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Ecological Modelling 191 (2006) 275–290

ECOLOGICAL MODELLING

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Analysis of the eastern Pacific yellowfin tuna fishery based on multiple management objectives

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

[a] *Programa Nacional de Aprovechamiento del Atun y de Protection de Delfines (PNAAPD), Km. 107, Carretera Tijuana-Ensenada, Campus CICESE, C.P. 22860, Ensenada, Baja California, Mexico*
[b] *Facultad de Ciencias Marinas, Universidad Autonoma de Baja California (UABC), Km. 103, Carretera Tijuana-Ensenada, campus UABC-Ensenada, Ensenada, Baja California, Mexico*

Received 29 May 2004; received in revised form 20 April 2005; accepted 29 April 2005
Available online 27 June 2005

Abstract

Vector optimization techniques were used to generate arbitrary segments of a policy frontier for a dynamic yellowfin tuna (*Thunnus albacares*) fishery model assuming fixed technology and considering four policy objectives: minimizing dolphin mortality, minimizing incidental catch (all species except dolphins), maximizing sustainable yield, and minimizing biological risk for the yellowfin tuna stock. Results show that along the policy frontier: (1) reducing incidental dolphin mortality increases the incidental catch of other species in a nonlinear way; (2) yield increases (subject to a biomass precautionary level) can only be obtained at the expense of higher levels of dolphin mortality and incidental catch; (3) biological risk increases as the level of tunas caught increases, but this increase depends on the type of fishery (longline fishing and three different modes of purse-seining: log-sets, dolphin-sets or school-sets) that dominates the fishing effort; (4) there is an indirect relationship between the dolphin mortality levels and those of biological risk; (5) there is a direct relationship between the incidental catch levels and biological risk. Catch obtained with dolphin-sets dominates the Pareto-optimal solutions with highest dolphin mortality levels but is associated with lower biological risk, whereas catch obtained with log-sets dominates in Pareto-optimal solutions with higher incidental catch and higher biological risk. In general, trade-offs or shadow prices among objectives are not linear, indicating that marginal costs vary along the policy frontier. Results of the trade-off analysis may provide useful information for decision-makers and other policy actors. Complete information about the preferences of the decision-makers regarding the objectives is necessary to recommend a specific management policy.

Keywords: Multiobjective; Yellowfin tuna; Biological risk; Dolphins; Incidental catch; Trade-offs; Pacific Ocean; Management

* Corresponding author at: PMB 302, 416 W San Ysidro Blvd., Ste L San Ysidro, CA 92173-2443, USA.
E-mail addresses: juangvaca@uabc.mx, juangvaca@hotmail.com (J.G. Vaca-Rodríguez).

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doi:10.1016/j.ecolmodel.2005.04.025

1. Introduction

Fishery models are, like all sorts of models, simplifications of reality. Some of these models are based on biological aspects of the resources, like those generated for estimating shape, volume, and resonance frequency of fish swimbladders (Schaefer and Oliver, 2000), or metabolic demands (Korsmeyer et al., 1996). Other models use both biological and fishery data for improving the management of fisheries by modeling, for example, different fishing scenarios (Mullen et al., 1996) or vessel movement to different fishing grounds (Dreyfus-Leon and Kleiber, 2001). Some models go even further and consider whole ecosystems in their fishery management schemes (Arreguín-Sánchez et al., 2004; Christensen and Pauly, 2004; Morales-Zárate et al., 2004).

Another type of models focuses on analyzing fisheries (and improving their management) considering more than one objective at the same time, in accordance to the new paradigm of fishery management expressed in the code of conduct for responsible fishing and the application of the precautionary principle (FAO, 1995). Charles (1989) combined in his model stock size, fishing effort, catch rates and labor levels. Other similar efforts include those of Sylvia and Enríquez-Andrade (1994), Senina et al. (1999), and Pan et al. (2001). More recently, Arreguín-Sánchez et al. (2004) developed an interesting model based on different scenarios and criteria, and focusing on optimal management of an ecosystem. Grasso (1998) compared two extractive activities, mangrove forestry and fisheries, and calculated trade-offs between them.

To improve the management of fisheries worldwide, an analytic tool is needed to evaluate the impacts of management strategies and actions from the perspective of the entire fishery (Pan et al., 2001), considering more than one of its management objectives, unlike it has been done in the numerous single-objective oriented models. Although several multi-objective programming models are currently applied in resource management, only a few of them have been used for fishery management and, to date, none has been applied to the eastern Pacific Ocean (EPO) tuna fishery, which is a very important natural resource of international concern with multiple management objectives. The model herein presented is among those models considering simultaneously more than one management objective, and calculating trade-offs between fishing scenarios.

The EPO yellowfin tuna *Thunnus albacares* (YFT) fishery is known worldwide for the successful reduction of incidental dolphin mortality, achieved through an international management scheme (Joseph, 1994; Hall, 1998; Inter-American Tropical Tuna Commission, 2002). However, there is increasing international concern regarding the incidental catch or by-catch (discarded portion of the total catch, both of target and non-target species other than dolphins), as well as the implications that dolphin mortality reduction measures may have on the main targeted fishery yield and its sustainability (Hall, 1996, 1998; Joseph, 1994).

At the meetings of the Inter-American Tropical Tuna Commission (IATTC), dolphin mortality was shown to decrease from an annual mean of 3300 (1993–1998) to less than 2000 individuals in 2001, 2002 and 2003 (http://www.iattc.org/, IATTC's web page, visited February 2004). Incidental catch levels have been highly variable (Inter-American Tropical Tuna Commission, 2002), increasing society's awareness of the problem. The YFT yield increased from an annual mean of 250,000 t (1993–1998) to nearly 310,000 (1998–2001) or more in 2002 and 2003, when historical records were obtained (http://www.iattc.org/, IATTC's web page, visited February 2004). Hence, the period 1998–2001 shows a trend towards lower dolphin mortality levels and higher YFT yields, with highly variable incidental catches.

This article summarizes the results of a dynamic multiobjective programming model designed for analyzing the trade-offs associated with current fishery management options. Four policy objectives were explicitly and simultaneously considered: (a) minimization of dolphin mortality; (b) minimization of incidental catch levels (all species except dolphins); (c) maximization of sustainable YFT yield; (d) minimization of biological risk (i.e., maximize stock biomass). The decision (control) variables used in this modeling exercise included the total annual catch and the proportional effort exerted by longliners and each of the purse-seining fishing modes: log-, dolphin- and school-sets. These controls are established annually. The results reported in this article are an extension of previous modeling of the YFT fishery based on three objectives, mainly focusing on the mortality trade-offs between dolphin and non-dolphin species (Enríquez-

Andrade and Vaca-Rodríguez, 2004). Here we explore in greater detail the implications of the dolphin-safe policy in terms of biological risk to the YFT stock. This exercise assumes no technological change in the fishery.

