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Bioeconomic Analysis of Management Options for Tropical Fisheries Using a Bicriteria Programming Model

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Abstract *A possible approach to the management of the multispecies multigear fishery in a developing country was explored. The small pelagics fishery in central Philippines was analyzed in three stages. A dynamic pool model represented the dynamics of the stocks. The optimal allocation of catch across competing fleets was modeled having regard for the pursuit of two conflicting objectives, maximizing employment and fishing profits. Alternative management schemes were then explored.*

On the basis of the criteria used, the optimal fleet size was a small fraction of the existing fleet size. Calculation of increased target yields through regulation of fishing mortality and selectivity showed that the increase in optimal fleet size would be moderate because the current level of exploitation is close to that producing the maximum yield-per-recruit. An agenda for exploration of further management alternatives appropriate to the social and economic policy objectives of a developing country is discussed.

Keywords bioeconomics, Philippines, small pelagics, multicriteria decision making, fishery economics, fishery management, tropical fisheries

Introduction

Tropical fisheries are complex resource systems. Fish resources are mostly multispecies and the degree of biotic diversity and interaction between species is more complex in tropical environments than in their temperate counterparts (Pauly 1989). There tend to be significant technological interrelationships in the harvesting process; most of the large number of fishing gears being used have limited selectivity.

Most tropical fisheries are in developing countries where there are serious economic and social problems. Fish resources are used to achieve various ends. FAO (1983) classifies the objectives in fishery exploitation into three groups—

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maintaining the resource, economic performance and equity (social needs). In addition, other authors (Charles 1988; Regier and Grima 1985; Copes 1969) include the following objectives: food production, maintaining employment for fishers and the well-being and viability of fishing communities. Often, the objectives are noncomplementary and this poses difficulties in managing the resource.

There is a pressing need to manage tropical fisheries owing to pervasive overexploitation. However, tropical fishery resource systems need to be well understood before attempts are made to design management programs. The multispecies multigear nature of tropical fisheries and the pursuit of several objectives in their exploitation present difficulties in the formulation of appropriate management plans. This paper attempts to develop a methodology that takes into account such characteristics of the fishery. A multicriteria linear optimization model as described by Evans (1984) is then applied in a pelagic fisheries context.

Methodology

The model that is formulated consists of several sub-models that accomplish the following tasks: the estimation of fishery yields, the allocation of these yields to competing fleets and the analysis of alternative management schemes. The biological model used to describe stock dynamics is an adaptation of the dynamic pool model developed by Beverton and Holt (1957). The yield from a cohort of fish, t, can be estimated with the following formula

$$Y_t = FR\exp(-M(t_p - t_r))W_\infty \sum_{n=0}^{3} \frac{\Omega_n \exp(-nKt_p)}{F + M + nK} \tag{1}$$

where F is the fishing mortality, M is natural mortality, t_p is the age-at-first-capture, t_r is the recruitment age, K is a curvature parameter which indicates the speed at which fish approaches the maximum possible weight attainable (W_∞), R is recruitment and Ω_n is equal to 1, −3, +3, −1 for n equal to 0, 1, 2, 3, respectively. In the above equation t_0 is assumed to be zero.

The above equation gives the yield for each species over the exploitable life span of a given year-class. It also gives the annual yield for all cohorts if recruitment is assumed constant and yearly. Of the parameters determining the yield-per-recruit, only F and t_p may be manipulated and are considered policy variables. Most of the applications of the Beverton-Holt model of stock assessment are on temperate and sub-temperate fishery stocks. Pauly (1989) noted that the M/K ratio is generally higher for tropical stocks than for temperate stocks. This has implications with regard to the kind of management advice that can be designed for the fishery when using such stock assessment models in tropical environments.

Most tropical fisheries support a large number of gears whose biological impact and economic performance vary. In this regard an important task is the determination of the optimum size of each fleet that can be supported by target yields for the fishery. In the process of determining the optimal fleet size the goals of fishery management need to be considered. Multi-objective mathematical programming may be employed to determine the desirable allocation of fishery yields while pursuing several fisheries management objectives.

Following Evans (1984), the allocation problem is that of selecting the values of a vector of decision variables $f = (f_1, f_2, \ldots, f_n)$ in order to optimize p ($p \geqslant 2$) objective functions $h_1(f), h_2(f), \ldots, h_p(f)$ subject to a constraint matrix imposed on the decision variable expressed as $f \in \phi$. Mathematically, the allocation problem is stated, in general form, as

$$\text{Max } h(f) = [h_1(f), h_2(f), \ldots, h_p(f)] \quad (2)$$

$$\text{subject to } f \in \phi$$

Here, f is the vector of standardized fishing efforts for the n fishing fleets and ϕ represents the set of feasible values of f. It is implicit in the constraint matrix that f should be nonnegative.

A solution which maximizes each of the objective functions simultaneously is called a superior solution. Since at least two objectives in a multi-objective programming problem are typically conflicting in nature, a superior solution rarely exists. Hence, the concern is on generating the set of efficient or nondominated solutions. There are several methods of generating the set of nondominated solutions. One method, the weighting method, transforms the multi-objective problem into a single objective programming format and then, by variation of the parameters used to effect the transformation, the set of nondominated solutions can be generated. A complete listing and description of methods to generate the nondominated set are found in Goicoechea *et al.* (1982).

Often, there is a large number of efficient solutions and it is necessary to narrow them to a more manageable number of alternatives. However, the methods for reducing the number of efficient solutions involve an articulation of the preferences of the decision maker. To avoid any subjectivity in the modeling process, an evaluation of a number of extreme points may be done and their characteristics compared. Some sort of a "menu" may be prepared from which the decision maker chooses the "desired" allocation. This becomes clearer in later sections.

To date, the applications of multi-objective programming to fisheries analysis are rather few. One of the earlier works is by Bishop *et al.* (1981) although they just outlined the procedure. Kendall (1984) developed a multi-objective approach to regional resource management planning but without an empirical application. Healey (1984) also developed a multi-objective fisheries model by considering conservation, economic development and social development goals. He used multi-attribute analysis, specifically, a linear utility model to assess the optimality of alternative yield strategies. He then applied the model to the New England herring fishery and the Skeena River salmon fishery. More recently, a more complicated approach was employed by Diaz-de-Leon and Seijo (1992).

