides a framework for more realistic policy modeling in fisheries, which often have multiple and conflicting objectives (Hanna, 1999; Healey, 1984; Bailey and Jentoft, 1990). The multiobjective approach has been used for the analysis of a range of fisheries management situations (Pan et al., 2001; Sylvia, 1994; Padilla and Copes, 1994; Sylvia and Enríquez-Andrade, 1994; Diaz-de-Leon and Seijo, 1992).

An important class of techniques within multiobjective decision analysis is vector optimization. Vector optimization uses mathematical programming models with vector valued objective functions. From the decision-making point of view, vector optimization is useful when the decision rule implies that each objective is to be kept as high (or low) as possible (Chankong and Haimes, 1983).

The general vector optimization problem is presented in Eqs. (1)–(3). Eq. (1) is a vector consisting of K (k=1,2,. . .,K) individual objective functions. In fishery problems, these functions may represent objectives such as yield biomass, net revenues, jobs, food production, maintaining spawning biomass and so on. The decision variables or policy instruments (e.g. fishing effort, quotas, mesh size, season length, number of boats) are represented by the n-dimensional vector $Y=(y_1, y_2,\ldots,y_n)$. In dynamic problems, this vector, in addition to the decision variables, is made up of the state variables (i.e. the variables determining the state of the system through time). Eq. (2) defines a set of m constraints. Eqs. (2) and (3) define the feasible region in decision space Ω_d (defined in the n-dimensional Euclidian space, Eq. (4)). In dynamic problems, the constraint condition typically includes the system's dynamics, expressed as a system of differential or difference equations (Conrad and Clark, 1989).

$$\text{Max. } Z(Y) = Z(z_1(Y), z_2(Y), \ldots, z_K(Y))$$
$$Y = y_1, y_2, \ldots, y_n \tag{1}$$

$$\text{s.t. } g_i(Y) \le 0 \qquad i = 1, 2, \ldots, m \tag{2}$$

$$y_j \ge 0 \qquad j = 1, 2, .., n \tag{3}$$

$$\Omega_\mathrm{d} = \{y \mid g_i(Y) \le 0, \forall i\} \tag{4}$$

An optimal or superior solution is one that results in the maximum value of each objective function simultaneously (Evans, 1984). Given that vector optimization problems consist of conflicting and often non-commensurate criteria, such an optimal solution seldom exists. Therefore, solving vector optimization problems usually entails finding a set of Pareto-optimal solutions (Chankong and Haimes, 1983) also known as efficient solutions (Evans, 1984), non-dominated solutions and noninferior solutions (Lai and Hwang, 1994). A feasible solution is Pareto-optimal if there exists no other feasible solution that will produce an increase in one objective without causing a decrease in at least one other objective (Cohon, 1978; Evans, 1984). More formally, y^* is Pareto-optimal if there exists no other feasible solution y, such that Eq. (5) holds.

$$Z_k(Y) \ge Z_k(Y^*), \ \forall k = 1, 2, \ldots, K, \text{ and}$$
$$Z_k(Y) > Z_k(Y^*) \text{ for at least one } k \tag{5}$$

In the general vector optimization problem presented in Eqs. (1)–(3), if a solution y^* is Pareto-optimal, then there exists a set of multipliers $\lambda_i \ge 0$, i=1,2,. . .,m and $w_k \ge 0$, k=1,2,. . .,K, with strict inequality holding for at least one k, such that the conditions in Eqs. (6)–(8) hold. Eqs. (6)–(8) are necessary for Pareto-optimality. These conditions are also sufficient if the K objective functions are concave, Ω_d is a convex set and $w_k>0$, $\forall k$ (Cohon, 1978).

$$Y^* \in \Omega_\mathrm{d} \tag{6}$$

$$\lambda_i g_i(Y^*) = 0, \ \forall i \tag{7}$$

$$\sum_k W_k \Delta Z_k(Y^*) - \sum_i \lambda_i \Delta g_i(Y^*) = 0 \tag{8}$$

An important characteristic of Pareto-optimal solutions is that in moving from one Pareto-optimal alternative to another the objectives must be traded off against each other. Note that this approach focuses on Pareto-optimality in production (technical efficiency), which is not necessarily the same as the more general formulation of Pareto-optimality used in welfare economics, i.e. that no move can be made to make a person better off without making a person worse off. A typical vector optimization problem has many Pareto-optimal solutions; the set of all these solutions is known as the Pareto-optimal set. In the context of public policy decision-making, Ballenger and McCalla (1986) refer to the Pareto-optimal set as the "policy frontier." The policy frontier explicitly reveals the tradeoffs associated to movements from one technically efficient policy alternative to another (Chankong and Haimes, 1983).