2. Materials and methods

The EPO tuna fishery was modeled by means of a discrete-time dynamic multiobjective mathematical program using a 10-year time horizon (a new fishery develops every 10 years). All model inputs corresponded to the period 1993–1998 (unless stated otherwise), since these were the latest available. Age-structure was considered because it is important to account for the effect of the fishery on the stock structure, and because the two different fisheries (purse-seine and longline) and the three modes of purse-seining generally select different age classes (Inter-American Tropical Tuna Commission, 1998).

The model considered only the catch and dynamics of YFT, since this is the main species caught in the EPO (Inter-American Tropical Tuna Commission, 2002), and it is also the main target of the purse-seine fleet. Catches and dynamics of skipjack (*Katsuwonus pelamis*), bluefin tuna (*T. thynnus orientalis*), bigeye tuna (*T. obesus*) and other tunas were not considered to keep the model simple.

In the model, YFT population dynamics was given by

$$X_{t=1,\alpha} = V_\alpha, \qquad X_{t+1,\alpha=1} = B_t - \sum_z C_{t,\alpha=1,z},$$

$$X_{t+1,\alpha+1} = \left(X_{t,\alpha} - \sum_z C_{t,\alpha,z}\right) e^{-M},$$

$$X_{t+1,\alpha=A} = X_{t,\alpha=A} e^{-M} + \left(X_{t,\alpha=A-1} - \sum_z C_{t,\alpha=A-1,z}\right) e^{-M}$$

where X is the YFT age-structure in number of organisms, V the initial age-structure vector in number of organisms, B the recruitment in number of organisms, C the catch in number of organisms, M the natural mortality coefficient, t the time in years, α the age class in years, A an additional age class that concentrates older organisms, z the type of fishery or purse-seine mode, and e is the Euler's number.

The estimate of V was obtained from a virtual population analysis (Inter-American Tropical Tuna Commission, 1999), and five age classes were considered with 60,040,040 fish for age 1, 19,700,000 for age 2, 5,034,000 for age 3, 575,000 for age 4, and 27,000 for age 5. Age A started with 11,000 organisms.

Both M and B were considered constant at 0.8 (Inter-American Tropical Tuna Commission, 1999; Wild, 1994) and 85 million organisms, respectively, using a conservative estimate from the last decade (Inter-American Tropical Tuna Commission, 1999). The stock–recruitment relationship for the YFT fishery is not known (Inter-American Tropical Tuna Commission, 1999; Wild, 1994). In our modeling exercise recruitment was considered constant, even though in practice it can be quite variable (estimates range from 47 million individuals in 1976 to 116 million in 1973, and an average of 80–90 million in the period 1989–1997). With an unknown stock–recruitment relationship, it is not possible to use a harvesting strategy with an equilibrium sustainable yield to manage the fishery. To model the effect of current fishing on future yields, we proceeded according to the precautionary principle, by incorporating a relative index defined in an ordinal scale, to measure biological risk (Sylvia and Enríquez-Andrade, 1994). It is assumed that biological risk is inversely proportional to the level of stock biomass. Based on an ordinal scale, for any two levels of stock biomass, say stock biomass$_t$ and stock biomass$_{t+1}$, if stock biomass$_t$ is greater than stock biomass$_{t+1}$ then the risk (probability of recruitment failure) associated with stock biomass$_{t+1}$ is equal or greater than the risk associated with stock biomass$_t$.

The biological risk index is based on the hypothesis that as stock biomass decreases, it will eventually fall below a certain, though unknown, critical value where recruitment, and therefore the health of the stock, will be significantly affected. Three threshold values of stock biomass were arbitrarily selected to define low (>500,000 t), medium (>300,000 but <500,000 t) and high (<300,000 t) levels of biological risk. These values were based on the three highest biomass quartiles given by the model. The values of the biological risk index were plotted on the policy frontier to provide a full spectrum considering all objectives.

A caveat concerning the numerical solutions must be noted. Although it is conceded that the probability of damaging the recruitment capacity of the stock increases as the stock biomass is allowed to fall, the present analysis implicitly assumes that such damage will not become evident during the time horizon of the analysis, but will occur, if at all, at a later period. This assumption becomes less valid as the stock level is allowed to fall.

Catch C was given by

$$C_{t,\alpha,z} = D_{\alpha,z} E_{t,z}$$

where D is the mean percentage of organisms caught per age and per fishery (longline and purse-seine) or purse-seine mode, for each effort unit E. Variables E and C (a linear transformation of E) are the decision or control variables calculated by the model to maximize or minimize the objectives, given the constraints.

Catch length histograms were used to estimate D (Table 1) (Inter-American Tropical Tuna Commission, 1989; Hall, 1998; Ortega-García, 1996), using the corresponding age-length relationship (Wild, 1994). These histograms contain the integrated effects of population changes, environmental and oceanographic variations, and the dynamics of the fishery itself.

Catch in biomass T (t), was given by

$$T_{t,\alpha,z} = \frac{C_{t,\alpha,z} W_\alpha}{1000}$$

where W is a mean weight vector (kg) of each age class (Inter-American Tropical Tuna Commission, 1999). Mean weight was 1.4175 kg for age 1, 9.8175 kg for age 2, 31.7475 kg for age 3, 64.1825 kg for age 4, and 97.5500 kg for age 5. Finally, the mean weight used for age A was 124.9725 kg.

Table 1
Mean percentage of tunas caught per age and fishery or purse-seine mode

Age class, α	Purse-seine mode			Longline
	Dolphin-sets	Log-sets	School-sets	
1	6.1525	57.650	26.1650	0.0000
2	36.9750	34.0500	60.5575	7.8606
3	40.2500	7.5875	11.3850	56.9692
4	13.2250	0.9275	2.2450	34.0357
5	2.9125	0.0000	0.2500	1.1000

The level of incidental catch Y was given by

$$Y_{y,t,z} = l_{y,z} \sum_{\alpha} \left(\frac{T_{t,\alpha,z}}{1000} \right)$$

where l is a table with values of incidental catch per 1000 t of YFT loaded in purse-seine sets (Inter-American Tropical Tuna Commission, 1999, 2000), and y is the incidentally caught species. An additional element was added to l, grouping all the incidental catch species different to dolphins (y = non-dolphins). This element is an incidental catch index representing those target and non-target organisms that were caught but discarded. These organisms were arbitrarily weighted depending on their trophic level, following the theoretical 10% energy flow (i.e., 100 kg of small fish = 10 kg of medium-sized fish = 1 kg of big fish). Mean lengths or weights, and the corresponding length–weight relationships were used to transform the number of organisms into biomass.