An Application of the Model

The model developed here is applied to the small pelagics fishery of Guimaras Strait and the Visayan Sea in central Philippines. The fishery is multispecies multigear. Based on Philippine fisheries policy several objectives are pursued in its exploitation. The application of the model considers only two management objectives explicitly; hence the problem becomes a special case of multi-objective programming. There are several advantages of a bicriteria programming model. First, numerical results may be easily derived and the tradeoffs between objectives may be clearly shown. Second, the procedure can be run in most linear programming packages and, hence, can be easily applied without use of specialized computer packages. More importantly, such formulation is adequate in representing the fisheries problem at hand.

Among the goals or objectives in fisheries exploitation outlined in Philippine fisheries policies are the following: maximizing economic utilization of fishery resources without endangering the sustainability of resource base, attaining self-sufficiency in fish supply, and achieving equitable distribution of benefits. The formulation of fisheries management objectives for the small pelagic fisheries of Guimaras Strait and the Visayan Sea follows from the above statement of policy. Hence, the following objectives were selected for analysis in this paper: maximization of fishing enterprise profits (in respect of capital inputs), maximization of fishing employment (in respect of labor inputs), catch optimization (in respect of resource utilization), and provision of equal access to competing groups of fishers (in respect of equity).

Of the four fishery management objectives, the first two objectives (maximization of profits and maximization of employment) remain as explicit objective functions while the others are captured in the constraints. The rationale is that the other two objectives (catch optimization and equity) may be more conveniently expressed as constraints. Since the model considers only two objectives explicitly, it may be considered a bicriteria programming model. Subsequent analyses shall focus on the two explicit objectives.

The two objectives in the programming model are as follows:

$$\text{Max } h_1(f) = \Sigma_i \Sigma_j \Sigma_s p_i q_{ijs} f_{js} - \Sigma_j \Sigma_s c_{js} f_{js} \tag{3}$$

$$\text{Max } h_2(f) = \Sigma_s \Sigma_j l_{js} f_{js} \tag{4}$$

Equation (4) specifies the maximization of fishing profits where *i* denotes species of fish and *j* the fleet (gear) while *s* is the sector (''municipal'', *i.e.*, artisanal vessels, or ''commercial'', *i.e.*, larger vessels). P_i is the unit price of the *i*th species and c_{js} is the unit cost of standardized effort for gear *j* in sector *s*. The objective of maximizing employment in the fishery may be expressed in equation (4) where l_{js} is the labor component for every unit of standardized fishing effort. The constraints imposed in the allocation process are:

$$H_i = \Sigma_j \Sigma_s q_{ijs} f_{js} \leq Y_i \tag{5}$$

$$f_{i1}/f_{j2} = CR_j \text{ for all j, and}$$

$$\Sigma_j f_{j1}/\Sigma_j f_{j2} = CR \tag{6}$$

$$f_j \geq \min(f_j) \tag{7}$$

In equation (5), catches for each species are limited to the biological potential of the resource. Total catch (H) for a given species, *i,* is the sum of the catches (or fishing mortalities) generated by all fleets 1,2, . . . , *i* in each of two sectors *s* (commercial and municipal). It must be less than or equal to Y_i, the target yield for each species group. For the base run of the model, target yields for each species group are equated to the average annual landings from 1978–1987, the period for which data on landings in the study site are available. Hence, the biological sub-model is not employed in the base run but only in the subsequent analysis of regulations on fishing mortality and mesh sizes.

Equity constraints are captured in equation (6). Since fishery rationalization entails an inevitable displacement of vessels and fishers, an important issue to resolve is from which fleet and sector (municipal and commercial) this reduction should come. For equity purposes it is considered that management regulation should not favor any group of fishers. Hence in the allocation process the current proportion of fishing effort exerted by the two sectors (f_1 and f_2) in each fleet (CR_j) and for the entire fishery (CR) should be maintained.

Equation (7) imposes minimum fleet size constraints to prevent the elimination of certain fleets in the optimal solution. The elimination of any fleet reduces the flexibility in adapting to changes in the course of managing the fishery in the future. Five fishing fleets or gears were considered in the model, namely: Danish seine, purse seine, encircling gill net, trawl and drift gill net. The first four fleets have both artisanal and commercial sectors while the drift gill net fleet consists only of artisanal fishers.

The q_{ijs} in equation (5) is the catchability coefficient for species *i* taken in fishery *j* and by sector *s*. In a mixed species fishery, the q_{ij} or the coefficient of proportionality between landings and fishing effort varies across q_{ijs} species and fleets, owing to differences in the availability of the various species and their vulnerability to the gear.

Fishing effort captured in the f vector is standardized. It is a production function involving fishing inputs, labor (measured by crewdays—CD) and capital (represented by the gross tonnage of the vessel—GRT). Dummy variables are added to include seasonal effects. This was done by dividing the data generated during a one-year monitoring of fishing operations in the study area into the four "seasons" identified by the Philippine meteorological bureau based on wind direction and velocity. The seasons are pre-monsoon (May–June), peak monsoon (July–September), post-monsoon (October–November), and calm (December–April). A Cobb-Douglas specification is selected and the fishing effort index is expressed as follows:

$$f = e^{\beta 0}(GRT)^{\beta 1}(CD)^{\beta 2}\exp(\Sigma_i \sigma_i S_i) \tag{8}$$

where f is standardized effort, β_is and σ_is are the parameters to be estimated and S_is are the seasonal dummies.

Although the small pelagics fishery is exploited by a large number of gears, only five are included in the model. These are the Danish seine, encircling gill net, purse seine, trawl and gill net fleets. The combined landings of these gears are at least 80% of the total catch for each small pelagic species group specified below. The small pelagics fishery draws on seven major families and in each family are several species.

The following species accounted for the largest share in each category of small pelagics: *Sardinella gibbosa* (sardines), *Rastrelliger brachysoma* (mackerels), *Se-*

laroides leptolepis (crevalles), *Stolephorus indicus* (anchovies), *Decapterus macrosoma* (round scads), *Dussumieria acuta* (round herring), *Selar crumenophthalmus* (big-eye scads). An important assumption with regard to the population dynamics parameters is that of knife-edge selection of the sample gear. The parameters specified in the Beverton-Holt equation were estimated by Padilla (1991) and are reproduced in the top portion of Table 1.