From the theoretical point of view, the Pareto-optimal set represents the production possibilities frontier for the objectives analyzed (given the model specifications and constraints); in fact, if decision-makers have monotonic preferences, then only Pareto-optimal solutions would be relevant to the decision-making process. Monotonicity of preferences states that, for each objective function z_k, an alternative having larger value of z_k is always preferred to an alternative having a smaller value of z_k, with the value for all other objective functions remaining equal.

In a real world situation, it will be highly unlikely to find a fishery operating on the policy frontier and the assumption of monotonicity of preferences may not hold. In this more general conceptualization, it is not possible to compare movements between two technically inefficient points or between a technically inefficient point to an efficient point. But even in this more general situation, we claim that the policy frontier and associated tradeoffs provide a useful reference that provides important information to decision-makers.

In a given policy problem, only one solution can be selected by the decision-makers. The solution that is actually selected (some times through the use of additional criteria) is called the best-compromise solution (Cohon, 1978) or preferred solution (Lai and Hwang, 1994). Note that, in the context of vector optimization, the selection of the best-compromise solution among the Pareto-optimal solutions is not the result of a formal maximization problem, but rather the result of a subjective evaluation of the importance of the objectives by the decision-makers.

3. Generating techniques

An important family of solutions to vector optimization problems are the generating techniques. These techniques, which follow directly from the Kuhn-Tucker conditions (Eqs. (6)–(8)), are expressly designed for finding Pareto-optimal solutions. Generating techniques do not require the estimation of a utility or welfare function (Cohon, 1978), all that is required is the statement of which objectives are relevant for the problem at hand. The assumption of monotonic preferences is desirable but not essential. The selection of the best compromise solution is deferred until the range of choice, ideally represented by the policy frontier, is identified and presented to decision-makers. The role of the analyst is to concentrate on the formulation and evaluation of noninferior alternatives, and when results are reported they need not recommend a specific alternative as the best. Analysts, instead, find themselves in the more comfortable and defensible position of information providers. The responsibility of selection rests in the decision-makers.

Instead of focusing on a single, supposedly optimal solution, Generating techniques allow the analyst to systematically investigate the range of choice and the tradeoffs involved in the selection of alternative policy options. By focusing on the relationships between the decision variables (policy instruments) and the social objectives, results from generating techniques can help decision-makers to better understand the impact of their decision on the environment, user groups, regions and on the overall level of benefits. This information also may help groups with different interest to bargain more efficiently in the policy arena (Sylvia, 1992).

3.1. The weighting method

Zadeh (1963) shows that the condition given in Eq. (8) implies that the solution to Eqs. (9) and (10) is, in general, Pareto-optimal where $w_k \geq 0$ for all k and strictly positive for at least one k. In essence, this means that a vector optimization problem can be transformed into a scalar optimization problem where the objective function is a weighted sum of the components of the original vector-valued function (Cohon and Marks, 1975). The optimal solution to the weighted problem is a Pareto-optimal solution to the vector optimization problem, provided that all the weights are nonnegative. The Pareto-optimal set can be generated by parametrically varying the weights w_k in the objective function (Gass and Saaty, 1955).

$$\text{Max. } Z(w,Y) = \sum_k w_k z_k(Y) \tag{9}$$

$$\text{s.t. } Y \in \Omega_\mathrm{d} \tag{10}$$

The weighting method is not an efficient method for finding an exact representation of the Pareto-optimal set (because some extreme points are skipped over). However, it is often used to obtain an approximation of this set: a number of different sets of weights are used until an adequate approximation of the Pareto-optimal set is obtained (Cohon, 1978).

3.2. The constraint method

An alternative interpretation of the third Kuhn-Tucker conditions for Pareto-optimality (Eqs. (6)–(8)) implies that Pareto-optimal solutions can be obtained by solving Eqs. (11) and (12). Where L_k is a lower bound on objective k (Cohon and Marks, 1975). This represents an alternative transformation from a vector-valued objective function to a scalar objective function. The Pareto-optimal set can be found by changing L_k parametrically. Thus, the constraint method operates by optimizing one objective, while all the others are constrained to some value.

$$\text{Max. } Z_h \tag{11}$$

$$\text{s.t. } Y \in \Omega_\mathrm{d},\ Z_k \geq L_k,\ \forall k \neq h \tag{12}$$