Longline incidental catch was not considered owing to the lack of data. The trade-offs involved in the minimization of incidental catch (non-dolphin) levels are, therefore, underestimated; however, since the interest of the study is focused primarily on purse-seine sets, this underestimation is not relevant for the negotiations occurring in this particular fishery.

The fishery management objectives were defined as

$$\text{OBJ}_a = \sum_{t,z} Y_{y=\text{dolphins},t,z},$$

$$\text{OBJ}_b = \sum_{t,z} Y_{y=\text{non-dolphins},t,z}, \qquad \text{OBJ}_c = \sum_{t,\alpha,z} T_{t,\alpha,z},$$

$$\text{OBJ}_d = \sum_{t,\alpha} \left(\frac{X_{t,\alpha} W_\alpha}{1000} \right)$$

where OBJ_a is dolphin mortality (to be minimized), OBJ_b the incidental catch index (to be minimized), OBJ_c the sustainable YFT yield (to be maximized), and OBJ_d is the YFT biomass (to be maximized).

These fishery management objectives were selected because the International Dolphin Conservation Program specifically emphasizes them, by being “committed to ensure the sustainability of tuna stocks in the eastern Pacific Ocean; progressively reduce the incidental mortality of dolphins in the fishery to levels approaching zero; reduce and minimize the incidental catch and discard of juvenile tunas, and incidental catch of non-target species" (Inter-American Tropical Tuna Commission, 2002). Although different policy frontiers can be generated among the objectives and trade-offs obtained (Leung et al., 2001), the one presented here has the highest impact on the fishery when the dolphin-safe issue is considered.

The complete multiobjective representation of the EPO YFT fishery used in the analysis can be written as follows:

$$\max/\min Z(T) = Z(\mathrm{OBJ}_a(T), \mathrm{OBJ}_b(T), \mathrm{OBJ}_c(T), \mathrm{OBJ}_d(T))$$

where $Z(T)$ is the p-dimensional objective function and $T_{t,\alpha,z}$ is the decision variable or policy instrument, subject to the dynamics of the fishery described above and the following constraints:

$$\sum_{\alpha}\left(\frac{X_{t,\alpha}W_{\alpha}}{1000}\right) \geq 100,000\,\mathrm{t},$$

$$\sum_{\alpha}\left(\frac{X_{t=10,\alpha}W_{\alpha}}{1000}\right) \geq 200,000\,\mathrm{t},$$

$$\sum_{\alpha,z} T_{t=10,\alpha,z} \leq 400,000\,\mathrm{t},$$

$$\sum_{t,\alpha} T_{t,\alpha,z=\mathrm{longline}} \leq 50,000\,\mathrm{t}, \qquad X_{t,\alpha} \geq 1,$$

$$\left|\sum_{\alpha} T_{t,\alpha,z} - \sum_{\alpha} T_{t+1,\alpha,z}\right| \leq 0.5\sum_{\alpha} T_{t,\alpha,z}$$

The first two constraints were introduced to keep YFT biomass above arbitrary minimum levels as a precautionary measure. The first constraint refers to year-to-year YFT biomass, set to a minimum of 100,000 t per year, as an extremely low level allowed. The second is an end restriction that assures a minimum precautionary level of biomass at the end of the modeling time horizon, and also avoids the modeling end-of-time-horizon frontier problem (the stock is left almost depleted by the end of the time horizon). It was arbitrarily set as double the amount of the previous years (first restriction).

The third constraint limits the YFT catch of the final year to levels approximately 50% higher than those historically recorded to allow increases similar to the current ones (2001 and 2002). Similarly, the fourth constraint keeps the longline catches below a level approximately 100% higher than those historically recorded throughout the whole simulated period (Inter-American Tropical Tuna Commission, 2002). The fifth constraint is a practical modeling constraint that limits the model to keep all age classes with at least one organism to avoid mathematical modeling problems (i.e., division by zero). The last constraint maintains the catch in year $t+1$ within a range with upper and lower limits of ±50% relative to the catch of the previous year, aiming to avoid unlikely sudden changes of fishing strategies.

The constraint method was used to generate a set of arbitrary Pareto-optimal solutions to outline slices of the feasible space and the policy frontier (Sylvia and Enríquez-Andrade, 1994; Enríquez-Andrade and Vaca-Rodríguez, 2004). This procedure allows the graphic representation of three objectives, where several efficiency frontiers of two objectives are depicted depending on the value of a third one. More recently, using similar conceptual techniques, Lotov and Bushenkov (2000) and Lotov et al. (2004) developed a software using Decision Maps and Interactive Decision Maps techniques, which allow fast display of decision maps for three, four, five and more objectives or criteria. These techniques assist in the approximation and visualization of the Pareto or policy frontier. The curves look like the height curves of a usual topographical map, and so they are quite easily understandable.

The constraint method is a generating technique that follows directly from the Kuhn–Tucker conditions for Pareto-optimality (Cohon and Marks, 1975; Cohon, 1978; Chankong and Haimes, 1983; Kuhn and Tucker, 1951). In the constraint method, Pareto-optimal solutions can be found by solving:

$$\begin{array}{ll} \max/\min\ Z_r(v) & \\ \text{subject to} & v \in \Omega,\ \text{and}\ Z_p(v) \geq L_p, \\ & \text{all}\ p \neq r \end{array}$$

where $Z(v)$ is the p-dimensional objective function, v the N-dimensional vector of decision variables, L_p the lower limit for objective p, and Ω is the N-dimensional Euclidian vector space. The objective r is maximized or minimized, arbitrarily chosen, or based on criteria given by the analyst. These equations transform the vector optimization problem into a scalar one so that it can be solved as a mathematical program with a single objective. The policy frontier is outlined with the parametric variation of L_p, using values chosen such that there are feasible solutions for the scalar objective function (Cohon, 1978). As the problem is solved, trade-offs between objectives are obtained as byproducts, given by the slope of the tangent line to the policy frontier. Trade offs are also called shadow prices or Lagrange multipliers (Chankong and Haimes, 1983).

While searching for a Pareto-optimal solution, the model did choose from among two fisheries (purse-seine and longline) and three purse-seine modes (a total of four different fishing practices) to accomplish the optimization. These controls were established annually. In general, log-sets dominate in the upper left-hand sections of the resulting slices of the frontier, and dolphin-sets dominate in the lower right-hand sections. While moving from one end to the other of the policy frontier, a series of fishery or purse-seine mode replacements take place in such a way that same YFT yields are achieved and constraints are not surpassed. First, the substitution is between log- and school-sets, and later on between school- and dolphin-sets. Throughout the whole process of purse-seine mode replacement, longline is often used as a wildcard because it does not contribute to either the incidental catch index or the dolphin mortality levels.