Results and Discussion

Efficient Allocation of Fishing Effort: Base Case Results

The Interactive Mathematical Programming System (IMPS) (Love and Stringer 1987) was used. The "hybrid" method (Chankong and Haimes 1983)—the combination of the weighting and constraint methods—was applied in generating noninferior solutions. The complete bicriteria programming model is in the appendix. We shall focus the succeeding discussions on the two explicit objectives while the implications of the implicit objectives (constraints) to the optimal solution are discussed in the section on shadow values.

Target yields were set equal to the average annual landings for the period 1978–1987 for the base case model (Table 2). The corner or pivot points of the feasible region in decision space, *i.e.*, in terms of the composition of fleet, are first identified. From these pivot points, the efficiency frontier is derived in objective space, *i.e.*, in terms of the values of the objective functions. The feasible region and the efficiency frontier, drawn in objective space, show the trade-offs between the two explicit objectives (Figure 1). The frontier indicates where the fishery can operate optimally depending on the desired combination of profits and employment. No specific point will be suggested as such decision is political. Instead, a "decision menu" will be presented to the decision maker from which a desired point may be chosen. The extreme points of the efficiency frontier and one intermediate point may adequately describe the set of efficient solutions, hence these constitute the menu. The characteristics of each menu item are described below.

The decision menu consists of corner points on the efficiency frontier A and C and the intermediate point B, all of which are corner points. Point A corresponds to the explicit policy objective of profit maximization (P_{max}) where total fishery profits amount to 416.9 million pesos[1] (P416.9 M) and incidental employment generated is 3.50 million crew-days. Point C, on the other hand, is the scenario of employment maximization (L_{max}) where total crewdays is equal to 3.93 million crew-days and profits equal P374.5 M. Point B is where the values of profits and employment are in between their respective minimum and maximum values. Between P_{max} and B, and B and L_{max}, respectively, profits decrease by 2.72% and 7.64% while labor utilization increases by 3.98% and 7.96%.

The output from the bicriteria programming model is the standardized fishing effort for each fleet which are then converted into the following variables: total catch, number of vessels, investments in fishing assets and the number of fishers, given information on the temporal operations of sample vessels. The three points

[1] Average conversion rate for 1988–89 was US$ 1 = P 21.42.

Table 1
Estimates of Biological and Technological Parameters for Small Pelagic Fish Species of Guimaras Strait and the Visayan Sea, Philippines

	Sardine	Mackerel	Crevalle	Anchovy	Round Scad	Round Herring	Big-Eye Scad
A. Basic parameters							
Mean asymptotic length (cm)	20.00	23.10	20.50	14.72	24.50	22.00	21.00
Mean asymptotic weight (yr)	106.65	217.52	148.76	29.05	205.15	135.43	102.19
Body growth coefficient (K)	1.00	1.00	0.55	0.90	0.96	0.80	0.89
Age at recruitment (yr)	0.470	0.393	0.630	0.249	0.511	0.251	0.779
Age at first capture (yr)	0.776	1.038	1.023	0.765	0.790	0.817	1.650
Natural mortality (M)	2.00	1.92	1.34	2.05	1.84	1.68	1.83
Fishing mortality (F)	3.76	3.06	0.84	0.45	3.81	3.01	3.58
B. Yield-per-recruit estimates (gm)							
Current pattern	8.73	13.79	6.00	0.49	18.38	6.01	7.12
$F_{0.1}$ mortality	7.76	13.07	6.70	1.08	16.15	5.34	6.76
F_{max} mortality	9.28	16.98	7.68	1.28	19.07	6.18	9.46
10-cm length	8.75	15.09	5.74	0.56	16.76	5.95	12.94
12-cm length	8.32	15.62	4.82	0.56	18.20	5.95	12.71
14-cm length	6.67	14.72	3.43	0.56	18.16	5.27	10.80

Table 2
Target Yields (Tons) for the Various Small Pelagic Fish Species of Guimaras Strait and the Visayan Sea

Species Group	Ave. Annual Landings (Base Model)	Target Fishing Mortality		Target Length-at-First-Capture		
		$F_{0.1}$	F_{max}	10 cm	12 cm	14 cm
Sardine	28,486	25,350	30,315	28,591	27,183	21,789
Mackerel	22,693	21,509	27,943	24,833	25,708	24,224
Crevalle	16,079	17,967	20,595	15,392	12,931	9,209
Anchovy	6,156	13,540	16,048	7,071	7,071	7,071
Round scad	6,931	6,088	7,189	6,319	6,861	6,846
Round herring	4,660	4,139	4,790	4,608	4,610	4,084
Big-eye scad	5,127	4,868	6,813	9,319	9,153	7,778
Total yield	90,132	93,461	113,693	96,133	93,517	81,001

on the efficiency frontier are compared with respect to these variables. The values are found in the first column of figures in Table 3.

The point L_{max} offers the highest catch at over 76,000 tons although the difference in catch with the other corner points is only a few million tons. The catch is valued at about 931.78 million pesos at P_{max} and 975.24 million pesos at L_{max}. The target yields are not fully utilized at the various points of the efficiency frontier. At P_{max}, the limiting species are sardine, mackerel and anchovy while at L_{max} these are sardine, mackerel and crevalle. Less than half of the target yields for round scad, round herring and big-eye scad are utilized at all corner points on the efficiency frontier. However, that part of target yields not caught by the fleets included in the model does not represent waste to the extent that these are