3.3. The hybrid method

A technique that combines the characteristics of the weighting method and the constraint method (Zadeh, 1963) can be used to generate Pareto-optimal solutions for a vector optimization problem. Chankong and Haimes (1983) call this procedure the hybrid method. According to the hybrid method Pareto-optimal solutions for a vector optimization model can be characterized in terms of optimal solutions of the problem presented in Eqs. (13) and (14) where w_k represents a set of arbitrary positive “weights” (at least one strictly positive) and L_h is a lower bound on the objective h. Pareto-optimal solutions can be generated by the parametric variation of w_k and L_h (see Chankong and Haimes, 1983 for a proof).

$$\text{Max. } Z(w,y) = \sum_k w_k z_k(y) \tag{13}$$

$$\text{s.t. } y \in \Omega_\mathrm{d},\ Z_h \geq L_h,\ \forall h \neq k \tag{14}$$

4. A vector optimization model of the Eastern Pacific yellowfin tuna fishery

A discrete time dynamic three-objective vector optimization (mathematical program) model with fixed technology is developed to analyze the implicit tradeoffs among biological objectives in the Eastern Pacific tuna fishery. Although some fishers in the Eastern Pacific also target skipjack, bigeye and bluefin (*Thunnus thynnus*) tunas, the yellowfin component of the total catch is the most important one (Anonymous, 1999). Due to this and to keep the model as simple as possible, only the dynamics of one species, yellowfin tuna, were modeled.

The objectives considered are: (a) minimizing dolphin mortality, (b) minimizing by-catch levels (of all species except dolphins) and (c) maximizing total yellowfin tuna yield. These objectives are represented by Eqs. (15)–(17), where OBJa is the level of dolphin mortality, OBJb is the level of by-catch, and OBJc is the yellowfin tuna yield. The description of the components of these objectives is presented below (Eqs. (19)–(27)).

$$\mathrm{OBJa} = \sum_{t,w} \mathrm{TB}_{\mathrm{b=dolphins},t,w} \tag{15}$$

$$\mathrm{OBJb} = \sum_{t,w} \mathrm{TB}_{\mathrm{b=non-dolphins},t,w} \tag{16}$$

$$\mathrm{OBJc} = \sum_{t,a,w} \mathrm{CB}_{t,a,w} \tag{17}$$

The vector valued objective function incorporating the objectives given in Eqs. (15)–(17) is presented in Eq. (18).

$$\text{Max. } Z(Y) = Z(-\mathrm{OBJa}(Y), -\mathrm{OBJb}(Y), \mathrm{OBJc}(Y)) \tag{18}$$

The population dynamics of yellowfin tuna are represented by Eq. (19), where X is the yellowfin tuna population age structure in number of organisms, CN is catch in number of organisms, M is the natural mortality coefficient, t is time in years, a is age in years, w is type of set or fishery (log-sets, school-sets, dolphin-sets and longline) and exp is Euler's number (ca. 2.71828).

$$X_{t+1,a+1} = \left(X_{t,a} - \sum_{w} \mathrm{CN}_{t,a,w} \right) \exp^{-M} \tag{19}$$

The initial age structure was taken from virtual population analysis (Anonymous, 1999). Five main age classes were considered. An average of the last five available years was taken, with a total of 60,040,040 organisms of age class 1, 19,700,000 of age class 2, 5,034,000 of age class 3, 575,000 of age class 4 and 27,000 of age class 5. One last age class (5+ or cumulative age class) was considered with 11,000 organisms. M was set as 0.8 and considered as a constant (Wild, 1994; Anonymous, 1999). Recruitment was considered constant using an estimated average for the last decade of 85,000,000 (Anonymous, 1999) since no stock-recruitment relationship has been found yet (Wild, 1994; Anonymous, 1999). Other recruitment schemes will be considered for future analysis.

Catch in numbers CN is represented by Eq. (20), where P is the percentage of organisms caught per age and type set or fishery (Anonymous, 1998; Hall, 1998; Ortega-García, 1996) for one unit of effort, reflecting the historically integrated effects of oceanographic phenomena and fisheries on population structure.

$$\mathrm{CN}_{t,a,w} = P_{a,w} \cdot \mathrm{NP}_{t,w} \tag{20}$$

NP is the number of units of effort generated by the model. NP is the free variable generated by the model to maximize or minimize the objectives, considering the constraints.