The current situation was used as a reference point (Leung et al., 2001) for the policy frontier, and was calculated using data from 1993 to 1998 (Inter-American Tropical Tuna Commission, 2000).

Like Pan et al. (2001), GAMS (1996) software was used to generate the policy frontier.

3. Results

Fig. 1 shows three slices (planes of equal total yield) of the feasible set, corresponding to YFT yields of 100,000, 200,000 and 300,000 t. The term feasible means that under the model restrictions and rationale, the solutions within this set are mathematically feasible or possible. The slice corresponding to 100,000 t is located closest to the origin, while the one corresponding to 300,000 t is farthest from the origin. Note that the shape and size of these segments vary depending on yield, suggesting non-linearity in the z-axis; the largest corresponds to the highest yield and vice versa. Since fishery managers aim to minimize both dolphin mortality (objective a) and incidental catch (objective b), the segments of the policy frontier are located in the lower left section of each slice of the feasible set. Fig. 2a the policy frontier corresponding to each of the slices in Fig. 1. Fig. 2b shows a better perspective of the behavior of the policy frontier and a dominating purse-seine mode, where dolphin mortality levels approach zero.

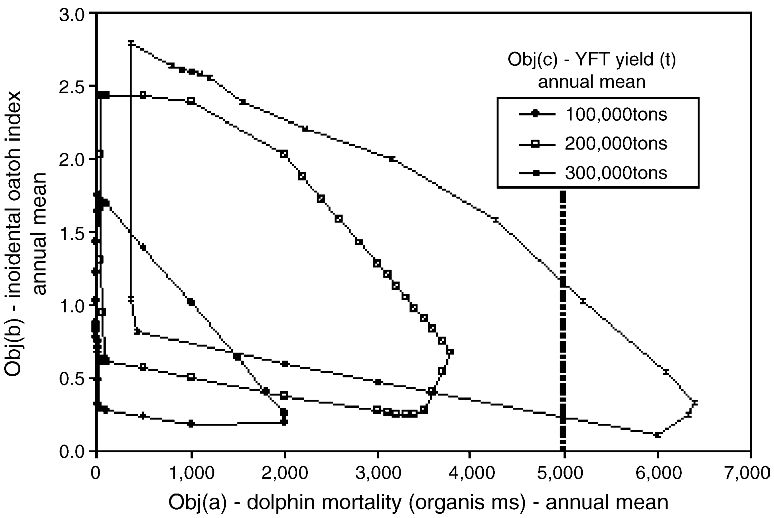

Fig. 1. Slices of the feasible set for objectives a–c. The vertical line represents the annual maximum dolphin mortality limit allowed by the Agreement on the International Dolphin Conservation Program (AIDCP).

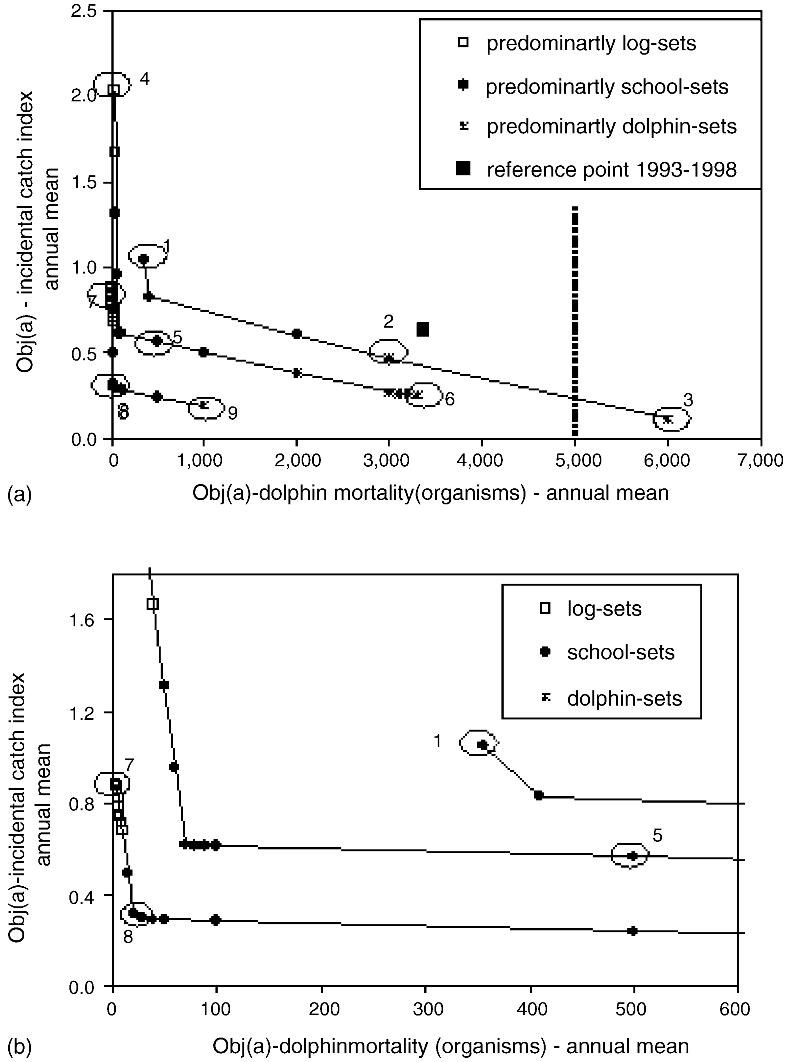

Fig. 2. (a) Slices of the policy frontier, reference point and purse-seine mode dominating the catch of each Pareto-optimal solution. Nine particular solutions are emphasized (1–9). The reference point mean values are: dolphin mortality = 3382 organisms, incidental catch index = 0.628, YFT yield = 257,700 t, longline fishery catch = 21,060 t, dolphin-set catch = 142,696 t, log-sets catch = 21,423 t, and school-set catch 72,521 t. (b) Zoom of the slices of the policy frontier to show the solutions close to zero dolphin mortality.

Along these slices of the policy frontier, reducing dolphin mortality can only be achieved by allowing higher incidental catch. Moving from one slice of the policy frontier to a higher one (i.e., increasing YFT yield) implies both higher dolphin mortality and incidental catch. That is, there is no solution which simultaneously achieves optimal values for these three objectives.