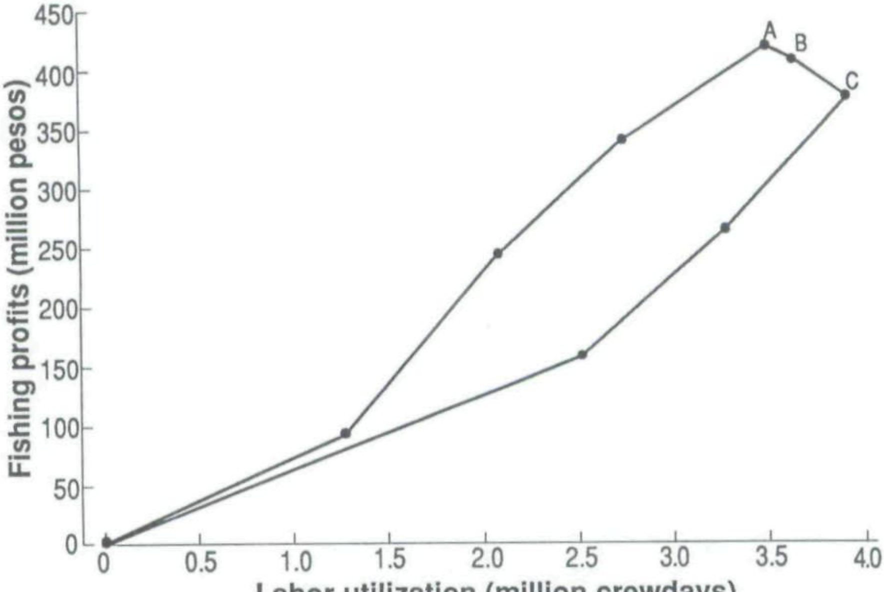

Figure 1. Feasible region in objective space: base case model

Table 3
Major Indicators of Fishery Performance for Various Regulations on Fishing Mortality (F)

Item	Base Case Model	Fishing Mortality		Percent Change from Base	
		$F_{0.1}$	F_{max}	$F_{0.1}$	F_{max}
Fishing profits (mil. pesos)					
P_{max}	416.87	397.17	517.37	−4.73	24.11
Intermediate point	405.51	376.27	489.15	−7.21	20.63
L_{max}	374.55	330.17	436.82	−11.85	16.63
Employment (mil. crewdays)					
P_{max}	3.498	3.164	3.937	−9.55	12.55
Intermediate	3.638	3.421	4.283	−5.98	17.73
L_{max}	3.927	3.852	4.773	−1.92	21.53
Number of fishermen					
P_{max}	25,845	20,345	24,844	−21.28	−3.87
Intermediate point	29,734	27,502	34,510	−7.51	16.06
L_{max}	31,616	30,305	37,691	−4.15	19.21
Total catch (tons)					
P_{max}	73,853	69,960	86,696	−5.27	17.39
Intermediate point	72,335	67,204	82,974	−7.09	14.71
L_{max}	76,027	72,671	89,180	−4.41	17.30
No. of vessels					
P_{max}	4,795	3,124	3,623	−34.85	−24.44
Intermediate point	6,168	5,650	7,034	−8.40	14.04
L_{max}	6,726	6,481	7,977	−3.64	18.60
Gross tonnage					
P_{max}	10,527	9,700	12,045	−7.86	14.42
Intermediate point	10,600	9,835	12,228	−7.22	15.36
L_{max}	11,056	10,514	12,998	−4.90	17.57
Total capitalization (million pesos)					
P_{max}	256.07	219.45	282.13	−14.30	10.18
Intermediate point	275.16	254.59	329.52	−7.48	19.76
L_{max}	267.45	243.13	316.30	−9.09	18.26

caught by the other fleets not included in the model. This, however, hinges on the extent of selectivity of the rest of the fishing gears.

There exist surplus vessels in the Danish seine and trawl fleets in both commercial and municipal sectors while more vessels are required over their current levels for the rest of the fleet. A transfer of the excess vessels from the Danish seine and trawl fleets to other fleets can only partially offset the significant reduction in the number of vessels in other fleets at each corner point. Along this line, the results of this regional study on small pelagics support the findings of Dalzell *et al.* (1987) in a nationwide study on the small pelagics fishery.

The preceding discussion shows that there are excess inputs in the fishery. Such is not an aberration as economic theory predicts that an open-access fishery has a tendency to attract input resources, especially capital, beyond what is optimal. The small pelagics fishery in its present state is not an exception. The estimated investment in fishing equipment for the nine fleets is currently about 614 million pesos, more than half of which is accounted for by the Danish seine fleet. Indeed the corner points of the efficiency frontier prescribe capital resource withdrawal from the fishery by as much as 52% of the present level.

The resulting distribution of fishers across fleets maximizes labor utilization (crewdays) as specified in the employment objective. The fishery currently provides part-time and full-time employment to about 76,000 fishers from the provinces of Iloilo and Negros Occidental. (On top of this number are fishing operators, shore-based workers, fish traders and other allied workers who depend largely on the fishing industry for employment). The points on the efficiency frontier, however, call for a considerably smaller number of fishers. Up to 50,375 (66%) of the current number of fishers will be displaced from the fishery or conversely 34% (25,845) will remain in the fishery[2]. This occurs at P_{max}. The largest number of fishers that may be optimally accommodated is 31,616 (41.5% of total) which corresponds to L_{max}.

The displacement of a large number of fishers creates the greatest difficulty but is the inevitable consequence of rationalizing the fishery. Although employment-sharing arrangements have been observed in the study area, the employment effects of such would not be substantial. At most, such arrangements could only provide temporary employment to displaced fishers but at the expense of reducing the length of participation of those left in the fishery. However, there are other possible adjustments, *e.g.*, regulating other components of fishing effort, that may be implemented to reduce the negative employment effects of rationalization.

Shadow Values

Of interest at this point is the determination of the effects of relaxing the binding constraints (or implicit objectives) on the value of the objective functions. The shadow value, which is the amount of change in the objective function per unit change in the binding constraint, measures this effect. For the constraint on target yields (biological constraints) the shadow values are computed for two policy options: exploiting the fishery where profits are maximized or where employment is maximized. In each policy scenario the effects on total profits and total employment are assessed. The shadow values for the biological constraints are listed in Table 4.

In the case where the resource manager opts to exploit the fishery where profits are maximized, increasing target yields for both sardines and mackerels would increase industry profits and employment. However, there is a tradeoff between profits and employment when relaxing the target yield for anchovy; each unit of increase in target yield would increase industry profits by 6.05 pesos but will decrease employment by 0.075 crewday. Where the policy objective is to maximize employment, the tradeoff between profits and employment occurs when the target yield for crevalle is changed. The figures in Table 4 also show that increasing the target yield for mackerel would have the biggest impact on industry profits and employment in each of the two policy scenarios.