Catch in biomass (t) CB is given by Eq. (21) where wg are average weights per age (Anonymous, 1999): 1.4175 kg for age class 1, 9.8175 kg for age class 2, 31.7475 kg for age class 3, 64.1825 kg for age class 4, 97.5500 kg for age class 5 and 124.9725 kg for age class 5+.

$$\mathrm{CB}_{t,a,w} = \frac{\mathrm{CN}_{t,a,w} \cdot \mathrm{wg}_a}{1000} \tag{21}$$

Eq. (22) represents by-catch level TB where bl is a database with by-catch levels per 1000 metric tons of yellowfin tuna loaded (Anonymous, 1999) and b is by-catch species sub-divided into "dolphins" and "non-dolphins". The "dolphins" by-catch represents the number of dolphins incidentally killed per type of set or fishery per 1,000 metric tons of yellowfin loaded. The "non-dolphins" by-catch is an integrated index representing all non-target and target species discarded, arbitrarily weighted depending on their trophic level following the theoretical 10% energy-flow rule (e.g. 100 kilograms of small fishes=10 kg of medium fishes=1 kg of big fish). Since complete by-catch levels for the longline fishery were not available or not reliable and, since the main focus was on the purse-seine fishery, it was decided for this exercise not to include the longline by-catch on the by-catch index. However, this will have the effect of underestimating over-all tradeoffs when longline is used as a main fishery option, but not when estimating tradeoffs among purse-seine set-types.

$$\mathrm{TB}_{b,t,w} = \mathrm{bl}_{b,w} \cdot \sum_{a} \mathrm{CB}_{t,a,w} \tag{22}$$

The constraints used for the exercise described are represented in Eqs. (23)–(27). Eqs. (23) and (24) constraint the yellowfin tuna biomass at time (*t*) to be greater than or equal to a certain arbitrary "security" level, Eq. (24) does this specifically for the last year (*t*=10) of the period modeled. These restrictions are introduced as a precautionary measure and to avoid "mining" the stock during the early years of the simulated period. Eqs. (25) and (26) constraint the catch at time (*t*) to just above historical records for longline (Anonymous, 1999), and for all types of sets or fisheries to 290,000 metric tons representing the catch quota for the region agreed on meetings of IATTC (Anonymous, 1999). This constraint is also usefully for preventing pulse fishing. Finally, Eq. (27) specifies that each age-class must have at least one organism on it.

$$\sum_{a} (x_{t,a} \cdot \mathrm{wg}_a) \geq 100,000\ \mathrm{t} \tag{23}$$

$$\sum_{a} (x_{10,a} \cdot \mathrm{wg}_a) \geq 200,000\ \mathrm{t} \tag{24}$$

$$\sum_{t,a} \mathrm{CB}_{t,a,w=longline} \leq 50,000\ \mathrm{t} \tag{25}$$

$$\sum_{a} \mathrm{CB}_{t,a,w} \leq 290,000\ \mathrm{t} \tag{26}$$

$$X_{t,a} \geq 1 \tag{27}$$

The constraint method was used to trace three arbitrary segments of the policy frontier, given the specification of the model described above. The tradeoffs were calculated on the basis of the marginal values (multipliers) from the output of the model. Some discrete solutions from the policy frontiers were selected to show average annual values of selected variables resulting from the optimization exercise. While searching for a Pareto-optimal solution, the model did chose from among two fisheries (purse-seine and longline) and three set-types in the case of purse-seining, that is a total of four different fishing practices. A 10-year time horizon was considered.

5. Results and discussion

Fig. 1 depicts a two-dimensional representation of values for the three policy objectives considered in the vector optimization problem described in the previous section. The by-catch index and the dolphin mortality are presented in the *y*- and *x*-axes, respectively, while the *z*-axis presents yellowfin tuna yield. The curves in the figure represent three arbitrary segments of the resulting policy frontier. Each curve in the figure connects points of equal values of yellowfin yield. This graphical construction highlights the non-linear nature of the tradeoffs between dolphin mortality and by-catch of all other species. Each contains all Pareto-optimal combinations of values for the two objectives while keeping yield constant. Since the aim is to

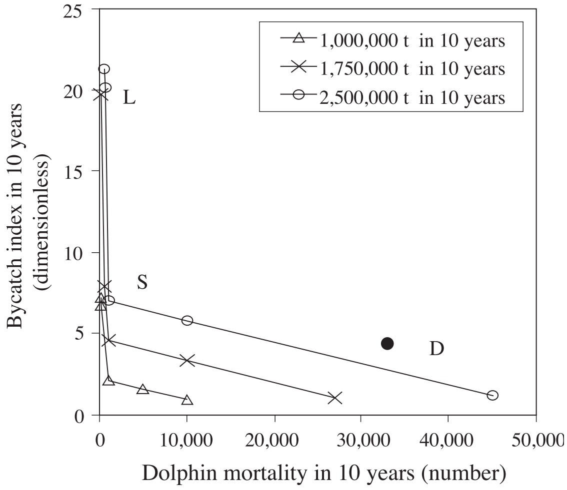

Fig. 1. Policy frontiers for three different levels of yellowfin tuna yield. D stands for dolphin-sets, L for log-sets and S for school-sets, representing the dominance of the catch for each Pareto-optimal solution by each type of set. The black dot represents actual behavior of the fishery generated with data observed in the period 1993–1998: mean dolphin mortality=3382 organisms/year; mean incidental catch index=0.628; mean YFT yield=257,700 metric tons/year; mean catch with longline=21,060 metric tons/year, with dolphin-sets=142,696 metric tons/year, with log-sets=21,423 metric tons/year and with school-sets 72,521 tons/year.