Each Pareto-optimal solution implies an optimal set of the decision variables for that particular solution (total catch and dominant fishery or purse-seine mode). Fig. 2a provides information regarding the dominant fishery and purse-seine mode required to achieve a particular solution. Only nine solutions are emphasized (1–9), for which greater details are shown in Fig. 3a–c for the purse-seining fishing modes. Even though long-

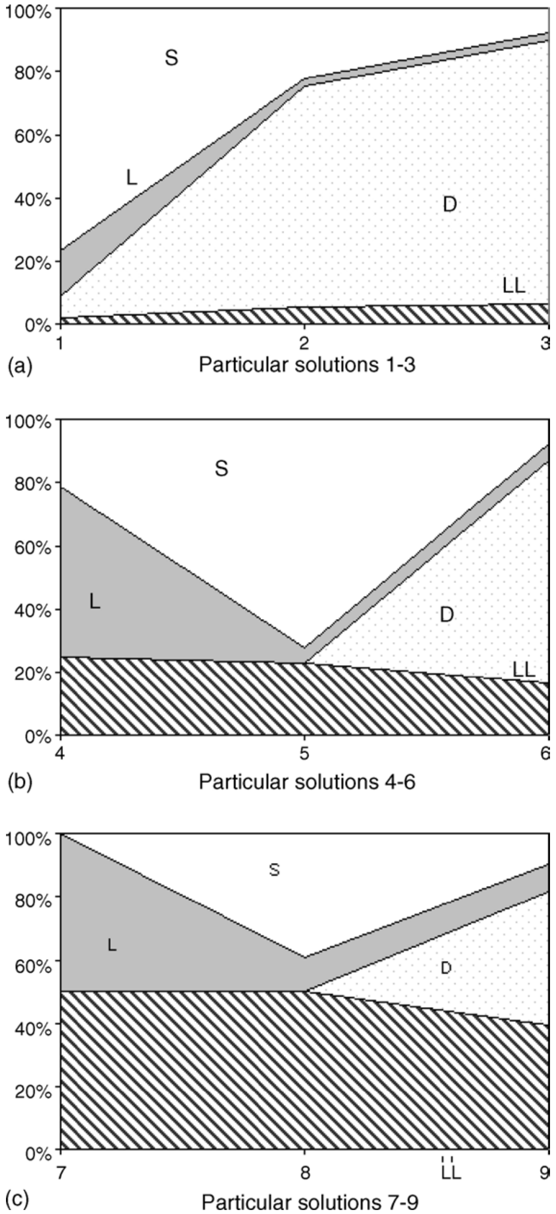

Fig. 3. Catch percentage of each fishery or purse-seine mode for nine particular solutions. S = school-sets, L = log-sets, D = dolphin-sets and LL = longline: (a) particular solutions 1–3; (b) particular solutions 4–6; (c) particular solutions 7–9.

line dominated the catch throughout the 100,000 t slice of the policy frontier, for graphic purposes the purse-seine mode with the second-highest catch was chosen for Fig. 2a (only for that slice of the policy frontier). Log-sets dominate in the upperleft segments of the policy frontier (higher values for the incidental catch index and lower for dolphin mortality), and dolphin-sets dominate in the lowerright segments (lower values for the incidental catch index and higher for dolphin mortality). School-sets tend to dominate in the middle sections, where the most obvious convexity occurs.

Only solution 3 falls out of the legal feasible sub-set. This solution achieves a mean dolphin mortality of 5996, surpassing the legal limit of 5000 dolphins per year established at the Agreement on the International Dolphin Conservation Program (AIDCP). The rest of the solutions fall within the legal feasible sub-set.

The reference point that describes the current performance of the fishery is depicted in Fig. 2a, obtained with actual mean data recorded in the period 1993–1998: dolphin mortality = 3382 organisms, incidental catch index = 0.628, YFT yield = 257,700 t, catch with longline fishery = 21,060 t, catch with dolphin-sets = 142,696 t, catch with log-sets = 21,423 t, and catch with school-sets 72,521 t (Inter-American Tropical Tuna Commission, 2000). This reference point falls within the feasible set and, as expected from a real situation, it is not located along the policy frontier.

Table 2 shows the changes of the decision variable through the time-horizon modeled for each of the three purse-seine modes. This behavior represents the optimal trajectory for these solutions, characterized by high variability in YFT catch throughout the ten years of the simulation.

Fig. 4a shows the same policy frontier but classified according to the YFT biomass level (objective d) expressed in terms of the relative biological risk index. Fig. 4b shows a better perspective of the behavior of the policy frontier and the relative biological risk, where dolphin mortality levels approach zero. There are three important noticeable trends:

(1) Along the z-axis of the policy frontier, the higher the YFT yield, the higher the biological risk. That is, these two objectives have a high degree of conflict between each other, since achieving desired levels of one (high YFT yield) produces undesirable levels of the other (a high biological risk index). Nevertheless, the biological risk is different when comparing solutions within the same slice of the policy frontier (same YFT yield), depending

Table 2
Decision variable (YFT catch in thousands of t per fishery or purse-seine mode) for Pareto-optimal solutions 1–3 (Fig. 2, YFT yield of 300,000 mt)

Year	Solution 1				Solution 2				Solution 3			
	LL	DS	SS	LS	LL	DS	SS	LS	LL	DS	SS	LS
1	0.1	0.2	36.4	128.5	0.2	52.1	34.9	28.9	25.0	96.5	34.9	79.3
2	0.1	0.4	18.2	256.9	0.4	104.3	17.5	57.9	50.0	193.0	17.5	39.7
3	0.2	0.8	9.1	215.2	0.8	208.5	8.7	115.8	25.0	386.0	8.7	19.8
4	0.5	1.6	4.7	239.6	1.6	417.0	4.4	54.0	12.5	193.0	4.4	9.9
5	0.9	3.3	9.3	232.8	3.1	208.5	2.2	108.0	12.5	386.0	2.2	5.0
6	1.9	6.5	18.7	222.5	6.3	244.5	1.1	15.7	25.0	297.2	1.1	3.7
7	3.8	13.0	37.3	226.6	12.5	323.7	0.5	31.4	12.5	145.5	0.5	7.5
8	7.5	26.1	74.7	235.3	25.0	161.9	0.3	62.7	6.3	291.0	0.3	14.9
9	15.0	52.2	149.4	330.8	50.0	134.1	0.1	125.4	12.5	175.0	0.1	29.9
10	30.0	104.3	74.7	211.7	50.0	268.3	0.1	62.7	6.3	350.0	0.1	14.9
Total	59.9	208.5	432.4	2300	149.8	2123	69.7	662.4	187.5	2513	69.7	224.6

LL: longline, DS: dolphin-set, SS: school-set, LS: log-set.

on the purse-seine mode dominating the catch. For the 300,000 t YFT yield slice, the biological risk is high with school-sets and medium with dolphin-sets. The same trend can be seen in the 200,000 t YFT yield slice, where those solutions with log-set dominance have a high biological risk, while those dominated by school- and dolphin-sets have a medium level. Finally, in the lowest YFT yield slice (100,000 t), low biological risk corresponds to solutions dominated by dolphin- and school-sets, while those dominated by log-sets show a medium biological risk. In general, biological risk is always lower for catches dominated by dolphin-sets and higher for those dominated by log-set, with intermediate levels for catches with predominance of school-sets.