We also investigate the impacts of relaxing the equity constraints on the two policy scenarios but only on the value of one objective—either profits or employment. The shadow values are listed in Table 5. The interpretation of the negative shadow values of the proportionality constraints when the policy objective is profit maximization should be clarified. From equation (6) the proportionality

[2] Optimal investment is underestimated if the unutilized yields of some species are harvested by other fleets not included in the model.

Table 4
Shadow Values of the Biological Constraints for the Base Run Under Two Policy Scenarios

Policy Scenario	Constraint on Target Yield for Species Group: Sardine	Mackerel	Crevalle	Anchovy	Round Scad	Round Herring	Big-eye Scad
A. Maximizing fishery profits							
Change in total profits (pesos)	3.87	13.34	n.a.	6.05	n.a.	n.a.	n.a.
Change in total employment (crewdays)	0.025	0.129	n.a.	−0.075	n.a.	n.a.	n.a.
B. Maximizing fishery employment							
Change in total profits (pesos)	3.737	16.543	−6.932	n.a.	n.a.	n.a.	n.a.
Change in total employment (crewdays)	0.027	0.0956	0.065	n.a.	n.a.	n.a.	n.a.

n.a. = not applicable, constraint is not binding.

Table 5
Shadow Values for the Proportionality and Minimum Fleet Size Constraints Under Two Policy Scenarios

	Policy Scenario	
	Profit Maximization	Employment Maximization
Constraint	Change in Total Profits (Pesos)	Change in Total Employment (Crewdays)
A. Proportionality Constraints		
Danish Seine	−3.5901	0.1314
Encircling Net	−2.8597	0.1207
Purse Seine	−4.5927	0.1276
Trawl	−4.8551	0.1890
All Fleets	4.1754	−0.1421
B. Minimum Fleet Size Constraints		
Danish Seine	−1.4365	n.a.
Encircling Net	n.a.	n.a.
Purse Seine	n.a.	n.a.
Trawl	n.a.	n.a.
Drift Gill Net	n.a.	−0.2586

n.a. = not applicable, constraint not binding.

constraints specify an acceptable ratio between the commercial and municipal fishing effort in each fleet and for the entire fleet. In the linear programming formulation, the constraint is transformed into $f_{i1} - (CR_j)f_{j2} = 0$. Thus, relaxing any of these constraints would mean a larger allocation to the commercial sector (f_{i1}) relative to the municipal sector (f_{j2}) in any given fleet. The negative shadow values for the four fleets would decrease total fishing profits if the policy objective is maximizing fishing profits. The only exception is for the entire fleet which has a positive shadow value. Where the policy objective is employment maximization, relaxing the same constraints implies the opposite effects, *i.e.*, such will increase fishing employment. For the minimum fleet size constraints, only one constraint is binding in each policy scenario.

Limitations of the Model

We should emphasize at this point that the fishery management prescriptions were derived from a bioeconomic model of the fishery wherein some simplifying assumptions had to be made. The general modelling approach[3] is static and deterministic. The model is "compartmentalized" with no feedback among the submodels. The output from the model may be considered "ballpark" figures in view of these assumptions.

An important specific assumption is the linearity of the objectives and constraints in the multicriteria decision framework. In each fleet, each unit of standardized fishing effort is considered to represent a constant number of crewdays

[3] Some of these major assumptions can be relaxed using a simulation-optimization approach; however, this is at the expense of a higher degree of complexity in model building and analysis.

of employment. Total employment in each fleet for any time period, then, is expressed as the product of the units of standardized fishing effort produced and the constant number of crewdays represented by a standardized unit of fishing effort.

With respect to the constraints, the catchability coefficients are also assumed constant over the range of possible values of fishing effort. It is conceivable that as the optimal size of a given fishing fleet increases the catchability coefficients decrease due to increasing competition and vice versa. Moreover, the assumption of constant catchability coefficients implies their density-independence. Some empirical studies, *e.g.*, of the California sardines purse seine fishery (MacCall 1976), show that the catchability coefficients for small pelagic fishes are inversely related to population abundance. To investigate the impacts of possible mis-estimation of the catchability coefficients, some sensitivity analyses on these parameters were performed with the policy scenario of maximizing employment. The results show that decreases (increases) in catchability coefficients by 5% and 10% in the Danish seine, purse seine and trawl fleets increases (decreases) the optimal number of fishers by 4.0% (3.6%) and 8.4% (6.9%), respectively.

The biological, technological and economic parameters used in the application of the model were derived from data collected during a year-long monitoring of fishing activities. The period covered (November 1988 to October 1989) is assumed to be a representative year. In particular, the estimated fishery yields are sensitive to the biological parameters as will be shown in the succeeding discussions. The following section which assesses the impacts on fishery indicators of various regulatory scenarios affecting target yields may be looked at as sensitivity analyses of the biological parameters.

Analysis of Alternative Fisheries Management Schemes

The fishery regulations analyzed in this section (regulations of F and t_p) may be considered complementary to a licensing scheme. The latter may be viewed as the primary regulatory scheme for the fishery, while the former are instruments that may be implemented to "fine tune" the fishery to the desired status.

Fishing Mortality Regulations

Regulations targeting two particular levels of fishing mortality are examined. The first aims at $F_{0.1}$ mortality, which corresponds to an effort level at which the marginal yield-per-recruit (from an additional unit of effort) is 0.1 of the yield-per-recruit at very low levels of fishing. The basis of $F_{0.1}$ is arbitrary. Its merit is that it is conservation oriented by comparison with a fishing strategy aiming at maximum (sustainable) catches. An alternative fishing mortality target is F_{max}, which corresponds to the fishing intensity that gives the maximum yield-per-recruit for each species. However, F_{max} may not be an appropriate target for the small pelagic stocks as it occurs at a high fishing mortality. This may lead to extremely low stock biomass and to recruitment failures if there is a strong stock-recruitment relationship. Nevertheless, F_{max} is often regarded to be a management strategy worth considering.