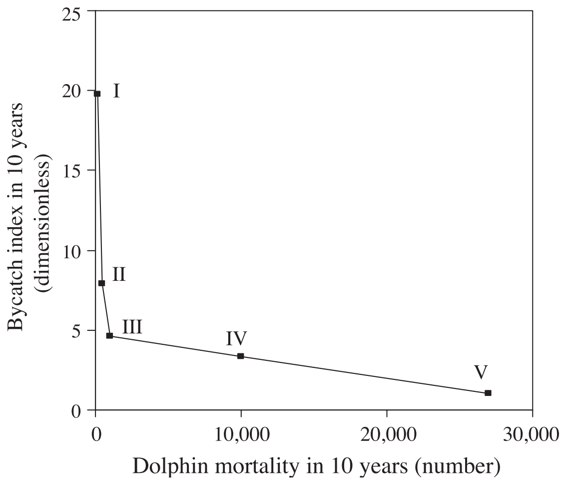

Fig. 2. Policy frontier for the level of 1,750,000 metric tons of yellowfin tuna yield in 10 years and five solution reference points (I to V).

minimize both dolphin mortality and by-catch index, the curves of equal yield values are convex to the origin.

Fig. 2 shows the segment of the policy frontier corresponding to an average annual yield of 175,000 metric tons. The Roman numerals I to V are used to label particular Pareto-optimal solutions that will be used below to make some remarks about the nature of the solutions of the vector optimization model. Figs. 1 and 2 show clearly the conflict among the objectives, since there is no solution achieving simultaneously the lowest values for dolphin mortality and the by-catch index, and at the same time achieving the maximum values for yellowfin tuna yield.

Average annual dolphin mortality increases from 17 in solution I to 2700 in solution V (Table 1). The opposite trend is observed in the values of the by-catch index and the corresponding number of organisms discarded. Yellowfin tuna stock biomass reached its lowest level in solution I, and its highest level in solution V, the lower the tuna biomass the higher the risk for the stock.

The decision or control variable is the proportion of catch by type fishery and type of set (i.e. set on logs, set on schools, etc.). The average annual catch necessary to achieve a given Pareto-optimal solution is shown in Table 2. Solution I is characterized by a higher by-catch index and a lower dolphin mortality, and its corresponding catch shows the dominance of log-sets (area depicted as “L” in Fig. 1). Solution III is dominated by school-sets (area depicted as “S” in Fig. 1), and was characterized by a moderate dolphin mortality and a lower by-catch index. Finally, solution reference point V was characterized by a high dolphin mortality and a lower by-catch index, and the catch was dominated by dolphin-sets (area depicted as “D” in Fig. 1). The other two solutions were characterized by transition trends of their neighbors.

Table 3 shows the average annual by-catch in numbers, for the particular species involved, for the reference solutions I to V in Fig. 2. This is done to give the reader an appreciation of the meaning of the by-catch index values in terms of numbers of organisms. Solution I corresponds to a fishery operating according to the “dolphin-safe” standards. Dolphin mortality would be very low, only 17 individuals per year. To get these low values of dolphin mortality, however, fishery actors must accept a by-catch of

Table 1
Average annual dolphin mortality, by-catch indexes, by-catch in terms of number or tonnage of organisms and yellowfin tuna biomass resulting at each of the five reference solutions selected in Fig. 2

Reference solution	Dolphin mortality (numbers)	By-catch index (dimensionless)	Non-dolphin by-catch		Yellowfin tuna biomass (metric tons)
			Non-target (numbers)	Yellowfin tuna (metric tons)	
I	17	1.976	5,995,358	62,655	425,644
II	50	0.793	2,365,383	27,617	629,037
III	100	0.460	1,341,344	17,868	662,267
IV	1000	0.337	994,096	13,215	679,782
V	2700	0.106	151,470	2489	722,305

By-catch of yellowfin tuna refers to juveniles that are discarded.