(2) At a given yield level, lower dolphin mortality is associated with higher biological risk and higher dolphin mortality is associated with lower biological risk. These two objectives also show a high degree of conflict between each other. Catches in those solutions with lower dolphin mortality are dominated by log-sets and this purse-seine mode is again associated with high or medium biological risk. The opposite occurs for those solutions with higher dolphin mortality levels, dominated by dolphin-sets, which are again associated with medium or low biological risk levels.

(3) At a given yield level, higher values of incidental catch index are associated with higher biological risk, while lower levels are associated with lower biological risk levels. These two objectives do not conflict since achieving desirable levels of one also produces desirable levels of the other. Catches of those solutions with higher levels of the incidental catch index are dominated by log-sets, and again this purse-seine mode is associated with high or medium biological risk. The opposite occurs for those solutions with lower levels of the incidental catch index, dominated by dolphin-sets, which are again associated with medium or low biological risk levels.

It is important to note that, when considering the four objectives simultaneously, there is no solution that achieves the best values for all objectives. Some Pareto-optimal solutions achieve low values of the incidental catch index and low biological risk (i.e., solution 9, Fig. 2a), but high dolphin mortality and low YFT yield. Other solutions achieve high YFT yield, but they also achieve higher dolphin mortality and incidental catch indexes than those desired (solution 2, Fig. 2a), as well as medium biological risk levels. Another example are those solutions with particularly low dolphin mortality levels but extremely high incidental catch, high biological risk and medium YFT yields (solution 4, Fig. 2a).

Numerical values for the trade-offs are shown in Table 3 for some solutions of the three slices of the policy frontier. These trade-offs are given considering the cumulative values of dolphin mortality, incidental catch index and YFT yield over the 10 years of

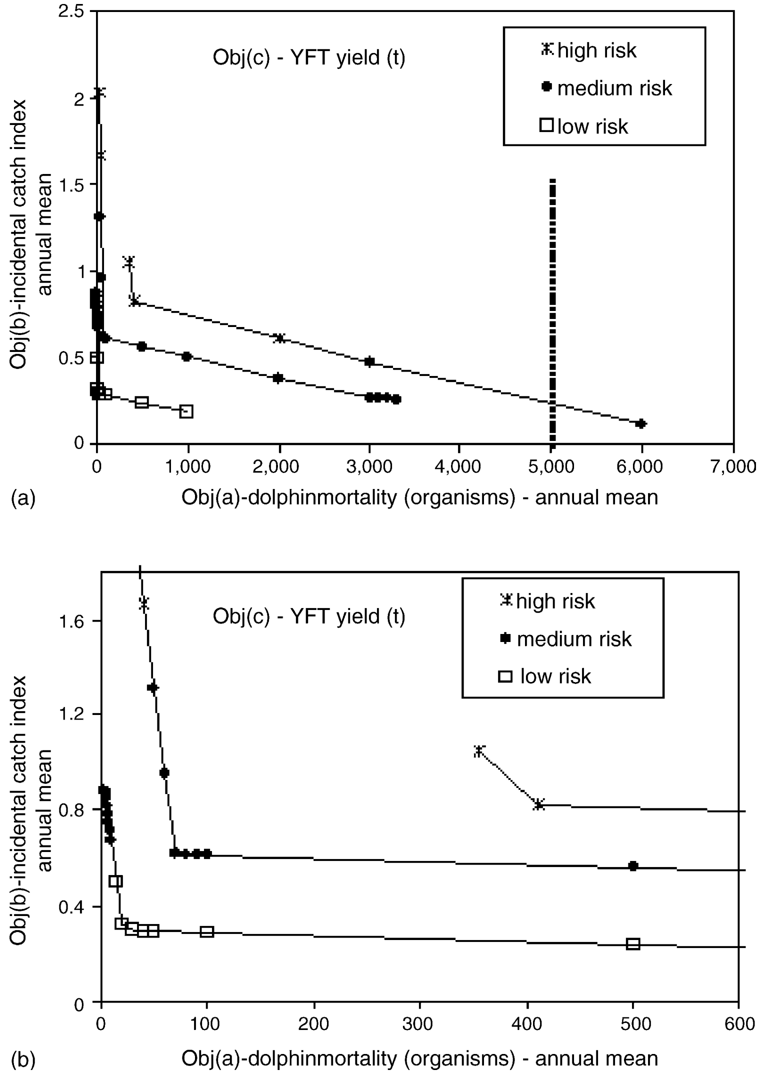

Fig. 4. (a) Slices of the policy frontier depicting the relative biological risk index based on YFT biomass levels. (b) Zoom of the slices of the policy frontier depicting the relative biological risk index based on YFT biomass levels.

simulations. Two types of trade-offs are shown: dolphin mortality and YFT yield. The first represents the increase or decrease of the incidental catch index per marginal dolphin mortality unit (number of organisms), while the second represents the increase or decrease of the incidental catch index per marginal YFT yield unit (t). These trade-offs should be interpreted as follows: at a 100,000 t YFT yield, if dolphin mortality increases from 43 to 44 (steep slope) the incidental catch index would decrease 0.03584 units, but it would decrease only 0.00012 units if dolphin mortality increases from 400 to 401 (gentle slope). Regarding the trade-offs between incidental catch index and YFT yield, if the latter increases from 1,000,000 to 1,000,001 t given a 43-dolphin mortality and an incidental catch index of 8.8, the incidental catch index would increase 0.00002068 units; however, it would increase only 0.00000067 units if YFT yield increases from 1,000,000 to 1,000,001 t given a 10,000-dolphin mortality and an incidental catch index of 1.9.