The estimated yield-per-recruit for the various species at $F_{0.1}$ and at F_{max} are listed in the bottom part of Table 1 while the target yields are in Table 2. Total target fishery yield corresponding to $F_{0.}$ is 93,461 tons while at F_{max} it is 113,693 tons. While these are greater than the current fishery yield of about 90,147 tons, the yields of species (sardines and mackerels) which are binding biological constraints in the allocation model have actually declined, but only at $F_{0.1}$. The largest increase in yield is for anchovy since current exploitation gives a very low yield-per-recruit which is less than half of that at $F_{0.1}$ and at F_{max}.

The values of the key indicators (Table 3) have actually declined for $F_{0.1}$ because of the reduction in yields of the constraining species. For F_{max} the values have generally increased compared to the base case figures. Hence, the two regulations of fishing mortality cause changes in the optimal composition of the fleet. A more interesting result is that in the process of maximizing fishery profits or labor utilization in the fishery, neither of the yields corresponding to the two target mortality rates can be obtained simultaneously across species. As in the base model, at least two species are fully exploited while there are surpluses in some species.

The efficiency frontiers are plotted in Figure 2. Only the frontier is drawn to show the full extent of the shifting. The two regulations increase the range of efficient points although the number of corner points is not changed. This means that the decision makers have a wider range of choices particularly at F_{max} which represents a substantial increase in profits and labor utilization in the fishery. This also allows an increase of about 19% in the number of vessels and the number of fishers at L_{max}. The employment effect will be greater if the unharvested yields by the fleets under study can be captured by other fleets. However, the levels of displacement of vessels and fishers remain large at about 39% and 51%, respectively.

Mesh Size Regulations

Regulations restricting mesh size of fish gears involve changes in the biological constraints following the concept of eumetric yield (Beverton and Holt 1957). A

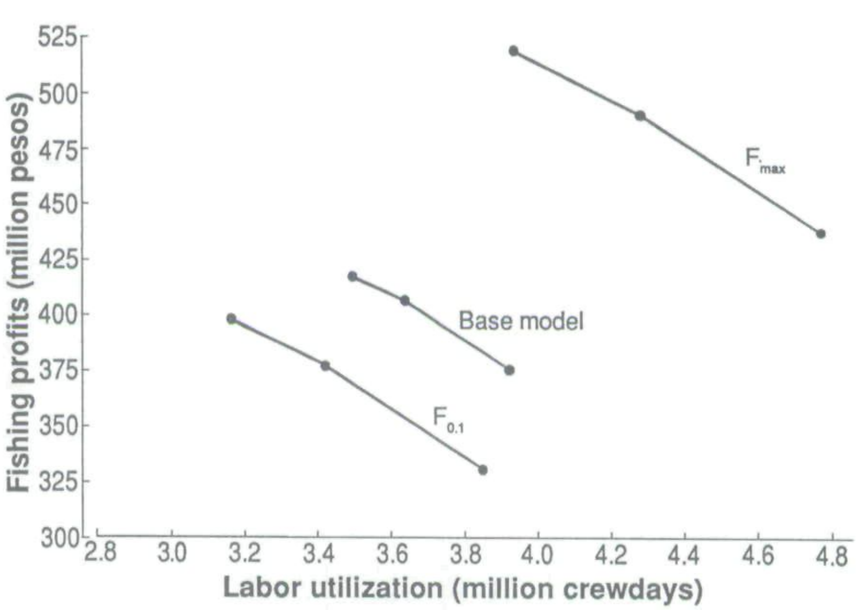

Figure 2. Efficiency frontier in objective space for various regulations of fishing mortality (F)

given yield for each species would be the maximum yield for a specific mesh given. However, the estimation of these yields requires selection data for each mesh size by species and by gear, which is not available.

To examine the effects of mesh size regulations, a simplifying assumption is made. The results in this section, based on this assumption, are illustrative in nature. Fishery yields are estimated by looking at a uniform fish length across species where each length is assumed to correspond to a specific mesh size. Three arbitrary lengths are considered and target fishery yields are computed given the yield-per-recruit curves and recruitment.

The yield-per-recruit and the target fishery yield for each species at various lengths-at-first capture are listed in Table 1 and Table 2, respectively. Combined fishery yield is at a maximum at 10-cm length and decreases with time (or length). This is because for most species, the gain from individual growth is outweighed by loss in natural mortality beyond the 10-cm length. The lengths (10 and 12 cm) considered give a larger yield-per-recruit for the two constraining species, sardine and mackerel. The inclusion of 14-cm length in the analysis is to show that there are limits of increasing the target length for the small pelagic fishes.

The values of the important indicators of fishery performance are given in Table 6. The values of the two explicit objective functions increase for the 10 and 12-cm lengths. The efficiency frontier is illustrated in Figure 3. For the 10 and 12-cm lengths, the number of corner points remains at three, while for the 14-cm fish length the number of corner points is two. Only two of mesh sizes considered yield an improvement over the base results in terms of employment. The number of fishers increased although the results are mixed with regard to the number of vessels. However, the increase in the number of fishers is rather insignificant and there would still be a large displacement of labor from the fishery. Optimizing yields with mesh size regulations alone does not reduce significantly the capital and labor displacement from the fishery.

Policy Response and Further Management Alternatives

This paper has developed a framework for evaluating management options in multispecies multigear fisheries and has applied it illustratively to the small pelagics fishery of Guimaras Strait and the Visayan Sea, which is typical of many fisheries in tropical developing countries. From a productivity perspective, the paper confirms severe overcapitalization and overemployment in the fishery. This is a common finding for open-access fisheries in regions with low alternative employment opportunities.

For the fishery under review, the calculations of this paper suggest that an efficient allocation of fishing effort would displace much more than half of the current labor force, along with a correspondingly large number of vessels, which would thus also reduce the level of capital investment considerably. However, capital invested in this fishery, generally, appears to be earning healthy returns but is declining over the years as the fishers themselves have indicated during the monitoring activities. This suggests a high opportunity cost for capital, owing to its relative scarcity and mobility. It may also reflect monopsonistic access for fishery entrepreneurs to a large supply of cheap, underemployed labor in fishing communities. Given the foregoing, one may well expect government policy to give greater weight to employment maximization than to profit maximization in balancing these dual explicit objectives.