Table 2
Average annual catch of yellowfin tuna (and its standard deviation) by each type of set for the five reference solutions

Reference solution	Average catches per year (metric tons)				Catch standard deviation (metric tons)			
	Longline	Dolphin-sets	Log-sets	School-sets	Longline	Dolphin-sets	Log-sets	School-sets
I	50,000	0	109,453	15,547	0	0	89,000	34,287
II	50,000	0	27,363	97,637	0	0	48,018	109,381
III	45,005	1654	3492	124,848	15,796	5225	11,044	117,396
IV	45,005	40,868	3492	85,634	15,796	87,695	11,044	107,426
V	45,005	114,939	3492	11,564	15,796	122,051	11,044	26,387

The standard deviation refers to the year to year variations of the catch along the non-inferior time trajectories associated with the reference solutions.

several million individuals of other species (second column in Table 3). On the other hand, in solution V, a good part of the fishermen would be setting their nets on dolphins. Dolphin mortality would be much higher at 2700 individuals (but still bellow the standard agreed upon in the Panama Declaration) but by-catch levels would be reduced to a little more than 150,000 individuals of other species (last column of Table 3).

In solution I, the marginal cost of reducing dolphin mortality is 108,770 non-target organisms and 1137 metric tons of target species (Table 4). However, for solution V, the marginal cost drops significantly to only 197 non-target organisms and 3 metric tons of target species, given the same level of yield. Hall (1998) reported that the differential cost of fishing of 1 dolphin+0.1 sailfish+0.1 manta ray obtained with dolphin sets was approximately 1833 non-target organisms and 15,620 target organisms (about 8 metric tons if we assume a weight of 2 kg/individual).

Maximum catch levels per year in the model were constrained by an ad hoc restriction based on catch quotas agreed on at IATTC meetings. However, there was no restriction regarding the minimal levels of catch per year. The resulting variation (see the last four columns in Table 2) of catches may cause uncertainty, instability and a sense of risk to fisher-

Table 3
Average annual by-catch (non-target species in number of organisms) for each of the selected reference solutions (in Fig. 2)

Species or group of species	Reference solutions				
	I	II	III	IV	V
Dolphins	17	50	100	1000	2700
Mahi-mahi	1,098,240	338,104	119,332	92,829	8061
Wahoo	589,909	156,793	31,186	27,456	1637
Rainbow runner	87,181	27,708	10,624	8152	733
Yellowtail	127,852	134,657	140,320	97,958	14,405
Other big fish	67,714	150,984	179,976	123,911	16,560
Triggerfish	1,737,810	454,695	82,310	74,101	3252
Other small fish	2,174,440	1,005,941	683,142	501,934	92,718
Shark and ray	103,575	87,957	85,696	61,376	12,461
Marine turtles	203	286	319	231	60
Unidentified fish	4522	2802	2366	1762	487
Other fauna	16	95	121	85	15
Sword fish	43	80	93	67	15
Blue marlin	1310	865	755	547	116
Black marlin	1163	731	621	453	101
Striped marlin	412	694	798	570	130
Shortbill marlin	18	9	7	7	7
Sail fish	554	2688	3404	2451	648
Unidentified marlin	275	214	202	152	49
Unidentified billfish	121	81	71	53	15
Total non-dolphin species	5,995,358	2,365,383	1,341,344	994,096	151,470

Table 4
Tradeoffs between dolphin mortality and the by-catch index for the 10-year simulation period

Reference number	By-catch index units per marginal unit of dolphin mortality	Organisms per marginal unit of dolphin mortality	
		Non-target species (number)	Yellowfin tuna (metric tons)
I	0.0358417	108,770	1137
II	0.0358417	106,937	1248
III	0.000135938	397	5
IV	0.000135938	401	5
V	0.000135938	197	3

Tradeoffs are presented both as the by-catch index and as the corresponding number of non-target organisms and tonnage of target species.

men. Decision-makers may wish to explore other model outputs with different constraints.

6. Conclusion

The resulting policy frontiers are useful in providing guidance to decision-makers and other policy actors to understand the implication of management decisions, structure the policy debate and aid policy participants (e.g., biologists, lawyers, politicians, environmentalists, commercial and sports fishermen, processors and consumers) in developing informed and balanced perspectives. It is important to underscore that the modeling approach used is a prescriptive one. Results are neither intended to describe nor to predict actual fisherman behavior. Rather its intent is to give information about desirable changes in fishing practices, which could improve the performance of the fishery.