Table 3
Cumulative values (sum of the 10 years simulated) of objectives and trade-offs of the Pareto-optimal solutions

Dolphin mortality (organisms)	Incidental catch index (dimensionless)	YFT yield (t)	YFT biomass (t)	Marginals[a]	
				Dolphin mortality	YFT yield
43	8.8	1000000	4501332	−0.03584	0.00002068
100	6.8	1000000	4793351	−0.03584	0.00002068
400	2.9	1000000	5246754	−0.00012	0.00000325
1000	2.9	1000000	5196360	−0.00012	0.00000325
10000	1.9	1000000	5895591	−0.00002	0.00000067
300	20.3	2000000	2064045	−0.03584	0.00002068
400	16.7	2000000	2422976	−0.03584	0.00002068
1000	6.1	2000000	3441937	−0.00012	0.00000325
10000	5.0	2000000	4014386	−0.00012	0.00000325
30000	2.7	2000000	4906226	−0.00008	0.00000359
3562	10.5	3000000	1665681	−0.00392	0.00018
4108	8.2	3000000	1743462	−0.00015	0.00018
20000	6.1	3000000	2256998	−0.00013	0.00006
30000	4.7	3000000	3127725	−0.00013	0.00006
59964	1.1	3000000	3934433	0.00010	0.00003

[a] Units of the incidental catch index per marginal unit of dolphin mortality (organisms) and YFT yield (t), respectively.

Table 4
Incidental catch index (ICI) and its translation to number of organisms (non-target species) and t (target species) for the YFT yield of 200,000 t

ICI	Dolphin-sets		Log-sets		School-sets		Total	
	Org	*t*	Org	*t*	Org	*t*	Org	*t*
2.03	0	0	5745261	59570	393178	5423	6138439	64993
1.67	0	0	4415341	45781	623106	8595	5038447	54375
0.61	474	11	455717	4725	1337461	18448	1793653	23184
0.50	15692	357	505037	5237	966325	13329	1487054	18923
0.27	49461	1125	596063	6180	198736	2741	844259	10047

Table 5
Cumulative values (sum of the 10 years simulated) of objectives and the translation of the incidental catch index of trade-offs for the YFT yield of 200,000 t

Dolphin mortality	Incidental catch index	Translation of the index to		Trade-offs[a]	Translation of the trade-off[b] to	
		Organisms (non-target species)	*t* (Target species)		Organisms (non-target species)	*t* (Target species)
300	20.27	61384387	649933	−0.03584	108563	1149
400	16.68	50384467	543754	−0.03584	108255	1168
1000	6.11	17936529	231842	−0.00012	356	5
10000	5.02	14870542	189225	−0.00012	359	5
30000	2.73	8442591	100468	−0.00008	262	3

[a] Units of the incidental catch index per marginal unit of dolphin mortality (organisms).
[b] Number of organisms (non-target species) and t (target species) per marginal unit of dolphin mortality (organisms).

Since the incidental catch index is dimensionless, it gives decision-makers little information regarding the numbers or biomass of target and non-target species discarded. To solve this, five different values of this index for the 200,000 t slice of the policy frontier were translated to their corresponding number of discarded organisms (non-target species) or t (target species), indicating the purse-seine mode in which they occurred (Table 4). Table 5 shows the marginal cost (in terms of incidental catch) per dolphin mortality unit, that is, the equivalence of one dolphin in terms of number of non-target organisms and *t* of target organisms for different solutions.

4. Discussion

The results of this analysis provide important information to managers and other policy actors regarding the consequences of alternative fishing practices. It is particularly useful in pointing out the trade-offs associated with enforcing or relaxing the current dolphin-safe policy. The modeling approach used is prescriptive in nature, so it is useful neither to describe nor to predict the real behavior of the fishery, but rather to provide information about desirable changes in fishing practices, which might improve their performance for society. Of particular interest for the decision-making process are solutions falling along the policy frontiers, since each of these implies an efficient (in the sense of Pareto) use of the fishery given a particular preference structure.

The reference point, describing the current performance of the fishery, has moved since 1998. The trend (based on the 1998–2001 period) is towards an increasing use of log-sets, particularly those on Fish Aggregating Devices (Inter-American Tropical Tuna Commission, 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, higher yellowfin tuna yield and higher biological risk (i.e., the fishery is moving towards the upper left corner of the feasible set in Fig. 1).

Numerical results from this model suggest that further reducing dolphin mortality (from current levels) in response to dolphin-safe policy pressure, implies an increasing marginal cost in terms of incidental catches of other species, many of them endangered such as sharks and sea turtles, and YFT juveniles. It also imposes higher biological risk for the YFT stock, jeopardizing not only the sustainability YFT, buy that of the entire pelagic ecosystem. The trade-offs between dolphin mortality and incidental catch are evident in Fig. 2a and Tables 3–5.

Dolphin-set and longline catches are composed of a larger proportion of mature YFT. Log-sets catch a large proportion of smaller, immature organisms. School-sets select organisms slightly larger than log-sets (Inter-American Tropical Tuna Commission, 1989; Hall, 1996). The trend towards increasing 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 (Inter-American Tropical Tuna Commission, 2002). Although the YFT stock is believed to be in relatively good shape according to all the models used by IATTC scientific staff (Dr. Shelton Harley, IATTC, pers. commun.), a precautionary adaptive approach has been in use for several years now, closing tuna (YFT and others) fishing for specific months, areas and purse-seine modes, depending on catch levels. In 2003, a particular area (http://www.iattc.org/, IATTC's web page, visited February 2004) was closed during December, and in 2004 the whole EPO was closed for fishing during 42 days and each fishing country had to choose from one of two available harvesting periods.

If only one objective were to be taken into consideration by decision-makers, the results would change in relation to this sole objective. If minimizing dolphin mortality were selected as the main and only objective to be pursued, log-sets would be the appropriate policy instrument; however, this situation would lead to low YFT yields, very high incidental catch levels and high biological risk for the YFT stock.

If minimizing incidental catch were chosen as the sole objective by decision-makers, then dolphin-sets would be the suitable policy instrument. This situation would achieve low biological risk, but YFT yield would be low and dolphin mortality would be high (yet within the legal feasible sub-set of maximum 5000 dolphins per year).

On the other hand, if maximizing YFT yield were the main objective chosen by decision-makers, either school- or dolphin-sets would be appropriate as policy instruments. Both dolphin mortality and incidental catch levels would be higher than desired, and the biological risk would be high or medium, depending on the predominant purse-seine mode.

If, however, the sole objective for decision-makers was to minimize biological risk, either dolphin- or school-sets would be suitable, although YFT yield would be low, and dolphin mortality and incidental catch levels would depend on the predominant purse-seine mode: low dolphin mortality if school-sets are chosen and low levels of incidental catch if dolphin-sets are selected.

Dolphin-sets could, therefore, be considered appropriate policy instruments for at least three of the four objectives considered in this model (minimizing incidental catch levels, maximizing YFT yield and minimizing biological risk). The great disadvantage of this purse-seine mode would be dolphin mortality, even though it is highly monitored and is currently considered one of the great successes of international fisheries management (Hall, 1996, 1998; Joseph, 1994).