Perhaps one policy option that is worth considering is not doing anything about

Table 6
Major Indicators of Fishery Performance for Various Regulations of Mesh Sizes (Indicated by Length at First Capture)

Item	Base Case Model	Length-at-First-Capture			Percent Change From Base		
		10 cm	12 cm	14cm	10cm	12 cm	14 cm
Fishing profits (million pesos)							
P_{max}	416.87	451.27	457.50	268.17	8.25	9.75	−35.67
Intermediate point	405.51	437.16	444.56		7.80	9.63	
L_{max}	374.55	415.11	441.50	247.09	10.83	17.87	−34.03
Employment (mil. crewdays)							
P_{max}	3.498	3.711	3.788	2.321	6.08	8.28	−33.66
Intermediate point	3.638	3.884	3.946		6.77	8.48	
L_{max}	3.927	4.090	3.975	2.426	4.15	1.22	−38.22
Number of fishers							
P_{max}	25,845	26.574	27.046	15,753	2.82	4.65	−39.05
Intermediate point	29,734	31,415	31,479		5.65	5.87	
L_{max}	31,616	32,749	31,665	19,962	3.58	0.15	−36.86
Total catch (tons)							
P_{max}	73,853	77,896	77,780	53,032	5.47	5.32	−28.19
Intermediate point	72,335	76,039	76,073		5.12	5.17	
L_{max}	76,027	78,650	76,436	50,385	3.45	0.54	−33.73
No. of vessels							
P_{max}	4,795	4,739	4,822	2,689	−1.17	0.56	−43.92
Intermediate point	6,168	6,447	4,364		4.52	−29.25	
L_{max}	6,726	6,842	6,442	4,250	1.72	−4.22	−36.81
Gross tonnage							
P_{max}	10,527	11,078	11,107	7,313	5.23	5.51	−30.53
Intermediate point	10,600	11,171	11,191		5.39	5.58	
L_{max}	11,056	11,495	11,236	7,265	3.97	1.63	−34.29
Total capitalization (million pesos)							
P_{max}	256.07	271.47	277.67	153.09	6.01	8.43	−40.22
Intermediate point	275.16	295.18	298.97		7.28	8.65	
L_{max}	267.45	289.99	298.25	170.95	8.43	11.52	−36.08

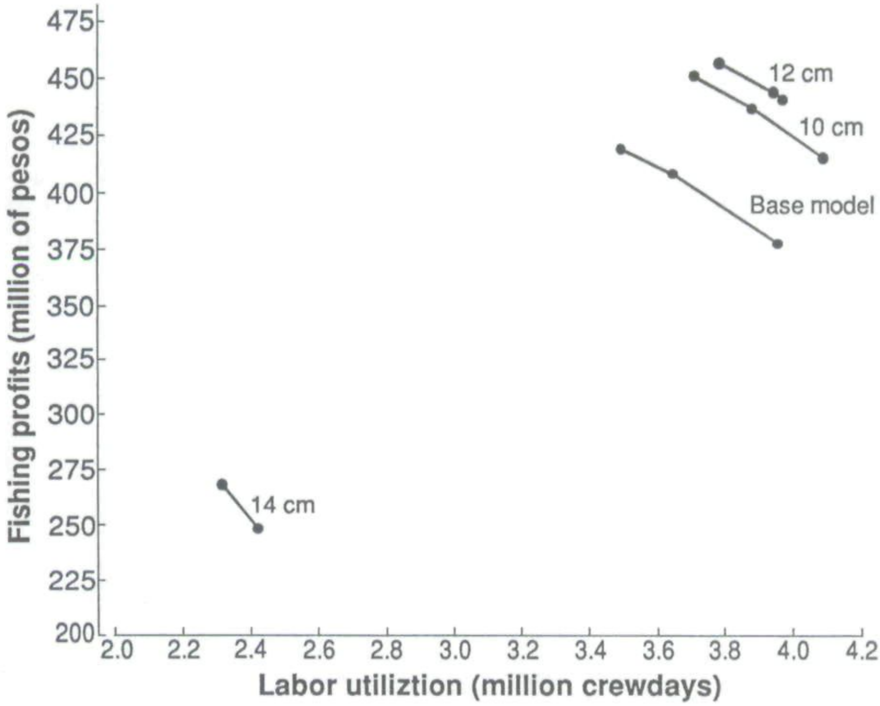

Figure 3. Efficiency frontier in objective space for various lengths-at-first-capture (t_p)

the fishery, *i.e.*, maintaining the status quo. This may be warranted considering the fact that the fishery is not seriously overfished; the average annual landings for each species are not way above the target yield corresponding to a conservative fishing mortality of $F_{0.1}$ (Table 2). It would also avoid the costs of additional regulation. A further option may be to seek gains in net returns from the fishery by realigning the present fleet to the optimal composition without drastically reducing total employment and investment.

Some specific management alternatives were modeled in the paper and tested for their ability to improve the fishery's performance in meeting the twin objectives of profit and employment maximization, subject to resource productivity and equity constraints. The results were not greatly encouraging. The base case modeled in this paper set target catches equal to the historical average yield for 1978–1987. Results were also modeled for two alternative regulated mortality levels. Catch regulation to meet the $F_{0.1}$ mortality criterion gave decidedly poorer results than the base case. The conservationist impact of $F_{0.1}$ management strategies has given reasonably good results with fisheries on longer-lived species in danger of stock depletion. With the shorter-lived species under consideration here, $F_{0.1}$ criteria appear inappropriate.

The model criteria of this paper was also used to test the results of an F_{max} strategy, aimed at maximum yield-per-recruit for each species. Indeed, the calculations based on this strategy offered the prospect of decidedly higher maxima for profits and employment than obtained in the base case. However, as noted above, the pursuit of F_{max} in a small pelagics fishery, with relatively short-lived species, is of dubious merit because the high level of mortality it calls for may involve a significant risk of recruitment overfishing and stock collapse. Given the foregoing considerations, neither the $F_{0.1}$ nor the F_{max} strategy warrants a recommendation for policy adoption.