A reference point describing the current performance of the fishery is depicted in Fig. 2, generated with data observed in the period 1993–1998: mean dolphin mortality equals 3382 organisms/year; mean incidental catch index equals 0.628; mean YFT yield is approximately 250,000 metric tons/year; mean catch with longline=21,060 metric tons/year, with dolphin-sets=142,696 metric tons/year, with log-sets=21,423 metric tons/year and with school-sets 72,521 metric tons/year (Anonymous, 2000). Meanwhile, the trend (based on the 1998–2001 period) is toward and increasing use of log-sets, particularly those with Fish Aggregating Devises (Anonymous, 1999, 2002). This behavior, due mainly to the way fishermen respond to “dolphin-safe” measures, is resulting in lower dolphin mortality levels, higher incidental catch and higher yellowfin tuna yield (i.e. is moving the fishery towards the upper left corner of the feasible set in Figs. 1 and 2).

Catches obtained by dolphin-sets and long line are composed of a larger proportion of mature yellowfin tuna individuals. Log-sets, which include the use of Fish Aggregating Devises, catch a large proportion of smaller immature organisms. School sets select organisms slightly larger than log-sets (Anonymous, 1989; Hall, 1996). The trend towards log-sets could have important implications for the sustainability of the stock, given that it moves the fishery to levels of higher biological risk. The international scientific community is concerned about the potential damage this could pose to the resource. This concern is reflected in the current system of space and time closures imposed in recent years based on total catches per species (Anonymous, 2002).

Results suggest that the marginal cost of reducing dolphin mortality along the policy frontier in terms of non-dolphin species does not increase linearly, rather it increases gradually up to a point—until log fishing starts to dominate the fishery—afterwards it increases rapidly. Solutions away from the extremes in the policy frontier, such as reference point III (dominated by school-sets) attain both lower dolphin mortality and by catch index. However, information such as the length of yellowfin tuna caught at each set, availability and readiness to make any type of set, economic viability and existing fishery management regulations should be used as additional criteria to make a selection. The reader should keep in mind that the five reference points used to underscore the nature of the tradeoffs between dolphin and non-dolphin by-catch were arbitrarily selected among a much larger Pareto-optimal set.

Using the model specification in this analysis as reference (we do not claim it is the ideal model specification nor the only one possible), two observations can be made: First, that it is possible to change current practices (with technology fixed) and improve simultaneously all objectives (a Pareto improvement). For instance, moving down from the point representing actual behavior of the fishery (black dot in Fig. 1) to the 2,500,000 metric tons policy frontier, it is possible to obtain about the same catch, the same dolphin mortality, but with less by-catch (and keep a higher yellowfin tuna stock biomass). Similarly, moving horizontally to the left of the black dot (in Fig. 1) up to the 2,500,000 metric tons policy frontier, it is possible to obtain less dolphin mortality while keeping the other objectives unchanged. Once the policy frontier is reached, any objective may only be increased at the expense, of at least, one of the remaining.

The shape of the resulting Policy frontier, also points out the increasing opportunity costs associated with the current radical position of many in the animal welfare movement, who keep pushing for zero levels of dolphin mortality. Other fact to consider is that the fishing grounds for dolphin-sets tends to be larger than those for other set-types (Anonymous, 1999), and that for this kind of sets there are proven successful management schemes in place to regulate dolphin mortality and by-catch of juvenile organisms of target species (Joseph, 1994; Anonymous, 1999); among other aspects.

Ballenger and McCalla (1986) emphasize that changing the set of policy instruments and adding or changing any parameters in a vector optimization model could shift or redefine the shape of the policy frontier. That is, the policy frontier for a given fishery policy problem may shift or change shape with changes in technology, policy instruments, institutional constraints, preferences, environmental conditions, etc. As stated before, this exercise assumes no technological changes in the fishery, adjustments are made on the basis of set-type (i.e.. dolphin sets, school sets or log-sets). This assumption represents accurately current fishing practices, which are largely motivated by the "dolphin-safe" principle.

This paper highlighted the usefulness of vector optimization, in particular generating techniques to evaluate tradeoffs in fisheries management. Rather than suggesting an optimal solution, this approach concentrates on providing information to the decision-makers regarding the range of choice and the consequences of policy options. Future research includes assessing a broader set of objectives in the Eastern Pacific tuna fishery, such as revenue, profits and employment.

Acknowledgements

The authors thank the *Pew Charitable Trusts* for its financial support and the Consejo Nacional de Ciencia y Tecnología (CONACyT) for a credit-scholarship given to one of the authors. We also appreciate the comments and suggestion of Dr. Saul Alvares-Borrego, Dr. Michel Dreyfus-Leon, Dr. Oscar Sosa Nishizaki and two referees. We accept full responsibility for all remaining deficiencies.

References

Anonymous, 1998. Annual Report of the Inter-American Tropical Tuna Commission (data for 1997). La Jolla, California, USA.

Anonymous, 1999. Annual Report of the Inter-American Tropical Tuna Commission (data for 1998). La Jolla, California, USA.