Decision-makers, however, are not single-objective oriented, especially in a fishery like this, involving at least 14 countries with competing fishing fleets and several NGOs, all working together within the IATTC. Trade-offs among objectives and decision-makers' preferences concerning the objectives would have to be considered to reach a preferred solution in terms of the policy instrument. The current model is just a simplification of the real world and the results generated should be treated as indicative of reality rather than an exact representation of actual effects, as pointed out by Pan et al. (2001).

Other facts to be considered are that fishing grounds vary in shape, size and location for the three different purse-seine modes (Inter-American Tropical Tuna Commission, 1999). They also depend on oceanographic phenomena such as the occurrence and location of upwelling, fronts, hurricanes, etc., as well as specific management schemes already in use, like those related to dolphin mortality and juvenile organisms of target species (Inter-American Tropical Tuna Commission, 1999, 2002; Joseph, 1994).

Several important variables were not considered in our model because, by definition, it is a simplification of reality. One of them is individual vessel behavior. A possible deviation of this omission is that biological risk would increase. Without considering individual behavior, each Pareto-optimal solution yield by the model is generated based on total catch by each fishery (purse-seine or longline) and its implications in terms of the management objectives. Total catch can be seen as the sum of individual catches per fishery, but if individual behavior is considered, each vessel would be a decision-maker trying to maximize its own objectives, with a strong preference towards YFT yield, i.e., profits. In this case, only the highest YFT yield slice of the policy frontier would be generated. As in many fisheries, however, vessels tend to work in groups and share information, therefore increasing fishing efficiency (Gaertner and Dreyfus, 2004). Abundance is then overestimated, directly affecting the biological risk level predicted by the model. The impacts would be lower if effort is mainly directed towards dolphin-sets and higher if directed towards log-sets, given the trend of the biological risk and the tuna sizes caught in each fishery (Vaca-Rodríguez and Dreyfus-León, 2000).

Another variable not taken into account in this version of the model is the discount rate (the interest rate used in determining the present value of future cash flows). In an earlier version, present value of net revenues was considered an objective instead of catches. The historical trend of catches throughout the years simulated was very different when positive discount rates (present income is more important than a similar one in the future) or negative ones (future income is more important than a present one) were used. The trend with positive rates was towards obtaining catches at the beginning of the simulated period, mainly small tunas with log-sets, with almost no dolphin-sets and no catches at the end of the period. The catch trend with negative rates was quite different, with low catches at the beginning of the simulated period and catches of large tunas with dolphin-sets at the end of the period. The magnitude of the present value of net revenues was almost half with positive rates and almost 10-fold with negative rates, compared with a standard run with a 0% discount rate. Negative discount rates were interpreted as a way of investing in natural capital.

Using the model described in this analysis as reference (we do not claim that it is the most ideal or the only possible one), two observations can be made. First, it is possible to change current practices (with fixed technology) and simultaneously improve all objectives (a Pareto improvement), for instance, moving down from the reference point (Fig. 2a) to the 300,000 t policy frontier, it is possible to obtain a greater catch, the same dolphin mortality and less incidental catch and biological risk. Second, once the policy frontier is reached, any objective can only be improved at the expense of at least one of those remaining.

It is important to keep in mind that the location, shape and size of the feasible set, and those of the policy frontier, depend on how the fishery problem is modeled (Ballenger and McCalla, 1986). A policy frontier for a given fishery problem can modify its shape or size with changes in technology, policy instruments, institutional constraints, preferences, environmental conditions, etc.

Different mathematical approaches have been used to generate policy frontiers in models related to fishery management, some much more complex than others (inter alia, Pan et al., 2001; Leung et al., 2001; Mardle and Pascoe, 1999; CEMARE group, http://www.port.ac.uk/research/cemare/publications/researchpapers/). Several computer softwares are also available to generate policy frontiers, and though the type or amount of objectives modeled may vary – and thus the results/implications from each model – all agree that trade-offs are not linear and are key elements to be considered by decision-makers, and that behind each policy frontier lies a huge amount of truly valuable information to both analysts and decision-makers.

Management objectives are usually in conflict among themselves and present non-linear trade-offs (Sylvia and Enríquez-Andrade, 1994; Pan et al., 2001; Leung et al., 2001), as found in this model. There is no single solution to attain desirable levels of all of them simultaneously. Policy frontiers have been shown to aid decision-makers to understand this situation, and thus provide a new perspective for fishery management policies. This type of multi-objective models differ from any other fishery models in that they attempt to consider a broader perspective of the fishery with the aim of attaining better management policies.

Regarding the dolphin mortality management measures, it is important to mention that there are currently two different dolphin-safe labels. One of them automatically considers non-dolphin-safe all the fish caught on any fishing trip in which even only one dolphin-set occurs, regardless of the outcome in terms of dolphin mortality or injuries, or the proportion of log- and school-sets on that particular trip. This definition is the one currently valid in United States legislation. The other definition considers non-dolphin-safe only the fish caught in the particular sets in which dolphins were killed or injured. This last definition is the result of international negotiations resulting in the AIDCP (http://www.iattc.org/, IATTC's web page, visited February 2004), and is the dolphin-safe-AIDCP label. The implications of the dolphin-safe policy on biological risk were made in relation to the first definition, since no dolphin-sets are allowed, while according to the second definition, dolphin-sets are allowed as long as there is no dolphin mortality or injury.

In summary, decision-makers should analyze trade-offs and policy frontiers to be aware of the potential impacts of their decisions, in particular in relation to the current dolphin-safe policy. Until now and without considering technological changes, dolphin-sets could be considered appropriate policy instruments for at least three of the four objectives considered in this model. Dolphin-mortality, YFT catch and, to some extent, biological risk are managed through international programs (Inter-American Tropical Tuna Commission, 2002); however, the management of incidental catch has only recently started, based on the recommendation to avoid catch of non-target organisms and, if caught, they should be released alive, with no penalty if ignored (Inter-American Tropical Tuna Commission, 2002). Therefore, emphasis should be placed on minimizing incidental catch by increasing its relative weight in decision-makers' preferences. Using the precautionary principle, log-sets should be limited since their incidental catch is higher and involve many species, including YFT and other species with different levels of endangered status. Finally, if any technological improvement is achieved, the model should be adjusted.

Acknowledgments

We thank the Mexican National Science and Technology Council (CONACyT) for the credit-scholarship given to one of the authors for the development of this study. We also thank two anonymous reviewers for their comments and suggestions.

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