A biologically low-risk management strategy is to regulate mesh size, with the aim of optimizing size-at-first-capture, in order to maximize annual net growth in the stock and thereby increase the surplus available for harvesting. Calculations showed, indeed, that modest improvements in the maxima for profits and employment could be achieved with mesh sizes targeting fish of 10–12 cm length. It is suggested that government give consideration to a policy of optimal mesh size regulation after detailed study to determine the precise biological and economic impacts, as well as the costs and benefits of effective enforcement.

Probably the greatest dilemma in most fisheries rationalization schemes is how to deal satisfactorily with the question of employment levels in the fishery (Copes 1987). The pursuit of economic efficiency, narrowly defined, almost always calls for a substantial reduction in labor inputs to the fishery. But, in very many cases, there are few realistic prospects for alternative jobs, at least in the short to intermediate term. This makes any substantial reduction in the number of fishers employed socially unacceptable and politically unrealistic. Such appears to be the case also in the fishery studied in this paper. The question then arises whether it is possible to achieve some improvement in economic efficiency without reducing the number of workers participating in the fishery.

What is required is a more labor-intensive fishing strategy. This does not (necessarily) mean any regression to a less advanced technology, but it does suggest a reduction in capital inputs relative to labor inputs. It should be noted that labor inputs in this case are measured in terms of the number of workers employed and not (necessarily) the number of worker-days expended. The reduction in investment should be reflected in both capital and operating cost savings, with a corresponding improvement in net earnings for the fishery. Essentially the approach suggested is one in which, much the same amount of fish is caught as before, with the same number of workers but with much less equipment. The precondition of overcapitalization in the fishery should make this a feasible proposition.

A number of approaches may be considered. The possibility of "employment sharing" has already been mentioned above. This could be achieved by reducing the number of vessels and running them with alternate crews. Undoubtedly there would be transaction costs involved in setting up and maintaining such an arrangement. On the other hand, with shorter individual working time, there would be opportunities to enhance incomes with greater inputs to household production.

Another approach would be to maintain existing fishing units with their full crews, but to reduce their operating costs by rationing gear use and/or fishing time. Gear rationing could be achieved, for instance, by limiting permissible headline lengths on trawls, numbers and sizes of traps used, fathoms of gill net allowed, number of hooks permitted, and length of longline authorized. Time rationing could be achieved either by periodic closures of the entire fishery or (if this caused undesirable interruptions in supply) by requiring different fleet components to fish in alternate periods.

The foregoing discussion suggests that there is room for exploration of additional approaches to achieve more effective management of fishery resources, with better returns to those dependent on the fishery for their livelihood. There are particularly severe difficulties in determining optimal management techniques in the complex case of multispecies multigear fisheries. The authors hope that the model developed in this paper will prove capable of adaptation and expansion, to make it a useful tool in testing new management designs for complex fisheries and in evaluating the prospects for successful implementation.

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Appendix
Bicriteria Programming Model in Numerical Form

Maximize:

$$h_1(f) = 1.8278f_1 + 2.9466f_2 + 8.0307f_3 + 6.5116f_4 + 9.1091f_5 + 8.8520f_6 + 3.4769f_7 + 2.9981f_8 + 1.8481f_9$$

$$h_2(f) = 0.0314f_1 + 0.0511f_2 + 0.0262f_3 + 0.0365f_4 + 0.0577f_5 + 0.0515f_6 + 0.0320f_7 + 0.0397f_g + 0.1253f_9$$

subject to:

Biological constraints

Sardines

$$0.0548f_1 + 0.0654f_2 + 1.7162f_3 + 1.1259f_4 + 0.3060f_5 + 0.1935f_6 + 0.0876f_7 + 0.0124f_8 + 1.1282f_9 \leqslant Y_{sardine}$$

Mackerels

$$0.1849f_1 + 0.3220f_2 + 0.0055f_3 + 0.1808f_4 + 0.5570f_5 + 0.5056f_6 + 0.0884f_7 + 0.1501f_8 + 0.0f_9 \leqslant Y_{mackerel}$$

Crevalle

$$0.3512f_1 + 0.3023f_2 + 0.0f_3 + 0.0013f_4 + 0.1624f_5 + 0.1229f_6 + 0.0f_7 + 0.0292f_8 + 0.0f_9 \leqslant Y_{crevalle}$$

Anchovy

$$0.0f_1 + 0.0f_2 + 0.0f_3 + 0.0f_4 + 0.1506f_5 + 0.0609f_6 + 0.4358f_7 + 0.4219f_8 + 0.0423f_9 \leqslant Y_{anchovy}$$

Round scad

$$0.0585f_1 + 0.0398f_2 + 0.0f_3 + 0.0f_4 + 0.0988f_5 + 0.0503f_6 + 0.0f_7 + 0.0f_8 + 0.0165f_9 \leqslant Y_{round\ scad}$$

Round herring

$$0.0f_1 + 0.0f_2 + 0.0364f_3 + 0.0627f_4 + 0.0019f_5 + 0.0037f_6 + 0.0f_7 + 0.0405f_8 + 0.1346f_9 \leqslant Y_{herring}$$

Big-eye scad

$$0.0024f_1 + 0.0068f_2 + 0.0f_3 + 0.0f_4 + 0.0376f_5 + 0.0f_6 + 0.0f_7 + 0.0f_8 + 0.0f_9 \leqslant Y_{big\text{-}eye\ scad}$$

Proportionality constraints

Danish seine	f_1/f_2	$= 0.7265$
Encircling gill net	f_3/f_4	$= 0.8800$
Purse seine	f_5/f_6	$= 0.8195$
Trawl	f_7/f_8	$= 0.2405$

All fleets

$$(f_1 + f_3 + f_5 + f_7)/(f_2 + f_4 + f_6 + f_8 + f_9) = 0.6644$$

Minimum constraints

Danish seine	$f_1 + f_2$	$\geqslant 23,300,000$
Encircling gill net	$f_3 + f_4$	$\geqslant 410,000$
Purse seine	$f_5 + f_6$	$\geqslant 2,464,000$
Trawl	$f_7 + f_8$	$\geqslant 2,750,000$
Drift net	f_9	$\geqslant 228,000$