Anonymous, 2000. Annual Report of the Inter-American Tropical Tuna Commission (data for 1999). La Jolla, California, USA.

Anonymous, 2001. Annual Report of the Inter-American Tropical Tuna Commission (data for 2000). La Jolla, California, USA.

Anonymous, 2002. Annual Report of the Inter-American Tropical Tuna Commission for 2001, La Jolla, California, USA.

Bailey, C., Jentoft, S., 1990. Hard choices in fisheries development. Marine Policy 14 (4), 333–344.

Ballenger, N.S., McCalla, A.F., 1986. Policy programming for Mexican agriculture: domestic choices and world market conditions. ERS Staff Report No. AGES860501, International Economics Division, Economic Research Service, US Department of Agriculture, Washington, DC.

Chankong, V., Haimes, Y., 1983. Multiobjective decision making. Theory and Methodology. North-Holland, USA.

Cohon, J., 1978. Multiobjective Programming and Planning. Academic Press, USA. 335 pp.

Cohon, J., Marks, D., 1975. A review and evaluation of multiobjective programming techniques. Water Resources Research II (2), 208–220.

Conrad, J., Clark, C., 1989. Natural resource economics. Notes and Problems. Cambridge Univ. Press, USA. 231 pp.

Diaz-de-Leon, A., Seijo, J.C., 1992. A multi-criteria non-linear optimization model for the control and management of a tropical fishery. Marine Resource Economics, 33–40.

Evans, G., 1984. An overview of techniques for solving multiobjective mathematical programs. Management Science 30 (11), 1268–1282.

Gass, S., Saaty, S.L., 1955. The computational algorithm for the parametric objective function. Naval Research Logistics Quarterly 2, 39–45.

Hall, M.A., 1996. On bycatches. Reviews in Fish Biology and Fisheries 6, 319–352.

Hall, M.A., 1998. An ecological view of the tuna-dolphin problem:

impacts and tradeoffs. Reviews in Fish Biology and Fisheries 8, 1–34.

Hanna, S., 1999. Strengthening governance of ocean fishery resources. Ecological Economics 31 (2), 275–286.

Healey, M.C., 1984. Multiattribute analysis and the concept of optimum yield. Canadian Journal of Fisheries and Aquatic Sciences 41, 1393–1404.

Joseph, J., 1994. The tuna-dolphin controversy in the eastern pacific ocean: biological, economic, and political impacts. Ocean Development and International Law 25, 1–30.

Lai, Y.J., Hwang, C.L., 1994. Fuzzy Multiple Objective Decision Making. Springer-Verlag, Germany. 450 pp.

Meier, P., Munasinghe, M., 1994. Incorporating environmental concerns into power sector decision making: a case study of Sri Lanka. World Bank Environment Paper, vol. 6. World Bank, Washington, DC, pp. 13–18.

Ortega-García, S., 1996. Interaction between Mexican longline and purse seine fisheries for yellowfin tuna in the eastern Pacific Ocean. In: Shomura, R.S., Majkowski, J.H., Robert, F. (Eds.), Status of Interactions of Pacific Tuna Fisheries in 1995. FAO Fisheries Technical Paper, vol. 365. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 350–362.

Padilla, J.E., Copes, P., 1994. Bioeconomic analysis of management options for tropical fisheries using a bicriteria programming model. Marine Resource Economics 9 (1), 47–66.

Pan, M., Leung, P., Pooley, S.G., 2001. A decision support model for fisheries management in Hawaii: a multilevel and multiobjective programming approach. North American Journal of Fisheries Management 21, 293–309.

Sylvia, G., 1992. Concepts in fisheries management: interdisciplinary gestalts and socioeconomic policy model. Society and Natural Resources 5, 115–133.

Sylvia, G., 1994. Market information and fisheries policy models: a multiple-objective analysis. North American Journal of Fisheries Management 14, 278–290.

Sylvia, G., Enríquez-Andrade, R.R., 1994. Multiobjective bioeconomic analysis: an application to the pacific whiting fishery. Marine Resource Economics 9 (4), 311–328.

Wild, A., 1994. Review of the biology and fisheries for yellowfin tuna, *Thunnus albacares*, in the eastern Pacific Ocean. In: Shomura, R.S., Majkowski, J.H., Robert, F. (Eds.), Status of Interactions of Pacific Tuna Fisheries in 1995. FAO Fisheries Technical Paper, vol. 336 (2). Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 52–107.

Zadeh, L.A., 1963. Optimality and nonscalar-valued performance criteria. IEEE Transactions on Automatic Control AC-8, 59–60.